THE QUANTIFICATION OF HAZARDS AT LPG INSTALLATIONS

ANAM MOHAMMED NASIR

Master of Philosophy

THE UNIVERSITY OF ASTON IN BIRMINGHAM

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SUMMARY

The literature relating to properties, utilisation, storage and transportation of LPG has been surveyed. Potential hazards were reviewed, particularly those related to fireballs arising from unconfined vapour clouds, boiling liquid / expanding vapour and pool fires. These confirmed the need for quantitative techniques for hazard evaluation and a critical analysis of such techniques, their applications and limitations was carried out.

The main parameters innvolved in evaluating thermal radiation hazards were: mass of fuel, equivalent spherical diameter, duration, height and surface temperature of the fireball.

Published empirical correlations for fireball size and radiation were compared with theoretical models and observations and the best fitting models were established, accurate to ± 5%.

Three new correlations have been proposed to fit published experimental data which relate radiation intensity on human skin to exposure time and to tissue damage, within ±8%.

Thermodynamic considerations have been applied to calculate the theoretical flame temperature of a fireball, giving good agreement with previous models.

A proposed correlation for radiation from pool fires also shows reasonable agreement with published results. However, many factors for pool fires remain unpredictable, such as: shape and size of flame envelope, its temperature and emissivity.

Four methods to find acceptable spacing distances between vessels in hazardous areas are discussed. The results show spacing distance related to fuel released and to explosion yield factor for different damage overpressures. The maximum predicted spacing distances are to be preferred because of the relative unpredicability of unconfined vapour cloud explosions.

The quantitative methods discussed enable a reasonable assessment of major LPG hazards. The possibility of a major fire or explosion at an LPG installation may be minimised by recommended safety measures.

The available hazard evaluation methods have been collected, compared and their limitations assessed in a manner which should be useful to engineers and safety and loss prevention personnel. .

Key words: Liquefied Petroleum Gas
Fire, Explosion, Hazards

I dedicate this thesis to the memory of my
father, to my mother for her patience and
to my husband for his support.

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CHAPTER ONE

INTRODUCTION

Liquefied Petroleum Gas (LPG) is a term used to describe a variety of hydrocarbons which exist as vapours under ambient conditions of temperature and pressure, but can be liquefied by the application of moderate pressure. LPG originates from oil or gas fields, or from refineries where the crude oil is processed. LPG is used mainly for heating or as a feedstock for chemical processes.

In recent years the rapid growth of operations involving the storage, transportation and use of LPG has resulted in problems related to environmental protection, energy conservation, safety and loss prevention. Despite the high standards of care taken in the design, construction and inspection of new and existing process plants, hazardous incidents still occur. The scale and variety of LPG operations have increased to an extent that fire and explosion incidents that occur may put not only the whole process plant and its personnel at risk, but also possibly a large number of inhabitants and buildings in the surrounding area. For example on November 19th, 1984 a disaster involving an LPG installation occured in Mexico City which resulted in the deaths of over 500 people and injury to 7,231, of whom 144 died in hospital.

The main types of hazard associated with LPG plants are:

i. Major fires: pool or flash fires can occur when the three conditions of fuel, air and ignition sources are available. Here radiant heat is the main effect causing burns to exposed persons, and a danger of secondary fires or explosions.

ii. Explosions: these include;

(a) Confined Vapour Cloud Explosions (CVCE): when a fuel/air mixture is ignited within equipment or buildings, allowing the pressure to build up inside the confined volume until rupture of the container or collapse of the building wall occurs.

(b) Unconfined Vapour Cloud Explosions (UVCE): when a large fuel/air cloud burns in free space at a sufficiently rapid rate to generate pressure waves which propagate both through the vapour cloud and into the surrounding environment.

(c) Boiling Liquid Expanding Vapour Explosions (BLEVE): when a pressure vessel containing flammable liquid is heated so that the metal loses strength and ruptures. The effects of BLEVEs are thermal radiation caused by a fireball, a blast wave and missiles.

Many experimental and theoretical approaches have been published in an attempt to analyse and mitigate the above problems. However, the subject is extremely complicated; it is affected by a number of factors, eg the physical properties and conditions of the gases and liquid involved, the nature and type of storage and transport, the degree of hazard involved, the topography of the region considered, the atmospheric and weather conditions and the density of neighbouring populations.

Therefore, quantitative methods for the identification and assessment of hazards have always been used by the process industries to try to ensure that plants are reasonably safe. The need to quantify hazards in process plants arises because of the need to avoid losses and costs that could cause business interruption and sometimes complete closure. Safety is an important factor in the appraisal of the acceptability of an industrial activity; it should be considered together with the economic benefits to the community.

The present work includes an evaluation of the hazard ranges for fireball and pool fires, to people, processes and buildings, based on the radiant flux densities which have an effect on human skin, buildings and processes. This study also includes predictions of spacing distances for plants involving UVCEs for which several methods have been proposed for the calculation of acceptable spacing.

The results computed from the various methods used have been compared. The maximum figure is preferred for conservative spacing and the design of mitigatory measures. The purpose of this study is to present an assessment of the main quantitative methods available to assess LPG hazards in the process industries and to draw together sufficient detail to be useful to engineers and safety and loss prevention personnel concerned with LPG handling and use.

CHAPTER TWO

GENERAL CHARACTERISTICS OF LIQUEFIED PETROLEUM GASES

2.1 DEFINITION

The term "liquefied petroleum gas" or LPG, refers to hydrocarbons obtained from petroleum refining operations (ie distillation, reforming, stabilisation), or from compression and/or absorption processing of natural gas and which are gases at normal atmospheric temperature and pressure, but can be readily liquefied with either a moderate increase in pressure or a moderate drop in temperature or both. These hydrocarbons including propane, butane, butylene and propylene and mixtures of these gases are the principal liquefied petroleum gases [1, 2, 4]. The more readily-liquefiable gases of this group are commercial propane and commercial butane, each of which contains several of the other hydrocarbons mentioned in varying amounts. Butadiene is also a liquefied petroleum gas; it is chiefly used in the rubber industry and not as a constituent of LPG fuels.

2.2 SOURCES OF LPG

The main sources of liquefied petroleum gases are natural gas the crude oil/gas mixtures that come out of actively producing oil and natural gas wells, which are removed as condensible products by compression and/or absorption processes, and from the crude oil stabilisation process which is applied in order to provide an appropriate vapour pressure for shipping. These sources are supplemented by secondary supplies produced within the course of certain refining processes in oil refineries [1, 2].

The composition of liquefied petroleum gases varies according to both the conditions used in the refining processes and the type of crude oil used as feedstock

2.3 GENERAL CHARACTERISTICS OF LPG

The two principle liquefied petroleum gases in general use are defined in BSS 4250 and, from the principle constituents, are termed 'commercial' propane and butane. The contaminants usually comprise varying amounts of, for example, propylene and butylene plus some ethane and possibly some methane. Almost pure propane and butane can be obtained for special purposes.

The general characteristics of LPG are summarised as follows [2, 3, 4, 5]:

a. LPG at normal temperature and pressure is a gas which is heavier than air. Butane is about twice as dense and propane one and a half times as dense as air at normal temperature and pressure.

b. LPG is easily-liquefied under moderate pressure at atmospheric temperature. The density of the liquid is approximately half that of water.

c. Pure LPG is non-corrosive to steel, copper and copper alloys.

d. LPG is colourless in the liquid and vapour phases. However, any leak is often detected by the presence of frost due to the evaporation of the LPG which causes a local reduction in temperature and freezing of moisture from the surrounding air.

e. LPG is odourless, so to assist detection a stenching agent (such as ethyl mercaptan) is added to enable detection by smell at a concentration of one fifth of the lower flammable limit [3], except when the intended use requires a gas free from odour, as in the manufacture of aerosols.

f. LPG is non-toxic but has anaesthetic properties when inhaled in quantities for a long period; inhalation in moderate concentration produces nausea and headache, ie at concentration of 10% the vapour is not noticeably irritating to the eyes, nose or lungs, but will produce slight dizziness in minutes [4]. Table 2.1 lists the properties of chemically pure hydrocarbons [6], and Table 2.2 lists the properties of commercial propane and butane [4, 7].

2.4 HAZARDOUS PROPERTIES OF LPG

Nowadays the preference for gaseous fuel rather than liquid or solid, has produced situations in which the public may be increasingly exposed to potential risk of injury from fires or explosions. The hazardous properties of LPG are summarised as follows:

a. LPG in the liquid phase has a low relative density, ie half that of water, and this has implications for the control of fire after large accidental spills, since it floats and will spread on water.

b. A large quantity of vapour can be obtained from a small quantity of liquid (1 volume of liquid produces over 200 volumes of vapour).

c. LPG becomes flammable when mixed with air in a concentration within the flammable range by volume, for example the flammability limits of LPG in air (by volume) are 1.5% to 10% [8]. So 4.5 litres of butane when vaporised will produce not less than 900 litres of gas at atmospheric pressure and 60 °F (15.6 °C); thus at 5% concentration in air, 18.12 m^3 of flammable mixture would be formed.

d. LPG vapour is denser than air , ie propane vapour at ambient temperature having a density of approximately one and a half times that of air, while that of butane is approximately twice the density of air, will sink to the lowest possible level, possibly through drains and sewers, cable conduits or natural fissures and flow downhill. Unless dispersed such accumulation may persist for long periods with the possibility of subsequent ignition at a considerable distance.

e. LPG has a calorific vlaue of 2 to 3 times that of natural gas, so heat radiation from LPG fires is relatively high.

f. LPG in the liquid phase evaporates rapidly at ambient temperature causing severe frost "burns" when in contact with skin.

2.5 UTILISATION

The expanding field of utilisation of liquefied gaseous fuels has been largely reflected in the increased number of uses for which these gases have been found acceptable. Because of the large population areas not served by gas mains, ie without convenient supplies of natural gas, its utilisation reaches from the more common domestic uses to specialised commercial applications [3, 7]. The farm, camp or resort operator now has clean, convenient LPG fuel available for the domestic gas range, the gas refrigerator, the gas water heater and the gas fired space heater, to mention the four principal gas fuel applications. More extended uses include that for commercial refrigeration in preserving fruits and vegetables, gas engine power for sawing wood and motor fuel for the operation of trucks and tractors used on the farm, and on construction and road building projects.

Another rapidly-growing classification is the commercial and industrial application in which the portability of the LPG cylinder is important. These include those of the plumber, mechanic, tinsmith, and other tradesmen serving the home and industry [3].

The utilisation field in internal combustion engines is very broad. It includes both the stationary type of gas engine, such as that used for the generation of electric power, for waste pumping and for oil field use.

In the transportation field its use extends from the smallest to the largest trucks and buses and its application in air-conditioning machines for rail cars.

The high octane value of LPG permits its use in all types of gasoline and oil engines after these have been converted with special tanks, heat exchangers and carburettors. Reduced maintenance costs, increased economy and saving in crank case oil consumption are some of the advantages obtained in using propane or butane as fuel. So there are benefits both to the industry in utilising LPG, and to the environment because of the low sulphur content which almost eliminates the production of sulphur dioxide (SO_2) during combustion [3, 7].

Many uses for these gases have been developed in chemicals manufacturing. At the present time iso-butane is made into motor fuel by suitable processes. Special grades of propane, normal butane, iso-butane and butadiene are being used in the manufacture of nitro-paraffins, plastics, synthetic rubber and synthetic textiles.

In summary, wherever heat, air conditioning, power or refrigeration is required there is scope for the utilisation of LPG.

TABLE 2.1

PHYSICAL PROPERTIES OF LIGHT HYDROCARBONS [6]

	Methane	Ethane	Propane	Isobutane	Butane	Pentane
Molecular volume of gas, cu.ft. @ 60 °F†	378.7	375.8	372.7	366.7	365.40	
Molecular weight of gas	16.04	30.07	44.09	58.12	58.12	72.15
Gal./lb.-mole at 60 °F	6.4 #	9.64	10.41	12.38	11.94	13.71
Weight:						
% carbon	74.88	79.88	81.72	82.66	82.66	83.33
% hydrogen	25.12	20.12	18.28	17.34	17.34	16.66
Specific gravity:						
Of liquid (water = 1)	0.248	0.377	0.508	0.563	0.584	0.631
Of liquid, °A.P.I	340 †	247	147	120	111	93
Of gas (air = 1)	0.555	1.048	1.550	2.077	2.084	2.490
Weights and volumes:						
Lb./gal. liquid	2.5 †	3.145	4.235	4.494	4.873	5.250
Cu. ft. gas/gal. liquid	59.0 †	39.69	36.28	30.65	31.46	27.67
Cu. ft. gas/lb. liquid	24.8	12.5	8.55	6.50		
Ratio, gas volume to liquid volume§	443 †	293.4	272.7	229.3	237.8	207.0
Initial boiling point (atmospheric pressure)	-259	-128.2	-43.7	10.9	31.1	97
Heat value (gross):						
B.t.u./cu. ft. gas	1,012	1,786	2,522	3,163	3,261	4,025
B.t.u./lb. liquid	23,885	22,323	21,560	20,732	21,180	21,110
B.t.u./gal. liquid		70,210	91,500	103,750	102,600	110,800
Vapour pressure, lb./sq. in. abs						
At -44 °F		88	0	-9	-12	-14
At 0 °F		206	38	12	-7	-13
At 33 °F		343	54	17	0	-11
At 70 °F		563	124	45	31	-6
At 90 °F		710	165	62	44	-
At 100 °F		-	189	72	52	4
At 130 °F		-	275	110	81	11
At 150 °F		-	346	138	87	21
Latent heat of vaporisation at boiling point:						
B.t.u./lb.	221	211	185	158	167	153
B.t.u./gal.	553	664	785	742	808	802
Specific heat:						
Of liquid, C_p at 60 °F., B.t.u./(lb.)(°F)		0.780	0.588	0.560	0.549	
Of gas, C_p at 60 °F., B.t.u./(lb.)(°F)	0.526	0.413	0.390	0.406	0.396	0.402
Of gas, C_v at 60 °F., B.t.u./(lb.)(°F)	0.402	0.347	0.346	0.373	0.363	0.376

† Ideal gas = 379.5 cu. ft. @ 60 °F or 15.5 °C
# Apparent values for dissolved methane at 60 °F
§ Based on "perfect gas".

TABLE 2.2

TYPICAL PROPERTIES OF COMMERCIAL LPG GRADES [4, 7]

Properties		Commercial butane	Commercial propane
Relative density of liquid at 15.6 °C (60 °F)		0.57 to 0.58	0.5 to 0.51
Imperial gallons/ton at 15.6 °C		385 to 393	439 to 448
Litre/tonne at 15.6 °C (60 °F)		1723 to 1760	1965 to 2019
Relative density of gas compared with air at 15.6 °C and 1015.9 mbar (30 in Hg)		1.90 to 2.10	1.40 to 1.55
Volume of gas (litres) per kg of liquid at 15.6 °C and 1015.9 mbar		406 to 431	537 to 543
Volume of gas (ft^3) per lb of liquid at 60 °F and 30 in Hg		6.5 to 6.9	8.6 to 8.7
Boiling point (°C) at atmospheric pressure		-2 approx	-45 approx
Vapour pressure (bars) for products at their maximum specified vapour pressure. Temp	-40 °C	-	1.38
	-17.8 °C	-	3.11
	0 °C	1.95	5.52
	37.8 °C	5.86	15.5
	45 °C	6.89	18.6
Latent heat of vaporisation (kJ/kg) at 15.6 °C		372.2	358.2

Cont'd/...

TABLE 2.2 - Continued/...

Properties	Commercial butane	Commercial propane
Latent heat of vaporisation (Btu/lb) at 15.6 °C	160	154
Specific heat of liquid at 15.6 °C (kJ/kg °C)	2.386	2.512
Specific heat of liquid at 60 °F (Btu/lb °F)	0.57	0.6
Sulphur content, percent weight	Negligible to 0.02	Negligible to 0.02
Calorific values		
Gross: MJ/m^3	121.8	93.1
MJ/kg	49.3	50
Net: MJ/m^3	112.9	86.1
MJ/kg	45.8	46.3
Therm/ton (gross CV)	475	485
Air required for combustion (m^3 to burn 1 m^3 of gas)	30	24
Limits of flammability (percentage by volume of gas in a gas-air mixture to form a combustible mixture)		
lower flammable limit	1.8	2.2
upper flammable limit	9.0	10.0

CHAPTER THREE

STORAGE, TRANSPORTATION AND MODES OF CONTAINER FAILURE

3.1 STORAGE SYSTEMS

Liquefaction of petroleum gases under certain conditions of pressure and temperature permits convenient and econmical storage and transportation of large quantities of these gases.

There are two types of storage:-

3.1.1 Pressurised Storage:

Light gases such as propane and butane liquefy readily when subjected to a pressure equal to their respective equilibrium vapour pressure; this pressure varies according to temperature [2, 3, 4].

		Temperature °C	
		15.6 °C (60 °F)	37.8 °C (100 °F)
Equilibrium vapour pressures	Butane	103 kPa (15 psig)	483 kPa (70 psig)
	Propane	518 kPa (75 psig)	1400 kPa (210 psig)

In practice the commercial grades of LPG are not pure, being contaminated with small amounts of other low molecular weight hydrocarbons. In the storage of commercial grades of LPG, it is necessary to take into consideration that the equilibrium vapour pressures of commercial grades of propane and butane are somewhat higher than those for the pure gases. This is illustrated in Figure

(3.1).

Pressure storage tanks must therefore be designed and constructed to withstand the highest vapour pressure encountered in use. This will depend upon the highest temperature to which the contents will be elevated in use, usually by solar heating.

Static installation tanks are usually constructed in accordance with a relevant standard such as BSS 5500, ACTC Rules and others. The design pressure must not in any case be less than 489 kPa for butane and 1470 kPa for propane.

Pressure storage tanks are fabricated from special steel and are inspected for soundness by a variety of sophisticated techniques for incipient cracking and full weld integrity. It is usual to inspect them at about five yearly intervals in service.

Occasionally pressure storage tanks at fixed installations are buried below ground to eliminate fire impingement and solar heating upon the shell. These are given external protective coatings to resist soil corrosion, and in addition cathodic protection is employed. It is important to ensure that such tanks are securely fixed since ingress of water around even full tanks will produce severe flotation induced stresses which could rupture associated piping. Indeed, any associated piping needs to be of high integrity and well-supported and protected.

These submerged tanks may be more expensive but are a viable proposition in congested areas where spacing requirements cannot be met.

Above ground pressure storage tanks at fixed installations are spaced to provide access for fire fighting [9] and to avoid the spread of fire from tank to tank. The tanks are usually elevated above the

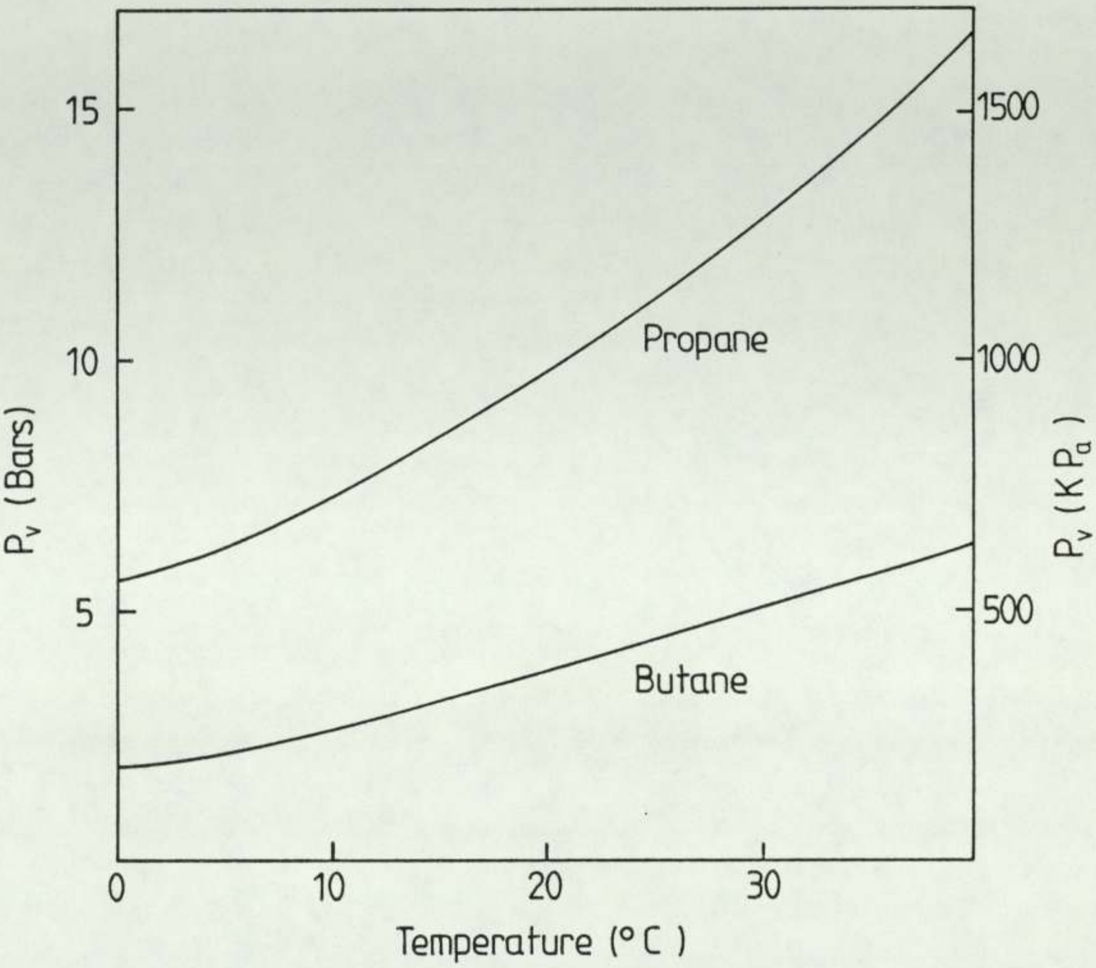


Figure 3·1 Approximate Maximum Vapour Pressures for Commercial Propane and Butane ground and the ground beneath them is concreted, and sloped away from the tank, to prevent accumulation of spilled LPG below the tank. Such installations are sometimes fitted with water drench systems intended to cool the shell of the tank in the event of a fire below, or of high radiant heating from adjacent fires. Such above ground tanks are often grouped in a fenced compound, to prevent trespassing or tampering. Sabotage is a very real threat.

All large scale pressure storage vessels are fitted with spring-loaded pressure relief valves set to vent vapour to atmosphere in the event of an undue pressure increase. Ideally the valve capacity should be such that it will cope with the maximum vapour production at the reference temperature plus the vapour production under fire conditions. Installation of a relief valve is not, unfortunately, sufficient to guarantee tank integrity in the event of fire; there are instances on the record of valves sticking shut.

These tanks need a variety of safety devices in addition to relief valves. All openings should be equipped with excess-flow valves that prevent uncontrolled product flow to atmosphere, in the event that piping connected to a tank opening is ruptured or broken-off. Some high pressure tanks are equipped with rupture disks which permit the vapour to escape at a greatly accelerated rate.

A precaution which must be taken into consideration for relief valves and rupture discs is that connections should be equipped with stacks so that discharged vapour will not strike personnel. These stacks should be located so that they will not vent into enclosed spaces or towards air intakes or sources of ignition.

Small scale storage of LPG is always under pressure in containers as diverse as the small disposable cartridges used for fuelling cigarette lighters, to the 100 kg cylinders, ie "bottles".

Cylinders are tested to the minimum pressures for commercial propane of 2200 kPa and for commercial butane of 750 kPa, and are provided with radically different coupling threads to prevent butane-rated equipment from being inadvertently fitted to a propane cylinder, and vice-versa.

Cylinders are subjected to visual examinations to check for any mechanical damage and that they are leak-free prior to filling. However, the accident record is replete with instances of cylinders attached to portable appliances being responsible for massive damage due either to slow leakage and accumulation and subsequent ignition of explosive levels of gas within buildings or by catastrophic failure when subject to fire. To counter this last threat, most cylinders are now being fitted with relief valves to relieve internal pressures caused at elevated temperatures.

The common configuration of storage tanks [10] as illustrated in Figure 3.2 and 3.3 are:

i) **Cylindrical** - these pressure tanks range in size from 4.35 kg "bottles" to approximately 165,000 gal "blimps" and in pressure from 200 bar (in small size only) down to 2 bar. The cylindrical type of tank is the most commonly used since it is economical to manufacture, of convenient configuration for movement, and can be mounted on single foundations using conventional erection procedures. It can be designed with good integral structural strength. Rail tank cars, transport trucks and barge tanks are invariably cylindrical.

ii) **Spherical** - these tanks are usually fabricated at the erection site. They are subject to the same limitations in size as horizon-

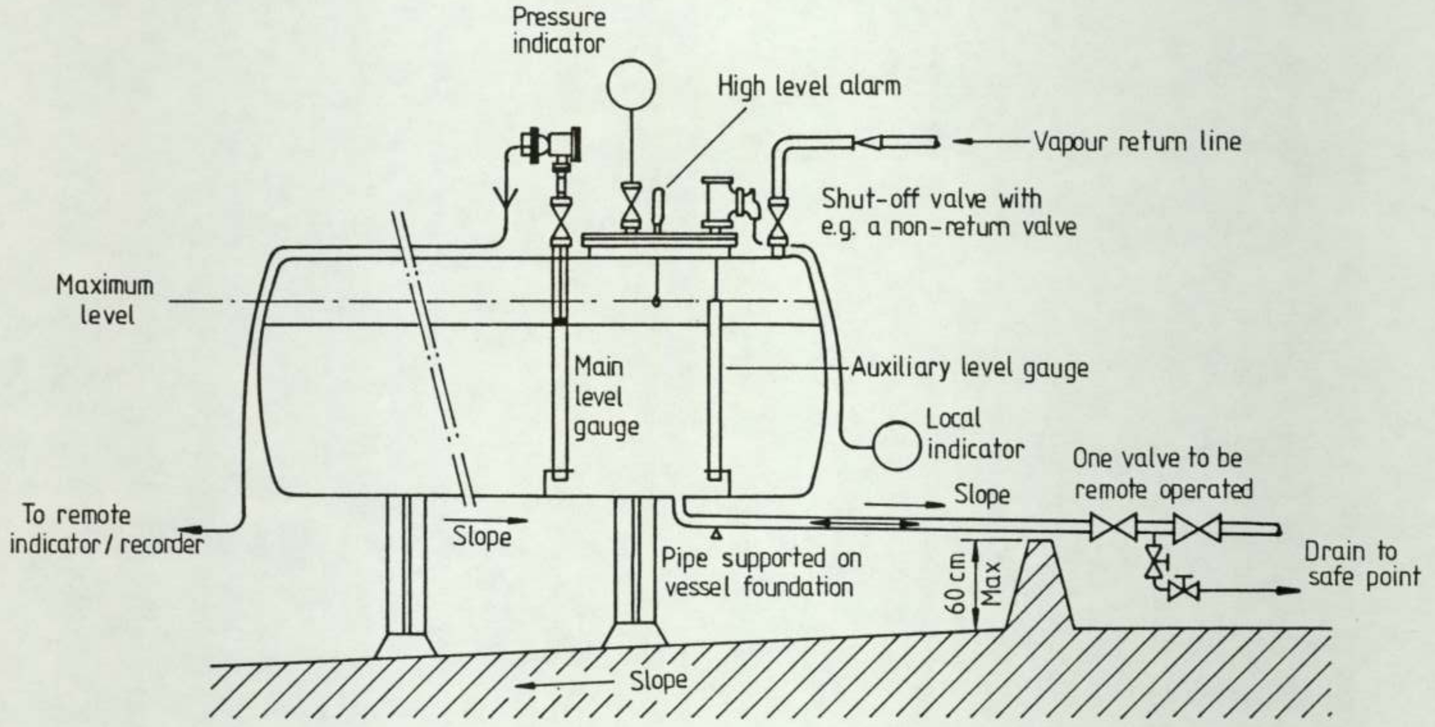
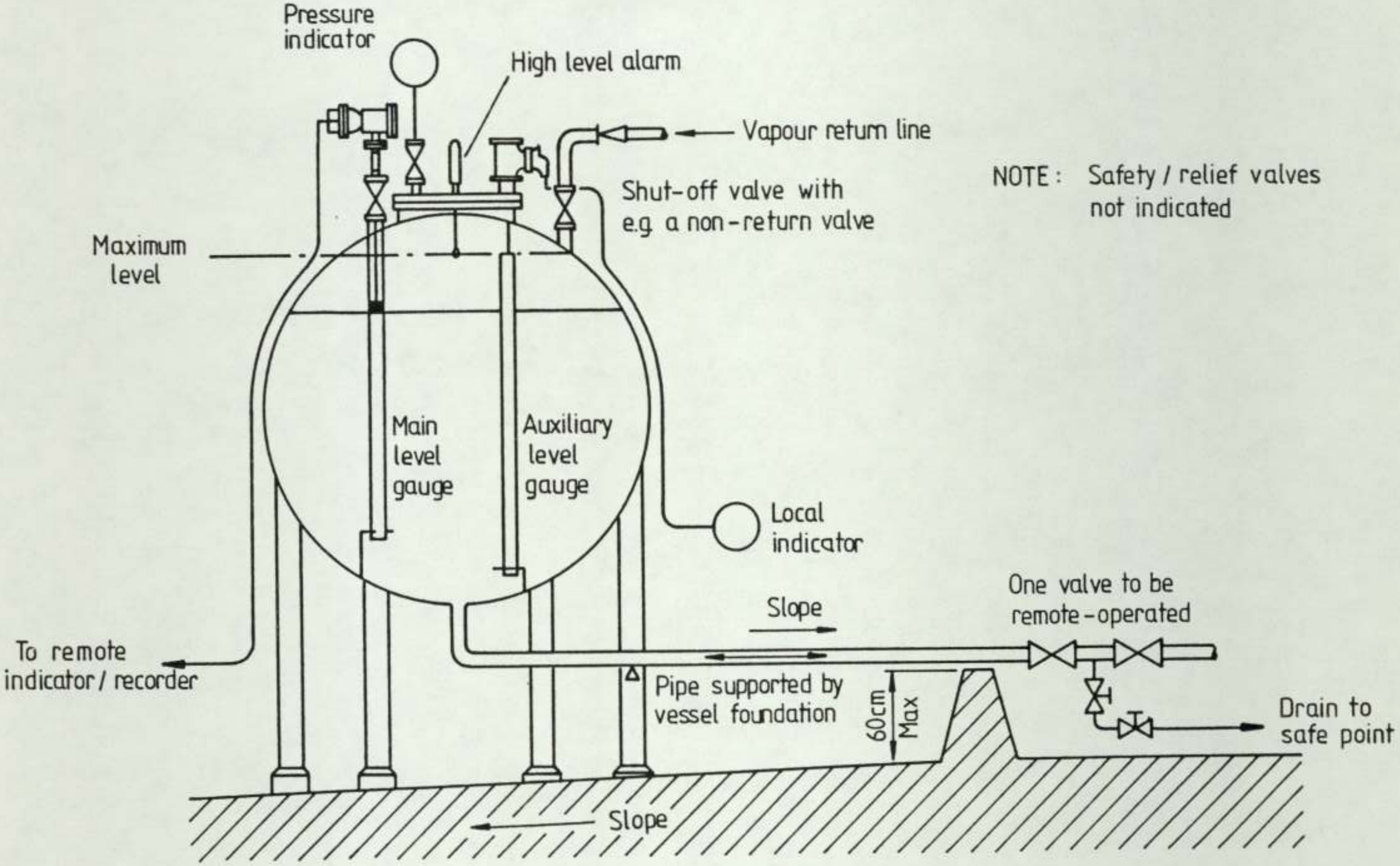


Figure 3·2 Typical LPG Atmospheric Temperature Storage Tank - Cylindrical
[n.b. Many companies instal a shut-off valve immediately beneath the vessel]



NOTE : Safety / relief valves not indicated

Figure 3.3 Typical LPG Atmospheric Temperature Storage Tank - Spherical.
[n.b. Many companies instal a shut-off valve immediately beneath the vessel.]

tal cylindrical tanks. Their principle advantage is that they represent a minimum expenditure on steel. Segments of spherical tanks can be formed at the factory and stacked for shipment; they are the favoured type for the export trade because of space saving during transportation.

iii) **Spheroid** - these tanks are generally used in the vapour pressure range below 15 psia. They can be made in very large sizes. Configurations may involve combinations of shapes such as the sphere/torus type and the more oblate spheroid type.

3.1.2 Refrigerated Storage

Butane and propane can easily be liquefied by cooling below their respective boiling points. When chilled as liquid they exert little pressure upon the container which has advantages for engineering purposes. The tank can be of relatively light construction and there are no construction material problems such as the cryogenic-shock associated with liquefied natural gas (methane) which has a boiling point of approximately –160 °C.

Refrigerated tanks are fitted with a pressure relief valve to relieve the increase in internal pressure following failure of the refrigerating system, or fire impingement.

It is usual to insulate such tanks heavily with a variety of materials: expanded polystyrene, rock wool and perlite are common. Any insulation material needs to fulfill a number of criteria, such as [3]:

a. withstanding impingement of water jets.

b. resisting the ingress of water vapour

c. maintaining effectiveness even if mechanically damaged.

d. resisting fire, either intrinsically or behind protective cladding.

Refrigerated storage tanks are constructed with an outer cladding, such as aluminium sheeting, to protect and contain the insulating material, which may be of the order of 900 mm in thickness; the interspace may also contain inert gas. Because the insulation and refrigeration systems add greatly to the complexity of such storage, refrigeration is usually only applied for large static installations of 2000 tonnes or more, or for bulk carriage by sea [2].

The Canvey Report [11] has identified a potential hazard from large refrigerated butane storage tanks that is of interest. Referring to British Gas refrigerated tanks of 5000 and 10,000 tonnes capacity, it points out that these are used near atmospheric pressure and were designed primarily to withstand the head of liquid. The mode of failure of such a tank when containing butane is diametrically opposed to that of an identical tank containing oil. If such a tank, containing oil, were to develop a horizontal split at a welded seam, then the weight of the upper part of the tank would tend to keep the split closed. Relief valves for refrigerated storage are set to quite low values, a few centimetres of water only; however this slight positive pressure in the same type of tank, but containing butane, would cause the top of the tank to lift and the split to gape further open. Thus the outflow of the tank contents would increase and possibly engulf the surroundings with consequent dangers.

Although bunding is not recommended around pressurised storage tanks or semi-refrigerated storage tanks, creating as this would the potential for a large pocket of explosive vapours, they are spaced at appropriate separation distances [12]. In general bunds are provided for atmospheric storage tanks and for fully refrigerated storage tanks to contain spilled refrigerated LPG. This has the effect of limiting heat input to the spilled liquid, reducing the rate of vapour generation and subsequent formation of a large explosive vapour cloud [12]. It is also argued that such containment of a large spill is desirable to facilitate 'mopping up' operations, where the liquid could be transferred to road or rail tankers and thus be contained under pressure conditions as the LPG liquid subsequently warmed to ambient temperature. So it is possible to envisage circumstances under which such bunding would be a positive disadvantage in the event of tank leakage. Should such a spill ignite there, a contained and possibly sustained fire would ensue at the tank wall, and the light cladding used to protect the insulation would probably fail. Heat input into the tank contents could then generate vapour in excess of relief valve capacity and perhaps lead to tank failure.

Furthermore the presence of a surrounding pool of cold butane would preclude the use of water to cool the tank wall, as this water would perforce drain into the bund. Experiments have shown that under these circumstances water freezes to form an ice slurry which, being denser than the butane, sinks to the bottom of the pool. In large quantities this would cause displacement of the butane onto the surrounding site, over the top of the bund. This would increase the rate of evaporation and the incident would escalate rapidly in both size and seriousness [3].

Some practical aspects of the design of bunds for flammable liquids have been discussed by Hearfield (12). One fact which should be noted is that a leak in the side of a tank may form a horizontal jet which may jump the bund if the latter is too close to the tank. Therefore the bund wall should be far enough from the side of the tank to prevent a jet jumping over or, alternatively, the bund should be surrounded by an impervious surface sloped inward to the bund drain area.

The corners of the bund should be rounded and not at a right angle, since it is difficult to extinguish a fire in a 90° angle corner because of the air compression effect.

The bund should be adequately drained, with a valve on the inlet end of the drain but outside the bund wall. Walls for full bunding should not be so high as to hinder fire fighting. The ICI LFG Code suggests a maximum height of 2 m with an allowance of 0.15 m freeboard above the predicted liquid level. This leaves room for a foam blanket. There should be a minimum of two access points on opposite sides of the bund to allow safe access in all wind directions. Access may be provided by steps over the bund.

Recommendations for pressure storage vessels vary. Hughes recommends that LPG vessels smaller than 30,000 UK gal (136 m^3) should be surrounded by a layer of gravel only, while vessels larger than this should stand on a concrete apron sloping down to a catchment area again provided with gravel to assist vaporisation. A low protective wall 0.4 m high may be provided if considered necessary.

The HSE recommendations for LPG are that there should be low walls not exceeding 0.61 m around the vessels [12]. These should be built sufficiently far from the vessels to allow free circulation of air, the minimum distance being 1.5 m even for small installations. The walls should not be designed to retain any specific quantity of liquid.

An unusual hazard from refrigerated LPG storage may occur when a large refrigerated tank is used to store high molecular weight hydrocarbon such as pentane in a warm climate [3]. In this case, refrigeration is necessary to keep the vapour pressure at a low value although the ambient temperature is high. However, in a reported incident when the refrigerant line started to leak the low molecular weight hydrocarbon refrigerant into the pentane this led to an increase in the vapour pressure to a value which was sufficient unduly to stress the tank, due to the fact that the relief valve was "stuck shut". In this case the tank attempted to become spherical and eventually the top blew off. In the description of this incident a cloud of vapour rose 45 to 60 metres in the air and then, being denser than air, as are propane and butane, settled back and spread over the surrounding area. After thirty seconds, or so, the cloud found an ignition source and a large fire storm ensued.

This incident may point to the need to ensure that all refrigerated storage of LPG utilises as refrigerant the same material as that to be stored.

3.2 TYPE OF CONTAINERS

3.2.1 Cartridges

Disposable cartridges are used in large numbers, largely in the leisure field, in content of weight of up to approximately 0.45 kg [7]. The major disadvantage of this type of cartridge is that it cannot be removed from the appliance until it is exhausted, otherwise the gas in its liquid phase may flash vaporise and may result in cold burns, or fire if a source of ignition is present.

3.2.2 Cylinders

Refillable cylinders are used mainly for domestic and light industrial applications and range in content weight from approximately 5 kg to 46 kg capacity. They are designed specifically for either butane or propane due to the considerable gauge pressure differences:

Butane: 2 bar (28 psig)

Propane : 7 bar (100 psig)

The fittings on these cylinders are not interchangable. These cylinders are pressure vessels and therefore have to be tested periodically before and during usage. The first retest is required 10 years after the date of manufacture with subsequent retest required at 5 year intervals. These retests may be accomplished by visual inspection procedures as prescribed by the ICC [13]. Each cylinder should bear a manufacturer's serial number, year of manufacture, the specification to which is was built; the date of test, the test pressure, and the minimum hydraulic capacity of the vessel. The cylinders are visually examined prior to filling and the valve checked for leaks with soap solution.

3.2.3 Bulk Tanks

Storage at user's premises normally consists of individual tanks ranging from under one tonne to over 100 tonnes capacity. At a small number of premises with large consumption and at refineries much larger tanks may be found. Most LPG tanks are cylinders with dished ends, although some small tanks and most very large ones are spherical in shape.

All the cylinders and bulk vessels referred to above must be physically adequate for the stresses involved. They must be gas tight, be provided with safety relief valves where necesary, and be marked for ready-identification. Their design, characteristics, testing, inspection, retesting, handling, and siting when stationary are all covered by established codes of practice, such as those issued by the LPGITA. Standards, or regulations, some of which are mandatory.

Before embarking on any project involving the installation of LPG facilities, it is important to ensure that any statutory requirement in respect of such installations will be compiled with. A check should be made that the proposed installation will comply with the requirements of all appropriate bodies, such as in the UK, the Factory Inspectorate, who administer the Highly Flammable Liquids and Liquefied Petroleum Gases Regulations 1972 (BI 917) made under the Factories Act 1961, and the Local Fire Authority.

In addition to conforming to any statutory requirements, it is advisable to be guided by appropriate Codes of Practice. In this connection a number of codes have been prepared by the LPGITA (UK) covering both LPG installation and the utilisation of LPG [4].

3.3 TRANSPORTATION

Producers and consumers are , in most instances, separated by considerable distances, since the production plants are located principally in the oil and gas producing regions of most countries, while the potential markets extend to sections far removed from these points. Hence large quantities of propane and butane must be transported over long distances by safe and economical methods.

For several years the only facilities for transporting these liquid gases were small metal cylinders, commonly called "bottled gas" cylinders, and only those customers who were reasonably close to the source of supply could economically use this type of fuel.

Liquefied petroleum gases are transported in much the same manner as other petroleum products, except that the metal containers must be of sufficient strength to withstand the vapour pressure resulting from certain maximum atmospheric temperatures that will be encountered. The containers must also be equipped with safeguards as called for by local regulations.

The pressure within the container increases with the temperature of the liquid, which in turn is governed by heat transfer from the outside temperature. This heat transfer is relatively slow, so tank temperatures, rarely approach maximum atmospheric temperatures, and are usually lower by -12 °C (10 deg F) or more [13]. LPG is transported in varying quantities by road, rail, ships and pipelines.

Road tankers are used for transporting bulk loads between 1 and 20 tonnes, and railcars carry individual bulk loads of 10 to 90 tonnes. Tanks of more than 5 m^3 capacity are fitted with internal baffles to minimise internal surging of the contents. The maximum capacity of the tankers for use on the road in the UK is determined by the current Motor Vehicle (Construction and Use) Regulations, and by ullage (air space) needed.

Liquefied petroleum gas has a relatively high volumetric coefficient of expansion and, therefore, any container should be filled to a limit which permits liquid expansion due to normal rises in temperature without danger of overstressing the container by hydraulic pressure. So it is necessary to ensure that the maximum amount of LPG in any road tanker should be such that the tank will be not more than 97% full with the contents at the highest temperature likely in service, this is termed the Reference Temperature for Filling Ratios and is currently in the UK 42.5 °C for tanks of 5 m^3 water capacity and below, and 38 °C for tanks over this [14]. The maximum permitted LPG filling by weight is given by [14]:

$$W_1(\text{kg}) = 0.97 \times V_1 \times \rho_{(\text{ref})} \qquad \text{.... (3.1)}$$

where: V_1 = water capacity of vessel in litres

$\rho_{(\text{ref})}$ = the relative density of LPG at the reference temperature for filling ratio (RTFR)

In any case, the tank should not be filled so that a liquid full condition can arise at a temperature 5 °C in excess of the RTFR [14].

At low ambient temperature there may be a fall in the LPG vapour pressure to a value below that of the atmosphere. Therefore the tank must be designed to withstand this unaccustomed external stress, or alternatively be equipped with some system to relieve the vacuum. It is usual to assume for this purpose a design temperature of -10 °C, when the vapour pressure of n-butane is about 35 kPa below atmospheric.

Tanks for road transport are frequently used to carry a variety of materials. If a tank is so used, it is essential to ensure that it is suitable for all the substances handled.

Some important features of road tankers which should be considered are:

i - design basis,
ii - material of construction,
iii - reference temperature,
iv - minimum wall thickness,
v - safety valves, and
vi - attachment to vehicle

LPG is transported by pipelines which are usually buried about a metre below ground. The older pipelines had no specific external protection, then the wrapping of lines was developed, culminating in the present practice of using a coal tar/glass fibre wrap [12]. But corrosion still occurred at points where the wrapping was badly done or was damaged or where there were line joints. This problem has been largely overcome by the use of cathodic protection. Minimum external corrosion rates are obtained with the new method of external protection which utilizes a combination of wrapping and cathodic protection.

Coastal and ocean going ships with multiple pressure storage tanks of up to 3000 tonnes total LPG capacity are in service, and refrigerated low pressure storage tankers of 3000 to 4000 tonnes LPG capacity have recently been introduced.

Hazards presented by the transport of hazardous material are mainly fire and explosion. Fire is more likely than explosion where there is a loss of containment of flammable material from a rail, barge or ship tank or from a pipeline. But Unconfined Vapour Cloud Explosions and Boiling Liquid Expanding Vapour Explosions may occur as a result of transport accidents.

Road accidents leading to the release of the flammable material are due in most cases to a tanker crashing or overturning.

Rail accidents are mostly due to train crash or derailment. Mechanical failures of rolling stock and faults in the rail track are frequent causes of these. Another hazard of railways is a fire along the track caused by engine or brake shoe sparks.

The main cause of failure of pipelines, besides corrosion, is interference. In particular damage occurs to pipeline from earth-moving and excavating equipment.

Finally the hazards associated with ships are fire or explosion on the ship itself, or spillage of flammable material from the ship.

Spillage at sea is likely to be the result of collision or stranding. Factors which increase the probability of collision are congestion of shipping lanes, fast steaming and difficult weather conditions.

The effects are limited to the ship itself or occasionally to other ships nearby if a spillage of flammable liquid occurs well out to sea. However, if it takes place near the coast, particularly in port, people on land may be endangered.

3.4 MODES OF CONTAINER FAILURE

Failures of LPG storage systems and the subsequent release of quantities of energy by fires and explosion have lead to massive losses of life and property. The actual potential of such fires and explosions are examined and quantified in Chapter 4; however, as the initiating failure of a storage system is of paramount importance in determining the ultimate scale of destruction, these failures are considered here. Assessment of the historical record allows identification of several modes of failure.

It is also possible to identify other failure modes that are feasible but have yet to be realised.

3.4.1 Spontaneous Structural Failure

In any large fabricated steel structure, there are inevitably small defects consisting usually of cracks up to 2 cm long by 0.5 cm deep [11]. These may be due to poor weld fusion, or may be due to a high cooling rate leading to embrittlement and crack generation by residual stresses in the so-called heat affected zone. These cracks grow slowly while the tank is in service, especially with a pressure tank, where there are many changes of stress as the tank adapts to varying load patterns. The longer the crack becomes, the faster it grows; if it is not repaired it can either lead to leakage or convert suddenly to a fast fracture mode allowing the tank to rupture suddenly with the generation of fragments.

3.4.2 Corrosion

The overall chemistry of the rusting process of iron and steel is complex, with the eventual formation of a complex of iron oxides and peroxides on to the surface of the corroding metal in the presence of water and a dilute acid. However, the first stage of the rusting process is the formation of ferrous ion according to the equation

$$\mathrm{Fe\ (s) + 2H^+\ (aq) = Fe^{2+}\ (aq) + H_2\ (g)} \qquad \text{.... (3.2)}$$

$$\hookrightarrow \text{to rust via other reaction} \longrightarrow$$

This can be further simplified as:

$$\mathrm{Fe\ (s) = Fe^{2+}\ (aq)} + 2\ \text{electrons} \qquad \text{.... (3.3)}$$

Rusting tends to occur in that part of an iron or steel object which is under some stress, producing an 'anodic' site relative to the remainder of the system.

LPG storage vessels, especially those buried below ground, are extensively protected against corrosion by both protective coating and by the use of cathodic protection. Examination of expression (3.3) allows an explanation of the mechanism by which cathodic protection operates. If the production of ferrous ions can be inhibited by supplying more electrons thus

$$Fe^{2+} (aq) + 2e^{-} = Fe \text{ (metal)} \qquad \text{.... (3.4)}$$

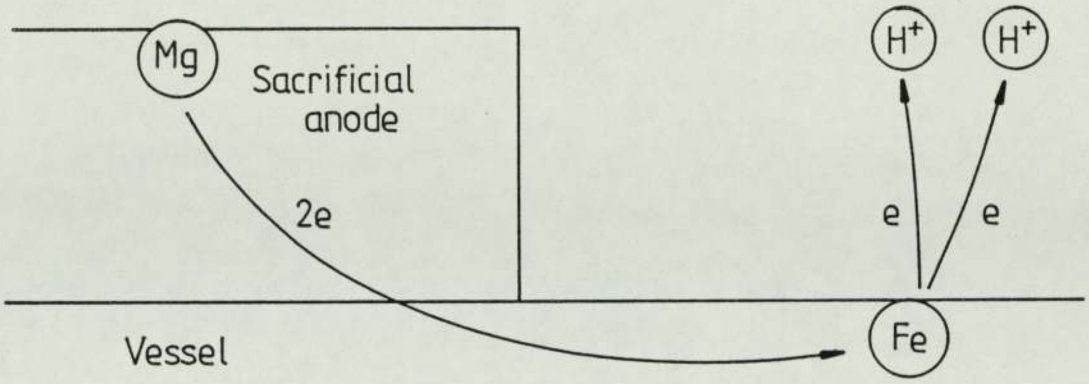
then corrosion will not take place whilst the supply of electrons lasts. In practice, this electron source is usually provided by the use of a metal such as magnesium or zinc, in close contact with the vessel to be protected, and which is a better reducing agent than iron or steel. The overall chemistry is

$$Mg (s) + Fe^{2+} (aq) = Mg^{2+} (aq) + Fe (s) \qquad \text{.... (3.5)}$$

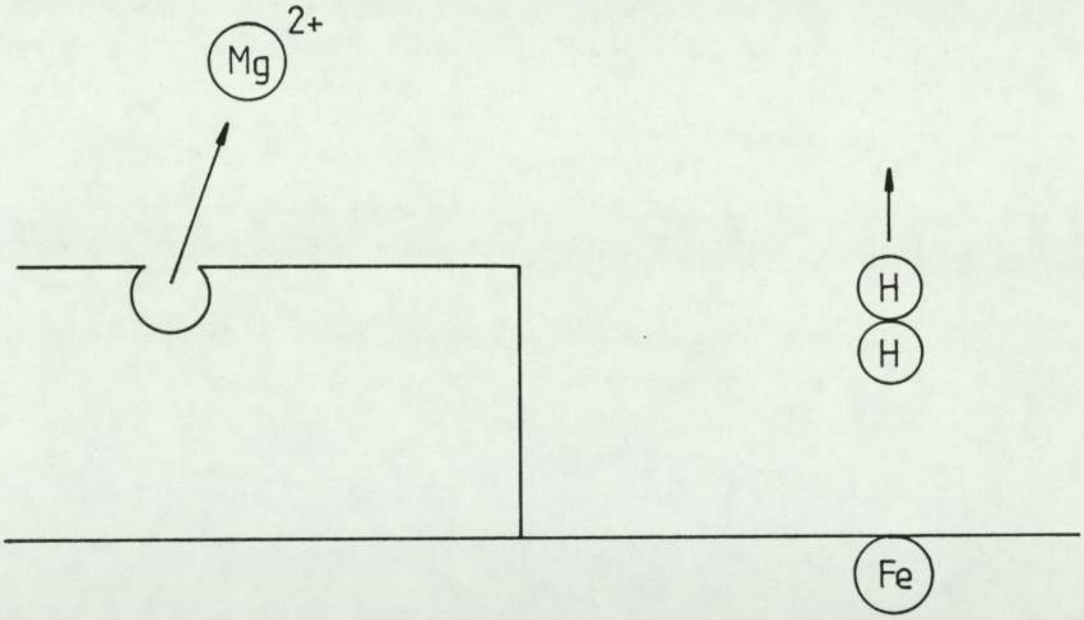
and in electrochemical terms, iron and magnesium are considered to form an electrochemical cell, with water as electrolyte. Within this notional cell, magnesium acts as the anode and iron as cathode (hence 'cathodic' protection) and the magnesium ions are lost in the water. So long as the iron continues to act as the cathode, reaction (3.3) cannot proceed [3]. The overall process is summarised in Figure 3.4.

3.4.3 Mechanical Damage

A variety of interactions have been identified which may cause mechanical damage to LPG storage vessels severe enough to cause loss of containment [11]. In the overwhelming majority of cases on record it is the damage to associated piping, caused for instance by vehicle impact, that causes this category of damage. Once containment is lost below the liquid level then massive pressure - driven discharge of the contents will ensue.



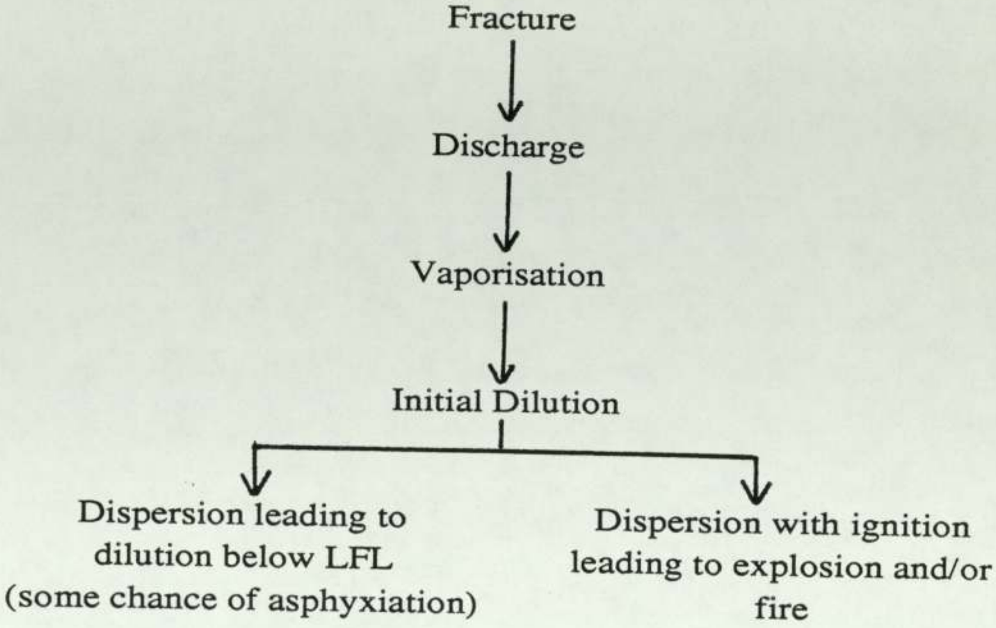
Stage 1 : Iron atom donates two electrons to hydrogen ions in solution in electrolyte. These are replaced by electrical conduction from a magnesium atom.



Stage 2 : The magnesium ion is now soluble in the electrolyte and is lost into solution. The two reduced hydrogen atoms combine to form a hydrogen molecule, which is lost as gas from the electrolyte. There is no loss of iron; therefore corrosion has been inhibited.

Figure 3·4 Mechanism of cathodic protection against corrosion

The course of events for mechanical damage to LPG storage is summarised below:



Damage to refrigerated storage tanks is more likely to occur due to their lighter construction. However, the lower rate of vaporisation for refrigerated LPG tends to limit the consequences of such a spill, providing that the spill is contained within a relatively small area to limit the input of heat. However, if the secondary containment were lost, then spread of liquid onto the surrounding site would be most serious, as unlimited heat would effectively be available to produce vaporisation [3].

3.4.4 Flame Impingement

When flames contact the vessel below the liquid level, the liquid serves to absorb the heat and tank metal below this level therefore remains at a safe temperature. But with continued relief valve operation, the liquid level will drop exposing a greater area of metal to the effects of heating. Flames contacting the tank above the liquid level can create temperatures within the metal high enough to weaken it seriously. When this happens the pressure within the tank can cause the metal to thin and eventually tear.

Therefore, if flames impinge upon LPG storage tanks, two consequences may arise:

(i) there is an increase in internal pressure as the contents increase in temperature.

(ii) the strength of the steel container decreases at elevated temperatures.

The heating is due in most cases to leakage of hydrocarbons under the tank, either from the same tank or from a neighbour. In theory the relief valve should vent the tank as the temperature rises, but in practice there have been cases of them sticking closed. In any event, the venting capacity may be inadequate and the pressure will be certain to increase. When tanks explode under these conditions, they are said to BLEVE. This is derived from the expression Boiling Liquid Expanding Vapour Explosion and is most simply described as the sudden rupture of a pressure vessel containing a flammable liquid above its normal boiling point, due to a fire surrounding the vessel. Such fires also lead to progressive weakening to the point of rupture. The main consequences of a BLEVE which are discussed in detail in Chapter 5 are:

1. intense transient radiation from the fire ball following a ground flash.
2. limited blast - as has been reported as severe blast wave damage from the BLEVE at Feyzin refinery [15].
3. missile generation, possibly involving large fragments of the

tank, being projected considerable distances . It has been reported in the Mexico disaster [15] that 15 of 48 cylindrical tanks each weighing at least 20 tones were trasnformed into missiles and flew over 100 m. Those travelling further landed 1000 or 1200 m away from the scene and destroyed everything in their path, including several houses.

There are many BLEVE incidents [15] in the accident record as shown in Table 3.1 concerned with rail and road tankers. Mississauga is an example of a rail incident which is described briefly in Table 3.2.

3.4.5 Blast Damage

One danger arises from the 'domino effect' where an intact LPG tank in close proximity to some initiating explosion is itself damaged, releasing additional fragments, LPG, or light hydrocarbons into the existing fire situation. In practice, LPG tanks are usually either spherical or cylindrical and are highly resistant to catastrophic failure from blast waves. However, there is a very great threat in the fact that blast wave energies are sufficient to actually move a tank on its mountings, thereby rupturing associated piping [3].

3.4.6 Missile Interactions

Missile interactions can perhaps be considered as a special case of mechanical failure, and an extension of the previous failure mode. Explosions in process vessels, storage vessels or buildings can be expected to produce a range of missiles, with different masses, travelling at various velocities. Upon impact with an LPG storage vessel there is a wide range of possible outcomes, ranging from elastic collision with little or no damage, to complete penetration of the vessel

TABLE 3.1

BLEVE INCIDENTS

Date	Country	Accident
Jan 4, 1966	Feyzin, France	Explosion of tanks at refinery. 18 fatalitites. 40 injuries
Jul 5, 1973	Kingman, Arizona, USA	BLEVE of tank car caused by explosion and fire of LPG distribution plant. 13 fatalities. 96 injuries.
Jun 21, 1970	Crescent City, Illinois, USA	Derailment and explosion of tank cars. 66 injuries.
Feb 9, 1972	Tewkesbury, USA	Collision tank vehicle with pipelines causing BLEVE of storage tank, 2 fatalities. 21 injuries.
Mar 3, 1980	Los Angeles, California, USA	Overturn and explosion tank vehicle loaded with gasoline. 2 fatalities. 2 injuries.
Jul 23, 1984	Illinois, USA	Explosion and fire at refinery. 15 fatalities. 22 injuries.
Nov 19, 1984	San Juanico, Mexico City	Series of explosions and fires. 500 fatalities. 7000 injuries.

TABLE 3.2

EXAMPLE OF A RAIL INCIDENT INVOLVING LPG (MISSISSAUGA DISASTER)

SCENARIO	
11.53	SATURDAY, NOV 10, 1979 Train 54 of CP Rail suffered a derailment in Mississauga. First car derailed was a toluene tank car Twenty-three cars went with it (21 tank cars) Involved 11 propane 4 NaOH 3 toluene 2 fiber glass insulation 3 styrene 1 chlorine Fire spread throughout most of derailed cars.
12.15/12.20	8th, 12th and 13th propane tank cars BLEVE'd. 7th car containing Cl_2 - 2½ feet hole in shell.
1.30	Readable copy of manifest obtained.
EVACUATION	Almost 250,000 people for periods up to 5 days.
CAUSE	The toluene car suffered a 'hot-box' in its right-rear journal box. The rear-axle and its two wheels separated from the truck and the car 1 mile before derailment.
DAMAGE	3 cars BLEVE'd within 30 minutes with 3 great fireballs. Large parts of bodies projected: 8-145 feet east 12-440 feet southeast 13-2222 feet northeast (other parts in all directions) 75,000 remained evacuated until Friday, 16th November.

wall and consequent release of the contents. It has been reported [16] that penetration by fragments of other tanks was responsible for the subsequent BLEVE's in Mexico's disaster.

3.4.7 Sabotage

The location of large amounts of stored energy in a relatively small space allows massive destruction by initiating fires or explosions by acts of sabotage.

The tanks should be enclosed to protect them against damage, a strong wire fence should be put up instead of a solid wall, which could contain any explosive mixture [1], and this security fence should be at distance of 15 m or more from the tank [2]. More stringent security measures may be appropriate if sabotage is a possibility.

The GAO Report recommended [3] that LPG sites should be situated in remote areas, and such siting is prudent not only on the grounds of public safety, but also on the basis of reduction of the propaganda value to terrorist organisations from destruction of such sites.

CHAPTER FOUR

CONSEQUENCES OF SYSTEM FAILURES AND THE HAZARDS INVOLVED

In the previous chapter, the systems of LPG storage and transport were reviewed together with various failure modes to which they are liable, some of which are probable and some remote. In each case of failure the end result was envisaged as a loss of containment. This would result in either a slumping vapour cloud or a jet depending on the mode of failure as discussed in 3.1 and 3.3.

It is now pertinent to consider the further consequences of these losses. The leak or cloud may of course disperse harmlessly (i.e without ignition or contact with personnel) depending on the circumstances, for example being well mixed by wind which may result in a gas concentration below the lower flammable limit so that the mixture is 'lean' with insufficient gas to support combustion or the ignition source might be well away from the plant in a harmless area. The consequences of releases of LPG are summarised in Figure 4.1. The diagram identifies a number of consequences which must be considered as serious hazards.

4.1. HAZARDS TO PERSONNEL

4.1.1 Cold "Burns"

When any liquid vaporises the heat required to effect the evaporation is drawn from the surroundings, which are cooled as a result to a lower temperature. Where the rate of evaporation is rapid,

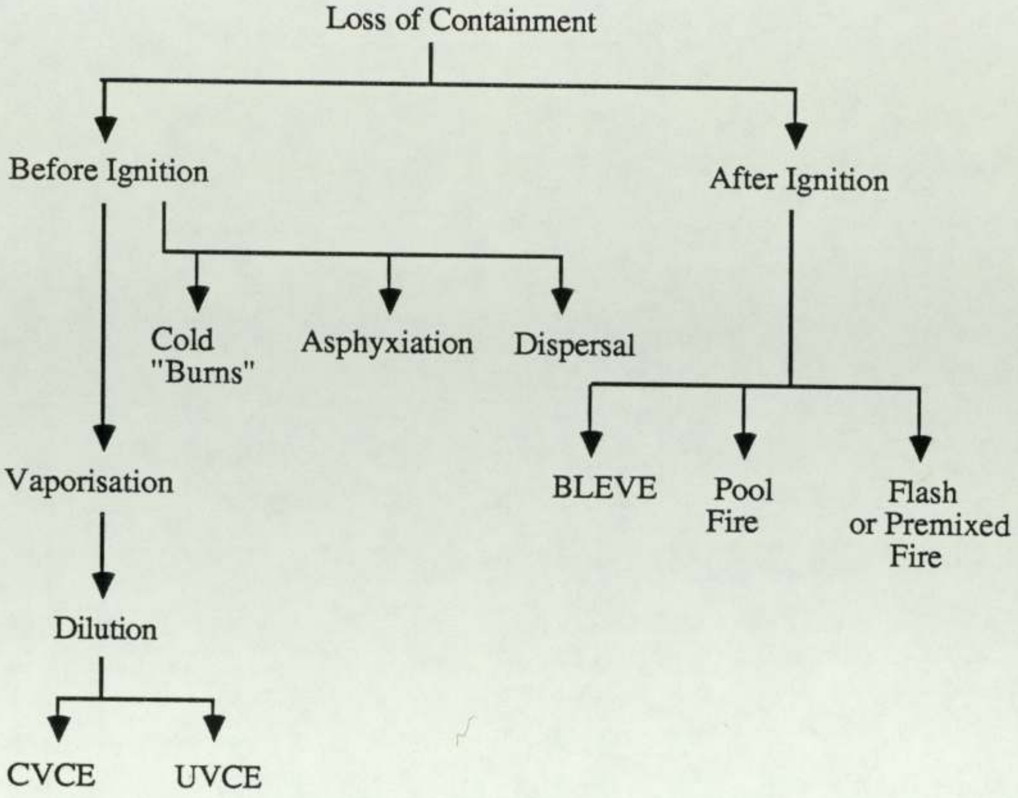


FIGURE 4.1

FLOW CHART OF CONSEQUENCES OF LPG FAILURES

as when a liquid is above its boiling point at ambient temperature (the case with a release of LPG), severe cold "burns" may result from skin contact.

4.1.2 Asphyxiation

Propane and butane are not 'toxic',in the normal sense of the word but possess anaesthetic properties, as do all petroleum vapours, and should not be inhaled in quantity. Occupation exposure limits are recommended by the Health and Safety Executive on advice from HSC's Advisory Committee on Toxic substances (ACTS). These limits are considered to represent good practice and realistic criteria for the control of exposure, plant design, engineering controls and if necessary, the selection and use of personal protective equipment.

It is important to control exposure so as to avoid both short term and long term effects. The long term exposure limit is concerned with the total intake over long periods and is therefore appropriate for protecting against the effects of long-term exposure or reducing the risks to an insignificant level. The short term exposure limit is aimed primarily at avoiding acute effects, or at least reducing the risk of their occurence. Both limits are expressed as time weighted average (TWA) concentrations which are simply airborne concentrations averaged over a specified period of time. The period for the long term limit is normally eight hours, while the short-term exposure limits are normally expressed as ten minute TWA's. The occupational exposure limits (threshold limit) for butane is 600 ppm at long term exposure limit and 750 ppm at short term exposure limit [17]; suprisingly no limit is stated for propane.

A large concentration of vapour in a confined space will displace air to an extent that there could be a deficiency of oxygen for normal respiration. At least 18 % oxygen is required in air, e.g in a confined space, for workers not wearing breathing apparatus. Concentrations liable to cause serious oxygen deficiency would always be in (or above)the flammable range and constitute a serious fire and explosion risk .

4.1.3 Thermal Radiation Effects

The effects of fires on human beings increase with the heat flux and exposure time. There is however, a threshold flux which can be sustained for a long period without causing serious injury. This flux was suggested to be 5 kW/m^2 [11].Further study [18] suggests that this value should be reduced slightly to 4 kW/ m^2. For shorter exposure times (as might be experienced near a fireball),the 'blistering of skin' criteria have been adopted by the Safety and Reliability Directorate (UKAEA). Much lower intensities can cause problems with the eyes by the focussing of radiation on to the retina.

TABLE 4.1

RELATION BETWEEN HEAT FLUX AND EXPOSURE TIME AND THE EFFECTS ON HUMANS; AND THE LIMITING FLUX FOR SECONDARY FIRES

Q *kW/m*^{2}	t	*Effect*
0.2	long	Limiting safe flux for eyes
4	long (>60 sec)	Limiting safe flux for humans
12.6	long	Limiting flux for secondary fires
6.5	~20 sec	Blistering of skin
11	~10 sec	Blistering of skin
20	~5 sec	Blistering of skin

Table 4.1 indicates that with long periods of exposure (> 30 seconds), the following criteria may be adopted [19]:

i. Secondary building fires are possible and people, whether indoors or outdoors, are at serious risk if the flux is greater than 12.6 kW/m^2.

ii Only people outdoors are at serious risk if the flux is greater than 4 kW/m^2.

The latter figure represents the flux which would cause skin blistering after 30 seconds this time being taken as representative of the time it may take to seek shelter or to escape.

For duration <30 seconds the fluxes necessary to cause skin blistering were adopted as the criteria of injury to people outdoors and secondary fires respectively [19].

In conclusion therefore all people inside the secondary fire radius are assumed to become casualties. Only those outdoors will be at risk between this radius and the radius for hazard range to people.

4.1.4 Explosion Effect

Explosion damage constitutes the effect of thermal radiation and the effect of pressure waves generated by the blast. The effects of the former were covered in the previous section. Humans are relatively resilient to overpressure generated in an explosion as shown in the Table 4.2 [20].

TABLE 4.2

EFFECT OF OVERPRESSURE ON HUMANS

Peak Overpressure		Human effects
(psi)	(kPa)	
5	34	Threshold of eardrum damage
10	69	Threshold of lung damage
40	276	Threshold of mortality

An explosion causes casualties primarily as a result of flying fragments, e.g of glass, and falling masonry as well as direct blast injuries. Damage caused by blast is shown in Table 4-3 [19, 21].

TABLE 4.3
STRUCTURAL DAMAGE CAUSED BY BLAST

Peak psi	Overpressure kPa	Structural Damage
<1	<7	Window breakage
1-3	7-21	Walls collapse
3-5	21-34	Reinforced structures distort, Atmospheric storage tanks fail
5-7	34-48	Wagons and plant items overturned
>7	>48	Extensive overall damage

4.2 FIRE HAZARDS

The greatest potential hazard associated with the bulk storage of LPG is that of fire and explosion.In the process industries, fires cause more serious accidents in total than explosions and toxic releases, although the accidents in which the greatest loss of life and damage occur are generally caused by explosion [22].

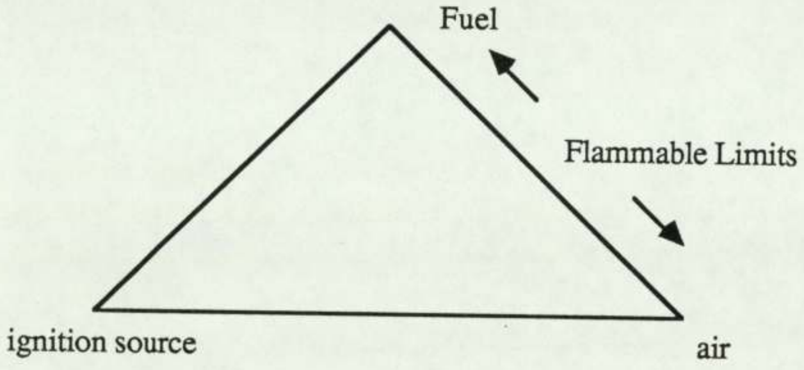
Fire or combustion, is a chemical reaction in which a substance reacts with oxygen from the air and heat is released. Thus fire occurs in the gaseous state, solids and liquids either vaporise, or yield combustible vapours, which ignite and burn. There are three conditions essential for a fire:

- A fuel; gas or vapour within certain concentration limits.
- An oxidant; usually air containing a minimum concentration of oxygen.

- Heat; an ignition source of minimum temperature and energy.

These three conditions are often represented as the fire triangle shown in Figure 4.2. If one of these conditions is missing fire will not generally occur (exceptions arise, e.g with oxidising agents, pyrophoric chemicals, etc).

FIGURE 4.2
FIRE TRIANGLE



4.2.1 Flammability Limits

A flammable gas burns in air only within a limited range of compositions. Below a certain concentration of the flammable gas, the lower flammability limit, the mixture is too 'lean', whilst above a certain concentration, the upper flammability limit, it is too 'rich'. The concentration between these limits constitutes the flammable range. The lower and upper flammability limits are generally expressed in per cent by volume of vapour in air as shown for selected substances in Table 4.4 [6].

TABLE 4.4

VALVES OF LOWER AND UPPER FLAMMABILITY LIMITS FOR DIFFERENT COMPONENTS

Component	Flamability Limits	
	Lower (% v/v)	Upper (% v/v)
Methane	5	15
Ethane	3	12.4
Ethylene	2.7	36
Propane	2.1	9.5
Propylene	2.4	11
n-Butane	1.8	8.4
Cyclohexane	1.3	7.8
Hydrogen	4	75
Ammonia	15	28
Acetylene	2.5	100
Carbon Monoxide	12.5	74

All gas compositions between the lower and upper limits are flammable. The energy produced by the combustion reaction is a minimum at the limits and proceeds with increasing magnitude to the maximum energy at the stoichiometric composition at which each reactant fully reacts. The rate at which a flame propagates through a gas is dependant on several factors, such as the pressure, temperature, composition and the type of event that initiated the reaction [23].

Flammability limits, are affected by pressure, temperature, and addition of inert gas [22, 23].

Normal variations of atmospheric pressure do not have any appreciable effect on flammability limits. The effect of larger pressure changes is specific to each mixture. A decrease in pressure below atmospheric can narrow the flammable range by raising the lower flammability limit and reducing the upper limit until the two limits coincide and the mixture becomes non-flammable. This effect is illustrated for methane in Figure 4-3 [22]. Conversely, an increase in pressure above atmospheric can widen the flammable range. This effect is shown in Figure 4.4 for natural gas [22]. It may be noted that the effect is more marked on the upper than on the lower flammability limit.

Flammability limits are also affected by temperature. This effect is illustrated for methane in air in Figure 4.5 [22]. An increase in temperature tends to widen the flammable range. The effect of both pressure and temperature for methane-air mixtures is illustrated in Figure 4.6 [23].

The flammability limits are also affected by the addition of inert gas such as nitrogen, carbon dioxide or steam. This effect is shown for methane in Figure 4.7 [22].

The oxygen concentration also affects the flammability limits. In general, increasing oxygen content alters the lower flammability limit only slightly, but it's affect in raising the upper flammmability is marked.

In general, carbon dioxide causes a greater narrowing of the flammable range than does nitrogen. For many flammable gas-air systems, the mixtures can be rendered non-flammable by the addition of approximately 30% of carbon dioxide or 40% of nitrogen [22].

4.2.2 Ignition Sources

When an accidental release of combustible substance has occured there is the possibility of a succeeding fire and explosion.

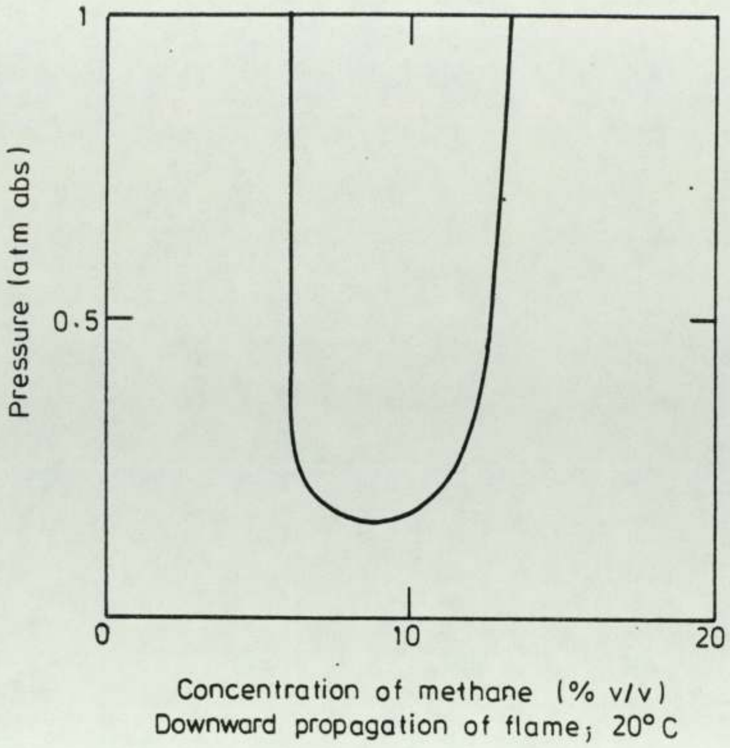


Figure 4·3 Effect of pressure on flammability limits of methane in air.

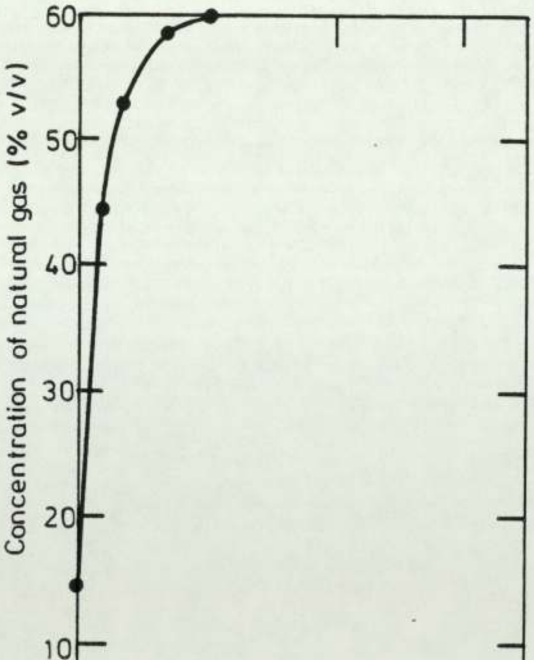


Figure 4·4 Effect of pressure on flammability limits of natural gas in air.

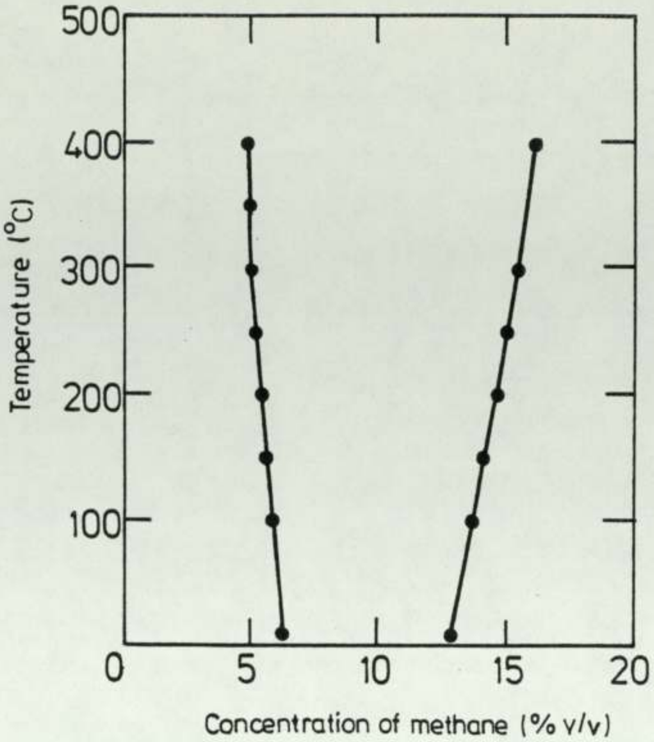


Figure 4.5 Effect of temperature on flammability limits of methane in air.

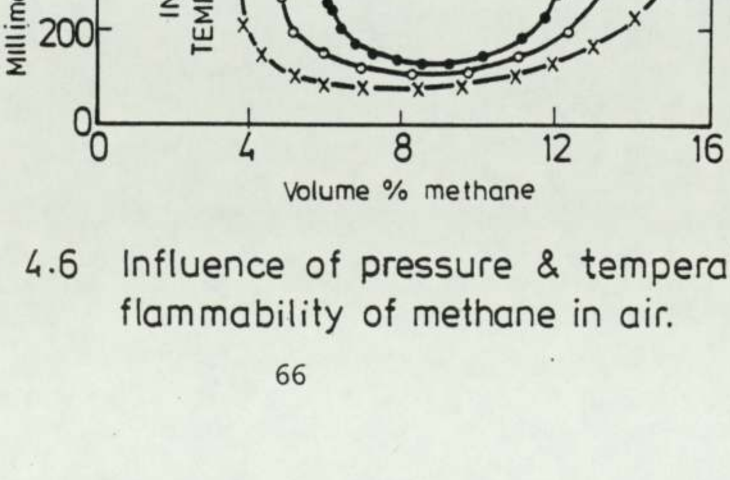


Figure 4.6 Influence of pressure & temperature on flammability of methane in air.

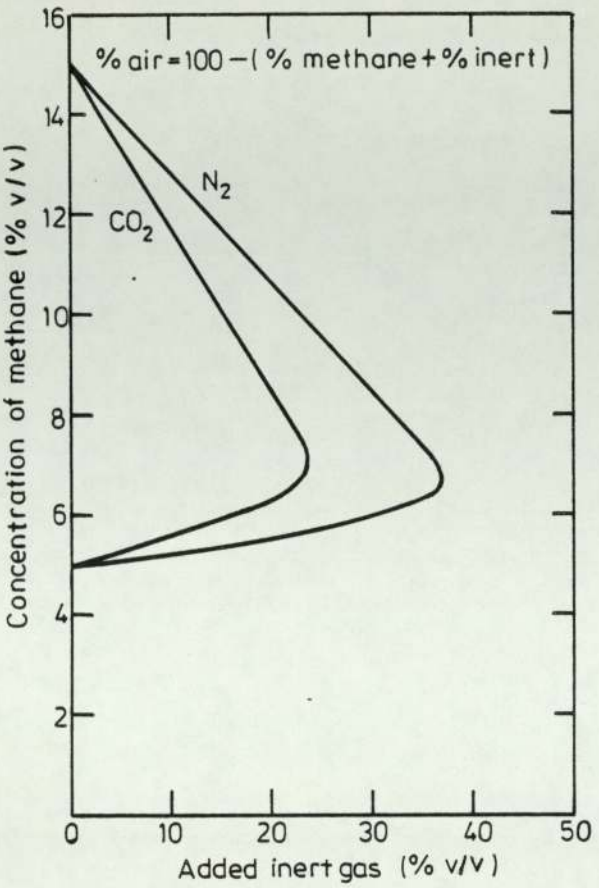


Figure 4·7 Effect of inert gases on flammability limits of methane in air.

There are normally a number of potential ignition sources within and in the neighbourhood of a chemical plant. Sources of ignition include the following [22]:

Flames, direct heat and hot surfaces,

Welding and cutting,

Mechanical sparks,

Vehicles: e.g, spark-ignition engines or the exhaust pipes on diesel engines,

Self heating e.g, as in lagging fires,

Static electricity e.g, discharges from hydrocarbon liquid fuels during pumping, splash-filling, rapid (air) venting.

4.2.2.1 Flames:

The flames of burners in fired heaters and furnaces, including boiler houses, may be sources of ignition on process plants. The source of ignition for the explosion at Flixborough may well have been burner flames on the hydrogen plant [22]. The flame at a flare stack may be another source of ignition.

Hot soot from chimneys of flare stacks [22] may be a source of ignition. This is a particularly important potential source of ignition on ships.

Cigarettes are another possible source of ignition. A cigarette itself is not always hot enough to ignite a flammable gas, but any match used for lighting is an effective ignition source. So smoking should be prohibited in the area of flammable hazards.

In welding operations it is necessary to ensure that no smouldering material such as oil-soaked rags have been left, e.g due to the spray of sparks, because smouldering material may act as a source of ignition. The welding torch itself is also a potent ignition source.

Machinery in distress, such as a pump with a faulty bearing, may run hot and this hot spot is a potential source of ignition. Small process fires of various kinds such as pump or flange fires, may consitute a source of ignition for a larger fire.

4.2.2.2 Welding and Cutting:

Acetylene welding, and oxy-acetylene cutting operations, are among the most common sources of ignition. Either the flame itself or the white hot shower of metal particles may reach and ignite flammables. The explosion hazard with 'empty' drums and tanks is well known; without adequate cleaning and purging such containers will retain flammable gas or vapours.

4.2.2.3 Mechanical Sparks:

Potential sources of mechanical sparks include metal tools, falling objects and cigarette lighter flints. Metal tools can, in principal, cause sparks. Evidently upon striking metal the sparks need to be above a certain minimum energy level. Non-sparking tools are available made of soft non-ferrous metals such as berylium-copper alloy; these are used extensively in the chemical industry but are not necessarily safer if there is a chance of picking up grit. In the presence of more easily ignited gases such as hydrogen however the hazard arising from the impact of steel on steel may be appreciably reduced if non-sparking tools are used but the greater risk due to impact of metal on rock would still remain. Smears of light alloy material on steel tools, particularly if the tools are rusty, significantly increase the ignition hazard and must be avoided if such tools are used.

Falling objects like tank washing machines or cathodic protection anodes in ships cargo tanks can cause sparks which may cause more serious hazards in a space which already contains a flammable atmosphere.

Finally cigarette lighter flints can also cause a mechanical spark if the lighter is dropped.

4.2.2.4 Vehicles:

A chemical works may contain at any given time considerable numbers of vehicles. These vehicles are potential sources of ignition. The ignition of the flammable vapour cloud in the Feyzin disaster may well have been caused by a car passing on a nearby road [22].

It is necessary therefore to exclude ordinary vehicles from the area of flammable hazards. Compression ignition (diesel) vehicles are usually considered safe because they have no high tension ignition system but spark arresters need to be fitted to their exhausts.

4.2.2.5 Self Heating:

Self heating, or spontaneous combustion, of a solid material is a process of slow oxidation. Material undergoing self-heating may act as a source of ignition or may give rise to a fire or an explosion.

Self-heating can occur in oil rags left on steam pipes, oil dispersed in cotton waste, in lagging soaked with oil and coal stored in heaps. The rate of heat loss is restricted by insulation in such cases so that the temperature, and hence the reaction rate, can escalate. Self heating requires that heat is generated in a mass of material more rapidly than it can be removed.The rate of reaction typically increases exponentially with temperature curve, H in Figure 4.8 [24]. In this Figure different rates of heat loss are presented as lines A, B, C and D. With a mass initially at temperature T_A, the temperature of the surroundings and the cooling rate following line A then clearly since the generation rate exceeds the removal rate the temperature of the mass increases. A stable situation will however occur at 'X'. If the initial temperature was T_B and the cooling rate followed line B the cooling is inadequate and a thermal runaway occurs which can lead to a fire. In this situation T_C represents the critical temperature of the surroundings.

The rate of cooling commencing at T_A might fall to follow to line D, e.g, due to insulation. Line D then represents a critical minimum rate to avoid a thermal runaway.

Mitigation of accidents due to self-heating can be achieved by good housekeeping, using appropriate lagging thicknesses and protection and by cooling hot materials before they are sent to storage, or it may be necessary to purge systems with inert gas in some cases, for instance where flammable solids of high specific surface are stored.

4.2.2.6 Static Electricity:

The hazard of static electricity usually occurs in the process industry in fluid handling operations such as pipeline flow, truck filling, in sprays and mists such as in steam cleaning and steam leaks.

Pumping of relatively pure organic materials can result in an accumulation of charge on the liquid surface in a receiving tank; if

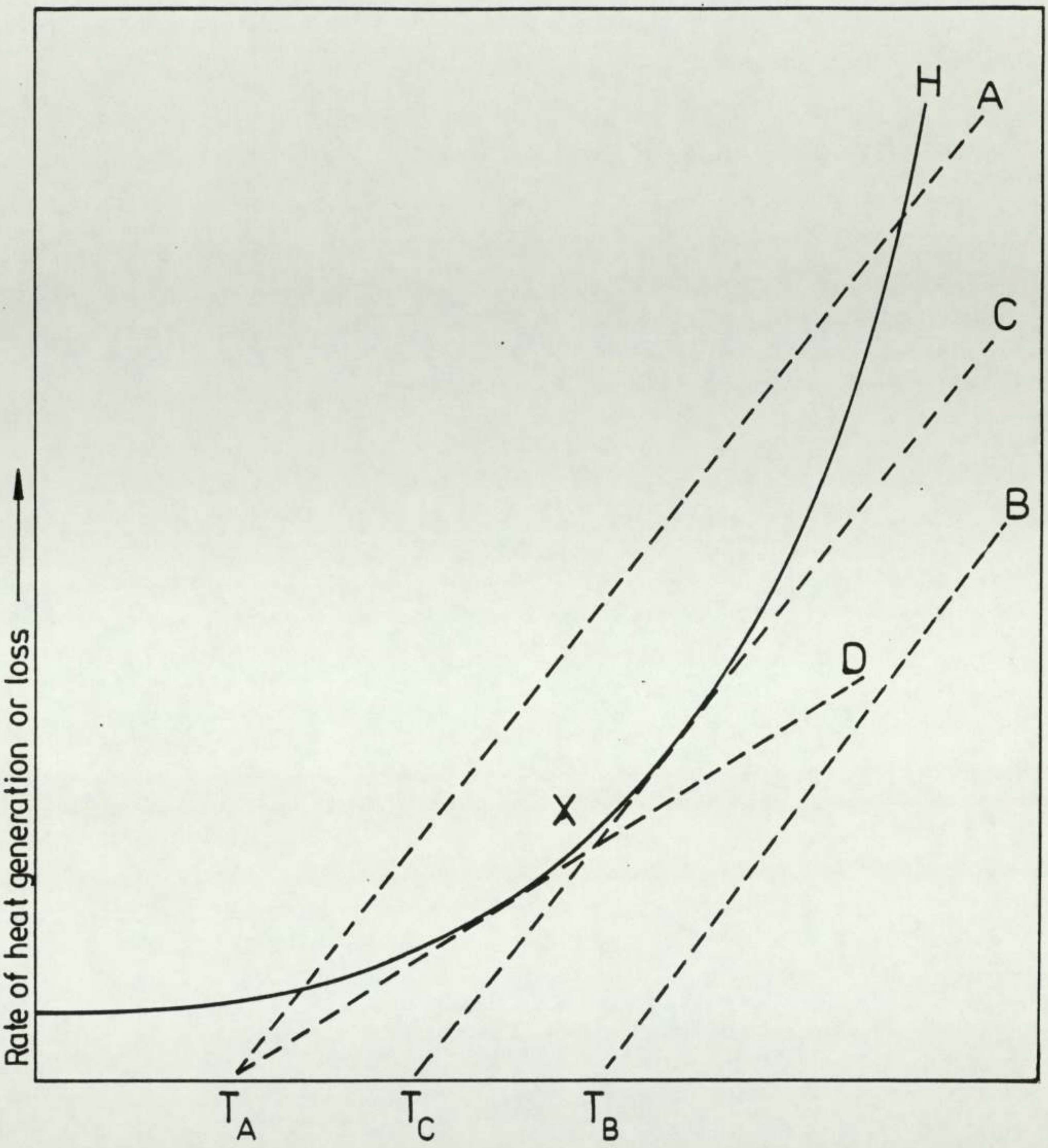


Figure 4.8 Heat Balance Relationship
H = rate of heat generation
A, B, C, D = rates of heat loss.

the liquid is insufficiently conductive the charge may build up over a period, then bleed off rapidly resulting in a spark. Slow pumping, subsurface discharge, earthing and bonding or the addition of anti-static additives may be used to avoid static electric discharge [22].

The Fire Protection Association have analysed 206 fires in the process industries over the period 1963-1974. The results of the analyses are shown in Table 4.5, giving the source of ignition for the ensuing fire [25]. It is impossible to eliminate all sources of ignition for hydrocarbon-air mixtures due to their very low ignition energies. The design philosophy for hydrocarbons should therefore be to keep them entirely separated from air, or to depress the limits of flammmability by inerting.

Typical sources of ignition in LPG facilities include naked lights, incendiary sparks, hot surfaces and electrical equipment [2].

TABLE 4.5

THE SOURCE OF IGNITION FOR FIRES WHICH THE FIRE PROTECTION ASSOCIATION ANALYSED IN THE PROCESS INDUSTRIES OVER THE PERIOD 1963-1974.

Source of Ignition	No. of fires	%
Electricity	30	14.6
Hot surfaces	30	14.6
Spontaneous ignition	20	9.7
Frictional heat and sparks	15	7.3
Gas burners and flames	12	5.8
Cutting and welding	12	5.8
Static	7	3.4
Other known	17	8.2
Unknown	63	30.6
	206	

4.3 EXPLOSION HAZARDS

An Explosion involves a rapid release of energy which causes a shock wave moving away from the source [26]. This energy may originally have been stored in the system in a variety of forms; these include nuclear, chemical, electrical, mechanical or pressure energy. However, the energy release is not usually considered to be explosive unless it is sufficiently rapid and concentrated to produce a pressure wave that can be heard.

Many types of processes may lead to explosions in the atmosphere. Table 4.6 gives a list of the more significant types of explosion including theoretical models, natural explosions, intentional explosions and accidental explosions.

TABLE 4.6

TYPES OF PROCESSES WHICH MAY LEAD TO EXPLOSION

Theoretical Models	Natural	Intentional	Accidental
Ideal gas	Lighting	Nuclear	Confined vapour in Enclosures
Real gas	Volcanoes	High Explosives	Unconfined vapour clouds
Constant velocity Piston	Meteors	Electical spark	Unstable materials during manufacture transport, storage and use
Bursting sphere	Fires	Bomb calorimeter	Nuclear reactor Runaway

One of the most important properties which determines the behaviour of any explosion process is the energy distribution in the system and the manner in which it changes with time as the pressure wave propagates away from the source. All the energy is initially stored in the source in the form of potential energy. At the instant when the explosion starts, this potential energy is redistributed to produce kinetic and potential energy in different parts of the system.

Another view of the source of the explosion reveals that the characteristics of an explosion depends upon the material involved.

High Explosives: are considered to be substances which detonate, (produce a shock wave faster than the speed of sound in the medium) releasing energy very rapidly and creating very high pressures.(e.g TNT)

Conversely low explosives: which are considered to be substances which deflagrate or burn rather than detonate, and therefore create lower pressures (e.g hydrocarbon components).

An explosion can be produced by the detonation by a high explosive, the rapid burning of a flammable gas cloud, or a sudden failure of a pressure vessel containing high pressure gas. When used to describe the rapid burning of a flammable gas cloud, the term explosion refers to events where the flame speed is >170m/sec [19]. In order to achieve this the flame must propagate through a cloud premixed with air. The resulting over-pressures are sufficient to cause damage inside and outside the cloud as the shock wave propagates into the atmosphere beyond the cloud. This type of explosion may also be referred to as a deflagration [19].

4.3.1 Occurrence of Explosive Vapour Clouds

Spillage of a flammable material due to a loss of containment or major release does not necessarily give rise to an explosion hazard, although it is always a potential source of fire. For a vapour cloud explosion to occur a substantial quantity of the flammable vapour must be released into the air as a cloud which must then be ignited by a source of sufficient energy.

The flammable materials that can form a potential vapour cloud are divided into the following categories [22, 26]:

1 - Liquid below its atmospheric boiling temperature
2 - Gas under pressure
3 - Liquid boiling below atmospheric temperature
4 - Liquid above atmospheric boiling temperature

In category 1, loss of containment due to the rupture of the pressure shell will cause a quantity of the liquid to flash off to form vapour. The amount flashed off depends upon such factors as the original pressure, the vapour pressure at storage temperature, and the ratio between specific and latent heats (27). This limited quantity of material may be increased by frothing and entrainment of air. Thus when liquid ammonia is lost from a vessel effective gas-liquid separation occurs only if the pressure is released slowly. If the vessel is suddenly de-pressurized gas bubbles will form throughtout the liquid and a mixture of gas and fine liquid aerosol will be ejected with explosive force. Even if the liquid contributes little to the explosive potential of the mixture the entrained fraction is available to feed subsequent fires and explosions and to vaporise on any warm plant in the vicinity of the leak and so add to the size of the cloud [28].

In the case of a gas emission (category 2), the amount released is usually limited because although gases are normally stored under high pressure their density is relatively low. Although large-scale, low pressure vessels exist, they rarely fail catastroph-ically. Failures of a non-catastrophic nature (usually referred to as 'leak-before-break') [21] occur more frequently but, because of the low pressure, do no generate large volumes of explosive mixtures.

Category 3, includes cryogenic liquids (e.g. LNG) which are intrinsically more dangerous if stored under high pressure than at low temperature. Refrigerated storage may pose other problems due to steel embrittlement at low temperatures.

In this case, loss of containment will not result in such rapid flashing of liquid and a vapour cloud can only be formed by evaporation from the cold liquid.

In category 4, liquids are the most hazardous. They contain pressure energy for atomisation and thermal energy to sustain evaporation. Furthermore, their density is likely to be more than that of category 3 flammable LNG and LPG, so the mass released is likely to be more than with category 3.

4.3.2 Vapour Cloud Dispersion

It is frequently asserted than any flammable vapour cloud which disperses near ground level within a process plant will find an ignition source. However, there are several documented incidents in which clouds have dispersed without ignition [29].

The main factors that determine the probability of ignition include the nature of the material, the size of the cloud, and location of the source. Small leaks have a high probability of harmless dispersion because concentration falls to well below the lower flammable limit before a source of igntion is encountered. For example leakage from a gasoline can during normal filling extends only of the order of 2 m downwind. This may also occur with large leaks in remote locations, such as storage areas. For large clouds in process areas, ignition is much more likely, and generally fairly immediate. Kletz [30] estimated that for small leaks about one in 30 ignites. It has also been suggested [30] that for releases greater than 10 tonnes of flammable vapour the probability of ignition can be as high as one in two.

The movement of the vapour cloud and the extent of its flammable region, depend upon the mixing process during the dispersion of the fuel. In general, by simple diffusional mixing, the pure fuel at the spill will be diluted to below the upper flammability limit somewhere in the inner region of the cloud and to below the lower flammability limit somewhere in the outer region of the cloud.

A variety of factors affects dispersion. Models should include the effect of the vapour density but common atmospheric dispersion models, like the Gaussian model [31] are only applicable to gases with a density approximately equal to that of air. Many gases have considerably higher or lower densities and a different dispersion behaviour may be expected, especially when large amounts are released. The direction and velocity of discharge, as well as the nature and size of spill, are other important factors affecting the dispersion model. There are two general classes of spill to consider: the massive single spill produced by the catastrophic or rapid rupture of a storage tank, and the continuous leak produced by either a relatively small hole in a tank or a break in a pipeline. Dispersion models for each type have been derived and may be applied to calculate the location of the upper and lower flammability limits for flammable materials. For a massive single spill the severity of the danger rises at first and then decreases as more and more of the spill is diluted to below the lower flammability limits of the fuel. In the case of a continuous spill, as long as the spill is occuring, the danger increases to an asymptotic limit as the delay to ignition increases, because the extent of the flammable region must eventually be stabilised by dispersion in the atmosphere [32].

The dispersion of an unconfined vapour cloud is dependent upon a variety of factors including direction and velocity of discharge, air temperature and wind conditions on site, effects of buildings and plant, vapour and ground temperatures, and density of the vapour [33]. Normal air pollution dispersion models have been used to predict dispersion of such vapour clouds, but for heavier than air vapours the clouds are likely to be more stable than predicted from Pasquill theories [34]. Experimentation in wind tunnels [35] showed that a rapid release of LPG vapour tended to produce plumes which were:

- Initially influenced by gravitational effects (slumping) giving rise to a rapid spread upwind as well as downwind of release,
- Greatly influenced by slope effects, i.e. topography, and would travel considerable distances downhill from the point of release,
- Relatively stable, i.e. turbulence within the plume due to ground roughness was suppressed, and
- Considerably affected by wind speed, i.e. high wind speeds greatly reduced the stability.

4.3.3 Ignition and Combustion

4.3.3.1 Ignition

A vapour cloud will continue to disperse into the atmosphere unless and until it is ignited upon reaching a suitable ignition source. From reported incidents only about 1 cloud in 6 has drifted more than 100 m before ignition occurred [29].

Immediate ignition of an instantaneous pressurised burst always gives rise to a fireball. An immediate ignition of a continuous pressurised release may be assumed to give rise to a torch. Immediate ignition of a refrigerated spill will give rise to a pool fire.

With both a pressurised release and a refrigerated spill a delay in ignition will give rise to an explosion [19].

Delays as long as 15 minutes have been reported with a large leak and proper wind conditions [29]; an enormous combustible volume can be formed in this time. The consequences of releases of pressurised and refrigerated liquefied flammable gases are shown in Table 4.7 [21].

TABLE 4.7

THE CONSEQUENCES OF RELEASES OF PRESSURISED AND REFRIGERATED LIQUEFIED FLAMMABLE GASES

Time of ignition	Refrigerated release	Pressurised release
Immediate (within seconds)	Pool fire	Fireball
Slightly delay (within 30 sec)	Diffusion flash fire	Premixed flash fire/explosion
Delayed (minutes)	Premixed flash fire/ explosion	Premixed flash fire/ explosion

4.3.3.2 Combustion

The way in which LPG releases burn is dependent upon a number of factors including [19]:

- the conditions under which the material is released, e.g. temperature, pressure, rate of release, quality of release,
- the nature of the flammable cloud at the point of ignition, e.g. its size, shape, composition, degree of confinement,
- the nature of the ignition source.

The modes of combustion can be described in terms of whether the flames are [19]:

- premixed or diffusion, and
- stationary or propagating.

Pool fires and torches are examples of stationary diffusion flames. Both represent combustion of the release at source. A necessary prerequisite for a pool fire is that the release gives rise to the formation of a liquid pool. Pool fires are, therefore, more likely for the release of liquids stored below their boiling point or for pressurised releases with a low flash fraction. Torches describe the combustion of gas or liquid sprays from pipework or a small hole. They will be most likely with pressurised releases.

Fireballs and diffusion flash fires are examples of propagating diffusion flames. They occur following the ignition of a cloud the bulk of which is above the UFL. The edges of the cloud, however, will be within the flammable range due to diffusion and mixing with the surrounding air. Ignition is possible at such points and may be followed by rapid flame propagation through the flammable region so that the central rich core of the cloud is enveloped in flame. Subsequent burning is controlled by the rate of entrainment of air and its mixing with fuel and will be a relatively slow process. The cloud burns as a fireball when the whole of the cloud will appear to be on fire, this taking place at eddy boundaries where the fuel-air composition is in the flammable range. Fireballs are more likely following ignition of a hemispherical or spherical cloud such as will exist shortly after a pressurised release. Diffusion flash fires are more likely following ignition of clouds with heights much less than their maximum width or length, e.g. those formed by slumped hemispherical clouds, by evaporation from liquid pools or plumes from continuous releases [19].

Propagating premixed flames occur when a cloud of gas mixture inside the flammable range is ignited. The flame propagates outwards from the ignition source consuming the mixture. For very low propagation speeds the rate at which hot combustion products are generated is low and so expansion can take place easily without any significant overpressure being generated. Under these circumstances the cloud will burn as a flash fire.

As flame speeds increase combustion products are generated more quickly so that pressure is built up both ahead and behind the flame front. At flame speeds >170-200 m/sec the overpressures are sufficient to cause extensive damage both within the cloud and outside it as the pressure waves propagate and decay in the atmosphere beyond the burning cloud. The event that produces damaging overpressure is referred to as an explosion [19].

4.3.4 Types of Explosion

4.3.4.1 Confined Vapour Cloud Explosion (CVCE)

Confined vapour cloud explosions occur when fuel-air mixtures are ignited in buildings or vessels and confinement allows the pressure to build up until the containing walls rupture due to the rise in the internal pressure [22, 36]. Whether or not this rise is sufficient to cause rupture depends upon many parameters such as:

- the design of the enclosure,
- the amount of hydrocarbon present,
- the degree of mixing with air,
- the extent and speed at which the enclosure or building vents the combustion products and so lowers the effective internal pressure.

In the case of a pressure vessel, where the bursting pressure should be known, the energy resulting from ignition of the mixture would be given by the isentropic expansion energy

$$\Delta E = \frac{P_o \ V_o}{\gamma - 1} \left[1 - \frac{P_o}{P_f} \right]^{1-\gamma} \qquad \text{.... 4.1}$$

where ΔE = Isentropic expansion energy, J

P_o, P_f = Initial and final absolute pressure, N/m^2

V_o = Original volume, m^3

γ = ratio of specific heats

This is the same equation as for the bursting of a pressure vessel and can be calculated in the same manner.

Normally P_f is unknown but is low in the case of confinement within ordinary buildings or structures. Following ignition of a massive release of materials, CVCE's will add substantially to the local severity within a UVCE and probably result in much of the major damage found within the confines of the cloud. However, confined vapour cloud explosions are generally insufficiently large to do more than local damage to the plant. This type of explosion is common where LPG cylinders develop a slow undetected leak which results in internal concentrations of air-vapour mixtures between the UFL and LFL. When an ignition source is suddenly introduced into the building, a violent explosion can result. There is probably a good case for always isolating portable LPG appliances at the cylinder outlet valve when not in use; this would greatly reduce the risk of confined vapour explosions. CVCE's will normally also be a hazard in situations where unconfined vapour cloud explosions are possible. The spacing policy relating to this type of explosion is related to the production of missiles from building or plant.

4.3.4.2 Unconfined Vapour Cloud Explosion (UVCE)

An unconfined vapour cloud explosion takes place when a large fuel-air cloud burns in a relatively unconfined area with sufficient speed to generate pressure waves which propagate through both the vapour cloud and the surrounding atmosphere [26, 37]. The pressure waves generated can be thought of as the physical mechanism by which chemical energy released during combustion of fuel-air cloud is transported to distant points where it may cause damage through the action of incident pressure waves on structures. Events of this type usually involve large releases of 5 tonnes or more of common hydrocarbons [19]. However, Briscoe [37] suggests that this should be over 10 tonnes.

Explosions are caused by local ignition (ie at a single point) followed by flame propagation throughout the rest of the vapour cloud. Hence the rate of combustion is directly related to the speed with which the flame propagates.

Two forms of propagation have been distinguished, deflagration when the flame advances at subsonic speed, and detonation when the flame advances at supersonic speed.

Flames in a deflagration may travel at a range of speeds; higher flame speeds produce higher pressure levels and gas velocities. Generally pressure levels are relatively low, ie less than 20 m/s flame speeds give negligible pressure levels and greater than 250 m/s give a level of 0.1 bar [37]. In the event of detonation, flame speeds of 2000 m/sec could produce pressure levels of approximately 16 bars, but these are unlikely in an UVCE. When the shock waves reach the end of the vapour cloud they begin to decay since they are no longer sustained by chemical energy. It is this decaying wave which causes most of the damage outside the factory site.

4.3.4.3 Boiling Liquid Expanding Vapour Explosion (BLEVE)

All liquefied gases are stored in containers at temperatures above their normal boiling points and remain under pressure only so long as the container remains closed to the atmosphere. This pressure ranges from less than 0.06 bar (1 psi) for some liquid natural gas containers to 15 bar (200 psi) for liquefied gas containers at normal storage temperatures. If the pressure is suddenly reduced to atmospheric, as would be the case if the container developed a crack, the sensible heat which is stored in the liquid at the high pressure causes the liquid to evaporate very rapidly with consequent rapid cooling of the liquid. Failure of the container is most often due to the weakening of the container due to flame impingement and consequently the metal temperature increasing. Most steels used for pressure vessels storing or transporting LPG will steadily lose tensile strength at temperatures above 400 °F. Thus, container steels exposed to an external fire above the liquid level within the container, above the vapour space, will increase in temperature unless they are thermally protected. The temperature of the container shell below the liquid level will remain very near to the boiling point of the pressurised stored liquid so long as the internal pressure does not decrease. The liquid to gas expansion ratio may be from 200:1 up to 600:1.

The expansion of the liquid into vapour due to a sudden decrease in internal container pressure is the very process that tends to increase the length of the small, initial crack at a rate close to the velocity of sound in metal.

There are three separate damage producing effects [22, 38]:

- A blast wave due to relief of internal pressure,
- Thermal radiation due to the effects of the fireball resulting from massive burning of the contents of the vessel in the air,
- Projection of large fragments, scattered for considerable distances, by the violent rupture of the tank.

The main effect arises from thermal radiation and people at distances of 300 metres or more have been cited as having been injured. The secondary, and more specific, hazard due to this type of occurrence is that of projectiles, extending to distances of 300 metres for large fragments and 500-600 metres for smaller fragments.

CHAPTER FIVE

BLEVE'S INVOLVING PRESSURISED STORAGE TANKS

5.1 LPG TANK FAILURE MECHANISMS

Most of the LPG storage tanks in service have been designed in accordance with the requirements stated in Codes of Practice [39]. Some Codes state that bulk pressure vessels must be designed and constructed to a recognised standard and give examples such as ASME, BS I5I5, BS 5500, etc., and that they must be designed for the highest pressure to which they will be subjected in service. Normally these LPG tanks are designed for a burst pressure of 1000 to 1250 psig. Safety pressure relief valves are installed to prevent the internal pressure from rising more than about 10 percent above the maximum design pressure. The flow capacity of the valves is designed to maintain safe tank internal pressure levels with the tank and its contents exposed to excessive heat gains, such as from a fire. It is generally accepted that the maximum allowable heat gain is about 1.43 x 10^9 kJ.sec/m^2 (35,000 Btu.h/ft^2) from a spill fire [39].

It is assumed that adequate welding procedures and inspections have been carried out during the fabrication of an LPG storage tank, in accordance with the appropriate pressure vessel Code, depending on whether or not the storage is refrigerated, e.g. BS 5500. Therefore, the most probable source of tank failure is explosive failure due to excessive heat gain by the tank during exposure to severe fire conditions. As is well documented by others [39], sudden release of the stored energy within a high temperature and high pressure LPG tank can produce hazards ranging from sudden total explosive disintegration of the tank, with resulting high velocity large metal sections, to projectile like motion of a large section of the tank.

An examination of the fire record relating to tank fires shows that four types of fire condition frequently occur. These types are as follows [39]:

Pressure relief valve vapour fires: This type of fire condition is caused by moderately high pressure vapours discharging through spring-loaded pressure relief valves which have to be located on all LPG storage tanks of an industrial size (30,000 gallon capacity or more). Ignition is usually produced by static discharge. The resultant fire can be extremely dangerous due to the high rate of heat input into the tank vapour space. Extinguishing such pressure relief flames is recommended to minimize such heat input conditions, providing an explosive situation will not be produced by the release of the LPG vapours through the relief valves.

Radiant heating effects from a remote fire: An LPG tank will be partially exposed to incident heat fluxes from fires at other locations such as adjacent tankage, spills at unloading stations, or other types of flammable hydrocarbon fires (e.g., liquid spills). If such fires are not controlled or extinguished, an unprotected LPG tank will eventually develop a pressure relief type valve fire as described above.

Direct contact heat transfer from spill fire flames: Many LPG tanks and tank farms utilize local impounding dikes to prevent the spread of flammable product and to limit the extent of flammable vapour dispersion. In many cases if a fire occurs this will result in direct flame contact on the bottom and lower sides of the LPG tank and radiation on to the upper surfaces.

High pressure impingement fire condition: This is the most dangerous type of fire due to the greatly increased heat fluxes, especially if the flame impingement is on the vapour space or on an empty LPG tank which does not have the heat capacity protection provided by the liquid contents of a full LPG tank. Such fires are experienced from the failure of loading lines, for instance, when a tank car turns over and both liquid and vapour are released through the relief valve.

The failure of an LPG tank exposed to a fire condition is related to its steel strength characteristics as a function of temperature. The strength of LPG tank steels increases initially as the temperature increases, up to a maximum somewhere between 350 and 450 °C beyond which the strength starts to decrease. At a temperature of about 540 °C the strength of a typical LPG tank will be reduced from a design pressure of about 7000 kPa to some 2000 kPa, and further heating to 600 °C will lower the strength still further to approximately 1300 kPa [39].

In heating LPG tanks by exposure to fire, some of the absorbed heat flux goes into raising the stored liquid temperature and some goes into raising the steel temperature. The heat absorbed by the liquid causes liquid to vaporise, with a resultant increase in tank vapour pressure. When this pressure reaches the relief setting of the safety relief valves, bursting discs, etc., this excess pressure is allowed to vent to the atmosphere. During severe fire conditions, such as in direct exposure to spill fires or impinging pressure fires, the heat input is sufficient to cause a continual increase in the tank internal pressure. Meanwhile the heat input into the tank steel not in contact with liquid product, causes an increase in the steel temperature. In time a point is reached where the steel temperature in a localised area is reduced to the local bursting strength below that being maintained by the tank pressure relief valve system. At that time the vessel will rupture and a boiling-liquid expanding vapour explosion (BLEVE) will result. A typical sequence is illustrated in Figure 5.1 [38].

5.2 DAMAGE PRODUCING EFFECTS OF BLEVE'S

There are three separate damage producing effects [22, 38]:

i A blast wave due to relief of internal pressure,

ii Thermal radiation due to the effects of the fireball resulting from the massive burning of the contents of the vessel in the air, which will be discussed in Chapter 6,

iii projection of large fragments, scattered for considerable distances by the violent rupture of the tank.

5.2.1 Blast wave effect

Damage from failure of a vessel under pressure is partly due to the shock wave produced in the surrounding air by the sudden release of energy.

The work of Strehlow and Ricker [40] showed a simple relationship between $\overline{P}s$, the dimensionless shock overpressure and $\overline{R}s$ the dimensionless shock radius for all sphere bursts. Their work presents a graphical method of predicting the shock overpressure at any radial distance from a spherical vessel which has burst. All pressures are reduced to dimensionless overpressures by means of the ambient atmospheric pressure Po. Thus the dimensionless over-

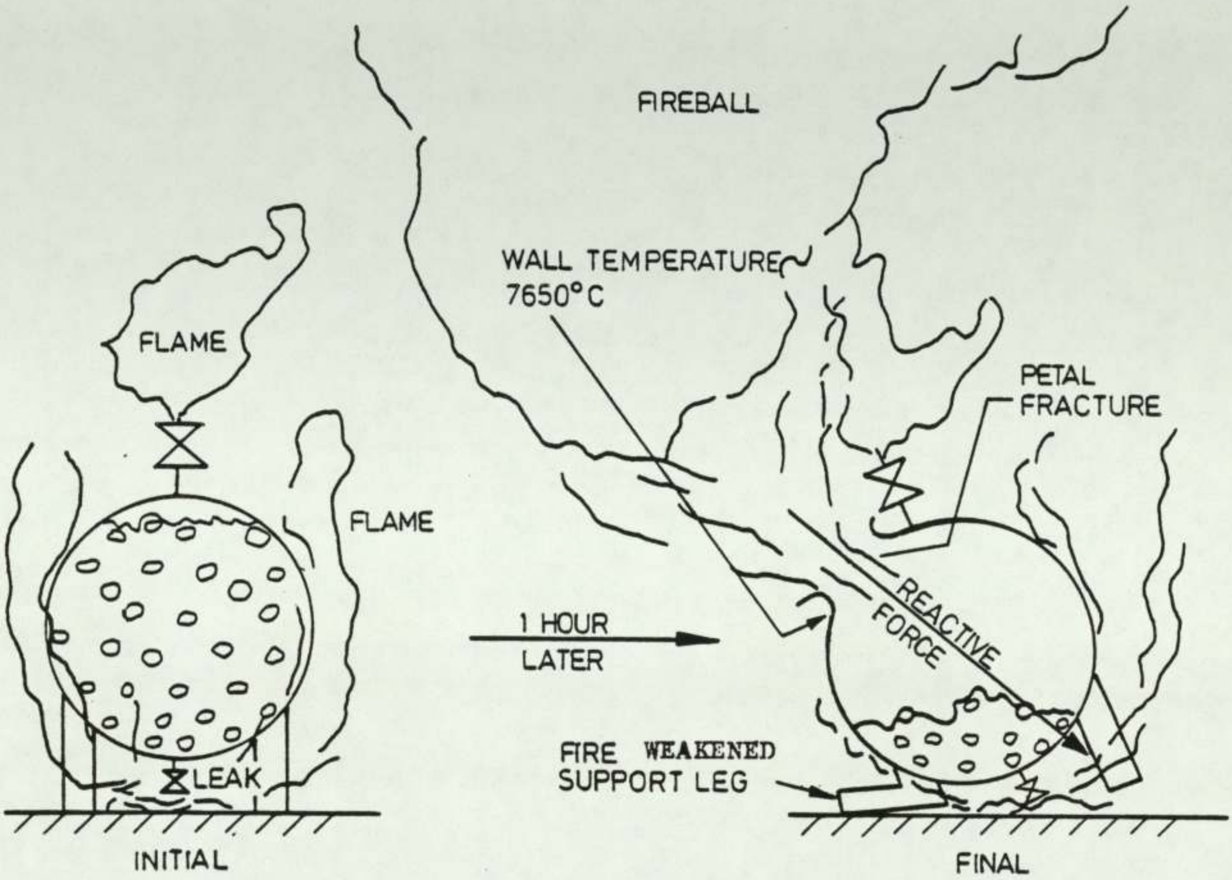


Figure 5.1 The development of a BLEVE

pressure in the sphere which is initially at absolute pressure P_2 is given by

$$\overline{P_2} = \frac{P_2 - P_o}{P_o} \qquad \text{.... 5.1}$$

similarly the shock overpressure

$$\overline{P_s} = \frac{P_s - P_o}{P_o} \qquad \text{.... 5.2}$$

The radial distances are made dimensionless by dividing by the radius R_o to which the gas in the sphere would have expanded adiabatically, if reduced from P_2 to P_o. The scaled radial distance of the shock front is given as,

$$\overline{R_s} = \frac{R_s}{R_o} \qquad \text{.... 5.3}$$

For a gas with a specific heat ratio of γ_1 initially stored at P_2 in a sphere of radius r_o.

$$R_o = [\frac{E_1}{P_o}]^{1/3} \qquad \text{.... 5.4}$$

Applying Brode's formula [40] which has been suggested for calculating the effective energy stored in a pressurised sphere of ideal gas, as shown in equation 5.5

$$E_1 = \left[\frac{P_2 - P_o}{(\gamma_1 - 1)} \right] Vo \qquad \text{.... 5.5}$$

with $V_o = \left[\frac{4\pi}{3} \right] r_o^3$, then equation 5.5 becomes

$$E_1 = \left[\frac{4\pi}{3} \right] \left[\frac{P_2 - P_o}{\gamma_1 - 1} \right] r_o^3 \qquad \text{.... 5.6}$$

then substituting equation 5.6 in equation 5.4 gives:

$$R_o = \left[\frac{4\pi \, (P_2 - P_o)}{3(\gamma_1 - 1) \, P_o} \right]^{\frac{1}{3}} r_o \qquad \text{.... 5.7}$$

At the instant of failure the scaled shock front radius $\overline{R}_{SO}$ is given by equation 5.8

$$\overline{R}_{so} = \frac{r_o}{R_o} = \left[\frac{3(\gamma_1 - 1)}{4\pi \, P_2} \right]^{\frac{1}{3}} \qquad \text{.... 5.8}$$

The contact surface pressure for the particular sphere gas/ambient air conditions, determines the initial reduced shock front overpressure $\overline{P}_{SO}$ at $\overline{R}_{SO}$. This value may be found from equation 5.9 by an iterative technique [40].

$$1 + \overline{P}_{so} = (1 + \overline{P}_2) \left[1 - \frac{(\gamma_1 - 1)\, \overline{P}_{so}\, (a_o / a_2)}{\{2\gamma_o\, [2\gamma_o + (\gamma_o + 1)\, \overline{P}_{so}]\}^{\frac{1}{2}}} \right]^{\frac{2\gamma_1}{\gamma_1 - 1}} \qquad .... \; 5.9$$

where

γ_1, γ_o = the specific heat ratio of the stored gas and air respectively

a_o, a_2 = the sonic velocity in air and in the sphere, respectively, at the instant of rupture

The initial values of $\overline{R}_s = \overline{R}_{so}$ and $\overline{P}_s = \overline{P}_{so}$ are plotted at the point 'x' in Figure 5.2, to determine the appropriate curve which predicts $\overline{P}s$ for $\overline{R}s$ beyond the sphere radius ro. Note from equations 5.8 and 5.9 that the initial point on Figure 5.2 [41] is independent of the size of the spherical vessel, but from equation 5.7, it is clear that the range Rs, which is obtained from equation 5.3 is directly related to the vessel radius r_o.

The fact that all the overpressure versus scaled distance curves shown in Figure 5.2 are roughly parallel allows construction of a graphical technique for determining the actual overpressure-distance relationship for any specific spherical vessel burst. Thus the same method is used to find the overpressure distribution for different storage pressures as shown in Figure 5.3, and for different sphere diameters as shown in Figure 5.4.

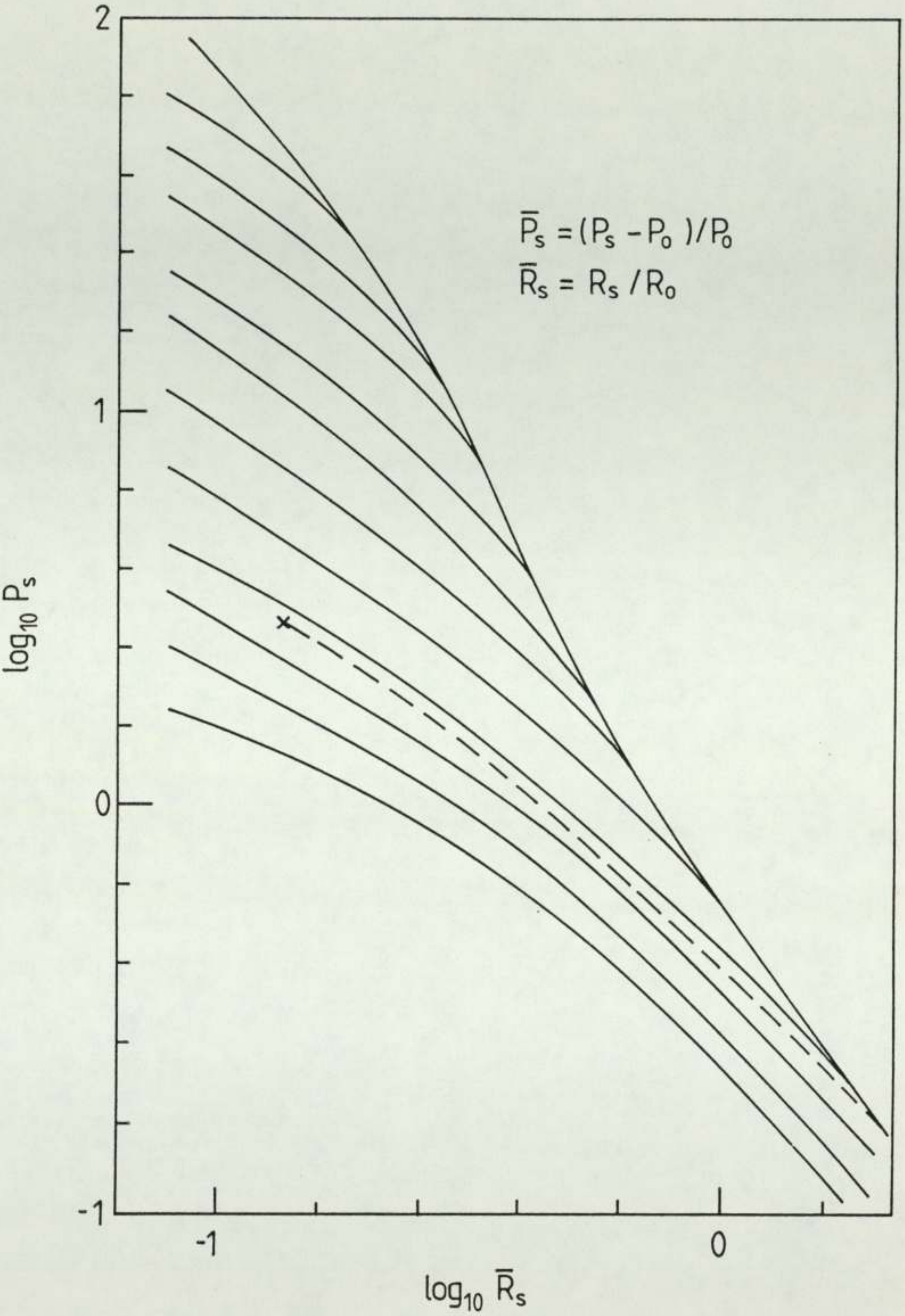


Figure 5·2 Reduced overpressure vs. reduced radius for burst sphere.

Example: Catastrophic Failure of Propane Tank

Mass of propane = 30 tonnes

Storage pressure = 20 bar gauge

Ambient temperature = 300 K

Diameter of storage sphere = 5 m

Calculation of blast damage from vessel rupture can be carried out by making an assumption such as, taking atmospheric pressure as 1 bar approximately, the reduced overpressure in the vessel initially is equal to the gauge pressure (ie $\overline{P}_2 = 20$) and the specific heat ratios for each of LPG and air are 1.2, 1.4 respectively.

So from equation 5.8

$$\overline{R}_{so} = \left(3 \times \frac{0.2}{80\pi}\right)^{1/3} = 0.134$$

$$\log \overline{R}_{so} = -0.874$$

since $$\frac{a_o}{a_2} = \left(\frac{\gamma_o}{\gamma_1}\right)^{1/2}$$

then
$$\frac{a_o}{a_2} = \left(\frac{1.4}{1.2}\right)^{1/2}$$
$$= 1.08$$

Substituting the values of $\overline{P}_2$, a_o/a_2, γ_1 and γ_o in equation 5.9 gives,

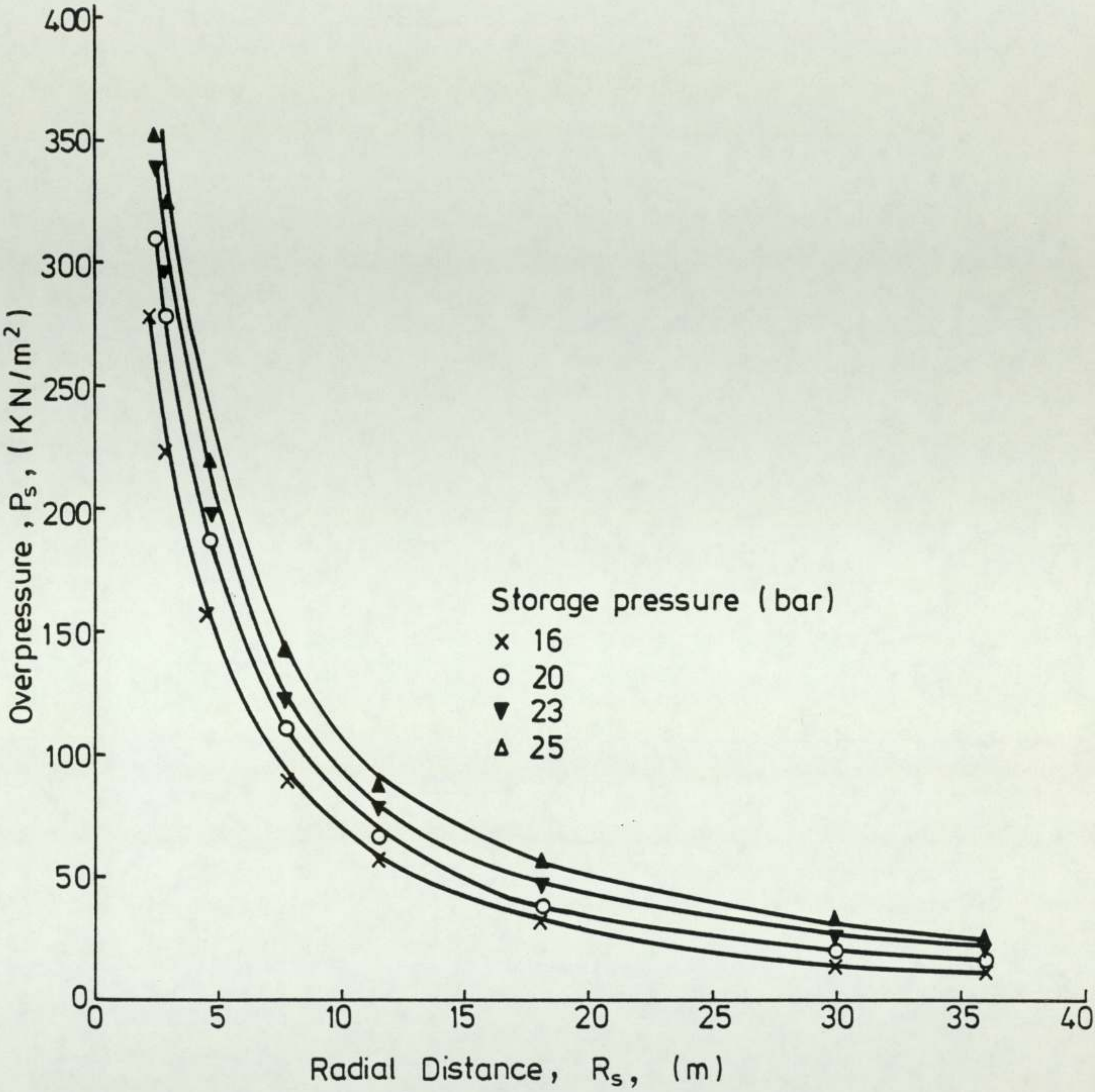


Figure 5·3 Overpressure vs Radial Distance following rupture of a 2·5 m Spherical Storage Diameter, assuming Different Storage Pressures.

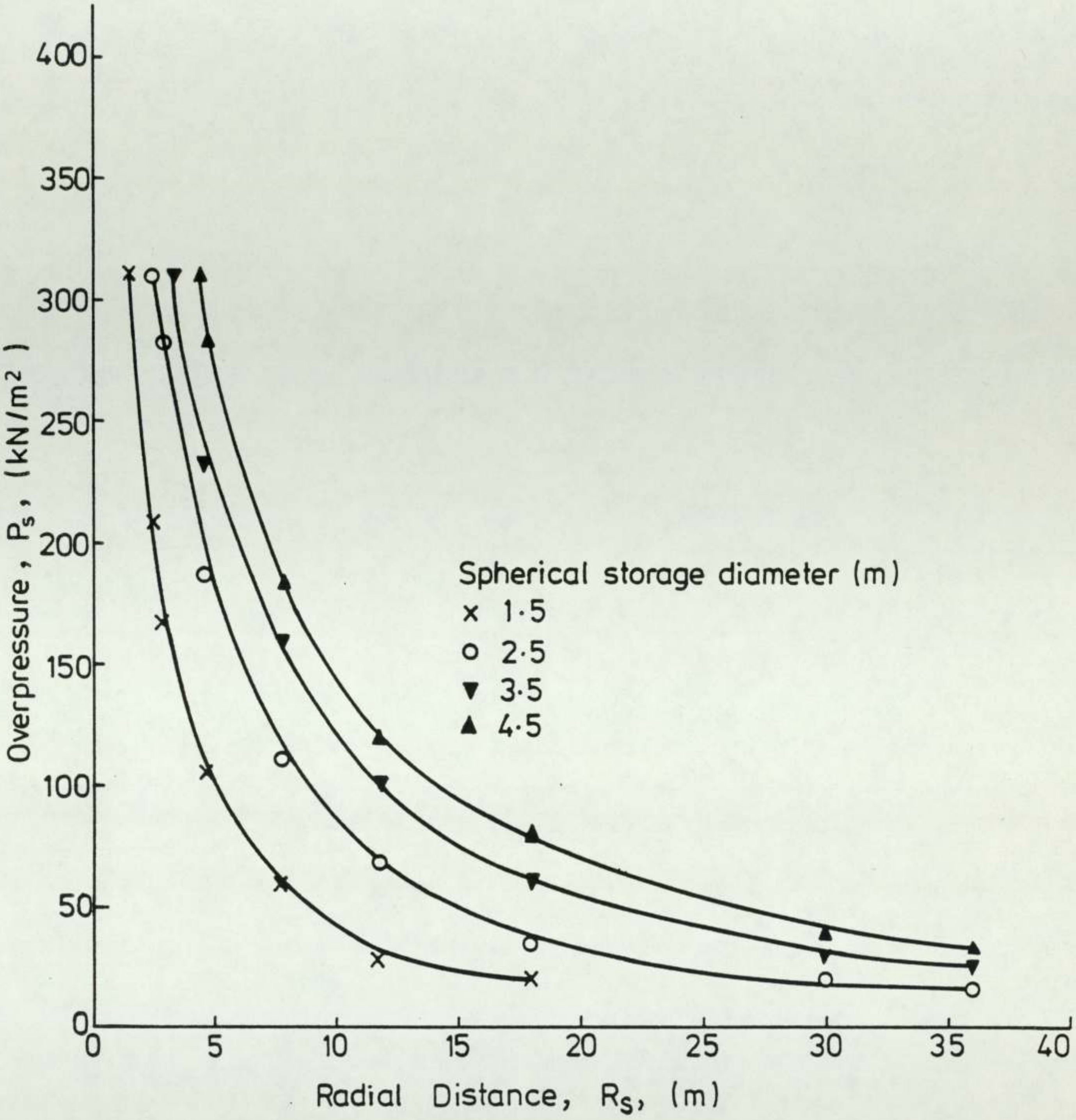


Figure 5·4 Overpressure vs. Radial Distance following rupture of Spheres at 20 Bar Storage Pressure, assuming Different diameters.

$$1 + \overline{P}_{so} = 21\left[1 - \frac{0.2 \text{ x } 1.08\,\overline{P}_{so}}{\{2.8\,(2.8 + 2.4\,\overline{P}_{so})\}^{\frac{1}{2}}}\right]^{12}$$

Solving this equation gives $\overline{P}_{SO} = 3.1$

$$\log\ \overline{P}_{SO} = 0.49$$

The conditions at the moment of rupture are located at the point 'x' on Figure 5.2, the overpressure distribution is found as follows from the broken line on Figure 5.2.

From equation 5.8

$$R_O = \frac{r_O}{\overline{R}_{SO}} = \frac{2.5}{0.134} = 18.7 \text{ m}$$

From equation 5.3

$$R_S = R_O\,\overline{R}_S = 18.7\,\overline{R}_S$$

The radii quoted in Table 5.1 were obtained knowing the value of $\overline{R}_S$ which corresponds to a known value of overpressure from Figure 5.2. A computer program was written to enable rapid calculations using this method; this is given in Appendix A and the result of typical calculations are given in Table 5.1. Typical damage at each radius can be estimated from Table 5.2 [42].

5.2.2 Projectiles

The sudden release of energy during an explosion may project from the epicentre a wide variety of missiles. In the case of BLEVE type incidents, the projectiles can range in size from small splinters of steel, to large storage tank sections of up to three quarters of the tank in size. Incidents are on record of such large fragments being projected for up to a mile and the danger these pose is apparent [3].

TABLE 5.1

OVERPRESSURE vs RADIAL DISTANCE FOLLOWING CATASTROPHIC FAILURE OF PROPANE TANK AT 20 BAR GAUGE STORAGE PRESSURE

Overpressure (kN/m^2)	Radial Distance (m)
309	2.5
281.5	2.95
189.2	4.69
111.68	7.7
69.1	11.79
36.8	18.79
22.4	30.32
17.13	36.3

The consequences from this type of event are very hard to predict because the trajectories of any fragments depend upon such variables as shape, size and angle of projection as well as the effect of wind. The wind direction (and its likely effect) in any particular incident is largely unpredictable and its effect on missiles is likely to be small.

Upon rupture tanks containing LPG usually fragment into a number of parts, eg 10 to 20. With cylindrical tanks the number is considerably less. Energy released upon rupture of LPG tanks is partly converted into kinetic energy of the fragments. As a result, the fragments may be scattered great distances. Figure 5.5 [16] shows the

TABLE 5.2

DAMAGE CAUSED BY VARIOUS AMPLITUDES OF SHOCK WAVES

PRESSURE kN/m^2	DAMAGE
0.2	Occasional breaking of large glass windows already under strain.
0.7	Breakage of windows, small, under strain.
1.0	Typical pressure of glass failure.
2.0	"Safe Distance" (probability 0.05 of no serious damage beyond this value).
2.0	Missile limit.
2.0	Some damage to house ceilings, 10% window glass broken.
2.8	Limited minor structural damage.
3.5-6.9	Large and small windows usually shattered; occasional damage to window frames.
4.8	Minor damage to house structure.
5.2	Breakage of small windows, not under strain.
6.9	Partial demolition of houses, made uninhabitable.
6.9-13.8	Corrugated asbestos shattered. Corrugated steel or aluminium panels,fastenings fail, followed by buckling wood panels (standard housing) fastenings fail, panels blown in.
9.0	Steel frame of clad building slightly distorted.
13.8	Partial collapse of walls and roofs of houses.
13.8-20.7	Concrete or cinder block walls, not reinforced, shattered.
15.2	Lower limit of serious structural damage.
17.3	50% destruction of brickwork of house.
20.7	Heavy machines (wt 1350 kg) in industrial buildings suffered little damage.
20.7	Frameless, self-framing, steel panel building demolished. Steel frame building distorted and pulled away from foundations.
20.7-27.6	Frameless, self-framing steel panel building demolished. Rupture of oil storage tanks.
27.6	Cladding of light industrial building ruptured.
34.5	Wooden utilities poles (telegraph etc) snapped. Tall hydraulic press (18000 kg) in building slightly damaged.
34.5-48.3	Nearly complete destruction of houses.
48.3	Loaded train wagons overturned.
48.3-55.2	Brick panels 0.2-0.3 m not reinforced, failed by shearing or flexure.
62.1	Loaded train/box-cars completely demolished.
69.0	Probable total destruction buildings. Heavy (3200 kg) machine tools moved and badly damaged. Very heavy (5500 kg) machine tools survived.
2000	Limit of crater lip.

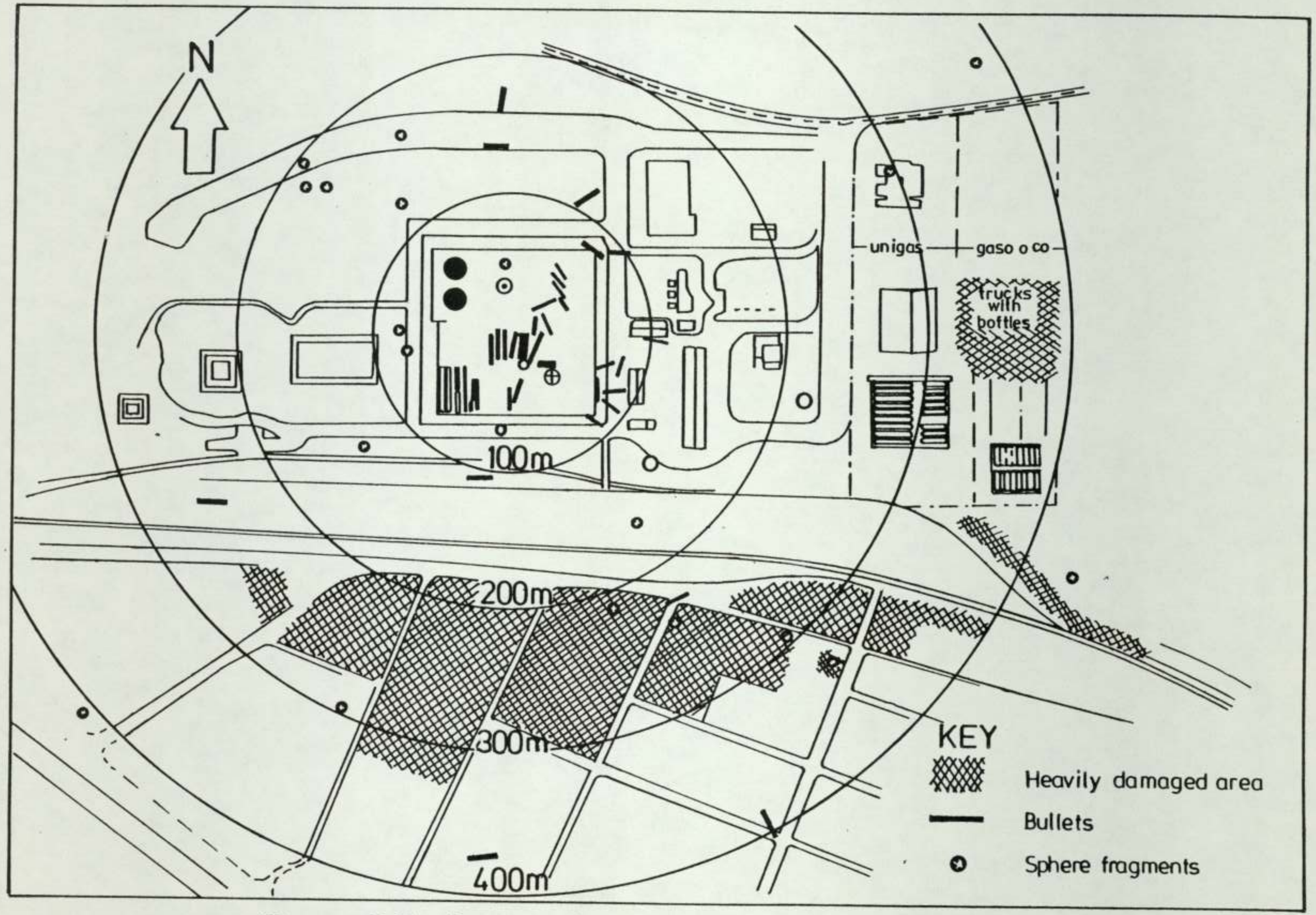


Figure 5.5 Damage Area at Mexico City Disarster.

position of the larger fragments of LPG tank in the San Juan Ixhuatepec incident up to distances of about 400 m. At least four large fragments came down at distances of 600, 750, 1100 and 1200 m [16]. It has been considered [3] that a safe evacuation radius from pressurised storage tanks of LPG should be a least 600 m.

There is, however, one area of consideration where the geometry of the projectiles, together with weight, is accurately known, that of gas bottles in storage at LPG facilities. The probability of a gas bottle striking LPG storage tanks and pipes, leading to large scale spills, is extensively covered in the Canvey Report [11]. The conclusion reached was that a 14.5 kg bottle with an initial velocity of 100 m/s will upon impact:

i bounce off storage spheres,
ii possibly penetrate cylindrical tanks (bullets),
iii certainly rupture piping.

Gas bottles are present at filling facilities in quite large numbers, and in the past a number of fires at these installations have resulted in projectile damage at distances up to some hundreds of metres. As a result of these experiences, there has been a move to fit relief valves to bottles to relieve any excessive pressure build-up in a fire situation. This measure substantially reduces the chance of failure of the bottle and subsequent BLEVE. However, the plume of burning gas from a relieving bottle will extend for some distance, endangering fire-fighters and spreading the fire. Furthermore, if the vapour vented from a fire exposed cylinder is not ignited immediately, due perhaps to a local oxygen deficiency, then delayed ignition might well lead to a semi-confined explosion with missiles ejected a considerable distance. To prevent this occurrence, bottles should not be stacked on pallets more than five high.

Finally, injury due to missiles has not been evident, in major incidents and, therefore, historically, missile production would appear to be a low risk primary hazard. (This effect is, of course a function of the distance of personnel from the epicentre of the BLEVE, so that in 'minor' incidents involving small cylinders being fitted/adjusted the incidence of injury from fragments would be expected to be greater.) These projectiles might, however, give rise to a secondary hazard on site due to rupture of storage tanks etc. Theoretically this low risk would appear to be a product of the small size of people in relation to the area in which the missiles fall and the fact that in urban environments the majority would be under cover giving an unquantifiable level of protection from a missile.

5.3 PROTECTION OF LPG TANKS

LPG tanks exposed to severe fire conditions suffer an increase in internal pressure while simultaneously undergoing a decrease in tank burst strength. Although the required safety valves can hold the internal pressure level to about 20% to 25% of the design burst strength, the heat absorption from exposure to a fire will rapidly lower the steel burst strength to a point where the steel is not capable of withstanding even this safe relief pressure and explosion results. Tests have been conducted in the USA [39] using a standard 30,000 gallon LPG blimp with a standard paint finish and filled with LPG which was exposed to direct flame contact from an impounded JP-4 fuel spill fire beneath the blimp. The tank vented after about 12 minutes of fire exposure and exploded after about 25 minutes, 60% of the contents still being liquid. This points to the need to keep the tem-

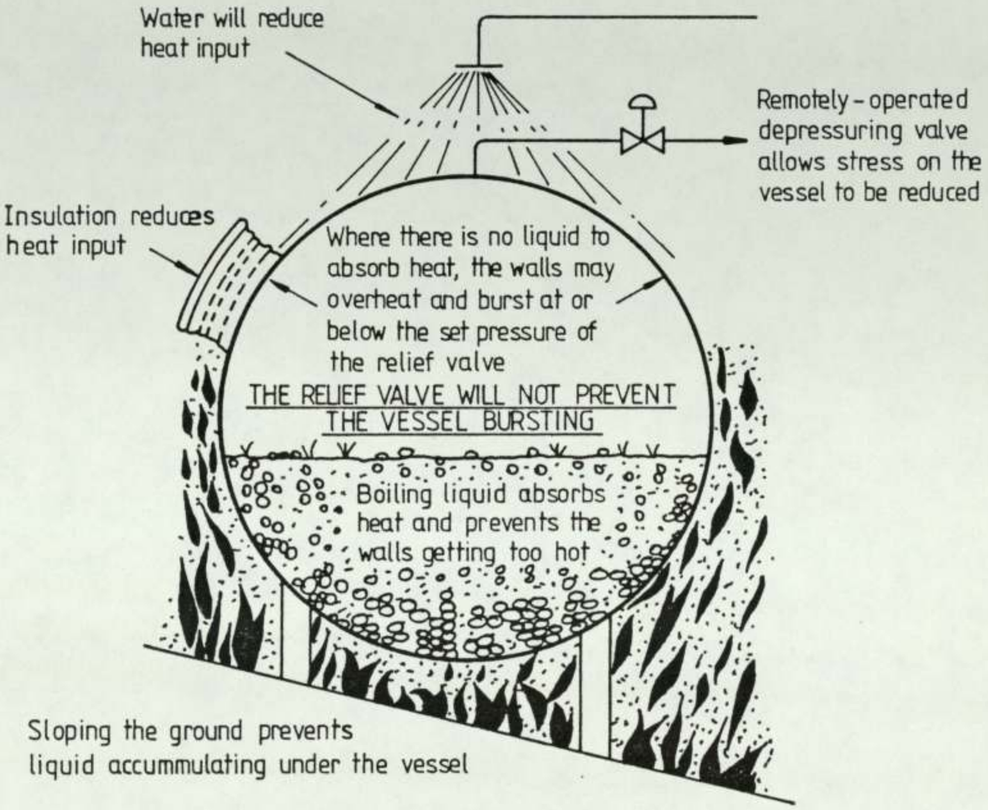


Figure 5.6 Methods of protecting a pressure vessel against fire (Support legs are also normally protected by insulation and water sprays)

perature of LPG storage tanks low, especially the parts of the tank that are not wetted (and thus cooled) by the internal contents.

There are several methods currently in use for thermal protection as shown in Figure 5.6 [43] and these will be discussed in turn.

5.3.1 Sloping the ground

The base on which the pressure vessel stands should be impervious and sloped so that any spillage is collected. A slope of 1 in 40 is recommended [44]. Spillage of flammable liquid cannot then accumulate under the vessels, as it did at Feyzin [43]. The collecting area should be such a distance away from the tanks, and of such a surface area, that the flame from a fire in the collecting pit will not impinge on the tank (considering that flames may be at angle of 45° to the vertical and that the flame length may be twice the pool diameter).

In the case of process vessels the principle of sloping should be applied so that the gradient is not less than 1 in 60. It should lead to a safe controlled drainage or collecting point. If the ground is level, or worse, slopes towards the centre of the plant, spillage will remain in the plant area. Also, hydrocarbons will float on top of the water used for cooling the vessels and could be a hazard to other plants nearby.

5.3.2 Water Cooling

Water application by either direct contact water spray fixed piped system, monitor nozzles, and hose lines are classic methods for cooling LPG tanks exposed to fire conditions. The theory is that, providing the water film is maintained over the tank, then the temperature cannot exceed the boiling point of water, and tank shell strength remains adequate. However, if the exposure to fire is very strength remains adequate. However, if the exposure to fire is very severe, the water may well be vaporised before contacting the vessel, or high velocity vapour and flame effects may blow aside the water film and permit direct flame impingement on the steel shell. There are recorded data which substantiate the inadequacy of water systems for LPG tank protection; their complexity makes them unreliable and very costly, both from an initial installation and from a maintenance viewpoint. Further, there is a lack of evidence to show the effectiveness of fixed water spray systems for the prevention of LPG tank explosions during tank exposure to flame contact from spill fires and impinging vapour/liquid pressure fires.

The rate of water application usually recommended where vessels are liable to be exposed to direct flame impingement is 10 litres/m^2/min [44]. Such a rate is hardly practicable to supply if a number of large vessels have to be cooled. For example, 450 m^3/hr are required for a 2000 m^3 sphere. This reinforces the case for sloping the ground. Where radiant heat alone has to be considered, much lower rates may be sufficient.

Water from fixed equipment may be applied to the top of the vessel in cases where it will be evenly distributed over the whole surface. In other cases, it should be applied directly on to all parts of the vessel as shown in Figure 5.7 [45]. The former is much cheaper but care must be taken to see that obstructions on the vessel do not impede the flow.

Fixed equipment should preferably be permanently drained, periodically tested and serviced to ensure that it does not freeze or rust.

Finally, care must be taken that there is adequate water in the

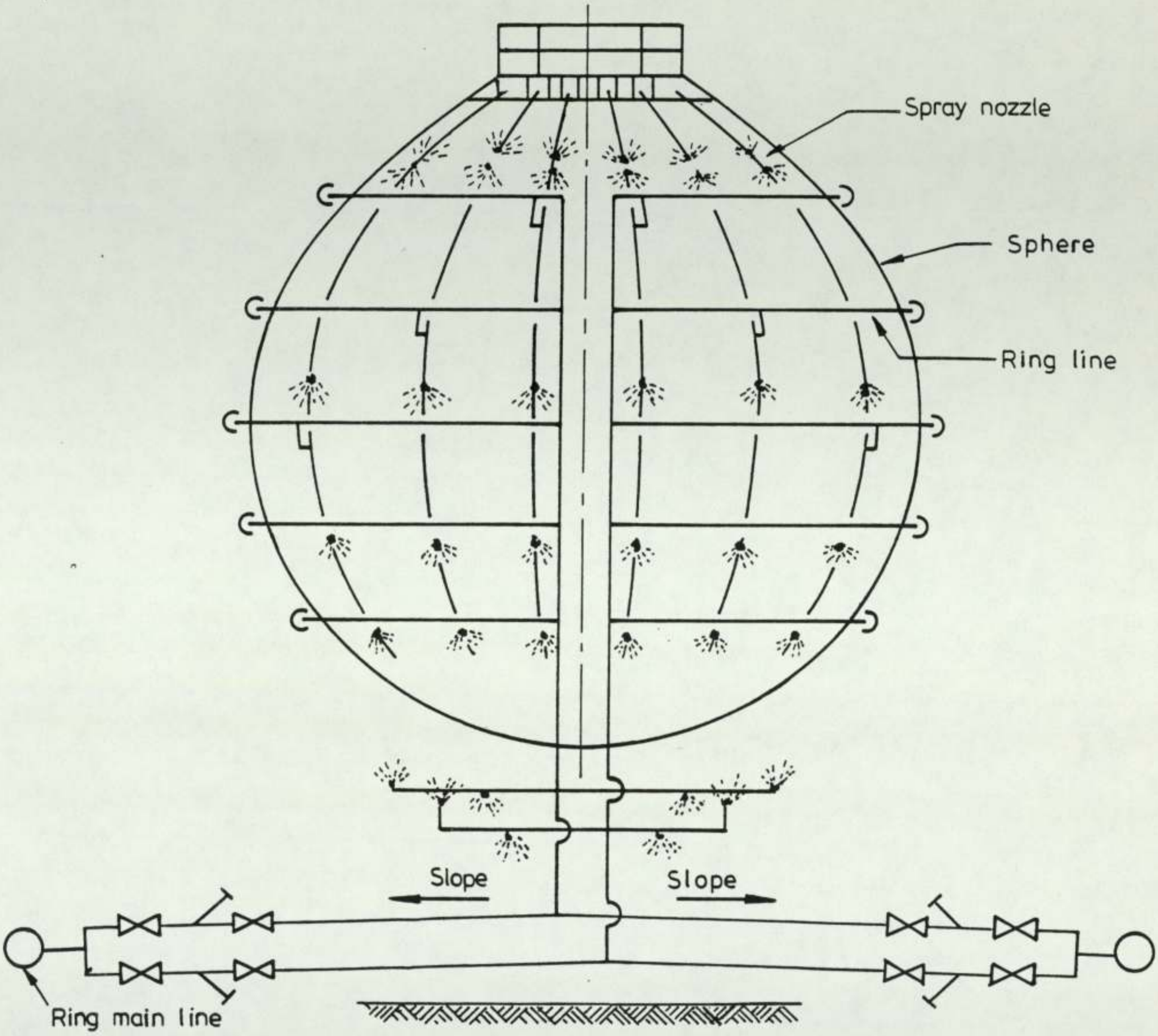


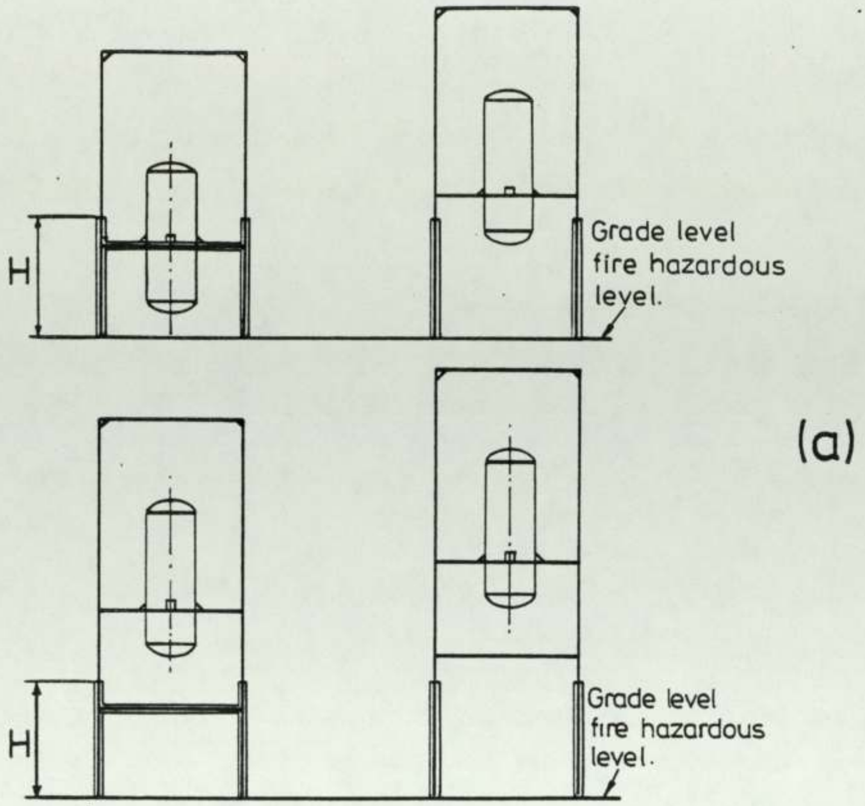
Figure 5.7 Spray System for Spherical Tank.

fire system or all times to operate the fixed water drenching installation. The quantity of water applied by a fixed system must leave an adequate balance in the total water supply system for use by mobile equipment. Provision must be made for controlled drainage of the applied water. It is not economically practicable in some cases to design and construct underground drains capable of handling the required flowrate.

5.3.3 Insulation

Insulation, particularly of vessels containing high risk material such as liquefied flammable gases, is recommended in some codes such as the ICI LFG Code but not in others [43]. Tests and fire experience have shown that insulation should withstand the jets from fire hoses.

Insulation is on the vessel as an immediate barrier to heat input before the water drench is applied. The advantage of it is when the water supply lines have been damaged by fire or any associated explosion. Nevertheless, insulation should be looked on as additional to water drenching, not as an alternative. Insulation slows down the rate of heat input to the vessel, typically by a factor of about ten [43], but it does not ultimately prevent the vessel getting too hot. With insulation there is more time to commission water drenching and augment fixed systems with portable monitor sprays. Figures 5.8 (a and b) show the application of insulation [45]. Methods which have been suggested as a means of providing fire insulation may be summarised as follows.



Equipment – supporting structures with fire hazardous level at grade level.

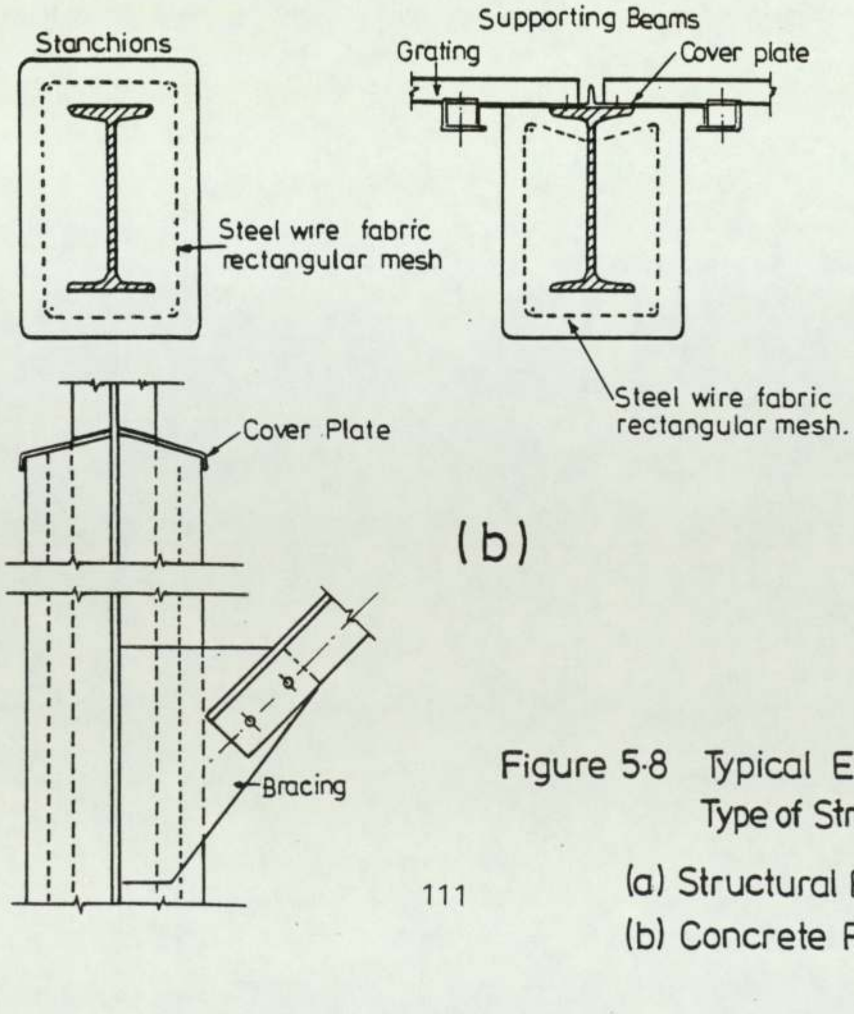


Figure 5·8 Typical Examples – Extent and Type of Structural Fire Protection.

(a) Structural Fire Protection, Elevation.

(b) Concrete Fire Protection.

5.3.3.1 Mounding or burying of the LPG Tank:

Below ground burial is the easiest method of thermal protection to understand and accomplish, but it is the least desirable method due to the high potential for corrosion and safety problems associated with undetected LPG leaks. The seriousness of underground leakage of LPG should not be underestimated; Andrews [3] reports on a test to determine the problems attendant upon the sealing of a leak in a 8" diameter LPG pipeline buried 4ft below ground in sandy soil. The pipeline was deliberately drilled with a 3/32 inch hole prior to burial, and upon pressurising the pipeline with LPG, the escaping vapour was ignited as it issued through the soil. After some hours a mechanical excavator was moved into position, protected by water sprayed from hoses, and proceeded to uncover the pipeline. However, at a depth of two feet the excavator met with rock-hard ground, which was in fact frozen sand and water and LPG due to the rapid evaporation at the point of leakage and a consequent drop in temperature. Two water jets were needed, over a considerable time, to soften the sand so that it could be removed. Even after removal it continued to burn. This is indicative of the type of difficulty that might well face the emergency services in the event of an accident with a buried LPG tank.

Above ground burial, or mounding, offers protection from flame impingement, but has inherent with it the problems of tank and piping system redesign or requalification if the tank to be mounded was initially designed for above ground service. All piping must usually be by way of top-side manhole connections. It has been recommended [43] that burying a tank never be used.

5.3.3.2 Standard Insulation Systems

Conventional or standard insulation systems such as cork, glass-wool or aggregates such as vermiculite, perlite or calcite require an outer metallic sheath for environmental protection and to provide mechanical attachment of the insulation. The lack of firm bonding between the insulation and the LPG tank shell permits moisture entrapment and subsequent corrosion. During severe flame impingement fires, the relatively thin metallic sheathing deforms with loss of the previously protected thermal insulation.

Tests have shown that vermiculite-concrete exposed to a fire, stands up well to fire and water jets without damage [43].

Low temperature vessels should be provided with fire protection on the outside of the heat insulation because the insulating materials available for low temperature duty do not have good fire resistance, for example, cork or foam glass covered with a vermiculite concrete layer 10-20 mm thick. One disadvantage with an insulating cover is that it is difficult to inspect the vessel or supports for corrosion. On one occasion a vessel collapsed due to corrosion of the supports. Fortunately this occured when it was filled with water for test. Insulation of a vessel should be designed so that sections can be removed for inspection of the vessel and supports.

5.3.3.3 Refractory protection systems

Refractory materials are normally used to give thermal protection to the inside of furnaces, kilns and high temperature process line [39]. When applied to the fire protection of steels where a hydrocarbon spill fire can be expected to reach maximum intensity within a few seconds, such materials will crack under the condition of large thermal stresses, leaving large areas of the tank shell exposed to direct flame. Basically most refractory materials are designed to be brought very slowly up to their operating temperature, as well as being cooled down quite slowly.

5.3.3.4 Cement Compounds

These compounds including ordinary concrete and gunite provide good fire protection insulation systems for steel structures [39]. They are, however, quite heavy, expensive, in most cases corrosive, and exhibit poor mechanical bonding properties.

5.3.3.5 Ablative Coating

These types of material provide good protection for structural steels. The fundamental principle is to apply a coating that gradually erodes due to the heat input from the impinging fire. The solid material changes into a gas, utilising heat energy that would otherwise be used for heating of the unprotected LPG tank. The temperature rise in the protected vessel is in direct proportion to the thickness of the coating and its thermal properties. Some ablative coatings result in a simultaneous generation of a tough microporous char layer which provides additional insulating properties. The main problem with such materials is the complexity in the application, which makes it quite costly on an installed basis [39].

5.3.4 Depressurisation

Reducing the pressure in a vessel exposed to fire leads to a reduction of the stress on the metal and removes the danger of the vessel bursting. Also, this method may be used to prevent damage to items of equipment which are expensive to replace and may take a long time to obtain.

The designer needs to decide how quickly the pressure should be reduced and by what means.

Klaassen [44] suggests that means for vapour depressurising should be provided on all vessels, handling flammable liquids which operates above 3 bar and that the depressurising valve should be sized so that the pressure falls to half of design pressure in ten minutes. The American Petroleum Institute [46] recommended that the pressure should be reduced to 8 bar or 50 percent of design, whichever is lower, in 15 minutes.

The stress to rupture depends on the temperature, falling rapidly for carbon steels at temperatures above about 500 °C. It is therefore important to know the temperature that can be attained by an unwetted vessel exposed to fire. The API [47] assumes 690 °C, but in theory, much higher temperatures can be reached [43]. Assuming a temperature, and using Figure A3 in "Design and Installation of Pressure Relieving Systems in Refineries", can provide guidance on the percent of depressurising. As an example with an assumed temperature of 750 °C and using the above mentioned Figure for carbon steel vessels designed to BS 1515 shows a need to depressurise to about 20 percent of design pressure.

As the steel subject to higher stresses can fail more quickly at the temperature assumed, the aim should be to achieve this pressure within ten minutes. This is the shortest time in which a vessel has been known to burst when exposed to a fire [43].

The allowable depressurising time is affected by insulation and sloping the ground. If the vessel is insulated the rate of heat input is reduced and this time can be extended to an extent which depends on the quality of the insulation. Therefore, an insulated vessel should be depressurised within thirty minutes. Also the heat input into the vessel will be reduced when the ground under the vessel is sloped. This will lead to an increase in the depressurising time to twenty minutes.

If a vessel is insulated and the ground is sloped, then the depressurising time becomes sixty minutes. However, although this may be adequate to protect the vessel, another purpose of de-pressurising is to reduce the size of any leak which occurs in the vessel or its connecting pipework.

Vapour depressurising can be achieved by de-pressurising the vessel through existing lines installed for process purposes. If these are not present, then a relief valve by-pass may be installed. The depressurising valves, whether part of the process or specially-installed, must be operable in a fire situation. This usually means that they have to be remotely operated by electric or pneumatic power. The operating button must be well away from the vessel or it may not be accessible when a fire occurs.

Instead of a relief valve by-pass, a relief valve can be obtained which can be lifted by a remotely-operated pneumatic device. When this device does not operate, the valve functions as a normal relief valve.

It is not necessary to provide depressurising facilities on every vessel. If a group of vessels are normally connected together they can be depressurised as a whole.

The material discharged through a vapour depressurising valve, like the material discharged through a relief valve, must be disposed of in a safe way. It may be discharged to a flare system or it may be discharged through a vent or tail-pipe at such velocity that good mixing occurs. In the case of fire on the tail-pipe of the vapour depressurising valve due to formation of a cloud of flammable vapour, steam dispersion may be installed.

Finally the tail-pipe should be positioned so that any flame on it cannot impinge on other equipment.

CHAPTER SIX

EVALUATION OF THERMAL RADIATION HAZARD RANGES

A number of accidents have occurred leading to a fireball. These have involved the release of the contents from pressurised installations, or storage, or rail and road tankers containing LPG fuels. A list of incidents for which quantitative data are available is shown in Table 6.1 [48], together with the source of that information.

In evaluation of the thermal radiation hazard represented by a fireball, there are four primary parameters which are relevant [48]:-

i the mass of fuel involved
ii the fireball diameter
iii the duration time, and
iv the surface temperature

The consequences of an LPG fireball which must be considered as serious hazards are:

i a Major fire
ii an Unconfined Vapour Cloud Explosion (UVCE)
iii a Boiling Liquid Expanding Vapour Explosion (BLEVE)

6.1 FIREBALL CHARACTERISTICS

The rapid combustion of flammable vapour in a spherical envelope is generally termed a fireball. The strong buoyancy forces of the hot, burning gases result in turbulent mixing and the formation of a mushroom-shaped cloud, often with a 'stem' of flame emanating

TABLE 6.1

DATA ON SOME INCIDENTS RESULTING IN FIREBALLS

Reference	Date	Place	Fuel container	Fuel	Quantity involved (tonnes)	Reported fireball diameter (m)
49	21.6.70	Crescent City Illinois, USA	Rail tank car	Propane	75	150-200
50	9.3.72	Lynchburg Virginia, USA	Tank truck	Propane	9	120
51	5.7.73	Kingman, Virginia, USA	Tank car	Propane	45	300
52	11.1.74	West St Paul, Minnesota, USA	Tank	LPG	10	100
53	17.1.74	Aberdeen, Scotland, UK	Road tanker	Butane	2	70
54	26.11.76	Belt, Montana USA	Rail tank car	LPG	80	300
55	28.12.77	Goldanna, Indiana, USA	Rail tank car	LPG	70	300-350
38	11.7.1978	San Carlos, Spain	Road tanker	Propylene	23.5	125
38	29.4.79	Eagle Pass, Texas, USA	Storage tank	LPG	25	340
16	19.11.84	San Juanico, Mexico City	Storage tanks	LPG	2500-3000	300

from the source of the fuel. It is the high degree of turbulent mixing and rapid air entrainment which allows large quantities of fuel to be consumed in a short period [48].

Large quantities of heat are radiated from the hot mass of burning gases and the high radiant flux levels represent the major hazard from fireballs, extending well beyond the region that the flame envelopes. The main parameters relevant to a fireball are presented in the following sections.

6.1.1 Fireball Duration

The duration of the fireball is related to the mass of combustible fuel by the relationship;

$$t = A\ m^{a} \qquad \text{.... } 6.1$$

where A and a are constants and m is the mass of fuel (kg). Table 6.2 and 6.3 [56] summarise the constants from reported data. Whilst there is some agreement between the various researchers this is not evidence for the adequate measurement of fireball duration since it can be partly attributed to the way in which the duration is defined by different researchers [48] .

Hasegawa and Sato [57] defined an effective fireball duration as the time for which the fireball area exceeded half the maximum value whereas Fay's data [58] for 'complete combustion' of the fuel, and the data presented by Hardee *et al* [59], are for the combustion time until the fireball starts to lift off the ground. He suggests that the total combustion time will be about twice the lift-off time and this is consistent with the total duration data presented by Fay & Lewis [48].

TABLE 6.2

VALUES OF THE PARAMETERS IN EQUATION 6.1 AND 6.2 FOUND EXPERIMENTALLY

Flammable	Scale	A	a	B	b	Authors
Methane	0.1-10 kg	2.57	1/6	6.36	0.325	Hardee et al
Propane	0.037-0.37 g	2.53	1/6	6.28	1/3	Fay and Lewis
Pentane	0.3-6.2 kg	1.10	0.1	5.28	0.277	Hasegawa
Propene	0.124-452 kg	0.32	1/3	3.51	1/3	Maurer *et al*

TABLE 6.3

VALUES OF PARAMETERS IN EQUATION 6.1 AND 6.2 PROPOSED IN VARIOUS REVIEW PAPERS

Authors	A	a	B	b
Gayle	0.245	0.356	3.68	0.326
Brasie	0.30	1/3	3.8	1/3
Marshall	0.38	1/3	5.5	1/3
Roberts	0.45	1/3	5.8	1/3

The difference between the exponents obtained may well be explained by the scale of the experiments. Small scale studies on quiescent fireballs by Fay [58], Hardee [59] and pressurised fuels by Hasegawa [57] all show low values while Maures [60] represents a higher exponent value. This implies that very small scale laboratory fireballs do not provide an accurate guide to the duration of larger scale events.

A computer program was written to enable rapid calculation of fireball duration using different authors' parameters; this is given in Appendix B. Typical results are shown in Table 6.4.

6.1.2 Fireball Diameter

Experimental studies of fireballs have been carried out with small quatities of quiescent gaseous fuels contained in soap bubbles by Fay and Lewis [58], Lihou and Maund [56], and in balloons and plastic bags as done by Hardee *et al* [59].

Studies have also been carried out by Hasegawa and Sato [57], Maurer *et al* [60], in which the fuel was rapidly released from a vessel after super-heating to a selected pressure.

The relationship obtained by different authors, relating maximum diameter with fuel mass is illustrated in equation 6.2. The parameters quoted in Table 6.2 and 6.3 are for a mass m (kg) of flammable producing a fireball of diameter Ds (m).

$$D_s = Bm^b \qquad \text{.... 6.2}$$

There is considerable disagreement between various authors concerning the correlation which should be used to predict the maxi-

TABLE 6.4

TYPICAL RESULTS OF FIREBALL DURATION (SEC) USING DIFFERENT AUTHORS' PARAMETERS

Mass (kg)	Gayle	Brasie	Marshall	Robert	Hardee	Fay
5	0.4	0.5	0.6	0.8	3.4	3.3
50	1.0	1.1	1.4	1.7	4.9	4.8
100	1.3	1.4	1.8	2.1	5.5	5.4
500	2.2	2.4	3.0	3.6	7.2	7.1
1,000	2.9	3.0	3.8	4.5	8.1	8.0
10,000	6.5	6.4	8.2	9.7	11.9	11.7
50,000	11.5	11.0	13.9	16.5	15.5	15.2
100,000	14.8	13.9	17.6	20.8	17.4	17.1
500,000	26.2	23.7	30.0	35.6	22.7	22.3

mum diameter of the fireball as shown in Tables 6.2 and 6.3.

A computer program was written to enable rapid calculation of fireball diameter using different authors' parameters; this is given in Appendix B. Typical results are shown in Table 6.5.

6.2 HAZARDS FROM FIREBALLS

Fireballs are hazardous because they are very hot, may be very large, and move in the atmosphere on currents of air. They are, therefore, a source of ignition and may ignite any combustible material in their path. More serious is their potential effect on people who can suffer severe burns from thermal radiation, even at some distance away from the fireball.

For example, the disaster on the Spanish Campsite in 1978 in which many people were killed and injured occurred when a cloud of propene escaped from a tanker and became a fireball when it found a source of ignition [56]. People were severely burnt by thermal radiation even some distance from the fireball because they were scantily clad. From the work of Stoll and Chianta [61] on the thermal radiation damage to pig skin, the following relationship has been derived. It enables the steady incident flux density q_2 (kW/m^2) to be related to the duration te (seconds) which will cause severe blistering

$$q_2 = 50/te^{0.71} \qquad \ldots.6.3$$

Stoll's equation has been used [56] in the estimation of spacing distances in previous work. A new correlation on thermal radiation damage to human skin has been obtained and this will be described in Section 6.3.

TABLE 6.5

TYPICAL RESULTS OF FIREBALL DIAMETER (m) USING DIFFERENT AUTHORS' PARAMETERS

Mass (kg)	Gayle	Brasie	Marshall	Robert	Hardee	Fay
5	6.2	6.5	9.4	9.9	10.7	10.7
50	13.2	14.0	20.2	21.3	22.7	23.1
100	16.5	17.6	25.5	26.9	28.4	29.1
500	27.9	30.1	43.6	45.9	47.9	49.7
1,000	35.0	37.9	54.9	57.9	60.0	62.7
10,000	74.1	81.6	118.1	124.6	126.9	134.9
50,000	125.2	139.5	201.9	212.9	214.1	230.5
100,000	157.0	175.7	254.3	268.2	268.2	290.4
500,000	265.3	300.3	434.6	458.3	452.5	496.3

With a steady radiant flux, secondary fires in buildings can occur when the flux density is 12.6 kW/m^2 or more. Process plants and flammable storage tanks suffer severe damage at 37.8 kW/m^2 [62]. As a general rule of thumb, one may assume that under the steady flux densities quoted above, building and process equipment will ignite after 1000 seconds (about 17 minutes) [56]. Thus the radiation dosage for secondary fires may be set out as follows;

For buildings:

$$12.6 \text{ kW/m}^2 \times 1000 = 12.6 \text{ MJ/m}^2 \qquad \text{..... } 6.4$$

For process equipment

$$37.8 \text{ kW/m}^2 \times 1000 = 37.8 \text{ MJ/m}^2 \qquad \text{.... } 6.5$$

6.3 THERMAL RADIATION DAMAGE CRITERIA

In estimating the hazard due to thermal radiation from LPG flames, calculation of the radiant intensity variation with distance from the flame is an important criterion. However, to quantify the hazards or to evaluate the risk to population and property, the damage criteria have to be considered.

In general, damage to skin exposed to thermal radiation depends on the intensity level and the duration of exposure, the protection offered by clothes and the natural cooling by perspiration and increased blood flow.

From the work of Stoll and Green [63] which includes exposure of human forearms to different intensities of radiation, the times required to produce threshold pain, threshold blister and full blister were determined.

Their data have been correlated in the present work using a computer curve fitting technique, as shown in Appendix C, to give three relationships which enable the thermal radiation incident on human skin to be related to the time of exposure as shown below.

Pain Threshold: $q = 28.2\ (t)^{-0.73}$ 6.6

Threshold Blister: $q = 60.5\ (t)^{-0.75}$ 6.7

Full Blister: $q = 61.8\ (t)^{-0.73}$ 6.8

where q is the radiation intensity (kW/m^2) and t is the time of exposure (sec).

Furthermore the data from their work which represents tissue damage for the threshold blister and full blister have been correlated using the same technique to give two relationships between the damage to tissue and the thermal radiation incident on human skin as shown below.

Threshold Blister: $Z = 2.61\ (q)^{1.09}$ 6.9

Full Blister: $Z = 3.65\ (q)^{1.31}$ 6.10

where Z represents the percent of tissue damage.

6.4 PREDICTION OF THERMAL RADIATION HAZARDS

Heat transfer from the fireball to the target will be primarily by thermal radiation. The radiation flux at a target q_2 (kW/m^2) is given by the equation:

$$q_2 = F_{21}\, \tau\, \alpha\, q_1 \qquad \text{.... 6.11}$$

where q_1 (kW/m^2) is the emitted flux from the surface of the fireball, τ is the atmospheric transmissivity, α the absorptivity of the target and F_{21} the view factor.

Transmissivity can be estimated from the following equation [56]

$$\tau = \exp\,(-7 \times 10^{-4}\, L) \qquad \text{.... 6.12}$$

where L is the distance from the edge of the fireball to the target area (m). The attenuation constant for the atmosphere can vary in value from 0.4 km^{-1} to 1.0 km^{-1} between a clear and a hazy day respectively [56]. An average value of 0.7 km^{-1} has been assumed in equation 6.12 and L can be found from the following equation.

$$L = \left[\left\{\left(\frac{H}{D_s} + 0.5\right)^2 + \left(\frac{R}{D_s}\right)^2\right\}^{1/2} - 0.5\right] Ds \qquad \text{.... 6.13}$$

where Ds is the spherical fireball diameter, H the height of the fireball (m) and R the radial distance (m).

For a spherical fireball of diameter Ds (m) and which has cleared the ground by a height of H (m), the value of F_{21} for a target at a radial distance R (m) from a point directly below the centre of the fireball is given by equation 6.14 which was used to prepare Table 6.6 [56].

TABLE 6.6

DIRECT EXCHANGE FACTORS FOR SPHERICAL FIREBALLS OF DIAMETER Ds TO TARGETS AT RANGE R, WHEN THE FIREBALL HAS CLEARED THE GROUND BY H

R/D_s	0	.25	.5	.6	.7	.8	.9	1.0	1.2	1.4	1.6	1.8	2.0	2.25	2.5	2.75	3.0
H/D_s						F_{21}: Incident Flux Density/Emitted Flux Density											
0	1.00	.716	.354	.262	.196	.149	.115	.089	.057	.038	.027	.019	.014	.010	.0075	.0057	.0044
0.1	.694	.546	.315	.246	.191	.150	.119	.095	.062	.042	.030	.022	.016	.012	.0088	.0067	.0052
0.2	.510	.426	.275	.233	.180	.146	.118	.096	.065	.046	.033	.024	.018	.013	.0100	.0077	.0060
0.3	.391	.340	.238	.200	.166	.138	.115	.095	.067	.048	.035	.026	.020	.015	.0111	.0085	.0067
0.4	.309	.276	.206	.178	.152	.129	.109	.092	.067	.049	.036	.028	.021	.016	.0120	.0093	.0073
0.5	.250	.228	.179	.158	.137	.121	.103	.088	.066	.049	.037	.029	.022	.017	.0128	.0100	.0079
0.6	.207	.192	.156	.140	.124	.109	.096	.084	.064	.049	.038	.029	.023	.018	.0135	.0106	.0084
0.7	.174	.163	.137	.124	.112	.100	.089	.079	.061	.048	.038	.030	.024	.018	.0141	.0111	.0089
0.75	.160	.151	.128	.117	.106	.096	.086	.076	.060	.047	.037	.030	.024	.018	.0143	.0113	.0091
0.8	.148	.140	.120	.111	.101	.091	.082	.074	.059	.047	.037	.030	.024	.019	.0145	.0115	.0093
0.9	.128	.122	.106	.099	.091	.084	.076	.069	.056	.045	.036	.030	.024	.019	.0149	.0119	.0096
1.0	.111	.107	.095	.089	.083	.076	.070	.064	.053	.043	.036	.029	.024	.019	.0151	.0122	.0099
1.2	.087	.084	.067	.073	.068	.064	.060	.055	.047	.040	.033	.028	.023	.019	.0154	.0126	.0104
1.4	.069	.067	.063	.060	.057	.054	.051	.048	.042	.036	.031	.026	.023	.019	.0153	.0127	.0106
1.6	.057	.056	.052	.050	.048	.046	.044	.042	.037	.033	.029	.025	.022	.018	.0151	.0127	.0107
1.8	.047	.046	.044	.043	.041	.040	.038	.036	.033	.029	.026	.023	.020	.017	.0147	.0125	.0106
2.0	.040	.039	.038	.037	.036	.035	.033	.032	.029	.027	.024	.021	.019	.016	.0141	.0122	.0105
2.2	.034	.034	.033	.032	.031	.030	.029	.028	.026	.024	.022	.020	.018	.016	.0135	.0118	.0103
2.4	.030	.029	.028	.028	.027	.027	.026	.026	.023	.022	.020	.018	.017	.015	.0129	.0114	.0100
2.6	.026	.026	.025	.025	.024	.024	.023	.022	.021	.020	.018	.017	.015	.014	.0123	.0109	.0097

$$F_{21} = \frac{(H/D_s + 0.5)}{4\{(H/D_s + 0.5)^2 + (R/D_s)^2\}^{3/2}} \quad \text{.... 6.14}$$

In this work τ and α have been taken for simplicity as unity although for long hazard ranges τ can have a value significantly less than one [19].

The emitted flux density q_1 from the surface of a fireball is dependent upon the fourth power of its absolute temperature Ts(°K) as given by the following equation

$$q_1 = \varepsilon\theta\, T_s^4 \quad \text{.... 6.15}$$

where ε is the emissivity and θ the Stefan-Boltzmann constant.

Recently surface temperatures were measured by two-colour pyrometry from colour cine films of fireballs which were made by igniting elevated hemispherical detergent bubbles filled with butane and with natural gas in the range 100 to 800 ml [56]. Empirical correlations with mass of flammable were found for maximum spherical diameter, maximum elevation and duration of the visible fireballs.

One way of assessing large-scale phenomena on a small scale is by modelling. Two models based upon material and heat balances have been developed by Lihou [56], which fit the observed diameter and elapsed time relationships. Both models are based upon the experimental observation that the diameters of fireballs increased at a constant rate. Both models will be described in the following section.

6.5 MATHEMATICAL MODELS FOR HEAT RADIATION

6.5.1 Hot Shell-Cold Core Model

In this model the temperature at the core of the fireball is assumed to be ambient temperature, ie 290 °K. Prior to neutral buoyancy, for a butane fireball, the core is assumed to contain no air. But when a fireball begins to rise air enters the core without being heated. Air required for combustion is consumed at the hot shell [56].

6.5.1.1 Pre-lift off Combustion of Butane

A heat balance for a butane cloud initially at 290 °K can be written as follows:

combustion rate = sensible heat to air + radiative heat loss

$$m\,h\,\frac{df}{dt} = mrC\,(T_S-290)\,\frac{df}{dt} + \pi D^2\,\theta\varepsilon T_s^4 \qquad \text{.... 6.16}$$

where m: mass of flammable originally in the cloud,

f: fraction of fuel burnt in time t

h: net calorific value

r: mass ratio of combustion products from the stoichiometric combustion of unit mass of the flammable gas

C: mean specific heat of combustion product

D: equivalent spherical diameter

Ts: temperature of the hot shell

ε: emissivity

θ: Stefan-Boltzmann constant.

It has been noted that throughout combustion, the equivalent spherical diameter increases at a constant rate $(dD/dt)_c$. Rearranging equation 6.16 will give:

$$mh - mrC\,(T_s-290)\,df = \pi D^2\,dt\,\theta\varepsilon\,T_s^4$$

Cancelling dt by making the substitution:

$$D^2dt = D^2\,dD\,(dt/dD)_c \qquad \text{.... 6.17}$$

integration can be carried out, with the boundary conditions f = o when D = Do where

$$Do = 3.57\,(m/M)^{1/3} \qquad \text{.... 6.18}$$

and M is the molecular weight of the flammable gas, then

$$[mh-mrC\,(T_s-290)]f = \pi/3\,\theta\varepsilon\,T_s^4\,(D^3-D_0^3)\,(dt/dD)_c$$

therefore

$$f = \frac{\pi\,\theta\varepsilon\,T_s^4\,(D^3-Do^3)}{3m\{h-rC\,(T_s-290)\}\,(dD/dt)_c} \qquad \text{.... 6.19}$$

At neutral buoyancy the fireball density equals that of the surrounding air. At 290 °K with a mean molecular weight of 29 this has a density of [273/290 x 29/22.4 = 1.22] kg/m^3. Let $f = f_1$ and $D = D_1$ at lift-off, the fireball mass is $m(1+rf_1)$ and its volume is $\pi/6\ D_1^3$. Equating its density to 273/224.

$\therefore$ density = mass/volume

$$1.22 = \frac{m(1+rf_1)}{\pi/6\ D_1{}^3} \quad \text{.... 6.20}$$

rearranging equation 6.20 gives,

$$D_1{}^3 = 1.567\ (1+rf_1)m \quad \text{.... 6.21}$$

Substituting f_1 and $D_1{}^3$ in equation 6.19 and substituting $\theta = 56.7\text{x}10^{-12}$ kW/m^2.k^4 gives the following general equation for denser than air gases;

$$f_1 = \frac{93.05\ \varepsilon\ (T_s/1000)^4\ (1 + rf_1 - 29/M)}{\{h - rC\ (T_s - 290)\}\ (dD/dt)_c} \quad \text{.... 6.22}$$

To obtain the relationships for butane the values of r, C, M, h, ε and Ts should be known, for example for butane [56] r = 17.14, C = 1.14 kJ/kg °K, M = 58, h = 45920 kJ/kg and from the experimental work Ts = 1300 K, ε = 1 and $(dD/dt)_c$ = 1 m/sec. Substituting these values in equations 6.22 gives f_1 = 0.00614. From equations 6.18 and 6.21 and putting (dD/dt)c = 1 m/sec give the following relationships for butane

$$D_o = 0.92\ m^{1/3} \quad \text{....6.23}$$

$$D_1 = 1.20\ m^{1/3} \quad \text{.... 6.24}$$

$$t_1 = 0.28\ m^{1/3} \quad \text{.... 6.25}$$

6.5.1.2 Dilution and Combustion

During the completion of combustion of butane clouds, and throughout the combustion of methane clouds, air at 290K enters the core at an average radial velocity $\overline{U}$(m/sec) through the hot shell. $\overline{M}$ is the average molecular weight of a stoichiometric mixture of combustion products. The rate of increase of volume can be expressed as follows:

$$\frac{\pi D^2}{2}\left(\frac{dD}{dt}\right)_c = \frac{mr}{\overline{M}} \times \frac{22.4}{273}\,(T_s - 290)\,\frac{df}{dt} + \pi D^2\overline{U} \qquad \text{.... 6.26}$$

the heat balance shown as equation 6.16 still applies, because the excess air enters the core without being heated. Combining equations 6.16 and 6.26 gives the following heat and mass balance relationship:

$$mh\,\frac{df}{dt} = \pi D^2\left[\theta\varepsilon T_s^4 + \frac{273\overline{M}C}{22.4}\left\{0.5\left(\frac{dD}{dt}\right)_c - \overline{U}\right\}\right] \qquad \text{.... 6.27}$$

the boundary conditions are $f=f_1$ at $D=D_1$; which is given by equation 6.21. This equation can be used to eliminate m, having made the substitution shown as equation 6.17 and integrating

$$f = f_1 + \frac{448\,(1 + rf_1)}{273h\left(\frac{dD}{dt}\right)_c}\left[\left(\frac{D}{D_1}\right)^3 - 1\right] \times Q \qquad \text{.... 6.28}$$

where Q = heat flux density function

$$Q = \theta\varepsilon T_s^4 + \frac{273\overline{M}C}{22.4}\left[0.5\,(\frac{dD}{dt})_c - \overline{U}\right] \qquad \text{.... 6.29}$$

Let D=Dc at the completion of combustion when f = 1.

The experimental data for butane is best fitted by putting $\overline{U} = 0.5$ (dD/dt)c, which eliminates the second term in equation 6.29. Additional constants for butane are $\overline{M} = 28.4$, $f_1 = 0.00614$ and $D_1 = 1.2\ m^{1/3}$. Substitution in equation 6.28 gives

$$D_c = 6.45\ m^{1/3} \qquad \text{.... 6.30}$$

since $tc = \dfrac{Dc\text{-}Do}{(dD/dt)_c}$ and $\left(\dfrac{dD}{dt}\right)_c = 1$ m/sec

So the following expression can be obtained for the duration of the combustion phase

$$tc = 5.53\ m^{1/3} \qquad \text{.... 6.31}$$

For methane, the boundary conditions for equation 6.27 are:

$$f = 0 \text{ at } D = D_o$$

in which D_o is found from equation 6.18 with M = 16.

Other constants are [56] r=19, C=1.22, $\overline{M}$=27.6, h=50213 kJ/kg and from the experiments the following mean values were found: Ts=1500K, ε= 0.5, $(dD/dt)_c = 1$ m/sec. These parameters used in equation 6.32 with f=1 at D=Dc and t=t_c, with Q given by equation

6.29 when $\overline{U}=0.5\ (dD/dt)_c$ will produce equations 6.33 and 6.34.

$$f = \frac{44.8 \times 290}{273Mh(dD/dt)_c}\left[(\frac{D}{Do})^3 - 1\right] \times Q \qquad \text{.... 6.32}$$

$$D_o = 1.42\ m^{1/3} \qquad \text{.... 6.33}$$

$$D_c = 6.95\ m^{1/3} \qquad \text{.... 6.34}$$

and $t_c = Dc\text{-}Do/(dD/dt)_c = Dc\text{-}Do$ 6.35

since $(dD/dt)c = 1$

The computer program presented in Appendix G was used to evaluate the fireball dimensions and hazard ranges by using this model. The predicted results are presented in the same Appendix. These results show that this model cannot be used for large quantities of hydrocarbon. However Lihou [56] suggested that this model gave a satisfactory result for small-scale experiments, ie in the range of 200-800 ml (0.134-0.536 gm).

6.5.2 Isothermal Model

In this model, the assumptions are [56]:

i The whole fireball burns at isothermal temperature (Tc)

ii Combustion is controlled by the supply of air and ceases after a time (tc) which is correlated empirically with the mass (m) of the flammable gas initially in the cloud.

iii The equivalent spherical diameter starts at Do and increases at a constant rate $(dD/dt)_c$ up to a diameter Dc at which the fuel has all disappeared.

iv A fraction $(1\text{-}f_c)$ of the fuel is assumed to be cracked to produce soot, the volume of which is neglected.

v The final diameter (Dc) is found for a stoichiometric mixture of combustion products from the burnt fraction (fc) of the fuel plus a fraction of residual air, all at temperature of Tc.

Since the volume of a sphere is

$$\overline{V} = (\pi/6)D^3 \qquad \text{....6.36}$$

differentiating the above equation to obtain the equation which presents the rate of increase of volume, as follows

$$\frac{\pi}{6} D^3 \left(\frac{dD}{dt}\right)_c = \frac{\pi}{2} D^2 \left(\frac{dD}{dt}\right) = \frac{VT_c}{290} \left(1 + \frac{nf_c}{\upsilon}\right) \qquad \text{.... 6.37}$$

where υ = the stoichiometric molar ratio of air to flammable gas
n = the increase in the total number of moles per mole of flammable gas burnt stoichiometrically
V = volumetric rate at which air flows into the fireball (m^3/sec)
D = equivalent spherical diameter
fc = fraction of fuel burnt at the end of combustion

Rearranging the above equation gives

$$V = \frac{290\, \pi D^2\, (dD/dt)_c}{2T_c\, (1 + nf_c/\upsilon)} \qquad \text{.... 6.38}$$

A heat balance equation can be written as follows:

combustion rate = sensible heat to air + radiative heat loss

$$\text{combustion rate} = \frac{273\ \text{VMh}\ f_c}{290 \times 22.4 \times \upsilon} \qquad \text{....}\ 6.39$$

substitution for V from equation 6.38 gives

$$\text{combustion rate} = \frac{273\ \text{Mh}\ f_c \left[\dfrac{290\ \pi D^2\ (dD/dt)_c}{2T_c\ (1 + n\ f_c/\upsilon)}\right]}{290 \times 22.4 \times \upsilon}$$

$$\text{sensible heat} = \frac{273 \times 29 \times V\ C_a\ (T_c\text{-}290)}{290 \times 22.4} \qquad \text{....}\ 6.40$$

substitution for V from equation 6.38 gives

$$\text{sensible heat} = \frac{273 \times 29 \times C_a\ (T_c - 290) \times \left[\dfrac{290\ \pi D^2\ (dD/dt)_c}{2\ T_c\ (1 + nfc/\upsilon}\right]}{290 \times 22.4}$$

$$= \frac{176.71\ C_a\ (T_c - 290)\ \pi D^2\ (dD/dt)_c}{Tc\ (1 + nfc/\upsilon)}$$

$$\text{radiative heat loss} = \pi D^2 \varepsilon \theta T_c^4 \qquad \text{....}\ 6.41$$

substituting $\theta = 56.7 \times 10^{-12}$ kW/m^2.k^4 and $C_{air} = 1.09$ kJ/kg °K, rewriting the heat balance equation:

$$\frac{6.09\ Mhf_c\ \pi D^2\ (dD/dt)_c}{T_c\ (\upsilon + nf_c)} = \frac{176.71x1.09\ (T_c - 290)\ x\ \pi D^2\ (dD/dt)_c}{T_c\ (1 + nf_c/\upsilon)} + 56.7x10^{-12}\varepsilon\pi D^2 T_c^4$$

.... 6.42

cancelling πD^2 from above equation gives:

$$\frac{6.09\ Mhf_c}{T_c\ (\upsilon + nf_c)} \left(\frac{dD}{dt}\right)_c - \frac{192.6\ (Tc-290)}{T_c\ (1 + nf_c/\upsilon)} \left(\frac{dD}{dt}\right)_c = 56.7x10^{-12}\varepsilon T_c^4$$

rearranging gives

$$\frac{6.09\ Mhf_c}{T_c\ (\upsilon + nf_c)} \left(\frac{dD}{dt}\right)_c - \frac{192.6\ \upsilon\ (Tc-290)}{T_c\ (\upsilon + nf_c)} \left(\frac{dD}{dt}\right)_c = 56.7x10^{-12}\varepsilon T_c^4$$

$$\left[\frac{6.09\ Mhf_c - 192.6\ \upsilon\ (T_c - 290)}{T_c\ (\upsilon + nf_c)}\right] \left[\frac{dD}{dt}\right]_c = 56.7\ x\ 10^{-12}\varepsilon T_c^4$$

$$\left[\frac{6.09\ Mhf_c - 31.6\ \upsilon\ (T_c - 290)}{T_c\ (\upsilon + nf_c)}\right] \left[\frac{dD}{dt}\right]_c = 9.30\ \varepsilon\ \left(\frac{T_c}{1000}\right)^4$$

.... 6.43

for a gas cloud of mass m, molecular weight M, initially at 290°K, the initial diameter is given as follows:

$$\text{volume of sphere } (\overline{V}) = \frac{\pi}{6} D^3 = \frac{\text{mass (m)}}{\text{density } (\rho)} \qquad .... 6.44$$

so $$D = \left(\frac{6\overline{V}}{\pi}\right)^{1/3}$$

$$= \left(\frac{6m}{\pi\rho_T}\right)^{1/3}$$

where ρ_T = density at given temperature

since $\rho_T = \rho_o \times \dfrac{298}{T + 273}$

and taking T = 17 °C, $\rho_o = M/22.4$

so $$\rho_T = \frac{M}{22.4} \times \frac{298}{290}$$

then $$D_o = \left[\frac{6\,m}{\pi \times \frac{M}{22.4} \times \frac{298}{290}}\right]^{\frac{1}{3}}$$

ie $$Do = 0.539\left[\frac{290\,m}{M}\right]^{1/3} \quad \text{.... 6.45}$$

The final diameter is given as shown below

$$Dc = 0.539\,\{\upsilon + (n+1)\,f_c\}^{1/3}\left\{\frac{Tc\,m}{M}\right\}^{1/3} \quad \text{.... 6.46}$$

The constant rate of increase of diameter is given by:

$$\left(\frac{dD}{dt}\right)_c = \frac{D_c - D_o}{t_c} = \frac{0.539\,(m/M)^{\frac{1}{3}}\,(T_c - 290)^{\frac{1}{3}}\,\{\upsilon + (n+1)fc\}^{\frac{1}{3}}}{t_c} \qquad \text{.... 6.47}$$

substituting for (dD/dt)c from equation 6.47 into the heat and material balance equation, gives

$$9.30\,\varepsilon t_c\left(\frac{T_c}{1000}\right)^4 = \left[\frac{Mhfc - 31.6\,\upsilon\,(T_c - 290)}{T_c\,(\upsilon+nfc)}\right]\left[\frac{0.539m\,(T_c - 290)\,\{\upsilon+(n+1)fc\}}{M}\right]^{\frac{1}{3}}$$

since tc = $Am^{1/3}$ from equation 6.1,

so the heat and material balance equation becomes as follows:

$$9.30\,\varepsilon Am^{\frac{1}{3}}\left(\frac{T_c}{1000}\right)^4 = \left[\frac{Mhfc-31.61\upsilon(T_c-290)}{T_c\,(\upsilon+nfc)}\right]\left[0.539\,m\right]^{\frac{1}{3}}\left[\frac{(T_c-290)\{\upsilon+(n+1)fc\}}{M}\right]^{\frac{1}{3}}$$

Cancelling $m^{1/3}$ and rearranging the above equation gives the final heat and mass balance equation from which the fireball temperature is related to A and f_c.

$$17.26\,A\varepsilon\left(\frac{T_c}{1000}\right)^4 = \left[\frac{Mhfc-31.61\upsilon(T_c-290)}{T_c(\upsilon+nfc)}\right]\left[\frac{\{\upsilon+(n+1)fc\}\,\{T_c-290\}}{M}\right]^{\frac{1}{3}}$$

.... 6.48

A computer program was written to enable the rapid calculation using this method and different authors' parameters to evaluate the fireball surface temperature. This program is given in Appendix D.

Insertion of the parameters proposed by several authors into the isothermal model gave values of B which were reasonably close to the values which they recommended as shown on Table 6.3. This is illustrated by the following example.

Taking the value of ε, h, M, υ, n and fc from Table 6.7 and substituting these in equation 6.48 and taking the value of A recommended by Roberts [64] in Table 6.3, gives the value of Tc.

For example, for butane $\varepsilon = 1$, $h = 45806$ kJ/kg, $M = 58$, $\upsilon = 30.95$, $n = 1.5$, $f_c = 0.95$ and taking $A = 0.45$, gives $Tc = 2016$ °K.

Taking $f_c = 0.95$ and $Tc = 2016$ °K, equation 6.46 gives the following expression for the final diameter of a butane fireball, which is in good agreement with the value of B recommended by Roberts [64] in Table 6.3.

$$Dc = 5.66\ m^{1/3} \qquad \text{.... } 6.49$$

and $$t = 0.45\ m^{1/3} \qquad \text{.... } 6.50$$

The initial diameter Do is given by equation 6.45. The duration of combustion is given by equation 6.50 from which the rate of growth of diameter for large fireballs would appear to be about 10.5 m/sec.

Similarly the value of A recommended by other authors, Gayle [65], Brasie [66] and Marshall [67] can be substituted in equation 6.48 to give the corresponding value of Tc.

The final diameter of a butane fireball can be obtained from equation 6.46 which is in good agreement with the value of B recomm-

TABLE 6.7

BASIC SET OF PARAMETERS USED IN EVALUATION OF FIREBALL SURFACE TEMPERATURE USING THE ISOTHERMAL MODEL

Component	r	f_c	n	υ	M	h(kJ/kg)
CH_4	18.16	0.906	0	9.52	16	50,145
C_3H_8	16.6	0.949	1	23.8	44	46,450
C_4H_{10}	16.39	0.95	1.5	30.95	58	45,806
C_5H_{12}	16.25	0.955	2	38.09	72	45,446

ended by Marshall in Table 6.3, but not with the value of B recommended by both Gayle and Brasie as shown below.

Taking $f_c = 0.95$, $A = 0.38$, the value recommended by Marshall in Table 6.3, equation 6.48 gives Tc = 2064 °K, substitution of Tc in equation 6.46 gives the final diameter of a butane fireball as follows.

$$Dc = 5.7 \, m^{1/3} \qquad \text{.... } 6.51$$

Taking $f_c = 0.95$ and $A = 0.3$, the value recommended by Brasie in Table 6.3, equation 6.48 gives Tc = 2132 °K, substitute Tc in equation 6.46 gives the following expression:

$$Dc = 5.76 \, m^{1/3} \qquad \text{.... } 6.52$$

Taking fc = 0.95 and A = 0.245, the value recommended by Gayle, use of equation 6.48 produces Tc = 2188 °K. Substitution of Tc into equation 6.46 gives the following expression:

$$Dc = 5.8 \, m^{1/3} \qquad \text{.... } 6.53$$

Finally the rate of growth of fireball diameter for a large fireball using other authors' parameters is presented in Table 6.8. it appears that only Roberts and Marshall's parameters give close values to those achieved by Lihou's model.

TABLE 6.8

PREDICTED RATES OF GROWTH OF FIREBALL DIAMETER USING VARIOUS AUTHORS' PARAMETERS

Author	Rate of growth (dD/dt)c (m/sec)
Gayle	19.9
Brasie	16
Marshall	12
Roberts	10.5

6.6 BOILING LIQUID EXPANDING VAPOUR EXPLOSIONS (BLEVE)

6.6.1 Size of BLEVE

Several correlations have been proposed for calculating the dimensions of a fireball originating from a BLEVE of flammable material as shown below. Some of these correlations are derived from experiments:

$$D = Bm^b \qquad \text{.... 6.54}$$

where D the diameter of the fireball (m)

m mass of fuel (kg)

Other correlations show that B depends not only on the mass of fuel, but also upon gas density as given in Lihou's [56] and Crawley's

[36] correlations as shown below

$$D = B\ [m/M]^b \qquad \text{.... } 6.55$$

Parameters for various authors which apply for both equations 6.54 and 6.55 are given in Table 6.9. In some equations the mass of fuel is in tonnes as used in Crawley's correlation [36].

TABLE 6.9

VALUES OF PARAMETERS PROPOSED BY DIFFERENT AUTHORS FOR USE IN EQUATIONS 6.54 AND 6.55

Author	B	b
Maurer	3.51	1/3
TNO	6.48	0.325
Crawley	105	1/3
Lihou	3.44	1/3

A computer program was written to enable rapid calculation of BLEVE fireball diameters and duration using different authors' parameters, this is given in Appendix H. Typical results are shown in Figure 6.1.

A comparison can be made between the values of diameter obtained by applying the various correlations mentioned above and the values obtained in real incidents as described below:

Incident: 1. Oneonta [36], charge 80 te of LPG, diameter observed 122 m.

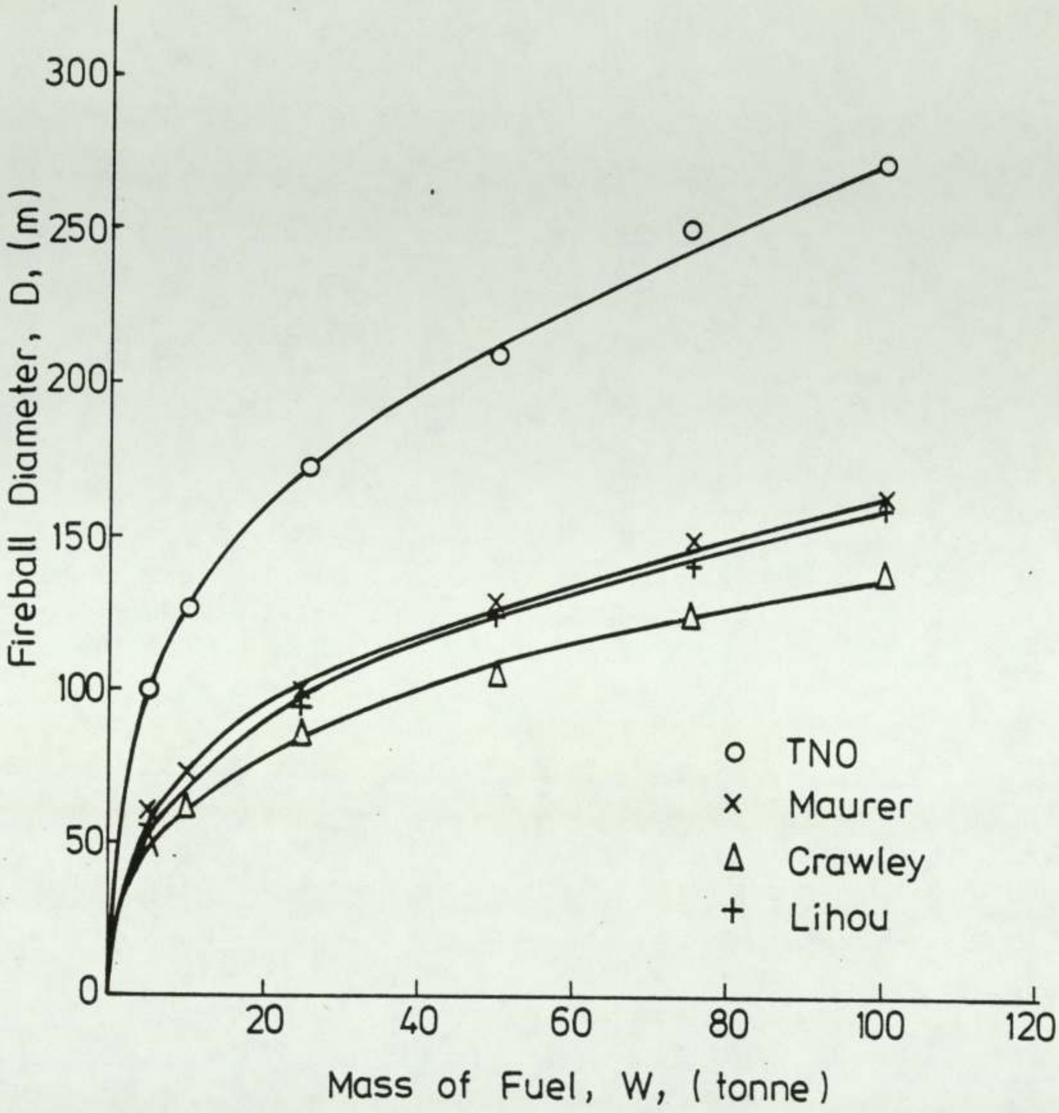


Figure 6.1 Variation of Fireball Diameter with Mass of Fuel based on Crawley, Maurer, Lihou and TNO correlations.

2. Mexico disaster [16], 1600 m^3 sphere filled to 90% capacity, at density of 512 kg/m^3, this would have amounted to 819,200 kg. Fireball dimensions, as shown in photographs and video, are estimated to have ranged from 200 to 300 m.

Comparison between predicted and observed results are shown in Table 6.10. These results show that the Crawley correlation gives a close result to those observed from the real BLEVE incidents mentioned above.

TABLE 6.10

COMPARISON BETWEEN CALCULATED AND OBSERVED FIREBALL DIAMETER

Mass of fuel	Diameter				
Tonne	Crawley	Maurer	TNO	Lihou	Observed
80	128	151	254	149	122
819	278	328	541	323	200-300

6.6.2 BLEVE Model

Based upon the work of Maurer *et al* [60], Lihou derived the following relationships for the duration and the diameter of a BLEVE fireball:

$$t_c = 0.31 \left[\frac{44.8\ m}{M}\right]^{\frac{1}{3}} \qquad \text{.... 6.56}$$

$$D_c = 3.44 \left[\frac{44.8\ m}{M}\right]^{\frac{1}{3}} \qquad \text{.... 6.57}$$

The work of Maurer *et al* [60] indicates that the maximum amount of LPG which will burn in the time available for mixing with air is 70%. Only about 40% of the flammable mass (that is 28% of the original contents of the vessel) can be sufficiently well-mixed with air to undergo percussive deflagration. Thus 42% of the flammable, originally in the tank, produces a fireball.

Using equations 6.56 and 6.57 in a heat balance, based upon 42% of m undergoing isothermal stoichiometric combustion at Tc, with a constant diameter Ds, the following equation can be used to find Tc.

$$\frac{69700}{M}\left[\frac{T_c}{1000}\right]^4 = h - 1000\,rC\left[\frac{T_c}{1000} - 0.29\right] \qquad \text{.... 6.58}$$

where Tc isothermal temperature of the fireball (°K)

h net calorific value of fuel (kJ/kg)

C specific heat of combustion products (kJ/kg.°K)

r mass ratio of combustion products per unit mass of flammable gas, from stoichiometric combustion.

A computer program was written to enable rapid calculation using this method to evaluate the fireball surface temperature; this is given in Appendix E.

6.7 FIREBALL SURFACE TEMPERATURE

The fireball surface temperature can be predicted from the isothermal model, the BLEVE model as done by Lihou [56] and also by a new proposal from thermodynamic calculations. The temperature calculated from thermodynamic considerations is termed the 'theoretical flame temperature'.

Since the final temperature of the combustion products is unknown and must be calculated, the process is assumed to be adiabatic. With the added assumption that kinetic and potential energy terms are negligible, the overall energy balance for this process reduces to

$$\Delta H = 0 \qquad \text{.... 6.59}$$

It is assumed that the combustion takes place at 298 °K (25 °C) and that the heat passes into the reaction products adiabatically, heating them to the flame temperature which is assumed at first

since $$\Delta H^{\circ}_{298} + \Delta H^{\circ}p = \Delta H = 0 \qquad \text{.... 6.60}$$

But $$\Delta H^{\circ}_{298} = \Delta H^{\circ}c \qquad \text{.... 6.61}$$

and $$\Delta Hp^{\circ} = \sum_{\text{products}} (nCp_m)\,(t-25)\ . \qquad \text{.... 6.62}$$

Thus $$\sum_{\text{products}} (nCp_m)(t-25) = \Delta H^\circ c \quad .... \ 6.63$$

where $\Delta H^\circ c$ = standard heat of combustion
Cp_m = mean specific heat of combustion product
n = number of moles

Since the combustion products are carbon dioxide and water, in addition to the nitrogen, excess oxygen and unburned hydrocarbon then

$$\Delta H_c^\circ = [(n_{CO_2}Cp_{CO_2}) + (n_{H_2O}Cp_{H_2O}) + (n_{N_2}Cp_{N_2}) + (n_{O_2}Cp_{O_2}) + (n_{H.C}Cp_{H.C})]\,[t - 25] \quad .... \ 6.64$$

A computer program was written to enable rapid calculations for fireball surface temperature using this method, this is given in Appendix F.

6.8 ELEVATION

The experimental results [56] with elevated fireballs showed that the velocity of rise was very nearly $(dD/dt)_c$. For butane equations 6.45, 6.46 and 6.50 indicate that for large scale fireballs $(dD/dt)_c$ = 10.5 m/sec. Similarly using the same equations shows that for large scale methane fireballs $(dD/dt)_c$ = 9.9 m/sec.

Taking a rate of rise of 10 m/sec as suggested by Lihou [56], the simple relationship for all large-scale fireballs is as follows:

$$H = 10\,t \quad .... \ 6.65$$

In the BLEVE model, Lihou suggests [56] the following equation should be used in calculation of the hazard range to people from a BLEVE

$$H = 0.5\ Ds \qquad \text{.... } 6.66$$

The final elevation given by equation 6.59, using Robert's parameter, is as follows:

$$H = 4.5\ m^{1/3} \qquad \text{.... } 6.67$$

The above equation agrees quite well with the correlation by Fay and Lewis [58] for propane, which is shown below

$$H = 4.1\ m^{1/3} \qquad \text{.... } 6.68$$

6.9 HAZARD RANGES

Hazard range can be predicted by using the appropriate correlation, then the duration of combustion can be used in equations 6.3 and 6.6 to obtain the limiting values of q_2. Fireball surface temperature (Tc) can be obtained from the isothermal model, BLEVE model and thermodynamic calculation. Substitution of (Ts) in equation 6.15 evaluates q_1. A computer program was written to enable rapid calculation for view factors and the ratio of height to fireball diameter, this is given in Appendix G. Table 6.6 is used to find the value of R/Ds for which F_{21} is approximately equal to the limiting values of q_2/q_1. Hazard ranges are found by multiplying the predicted fireball diameter Ds(m) by the limiting value of R/Ds. Typically, allowance for attenuation will reduce the hazard ranges by up to 20%. Typical results for hazard ranges for 10 tonnes of butane are given in Table 6.11.

TABLE 6.11

TYPICAL RESULTS FOR HAZARD RANGES (m) FOR 10 TONNES BUTANE FIREBALL USING DIFFERENT AUTHORS' PARAMETERS

Author	human range	building range	process range
Gayle	218.61	207.49	133.39
Brasie	265.26	220.37	138.75
Marshall	378.02	307.14	189.01
Robert	404.87	323.89	193.09

6.10 POOL FIRES

A leak of flammable liquid ie oil, oil products or refrigerated LPG contained within a bund will produce a pool which, upon ignition will result in a pool fire.

The application of engineering calculations to separation distances for storage tanks has been treated by Hearfield [12].

Calculations of separation distances related to heat effects are usually based on direct flame impingement and on heat radiation.

It is commonly assumed that in a storage tank fire, the tank is effectively a pool of liquid with a flame burning on its surface and that on a tank of diameter D, the height of the flame in still air is 2D [62, 68].

If there is a wind, however, the flame is distorted, At a wind speed of 2m/s it has been observed that the flame is deformed to an angle of 45˘ to the horizontal and that on the downwind side of the fire the flame hugs the ground for a distance of about 0.5 D [62].

For the heat radiated from the flame it is usually assumed for simplicity that still-air conditions prevail [62]. The heat radiated is calculated and compared with limiting values.

An equation given by Hearfield [12] for the heat radiated from the envelope of a flame burning on a liquid pool in a storage tank is:

$$Q_1 = K\,A\,r\,\rho C \qquad \text{.... 6.69}$$

where	A	the surface area of pool, m^2
	C	the calorific value of liquid, kJ/kg
	Q_1	the quantity of heat radiated from the envelope, kW
	r	the liquid burning rate, m/s
	ρ	the density of liquid. kg/m^3
	K	constant (the value generally used by the author is 0.3)

The rate of burning can be predicted from the derivation of Moorhouse [48] which is based on a heat balance on a simple vertical cylindrical flame from a pool fire as shown below.

heat radiated
to surroundings = flame surface area x surface emissive power

$$= \left[(\pi/4)D^2 + \pi DL\right].E \qquad \text{.... 6.70}$$

The above equation can be equated to the fraction of the total heat liberated by combustion, as shown below

$$\left[(\pi/4)D^2 + \pi DL\right].E = f \,.\, \ddot{m} \,.\, Hc \,.\, \pi D^2/4 \qquad .... \; 6.71$$

Rearranging the above equation, gives

$$\ddot{m} = \frac{E}{f\,Hc}(1 + 4\,L/D) \qquad .... \; 6.72$$

where $\ddot{m}$ = fuel burning rate, kg/m^2.sec

E = flame surface emissive power, kW/m^2

Hc = heat of combustion, kJ/kg

f = fraction of heat of combustion of fuel which is radiated (the value suggested by the author in the range of 0.2-0.4)

L/D = ratio of flame length to diameter

Taking the value of $K = 0.3$, $f = 0.3$, $r = \ddot{m}/\rho$ and substituting the value of $\ddot{m}$ from equation 6.72 in equation 6.69, gives

$$Q_1 = A.\, E\,(1 + 4\,L/D) \qquad .... \; 6.73$$

Since

$$E = \varepsilon\theta T_f^4 \qquad .... \; 6.74$$

where ε = emmissivity (for simplicity assumed unity)

θ = Stefan-Boltzmann constant (56.7×10^{-12} kW/m^2.k^4)

T_f = flame surface temperature

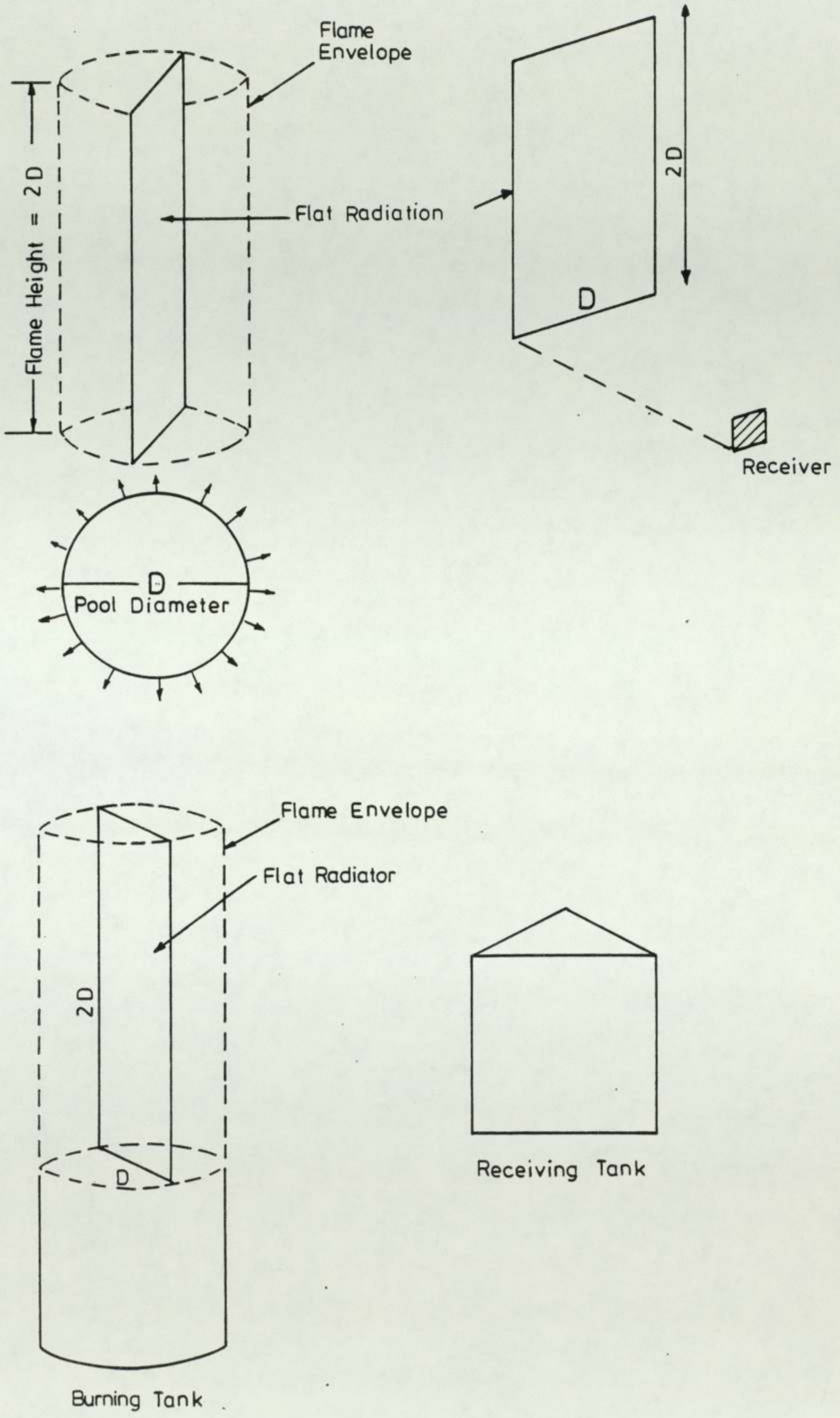


Figure 6·2 Radiation from Pool Fires.

The application of equation 6.69 is described by Robertson [62] as follows. It is assumed that the tank roof has completely blow off presenting a pool fire where the diameter of the pool is the diameter of the tank, which is assumed to be cylindrical. If still air conditions are assumed the flame envelope is a cylinder of diameter D with a height of 2D as shown in Figure 6.2 [62]. It is further assumed that the heat radiated from the envelope is in turn equivalent to radiation from a radiating area which is a vertical rectangular plane through the diameter of the flame envelope of width D and height 2D. The flame temperature which is used in equation 6.74 is the flame temperature obtained from the thermodynamic calculation mentioned earlier, ie the flame temperature obtained for propane is 1840 °C (2113°K).

The heat flux received by an object varies roughly according to inverse square of the distance between the radiator and the receiver [62], which can be described for a point source as follows:

$$Q_2 = \frac{Q_1}{4\pi d^2} \qquad \text{.... 6.75}$$

where Q_1 = the quantity of heat radiated, (kW)
Q_2 = radiant flux intensity, kW/m^2
d = distance from tank to the receiver, m

There are three important radiation flux bands to be considered:

i A flux of 37.8 kW/m^2 is the approximate maximum radiation any tank should receive from an adjacent tank fire.

ii The second band of flux is 12.6 kW/m^2. This flux is the threshold limit over which the resins in wood, building roofing felt, oily rugs and paper will start to emit flammable vapours which are easily ignited by flying sparks.

iii A flux of 4.7 kW/m^2 is the approximate threshold of pain on any exposed part of the human body. At this blistering of the skin takes place.

A computer program was written to assist rapid calculation for the distances from a burning tank to the flux band stated above; this is shown in Appendix I.

6.11 WATER REQUIREMENTS

In certain circumstances when a tank farm is constructed, it is not possible to leave a safe distance between each tank due to economic reasons and/or lack of space. Under these circumstances, it is necessary to install water sprinklers near the tanks to spray water onto adjacent tanks to keep them cool should a tank catch fire.

Only those parts of the adjacent tanks 'seen' from the burning tank need to be kept cool using the water, eg the shaded part shown in Figure 6.3. As the tanks are cylindrical, this accounts for half the tank surface which is exposed to the heat [62].

It is possible to calculate the heat flux received by the adjacent tank using equation 6.73. As only half the adjacent tank will receive the heat from the fire [62], the total amount of heat absorbed is by this half of the tank. Therefore, the effective area of the tank receiving the heat is:

$$\text{Area} = \frac{\pi \text{ x diameter x height}}{2} \qquad \text{.... 6.76}$$

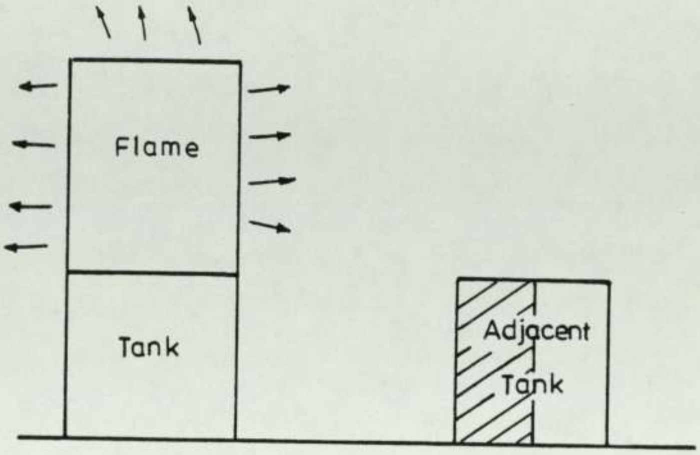


Figure (6.3) Effect of radiant heat on adjacent tank.

Therefore the heat flux reaching the tank divided by the area calculated in equation 6.76 gives the amount of heat received by the adjacent tank per square metre.

If water is sprayed onto the adjacent tank, a heat balance over the tank enables the amount of water required to remove the heat from the surface of the tank to be calculated. The heat balance is given by

$$Q = m_1 \, Cp \, \Delta T \qquad \text{.... 6.77}$$

where Q = heat received on the surface of the tank
m_1 = mass of water required to remove the heat
Cp = specific heat capacity of the water
ΔT = temperature rise of the water

But to apply the above equation, the following assumptions had to be made.

1. The water used is initially at 20 °C and rises to 90 °C when sprayed onto the adjacent tank wall. Therefore ΔT in equation 6.77 will be 70.

2. The specific heat capacity of the water varies between 4.183 kJ/kg K at 20 °C to 4.208 kJ/kg K at 90 °C but it is assumed to be constant at 4.191 kJ./kg K. Since 1 kg of water = 1 litre of water, the amount of water needed to keep the surface of the tank cool can be evaluated in litres/m^2/sec or litres/m^2/min as required.

A computer program including the preliminary estimation of the amount of water required was written to enable rapid calculation using the above method, this is shown in Appendix I. Clearly this can be adopted for different water temperatures. An allowance must also be made for any inefficiencies in water usage.

6.12 ANALYSIS OF THERMAL RADIATION RESULTS

The hazard ranges to people, buildings, and process equipment and the diameter, duration and height of a fireball which is growing and rising steadily with time, have been evaluated.

There is considerable disagreement between various authors regarding the appropriate values of numerical parameters to be used for predicting duration, equivalent spherical diameter, height, and hazard ranges from a fireball as shown in Figures 6.4 to 6.7. These Figures show the relationship between duration, diameter, height, and human hazard range with the mass of fuel. These graphs also show different values at each given mass of fuel for different author's parameters.

The results, as presented in Appendix G, are evaluated in terms of diameter, duration, height of fireball, and human, building and process equipment hazard ranges related to the flammable mass of hydrocarbon gases released. Calculations have been performed using various authors' parameters and Hot Shell-Cold Core, Isothermal and BLEVE models, as presented in Appendix G, to enable a quantitative assessment and comparison of all the methods. It must be accepted that the comparison is limited by the considerable number of assumptions mentioned earlier in Sections 6.4, 6.5 and 6.6. These assumptions may not always be true in real incidents. However, the mathematical models can be applied to compare various layout arrangements and the associated hazard ranges for humans, buildings and equipment can be predicted for different quantities of flammable fuels.

The results illustrated in Figures 6.8 to 6.15 according to different models show that the prediction of diameter and hazard ranges according to the isothermal and BLEVE models have gross deviations due to several assumptions and empirical equations which may affect their accuracy. In the meantime the hot shell-cold core model gives unreasonable results for large scale scenarios, as presented in Appendix G. However, Lihou [56] suggested that this model had been used satisfactorily for small scale predictions.

The lack of accuracy of the above models may be due to a combination of the following:

i It has been assumed that the diameter of a fireball is equivalent to the spherical diameter. However, the fireball shape changes with rise. At ignition, it is hemispherical then spherical and after lift off it takes several shapes [69].

ii A fraction of fuel is assumed to be cracked to produce soot , the volume of which is neglected. However in real incidents luminous flames have high heat radiation rates and these represent the major hazard from fireballs and may cause fatal burns and secondary fires.

iii Accurate calculation of the thermal radiation incident upon a receiving surface requires knowledge of the degree of attenuation of the radiation by the atmosphere between the flame and the receiver. This is a requirement common to both fireballs and pool fires [48].

iv All the models are based upon small-scale experimental work in which the equivalent spherical diameter of the fireball increased at a constant rate. Therefore, resolution of the lack of accuracy of the above methods must await large scale experiments.

v In the case of pool fires, the speed and extent of the spread across any surface will depend upon local topography and wind speed and direction.

The results for fireballs, which are presented in Figures 6.4 and 6.5 show that the four authors' correlations for fireball duration and diameter all give different results, and the deviations between them increase in proportion to the flammable quantity of fuel involved.

For flammable quantities less than 1 tonne, the four authors' correlations give essentially similar hazard ranges. On the contrary, when the flammable quantity is bigger than 1 tonne, the four correlations can clearly be distinguished from each other. In general the difference between the results are not too large, in particular the results for Marshall's and Robert's correlations. However, they are significant and cannot be neglected. In Figure 6.7, it is shown that the Roberts correlation generally provides the biggest human hazard range and the Gayle correlation usually gives the shortest values of human hazard range

In general, as would be expected, all four correlations provide the biggest ranges for human hazard and usually give the shortest values of process equipment ranges, as shown in Figure 6.8.

Also fireball diameter increases linearly with the duration of combustion in both isothermal and BLEVE models, as shown in Figures 6.9 and 6.10, because the assumption is that the fireball size in each model increases at a constant rate throughout combustion.

The results for hazard ranges based on the fireball surface temperature predicted using the thermodynamic equation give slightly smaller hazard ranges than those based on temperature predicted using the isothermal equation, as illustrated in Figure 6.11.

These differences between isothermal and thermodynamic temperature results are not significant, and can be neglected for large scale fireballs. Hence either method could be use to predict the

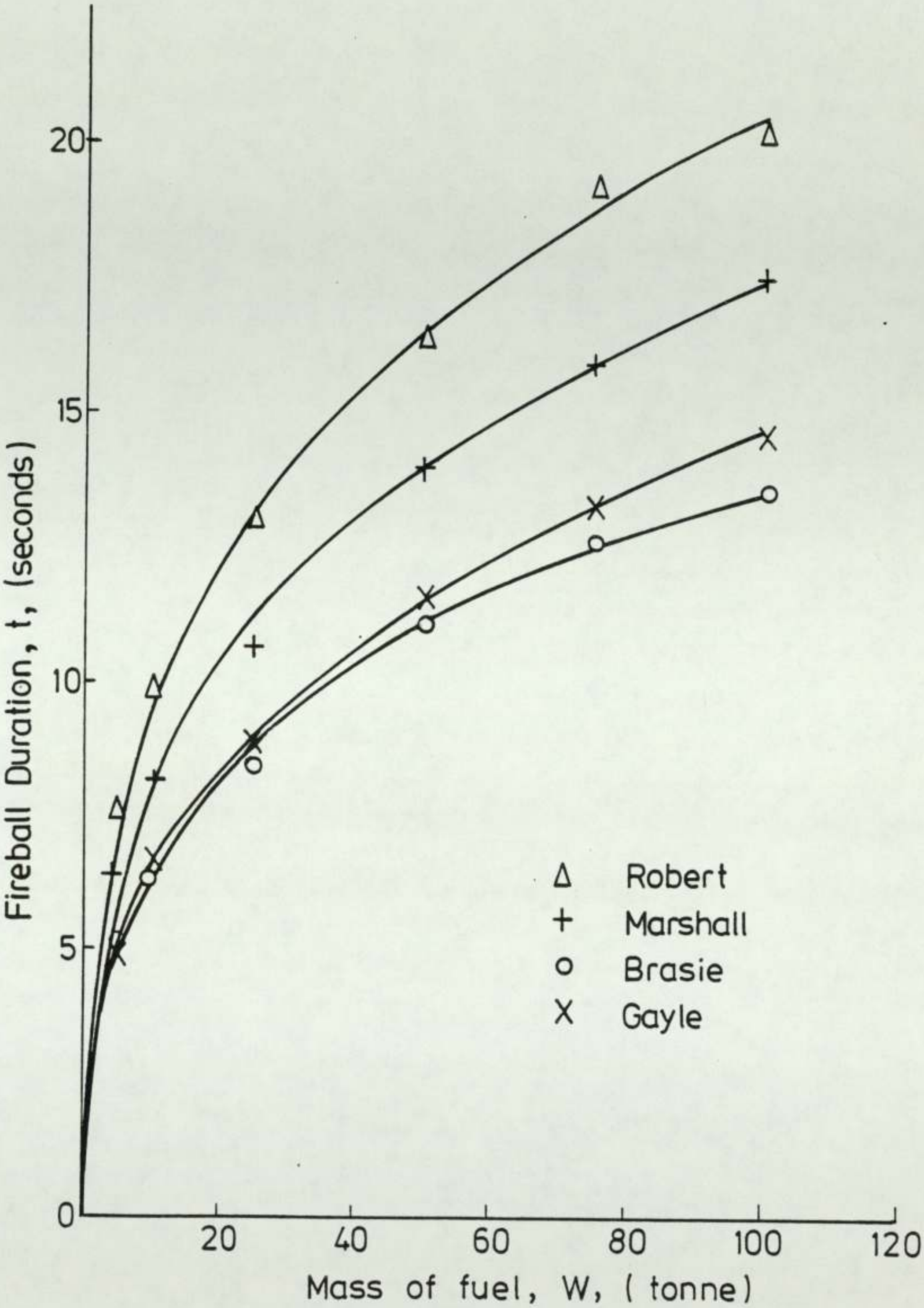


Figure 6.4 Variation of Fireball Duration with Mass of Fuel based on Different Authors' parameters.

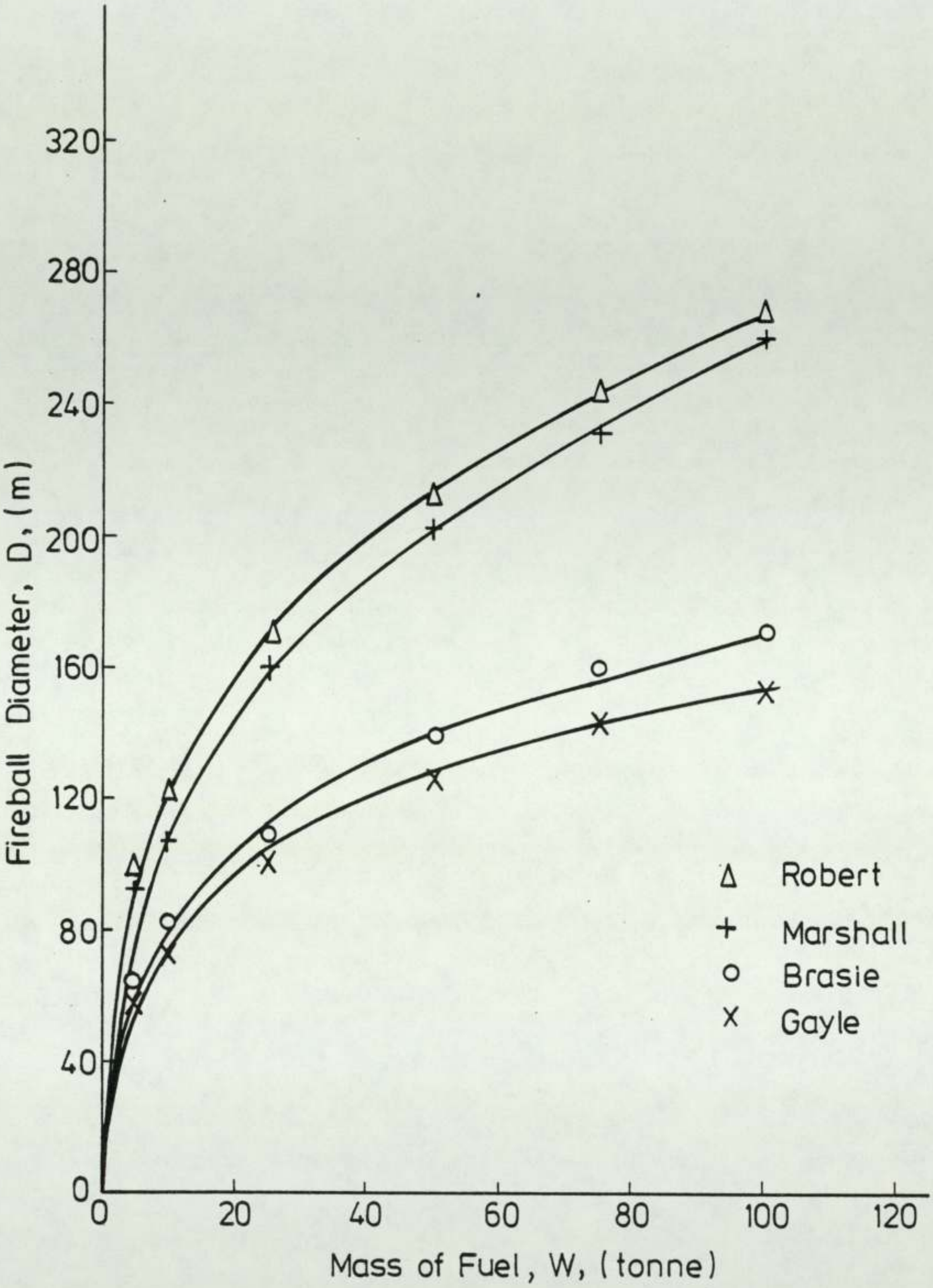


Figure 6.5 Variation of Fireball Diameter with Mass of Fuel based on different Authors parameters.

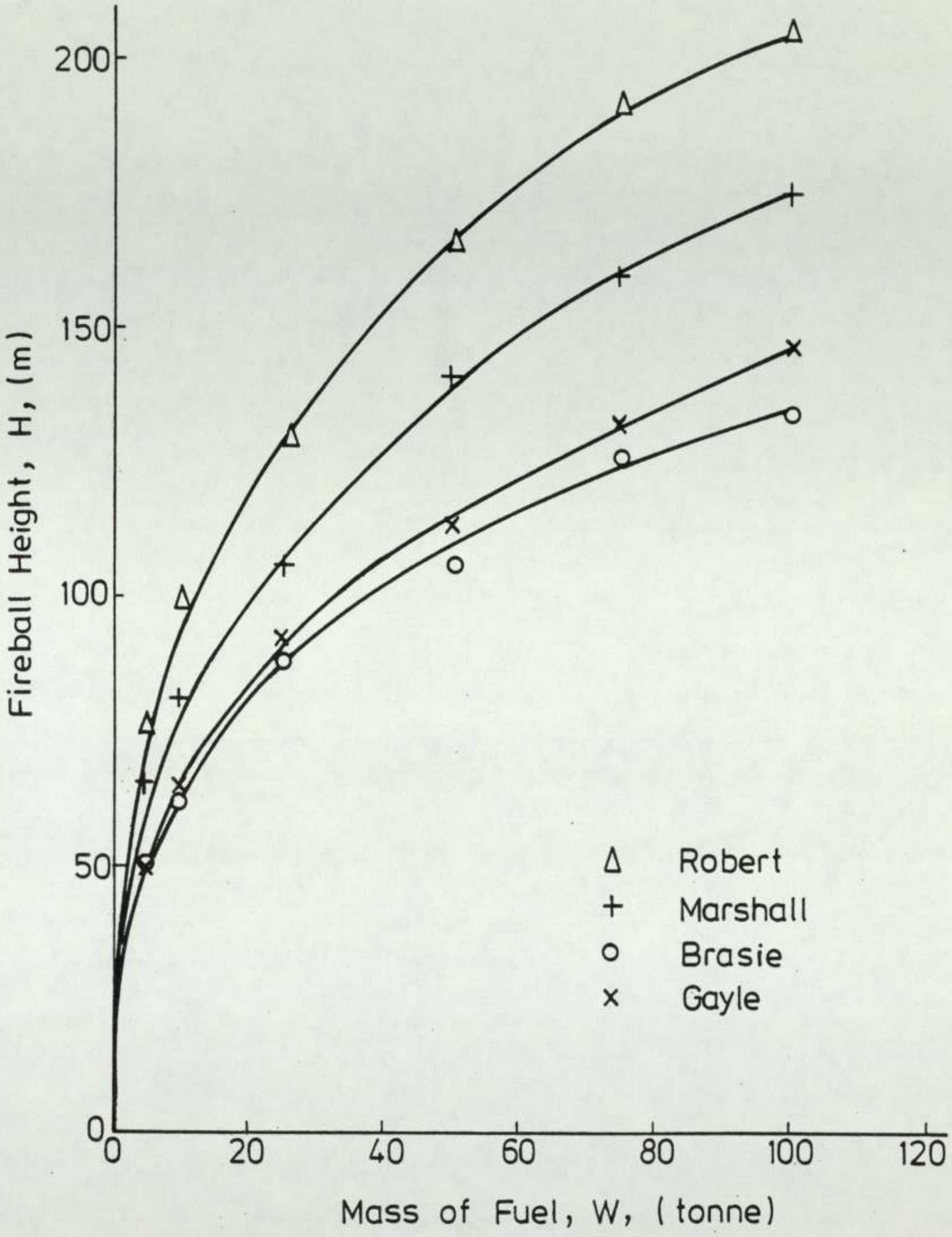


Figure 6.6 Variation of Fireball Height with Mass of Fuel based on different Authors parameters.

surface temperature of a fireball theoretically. But in the case of the BLEVE model the results for hazard ranges predicted by thermodynamic calculation have larger deviations from the hazard ranges than those based on temperature predicted using the BLEVE equation, as illustrated in Figure 6.12.

In general, results from the two models increase in proportion to the increase of the mass of fuel. The difference between the results of the two models are signficant and cannot be neglected, as shown in Figure 6.11 to 6.15. Figure 6.13 shows that the hazard ranges provided by the BLEVE model increase with decreasing number of carbon atoms (ie methane hazard range is the biggest while pentane hazard range is the shortest).

The difference between the four authors' correlations, Hot Shell-Cold Core, Isothermal and BLEVE models appear to be due to the different theoretical bases used for each method, although some common assumptions have been made in all the correlations and models, such as the assumption that the diameter of the fireball is the equivalent spherical diameter. Each method also contains several other assumptions that might cause considerable errors in the calculations. Moreover many factors involved in fireball combustion and growth remain unpredictable (eg wind velocity and direction, weather conditions, degree of confinement).

Therefore, the validity of these results remains unproven so average figures would be expected to give a more realistic answer. However, experience obtained from investigation of real incidents leads to the conclusion that maximum figures are to be preferred wherever possible.

The results for pool fires, which are presented in Appendix I

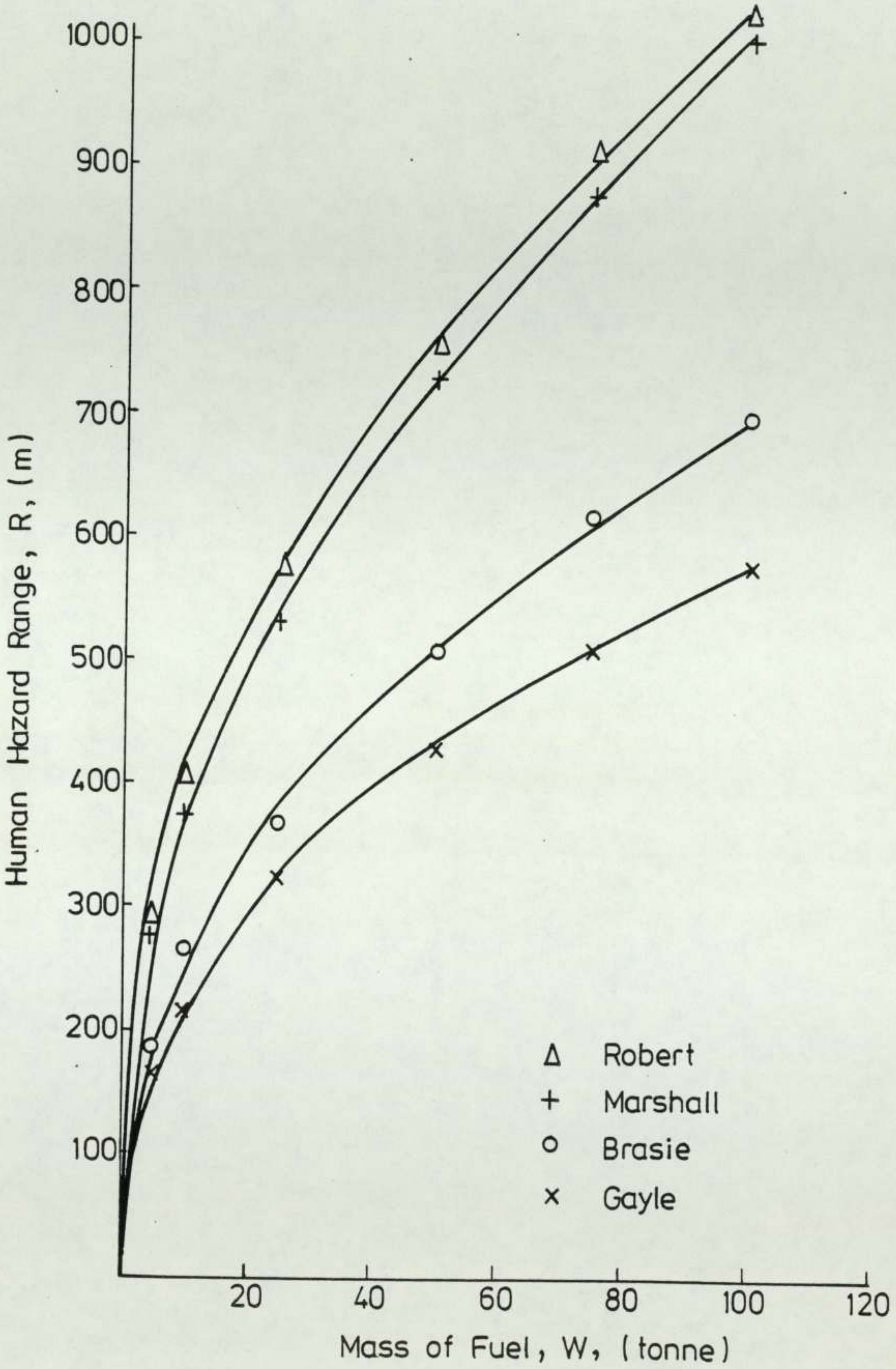


Figure 6.7 Variation of Human Hazard Range with Mass of Fuel based on different Authors parameters.

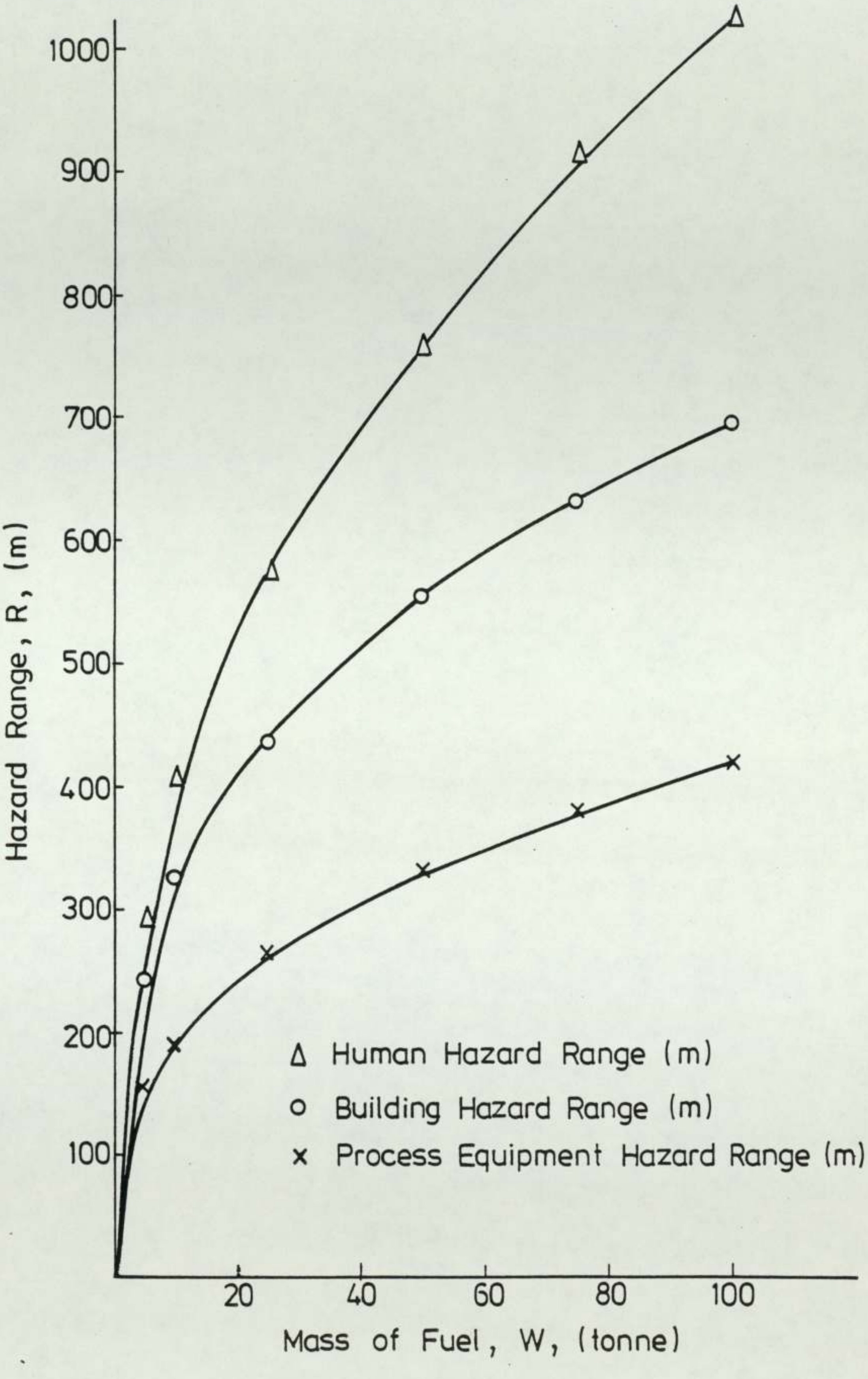


Figure 6.8 Variation of the Hazard Range with Mass of Fuel using Robert Correlation.

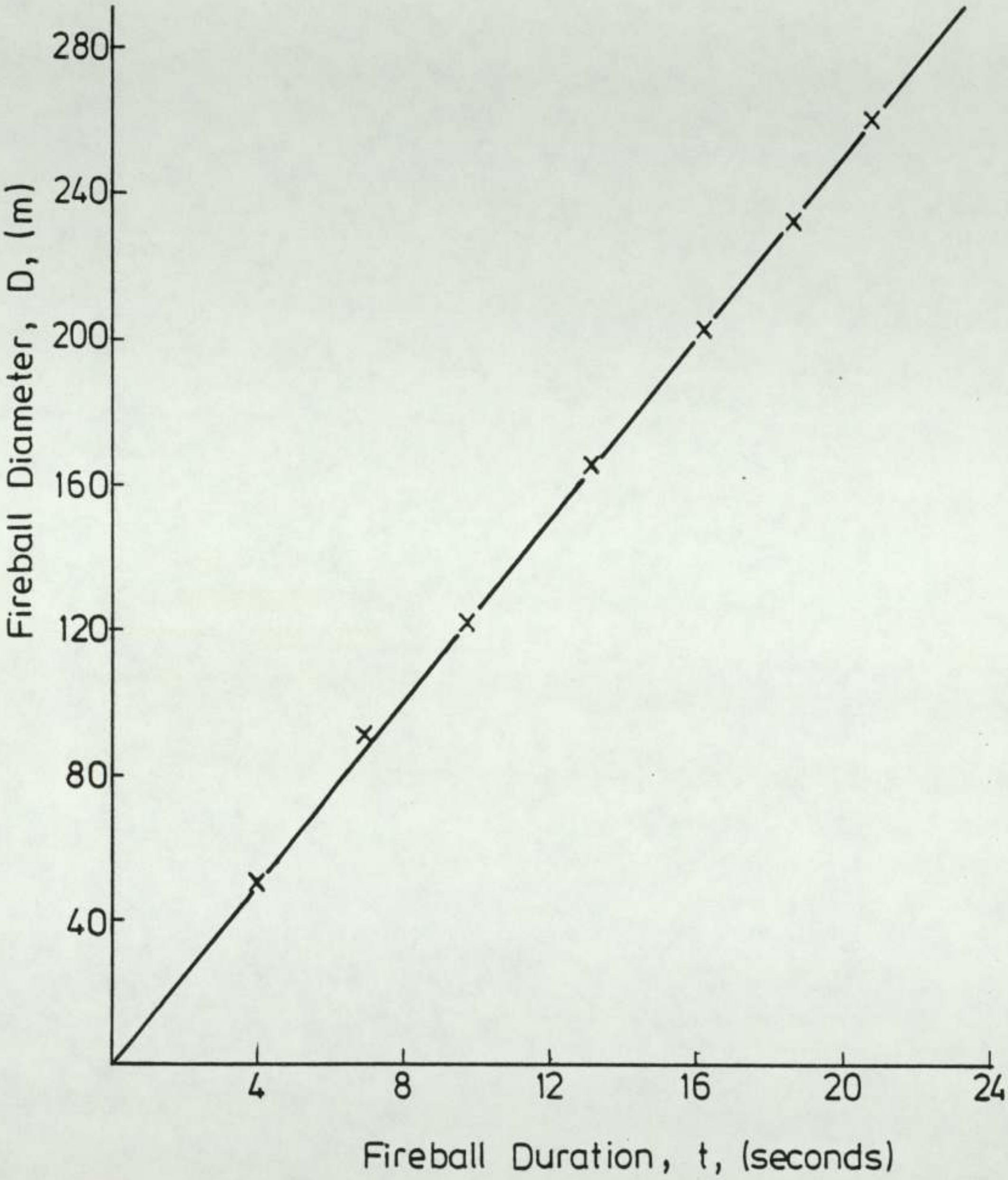


Figure 6.9 Relationship between Fireball Diameter and Fireball Duration according to Isothermal Model.

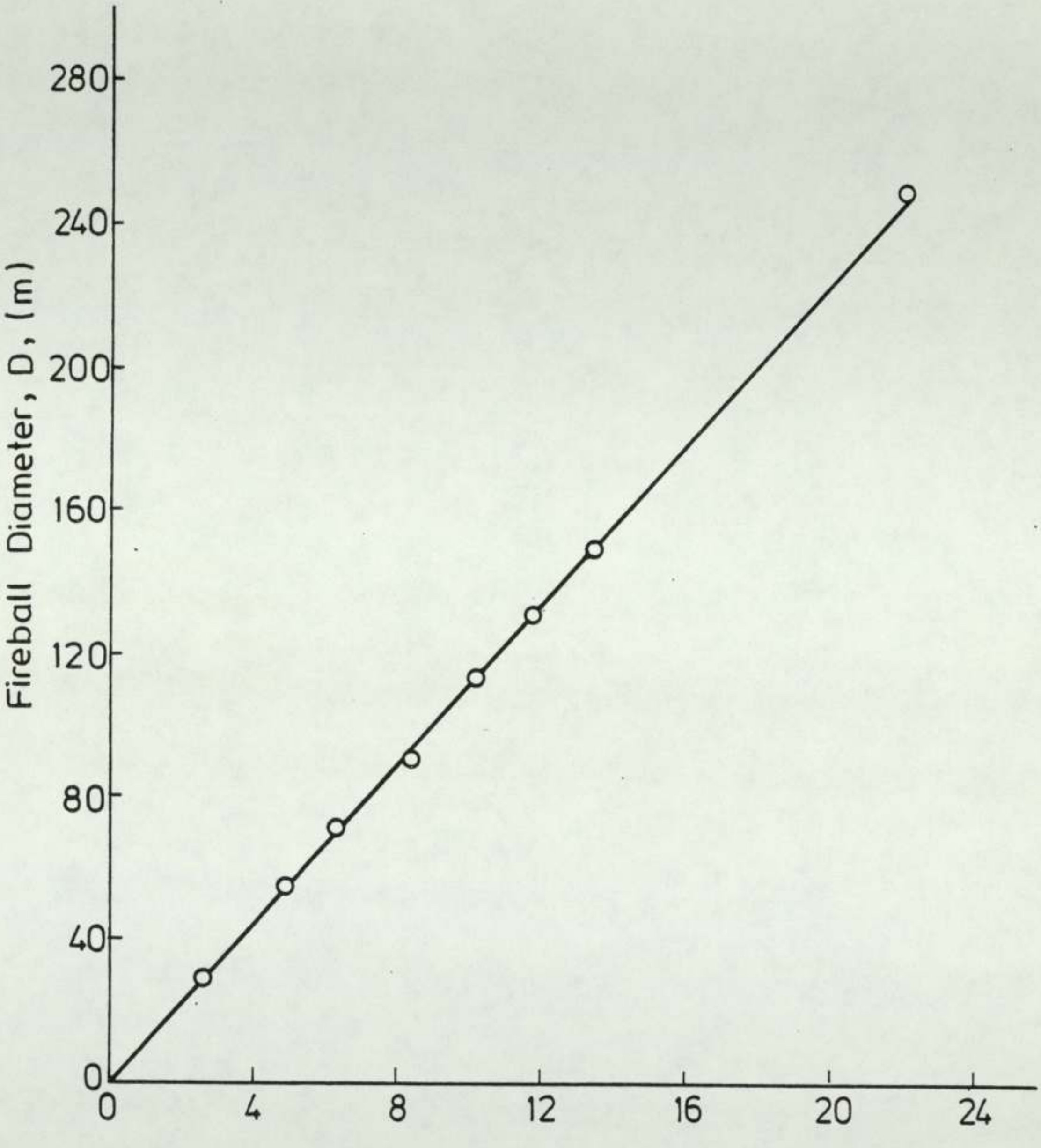


Figure 6.10 Relationship between Fireball Diameter and Fireball Duration according to BLEVE Model

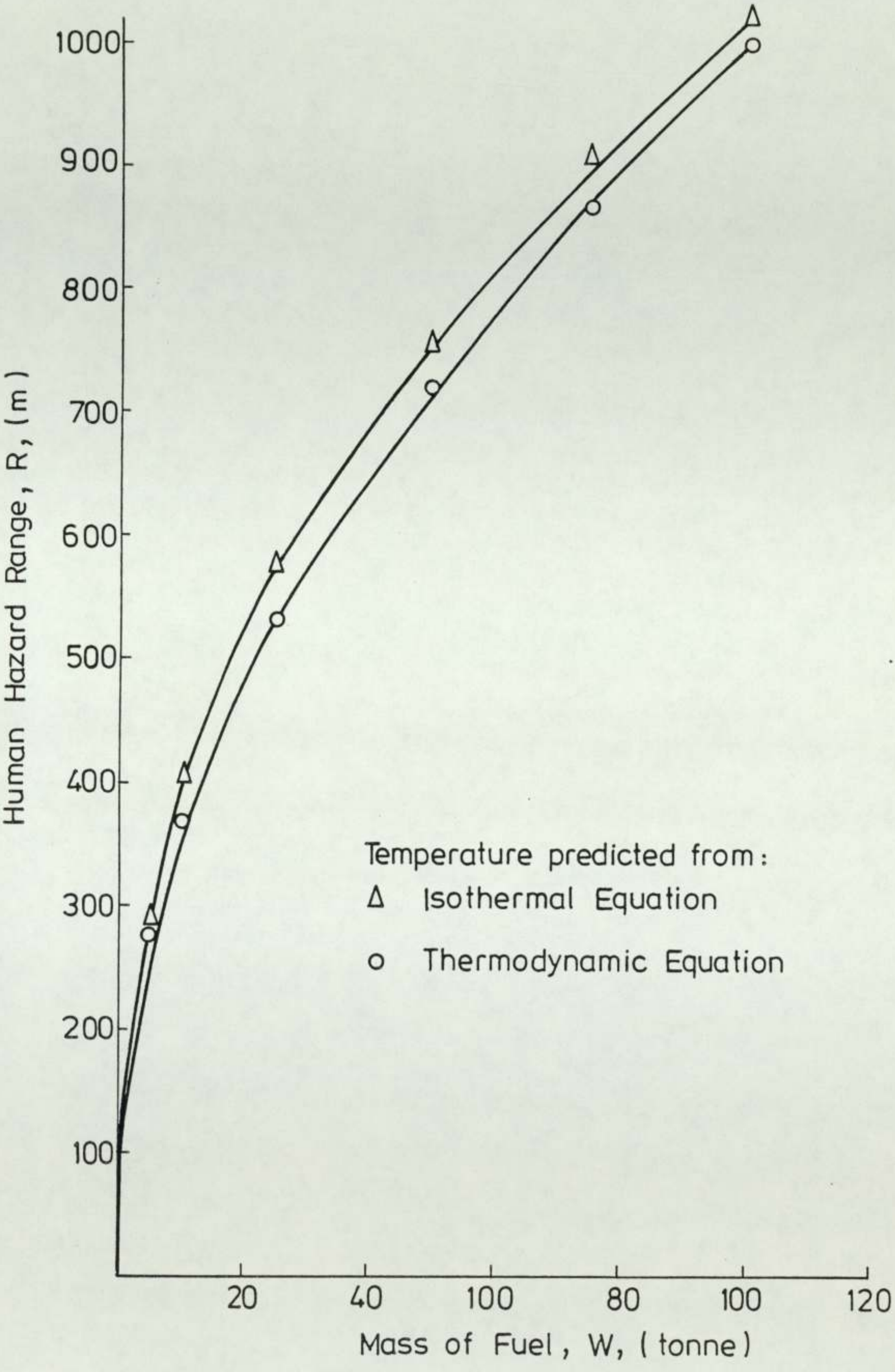


Figure 6.11 Variation of Human Hazard Range with Mass of Fuel using Isothermal Model

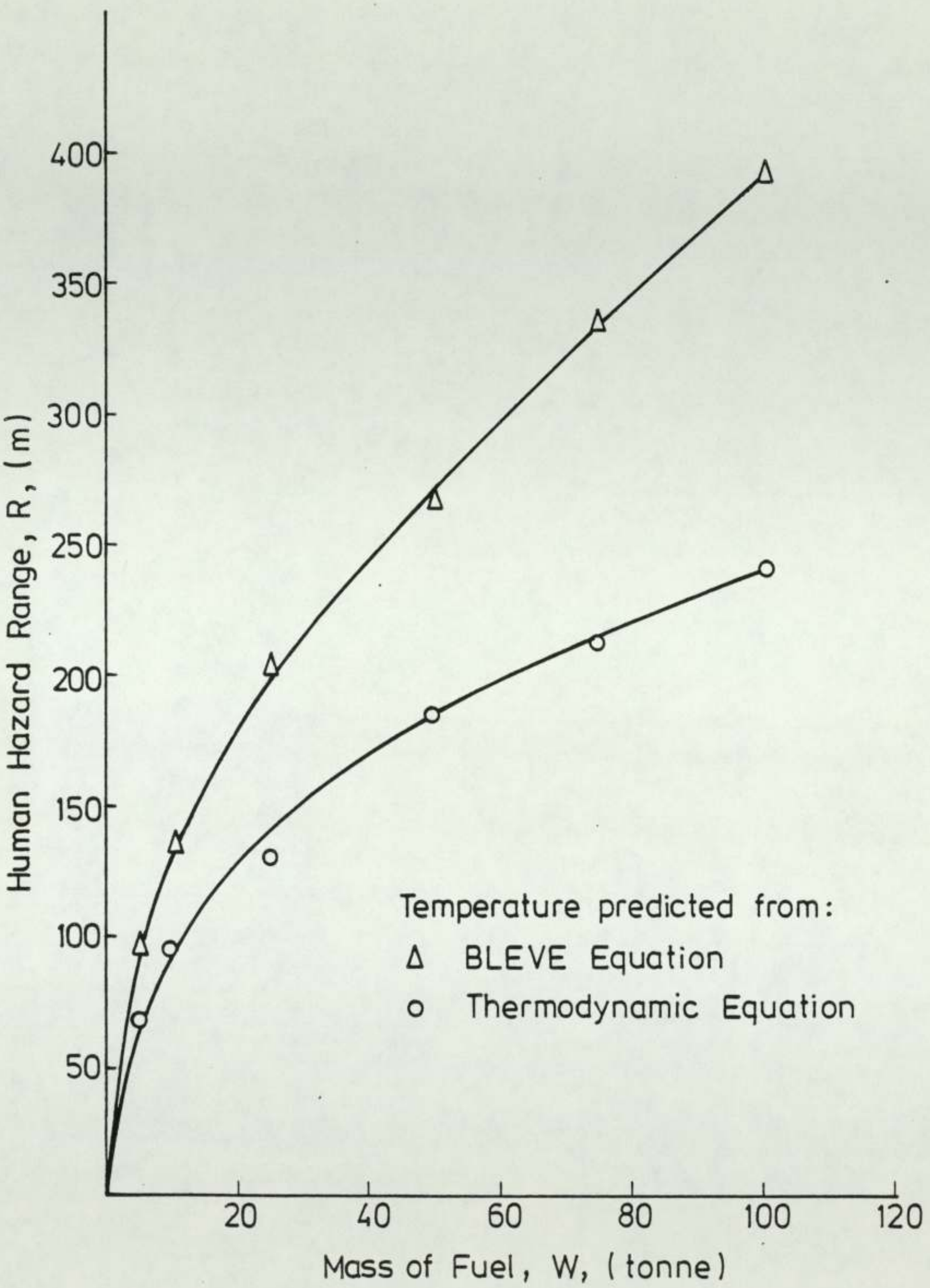


Figure 6·12 Variation of Human Hazard Range with Mass of Fuel using BLEVE Model.

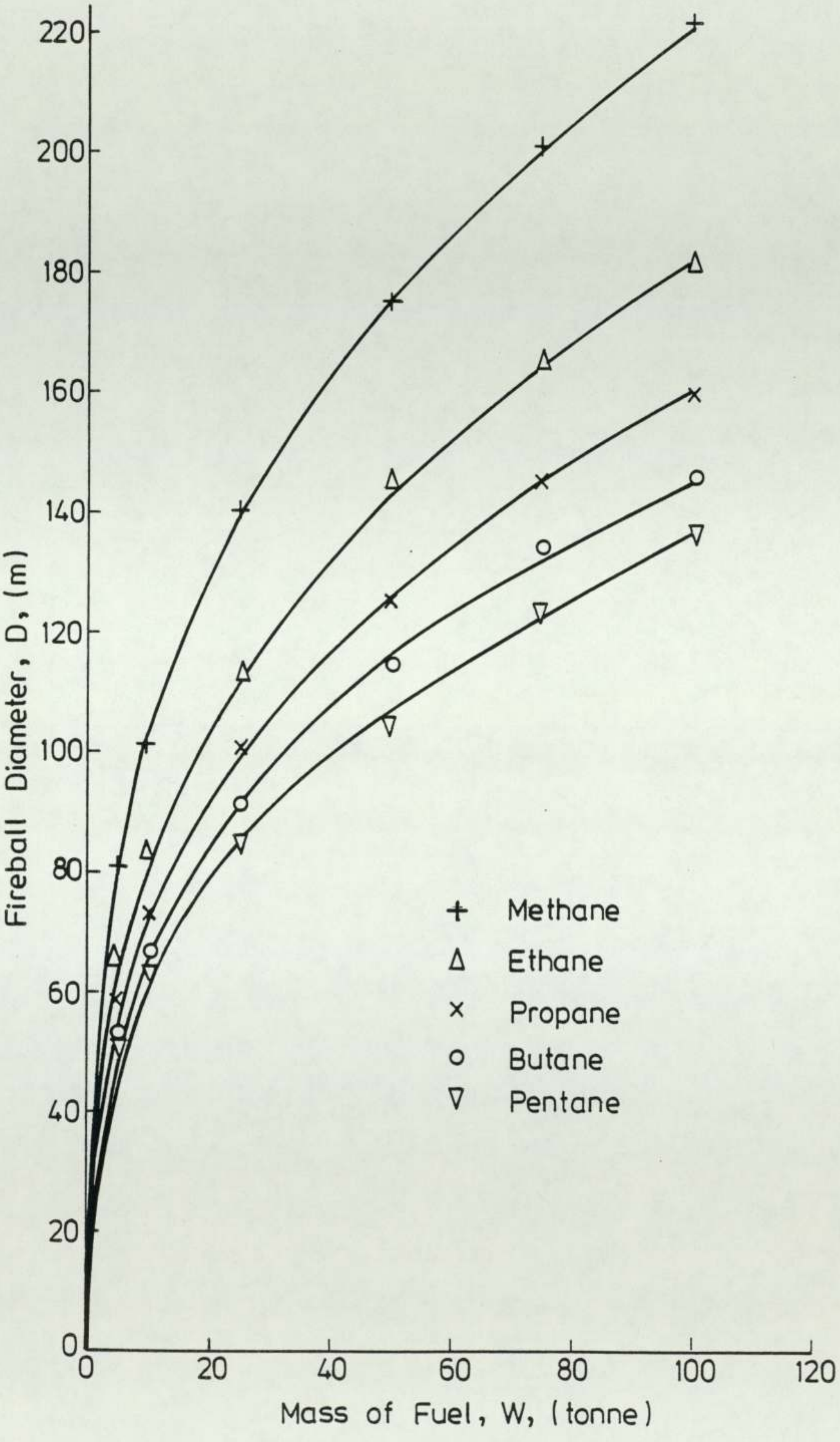


Figure 6.13 Variation of Fireball Diameter with Mass of Fuel using BLEVE Model for different Hydrocarbon gases.

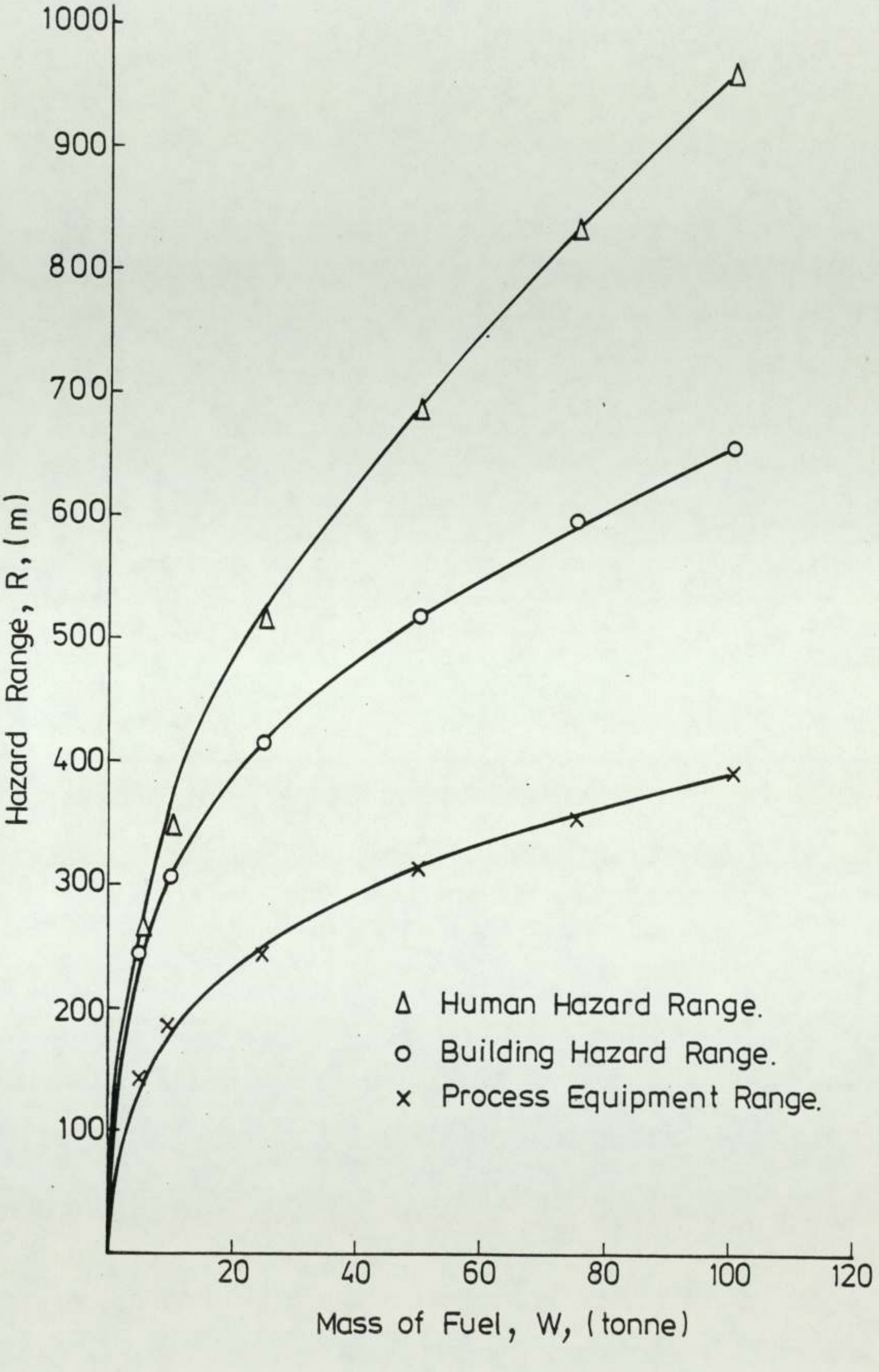


Figure 6·14 Variation of Hazard Range with Mass of Fuel using Isothermal Model.

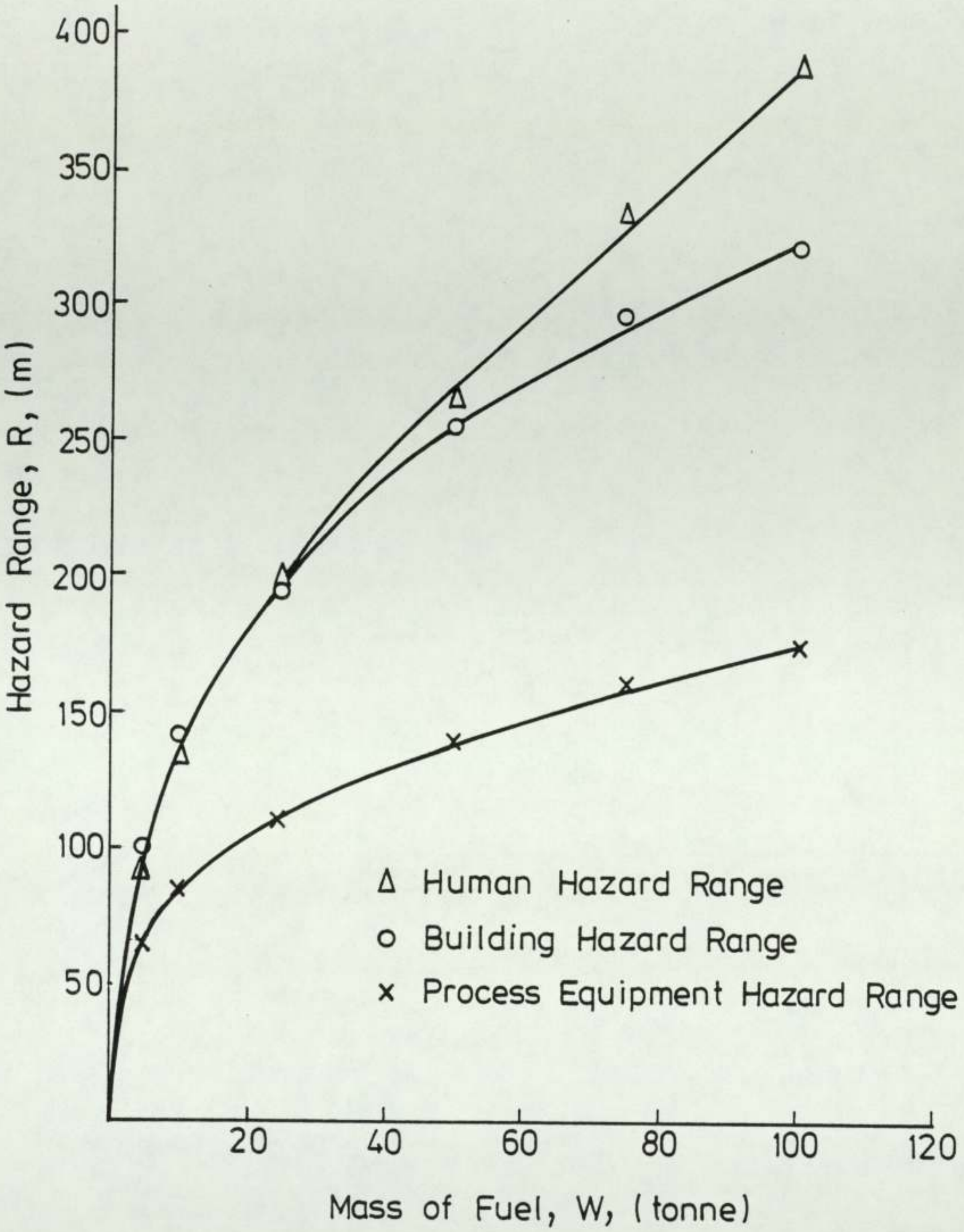


Figure 6.15 Variation of Hazard Range with Mass of Fuel using BLEVE Model.

and Figures 6.16 to 6.19, show that the method which is proposed in this study provides reasonable hazard ranges for humans, buildings and process equipment and the quantity of water rate required (litre/min.m^2) to prevent a secondary fire.

Whilst it is not possible to deduce from these calculations the validity of the results obtained, a comparison with those published in the literature shows that they are in good agreement. However, many factors involved in a pool fire remain unpredictable (eg shape and size of the flame envelope, temperature and thermal emissive power of the flame). It is possible using the method proposed in this study to predict the spacing distance at which the values of L/D are appropriate for a pool fire for different masses of flammable liquid involved in the pool fire.

Figures 6.16 and 6.17 show that the spacing distances to humans, buildings and process equipment increase linearly with the increase of flammable mass and with increasing L/D value. Also the rates of water requirement to prevent secondary fires increases exponentially with the increase of L/D value and mass of flammable liquid, as illustrated in Figures 6.18 and 6.19. The water rate is consistent with government guideline figures.

The results are useful when designing the layout of plant and restricting access of persons to hazard areas. However, the effect of wind on the envelope of the flame is not taken into account in this study.

All the criteria and information presented so far, illustrate the high degree of uncertaintly associated with the prediction of the occurrence and the damage effects of fireballs and pool fires. It is therefore evident that the determination of spacing distance to ensure

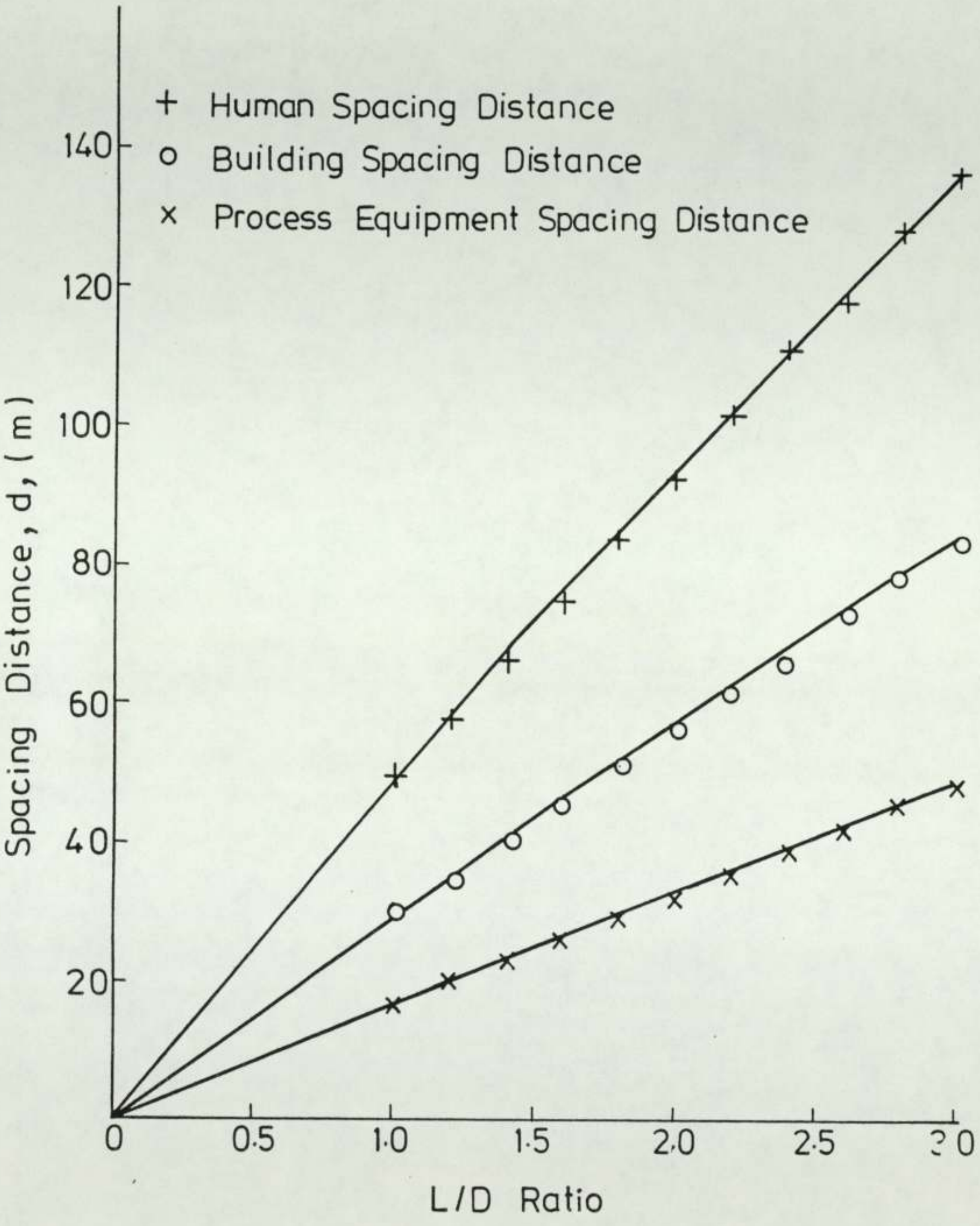


Figure 6.16 Variation of Spacing Distance with L/D Ratio for 5m Diameter Pool Fire.

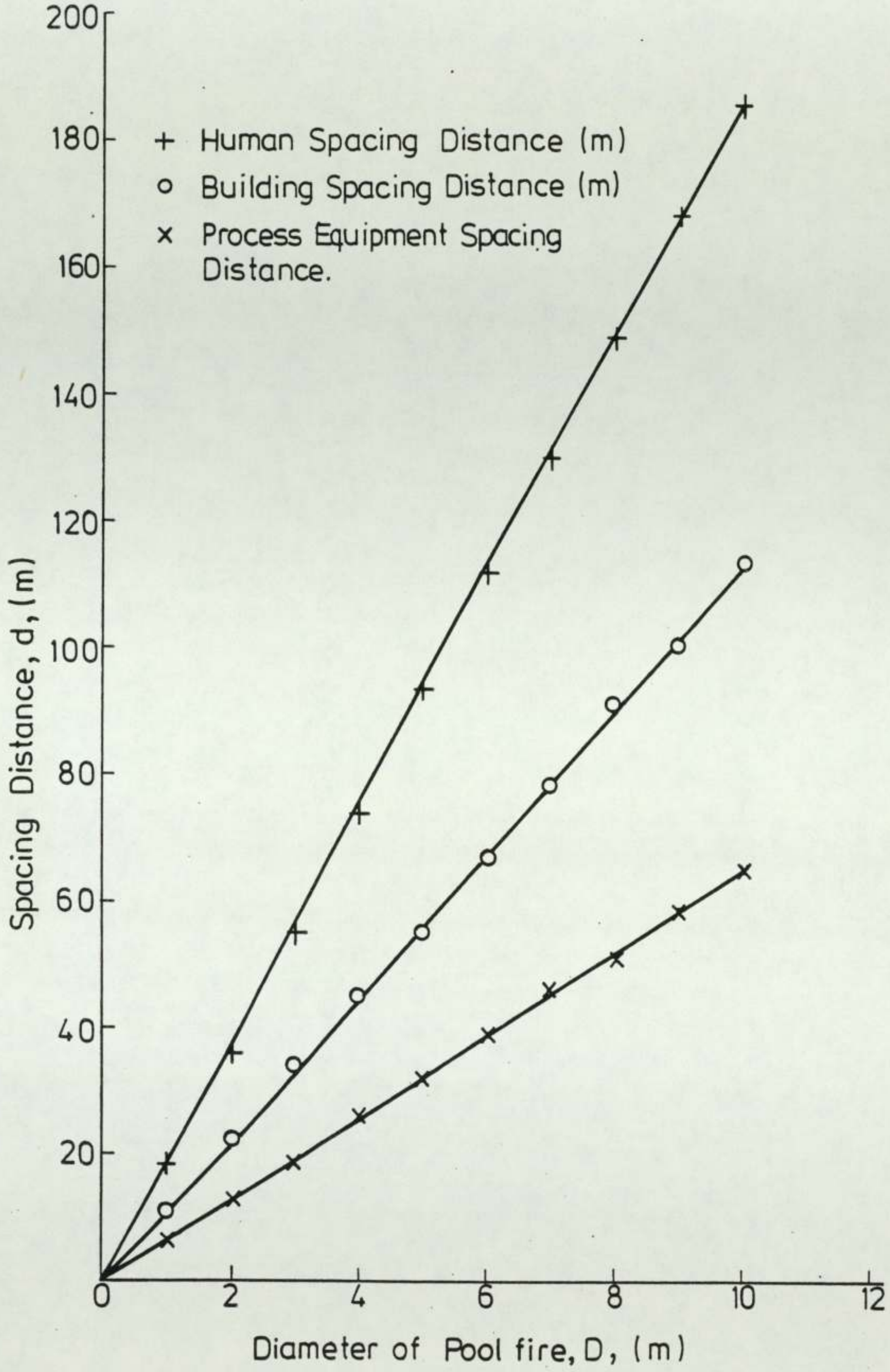


Figure 6.17 Variation of Spacing Distance with Diameter of Pool fire for 2.0 L/D Ratio.

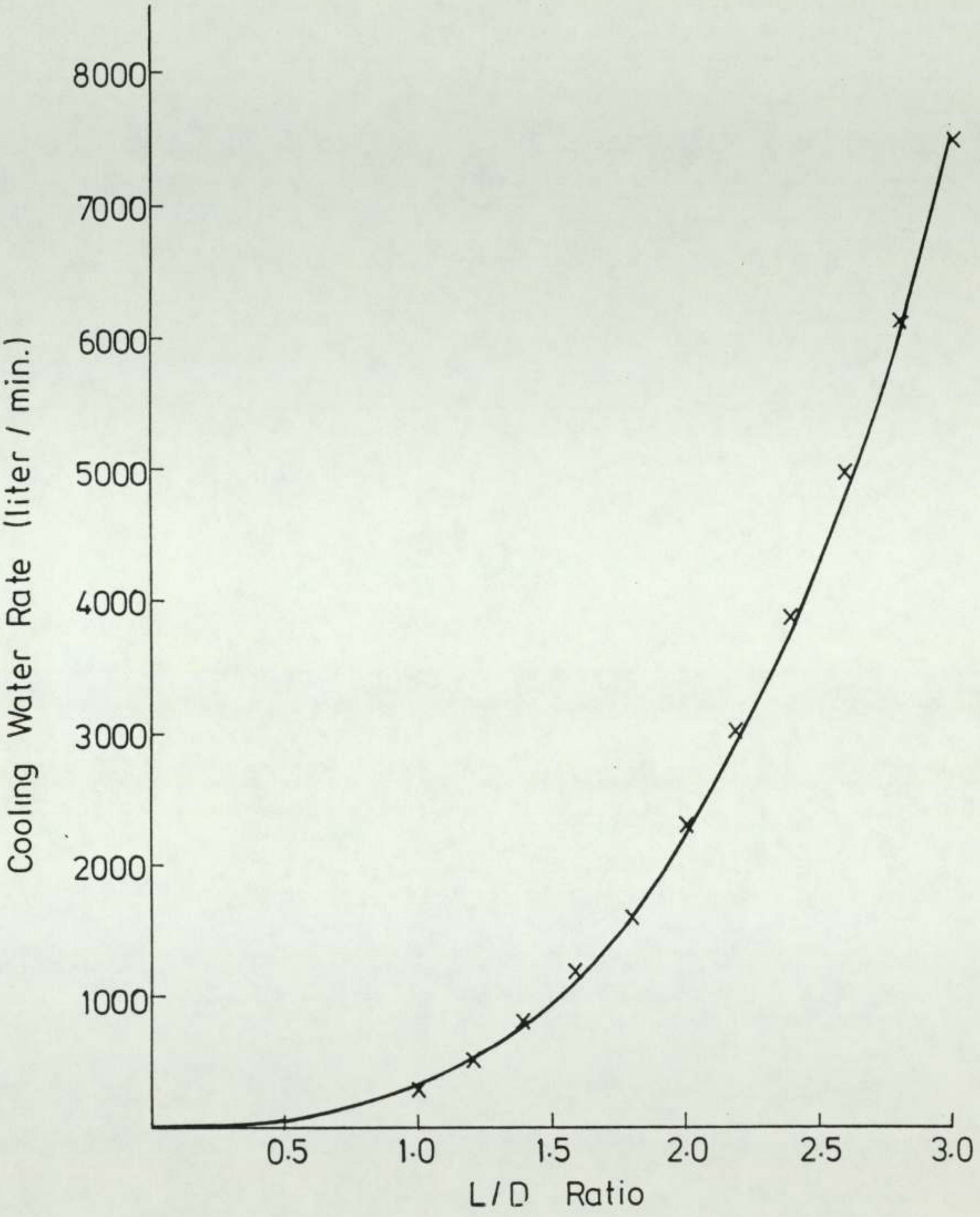


Figure 6.18 Variation of Cooling Water Rate with L/D Ratio for 5 m Diameter Pool Fire.

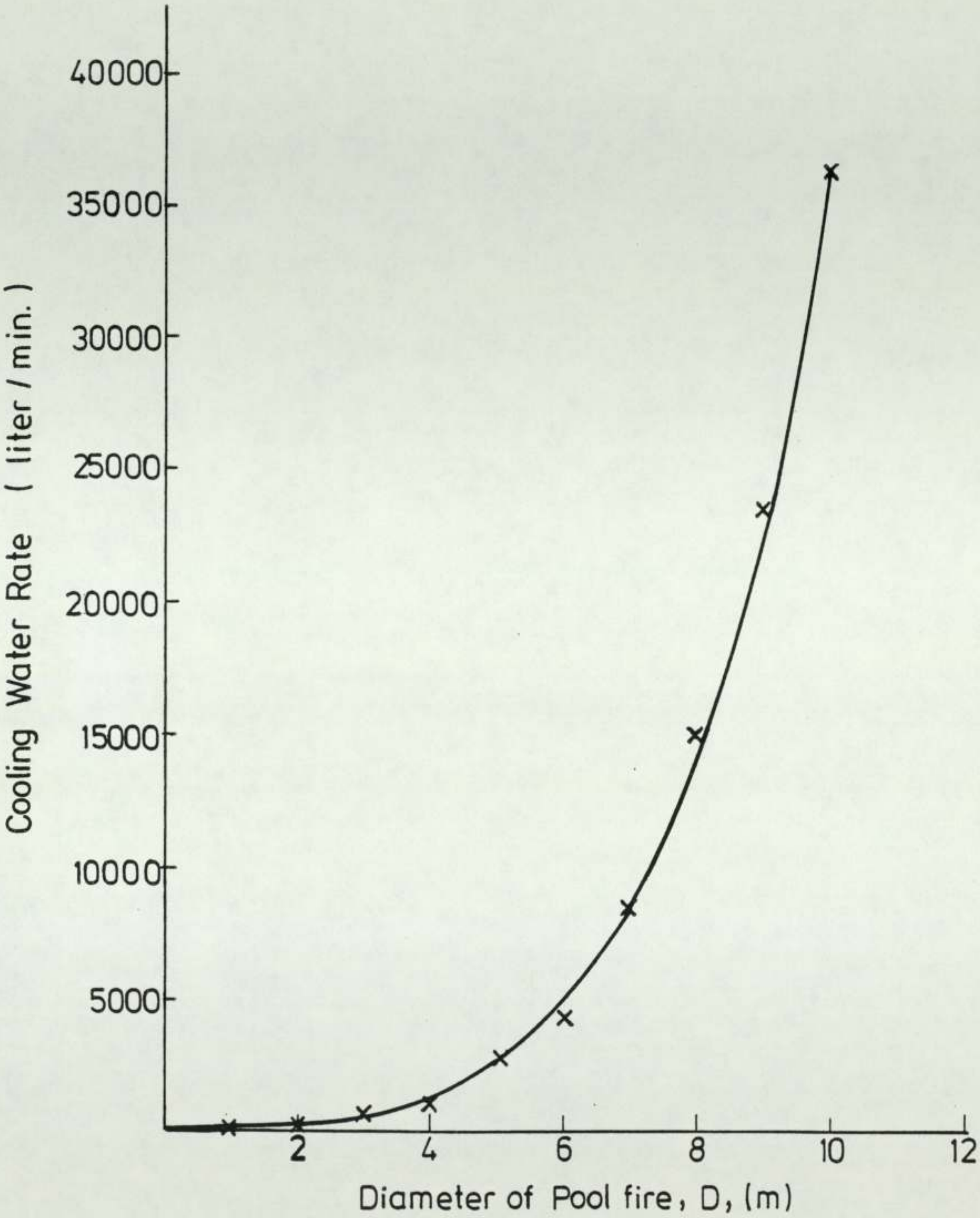


Figure 6.19 Variation of Cooling Water Rate with Diameter of Pool fire for 2·0 L/D Ratio.

sufficient safety for the public and the environment cannot be performed with any precision with the present level of knowledge. However, there have been a number of quantitative assessments and several recommendations have been proposed. Most use an empirical form of approach. In all calculations a fundamental decision must be made as to an acceptable criterion for damage. This generally leads to the conclusion that maximum spacing distances are to be preferred.

Undoubtedly the prediction of safe and socially-acceptable spacing distances and determination of positioning of plant and/or storage facilities in relation to public buildings and constructions requires great skill and social responsibility. Therefore the best solution is the attainment of a high degree of safety without any considerable economic loss from spacing and siting policy, by optimising the process and reducing the risk to as low a value as possible.

CHAPTER SEVEN

PREDICTION OF ACCEPTABLE SPACING DISTANCES FOR PLANTS INVOLVING AN UNCONFINED VAPOUR CLOUD EXPLOSION HAZARD

The process industries handle a wide range of materials, a significant proportion of which can be regarded as hazardous. Many of the processes also require careful control to ensure safe operation. Failure of either equipment or operational standards could result in an explosion, for example, the explosive failure of a pressure vessel due to overpressurisation, or a vapour cloud explosion. Therefore, it is necessary to be able to assess the probable consequences of an explosion in terms of damage to the plant itself, to any neighbouring plants and the effects on operating personnel and the general public.

7.1 EXPLOSION

An explosion may be defined as a process whereby a pressure wave is generated in air by a rapid release of energy which causes a shock wave, moving away from the source [70]. An explosion can be produced by the detonation of a high explosive, the rapid burning of a flammable gas cloud, or the sudden failure of a pressure vessel containing high pressure gas. However, irrespective of the source of the released energy a pressure disturbance will be created in the surrounding air, and because of its compressibility, the air becomes heated locally with a corresponding increase in the velocity of sound leading to the front of disturbance becoming steeper as it passes through the air, with consequent increases in density and pressure. The resulting blast wave is largely responsible for the damage caused inside and outside the cloud as the shock wave propagates in the atmosphere beyond the cloud.

7.2 DAMAGE PREDICTIONS FROM OVERPRESSURES

It has been explained above how explosions produce a shock wave. This is a narrow band of high pressure travelling away from the explosion at sonic velocity. This overpressure applies impulsive forces to structures, the effect of which, in structural stress, may be up to twice that of a steadily applied pressure difference of the same magnitude.

Following the shock wave, structures will also be subjected to winds of high velocity. This creates a dynamic pressure which persists for much longer than the overpressure; especially after a UVCE the release of energy from which takes much longer than for a high explosion. Table 7.1 [41] shows the relative values of these pressures and the wind; they have been calculated from published relationships [71].

TABLE 7.1

PRESSURE PEAKS AND WIND VELOCITY FOLLOWING EXPLOSIONS

Overpressure (kN/m^2)	14	35	70	140
Dynamic pressure (kN/m^2)	0.7	4.9	14	56
Wind Velocity (km/h)	112	256	464	752

The response of structures to a dynamic pressure has been extensively studied for military purposes. The results are generally expressed as the damage to be expected from a shock of specified overpressure.

Table 5.2 shows the likely damage from various peak overpressures. These have been derived from compiled data [42] on the damage resulting from TNT explosions. The estimation of generally acceptable peak pressure values for the safety of constructions is very complicated. It is even more difficult to predict an overpressure value at which people will not be harmed since the majority of injuries to persons outside the perimeter of the vapour cloud are due to building collapse or debris arising from buildings, in particular fragments from windows.

Several methods have been proposed for the calculation of acceptable spacing distances from the epicentre of a UVCE. The most important of them have been used in this study and are presented in the following paragraphs.

7.3 TNT EQUIVALENCE MODEL

The energy released by the explosive is the limiting factor to the magnitude of the blast wave. Therefore it is possible to quantify the potential energy of a conventional explosive, such as TNT, and compare this with that of LPG to arrive at some idea of the potential destructiveness of hydrocarbon explosions.

It has become customary to equate the damage caused by a UVCE to that caused by an equivalent mass of TNT. According to this method, the damage caused by an UVCE due to overpressure can normally be described as a function of a known amount of standard explosive (TNT) and the distance from the blast, ie the "TNT equivalence" system.

The equivalent amount of TNT is usually calculated by the following steps [26]:

a. Estimation of the quantity of vapour which has escaped (or in case of prediction is likely to escape).
b. An assumption that all of this vapour burns explosively.
c. Evaluation of the combustion energy released from this quantity of vapour.
d. Division of this calculated energy release by the energy released upon the detonation of unit mass of TNT (about 1100 kcal/kg).
e. Evaluation of the actual explosion yield using the explosion yield factor.

Most hydrocarbons display a maximum combustion energy release of around 10,000 to 12,000 kcal/kg compared with 1,100 kcal/kg for the usable energy in TNT. Therefore, on pure energy considerations alone, these hydrocarbons are ten times more potent than TNT. However, the rate of energy release is normally too low to create a shock wave. Therefore, an "efficiency factor" is normally used to determine the equivalent amount of TNT which corresponds to a given amount of hydrocarbon vapour. Various values have been suggested for this factor, eg 3% or 4% is recommended by the Second Report of the Advisory Committee on Major Hazards [72].

For design purposes, Brasie [73] recommends that yields of 2, 5 and 10% may be used to compare the sensitivity of various layout arrangements. Thus the overpressure, and, therefore the damage, can be predicted for different radial ranges. This has been done in the present work for the case of a 10 tonne propane UVCE and the results of calculations for different yields are given in Table 7.3.

When the equivalent weight of TNT has been calculated the overpressure and , therefore, the damage can be calculated for a given radius. There are a variety of methods for calculating this; the most common are summarised in the following paragraphs.

7.3.1 Jarrett's Equation

There are a variety of numerical equations, expressing the relation between the TNT equivalent amount and the distance from the epicentre of the UVCE, but the most widely used is the equation proposed by Jarrett [74]. The following equation is used by the UK. Explosives Storage and Transport Committee to assess the range at which different categories of damage may be expected [74]

$$R = \frac{k\,W^{1/3}}{\left[1 + \left({}^{6996}/_{w}\right)^{2}\right]^{1/6}} \qquad \text{.... } 7.1$$

where R = distance from the explosion in feet,
W = weight of TNT in pounds,
K = constant appropriate to various degrees of damage; set out below:

K = 9.6 - almost complete demolition
K = 13.9 - 50-70% external brickwork destroyed
K = 24 - houses uninhabitable - partial or total collapse of house walls and roofs
K = 70 - minor structural damage to buildings.
K = 140 - remaining inhabitable after repair, some damage to ceiling and tiling, more than 10 percent window glass broken.

The constant K, involved in Jarrett's equation takes a different value for every characteristic value of overpressure according to Figure 7.1 [29].

The quantitative assessment of spacing distance according to the TNT Equivalence Model using Jarrett's equation including the assumption of explosion yield factor of 2%, shows that one tonne of TNT is equivalent to 4.95 tonnes of propane. The constant K, involved in equation 7.1 takes a different value for every characteristic value of overpressure as mentioned earlier. A computer program was written to enable rapid calculations using this method; this is given in Appendix J, and the results of typical calculations are given in Table 7.2.

7.3.2 Hopkinson's Law

Another method to estimate the blast effect is based on the common scaling law of Hopkinson [3] which states that:

> "Identical blast waves are produced at identical scaled distances when two explosive charges of the same geometry and explosive material, but differing in size, explode in the same atmosphere".

It is important that only the scale is varied, and it is found that the overpressure at a given radius is proportional to the cube root of the energy or mass content of the charge [3].

This law is the basis of a curve relating scaled ranges (distance/mass$^{1/3}$) to overpressure. The curve of scaled distance versus overpressure which is represented in Figure 7.2 was derived from a large series of trials carried out with surface bursts of hemispherical TNT charges [75]. It should be noted that this curve is only appropriate for conditions where the terrain and atmospheric conditions have no significant effect.

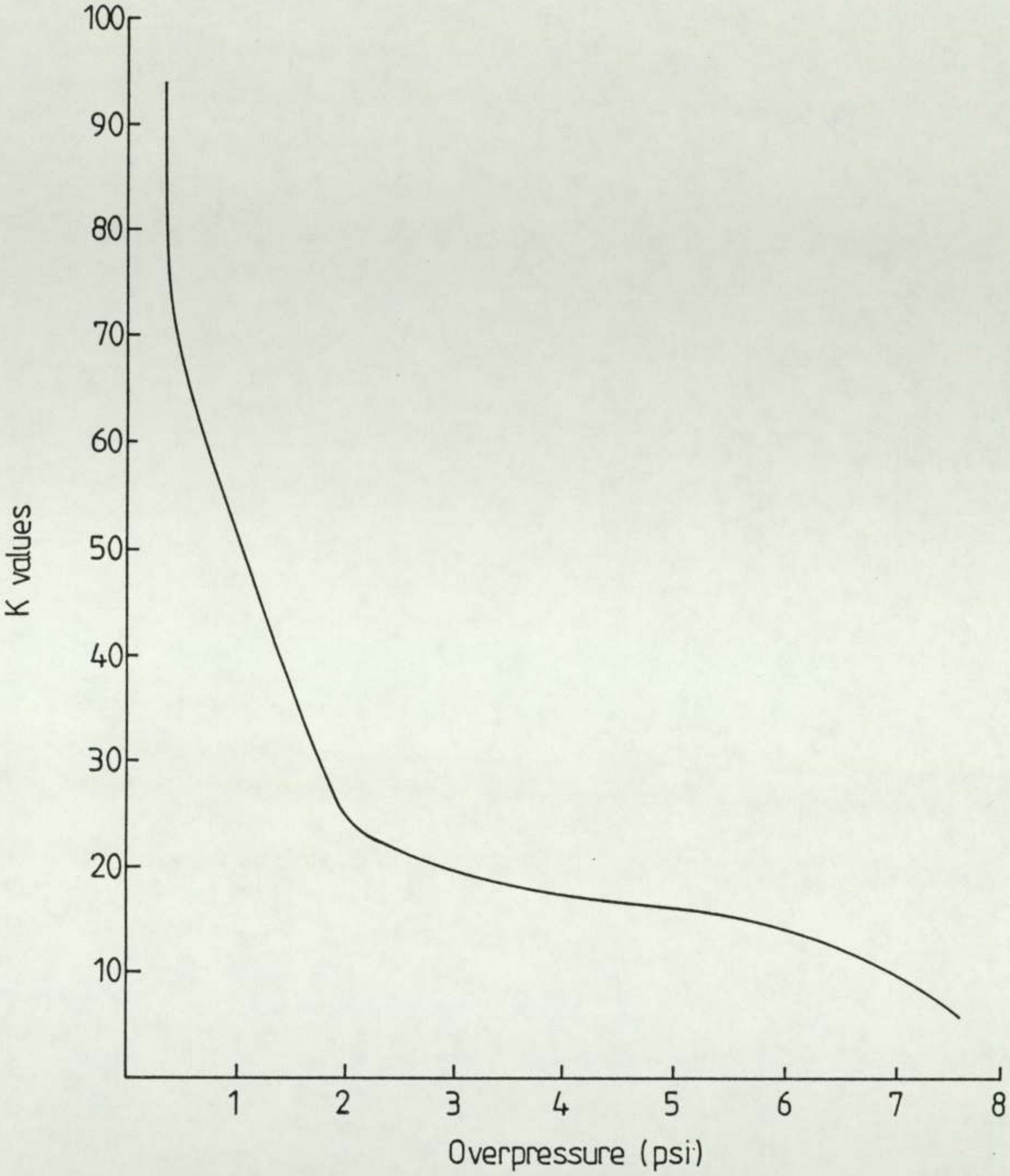


Figure 7.1 The values of constant K (Jarrett's equation) at different overpressures

TABLE 7.2

OVERPRESSURE VERSUS SPACING DISTANCE USING TNT EQUIVALENCE MODEL FOR DIFFERENT TONNAGES OF PROPANE

Overpressure		Amount released tonnes H/C equivalent					
		5	10	20	30	40	50
kN/m^2	K Values	spacing distance (m)					
69	3	7.9	12.1	17.4	20.7	23.2	25.2
42	13.9	37	56.4	80.7	96.1	107.5	116.8
34.5	16.3	43.4	66.1	94.6	112.7	126.1	136.9
20.7	19.8	52.7	80.3	114.9	136.9	153.2	166.4
15.9	22.8	60.7	92.5	132.4	157.6	176.4	191.6
10.35	37	98.5	150.1	214.8	255.9	286.3	310.9
6.9	51	137.1	208.9	299	356.2	398.5	432.8
4.8	61	163.4	249.1	356.5	424.6	475.1	516.0
2.76	72	191.7	292.1	418.0	497.9	557.2	605.1
2	99	263.5	401.7	574.8	684.7	766.1	832.0

TABLE 7.3

OVERPRESSURE VERSUS SPACING DISTANCE USING TNT EQUIVALENCE MODEL OF 10 TONNES PROPANE FOR DIFFERENT YIELD FACTORS

Overpressure kN/m^2	Spacing distance (m) for different yield factors		
	2%	5%	10%
69	12.2	19.2	25.2
42	56.4	89.1	116.8
34.5	66.1	104.5	136.9
20.7	80.3	126.9	166.4
15.9	92.5	146.2	191.6
10.35	150.1	237.2	310.9
6.9	208.9	330.2	432.8
4.8	249.1	393.6	516.0
2.76	292.2	461.6	605.1
2	401.7	634.7	832.0

In this method values of an explosion efficiency (the ratio of the energy in the blast wave to the energy theoretically available from the heat of combustion, usually expressed as a percentage) of 2, 5 and 10% has been used as recommended by Brasie.

For any overpressure, the scaled distance can be read from Figure 7.2 [70]. The actual distance can be obtained when the equivalent amount of TNT is known.

The quantitative assessment of spacing distance according to TNT Equivalent using Hopkinson's law including the assumption of 2% explosion yield factor shows that 2 tonnes of TNT are equivalent to 10 tonnes of propane in the cloud.

The overpressures developed at various distances can be obtained from Figure 7.2. A computer program was written to enable rapid calculations using this method; this is given in Appendix K and the results of typical calculations with different yield factors are given in Table 7.4.

7.4 GUGAN'S MODEL

This model is based on the concept that percussive combustion initially produces blast waves. These waves are unstable and become shock waves after t_S (seconds) at a radius R_S (metres) where the overpressure will be a maximum. The shock pressure P_S (kN/m^2) decreases with range R (metres) according to the semi-empirical equation 7.2 below [41].

$$P_S = 37.86 \left[\frac{Eo^{1/3}}{R}\right]^{1.5} \qquad \text{.... 7.2}$$

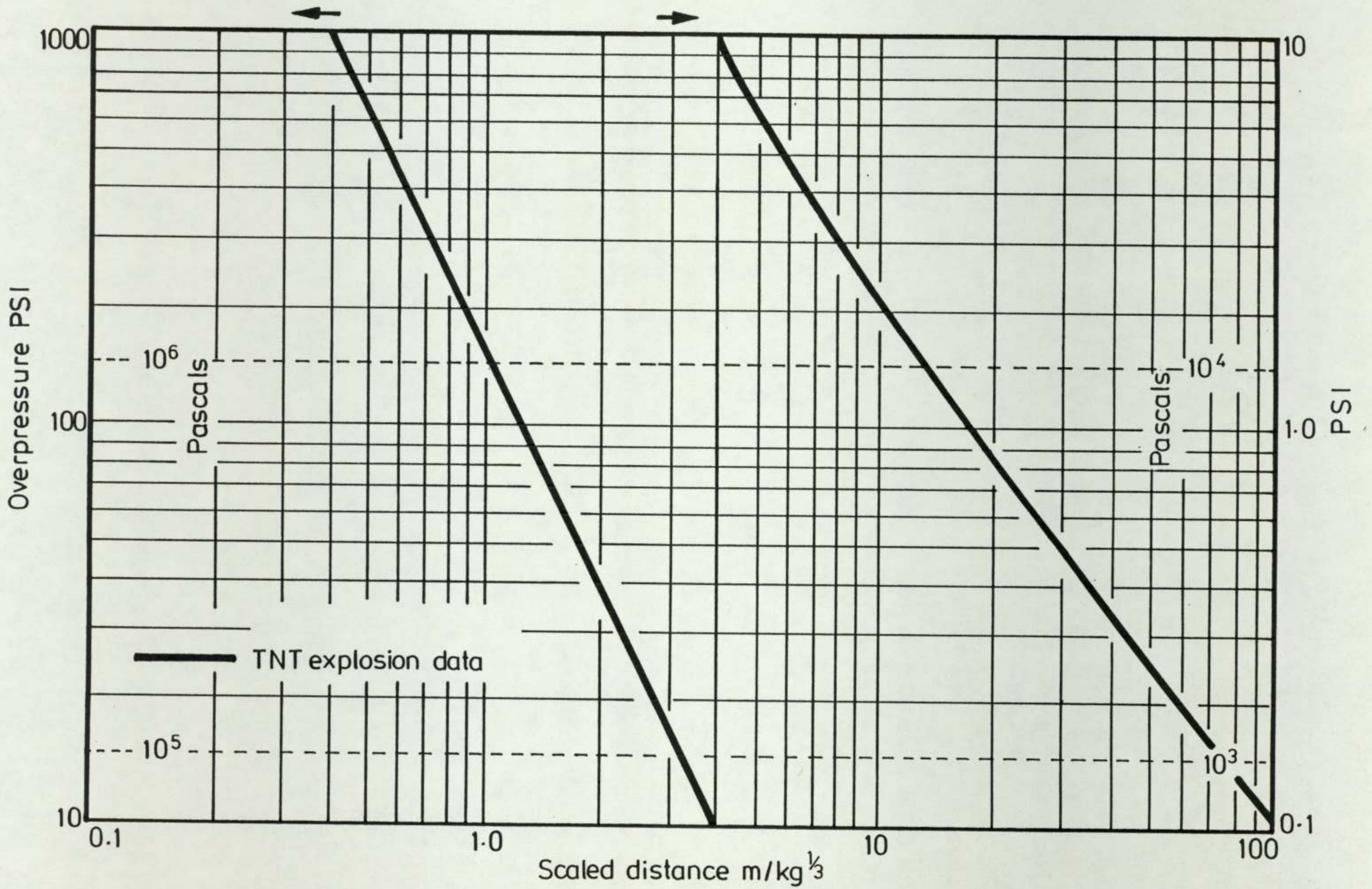


Figure 7·2 Scaled range vs. overpressure for TNT explosion data.

TABLE 7.4

OVERPRESSURE VERSUS SPACING DISTANCE USING TNT EQUIVALENT MODEL (HOPKINSON'S LAW) FOR DIFFERENT YIELD FACTORS OF 10 TONNES OF PROPANE

Overpressure kN/m^2	Spacing distance (m) for different yield factors		
	2% yield	5% yield	10% yield
69	50.4	68.4	86.2
42	69.3	94.0	118.5
34.5	75.6	102.6	129.2
20.7	107.1	145.3	183.1
15.9	124.7	169.2	213.2
10.35	176.3	239.3	301.5
6.9	226.7	307.7	387.7
4.8	302.3	410.3	516.9
2.76	440.9	598.3	753.8
2	579.4	786.4	990.7

where Eo is the total combustion energy released (MJ)

$$t_S = 1.5 \times 10^5/\dot{P}_C \qquad .... \; 7.3$$

$$R_S = 4.95 \times 10^7/\dot{P}_C \qquad .... \; 7.4$$

In equations 7.3 and 7.4, $P_C{}^{\circ}$ is the rate of pressure rise (N/m^2s) at the centre of the initial explosion.

Gugan [26] gives a relationship whereby $P_C{}^{\circ}$ may be calculated,

$$\dot{P}_C = 1.75 \times 10^6 \, Eo/a^3 \, t_0{}^4 \qquad .... \; 7.5$$

and $$t_o = Dc/a \qquad .... \; 7.6$$

where a = sonic velocity in air; 330 m/s

t_o = the duration of explosive release of energy, (s)

Dc = the initial hemispherical diameter of the cloud at NTP, (m)

The quantitative assessment of spacing distance according to Gugan's model is exemplified by the following example:

Consider the explosion of 10 tonnes of propane. Assuming a stoichiometric propane-air mixture of molar air: propane ratio of 23.8 and molecular weight of 44 gives the hemispherical diameter of the cloud as below

$$\text{volume of cloud at NTP} = \frac{(1 + 23.8) \times 22.4 \times 10 \times 10^3}{44}$$

$$= 126 \times 10^3 \text{ m}^3$$

therefore, hemispherical diameter of cloud $= 78.4$ m

Energy release $Eo = 46.45 \times 10 \times 10^3 = 464.5 \times 10^3$ MJ

$$\text{from equation 7.5, } \dot{P}_C = \frac{1.75 \times 464.5 \times 10^3 \times 330}{(78.4)^4} = 7.12 \text{ MN/m}^2 \text{ s}$$

$$\text{from equation 7.4, } R_S = \frac{4.95 \times 10^7}{7.12 \times 10^6} = 6.95 \text{ m}$$

$$\text{from equation 7.6, } t_O = \frac{78.4}{330} = 0.238 \text{ sec}$$

Thus Gugan's model indicates a duration of the explosive release of energy of 0.238 sec and extensive damage about 6.95 m from the epicentre, where the blast transforms into a shock wave.

Using equation 7.2, with $Eo = 464.5 \times 10^3$, the range at which the overpressure P_S kN/m^2 occurs is given in equation 7.2.

Rearranging equation 7.2 gives

$$R = \left[\frac{37.86\, Eo^{1/2}}{P_S}\right]^{2/3} \qquad \text{.... 7.7}$$

A computer program was written to enable rapid calculations using this method; this is given in Appendix L and the results of typical calculations are given in Table 7.5.

7.5 CLANCEY'S MODEL

Clancey's model is based upon the concept of a large quantity of vapour being released instantaneously to form a cloud which develops into a hemisphere in which the vapour concentration assumes a Gaussian distribution of the form [76]:

TABLE 7.5

RANGES OF OVERPRESSURES PREDICTED BY GUGAN'S MODEL FOR UVCE OF 10 TONNES PROPANE

Overpressure (kN/m^2)	Radial range (m)
69	51.9
42	72.3
34.5	82.4
20.7	116
15.9	138
10.35	184
6.9	241
4.8	307
2.76	444
2	550

$$C_{(r)} = \frac{2W}{(2\pi)^{3/2}\,\sigma^3} \exp\left[-\frac{r^2}{2\sigma^2}\right] \qquad \text{.... 7.8}$$

The first term is the concentration at the centre, Co, so that

$$C_{(r)} = Co \exp\left[\frac{-r^2}{2\sigma^2}\right] \qquad \text{.... 7.9}$$

and

$$Co = \frac{2W}{(2\pi)^{3/2}\,\sigma^3} \qquad \text{.... 7.10}$$

where W = total quantity of vapour in cloud (kg)

$C_{(r)}$ = vapour concentration at distance r from centre (kg/m^3)

Co = vapour concentration at centre of cloud (kg/m^3)

r = radius m

σ = standard deviation of concentration distribution (m)

If C_2 and C_1 are the concentrations at the upper and lower flammable limits it can be shown that the maximum amount of vapour in the cloud occurs when the concentration at the centre is C_2 or when

$$Co = C_2 \qquad \text{.... 7.11}$$

substituting from equation 7.10

$$C_2 = \frac{2W}{(2\pi)^{3/2}\,\sigma_m{}^3} \qquad \text{.... 7.12}$$

Rearranging equation 7.12 gives,

$$\sigma_m = \left[\frac{2W}{(2\pi)^{3/2} C_2} \right]^{1/3} = 0.5 \left[\frac{W}{C_2} \right]^{1/3} \qquad \text{.... 7.13}$$

Having obtained σ_m the standard deviation, when the cloud presents the maximum hazard, it is possible to find the radius r_1, at which the concentration is at the lower flammable limit,

$$C_1 = Co \exp \left[\frac{-r_1 2}{2\, \sigma_m 2} \right] \qquad \text{.... 7.14}$$

Rearranging equation 7.14 gives,

$$r_1 = \left[2\sigma_m 2 \ln \left(\frac{C_2}{C_1} \right) \right]^{1/2} \qquad \text{.... 7.15}$$

$$r_1 = \left[\sigma_m \;\; 2 \ln \left(\frac{C_2}{C_1} \right) \right]^{1/2}$$

$$= 0.71 \left[\frac{W}{C_2} \right]^{1/3} \left[\ln \left(\frac{C_2}{C_1} \right) \right]^{1/2} \qquad \text{.... 7.16}$$

This is in the absence of combustion. However, combustion will cause an eight-fold increase in volume. Thus, the radius Re of the edge of the cloud, when it is reached by the combustion wave is $2r_1$,

$$\text{therefore,}\quad Re = 1.42\left[\frac{W}{C_2}\right]^{1/3}\left[\ln\left(\frac{C_2}{C_1}\right)\right]^{1/2} \qquad \text{.... 7.17}$$

Clancey [76] suggests that the maximum pressure of 69 kN/m^2 (10 psi) is produced at ranges of Re, decaying at longer ranges.

The quantitative assessment of spacing distance according to Clancey's model is exemplified by the folloing example:

Consider the catastrophic failure of a tank containing 28 tonnes of propane at 20 °C (293 °K). The atmospheric boiling point of propane is 42 °C (231K). Mean specific heat of liquid propane over the temperature range 293 °K to 231 °K is 2.41 kJ/kg.°K, and latent heat at 231 °K is 410 kJ/kg.

$$\text{then mass of propane flashing } W = \frac{28 \times 2.41 \times (293-231)}{410}$$

$$= 10 \text{ tonnes}$$

Flammable limits for propane in air, $f_1 = 0.024$ and $f_2 = 0.095$.

Converting these into flammable concentration at 293 °K

$$C_1 = \frac{0.024 \times 44 \times 273}{22.4 \times 293} = 0.04 \text{ kg/m}^3$$

$$C_2 = \frac{0.095 \times 44 \times 273}{22.4 \times 293} = 0.17 \text{ kg/m}^3$$

From equation 7.13, $\sigma_m = 0.5\left[\dfrac{10{,}000}{0.17}\right]^{1/3} = 19.23$ m

From equation 7.16, $r_1 = 0.71\left[\dfrac{10{,}000}{0.17}\right]^{1/3}\left[\ln\left(\dfrac{0.17}{0.04}\right)\right]^{1/2}$

$= 32.03$ m

From equation 7.17, $Re = 2r_1$

$= 2 \times 32.03 = 64.06$ m.

The overpressure predicted by Clancey's model beyond Re can be calculated as follows:-

Figure 7.3 was redrawn by Lihou [41] in SI units from a similar chart presented by Brasie and Simpson [77]. It shows the overpressure as a function of scaled distance; that is the radial distance (m) from the epicentre of the explosion divided by the cube root of the heat of combustion (MJ) of the total mass of flammable in the cloud. The actual range of any overpressure P_s is Re $(r_s/0.48)$, where r_s is the scaled range corresponding to P_s on Figure 7.3.

A computer program was written to enable rapid calculations using this method; this is given in Appendix M and the results of typical calculations are given in Table 7.6.

7.6 ANALYSIS OF BLAST WAVE RESULTS

Overpressure is one of the key parameters in the analysis of explosions. There has been extensive research into the relationship between overpressure and distance, chiefly for military purposes. For

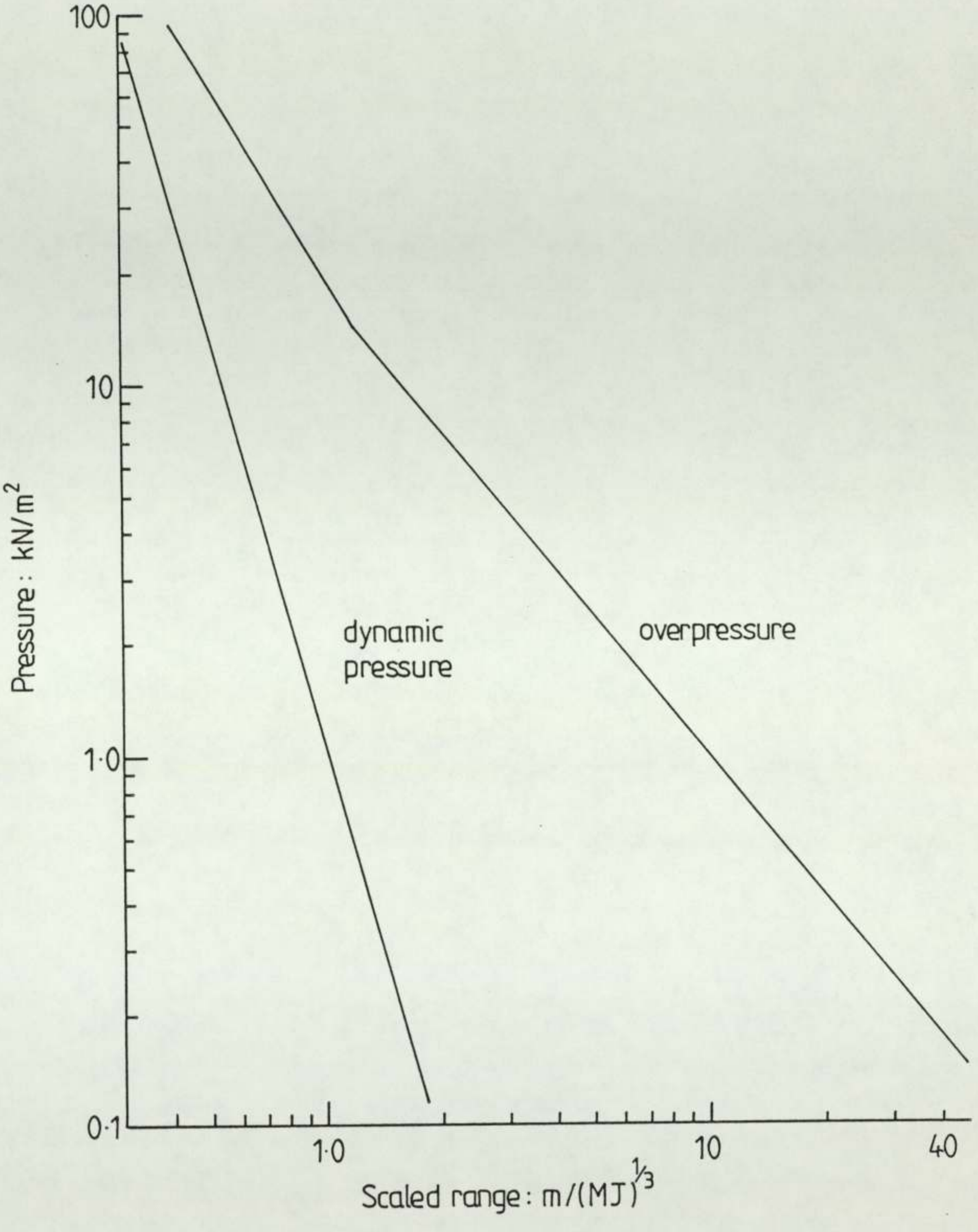


Figure 7.3 Peak pressure distribution from given combustion energy assuming 2% yield.

TABLE 7.6

RANGES OF OVERPRESSURE PREDICTED BY CLANCEY'S MODEL FOR A UVCE INVOLVING 10 TONNES PROPANE

Overpressure, kN/m^2	Radial range, m
69	64.06
42	93.4
34.5	100.0
20.7	130.8
15.9	149.5
10.35	204.2
6.9	280.3
4.8	373.7
2.76	747.4
2	1281.2

example, Figure 7.1-7.3 show the relationship between scaled range and overpressure. These curves show differing values of overpressure at a given scaled distance. There is a great deal of variance in results and the graphs represent "best fit" relationships [38].

The results, as tabulated in Table 7.2 -7.6, are derived in terms of spacing distance (metres) related to the flammable quantity released and to several characteristic values of overpressure which correspond to different levels of damage effect, as shown in Table 5.2. Calculations have been performed, using each of the above methods, and are presented in Appendices J, K, L and M, to enable a quantitative assessment and comparison of all the methods. It must be accepted that the comparison is limited by the considerable numbers of assumptions mentioned earlier. An important assumption for example is that the explosion yield factor does not exceed 2% in Gugan's and Clancey's models. This may not always be true in real incidents in which the yield factor has been over 10% or even below 1%. Nevertheless, these mathematical models with the explosion yield factors of 2% , 5% asnd 10% may be used to compare various layout arrangements.

The results illustrated in Figures 7.4 -7.13 show that the calculated distances according to TNT equivalent methods, Gugan and Clancey have gross deviations due to several assumptions and empirical equations which may effect their accuracy.

The accuracy of each of the above methods may be subject to the following limitations,

i the inherent accuracy is uncertain as demonstrated by the data from real incidents [26] which are shown in Table 7.7, in which topography, atmospheric conditions, etc. cause considerable variations

TABLE 7.7

DATA FOR SOME PRINCIPAL UVCE's

Date	Place	Flammable	Source	Quantity (kg)	TNT Equiv. (kg)
23.8.1921	Hull England	Hydrogen	Dirigible ZR-2	6,900	450 kg

Yield measured: 0.25%. Windows broken (0.5 psi) within 3.2 km area. Blast heard 8.4 km away. Tremors felt 80 km. Fatality 1.

16.1.1966	Caltex W. Germany	Methane	Process	500	1000-1200

Yield measured: 18-36%. Liquid methane vented at high level -subsequently formed a low lying dispersion. Blast damage to plant not particularly severe. Extensive glass breakage at 400 m, minor breakage at 1200 m. Fatality 1.

9.12.1970	Franklin Co. Port Hudson USA	Propane	Pipeline	70,000	50,000

Yield measured: 7.5%. The overpressure was 1 psi at 585 m and 0.5 psi at 1,100 m. No fatalities.

1974	England	Ethylene	Process	910-2700	7+

Leak from high pressure piping caused spill lasting about 30 min. before ignition. Windows broken (0.3 psi) in 180 m radius. Roof and ceiling in 4 buildings damaged. No fatalities.

1.6.1974	Flixborough England	Cyclohexane	Process	36,000	18,000

Yield measured: 5%. Poorly installed 500 cm temporary pipe failed. Ignition in 25–35 seconds created large overpressures. Fatalities: 28.

20.2.1977	Dallas Texas	Isobutane	Rail tank car	68.200	1600

Yield measured: 0.25%. Tank car punctured during derailment. Delay to ignition about 2.5 minutes. The open-air explosion was extremely violent and the shock was felt for miles around. Locomotives would appear to have been exposed to about 3.5 kPa at a distance of about 300 m from punctured tank car. No fatalities.

in the overpressure profiles.

ii it may be argued that not only overpressure but also duration is significant when damage potential is considered. Thus the overpressure required to produce a given level of damage may vary in cases where the duration is different [38]. However, in this study, the duration is fixed for a given level of overpressure. In principle this may not be true between one explosion and another.

iii examination of damage at UVCE sites gives two distinct regions, the region enveloped by the cloud and that beyond the periphery of the cloud. This difference should lead to the development of sophisticated mathematical models to explain the blast wave phenomena in UVCE's [3].

iv the statistics on flammable material involved show that they have a very wide range of physical, chemical and combustion properties. The only common factors would appear to be that the materials must be flammable and must be readily able to form mixtures with air within the appropriate flammable range [26].

The results, which are presented in Table 7.2-7.6, Figures 7.4-7.13 and Appendices J, K, L and M show that the four methods always provide spacing distances of the same order for almost every overpressure value, and the difference between results of the four methods increases in proportion to the increase of the flammable quantity (expressed in tonnes of hydrocarbon equivalent).

For flammable quantities less than 5 tonnes, the four methods give similar spacing distances. On the contrary, when the flammable quantity is bigger than 5 tonnes, the four methods can clearly be distinguished from each other. In general the differences between the results are not too large. However, they are significant and cannot be neglected.

In Figures 7.10-7.13, the explosion yield factor was assumed to be constant at 2% for every method and the results demonstrate that the Clancey model generally provides the biggest spacing distances and the Jarrett equation usually gives the smallest values of spacing distance.

The 2% yield factor is often not conformed with in practice [26, 38]. In this work, Jarrett's equation and Hopkinson's Law were used to obtain results with 5% and 10% yield factors as well as with 2%, as are shown in Figure 7.5 and 7.7. These results show that as expected the spacing distance increases with increasing yield factor.

The differences between the 4 methods appear to be due to the different theoretical bases used for each method, although some common assumptions have been made in all the methods, eg, explosion yield factors. Also, each method contains several other assumptions that might cause considerable errors in the calculations.

In conclusion, it is possible using these methods to predict the spacing distance at which characteristic values of overpressure are probable from a UVCE. As many factors involved in the potential cloud explosion remain unpredictable (eg wind velocity and direction, weather conditions, degree of confinement, spill rate and operator response), the explosion yield factor is taken at a more conservative value than previously ie 10%. Because all criteria and information illustrate the high degree of uncertainty associated with the prediction of the occurence and the damage effects of UVCE and as none of the four methods of calculation used is more or less credible than the others based on experience from real incidents, this leads to the conclusion that maximum figures are to be preferred.

The best solution is always the attainment of a high degree of safety without any significant economic loss by appropriate spacing and siting policy, in optimizing the process and reducing the risk to as low value as possible. However, the incidents that have arisen in recent years suggest that more importance ought to be given to safety considerations than to economic ones in designing appropriate spacing distances.

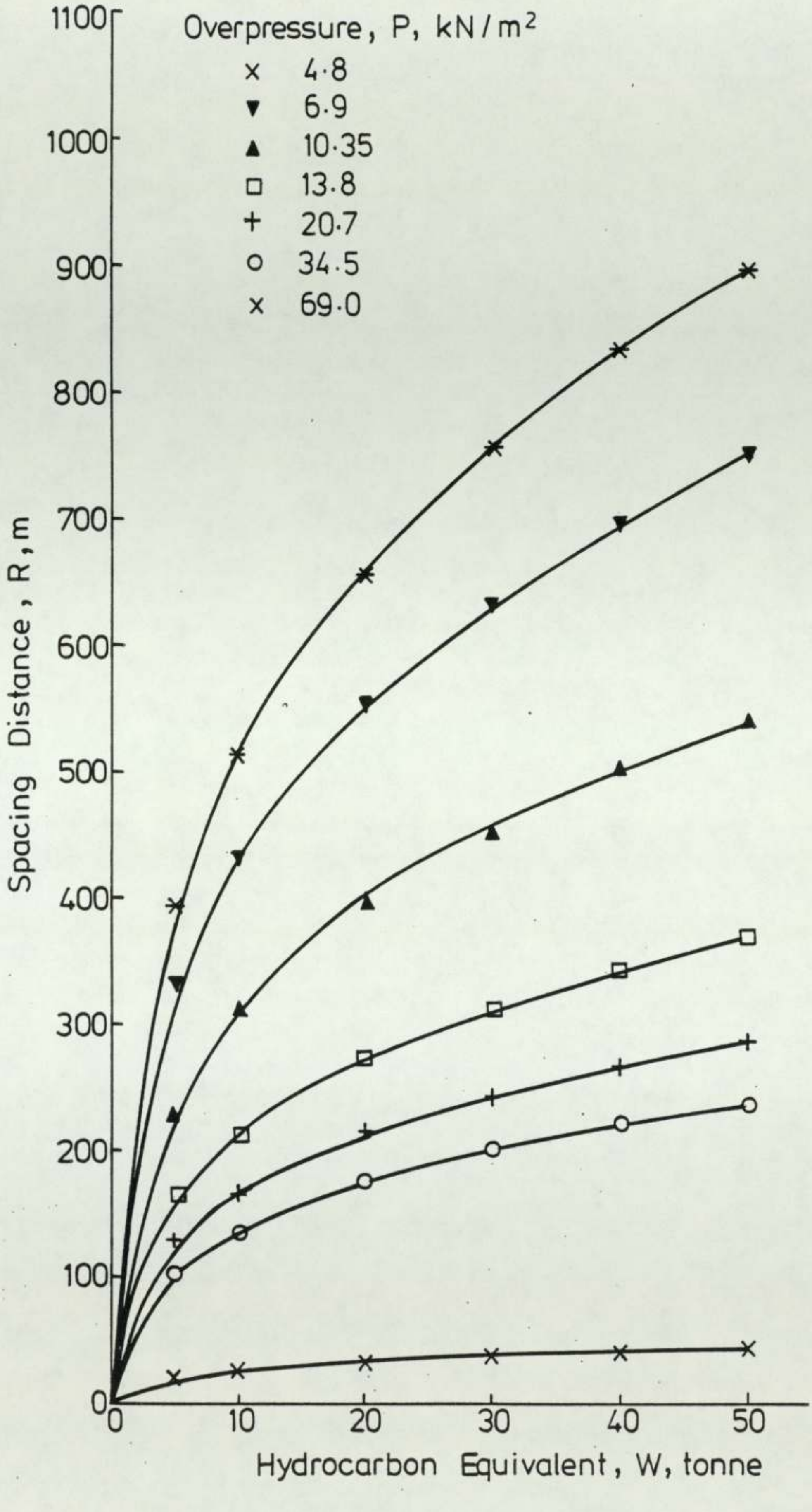


Figure 7.4

Variation of spacing distance with hydrocarbon equivalent for 10% explosion yield factor at different overpressures according to TNT equivalent model (Jarrett equation)

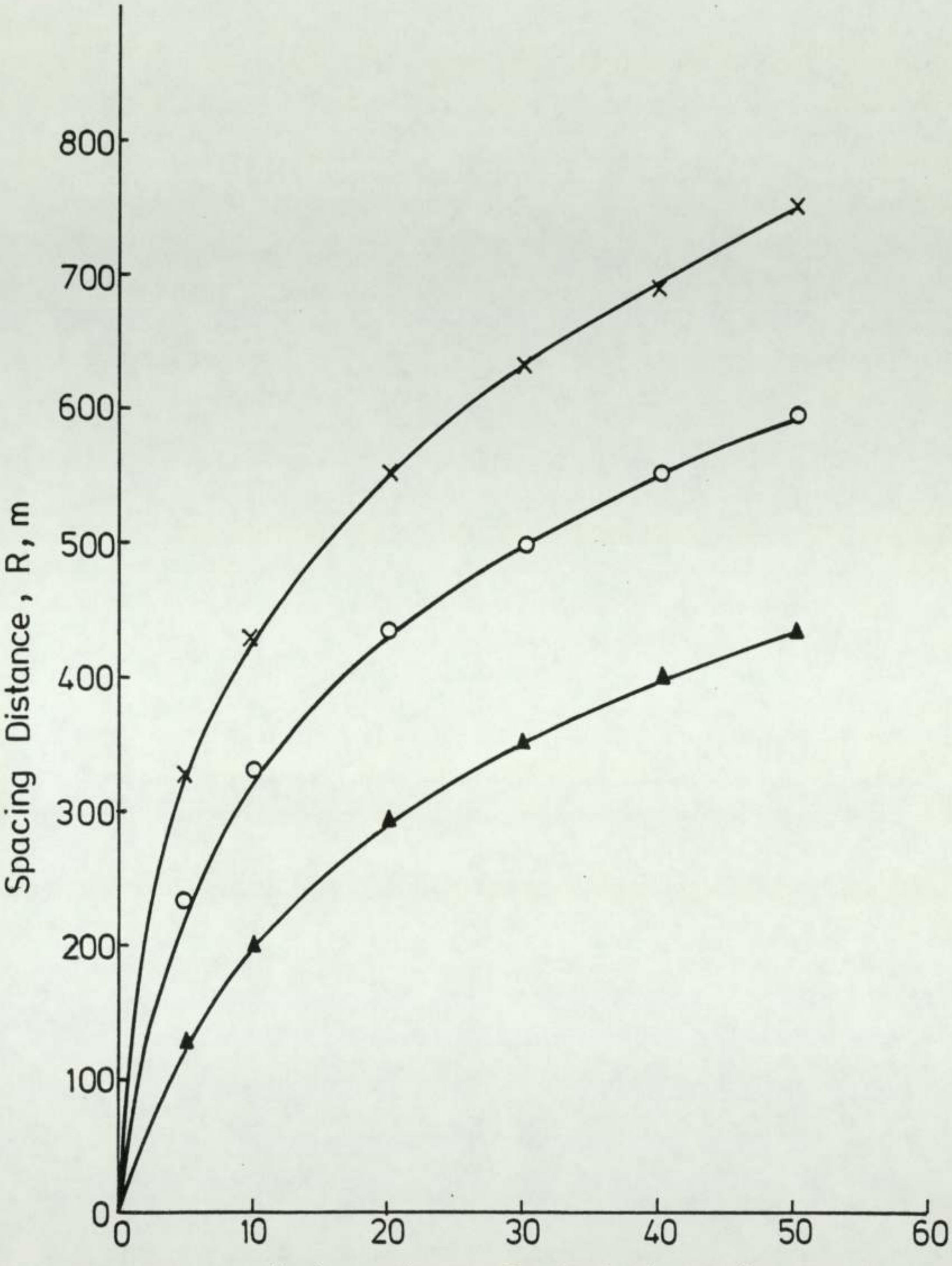


Figure 7.5 Variation of spacing distance with hydrocarbon equivalent for 6.9 kN/m^2 overpressure at different explosion yield factors according to TNT equivalent model (Jarrett equation)

Explosion yield factor
▲ 2%
○ 5%
× 10%

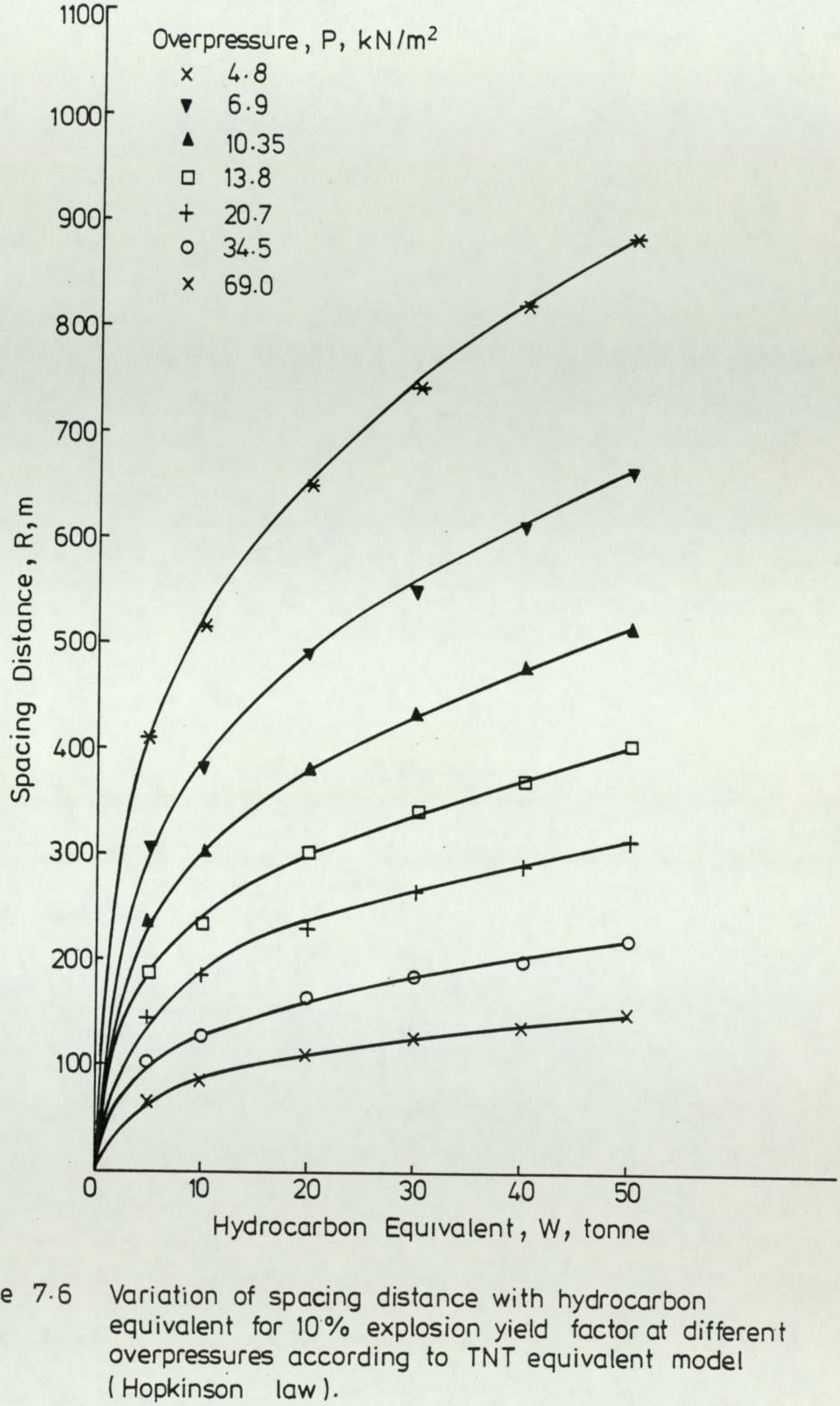


Figure 7·6 Variation of spacing distance with hydrocarbon equivalent for 10% explosion yield factor at different overpressures according to TNT equivalent model (Hopkinson law).

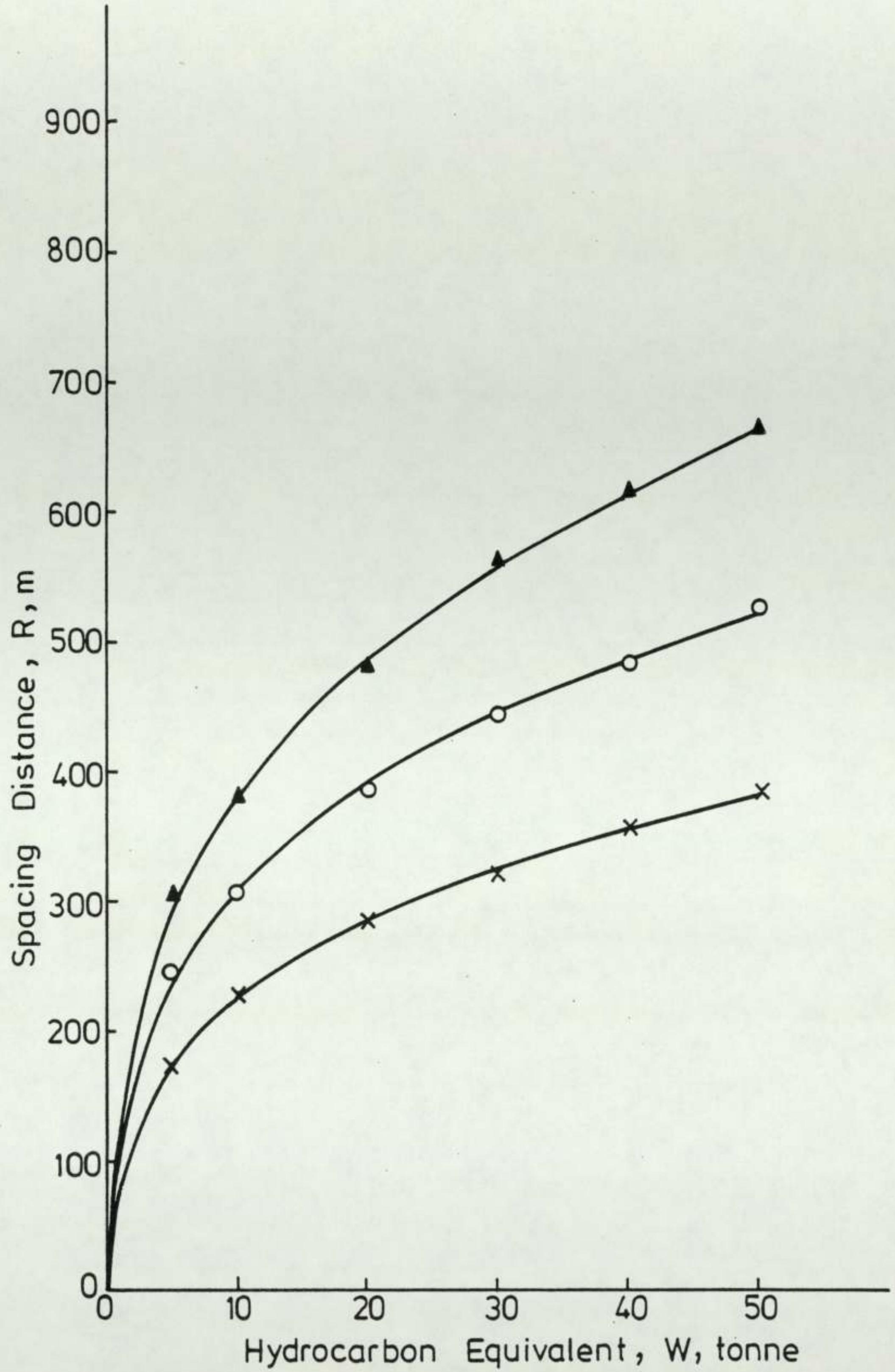


Figure 7·7 Variation of spacing distance with hydrocarbon equivalent for 6·9 kN/m^2 overpressure at different explosion yield factors according to TNT equivalent model (Hopkinson law)

Explosion yield factor

× 2%
○ 5%
▲ 10%

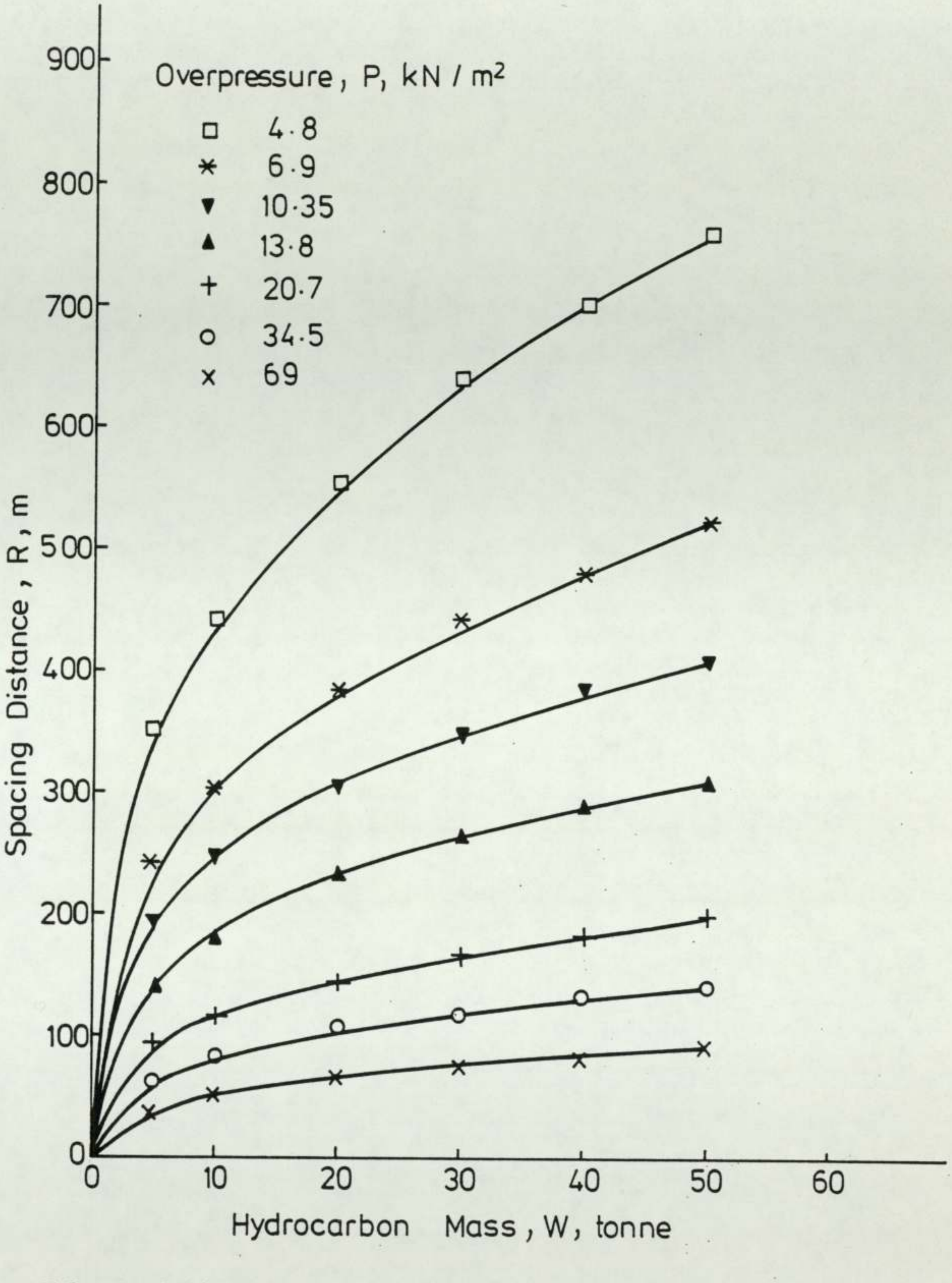


Figure 7.8 Variation of spacing distance with hydrocarbon mass at different overpressures according to Gugan's equation.

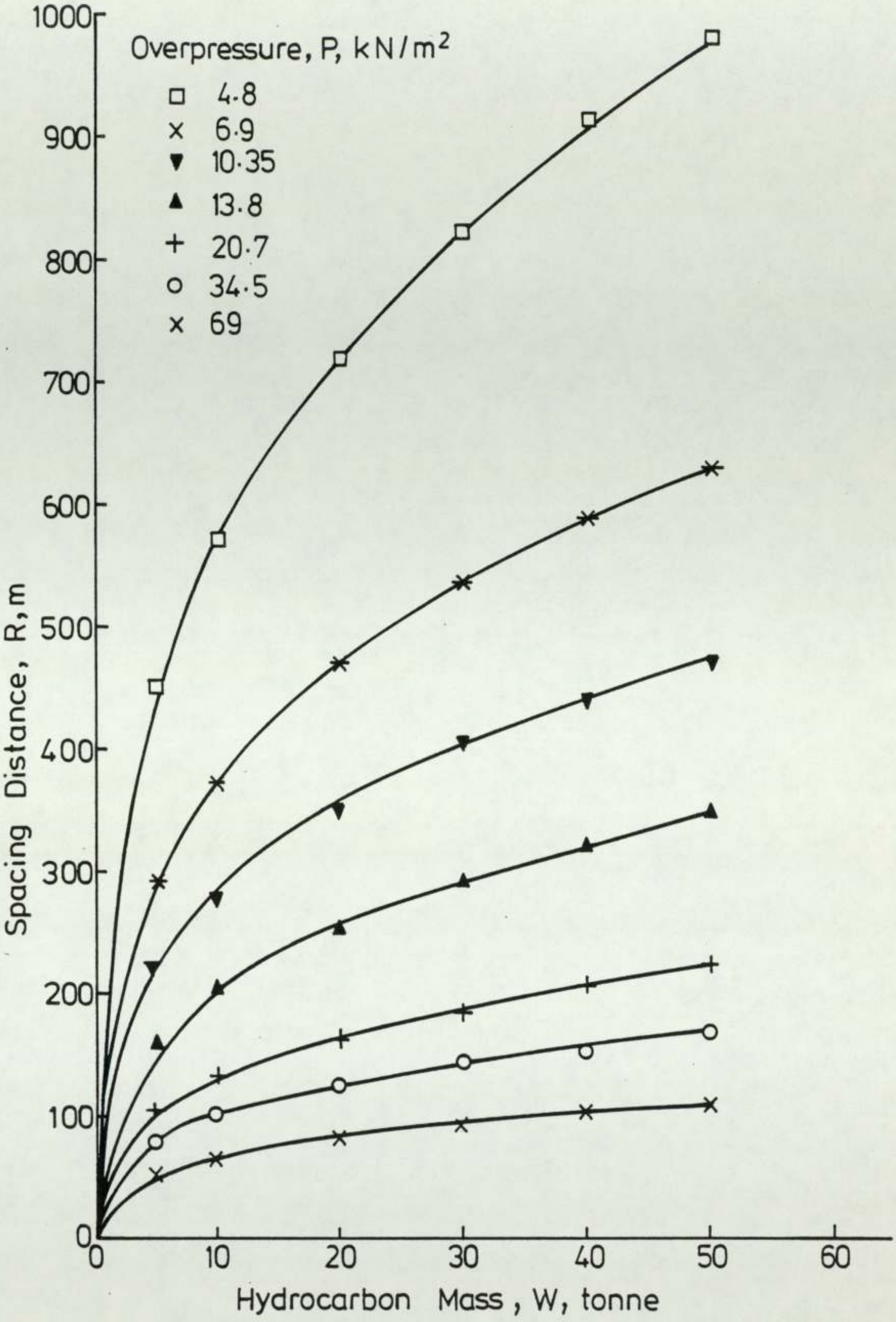


Figure 7·9 Variation of spacing distance with hydrocarbon mass at different overpressures according to Clancey's equation.

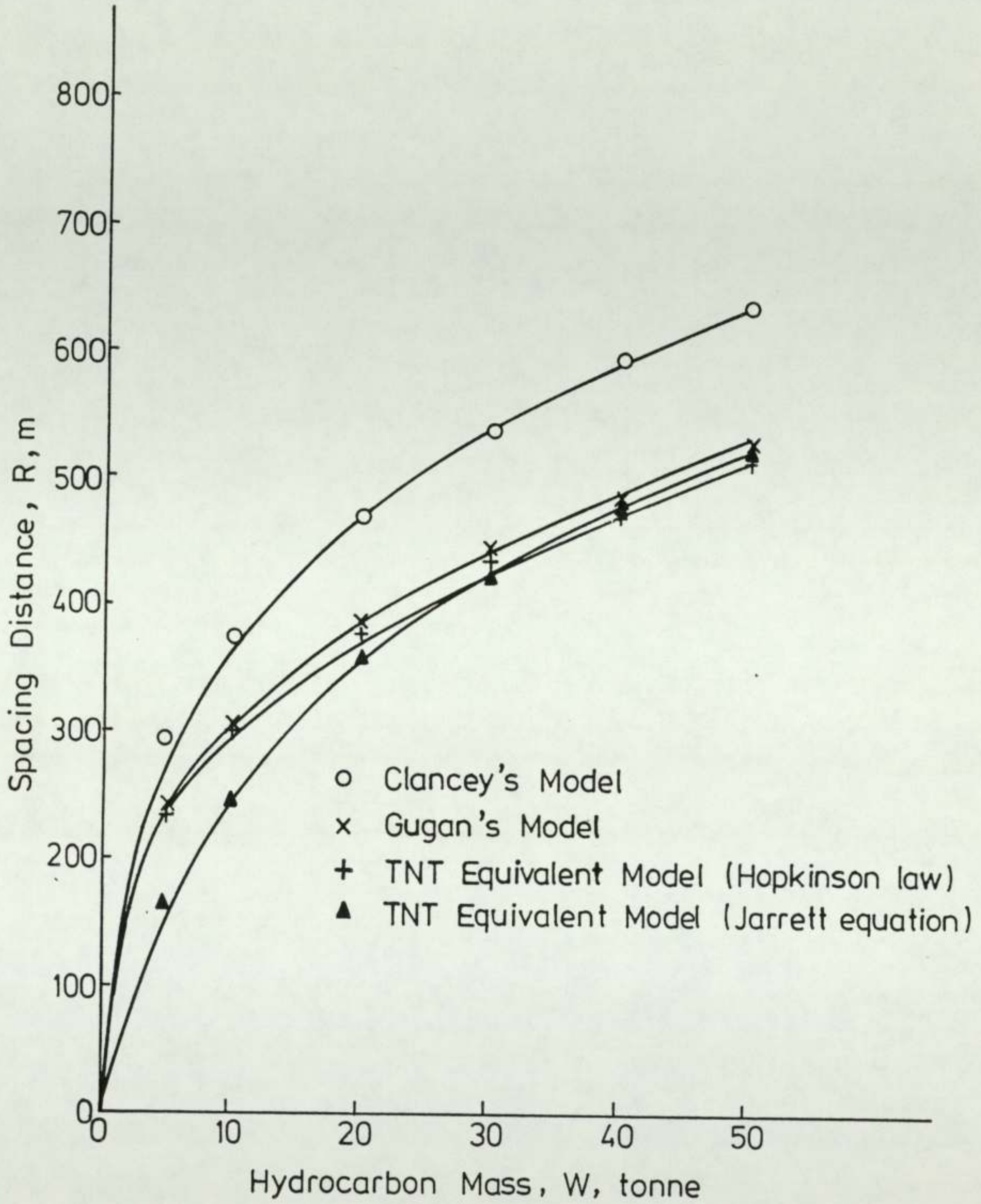
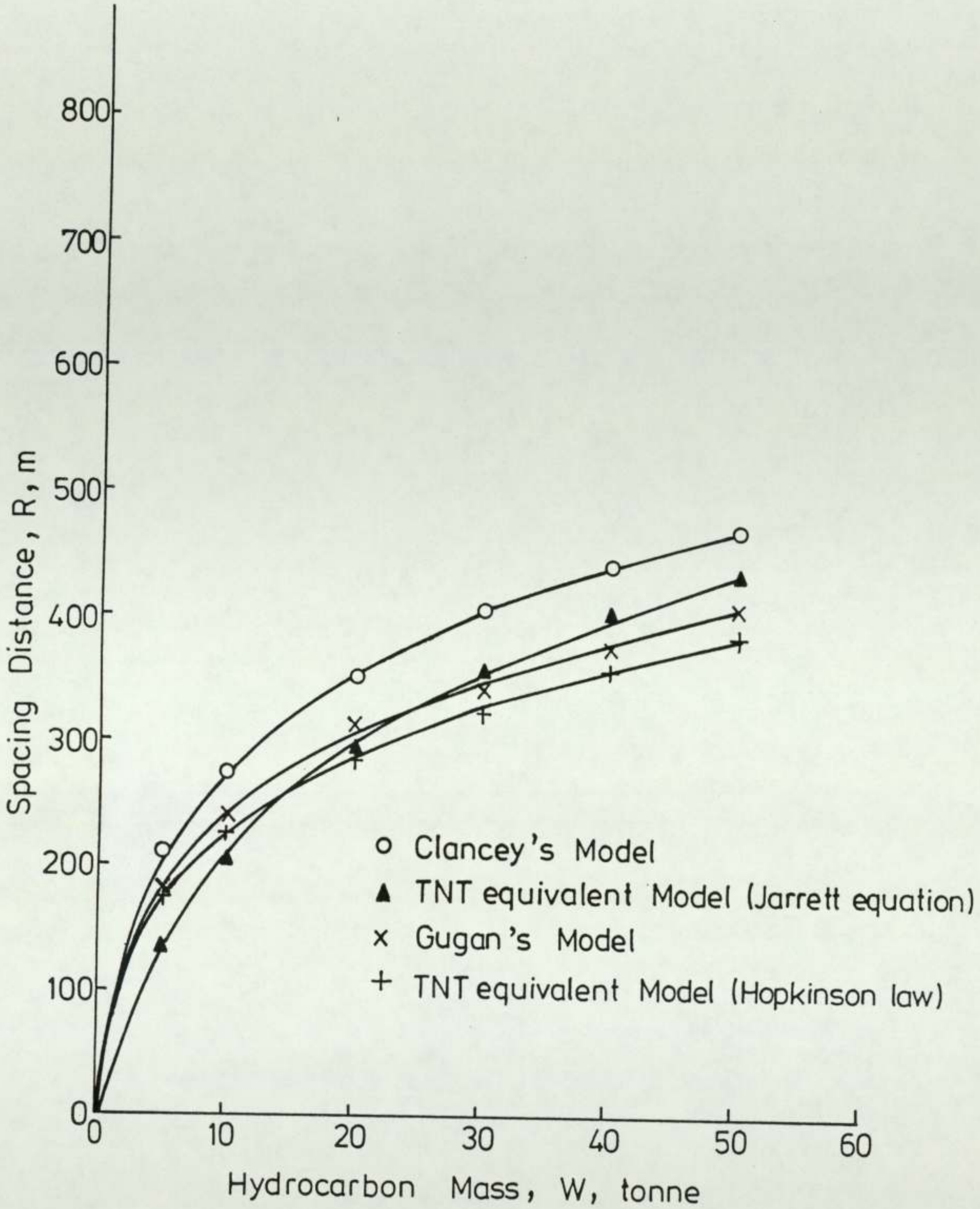


Figure 7.10 Variation of Spacing Distance to 4·8 kN/m² Overpressure based on Different UVCE Calculation Methods.



ure 7.11 Variation of Spacing Distance to 6·9 kN/m^2 Overpressure based on Different UVCE Calculation Methods.

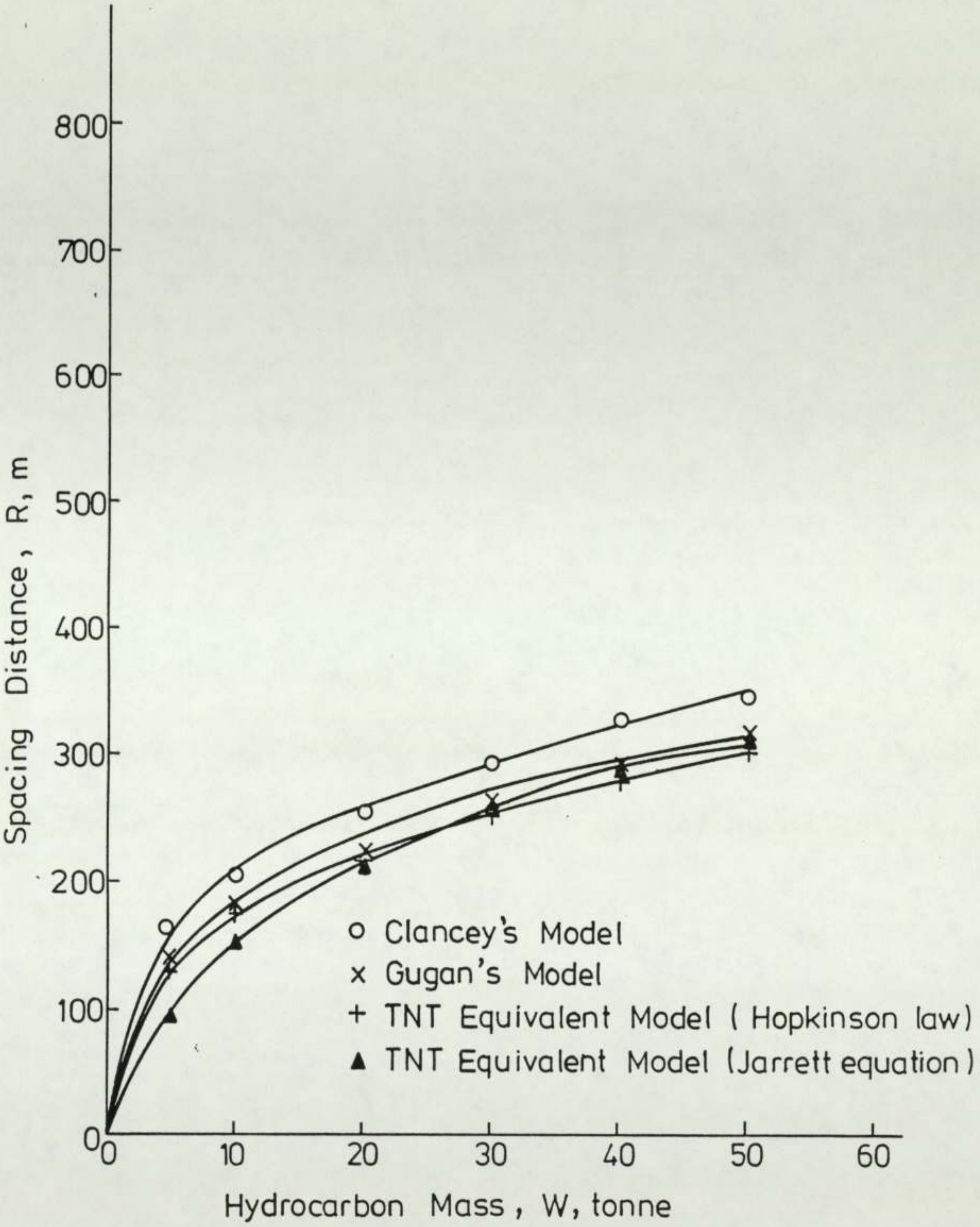


Figure 7·12 Variation of Spacing Distance to 10·35 kN/m^2 Overpressure based on Different UVCE Calculation Methods.

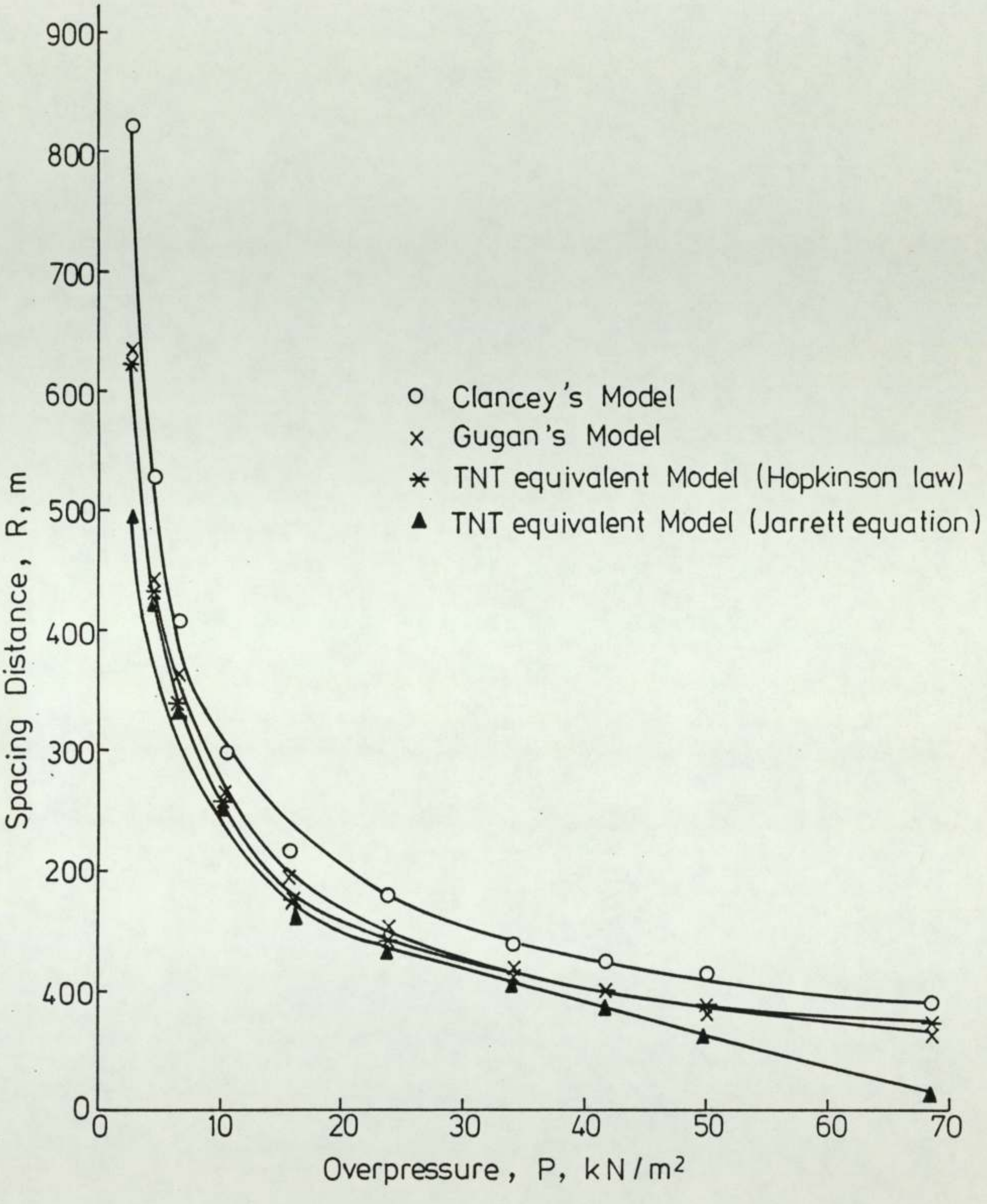


Figure 7·13 Comparison between the Different UVCE Calculation Methods for 30 tonnes propane at 2% Yield Factor.

CHAPTER EIGHT

SAFETY MEASURES IN LPG INSTALLATIONS

This chapter is concerned with the control of major LPG hazards, the prevention of their realization, and the limitation of their consequences. It has to be recognised that if a hazard exists, the likelihood of its realization can never be reduced to zero. If it cannot be eliminated entirely, control must aim to reduce the individual or social risk associated with the hazard to a level which is tolerable,acceptable, or justifiable to society as a whole.

Quantification methods are a vital part of the process of assessment of LPG hazards and risks. Some of these techniques have been discussed in detail in Chapters 6 and 7.

Therefore, the possible occurrence of a major LPG fire or explosion can be minimized by sound engineering, plant design and layout, good operating practice and proper training of personnel in both routine operations and actions to be taken in an emergency.

8.1 DESIGN CONSIDERATIONS FOR LPG INSTALLATIONS

8.1.1 Bulk LPG Storage Installations

The following are important factors in plant design (4, 45) :

a. The maximum weekly offtake , in conjunction with the type and rate of supply , as a guide to determine storage capacity,

b. The maximum instantaneous and average hourly offtake to determine the size of vaporizer or the capacity of LPG air-plant,

c. The possibility of future extensions to the plant capacity,

d. The need for standby facilities,

e. Access facilities for road delivery vehicles including road widths and suitability of roadways for axle loadings,

f. Minimum winter temperature, to determine natural vaporization rates from LPG vessels,

g. The pattern of operation required, i.e continuous or intermittent,

h. No bund walls are permitted around pressure vessels,

i. The design pressure for the top of the vessel should be 110% of maximum operating pressure,

j. The design pressure used for the bottom of the vessel should be that for the top of the vessel plus the static head of the maximum contents of the vessel,

k. Only one product line should be provided at the bottom of the vessel , to be used for filling , discharge and draining,

l. A manually-operated fire-safe valve and a remote controlled fail -safe emergency valve should be provided at the manifold side,

m. Separate safety/relief valves should be provided to protect against overpressure due to abnormal operational conditions,

n. Overfill protection, should also be provided, in addition to relief valves, in the form of instrumentation. This is particularly important for very high thermal expansion material such as LPG.

In addition to the above requirements for the design of LPG installations, guidance is available on the location, spacing, layout etc, in various LPG Codes of Safe Practice, eg, produced in the UK by the Institute of Petroleum [78] LPG ITA [9], the Home Office and the

HSE [11].

8.1.2 Pipework, Valves, Pipe Fittings and LPG Pumps

All materials used, including non-metallic parts for valves, seals, gaskets, diaphragms, etc, must be resistant to the action of LPG under their operating conditions.

i. Fixed Pipework:

Only steel piping may be used for liquid line service, although vapour lines may either be of steel or solid drawn copper. Pipework for liquid and vapour lines adjacent to storage vessels must be flexible enough to accommodate any settling of the storage tanks or other equipment, any thermal expansion or contraction, and any other stresses that may occur in the pipework system. Flexible hoses used for this purpose should not be greater than 230 mm (9 in) long of 25 mm (1 in) bore, and should be used only on installations of up to 2 tonnes nominal LPG capacity. Flexible connections should have a minimum bursting pressure of four times the maximum pressure they will bear in service. Corrosion-resistant braiding should be used [4, 79].

ii Pipe Joints:

Steel joints on pipework with a bore of 50 mm (2 in) or more should be welded or flanged. Joints on pipes with a bore of less than 50 mm (2 in) may be welded, flanged or screwed, although liquid lines should preferably be welded or flanged. Copper pipework up to a maximum size of 12.5 mm (1/2 in) should only be used for vapour lines. All joints should be made using compression-type fittings designed to withstand four times the maximum pressure they will carry in service. Alternatively they may be silver soldered or brazed using material with a melting point of about 540 °C [4].

Flexible connections and hoses must be resistant to the action of LPG in accordance with the specification of the LPGITA (UK) [9]. Care should be taken to avoid undue stressing when installing flexible hoses. Where hoses are exposed to the possibility of mechanical damage or wear, they should be armoured; where they are likely to be subjected to high temperature, the advice of the manufacturer should be sought. All jointing compounds should be resistant to the action of LPG and should conform to the requirements of BS 5292 or an equivalent specification.

iii Valves and Fittings:

Valves should preferably be made from steel, forged steel, or brass which has been produced by extrusion or rolling. Cast iron valves should not be used. Ball valves are particularly suitable for liquids and retain their seal if involved in fire, ie they have 'fire-safe' characteristics. They should however conform to BS 5351 'Steel Ball-Valves for the Petroleum Industry'.

All steel flanges and flanged fittings used should conform to BS 1560 or equivalent standard. If fittings are 50 mm (2 in) diameter or above, the flanges should be welded, although screwed flanges may be allowed [4].

Steel butt welded fittings, steel socket welded and screwed fittings, and bolting should conform with BS 1965, BS 3799 and BS 4882 respectively or an equivalent specification.

iv LPG Pumps [4]:

Many LPG installations require liquid to be pumped between the storage vessel and the vaporiser. Pumps for this purpose must be suitable for pumping LPG which has no lubrication properties and a low viscosity. They must also be continuously rated and, if electrically-driven, require a flameproof motor. If compressed air is available, air operated reciprocating pumps are available which are very suitable for use in hazardous areas.

Liquid pumps should be provided with a means of pressure relief, discharging back to the storage vessel or to the pump inlet to protect the pump against overload. Pressure relieving devices fitted to pumps are often not designed to maintain a constant delivery pressure, but discharge when a pre-set differential pressure is reached. The inlet pressure at the pump will, however, vary with storage pressure which will in turn depend upon the ambient temperature, thus causing the relief pressure to vary. To maintain a constant outlet pressure, a separate pressure sustaining valve should be used.

Use should be made of adequate suction pipe siting and adequate static head to ensure that a satisfactory NPSH (ie nett positive suction head) is achieved under all conditions. Pumps should always be installed in accordance with manufacturer's instructions, taking special care that the piping places no strain on the pump casing.

Before any pipe run is tested, it must be blown through with nitrogen to purge oxygen from the system and to remove any remaining foreign matter which could foul the pressure regulator or cause trouble with the sealing of valves in the line . After installation, the pipework must be pressure tested to ensure that it is gas tight and free from leaks. A pressure gauge should be fitted in the line and pressure testing carried out with nitrogen gas to a maximum of 1.5 times the maximum operating pressure of 6.90 bars (100 lb_f/in^2 gauge) whichever is the greater. Joints must always be tested using detergent solution. All pressure testing on underground pipework should be carried out before the pipework is wrapped.

8.2 FIRE PREVENTION, PROTECTION AND CONTROL

Fire prevention and protection measures for process plants, storage tanks and other facilities need to be integrated during design to the degree necessary to prevent a fire occuring, to detect any fire which does occur, and to restrict its spread.

Within the U.K. the safety requirements for the storage and transport of LPG, both in bulk and in cylinders, in factories and other premises to which the Factories Act 1961 applies, is covered by the Highly Flammable Liquids and Liquefied Petroleum Gases Regulations, 1972. It is important that the requirements are not infringed by site modifications or any extensions to existing storage. The Codes of Practice published by The Liquefied petroleum Gas Industry Technical Association - U.K. (LPGITA) [8] should be consulted and their recommendations taken as the minimum standards applicable.

Generally, the design and engineering of LPG process plants requires [45, 8]:

a. The correct selection and use of materials and methods in the plant construction.

b. Establishment of correct process conditions (eg maximum and minimum temperatures and pressures).

c Incorporation of process control and safe guarding systems, eg protection against over pressure (safety relief valves), instrumentation providing automatic alarms and trips, systems for safe emergency disposal of excess hydrocarbon gases.

d. Attention to the layout and spacing of plant and facilities.

e. Correct choice of electrical equipment for use in hazardous areas by defining such areas in accordance with Area Classification Codes, eg in the U.K. - BS 5345 and IP Electrical Safety Code.

f. Detection of leakage, eg gas detection on LPG pump seals; or of fire, eg hot oil pumps, or of overheating, eg pump and motor bearings

g. provision of fire protection to load-bearing elements of steel structures.

h. Provision of adequate drainage facilities for the removal of fire-fighting water.

i. Provision of fire-fighting water systems, fire detection and alarm systems, fire-fighting fixed and mobile systems, etc.

To minimise the risk of fire, and its spread there are two major requirements for safe operation [45].

i. The development, and effective use, of comprehensive operating procedures and the training of all personnel in the various aspects of normal and emergency situations; and

ii. Ensuring that the installed systems continue to perform to the standards of safety specified by the designers.

With regard to (i), Permit-to-Work procedures are an essential part of such training and both operation and engineering personnel must be instructed with regard to the scope of their responsibilities and the authority levels for safe work. Personnel must be trained in the normal and abnormal conditions of operations and their procedures, and in emergency plans covering fire and explosion, spillage and gas escape.

With regard to (ii), to ensure continuity of safety standards, it is essential that inspection, tests and checks are carried out at regular intervals and that the engineering integrity of the systems is correctly maintained. The frequency of periodic inspections and tests will vary but agreed frequencies and procedures should be laid down as a written Code of Practice, eg an important instrument trip/alarm function may require a monthly check but others may be quarterly.

8.3 FIRE-FIGHTING SYSTEMS

As a matter of company policy, the design and engineering of fire fighting systems should meet national or local requirements. The requirements are based on the assumption that there will be only one major fire at a time. This does not exclude the possiblity of more than one major fire on any site simultaneously, since this has occurred infrequently in the past, but is a reasonable economic judgement.

8.3.1 Fire Fighting Water Systems

a. An open source is preferred for water for fire-fighting.

b. A ring main system should be provided which surrounds process plants, loading areas for road and rail, storage facilities, workshops, etc. The capacity of the ring main system must be large enough to provide for the largest single water demand.

c. Block valves should be provided in the ring main to enable isolation of parts in case of damage and for repair.

d. Permanent hydrants should be provided and must be readily accessible from the LPG plant roads.

e. The capacity of the ring main system must not be less than 720, m^3/hr (or 2600 gal./min). In practice LPG installations have been provided with capacities ranging up to 10,500 gal./min depending on their requirements for water quantities for making foam and for exposure protection of adjacent facilities and installations.

f. The water distribution system should be maintained liquid full and permanently pressurised to 3 bar by a small pressurising pump or by connection to the plant cooling water system [45, 8].

8.3.2 Pumps for Fire-fighting Water

At least two identical submerged pumps are required, one electrical motor-driven and one diesel-driven as a spare, taking suction from open water. These pumps must be capable of starting against an open discharge so the power drives must be rated accordingly. The pump drives should be provided with automatic starting devices. Manual start/stop should be provided from the control room or fire station and of course at the pumps. To maintain a system pressure of 10 bar at the furthest hydrant under full flow conditions, the pump discharge pressure could be 15 bar. A pressure indicator controller should be installed at the common discharge to enable adjustment to the pressure required when fire-fighting water is taken from close to the pump area. This makes it safe for personnel handling fire hoses [45].

8.3.3 Fixed Automatic Water Spray Systems for LPG Spheres and Horizontal Vessels

LPG pressure storage should be provided with fixed automatic water spray facilities to protect the sphere or horizontal vessel against radiation during a fire.

None-clogging type open sprinklers are to be fitted over the entire surface to ensure an even distribution of water rgardless of wind direction or wind force. The design criteria includes [45, 8, 80]

i Piping supports must not be welded to the vessel.

ii Heavy quality galvanised piping to BS 1387 is normally to be specified.

iii The water spray system on each vessel is to be divided into two separate sections; each section being opposite to an adjacent storage vessel.

iv The supply of water should be possible from two sides, preferably opposite each other. Strainers at the ring main shall be fitted between block valves.

v The block valves and strainers should be placed at least 30 m from the periphery of the vessel.

vi The system downstream of the valves shall slope upwards for self-draining via an 8 mm diameter hole near the valves.

vii The capacity of the water spray systems fitted to the LPG storage is to be 10 litre/min/m^2 of surface to be protected.

viii The automatic sprinkler systems must be installed over the pumps. Also, the sprinkler heads are to be located to give effective cover of the pump area and a surrounding area of 1.5 m width.

The automatic fire detector installed should consist of a plastic tube kept under instrument air pressure. In the event of a fire this plastic tubing will melt at approximately 90 °C causing the air pressure to fall, which will actuate an alarm in the control room and start the fire-water pump [45, 80].

8.4 SAFETY OF PERSONNEL

There are many hazards in LPG installations, especially when a fire or explosion occurs, and the following are rules which should be observed by safety officers and personnel in the interests of general safety [79].

a. Any crew of fire-fighting personnel stationed in a hazardous position should have an observer attached to it whose task is to warn the men when danger is imminent, and a prearranged signal for this purpose should be agreed upon. This observer should preferably be a safety officer whose technical knowledge is such that he will be intimate with the main dangers, and a fire brigade officer should act as a liaison officer.

b. Men should not work inside a bund wall if there is any leakage of LPG, or if the work can be done adequately from outside. When it is necessary to work within a bund, points of egress should be agreed upon.

c. Where necessary, men should be protected from radiated heat by improvised shields, and reliefs, ie relief of personnel, should be arranged at frequent intervals. This protection should be given even if the heat does not make it immediately necessary, as a change of wind may easily increase the heat.

d. Men should not be allowed on tank roofs unless absolutely necessary, and never on empty tanks which are on fire. If men have to go on to a tank roof (eg for a vent fire), they should take lines with them in case they are cut-off from the ladder.

e Breathing apparatus should be worn when necessary to protect against toxic or asphyxiating vapours or gases.

f Personnel should not be allowed to smoke. It may not be dangerous in the vicinity of the fire, yet highly so if the men move within the range of vapours elsewhere in the LPG installation.

g Personnel should not approach the fire or gas leak from upwind.

h All persons should be kept out of any vapour cloud area. Any area which is in the path of the vapour cloud should be evacuated immediately, eliminating all sources of ignition at the same time.

i All persons except those necessary to cope with the incident should be kept away from the human hazard range by policing the dangerous area.

8.5 PREVENTION OF, AND PROTECTION FROM, VAPOUR CLOUD EXPLOSIONS

If LPG is allowed to mix with air and form a concentration between 2%-10% in an enclosed space and is subsequently ignited it will burn and very probably give a pressure wave in front of the flame. In these incidents the pressure can rise up to about 100 psi and destroy vessels and buildings. This explosion risk is common to all fuel gases including LPG and is most likely to occur inside items of plant such as storage tanks etc [26]. The quantification of LPG vapour cloud explosions has been discussed in detail in Chapter 7.

8.5.1 Prevention

Prevention in this context means prevention of CVCE and UVCE, not necessarily prevention of a fireball, still less of escape of flammable material. Whilst the latter undoubtedly is the desirable objective, it is largely a matter of assiduous but ordinary operating and engineering competence [26].

Prevention of ignition may be possible. There are many instances on record [81] where ignition has not occured. But sources of ignition are legion and those cases of non-ignition of major clouds must be considered to have happened by chance rather than by design. Moreover, the emission itself my generate ignition sources, especially if it is forceful. Therefore, ignition at any escape of vapour must be considered likely. Experimental work [82, 83] suggests that conventional water sprays at best have no effect. The criteria for extinction are not as yet precisely quantified. Therefore, techniques of prevention by other means may be envisaged [26]. At the present time prevention can be achieved economically and with certainty only by assuring plant integrity and sound engineering and design, as described in Section 8.1.

8.5.2 Protection

Unconfined vapour cloud explosions may be predicted and their effects forecast by the methods described in detail in Chapter 7. At present they cannot be prevented. Given a major escape the probability is that ignition will occur rather more frequently than 14 times in every 15 incidents [81], and that blast will occur in rather more than half of those occasions.

Therefore, protection is desirable. Unfortunately, like many desirable objectives, it is not easy to achieve. Protection is two-fold, of the process workers and plant, and of the surrounding community and its buildings. Because most communities and industries are independent entities, despite their obvious dependence upon each other, their contiguous development can only be prevented by law. This can be the only socially certain method of community protection whatever view is taken of the real risks [26].

Buildings can be built to withstand blast. It is desirable, if these buildings are built and designed to accommodate personnel, that they also protect persons within them,. Therefore, all openings and glazed areas should be sealed and should be of no less strength to pressure than the structure itself. Also, self-contained atmospheres within buildings occupied by personnel would be essential to eliminate the possibility of invasion of these atmospheres by hot, and probably toxic, combustion products resulting from vapour cloud explosions.

There are no new concepts involved in protection within process plants. However, civil engineering will enable the design of structures for the process plant of any reasonable process size to withstand statically applied pressure. The pressure involved will be inversely related to the distance of the structures from the explosion centre. Therefore, a degree of compromise exists in most practical situations [26].

8.6 OTHER SAFETY PRECAUTIONS IN THE RUNNING OF LPG PLANT

8.6.1 Inspection of LPG Installations

The following stages of inspection of the installation should be applied [4, 14]:

a During Manufacture:

All vessels, process equipment, pipework etc must be inspected during maufacture, modification or repair by an approved inspection authority. Such inspection and testing should be in accordance with the Code to which the equipment, vessel or pipework is constructed.

b Before service:

All equipment, vessels, valves and accessory joints must be tested by a competent person for soundness at the maximum working pressure and a suitable record should be kept.

c Periodically [14]:

After being brought into service, all equipment, vessel and pipework shall be subjected to one of the following tests,at least every five years by an approved inspection authority:

- i A hydraulic pressure test
- ii Uninsulated equipment shall be fully-examined internally and externally, or
- iii Alternatively, all welds of the equipment, vessels and pipework may be subjected to an ultrasonic or a radiographic test.

Finally, a certificate should be issued, and kept on record, for each piece of equipment, vessel, etc, after each of the tests mentioned above.

8.6.2 Maintenance

The aim of maintenance is to ensure that an LPG installation is always in good working order and will not give unpleasant surprises.

Surprises that are most likely to upset safety. Therefore, in addition to a rigidly-applied Permit-to-Work system, the following points should be taken into consideration in the maintenance of any LPG plant [9, 84].

i Setting up system for sufficient stock of spare parts with maximum and minimum stock figures, and keeping the stock up to date.

ii Keeping the plant clean and tidy with no unnecessary obstructions upsetting the work, free access to emergency exits and free access to all operations. It is very difficult to maintain a high degree of safety when things are in a mess.

iii Keeping all guarding in place, it might be necessary during maintenance to erect fencing around certain equipment or parts of installations.

iv Coloured paint on the floor and walls can be used to give information to the staff about risks when they cross the painted line on the floor, such as when there is danger to the eyes or the need to use face masks.

v During maintenance, staff should always use work gloves, helmets and safety footwear when these make work safer. Synthetic fibres can create static electricity, therfore, these fibres should be avoided in clothing.

vi Finally, maintenance should be carried out at frequent intervals on all installations including vehicles, pipework, hoses and ancilliary equipment [9].

8.6.3 Training of Staff

The training of staff must be regarded as most vital. Many managers consider, quite wrongly that anybody is capable of running an LPG plant. Good workers are absolutely necessary for sound performance of the various operations involved in an LPG plant and maintenance or repair requires a really expert technician. Such qualities as care and intelligence are imperative for anybody who handles LPG, or is present within the hazardous area.

One must educate and train the staff, not merely by teaching them how to operate the equipment and how to carry out various operations, but by providing a thorough understanding of the nature of LPG. This should cover how LPG 'reacts' under various conditions and how they themselves should react under certain circumstances. Also the staff should be made completely familiar with the safety regulations.

Many accidents at LPG plants are caused not only by carelessness or non-observance of the precautionary measures, but primarily because of insufficient knowledge of the product handled, lack of education or training in the performance of the actual operations, or ignorance and insufficient understanding of the safety regulations. Such accidents are absolutely unnecessary and it should be emphasised that an LPG plant is not a risky or dangerous place of work provided the regulations are observed. The safety level at any LPG plant is directly proportional to the staff's knowledge of the product, and their training in running of LPG plant [84].

A brief survey of the practical subjects that should be included in the training of operational staff beyond the information about the nature of LPG and the ways it reacts, and the training in understanding and observing the safety regulations follows [84]:

i Daily start-up

ii Knowledge of the installation and function of the machinery iii General, practical maintenance and service.

iv Trouble-shooting and repair.

v Knowledge of spare parts and their specifications

vi Knowledge of the instruction manual for the plant.

Such a training course should be held in the LPG plant and should be a practical and thorough instruction in the use of all machinery and equipment in order to make sure that the staff will really familiarise themselves with the equipment and the operations they have to perform.

Finally, the drivers of LPG vehicles should be mature with a high sense of responsibility. They must be able to work correctly without supervision and must possess the ability to evaluate emergency situations and to reach sensible decisions. Also, the driver of a vehicle conveying LPG and any other person engaged in conveyance should be trained in the properties of LPG and the handling methods applicable to the grades being carried, in the use of the fire extinguishing equipment carried on the vehicle, and in the emergency procedure to be followed.

8.6.4 Emergency Planning

Emergency planning with LPG incidents should include the following:

i Teaching:

The emergency procedures should be comprehensively covered in the classroom by both civilian tutor and Fire Service instructor. These procedures are to be then put to the test in two practical ways. Firstly, a tactical exercise should be staged using a floor map where the staff discuss the problems and the subsequent tactics they will adopt for a carefully planned situation. Secondly, a major exercise is staged on site which may involve a tank fire or LPG spillage. The objects of these exercises include confirmation for the staff that the previous instruction has been correctly assimilated; the checking of the command and control capabilities of staff nominated to be safety officers in charge of the exercise, and to give all staff the necessary confidence in themselves and their equipment to deal with a potentially hazardous situation [85].

ii Pre-planning:

While it is not possible to conduct operations according to a precise set of rules it is essential that proper emergency pre-planning is carried out. The success of operations at any incident will largely depend upon the adequacies of pre-planning and training directly related to each of the situations likely to be encountered. These pre-planning operations may include the police, ambulance and local authority departments [85].

iii Water Supplies:

To protect an LPG vessel from fire it is necessary to apply sufficient cooling water. The Technical Bulletin [45] recommends a minimum rate of 0.1 min/m^2. Because of difficulties in obtaining uniform complete coverage of tank services with water, much higher rates of application will often be required in practice.

It must be remembered that peak requirements in terms of water will necessarily occur at the earlier stage of emergency operations and may need to be sustained for a prolonged period. Pre-planning must therefore include consideration as to the availability of adequate water supplies and to ensure they do not fail during such operations [85, 86].

iv Communications and Emergency Control Centre:

The ideal method is a detection sytem which gives an alarm and possibly activates a suppression system. This may not always be practicable on a large open site. Therefore, some combination of break-glass alarms, telephones connected to a multi-line emergency panel, and pocket radios is required [85].

In order to cope with any major incident, provision should be made for a permanent Control and Communication Centre near a main entrance and remote from any operating area [88]. Its function is to receive information and to transmit it to the centres and services concerned, eg Works and City Fire Services, Police, Work Security, other plants on the site, Medical Authorities, etc. The control centre should obviously be provided with detailed site and plant layouts, drawings and a 'call out' list of essential personnel for expert technical assistance for each plant or area. There should also be spare telephones and pocket radios for incident control and an information room to cope with press and radio [87].

Finally, as in any emergency situation, it is of paramount importance to avoid endangering human life in the event of fire involving or seriously exposing LPG equipment, or serious leakage of LPG without a fire. Also, the evacuation of people around the hazardous area should be pre-planned as an emergency evacuation plan.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

9.1.1 Main Conclusions

The main conclusions arising from this work are:

1. Numerous accidents have occurred at LPG Installations leading to a fireball, blast wave or pool fire. These incidents have involved the release of the contents from bulk storage vessels, or rail and road tankers; a list of such incidents is shown in Table 6.1. the three main hazards associated with major LPG releases are:

   i A Major Fire, including a pool fire

   ii An Unconfined Vapour Cloud Explosion (UVCE), or,

   iii A Boiling Liquid Expanding Vapour Explosion (BLEVE)

2. In any evaluation of thermal radiation hazards resulting from fireballs, there are five primary parameters which should be considered:

   i mass of fuel released

   ii fireball equivalent spherical diameter

   iii duration time

   iv fireball height

   v fireball surface temperature

3. New correlations for thermal radiation damage criteria have been

proposed to fit the data of Stoll and Green [63], which include the exposure of a human forearm to different radiation intensities, using a least square curve fitting technique, as shown in Appendix C, to give three relationships which enables the thermal radiation intensity on human skin to be related to the time of exposure as:

Pain Threshold $q = 28.2\ (t)^{-0.73}$
Threshold Blister $q = 60.5\ (t)^{-0.75}$
Full Blister $q = 61.8\ (t)^{-0.73}$

Furthermore the data from their work which represent tissue damage for the threshold and full blister have been correlated using the same technique to give two relationships between the damage to tissue and the thermal radiation incident on human skin as:

Threshold Blister $Z = 2.61\ (q)^{1.09}$
Full Blister $Z = 3.65\ (q)^{1.31}$

The results predicted from the above correlations exhibited a maximum error of 8% from the Stoll and Green experimental data.

4. Using an isothermal model for different authors' parameters shows that both Roberts' and Marshall's correlations fit the model, giving values very close to those recommended by them in Table 6.3. Also, it appears that Roberts' and Marshall's

parameters give values of the rate of growth of fireball diameter close to that achieved by an isothermal model and prove that only these parameters fit an isothermal model.

5. The comparison between the values of BLEVE fireball diameter obtained by applying various authors' correlations mentioned in Table 6.7 and the value of fireball diameter obtained from real incidents shows that Crowley's correlation gives a close fit of fireball diameter as shown in Table 6.8 to those observed from real BLEVE incidents mentioned in Section 6.6.

6. Whilst it is not possible to deduce from the pool fire thermal radiation calculation procedure the validity of the results obtained, comparison of the results with those published in the literature showed good agreement. However, many factors involved in the pool fire remain unpredictable. It is possible using the method proposed for pool fires in this study as described in Section 6.10 to predict the spacing distance for different values of L/D and mass of flammable material involved for humans, buildings and process equipment. The water rate obtained by the proposed method is consistent with a government guideline and is useful when designing the layout of plant and to keep people away from hazardous areas.

7. The TNT equivalent model including Jarrett's equation and Hopkinson's law, Gugan's and Clancey's models have been used to predict the spacing distance at which characteristic values of overpressure are probable from a UVCE. As many

factors involved in the UVCE remain unpredictable, the explosion yield factor is taken at a more conservative value than previously, ie 10%.

None of the four methods of prediction for the spacing distance used is more or less credible than the others using experience from real incidents. Therefore, in general, it is concluded that maximum figures are to be preferred for conservative estimates for use in site layout, emergency planning, etc.

8. The blast wave results demonstrate that the Clancey model generally provides the biggest spacing distances and Jarrett's equation usually gives the shortest spacing distance. Also, these results show that, as expected, the spacing distance increases with increasing yield factor.

9. Quantification methods, which are recommended in this study, are a vital part of the process of assessment of LPG hazards and risks. These techniques have been discussed in detail in Chapter 6 and 7. The possibility of an LPG major fire and explosion occurrence can be minimised by sound engineering in plant design and layout, good operating practice, proper fire-fighting systems including spray water, proper inspection methods of LPG installations, good maintenance and proper training of personnel in both routine operations and on actions to be taken in an emergency as described in detail in Chapter 8.

10. The safety recommendations and restrictions outlined in detail in Chapter 8 may often have considerable economic consequences.

This economic obstacle should generally be put aside in favour of public safety. Certainly the best solution is always the attainment of a high degree of safety without any significant economic loss from spacing, by optimising the process and reducing the risk as much as possible.

9.1.2 Minor Conclusions

In addition the following minor conclusions arose:

1. Correlations which were used to predict fireball diameter and duration: it is interesting to note that the average of all exponents is $1/3$ (ie the value of a and b in equations 6.1 and 6.2). It is recommended that Robert's parameters (A, B) be used to evaluate the fireball diameter and duration because maximum figures, which Robert's correlations provided, are to be preferred.

2. The fireball diameter, duration, height and hazard ranges for humans, buildings and process equipment increase in proportion to the increase of the flammable quantity of fuel.

3. The results of blast waves are presented in terms of spacing distance related to the flammable quantity released and to several characteristic values of overpressure which correspond to different levels of damage effect, as shown in Table 5.2. Also these results show that predicted spacing distances according to TNT equivalent methods, Gugan and Clancey have gross deviations due to several assumptions and empirical equations which may affect their accuracy.

4. In the case of fireballs resulting from UVCE, the hazard ranges based on fireball surface temperature predicted using the thermodynamic equation gives a slightly smaller hazard range than the results based on temperature predicted using isothermal equation. However, the difference between isothermal and thermodynamic temperature results are not significant and can be neglected in large scale fireballs resulting from UVCE. Either method could be used to predict the theoretical surface temperature of a fireball.

   But in the case of a fireball resulting from a BLEVE, the hazard ranges based on temperature obtained from the thermodynamic equation have large deviations compared with the hazard ranges predicted by using the temperature obtained from the BLEVE equation.

5. No precise method can be proposed for full hazard assessment. Each method has its advantages and disadvantages depending on the assumptions and experimental observations. Therefore, the choice of a quantified method depends entirely on the purpose, urgency and accuracy of results and no method can fully identify all the hazards in LPG plants, such as human error which is a major source of risk.

6. Fireball diameter increases linearly with the duration of combustion both in the isothermal and BLEVE models, and that is because it has been assumed that the equivalent spherical diameter of fireball increases at constant rate throughout

combustion.

9.2 RECOMMENDATIONS FOR FURTHER WORK

As a continuation of this work, the following areas appear worth studying:

1. The shape of the fireball changes continuously during its rise. At ignition, it is hemispherical, then spherical and after lift-off takes several shapes, eg oblate, spheroidal or mushroom. Therefore models could be derived which take account of the change in shape as a function of time.

2. All the present models and correlations for UVCE and BLEVE effects are based upon small-scale experimental work. Therefore, the accuracy and the validity of this work upon scale-up by a factor of several thousands remains unproven. Large scale experiments would therefore be desirable in order to approach more closely the size of real incidents.

   For BLEVE experiments as a first attempt, masses of approximately 1 tonne are recommended. These BLEVE'S could be engineered using explosively-ruptured tanks (as at SMRE) or using large piston releases at atmospheric pressure. The amount required to generate a realistic >5 tonnes UVCE may be impracticable on economic and environmental grounds. However, release of a premixed vapour air mixture could be engineered using plastic balloons.

3. The quantification and assessment of hazards by mathematical

models described in Chapters 6 and 7, shows that prediction of safe and socially acceptable spacing distances require further study. Social and economic aspects should be considered by optimising the process and reducing the risk to the public and the environment as far as possible because these aspects cannot be determined with any precision with the present level of knowledge.

4. Further investigations and studies are required to cover many factors involved in a vapour cloud explosion, the effects of which are still difficult to predict (eg wind velocity and direction, weather conditions, degree of confinement, spill rate and operator response).

5. Further experimental and theoretical studies are recommended to reduce the lack of accuracy of many factors affecting the thermal radiation hazard ranges related to fireballs or pool fires (eg fraction of fuel cracked to produce soot, air relative humidity, wind speed and direction, and local topography).

APPENDIX A

Computer program for evaluation of initial reduced overpressure ($\overline{P}_{so}$)

```
C
C
C     EVALUATION OF INITIAL REDUCED OVERPRESSURE (PSO):
C     *************************************************
C
C
C
      DIMENSION PSO(500),PSNC(10),DIFF(500),RS(500),FS(500)
       PRINT 15
  15  FORMAT(//10X,'INITIAL REDUCED OVERPRESSURE (PSO) ',
     @'RESULTS:',/10X,43('*')/)
         READ *,N
        READ *,(PSNC(II),II=1,N)
C
        DO 3 K=1,N
C
C
        PRINT 40,K,PSNC(K)
  40  FORMAT(/10X,'ESTIMATED STORAGE PRESSURE (',I1,')=',F8.1,
     @/10X,26('-')/)
       I=1
       PSO(I)=1.0
  10   RS(I)=(1.0+PSNC(K))*((1.0-((0.2*1.08*PSO(I))/((2.8*(2.8+2.4
     @*PSO(I)))**0.5)))**12.0)
C
      FS(I)=1.0+PSO(I)
      DIFF(I)=FS(I)-RS(I)
       IF (ABS(DIFF(I)).GT.0.3) THEN
     PSO(I+1)=PSO(I)+0.2
      I=I+1
       GO TO 10
         ELSE
C
     PRINT 300,I,DIFF(I)
  300 FORMAT(10X,'DIFFERENCE(',I2,')=',F8.4/)
C
C
     PRINT 400,I,PSO(I)
 400 FORMAT(10X,'THE VALUE OF PSO(',I2,')=',F8.1/)
C
C
       ENDIF
C
  3         CONTINUE
C
         STOP
C
            END
```

```
INITIAL REDUCED OVERPRESSURE (PSO) RESULTS:
*****************************************


ESTIMATED STORAGE PRESSURE (1)=    16.0
--------------------------

DIFFERENCE(10)= -0.0119

THE VALUE OF PSO(10)=     2.8

ESTIMATED STORAGE PRESSURE (2)=    20.0
--------------------------

DIFFERENCE(12)=  0.1185

THE VALUE OF PSO(12)=     3.2

ESTIMATED STORAGE PRESSURE (3)=    23.0
--------------------------

DIFFERENCE(13)=  0.0447

THE VALUE OF PSO(13)=     3.4

ESTIMATED STORAGE PRESSURE (4)=    25.0
--------------------------

DIFFERENCE(14)=  0.1870

THE VALUE OF PSO(14)=     3.6
```

APPENDIX B

Computer program for evaluation of fireball duration and diameter using different authors' parameters

```
C
C
C PROGRAM FOR EVALUATION OF FIREBALL DURATION AND DIAMETER
C ========================================================
C USING GAYLE,BRASIE,MARSHALL,ROBERT,HARDEE,AND FAY EQUATIONS:
C ============================================================
C
C
C
      DIMENSION W(30),DG(30),DB(30),DM(30),DR(30),DH(30),DF(30),
     @TG(30),TB(30),TM(30),TR(30),TH(30),TF(30)
C
C
      PRINT 21
 21   FORMAT(/10X,'FIREBALL DURATION & DIAMETER RESULTS:',/
     @10X,37('*')//)
C
C
      READ *,N
      READ *,(W(II),II=1,N)
C
C
      DO 3 I=1,N
      TG(I)=0.245*(W(I)**0.356)
      TB(I)=0.300*(W(I)**0.333)
      TM(I)=0.380*(W(I)**0.333)
      TR(I)=0.450*(W(I)**0.333)
      TH(I)=2.570*(W(I)**0.166)
      TF(I)=2.530*(W(I)**0.166)
C
C
      DG(I)=3.680*(W(I)**0.326)
      DB(I)=3.800*(W(I)**0.333)
      DM(I)=5.500*(W(I)**0.333)
      DR(I)=5.800*(W(I)**0.333)
      DH(I)=6.360*(W(I)**0.325)
      DF(I)=6.280*(W(I)**0.333)
C
  3        CONTINUE
C
C
      PRINT 100
 100  FORMAT(10X,'FIREBALL DURATION (SECONDS):',/,10X,25('-')//)
C
      PRINT 200
 200  FORMAT(8X,' MASS   GAYLE  BRASIE MARSH ROBERT  HARDEE  FAY',/
     @5X,50('-'))
C
      DO 5 J=1,N
      PRINT 300,W(J),TG(J),TB(J),TM(J),TR(J),TH(J),TF(J)
 300  FORMAT(5X,F9.1,6(F6.1,1X))
C
 5     CONTINUE
C
```

```
C
      PRINT 400
  400 FORMAT(///10X,'FIREBALL DIAMETER (METERS):',/10X,27('-')//)
C
      PRINT 500
  500 FORMAT(8X,' MASS   GAYLE BRASIE  MARSH ROBERT HARDEE  FAY',/
     @5X,50('-'))
C
      DO 10 M=1,N
      PRINT 600,W(M),DG(M),DB(M),DM(M),DR(M),DH(M),DF(M)
  600 FORMAT(5X,F9.1,6(F6.1,1X))
C
   10    CONTINUE
C
      STOP
      END
```

```
FIREBALL DURATION & DIAMETER RESULTS:
*************************************


FIREBALL DURATION (SECONDS):
--------------------------


   MASS    GAYLE  BRASIE MARSH ROBERT  HARDEE  FAY
--------------------------------------------------
      0.1   0.1    0.1    0.2    0.2    1.8    1.7
      1.0   0.2    0.3    0.4    0.5    2.6    2.5
      5.0   0.4    0.5    0.6    0.8    3.4    3.3
     10.0   0.6    0.6    0.8    1.0    3.8    3.7
     25.0   0.8    0.9    1.1    1.3    4.4    4.3
     50.0   1.0    1.1    1.4    1.7    4.9    4.8
     75.0   1.1    1.3    1.6    1.9    5.3    5.2
    100.0   1.3    1.4    1.8    2.1    5.5    5.4
    250.0   1.7    1.9    2.4    2.8    6.4    6.3
    500.0   2.2    2.4    3.0    3.6    7.2    7.1
    750.0   2.6    2.7    3.4    4.1    7.7    7.6
   1000.0   2.9    3.0    3.8    4.5    8.1    8.0
   5000.0   5.1    5.1    6.5    7.7   10.6   10.4
  10000.0   6.5    6.4    8.2    9.7   11.9   11.7
  25000.0   9.0    8.7   11.1   13.1   13.8   13.6
  50000.0  11.5   11.0   13.9   16.5   15.5   15.2
  75000.0  13.3   12.6   16.0   18.9   16.6   16.3
 100000.0  14.8   13.9   17.6   20.8   17.4   17.1
 250000.0  20.5   18.8   23.8   28.2   20.2   19.9
 500000.0  26.2   23.7   30.0   35.6   22.7   22.3
 750000.0  30.2   27.1   34.4   40.7   24.3   23.9
1000000.0  33.5   29.9   37.8   44.8   25.5   25.1


FIREBALL DIAMETER (METERS):
---------------------------


   MASS   GAYLE BRASIE  MARSH ROBERT HARDEE   FAY
--------------------------------------------------
      0.1   1.7    1.8    2.6    2.7    3.0    2.9
      1.0   3.7    3.8    5.5    5.8    6.4    6.3
      5.0   6.2    6.5    9.4    9.9   10.7   10.7
     10.0   7.8    8.2   11.8   12.5   13.4   13.5
     25.0  10.5   11.1   16.1   16.9   18.1   18.3
     50.0  13.2   14.0   20.2   21.3   22.7   23.1
     75.0  15.0   16.0   23.2   24.4   25.9   26.4
    100.0  16.5   17.6   25.5   26.9   28.4   29.1
    250.0  22.3   23.9   34.6   36.5   38.3   39.5
    500.0  27.9   30.1   43.6   45.9   47.9   49.7
    750.0  31.9   34.4   49.9   52.6   54.7   56.9
   1000.0  35.0   37.9   54.9   57.9   60.0   62.7
```

5000.0	59.1	64.8	93.8	98.9	101.3	107.1
10000.0	74.1	81.6	118.1	124.6	126.9	134.9
25000.0	99.9	110.7	160.3	169.0	170.9	183.0
50000.0	125.2	139.5	201.9	212.9	214.1	230.5
75000.0	142.9	159.7	231.1	243.7	244.3	263.8
100000.0	157.0	175.7	254.3	268.2	268.2	290.4
250000.0	211.6	238.4	345.0	363.9	361.2	394.0
500000.0	265.3	300.3	434.6	458.3	452.5	496.3
750000.0	302.8	343.7	497.5	524.6	516.2	568.0
1000000.0	332.5	378.3	547.5	577.3	566.8	625.1

APPENDIX C

Regression Analysis Computer Program

```
C
C PROGRAM FOR MULTIPLE LINEAR REGRASSION ANALYSIS:
C ================================================
C
C
C
C     MAIN PROGRAM
C     ------------
C
C
      DIMENSION X(16,2),Y(16),A(4),B(2),XBAR(2),YHAT(16),
     @AA(2,2),T(16),F21(16)
C
C
      READ *,NB,NX,M
C
        NN=NB*NB
       IF(NB.LE.0) THEN
        GO TO 555
          ELSE
          READ *,(F21(KK),KK=1,M)
C
       DO 1 K=1,M
C
C
          X(K,1)=ALOG(F21(K))
C
C
  1         CONTINUE
C
C
        READ *,(T(JJ),JJ=1,M)
C
           DO 3 I=1,M
           Y(I)=ALOG(T(I))
  3        CONTINUE
C
C
       CALL LESQ(X,Y,NB,M,A,B,XBAR,YHAT,AA,NN)
 555         STOP
               ENDIF
             END
C
C
C
C
      SUBROUTINE LESQ(X,Y,N,M,A,B,XBAR,YHAT,AA,N2)
C
      DIMENSION X(M,N),Y(M),A(N2),B(N),XBAR(N),YHAT(M),AA(N,N)
C
C
         PRINT 101
 101    FORMAT(10X,'MULTIPLE LINEAR REGRESSION ANALYSIS',/10X,40('-')//)
C
```

```
C CALCULAT AVERAGE X AND Y VALUES
C
C
        DO 8 I=1,N
         SUMX=0.0
        DO 13 J=1,M
  13     SUMX=SUMX+X(J,I)
  8      XBAR(I)=SUMX/FLOAT(M)
          SUMY=0.0
         DO 15 K=1,M
  15      SUMY=SUMY+Y(K)
         YBAR=SUMY/FLOAT(M)
       PRINT 180
 180   FORMAT(//,6X,'VARIABLE AVERAGE VALUES',/,6X,23('-')/)
       PRINT 240,(II,XBAR(II),II=1,N)
 240   FORMAT(6(6X,'XBAR(',I2,')=',1PE14.7)/)
        PRINT 260,YBAR
 260   FORMAT(6X,'YBAR=',1PE14.7,/)
C
C
C   CALCULATE REGRESSION MATRICES
C   ==============================
C
C
      KK=1
      DO 25 I=1,N
      DO 25 J=1,N
      SUMA=0.0
      SUMB=0.0
       DO 30 K=1,M
      SUMA=SUMA+(X(K,I)-XBAR(I))*(X(K,J)-XBAR(J))
 30    SUMB=SUMB+(Y(K)-YBAR)*(X(K,I)-XBAR(I))
      AA(I,J)=SUMA
      A(KK)=SUMA
        KK=KK+1
 25   B(I)=SUMB
      PRINT 310
 310  FORMAT(//,10X,' A MATRIX',/,10X,9('-')/)
       DO 55 II=1,N
  55   PRINT 360,(AA(II,JJ),JJ=1,N)
 360   FORMAT(/,50(2X,E10.4))
       PRINT 410
 410   FORMAT(//,6X,'B MATRIX',/,6X,9('-'))
       PRINT 440,(B(KK),KK=1,N)
 440   FORMAT(/,50(2X,E10.4))
C
C
C  SOLVE REGRESSION MATRICES FOR COEFFICIENTS
C  ==========================================
C
C
      CALL STMG(A,B,N,KS,N2)
       SUMX=0.0
       DO 60 I=1,N
```

```
 60    SUMX=SUMX+B(I)*XBAR(I)
       AZERO=YBAR-SUMX
        PRINT 460
 460    FORMAT(//10X,'VALUES OF THE REGRESSION COEFFICIENTS',/,
      @10X,40('-')/)
       PRINT 470,(JJ,B(JJ),JJ=1,N)
 470   FORMAT(5(6X,'AHAT(',I2,')=',1PE16.8,/))
        PRINT 480,AZERO
 480    FORMAT(6X,' AZERO=',1PE16.8,/)
C
          AHATO=EXP(AZERO)
         PRINT 490,AHATO
 490    FORMAT(6X,' AHAT(0)=',1PE16.8,/)
C
C
C
C     CALCULATE S AND R VALUES
C ==============================
C

C
       STEST=0.0
       DO 80 J=1,M
       SUMS1=0.0
       DO 90 K=1,N
  90    SUMS1=SUMS1+B(K)*X(J,K)
       YHAT(J)=AZERO+SUMS1
       DIFF=(Y(J)-YHAT(J))**2
  80   STEST=STEST+DIFF
       SUMST=0.0
       DO 92 I=1,M
  92   SUMST=SUMST+(Y(I)-YBAR)**2
       SUMSR=SUMST-STEST
       RTEST=SUMSR/SUMST
        PRINT 520
 520   FORMAT(////,6X,'EXPERIMENTAL VALUES',11X,'REGRESSION VALUES',
      @/,6X,50('-'))
C
C
       DO 115 KK=1,M
 115   PRINT 555,KK,Y(KK),KK,YHAT(KK)
 555   FORMAT(/7X,'Y(',I2,')=',1PE16.6,12X,'YHAT(',I2,')=',1PE16.6)
C
        PRINT 560,SUMST,STEST,RTEST
 560    FORMAT(///,6X,'SUMST=',1PE16.8,/,6X,'STEST=',1PE16.6,/,
      @6X,'RTEST=',1PE16.6,/)
C
         RETURN
         END
C
C
C
C
      SUBROUTINE STMG(A,B,N,KS,NS)
```

```
       DIMENSION A(NS),B(N)
       TOL=0.0
       KS=0
       JJ=-N
       DO 65 J=1,N
       JY=J+1
       JJ=JJ+N+1
       BIGA=0.0
        II=JJ-J
      DO 33 I=J,N
C
C
C   SEARCH FOR MAXIMUM COEFFICIENT IN COLUMN:
C   ==========================================
C
      IJ=II+1
      IF((ABS(BIGA)-ABS(A(IJ))).GE.0.0) THEN
       GO TO 33
        ELSE
       BIGA=A(IJ)
       IMAX=I
            ENDIF
  33    CONTINUE
C
C  TEST FOR PIVOT LESS THAN TOLERANC
C
       IF((ABS(BIGA)-TOL).GT.0.0) THEN
        GO TO 40
         ELSE
       KS=1
       RETURN
C
C   INTERCHANE ROWS IF NECEEARY
C   ===========================
C
  40   I1=J+N*(J-2)
          ENDIF
      II=IMAX-J
       DO 51 K=J,N
      I1=I1+N
      I2=I1+II
      SAVE=A(I1)
      A(I1)=A(I2)
      A(I2)=SAVE
C
C    DIVIDE EQUATION BY LEADING COEFFICIENT
C
 51    A(I1)=A(I1)/BIGA
      SAVE=B(IMAX)
      B(IMAX)=B(J)
      B(J)=SAVE/BIGA
C
C    ELIMINATE NEXT VARIABLE
C
```

```
         IF((J-N).EQ.0) THEN
       GO TO 70
        ELSE
       IQS=N*(J-1)
          ENDIF
       DO 65 IX=JY,N

       IXJ=IQS+IX
       II=J-IX
       DO 61 JX=JY,N
       IXJX=N*(JX-1)+IX
       JJX=IXJX+II
 61    A(IXJX)=A(IXJX)-(A(IXJ)*A(JJX))
       B(IX)=B(IX)-(B(J)*A(IXJ))
 65          CONTINUE
C
C
C     BACK SOLUTION
C
  70   NY=N-1
       II=N*N
        DO 81 J=1,NY
        IA=II-J
        IB=N-J
        IC=N
       DO 81 K=1,J
        B(IB)=B(IB)-A(IA)*B(IC)
        IA=IA-N
  81     IC=IC-1
         RETURN
          END
```

```
        MULTIPLE LINEAR REGRESSION ANALYSIS
        -----------------------------------


           (FOR HUMAN PAIN)
           ================

    VARIABLE AVERAGE VALUES
    -----------------------

    XBAR( 1)= 1.6177132E+00        XBAR( 2)= 0.0000000E+00        XBAR(
    YBAR= 2.1478679E+00


         A MATRIX
        ----------

0.2184E+01  0.0000E+01

0.0000E+01  0.0000E+01

    B MATRIX
    ----------

-.1607E+01  0.0000E+01


        VALUES OF THE REGRESSION COEFFICIENTS
        -------------------------------------

    AHAT( 1)= -7.35716443E-01
    AHAT( 2)=  0.00000000E+00
    AHAT(
     AZERO=  3.33804613E+00

     AHAT(0)=  2.81640445E+01



    EXPERIMENTAL VALUES              REGRESSION VALUES
    -------------------------------------------------

     Y( 1)=     2.817204E+00             YHAT( 1)=     2.757965E+00

     Y( 2)=     2.529721E+00             YHAT( 2)=     2.635061E+00

     Y( 3)=     2.124415E+00             YHAT( 3)=     2.070578E+00
```

```
 Y( 4)=     1.836733E+00                YHAT( 4)=     1.790000E+00

 Y( 5)=     1.431268E+00                YHAT( 5)=     1.485735E+00


SUMST=  1.20469258E+00
STEST=     2.265476E-02
RTEST=     9.811946E-01
```

```
        MULTIPLE LINEAR REGRESSION ANALYSIS
        -------------------------------------------

          (FOR HUMAN THRESHOLD BLISTER)
          ===============================

      VARIABLE AVERAGE VALUES
      ------------------------

      XBAR( 1)= 2.5855118E+00        XBAR( 2)= 0.0000000E+00        XBAR(
      YBAR= 2.1478679E+00


        A MATRIX
        ----------

    0.2103E+01  0.0000E+01

    0.0000E+01  0.0000E+01

      B MATRIX
      ----------

    -.1590E+01  0.0000E+01

        VALUES OF THE REGRESSION COEFFICIENTS
        -------------------------------------------

      AHAT( 1)= -7.56293498E-01
      AHAT( 2)=  0.00000000E+00
      AHAT(
       AZERO=  4.10327367E+00

       AHAT(0)=  6.05381519E+01



      EXPERIMENTAL VALUES              REGRESSION VALUES
      -------------------------------------------------------

       Y( 1)=     2.817204E+00              YHAT( 1)=     2.800356E+00

       Y( 2)=     2.529721E+00              YHAT( 2)=     2.549753E+00

       Y( 3)=     2.124415E+00              YHAT( 3)=     2.140499E+00
```

```
Y( 4)=     1.836733E+00              YHAT( 4)=     1.807958E+00

Y( 5)=     1.431268E+00              YHAT( 5)=     1.440772E+00


SUMST=  1.20469258E+00
STEST=     1.862134E-03
RTEST=     9.984543E-01
```

```
        MULTIPLE LINEAR REGRESSION ANALYSIS
        -----------------------------------


             (FOR HUMAN FULL BLISTER)
             ========================


    VARIABLE AVERAGE VALUES
    -----------------------

    XBAR( 1)= 2.9875514E+00        XBAR( 2)= 0.0000000E+00        XBAR(
    YBAR= 1.9325737E+00


         A MATRIX
         --------


0.1137E+01  0.0000E+01

0.0000E+01  0.0000E+01

    B MATRIX
    --------

-.8341E+00  0.0000E+01

        VALUES OF THE REGRESSION COEFFICIENTS
        -------------------------------------

    AHAT( 1)= -7.33791171E-01
    AHAT( 2)=  0.00000000E+00
    AHAT(
     AZERO=  4.12481256E+00

     AHAT(0)=  6.18562200E+01



    EXPERIMENTAL VALUES               REGRESSION VALUES
    ------------------------------------------------------

     Y( 1)=    2.529721E+00           YHAT( 1)=    2.545868E+00

     Y( 2)=    1.836733E+00           YHAT( 2)=    1.780656E+00

     Y( 3)=    1.431268E+00           YHAT( 3)=    1.471197E+00
```

```
SUMST=  6.17077655E-01
STEST=    4.999757E-03
RTEST=    9.918977E-01
```

```
        MULTIPLE LINEAR REGRESSION ANALYSIS
        -----------------------------------


          (HUMAN TISSUE DAMAGE FOR THE THRESHOLD BLISTER)
          ===============================================


     VARIABLE AVERAGE VALUES
     -----------------------

     XBAR( 1)= 2.1537312E+00        XBAR( 2)= 0.0000000E+00        XBAR(
     YBAR= 3.3139853E+00


        A MATRIX
       ---------

 0.1204E+01   0.0000E+01

 0.0000E+01   0.0000E+01

     B MATRIX
     ---------

 0.1316E+01   0.0000E+01


        VALUES OF THE REGRESSION COEFFICIENTS
        -------------------------------------

     AHAT( 1)=   1.09334027E+00
     AHAT( 2)=   0.00000000E+00
     AHAT(
      AZERO=   9.59224212E-01

      AHAT(0)=   2.60967137E+00



     EXPERIMENTAL VALUES            REGRESSION VALUES
     -------------------------------------------------

      Y( 1)=      2.708050E+00          YHAT( 1)=     2.524087E+00

      Y( 2)=      2.833213E+00          YHAT( 2)=     2.967398E+00

      Y( 3)=      3.295837E+00          YHAT( 3)=     3.725070E+00
```

```
  Y( 4)=     4.418841E+00                      YHAT( 4)=     4.039386E+00


 SUMST=  1.81933363E+00
 STEST=     3.800745E-01
 RTEST=     7.910914E-01
```

```
        MULTIPLE LINEAR REGRESSION ANALYSIS
        -----------------------------------


          (HUMAN TISSUE DAMAGE FOR THE FULL BLISTER)
          ==========================================


      VARIABLE AVERAGE VALUES
      -----------------------

      XBAR( 1)= 1.9325737E+00       XBAR( 2)= 0.0000000E+00       XBAR(
      YBAR= 3.8318586E+00


          A MATRIX
        ----------


  0.6171E+00  0.0000E+01

  0.0000E+01  0.0000E+01

      B MATRIX
      --------

  0.8096E+00  0.0000E+01


        VALUES OF THE REGRESSION COEFFICIENTS
        -------------------------------------

      AHAT( 1)=  1.31192471E+00
      AHAT( 2)=  0.00000000E+00
      AHAT(
       AZERO=  1.29646737E+00

       AHAT(0)=  3.65635754E+00



      EXPERIMENTAL VALUES           REGRESSION VALUES
      ------------------------------------------------

       Y( 1)=     2.995732E+00          YHAT( 1)=    3.174183E+00

       Y( 2)=     3.988984E+00          YHAT( 2)=    3.706123E+00

       Y( 3)=     4.510860E+00          YHAT( 3)=    4.615270E+00
```

```
SUMST=  1.18483787E+00
STEST=    1.227569E-01
RTEST=    8.963935E-01
```

APPENDIX D

Computer program for evaluation of fireball surface temperatures using isothermal model equation for different authors' parameters

```
C
C
C
C
C
C    PROGRAM FOR EVALUATION OF FIREBALL SURFACE TEMPERATURES:
C    ****************************************************
C       (USING ISO-THERMAL MODEL EQUATION )
C       ********************************
C
C
C
C
      PRINT 11
   11 FORMAT(5X,'METHANE FIREBALL SURFACE TEMPERATURE:',/,5X,42('*')//)
C
      CALL TEMP(GN,FC,V,SECMA,TS)
C
C
      PRINT 33
   33 FORMAT(5X,'ETHANE FIREBALL SURFACE TEMPERATURE:',/,5X,42('*')//)
C
        CALL TEMP(GN26,FC26,V26,SECMA26,TS26)
C
C
      PRINT 12
   12 FORMAT(5X,'PROPANE FIREBALL SURFACE TEMPERATURE:',/,5X,43('*')//)
C
      CALL TEMP(GN1,FC1,V1,SECMA1,TS1)
C
C
      PRINT 13
   13 FORMAT(5X,'BUTANE FIREBALL SURFACE TEMPERATURE:',/,5X,43('*')//)
C
      CALL TEMP(GN2,FC2,V2,SECMA2,TS2)
C
C
      PRINT 14
   14 FORMAT(5X,'PENTANE FIREBALL SURFACE TEMPERATURE:',/,5X,43('*')//)
C
      CALL TEMP(GN3,FC3,V3,SECMA3,TS3)
C
C
       STOP
       END
C
C
C
C
      SUBROUTINE TEMP(GN,FC,V,SECMA,TS)
C
C
C
C
```

```
      DIMENSION T(1000),R1(1000),R2(1000),DIF(1000)
C
      READ *,WTM,GN,FC,V,SECMA,A,ZH,TS
C
        I=1
       T(I)=TS
   5  R1(I)=(17.26*A*SECMA)*((T(I)/1000.0)**4.0)
      R2(I)=(((WTM*ZH*FC)-((31.61*V)*(T(I)-290.0)))/((T(I)*(V+
     @(GN*FC)))))*((((V+(GN+1.0)*FC)*(T(I)-290.0))/WTM)**0.33333)
C
C
C
        DIF(I)=R2(I)-R1(I)
        IF (ABS(DIF(I)).GT.1.0) THEN
        T(I+1)=T(I)+2.0
       I=I+1
          GO TO 5
           ELSE
      PRINT 66,I,R1(I)
  66  FORMAT(10X,' THE VALUE OF RIGHT TERM (',I3,')=',F10.5)
C
      PRINT 67,I,R2(I)
  67  FORMAT(10X,' THE VALUE OF LEFT TERM (',I3,')=',F10.5)
C
      PRINT 68,I,DIF(I)
 68   FORMAT(10X,' THE DIFFERANCE (',I3,')=',F10.5)
C
       PRINT 100,I,T(I)
 100   FORMAT(10X,'SURFACE TEMPERATURE (',I3,')=',F10.3,' K.DEGREE')
         ENDIF
             PRINT 16
  16      FORMAT(3X,///)
         RETURN
         END
C
C
```

```
ISOTHERMAL FIREBALL SUREFACE TEMPERATURE RESULS
===============================================

 THESE RESULTS ARE BASED ON GAYLE PARAMETERS
 ===========================================

METHANE FIREBALL SURFACE TEMPERATURE:
*****************************************


      THE VALUE OF RIGHT TERM (270)=  88.35633
      THE VALUE OF LEFT TERM (270)=  89.26959
      THE DIFFERANCE (270)=   0.91326
     SURFACE TEMPERATURE (270)=  2138.000 K.DEGREE



ETHANE FIREBALL SURFACE TEMPERATURE:
*****************************************


      THE VALUE OF RIGHT TERM (292)=  95.85745
      THE VALUE OF LEFT TERM (292)=  96.61901
      THE DIFFERANCE (292)=   0.76156
     SURFACE TEMPERATURE (292)=  2182.000 K.DEGREE



PROPANE FIREBALL SURFACE TEMPERATURE:
*****************************************


      THE VALUE OF RIGHT TERM (295)=  96.91615
      THE VALUE OF LEFT TERM (295)=  97.78817
      THE DIFFERANCE (295)=   0.87202
     SURFACE TEMPERATURE (295)=  2188.000 K.DEGREE



BUTANE FIREBALL SURFACE TEMPERATURE:
*****************************************


      THE VALUE OF RIGHT TERM (295)=  96.91615
      THE VALUE OF LEFT TERM (295)=  97.69197
      THE DIFFERANCE (295)=   0.77582
     SURFACE TEMPERATURE (295)=  2188.000 K.DEGREE
```

```
PENTANE FIREBALL SURFACE TEMPERATURE:
*******************************************


      THE VALUE OF RIGHT TERM (296)=  97.27099
      THE VALUE OF LEFT TERM (296)=  98.07716
      THE DIFFERANCE (296)=   0.80617
     SURFACE TEMPERATURE (296)=  2190.000 K.DEGREE
```

```
 ISOTHERMAL FIREBALL SURFACE TEMPERATURE RESULTS
 ===============================================

     THESE RESULTS ARE BASED ON BRASIE PARAMETERS
     ============================================


METHANE FIREBALL SURFACE TEMPERATURE:
******************************************


      THE VALUE OF RIGHT TERM (244)=  98.04360
      THE VALUE OF LEFT TERM (244)=  98.93226
      THE DIFFERANCE (244)=   0.88866
     SURFACE TEMPERATURE (244)=  2086.000 K.DEGREE



ETHANE FIREBALL SURFACE TEMPERATURE:
******************************************


      THE VALUE OF RIGHT TERM (264)= 105.78281
      THE VALUE OF LEFT TERM (264)= 106.54972
      THE DIFFERANCE (264)=   0.76691
     SURFACE TEMPERATURE (264)=  2126.000 K.DEGREE



PROPANE FIREBALL SURFACE TEMPERATURE:
******************************************


      THE VALUE OF RIGHT TERM (267)= 106.98203
      THE VALUE OF LEFT TERM (267)= 107.54098
      THE DIFFERANCE (267)=   0.55895
     SURFACE TEMPERATURE (267)=  2132.000 K.DEGREE



BUTANE FIREBALL SURFACE TEMPERATURE:
******************************************


      THE VALUE OF RIGHT TERM (267)= 106.98203
      THE VALUE OF LEFT TERM (267)= 107.35042
      THE DIFFERANCE (267)=   0.36839
     SURFACE TEMPERATURE (267)=  2132.000 K.DEGREE
```

```
PENTANE FIREBALL SURFACE TEMPERATURE:
****************************************


       THE VALUE OF RIGHT TERM (268)= 107.38403
       THE VALUE OF LEFT TERM (268)= 107.67764
       THE DIFFERANCE (268)=   0.29361
      SURFACE TEMPERATURE (268)=  2134.000 K.DEGREE
```

```
ISOTHERMAL FIREBALL SURFACE TEMPERATURE RESULTS
===============================================


    THESE RESULTS ARE BASED ON MARSHALL PARAMETERS
    ==============================================


METHANE FIREBALL SURFACE TEMPERATURE:
*****************************************


      THE VALUE OF RIGHT TERM (213)= 110.06935
      THE VALUE OF LEFT TERM (213)= 110.86079
      THE DIFFERANCE (213)=   0.79143
     SURFACE TEMPERATURE (213)=  2024.000 K.DEGREE



ETHANE FIREBALL SURFACE TEMPERATURE:
*****************************************


      THE VALUE OF RIGHT TERM (231)= 118.11179
      THE VALUE OF LEFT TERM (231)= 118.69158
      THE DIFFERANCE (231)=   0.57978
     SURFACE TEMPERATURE (231)=  2060.000 K.DEGREE



PROPANE FIREBALL SURFACE TEMPERATURE:
******************************************


      THE VALUE OF RIGHT TERM (233)= 119.03184
      THE VALUE OF LEFT TERM (233)= 119.83356
      THE DIFFERANCE (233)=   0.80171
     SURFACE TEMPERATURE (233)=  2064.000 K.DEGREE



BUTANE FIREBALL SURFACE TEMPERATURE:
******************************************


      THE VALUE OF RIGHT TERM (233)= 119.03184
      THE VALUE OF LEFT TERM (233)= 119.52421
      THE DIFFERANCE (233)=   0.49237
     SURFACE TEMPERATURE (233)=  2064.000 K.DEGREE
```

```
PENTANE FIREBALL SURFACE TEMPERATURE:
*******************************************


      THE VALUE OF RIGHT TERM (234)= 119.49388
      THE VALUE OF LEFT TERM (234)= 119.77812
      THE DIFFERANCE (234)=   0.28424
     SURFACE TEMPERATURE (234)=  2066.000 K.DEGREE
```

```
ISOTHERMAL FIREBALL SURFACE TEMPERATURE RESULTS
===============================================


     THESE RESULTS ARE BASED ON ROBERT PARAMETERS
     ============================================


METHANE FIREBALL SURFACE TEMPERATURE:
*****************************************


      THE VALUE OF RIGHT TERM (191)= 119.37519
      THE VALUE OF LEFT TERM (191)= 119.61138
      THE DIFFERANCE (191)=   0.23619
     SURFACE TEMPERATURE (191)=  1980.000 K.DEGREE



ETHANE FIREBALL SURFACE TEMPERATURE:
*****************************************


      THE VALUE OF RIGHT TERM (207)= 127.28148
      THE VALUE OF LEFT TERM (207)= 127.83855
      THE DIFFERANCE (207)=   0.55707
     SURFACE TEMPERATURE (207)=  2012.000 K.DEGREE



PROPANE FIREBALL SURFACE TEMPERATURE:
*****************************************


      THE VALUE OF RIGHT TERM (209)= 128.29668
      THE VALUE OF LEFT TERM (209)= 128.82691
      THE DIFFERANCE (209)=   0.53023
     SURFACE TEMPERATURE (209)=  2016.000 K.DEGREE



BUTANE FIREBALL SURFACE TEMPERATURE:
*****************************************


      THE VALUE OF RIGHT TERM (209)= 128.29668
      THE VALUE OF LEFT TERM (209)= 128.43076
      THE DIFFERANCE (209)=   0.13408
     SURFACE TEMPERATURE (209)=  2016.000 K.DEGREE
```

```
PENTANE FIREBALL SURFACE TEMPERATURE:
****************************************

     THE VALUE OF RIGHT TERM (209)= 128.29668
     THE VALUE OF LEFT TERM (209)= 129.00556
     THE DIFFERANCE (209)=   0.70889
    SURFACE TEMPERATURE (209)=  2016.000 K.DEGREE
```

APPENDIX E

Computer program for evaluation of fireball surface temperatures using BLEVE's model equation

```
C
C
C
C
C
C    PROGRAM FOR EVALUATION OF FIREBALLS SURFACE TEMPERATURES:
C    *******************************************************
C       ( OF B.L.E.V.E. FIREBALLS )
C       ***************************
C
C
C
C
      PRINT 11
 11   FORMAT(5X,'METHANE FIREBALL SURFACE TEMPERATURE:',/,5X,42('*')//)
C
      CALL TEMP(TS1,RS1,C1)
C
      PRINT 26
 26   FORMAT(5X,'ETHANE FIREBALL SURFACE TEMPERATURE:',/,5X,42('*')//)
C
       CALL TEMP(TS2,RS2,C2)
C
C
      PRINT 12
 12   FORMAT(5X,'PROPANE FIREBALL SURFACE TEMPERATURE:',/,5X,43('*')//)
C
      CALL TEMP(TS3,RS3,C3)
C
C
      PRINT 13
 13   FORMAT(5X,'BUTANE FIREBALL SURFACE TEMPERATURE:',/,5X,43('*')//)
C
      CALL TEMP(TS4,RS4,C4)
C
C
      PRINT 14
 14   FORMAT(5X,'PENTANE FIREBALL SURFACE TEMPERATURE:',/,5X,43('*')//)
C
      CALL TEMP(TS5,RS5,C5)
C
C
       STOP
       END
C
C
C
C
      SUBROUTINE TEMP(TS,RS,C)
C
C
C
C
      DIMENSION T(900),R1(900),R2(900),DIF(900)
```

```
C
      READ *,WTM,ZH,TS,RS,C
C
        I=1
       T(I)=TS
  5    R1(I)=(69700/WTM)*((T(I)/1000.0)**4.0)
      R2(I)=ZH-(((1000.0*RS*C)*(((T(I)/1000.0)-0.290))))
C
C
C
C
         DIF(I)=R2(I)-R1(I)
         IF (ABS(DIF(I)).GT.200.0) THEN
         T(I+1)=T(I)+2.0
       I=I+1
           GO TO 5
            ELSE
      PRINT 66,I,R1(I)
  66  FORMAT(10X,' THE VALUE OF RIGHT TERM (',I3,')=',F12.3)
C
      PRINT 67,I,R2(I)
  67  FORMAT(10X,' THE VALUE OF LEFT TERM (',I3,')=',F12.3)
C
      PRINT 68,I,DIF(I)
 68   FORMAT(10X,' THE DIFFERANCE (',I3,')=',F12.3)
C
       PRINT 100,I,T(I)
 100   FORMAT(10X,'B.L.E.V.E. SURFACE TEMPERATURE (',I3,')=',F10.3,
     @' K.DEGREE',/)
C
        ENDIF
            PRINT 16
  16      FORMAT(3X,///)
        RETURN
        END
C
C
```

```
     BLEVE FIREBALL SURFACE TEMPERATURE RESULTS
     ==========================================



METHANE FIREBALL SURFACE TEMPERATURE:
*******************************************


        THE VALUE OF RIGHT TERM (142)=   21013.849
        THE VALUE OF LEFT TERM (142)=   21138.395
        THE DIFFERANCE (142)=      124.546
      B.L.E.V.E. SURFACE TEMPERATURE (142)=  1482.000 K.DEGREE




ETHANE FIREBALL SURFACE TEMPERATURE:
*******************************************


        THE VALUE OF RIGHT TERM (222)=   16889.008
        THE VALUE OF LEFT TERM (222)=   17024.280
        THE DIFFERANCE (222)=      135.272
      B.L.E.V.E. SURFACE TEMPERATURE (222)=  1642.000 K.DEGREE




PROPANE FIREBALL SURFACE TEMPERATURE:
*******************************************


        THE VALUE OF RIGHT TERM (221)=   14520.350
        THE VALUE OF LEFT TERM (221)=   14677.600
        THE DIFFERANCE (221)=      157.250
      B.L.E.V.E. SURFACE TEMPERATURE (221)=  1740.000 K.DEGREE




BUTANE FIREBALL SURFACE TEMPERATURE:
*******************************************


        THE VALUE OF RIGHT TERM (210)=   13127.448
        THE VALUE OF LEFT TERM (210)=   13248.904
        THE DIFFERANCE (210)=      121.456
      B.L.E.V.E. SURFACE TEMPERATURE (210)=  1818.000 K.DEGREE
```

```
PENTANE FIREBALL SURFACE TEMPERATURE:
******************************************

     THE VALUE OF RIGHT TERM (243)=   12196.181
     THE VALUE OF LEFT TERM (243)=   12310.800
     THE DIFFERANCE (243)=      114.619
    B.L.E.V.E. SURFACE TEMPERATURE (243)=  1884.000 K.DEGREE
```

APPENDIX F

Computer program for evaluation of fireball surface temperature using thermodynamic equation

```
C
C
C
C
C  PROGRAM FOR EVALUATION OF FIREBALL SURFACE TEMPERATURE
C  ***************************************************
C  USING THERMODYNAMIC EQUATION:
C  ****************************
C
C
C
C
      PRINT 15
   15 FORMAT(5X,'METHANE FIREBALL SURFACE TEMPERATURE :',/,5X,42('=')//)
C
        CALL TEMTHR(Q,G1,G2,G3)
C
C
      PRINT 17
  17  FORMAT(5X,'ETHANE FIREBALL SURFACE TEMPERATURE:',/,5X,42('*')//)
C
         CALL TEMTHR(Q,G1,G2,G3)
C
C
      PRINT 20
  20  FORMAT(5X,'PROPANE FIREBALL SURFACE TEMPERATUE :',/,5X,43('=')//)
C
        CALL TEMTHR(Q,G1,G2,G3)
C
C
      PRINT 30
  30  FORMAT(5X,'BUTANE FIREBALL SURFACE TEMPERATURE :',/,5X,43('=')//)
C
       CALL TEMTHR(Q,G1,G2,G3)
C
C
      PRINT 35
  35  FORMAT(5X,'PENTANE FIREBALL SURFACE TEMPERATURE :',/,5X,43('=')//)
C
       CALL TEMTHR(Q,G1,G2,G3)
C
C
C
C
C
       STOP
       END
C
C
C
       SUBROUTINE TEMTHR(Q,GN1,GN2,GN3)
C
C
C
```

```
       DIMENSION TS(400),T(400),CPN2(400),CPCO2(400),
      @CPO2(400),TSN(400),CPH2O(400),DIF(400)
C
        READ *,GN1,GN2,GN3,GN4,Q,FC
C
           Q1=Q-(GN3*10520.0)
C
        I=1
         TS(I)=1600.0
 5      T(I)=TS(I)+273.0
        CPN2(I)=6.83+(0.0009*T(I))-(12000.0/(T(I)**2.0))
        CPCO2(I)=10.57+(0.0021*T(I))-(206000.0/(T(I)**2.0))
        CPH2O(I)=7.30+(0.00246*T(I))
       CPO2(I)=7.16+(0.001*T(I))-(40000.0/(T(I)**2.0))
        TSN(I)=((FC*Q1)/((GN1*CPN2(I))+(GN2*CPCO2(I))+(GN3*CPH2O(I))
      @+(GN4*CPO2(I))))+25.0
C
C
        DIF(I)=TSN(I)-TS(I)
        IF (ABS(DIF(I)).GT.1.0) THEN
         TS(I+1)=TS(I)+1.0
         I=I+1
         GO TO 5
         ELSE
         PRINT 55,I,TS(I)
  55    FORMAT(5X,'ASSUME SURFACE TEMPERATURE (',I3,')=',
      @F10.3,' C.DEGREE')
C
        PRINT 56,I,CPN2(I)
 56     FORMAT(5X,' THE VALUE OF CPN2(',I3,')=',F7.3)
C
        PRINT 57,I,CPCO2(I)
 57     FORMAT(5X,' THE VALUE OF CPCO2 (',I3,')=',F7.3)
C
        PRINT 58,I,CPH2O(I)
 58      FORMAT(5X,' THE VALUE OF CPH2O (',I3,')=',F7.3)
C
       PRINT 79,I,CPO2(I)
  79   FORMAT(5X,'THE VALUE OF CPO2(',I3,')=',F7.3)
C
        PRINT 100,I,TSN(I)
 100    FORMAT(10X,' SURFACE TEMPERATURE (',I3,')=',F10.3,
      @' C.DEGREE ')
       TSK=TSN(I)+273.0
       PRINT 150,I,TSK
 150   FORMAT(/,10X,'SURFACE TEMPERATURE OF FIRE BALL (',I3,')=',
      @F10.3,'  BY K.DEGREE',////)
          ENDIF
           RETURN
               END
```

```
THERMODYNAMIC FIREBALL SURFACE TEMPERATURE RESULTS
==================================================


METHANE FIREBALL SURFACE TEMPERATURE :
==========================================


ASSUME SURFACE TEMPERATURE (142)=  1741.000 C.DEGREE
 THE VALUE OF CPN2(142)=  8.640
 THE VALUE OF CPCO2 (142)= 14.749
 THE VALUE OF CPH2O (142)= 12.254
THE VALUE OF CPO2(142)=  9.164
      SURFACE TEMPERATURE (142)=  1741.468 C.DEGREE

     SURFACE TEMPERATURE OF FIRE BALL (142)=  2014.468  BY K.DEGREE



ETHANE FIREBALL SURFACE TEMPERATURE:
******************************************


ASSUME SURFACE TEMPERATURE (220)=  1819.000 C.DEGREE
 THE VALUE OF CPN2(220)=  8.710
 THE VALUE OF CPCO2 (220)= 14.916
 THE VALUE OF CPH2O (220)= 12.446
THE VALUE OF CPO2(220)=  9.243
      SURFACE TEMPERATURE (220)=  1819.953 C.DEGREE

     SURFACE TEMPERATURE OF FIRE BALL (220)=  2092.953  BY K.DEGREE



PROPANE FIREBALL SURFACE TEMPERATUE :
==========================================


ASSUME SURFACE TEMPERATURE (241)=  1840.000 C.DEGREE
 THE VALUE OF CPN2(241)=  8.729
 THE VALUE OF CPCO2 (241)= 14.961
 THE VALUE OF CPH2O (241)= 12.498
THE VALUE OF CPO2(241)=  9.264
      SURFACE TEMPERATURE (241)=  1840.337 C.DEGREE

     SURFACE TEMPERATURE OF FIRE BALL (241)=  2113.337  BY K.DEGREE



BUTANE FIREBALL SURFACE TEMPERATURE :
```

```
============================================

ASSUME SURFACE TEMPERATURE (248)=  1847.000 C.DEGREE
 THE VALUE OF CPN2(248)=  8.735
 THE VALUE OF CPCO2 (248)= 14.976
 THE VALUE OF CPH2O (248)= 12.515
THE VALUE OF CPO2(248)=  9.271
      SURFACE TEMPERATURE (248)=  1847.308 C.DEGREE

     SURFACE TEMPERATURE OF FIRE BALL (248)=  2120.308  BY K.DEGREE



PENTANE FIREBALL SURFACE TEMPERATURE :
============================================

ASSUME SURFACE TEMPERATURE (255)=  1854.000 C.DEGREE
 THE VALUE OF CPN2(255)=  8.742
 THE VALUE OF CPCO2 (255)= 14.991
 THE VALUE OF CPH2O (255)= 12.532
THE VALUE OF CPO2(255)=  9.278
      SURFACE TEMPERATURE (255)=  1854.224 C.DEGREE

     SURFACE TEMPERATURE OF FIRE BALL (255)=  2127.224  BY K.DEGREE
```

```
C  PROGRAM FOR EVALUATION OF BLEVE FIREBALL SURFACE TEMERATURE
C  **************************************************************
C  USING THERMODYNAMIC EQUATION:
C  ****************************
C
      PRINT 15
   15 FORMAT(5X,'METHANE FIREBALL SURFACE TEMPERATURE :',/,5X,42('=')//)
C
        CALL TEMTHR(Q,G1,G2,G3)
C
C
      PRINT 17
  17  FORMAT(5X,'ETHANE FIREBALL SURFACE TEMPERATURE:',/,5X,42('*')//)
C
         CALL TEMTHR(Q,G1,G2,G3)
C
C
      PRINT 20
  20  FORMAT(5X,'PROPANE FIREBALL SURFACE TEMPERATUE :',/,5X,43('=')//)
C
        CALL TEMTHR(Q,G1,G2,G3)
C
C
      PRINT 30
  30  FORMAT(5X,'BUTANE FIREBALL SURFACE TEMPERATURE :',/,5X,43('=')//)
C
       CALL TEMTHR(Q,G1,G2,G3)
C
C
      PRINT 35
  35  FORMAT(5X,'PENTANE FIREBALL SURFACE TEMPERATURE :',/,5X,43('=')//)
C
       CALL TEMTHR(Q,G1,G2,G3)
C
C
C
C
C
       STOP
       END
C
C
C
       SUBROUTINE TEMTHR(Q,GN1,GN2,GN3)
C
C
C
      DIMENSION TS(999),T(999),CPN2(999),CPCO2(999),
     @CPCH(999),CPO2(999),TSN(999),CPH2O(999),DIF(999)
C
       READ *,GN1,GN2,GN3,GN4,GN5,Q,FC
C
          READ *,A,B,C
C
```

```
          Q1=Q-(GN3*10520.0)
C
        I=1
          TS(I)=700.0
 5      T(I)=TS(I)+273.0
        CPN2(I)=6.83+(0.0009*T(I))-(12000.0/(T(I)**2.0))
        CPCO2(I)=10.57+(0.0021*T(I))-(206000.0/(T(I)**2.0))
        CPH2O(I)=7.30+(0.00246*T(I))
       CPO2(I)=7.16+(0.001*T(I))-(40000.0/(T(I)**2.0))
         CPCH(I)=A+(B*T(I))-(C*(T(I)**2.0))
        TSN(I)=((FC*Q1)/((GN1*CPN2(I))+(GN2*CPCO2(I))+(GN3*CPH2O(I))
      @+(GN4*CPO2(I))+(GN5*CPCH(I))))+25.0
C
C
        DIF(I)=TSN(I)-TS(I)
        IF (ABS(DIF(I)).GT.1.0) THEN
         TS(I+1)=TS(I)+1.0
         I=I+1
         GO TO 5
         ELSE
         PRINT 55,I,TS(I)
  55    FORMAT(5X,'ASSUME SURFACE TEMPERATURE (',I3,')=',
      @F10.3,' C.DEGREE')
C
        PRINT 56,I,CPN2(I)
 56     FORMAT(5X,' THE VALUE OF CPN2(',I3,')=',F7.3)
C
        PRINT 57,I,CPCO2(I)
 57     FORMAT(5X,' THE VALUE OF CPCO2 (',I3,')=',F7.3)
C
        PRINT 58,I,CPH2O(I)
 58      FORMAT(5X,' THE VALUE OF CPH2O (',I3,')=',F7.3)
C
       PRINT 79,I,CPO2(I)
  79   FORMAT(5X,'THE VALUE OF CPO2(',I3,')=',F7.3)
C
       PRINT 88,I,CPCH(I)
 88    FORMAT(5X,'THE VALUE OF CPCH(',I3,')=',F8.3,/)
C
        PRINT 100,I,TSN(I)
 100    FORMAT(10X,' SURFACE TEMPERATURE (',I3,')=',F10.3,
      @' C.DEGREE ')
       TSK=TSN(I)+273.0
       PRINT 150,I,TSK
 150   FORMAT(/,10X,'SURFACE TEMPERATURE OF FIRE BALL (',I3,')=',
      @F10.3,'  BY K.DEGREE',////)
          ENDIF
           RETURN
               END
```

```
  THERMODYNAMIC BLEVE FIREBALL SURFACE TEMPERATURE RESULTS
  ==========================================================



METHANE FIREBALL SURFACE TEMPERATURE :
===========================================


ASSUME SURFACE TEMPERATURE (235)=   934.000 C.DEGREE
 THE VALUE OF CPN2(235)=  7.908
 THE VALUE OF CPCO2 (235)= 12.963
 THE VALUE OF CPH2O (235)= 10.269
THE VALUE OF CPO2(235)=  8.340
THE VALUE OF CPCH(235)=  18.896

      SURFACE TEMPERATURE (235)=   934.654 C.DEGREE

     SURFACE TEMPERATURE OF FIRE BALL (235)=  1207.654  BY K.DEGREE



ETHANE FIREBALL SURFACE TEMPERATURE:
*******************************************


ASSUME SURFACE TEMPERATURE (247)=   946.000 C.DEGREE
 THE VALUE OF CPN2(247)=  7.919
 THE VALUE OF CPCO2 (247)= 12.991
 THE VALUE OF CPH2O (247)= 10.299
THE VALUE OF CPO2(247)=  8.352
THE VALUE OF CPCH(247)=  32.396

      SURFACE TEMPERATURE (247)=   946.642 C.DEGREE

     SURFACE TEMPERATURE OF FIRE BALL (247)=  1219.642  BY K.DEGREE



PROPANE FIREBALL SURFACE TEMPERATUE :
===========================================


ASSUME SURFACE TEMPERATURE (248)=   947.000 C.DEGREE
 THE VALUE OF CPN2(248)=  7.920
 THE VALUE OF CPCO2 (248)= 12.994
 THE VALUE OF CPH2O (248)= 10.301
THE VALUE OF CPO2(248)=  8.353
THE VALUE OF CPCH(248)=  46.092

      SURFACE TEMPERATURE (248)=   947.490 C.DEGREE
```

```
     SURFACE TEMPERATURE OF FIRE BALL (248)=  1220.490  BY K.DEGREE



BUTANE FIREBALL SURFACE TEMPERATURE :
===========================================


ASSUME SURFACE TEMPERATURE (248)=   947.000 C.DEGREE
 THE VALUE OF CPN2(248)=  7.920
 THE VALUE OF CPCO2 (248)= 12.994
 THE VALUE OF CPH2O (248)= 10.301
THE VALUE OF CPO2(248)=  8.353
THE VALUE OF CPCH(248)=  59.611

      SURFACE TEMPERATURE (248)=   947.024 C.DEGREE

     SURFACE TEMPERATURE OF FIRE BALL (248)=  1220.024  BY K.DEGREE



PENTANE FIREBALL SURFACE TEMPERATURE :
===========================================


ASSUME SURFACE TEMPERATURE (248)=   947.000 C.DEGREE
 THE VALUE OF CPN2(248)=  7.920
 THE VALUE OF CPCO2 (248)= 12.994
 THE VALUE OF CPH2O (248)= 10.301
THE VALUE OF CPO2(248)=  8.353
THE VALUE OF CPCH(248)=  73.100

      SURFACE TEMPERATURE (248)=   947.514 C.DEGREE

     SURFACE TEMPERATURE OF FIRE BALL (248)=  1220.514  BY K.DEGREE
```

APPENDIX G

Two computer programs for evaluation of

i. View Factors, and the ratio of height to diameter of the fireball

ii. Fireball dimensions and hazard ranges using different authors' parameters, hot shell-cold core, isothermal and BLEVE models.

```
C
C
C
C PROGRAM FOR EVALUATION OF VIEW FACTOR AND THE RATIO OF THE
C ============================================================
C HEIGHT TO DIAMETER OF THE FIREBALL:
C ===================================
      DIMENSION W(25)
C
            READ *,N
        READ *,(W(I),I=1,N)
C
C
      PRINT 77
 77   FORMAT(//12X,'VIEW FACTOR AND (H/DS) RESULTS:',
     @/12X,30('-')//)
C
C
C
      PRINT 13
 13   FORMAT(5X,'FIREBALL RESULTS USING PREVIOUS WORK',
     @' EQUATIONS & PARAMETERS:',/5X,60('=')//)
C
C
C
C    CALCULATION OF FIREBALL DIMENSIONS BY USING PREVIOUS WORK.
C    -----------------------------------------------------------
C
C
C
C
C
      READ *,THETA,V,V2,V3,V4,V5,GN,GN2,GN3,GN4,GN5,FC,FC2,
     @FC3,FC4,FC5,WTM,WTM2,WTM3,WTM4,WTM5
C
      PRINT 19
 19   FORMAT(10X,'USING GAYLE PARAMETERS (A,AS,B & BS)',/,10X,37('=')//)
C
       READ *,SECMA,TEMS1,TEMS2,TEMS3,TEMS4,TEMS5
C
C
      READ *,A,AS,B,BS,A2,AS2,B2,BS2,A3,AS3,B3,BS3,A4,AS4,B4,BS4
     @,A5,AS5,B5,BS5
C
      CALL FIRBAL(N,W,THETA,V,V2,V3,GN,GN2,GN3,FC,FC2,FC3,WTM,WTM2
     +,WTM3,A,A2,A3,AS,AS2,AS3,B,B2,B3,BS,BS2,BS3,A4,AS4,B4,BS4,
     @A5,AS5,B5,BS5,SECMA,V4,GN4,FC4,WTM4,V5,GN5,FC5,WTM5,
     @TEMS1,TEMS2,TEMS3,TEMS4,TEMS5)
C
C
C
      PRINT 21
 21    FORMAT(10X,'USING BRASIE PARAMETERS (A,AS,B & BS)',/,10X,
     +40('=')//)
```

```
C
          READ *,SECMA,TEMS1,TEMS2,TEMS3,TEMS4,TEMS5
C
C
       READ *,A,AS,B,BS,A2,AS2,B2,BS2,A3,AS3,B3,BS3,A4,AS4,B4,BS4
     @,A5,AS5,B5,BS5
       CALL FIRBAL(N,W,THETA,V,V2,V3,GN,GN2,GN3,FC,FC2,FC3,WTM,WTM2,
     @WTM3,A,A2,A3,AS,AS2,AS3,B,B2,B3,BS,BS2,BS3,A4,AS4,B4,BS4,
     @A5,AS5,B5,BS5,SECMA,V4,GN4,FC4,WTM4,V5,GN5,FC5,WTM5,
     @TEMS1,TEMS2,TEMS3,TEMS4,TEMS5)
C
C
C
       PRINT 22
  22   FORMAT(10X,'USING MARSHALL PARAMETERS (A,AS,B & BS):',/,10X,
     @40('=')//)
C
          READ *,SECMA,TEMS1,TEMS2,TEMS3,TEMS4,TEMS5
C
C
       READ *,A,AS,B,BS,A2,AS2,B2,BS2,A3,AS3,B3,BS3,A4,AS4,B4,BS4
       CALL FIRBAL(N,W,THETA,V,V2,V3,GN,GN2,GN3,FC,FC2,FC3,WTM,WTM2,
     @WTM3,A,A2,A3,AS,AS2,AS3,B,B2,B3,BS,BS2,BS3,A4,AS4,B4,BS4,
     @A5,AS5,B5,BS5,SECMA,V4,GN4,FC4,WTM4,V5,GN5,FC5,WTM5
     @,TEMS1,TEMS2,TEMS3,TEMS4,TEMS5)
C
C
C
       PRINT 23
  23   FORMAT(10X,'USING ROBERTS PARAMETERS (A,AS,B & BS):',/,10X,
     @40('=')//)
C
C
          READ *,SECMA,TEMS1,TEMS2,TEMS3,TEMS4,TEMS5
C
       READ *,A,AS,B,BS,A2,AS2,B2,BS2,A3,AS3,B3,BS3,A4,AS4,B4,BS4
     @,A5,AS5,B5,BS5
       CALL FIRBAL(N,W,THETA,V,V2,V3,GN,GN2,GN3,FC,FC2,FC3,WTM,WTM2,
     @WTM3,A,A2,A3,AS,AS2,AS3,B,B2,B3,BS,BS2,BS3,A4,AS4,B4,BS4,
     @A5,AS5,B5,BS5,SECMA,V4,GN4,FC4,WTM4,V5,GN5,FC5,WTM5,
     @TEMS1,TEMS2,TEMS3,TEMS4,TEMS5)
C
C
C
       PRINT 31
  31   FORMAT(10X,'USING HOT SHELL-COLD CORE MODEL:',/,10X,
     @35('=')//)
C
C
       PRINT 201
 201   FORMAT(10X,' METHANE RESULTS OF HOT SHELL-COLD CORE MODEL:',
     @/,10X,46('*')/)
C
C
```

```
C
       CALL HOTMET(N,W,THETA)
C
C
      PRINT 203
 203  FORMAT(//10X,' BUTANE RESULTS OF HOT SHELL-COLD CORE MODEL:',
     @/,10X,46('*')/)
C
      CALL HOTSHE(N,W,THETA,SECMA)
C
C
C
      PRINT 32
  32  FORMAT(10X,'USING ISO-THERMAL MODEL:',/,10X,23('=')//)
C
C
C
      PRINT 204
 204  FORMAT(10X,' METANE RESULTS OF ISO-THERMAL MODEL:',
     @/,10X,37('=')/)
C
      READ *,SECMA5,V5,GN5,WTM5,FC5,TEMS11
      CALL ISOTHR(N,W,THETA,SECMA5,V5,GN5,WTM5,FC5,TEMS11)
C
C
      PRINT 1266
 1266 FORMAT(10X,'ETHANE RESULTS OF ISO-THERMAL MODEL:',
     @/,10X,37('=')/)
C
       READ *,SECMA26,V26,GN26,WTM26,FC26,TEMS26
C
      CALL ISOTHR(N,W,THETA,SECMA26,V26,GN26,WTM26,FC26,TEMS26)
C
C
      PRINT 206
 206  FORMAT(10X,' PROPANE RESULTS OF ISO-THERMAL MODEL:',
     @/,10X,39('=')/)
C
      READ *,SECMA6,V6,GN6,WTM6,FC6,TEMS12
      CALL ISOTHR(N,W,THETA,SECMA6,V6,GN6,WTM6,FC6,TEMS12)
C
C
      PRINT 207
 207  FORMAT(10X,' BUTANE RESULTS OF ISO-THERMAL MODEL:',
     @/,10X,38('=')/)
C
      READ *,SECMA7,V7,GN7,WTM7,FC7,TEMS13
      CALL ISOTHR(N,W,THETA,SECMA7,V7,GN7,WTM7,FC7,TEMS13)
C
C
      PRINT 208
 208  FORMAT(10X,' PENTANE RESULTS OF ISO-THERMAL MODDEL:',
     @/,10X,37('=')/)
C
```

```
      READ *,SECMA8,V8,GN8,WTM8,FC8,TEMS14
      CALL ISOTHR(N,W,THETA,SECMA8,V8,GN8,WTM8,FC8,TEMS14)
C
C
C
      PRINT 901
 901  FORMAT(///10X,' B.L.E.V.E FIREBALL RESULTS:',/,10X,30('*')//)
C
C
C
      PRINT 902
 902  FORMAT(10X,' METHANE BLEVE FIREBALL RESULTS:',/,10X,35('=')/)
C
C
      READ *,SECMA,WTM,TEMS6
      CALL BLEVE(N,W,THETA,SECMA,TEMS6,WTM)
C
      PRINT 1623
 1623 FORMAT(10X,'ETHANE BLEVE FIREBALL RESULTS:',/,10X,35('=')/)
C
       READ *,SECMA,WTM,TEMS27
       CALL BLEVE(N,W,THETA,SECMA,TEMS27,WTM)
C
C
      PRINT 903
 903  FORMAT(10X,'PROPANE BLEVE FIREBALL RESULTS:',/,10X,35('=')/)
C
      READ *,SECMA,WTM,TEMS7
      CALL BLEVE(N,W,THETA,SECMA,TEMS7,WTM)
C
C
      PRINT 904
 904  FORMAT(10X,' BUTANE BLEVE FIREBALL RESULTS:',/10X,35('=')/)
C
      READ *,SECMA,WTM,TEMS8
      CALL BLEVE(N,W,THETA,SECMA,TEMS8,WTM)
C
C
      PRINT 906
 906  FORMAT(10X,' PENTANE BLEVE FIREBALL RESULTS:',/,10X,35('=')/)
C
      READ *,SECMA,WTM,TEMS9
      CALL BLEVE(N,W,THETA,SECMA,TEMS9,WTM)
C
C
                STOP
                 END
C
C
C
C
C
C
C
```

```
C
C
C  SUBROUTINE PROGRAM FOR CALCULATION OF TC,DC,HIGHT,F21,RANGE
C  ===========================================================
C  Q1,Q2PIG,TEMP.OF FIREBALL SURFACE,DISTANCE OF THE TARGETS,TAW,Q2.
C  =================================================================
C  BY USING PREVIOUS WORK:
C  =======================
C
C
C
       SUBROUTINE FIRBAL(II,W,THETA,V,V2,V3,GN,GN2,GN3,FC,FC2,FC3,
     +WTM,WTM2,WTM3,A1,A2,A3,AS1,AS2,AS3,B1,B2,B3,BS1,BS2,BS3,
     @A4,AS4,B4,BS4,A5,AS5,B5,BS5,SECMA,V4,GN4,FC4,WTM4,
     @V5,GN5,FC5,WTM5,TEMS1,TEMS2,TEMS3,TEMS4,TEMS5)
C
C
C
C
C
C
C
      DIMENSION Q1(10),DSH(10),F21(10),Y(10),DS(10),
     @Q2HUM(10),F21HUM(10),F21PIG(10),TC(10),F21B(10),
     @W(10),Q2PIG(10),F21PE(10)
C
C
            TAW=1.0
            QB=12.6
            QPE=37.8
C
C
C
C   CALCULATION OF METHANE FIREBALL DIMENSIONS & HAZARDS
C   ====================================================
C
C
        PRINT 11
  11    FORMAT(10X,' METHANE FIREBALL RESULTS:',/,10X,26('*')/)
C
C
C
C
C
C
C
C
        DO 5 I=1,II
        TC(I)=A1*(W(I)**AS1)
        DS(I)=B1*(W(I)**BS1)
        Y(I)=10*TC(I)
       Q1(I)=SECMA*THETA*(TEMS1**4.0)
       Q2HUM(I)=60.53/(TC(I)**0.756)
        Q2PIG(I)=50.0/(TC(I)**0.71)
```

```
        DSH(I)=Y(I)/DS(I)
        F21HUM(I)=Q2HUM(I)/(TAW*Q1(I))
        F21PIG(I)=Q2PIG(I)/(TAW*Q1(I))
        F21B(I)=QB/(TAW*Q1(I))
        F21PE(I)=QPE/(TAW*Q1(I))
   5      CONTINUE
C
C
      PRINT 100
 100  FORMAT(1X,
     @'   MASS      TEMP     H/DS  F21-HUMAN   F21-ANIM  F21-BUILD',
     @'  F21-PROCESS',/,72('-'))
C
      DO 6 N=1,II
      PRINT 105,W(N),TEMS1,DSH(N),F21HUM(N),F21PIG(N),F21B(N),F21PE(N)
 105   FORMAT(2F9.2,5(1X,F9.5))
C
C
  6     CONTINUE
C
C
C
C
C  CALCULATION OF ETHANE FIREBALL DIMENSIONS & HAZARDS:
C  ===================================================
C
C
         PRINT 5000
 5000      FORMAT(10X,///)
C
C
      PRINT 261
 261  FORMAT(10X,' ETHANE FIREBALL RESULTS:',/,10X,26('*')/)
C
C
C
C
C
C
        DO 51 J=1,II
       TC(J)=A2*(W(J)**AS2)
       DS(J)=B2*(W(J)**BS2)
       Y(J)=10*TC(J)
       Q1(J)=SECMA*THETA*(TEMS2**4.0)
       Q2HUM(J)=28.16/(TC(J)**0.735)
       Q2PIG(J)=50.0/(TC(J)**0.71)
       DSH(J)=Y(J)/DS(J)
       F21HUM(J)=Q2HUM(J)/(TAW*Q1(J))
       F21PIG(J)=Q2PIG(J)/(TAW*Q1(J))
       F21B(J)=QB/(TAW*Q1(J))
       F21PE(J)=QPE/(TAW*Q1(J))
C
  51     CONTINUE
C
```

```
C
      PRINT 500
 500  FORMAT(1X,
     @'    MASS    TEMP      H/DS   F21-HUMAN  F21-ANIM  F21-BUILD',
     @'  F21-PROCESS',/,1X,72('-'))
C
C
        DO 76 M=1,II
      PRINT 1051,W(M),TEMS2,DSH(M),F21HUM(M),F21PIG(M),F21B(M),F21PE(M)
 1051 FORMAT(2F9.2,1X,5(1X,F9.5))
C
  76      CONTINUE
C
C
C
C
C
C  CALCULATION OF PROPANE FIREBALL DIMENSIONS & HAZARDS:
C  ============================================================
       PRINT 260
 260   FORMAT(10X,///)
C
       PRINT 150
 150    FORMAT(10X,'PROPANE FIREBALL RESULTS:',/,10X,24('*')/)
C
C
C
       DO 10 M=1,II
       TC(M)=A3*(W(M)**AS3)
       DS(M)=B3*(W(M)**BS3)
       Y(M)=10*TC(M)
C
      Q1(M)=SECMA*THETA*(TEMS3**4.0)
       Q2HUM(M)=28.16/(TC(M)**0.735)
       Q2PIG(M)=50.0/(TC(M)**0.71)
        DSH(M)=Y(M)/DS(M)
        F21HUM(M)=Q2HUM(M)/(TAW*Q1(M))
        F21PIG(M)=Q2PIG(M)/(TAW*Q1(M))
        F21B(M)=QB/(TAW*Q1(M))
        F21PE(M)=QPE/(TAW*Q1(M))
 10     CONTINUE
C
C
C
      PRINT 200
 200  FORMAT(1X,
     @'    MASS    TEMP      H/DS   F21-HUMAN F21-ANIM  F21-BULID',
     @'  F21-PROCESS',/,1X,72('-'))
       DO 15 MM=1,II
      PRINT 210,W(MM),TEMS3,DSH(MM),F21HUM(MM),F21PIG(MM),
     @F21B(MM),F21PE(MM)
 210     FORMAT(2F9.2,5(1X,F9.5))
  15    CONTINUE
C
```

```
C
C
C   CALCULATION OF BUTANE FIREBALL DIMENSIONS & HAZARDS:
C   ==========================================================
C
C
C
      PRINT 360
 360  FORMAT(2X,///)
C
       PRINT 255
 255   FORMAT(10X,'BUTANE FIREBALL RESULTS:',/,10X,25('*')/)
C
C
C
C
C
C
C
       DO 20 J=1,II
      TC(J)=A4*(W(J)**AS4)
      DS(J)=B4*(W(J)**BS4)
      Y(J)=10.0*TC(J)
     Q1(J)=SECMA*THETA*(TEMS4**4.0)
       Q2HUM(J)=28.16/(TC(J)**0.735)
      Q2PIG(J)=50.0/(TC(J)**0.71)
        DSH(J)=Y(J)/DS(J)
        F21HUM(J)=Q2HUM(J)/(TAW*Q1(J))
        F21PIG(J)=Q2PIG(J)/(TAW*Q1(J))
        F21B(J)=QB/(TAW*Q1(J))
        F21PE(J)=QPE/(TAW*Q1(J))
 20     CONTINUE
C
C
C
      PRINT 300
 300 FORMAT(1X,
    @'   MASS    TEMP     H/DS   F21-HUMAN  F21-ANIM  F21-BUILD ',
    @' F21-PROCESS',/1X,72('-'))
C
        DO 25 L=1,II
      PRINT 320,W(L),TEMS4,DSH(L),F21HUM(L),F21PIG(L),
    @F21B(L),F21PE(L)
  320   FORMAT(2F9.2,5(1X,F9.5))
C
   25    CONTINUE
C
C
C
        PRINT 811
 811    FORMAT(5X,///)
C
C
C
```

```
C  CALCULATION OF PENTANE FIREBALL DIMENSIONS & HAZARDS:
C  ==========================================================
C
C
C
      PRINT 301
 301  FORMAT(10X,'PENTANE FIREBALL RESULTS:',/,10X,26('*')/)
C
C
      DO 77 L=1,II
      TC(L)=A5*(W(L)**AS5)
      DS(L)=B5*(W(L)**BS5)
      Y(L)=10.0*TC(L)
       Q1(L)=SECMA*THETA*(TEMS5**4.0)
       Q2HUM(L)=28.16/(TC(L)**0.735)
      Q2PIG(L)=50.0/(TC(L)**0.71)
        DSH(L)=Y(L)/DS(L)
        F21HUM(L)=Q2HUM(L)/(TAW*Q1(L))
        F21PIG(L)=Q2PIG(L)/(TAW*Q1(L))
        F21B(L)=QB/(TAW*Q1(L))
        F21PE(L)=QPE/(TAW*Q1(L))
  77    CONTINUE
C
C
C
      PRINT 303
 303  FORMAT(1X,
     @'   MASS      TEMP     H/DS  F21-HUMAN  F21-ANIM  F21-BUILD',
     @'  F21-PROCESS',/,1X,72('-'))
C
C
C
      DO 27 K=1,II
       PRINT 306,W(K),TEMS5,DSH(K),F21HUM(K),F21PIG(K),
     @F21B(K),F21PE(K)
C
C
  306     FORMAT(2F9.2,5(1X,F9.5))
C
  27   CONTINUE
C
C
          PRINT 99
  99    FORMAT(10X,////)
C
           RETURN
            END
C
C
C
C SUBROUTINE FOR METHANE ONLY (USING HOT SELL-COLD CORE MODEL):
C ***************************************************************
C
C
```

```
C
      SUBROUTINE HOTMET(M,W,THETA)
      DIMENSION Q1(25),Y(25),DC(25),F21HUM(25),F21PIG(25),F21B(25),
     @TC(25),W(25),DO(25),Q2PIG(25),F21PE(25),DSH(25)
     @,Q2HUM(25)
C
C
         TAW=1.0
      SECMA=0.5
      QB=12.6
      QPE=37.8
C
         READ *,WTM,TEMS,ZH
C
C
      DO 140 I=1,M
      Q1(I)=SECMA*THETA*(TEMS**4.0)
      DO(I)=1.42*(W(I)**0.3334)
      DC(I)=DO(I)*((((273.0*WTM*ZH)/(44.8*290*Q1(I)))+1.0)**0.3334)
      TC(I)=(DC(I)-DO(I))/1.0
      Y(I)=1.0*TC(I)
       Q2HUM(I)=28.16/(TC(I)**0.735)
      Q2PIG(I)=50.0/(TC(I)**0.71)
      DSH(I)=Y(I)/DC(I)
        F21HUM(I)=Q2HUM(I)/(TAW*Q1(I))
        F21PIG(I)=Q2PIG(I)/(TAW*Q1(I))
C
        F21B(I)=QB/(TAW*Q1(I))
        F21PE(I)=QPE/(TAW*Q1(I))
 140  CONTINUE
C
C
      PRINT 1421
 1421 FORMAT(1X,
     @'  MASS      TEMP    H/DS   F21-HUMAN  F21-ANIM  F21-BUILD',
     @'  F21-PROCESS',/,1X,72('-'))
C
C
      DO 145 J=1,M
      PRINT 1400,W(J),TEMS,DSH(J),F21HUM(J),F21PIG(J),
     @F21B(J),F21PE(J)
 1400  FORMAT(2F9.2,5(1X,F9.5))
  145    CONTINUE
C
C
C
        RETURN
         END
C
C
C
C
C
C    SUBROUTINE PROGRAM FOR CALCULATION OF FIREBALLS
```

```
C     DIMENSIONS BY USING HOT SHELL-COLD CORE MODEL:
C     ==============================================
C
C
      SUBROUTINE HOTSHE(MM,W,THETA,SECMA)
C
C
C
      DIMENSION Q1(25),Y(25),DC(25),F21HUM(25),F21PIG(25),F21B(25),
     @F21PE(25),DSH(25),TC(25),DO(25),Q2PIG(25),D1(25),
     @W(25),Q2HUM(25)
C
C
C
C     CALCULATION OF FIREBALL BY USING HOT SHELL-COLD CORE MODEL:
C     -----------------------------------------------------------
C
C
C
         TAW=1.0
        QB=12.6
        QPE=37.8
C
C
        READ *,TEMS,WTM,C,RS,ZH
C
C
C
C
C
C
      F1=((1.0-(29.0/WTM))*(93.05*SECMA*((TEMS/1000.0)**4.0)))/(ZH
     @-RS*C*(TEMS-290.0)-93.05*SECMA*((TEMS/1000.0)**4.0)*RS)
C
C
C
      PRINT 333,F1
  333  FORMAT(/10X,'THE VALUE OF F1 =',F10.3,/)
C
C
C
       IF(F1.LT.0.0) THEN
       PRINT 1222
 1222  FORMAT(//,5X,'THIS MODEL SHOUD NOT USED IN THESE CONDITIONS',
     @/,5X,'BECAUSE F1 VALUE IS NEGATIVE & IT MUST BE POSTIVE',//)
C
C
C
             ELSE
C
C
C
        DO 40 K=1,MM
      Q1(K)=SECMA*THETA*(TEMS**4.0)
```

```
C
      D1(K)=(1.567*(1.0+(RS*F1))*W(K))*0.3334
      DO(K)=3.57*((W(K)/WTM)**0.3334)
      DC(K)=((((273.0*ZH*(1.0-F1))/(448.0*Q1(K)*(1.0+RS*F1)))
     @+1.0)**0.3334)*D1(K)
C
       TC(K)=(DC(K)-DO(K))/1.0
C
C
C
        Y(K)=10.0*TC(K)
        Q2HUM(K)=28.16/(TC(K)**0.735)
        Q2PIG(K)=50.0/(TC(K)**0.71)
            DSH(K)=Y(K)/DC(K)
        F21HUM(K)=Q2HUM(K)/(TAW*Q1(K))
        F21PIG(K)=Q2PIG(K)/(TAW*Q1(K))
        F21B(K)=QB/(TAW*Q1(K))
        F21PE(K)=QPE/(TAW*Q1(K))
C
 40     CONTINUE
C
C
C
      PRINT 421
 421  FORMAT(1X,
     Q'   MASS        TEMP  H/DS    F21-HUMAN  F21-ANIM F21-BUILD',
     @'  F21-PROCESS',/,1X,72('-'))
C
         DO 45 KI=1,MM
        PRINT 493,W(KI),TEMS,DSH(KI),F21HUM(KI),F21PIG(KI)
     @,F21B(KI),F21PE(KI)
 493    FORMAT(2F9.2,5(1X,F9.5))
C
 45     CONTINUE
C
C
C
      IF(DSH(1).GT.2.5) THEN
C
        PRINT 221,DSH(1)
 221    FORMAT(/10X,'THE VALUE OF H/DS =',F10.3,/)
C
C
C
      PRINT 1223
 1223 FORMAT(//,5X,'THE VALUE OF F21 BECOMES VERY SMALL AND THAT MEAN',
     @/,5X,'THE VALUE OF F21 APPROACHES ZERO.',
     @/,5X,'THEN THIS MODEL MUST NOT USED IN THESE CONDITIONS.',///)
C
C
C
         ELSE
C
C
```

```
        PRINT 29
 29     FORMAT(3X,76('*')////)
C
                 ENDIF
                   ENDIF
C
C
C
        RETURN
        END
C
C
C
C
C    SUBROUTINE PROGRAM FOR CALCULATION OF FIREBALL
C    ==============================================
C    BY USING ISO-THERMAL MODEL EQUATIONS:
C    =====================================
C
C
C
      SUBROUTINE ISOTHR(LL,W,THETA,SECMA,V,GN,WTM,FC,TEMS)
C
C
      DIMENSION W(25),F21HUM(25),TC(25),DC(25),DO(25),
     @F21PIG(25),F21B(25),F21PE(25),Y(25),Q1(25),Q2PIG(25),
     @Q2HUM(25),DSH(25)
C
C
C
C
C
C    CALCULATION OF FIREBALL BY USING ISOTHERMAL MODEL:
C    ------------------------------------------------------
        TAW=1.0
       QB=12.6
       QPE=37.8
C
C
C
C
C
       DO 50 L=1,LL
       DO(L)=0.539*((290.0*W(L)/WTM)**0.3333)
       DC(L)=0.539*((V+(GN+1.0)*FC)**0.3333)*((TEMS*W(L)/WTM)**0.3333)
       TC(L)=0.45*(W(L)**0.3334)
C
       Y(L)=10.0*TC(L)
       Q1(L)=SECMA*THETA*(TEMS**4.0)
       Q2HUM(L)=28.16/(TC(L)**0.735)
        Q2PIG(L)=50.0/(TC(L)**0.71)
       DSH(L)=Y(L)/DC(L)
       F21HUM(L)=Q2HUM(L)/(TAW*Q1(L))
       F21PIG(L)=Q2PIG(L)/(TAW*Q1(L))
```

```
         F21B(L)=QB/(TAW*Q1(L))
         F21PE(L)=QPE/(TAW*Q1(L))
C
 50       CONTINUE
C
C
      PRINT 752
 752  FORMAT(1X,
     @'   MASS      TEMP      H/DC   F21-HUMAN   F21-ANIM  F21-BUILD ',
     @'  F21-PROCESS',/,1X,74('-'))
C
C
C
      DO 55 N=1,LL
      PRINT 500,W(N),TEMS,DSH(N),F21HUM(N),F21PIG(N),
     @F21B(N),F21PE(N)
 500    FORMAT(2F9.2,5(2X,F9.5))
 55      CONTINUE
C
       PRINT 43
 43    FORMAT(2X,/)
C
C
                RETURN
                 END
C
C
C
C
C
C  SUBROTINE USED TOCALCULATE B.L.E.V.E. FIREBALL
C  ====================================================
C  DIMENSIONS AND PROPERTIES:
C  ===========================
C
C
C
C
      SUBROUTINE BLEVE(M,W,THETA,SECMA,TEMS,WTM)
C
C
C
      DIMENSION W(25),F21HUM(25),TC(25),DC(25),F21PIG(25),
     @Y(25),Q1BL(25),F21B(25),F21PE(25),DSH(25),
     @Q2PIG(25),Q2HUM(25)
C
C
C
         TAW=1.0
       QB=12.6
       QPE=37.8
C
C
C
```

```
C
C
      DO 83 N=1,M
      TC(N)=0.31*((44.8*W(N)/WTM)**0.3333)
      DC(N)=3.44*((44.8*W(N)/WTM)**0.3333)
C
      Y(N)=0.5*DC(N)
      Q1BL(N)=SEGMA*THETA*(TEMS**4.0)
        Q2HUM(N)=28.16/(TC(N)**0.735)
        Q2PIG(N)=50.0/(TC(N)**0.71)
         DSH(N)=Y(N)/DC(N)
        F21HUM(N)=Q2HUM(N)/(TAW*Q1BL(N))
        F21PIG(N)=Q2PIG(N)/(TAW*Q1BL(N))
        F21B(N)=QB/(TAW*Q1BL(N))
        F21PE(N)=QPE/(TAW*Q1BL(N))
  83   CONTINUE
C
C
      PRINT 703
 703  FORMAT(1X,
     @'    MASS      TEMP      H/DC      F21-HUMAN  F21-ANIM  F21-BUILD     ',
     @' F21-PROCESS',/,1X,74('-'))
C
C
      DO 87 K=1,M
      PRINT 808,W(K),TEMS,DSH(K),F21HUM(K),F21PIG(K),
     @F21B(K),F21PE(K)
 808       FORMAT(2F9.2,5(2X,F9.5))
C
 87          CONTINUE
C
C
        PRINT 819
 819       FORMAT(2X,//)
C
            RETURN
             END
C
C
C
```

```
VIEW FACTOR AND (H/DS) RESULTS:
-------------------------------

(FOR ISOTHERMAL FIREBALL TEMPERATURES)
**************************************


FIREBALL RESULTS USING PREVIOUS WORK EQUATIONS & PARAMETERS:
============================================================


    USING GAYLE PARAMETERS (A,AS,B & BS)
    ====================================


    METHANE FIREBALL RESULTS:
    *************************

    MASS      TEMP      H/DS   F21-HUMAN   F21-ANIM   F21-BUILD   F21-PROCESS
----------------------------------------------------------------------------
  1000.00   2138.00   0.81906   0.02305   0.01999   0.01064   0.03191
  5000.00   2138.00   0.85958   0.01495   0.01331   0.01064   0.03191
 10000.00   2138.00   0.87764   0.01241   0.01117   0.01064   0.03191
 25000.00   2138.00   0.90210   0.00969   0.00886   0.01064   0.03191
 50000.00   2138.00   0.92106   0.00804   0.00744   0.01064   0.03191
 75000.00   2138.00   0.93233   0.00721   0.00671   0.01064   0.03191
100000.00   2138.00   0.94041   0.00668   0.00624   0.01064   0.03191
500000.00   2138.00   0.98693   0.00433   0.00416   0.01064   0.03191


    ETHANE FIREBALL RESULTS:
    ************************

    MASS      TEMP      H/DS   F21-HUMAN   F21-ANIM   F21-BUILD   F21-PROCESS
----------------------------------------------------------------------------
  1000.00   2182.00   0.81906   0.01011   0.01842   0.00980   0.02941
  5000.00   2182.00   0.85958   0.00663   0.01227   0.00980   0.02941
 10000.00   2182.00   0.87764   0.00553   0.01029   0.00980   0.02941
 25000.00   2182.00   0.90210   0.00435   0.00817   0.00980   0.02941
 50000.00   2182.00   0.92106   0.00363   0.00685   0.00980   0.02941
 75000.00   2182.00   0.93233   0.00327   0.00619   0.00980   0.02941
100000.00   2182.00   0.94041   0.00303   0.00575   0.00980   0.02941
500000.00   2182.00   0.98693   0.00199   0.00383   0.00980   0.02941


    PROPANE FIREBALL RESULTS:
    *************************
```

```
     MASS      TEMP       H/DS    F21-HUMAN F21-ANIM  F21-BULID  F21-PROCESS
-----------------------------------------------------------------------------
   1000.00   2188.00    0.81906    0.01000   0.01822   0.00970    0.02909
   5000.00   2188.00    0.85958    0.00656   0.01213   0.00970    0.02909
  10000.00   2188.00    0.87764    0.00547   0.01018   0.00970    0.02909
  25000.00   2188.00    0.90210    0.00431   0.00808   0.00970    0.02909
  50000.00   2188.00    0.92106    0.00359   0.00678   0.00970    0.02909
  75000.00   2188.00    0.93233    0.00323   0.00612   0.00970    0.02909
 100000.00   2188.00    0.94041    0.00300   0.00569   0.00970    0.02909
 500000.00   2188.00    0.98693    0.00197   0.00379   0.00970    0.02909



            BUTANE FIREBALL RESULTS:
            *************************

     MASS      TEMP       H/DS    F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
-----------------------------------------------------------------------------
   1000.00   2188.00    0.81906    0.01000   0.01822   0.00970    0.02909
   5000.00   2188.00    0.85958    0.00656   0.01213   0.00970    0.02909
  10000.00   2188.00    0.87764    0.00547   0.01018   0.00970    0.02909
  25000.00   2188.00    0.90210    0.00431   0.00808   0.00970    0.02909
  50000.00   2188.00    0.92106    0.00359   0.00678   0.00970    0.02909
  75000.00   2188.00    0.93233    0.00323   0.00612   0.00970    0.02909
 100000.00   2188.00    0.94041    0.00300   0.00569   0.00970    0.02909
 500000.00   2188.00    0.98693    0.00197   0.00379   0.00970    0.02909



            PENTANE FIREBALL RESULTS:
            **************************

     MASS      TEMP       H/DS    F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
-----------------------------------------------------------------------------
   1000.00   2190.00    0.81906    0.00996   0.01816   0.00966    0.02898
   5000.00   2190.00    0.85958    0.00654   0.01209   0.00966    0.02898
  10000.00   2190.00    0.87764    0.00545   0.01015   0.00966    0.02898
  25000.00   2190.00    0.90210    0.00429   0.00805   0.00966    0.02898
  50000.00   2190.00    0.92106    0.00358   0.00675   0.00966    0.02898
  75000.00   2190.00    0.93233    0.00322   0.00610   0.00966    0.02898
 100000.00   2190.00    0.94041    0.00298   0.00567   0.00966    0.02898
 500000.00   2190.00    0.98693    0.00196   0.00377   0.00966    0.02898



            USING BRASIE PARAMETERS (A,AS,B & BS)
            =====================================


            METHANE FIREBALL RESULTS:
```

```
     *************************

  MASS       TEMP      H/DS  F21-HUMAN   F21-ANIM  F21-BUILD  F21-PROCESS
--------------------------------------------------------------------------
   1000.00  2086.00  0.78947   0.02461   0.02138   0.01174   0.03521
   5000.00  2086.00  0.78947   0.01641   0.01462   0.01174   0.03521
  10000.00  2086.00  0.78947   0.01379   0.01241   0.01174   0.03521
  25000.00  2086.00  0.78947   0.01095   0.00999   0.01174   0.03521
  50000.00  2086.00  0.78947   0.00919   0.00848   0.01174   0.03521
  75000.00  2086.00  0.78947   0.00830   0.00770   0.01174   0.03521
 100000.00  2086.00  0.78947   0.00772   0.00720   0.01174   0.03521
 500000.00  2086.00  0.78947   0.00515   0.00492   0.01174   0.03521


      ETHANE FIREBALL RESULTS:
     *************************

  MASS      TEMP      H/DS   F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
--------------------------------------------------------------------------
   1000.00  2126.00   0.78947   0.01086   0.01982   0.01088   0.03263
   5000.00  2126.00   0.78947   0.00732   0.01355   0.01088   0.03263
  10000.00  2126.00   0.78947   0.00618   0.01150   0.01088   0.03263
  25000.00  2126.00   0.78947   0.00494   0.00926   0.01088   0.03263
  50000.00  2126.00   0.78947   0.00417   0.00786   0.01088   0.03263
  75000.00  2126.00   0.78947   0.00377   0.00714   0.01088   0.03263
 100000.00  2126.00   0.78947   0.00352   0.00667   0.01088   0.03263
 500000.00  2126.00   0.78947   0.00237   0.00456   0.01088   0.03263


     PROPANE FIREBALL RESULTS:
     ************************

  MASS      TEMP      H/DS    F21-HUMAN F21-ANIM  F21-BULID  F21-PROCESS
--------------------------------------------------------------------------
   1000.00  2132.00  0.78947   0.01074   0.01960   0.01076   0.03227
   5000.00  2132.00  0.78947   0.00724   0.01339   0.01076   0.03227
  10000.00  2132.00  0.78947   0.00611   0.01137   0.01076   0.03227
  25000.00  2132.00  0.78947   0.00488   0.00916   0.01076   0.03227
  50000.00  2132.00  0.78947   0.00412   0.00777   0.01076   0.03227
  75000.00  2132.00  0.78947   0.00373   0.00706   0.01076   0.03227
 100000.00  2132.00  0.78947   0.00348   0.00660   0.01076   0.03227
 500000.00  2132.00  0.78947   0.00235   0.00451   0.01076   0.03227


     BUTANE FIREBALL RESULTS:
     ************************

  MASS      TEMP      H/DS   F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
```

```
--------------------------------------------------------------------------------------------
   1000.00  2132.00    0.78947    0.01074    0.01960    0.01076    0.03227
   5000.00  2132.00    0.78947    0.00724    0.01339    0.01076    0.03227
  10000.00  2132.00    0.78947    0.00611    0.01137    0.01076    0.03227
  25000.00  2132.00    0.78947    0.00488    0.00916    0.01076    0.03227
  50000.00  2132.00    0.78947    0.00412    0.00777    0.01076    0.03227
  75000.00  2132.00    0.78947    0.00373    0.00706    0.01076    0.03227
 100000.00  2132.00    0.78947    0.00348    0.00660    0.01076    0.03227
 500000.00  2132.00    0.78947    0.00235    0.00451    0.01076    0.03227


           PENTANE FIREBALL RESULTS:
           **************************

      MASS       TEMP       H/DS  F21-HUMAN   F21-ANIM  F21-BUILD  F21-PROCESS
--------------------------------------------------------------------------------------------
   1000.00  2134.00    0.78947    0.01070    0.01952    0.01072    0.03215
   5000.00  2134.00    0.78947    0.00722    0.01334    0.01072    0.03215
  10000.00  2134.00    0.78947    0.00609    0.01133    0.01072    0.03215
  25000.00  2134.00    0.78947    0.00487    0.00912    0.01072    0.03215
  50000.00  2134.00    0.78947    0.00411    0.00774    0.01072    0.03215
  75000.00  2134.00    0.78947    0.00372    0.00703    0.01072    0.03215
 100000.00  2134.00    0.78947    0.00347    0.00657    0.01072    0.03215
 500000.00  2134.00    0.78947    0.00234    0.00449    0.01072    0.03215



           USING MARSHALL PARAMETERS (A,AS,B & BS):
           ========================================


           METHANE FIREBALL RESULTS:
           **************************

      MASS       TEMP       H/DS  F21-HUMAN   F21-ANIM  F21-BUILD  F21-PROCESS
--------------------------------------------------------------------------------------------
   1000.00  2024.00    0.69091    0.02323    0.02040    0.01324    0.03973
   5000.00  2024.00    0.69091    0.01549    0.01394    0.01324    0.03973
  10000.00  2024.00    0.69091    0.01301    0.01184    0.01324    0.03973
  25000.00  2024.00    0.69091    0.01033    0.00953    0.01324    0.03973
  50000.00  2024.00    0.69091    0.00868    0.00809    0.01324    0.03973
  75000.00  2024.00    0.69091    0.00783    0.00735    0.01324    0.03973
 100000.00  2024.00    0.69091    0.00729    0.00687    0.01324    0.03973
 500000.00  2024.00    0.69091    0.00486    0.00469    0.01324    0.03973


           ETHANE FIREBALL RESULTS:
           **************************
```

```
   MASS      TEMP       H/DS    F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
--------------------------------------------------------------------------
  1000.00  2060.00    0.69091    0.01036   0.01901    0.01234    0.03702
  5000.00  2060.00    0.69091    0.00698   0.01299    0.01234    0.03702
 10000.00  2060.00    0.69091    0.00589   0.01103    0.01234    0.03702
 25000.00  2060.00    0.69091    0.00471   0.00888    0.01234    0.03702
 50000.00  2060.00    0.69091    0.00398   0.00754    0.01234    0.03702
 75000.00  2060.00    0.69091    0.00360   0.00685    0.01234    0.03702
100000.00  2060.00    0.69091    0.00335   0.00640    0.01234    0.03702
500000.00  2060.00    0.69091    0.00226   0.00437    0.01234    0.03702


          PROPANE FIREBALL RESULTS:
          *************************

   MASS      TEMP       H/DS    F21-HUMAN F21-ANIM  F21-BULID  F21-PROCESS
--------------------------------------------------------------------------
  1000.00  2064.00    0.69091    0.01028   0.01886    0.01224    0.03673
  5000.00  2064.00    0.69091    0.00693   0.01289    0.01224    0.03673
 10000.00  2064.00    0.69091    0.00585   0.01094    0.01224    0.03673
 25000.00  2064.00    0.69091    0.00467   0.00881    0.01224    0.03673
 50000.00  2064.00    0.69091    0.00394   0.00748    0.01224    0.03673
 75000.00  2064.00    0.69091    0.00357   0.00680    0.01224    0.03673
100000.00  2064.00    0.69091    0.00333   0.00635    0.01224    0.03673
500000.00  2064.00    0.69091    0.00225   0.00434    0.01224    0.03673


          BUTANE FIREBALL RESULTS:
          **************************

   MASS      TEMP      H/DS    F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
--------------------------------------------------------------------------
  1000.00  2064.00   0.69091    0.01028   0.01886    0.01224    0.03673
  5000.00  2064.00   0.69091    0.00693   0.01289    0.01224    0.03673
 10000.00  2064.00   0.69091    0.00585   0.01094    0.01224    0.03673
 25000.00  2064.00   0.69091    0.00467   0.00881    0.01224    0.03673
 50000.00  2064.00   0.69091    0.00394   0.00748    0.01224    0.03673
 75000.00  2064.00   0.69091    0.00357   0.00680    0.01224    0.03673
100000.00  2064.00   0.69091    0.00333   0.00635    0.01224    0.03673
500000.00  2064.00   0.69091    0.00225   0.00434    0.01224    0.03673


          PENTANE FIREBALL RESULTS:
          ***************************

   MASS       TEMP       H/DS  F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
--------------------------------------------------------------------------
  1000.00  2066.00   0.78947   0.01218   0.02222    0.01220    0.03659
```

```
   5000.00  2066.00   0.78947   0.00821   0.01519   0.01220   0.03659
  10000.00  2066.00   0.78947   0.00693   0.01289   0.01220   0.03659
  25000.00  2066.00   0.78947   0.00554   0.01038   0.01220   0.03659
  50000.00  2066.00   0.78947   0.00467   0.00881   0.01220   0.03659
  75000.00  2066.00   0.78947   0.00423   0.00801   0.01220   0.03659
 100000.00  2066.00   0.78947   0.00395   0.00748   0.01220   0.03659
 500000.00  2066.00   0.78947   0.00266   0.00511   0.01220   0.03659



           USING ROBERTS PARAMETERS (A,AS,B & BS):
           =======================================


            METHANE FIREBALL RESULTS:
           **************************

     MASS       TEMP      H/DS  F21-HUMAN   F21-ANIM  F21-BUILD  F21-PROCESS
 ------------------------------------------------------------------------
   1000.00  1980.00   0.77586   0.02232   0.01975   0.01446   0.04338
   5000.00  1980.00   0.77586   0.01488   0.01350   0.01446   0.04338
  10000.00  1980.00   0.77586   0.01250   0.01146   0.01446   0.04338
  25000.00  1980.00   0.77586   0.00992   0.00923   0.01446   0.04338
  50000.00  1980.00   0.77586   0.00834   0.00783   0.01446   0.04338
  75000.00  1980.00   0.77586   0.00753   0.00712   0.01446   0.04338
 100000.00  1980.00   0.77586   0.00700   0.00665   0.01446   0.04338
 500000.00  1980.00   0.77586   0.00467   0.00455   0.01446   0.04338



            ETHANE FIREBALL RESULTS:
           **************************

     MASS      TEMP       H/DS   F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
 -------------------------------------------------------------------------
   1000.00  2012.00   0.77586   0.01005   0.01853   0.01356   0.04068
   5000.00  2012.00   0.77586   0.00678   0.01266   0.01356   0.04068
  10000.00  2012.00   0.77586   0.00572   0.01075   0.01356   0.04068
  25000.00  2012.00   0.77586   0.00457   0.00866   0.01356   0.04068
  50000.00  2012.00   0.77586   0.00386   0.00735   0.01356   0.04068
  75000.00  2012.00   0.77586   0.00349   0.00668   0.01356   0.04068
 100000.00  2012.00   0.77586   0.00326   0.00624   0.01356   0.04068
 500000.00  2012.00   0.77586   0.00220   0.00426   0.01356   0.04068



           PROPANE FIREBALL RESULTS:
           ************************

     MASS      TEMP       H/DS   F21-HUMAN F21-ANIM  F21-BULID  F21-PROCESS
```

```
-----------------------------------------------------------------------------------------
  1000.00   2016.00    0.77586   0.00997   0.01838   0.01345   0.04036
  5000.00   2016.00    0.77586   0.00672   0.01256   0.01345   0.04036
 10000.00   2016.00    0.77586   0.00567   0.01066   0.01345   0.04036
 25000.00   2016.00    0.77586   0.00453   0.00859   0.01345   0.04036
 50000.00   2016.00    0.77586   0.00383   0.00729   0.01345   0.04036
 75000.00   2016.00    0.77586   0.00347   0.00662   0.01345   0.04036
100000.00   2016.00    0.77586   0.00323   0.00619   0.01345   0.04036
500000.00   2016.00    0.77586   0.00218   0.00423   0.01345   0.04036


          BUTANE FIREBALL RESULTS:
          *************************

   MASS       TEMP       H/DS   F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
-----------------------------------------------------------------------------------------
  1000.00   2016.00    0.77586   0.00997   0.01838   0.01345   0.04036
  5000.00   2016.00    0.77586   0.00672   0.01256   0.01345   0.04036
 10000.00   2016.00    0.77586   0.00567   0.01066   0.01345   0.04036
 25000.00   2016.00    0.77586   0.00453   0.00859   0.01345   0.04036
 50000.00   2016.00    0.77586   0.00383   0.00729   0.01345   0.04036
 75000.00   2016.00    0.77586   0.00347   0.00662   0.01345   0.04036
100000.00   2016.00    0.77586   0.00323   0.00619   0.01345   0.04036
500000.00   2016.00    0.77586   0.00218   0.00423   0.01345   0.04036


          PENTANE FIREBALL RESULTS:
          **************************

   MASS        TEMP       H/DS  F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
-----------------------------------------------------------------------------------------
  1000.00   2016.00    0.77586   0.00997   0.01838   0.01345   0.04036
  5000.00   2016.00    0.77586   0.00672   0.01256   0.01345   0.04036
 10000.00   2016.00    0.77586   0.00567   0.01066   0.01345   0.04036
 25000.00   2016.00    0.77586   0.00453   0.00859   0.01345   0.04036
 50000.00   2016.00    0.77586   0.00383   0.00729   0.01345   0.04036
 75000.00   2016.00    0.77586   0.00347   0.00662   0.01345   0.04036
100000.00   2016.00    0.77586   0.00323   0.00619   0.01345   0.04036
500000.00   2016.00    0.77586   0.00218   0.00423   0.01345   0.04036


          USING HOT SHELL-COLD CORE MODEL:
          ===================================


          METHANE RESULTS OF HOT SHELL-COLD CORE MODEL:
          **********************************************
```

```
    MASS       TEMP      H/DS    F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
----------------------------------------------------------------------------
   1000.00   1500.00   0.79645   0.01024   0.02010   0.08779    0.26337
   5000.00   1500.00   0.79645   0.00690   0.01373   0.08779    0.26337
  10000.00   1500.00   0.79645   0.00582   0.01165   0.08779    0.26337
  25000.00   1500.00   0.79645   0.00465   0.00938   0.08779    0.26337
  50000.00   1500.00   0.79645   0.00392   0.00796   0.08779    0.26337
  75000.00   1500.00   0.79645   0.00355   0.00723   0.08779    0.26337
 100000.00   1500.00   0.79645   0.00331   0.00676   0.08779    0.26337
 500000.00   1500.00   0.79645   0.00223   0.00462   0.08779    0.26337


           BUTANE RESULTS OF HOT SHELL-COLD CORE MODEL:
           *******************************************


           THE VALUE OF F1 =      0.007

    MASS        TEMP   H/DS     F21-HUMAN  F21-ANIM F21-BUILD  F21-PROCESS
----------------------------------------------------------------------------
   1000.00   1300.00   9.97053   0.00047   0.00102   0.07781    0.23342
   5000.00   1300.00   9.98992   0.00014   0.00032   0.07781    0.23342
  10000.00   1300.00   9.99365   0.00009   0.00020   0.07781    0.23342
  25000.00   1300.00   9.99655   0.00004   0.00010   0.07781    0.23342
  50000.00   1300.00   9.99783   0.00003   0.00006   0.07781    0.23342
  75000.00   1300.00   9.99834   0.00002   0.00005   0.07781    0.23342
 100000.00   1300.00   9.99863   0.00002   0.00004   0.07781    0.23342
 500000.00   1300.00   9.99953   0.00000   0.00001   0.07781    0.23342

           THE VALUE OF H/DS =      9.971


       THE VALUE OF F21 BECOMES VERY SMALL AND THAT MEAN
       THE VALUE OF F21 APPROACHES ZERO.
       THEN THIS MODEL MUST NOT USED IN THESE CONDITIONS.


           USING ISO-THERMAL MODEL:
           =======================


           METANE RESULTS OF ISO-THERMAL MODEL:
           ====================================

    MASS      TEMP        H/DC   F21-HUMAN    F21-ANIM  F21-BUILD   F21-PROCESS
-------------------------------------------------------------------------------
   1000.00  1980.00    0.76761    0.01069    0.01972    0.01446     0.04338
   5000.00  1980.00    0.76773    0.00721    0.01347    0.01446     0.04338
  10000.00  1980.00    0.76779    0.00608    0.01143    0.01446     0.04338
  25000.00  1980.00    0.76786    0.00486    0.00920    0.01446     0.04338
  50000.00  1980.00    0.76791    0.00410    0.00781    0.01446     0.04338
  75000.00  1980.00    0.76794    0.00371    0.00709    0.01446     0.04338
```

```
100000.00  1980.00    0.76796    0.00346    0.00663    0.01446    0.04338
500000.00  1980.00    0.76809    0.00233    0.00453    0.01446    0.04338


            ETHANE RESULTS OF ISO-THERMAL MODEL:
            ====================================

      MASS        TEMP      H/DC   F21-HUMAN   F21-ANIM  F21-BUILD   F21-PROCESS
--------------------------------------------------------------------------------
    1000.00  2012.00    0.78380    0.01003    0.01849    0.01356    0.04068
    5000.00  2012.00    0.78393    0.00676    0.01263    0.01356    0.04068
   10000.00  2012.00    0.78398    0.00570    0.01072    0.01356    0.04068
   25000.00  2012.00    0.78405    0.00456    0.00863    0.01356    0.04068
   50000.00  2012.00    0.78411    0.00385    0.00732    0.01356    0.04068
   75000.00  2012.00    0.78414    0.00348    0.00665    0.01356    0.04068
  100000.00  2012.00    0.78416    0.00324    0.00622    0.01356    0.04068
  500000.00  2012.00    0.78429    0.00219    0.00425    0.01356    0.04068


            PROPANE RESULTS OF ISO-THERMAL MODEL:
            =====================================

      MASS        TEMP      H/DC   F21-HUMAN   F21-ANIM  F21-BUILD   F21-PROCESS
--------------------------------------------------------------------------------
    1000.00  2016.00    0.79137    0.00995    0.01834    0.01345    0.04036
    5000.00  2016.00    0.79150    0.00671    0.01253    0.01345    0.04036
   10000.00  2016.00    0.79155    0.00566    0.01064    0.01345    0.04036
   25000.00  2016.00    0.79163    0.00452    0.00856    0.01345    0.04036
   50000.00  2016.00    0.79168    0.00382    0.00727    0.01345    0.04036
   75000.00  2016.00    0.79171    0.00345    0.00660    0.01345    0.04036
  100000.00  2016.00    0.79174    0.00322    0.00617    0.01345    0.04036
  500000.00  2016.00    0.79186    0.00217    0.00421    0.01345    0.04036


            BUTANE RESULTS OF ISO-THERMAL MODEL:
            ====================================

      MASS        TEMP      H/DC   F21-HUMAN   F21-ANIM  F21-BUILD   F21-PROCESS
--------------------------------------------------------------------------------
    1000.00  2016.00    0.79566    0.00995    0.01834    0.01345    0.04036
    5000.00  2016.00    0.79579    0.00671    0.01253    0.01345    0.04036
   10000.00  2016.00    0.79584    0.00566    0.01064    0.01345    0.04036
   25000.00  2016.00    0.79591    0.00452    0.00856    0.01345    0.04036
   50000.00  2016.00    0.79597    0.00382    0.00727    0.01345    0.04036
   75000.00  2016.00    0.79600    0.00345    0.00660    0.01345    0.04036
  100000.00  2016.00    0.79602    0.00322    0.00617    0.01345    0.04036
  500000.00  2016.00    0.79615    0.00217    0.00421    0.01345    0.04036


            PENTANE RESULTS OF ISO-THERMAL MODDEL:
            ======================================

      MASS        TEMP      H/DC   F21-HUMAN   F21-ANIM  F21-BUILD   F21-PROCESS
--------------------------------------------------------------------------------
```

```
   1000.00  2016.00     0.79837     0.00995     0.01834     0.01345     0.04036
   5000.00  2016.00     0.79850     0.00671     0.01253     0.01345     0.04036
  10000.00  2016.00     0.79855     0.00566     0.01064     0.01345     0.04036
  25000.00  2016.00     0.79863     0.00452     0.00856     0.01345     0.04036
  50000.00  2016.00     0.79868     0.00382     0.00727     0.01345     0.04036
  75000.00  2016.00     0.79871     0.00345     0.00660     0.01345     0.04036
 100000.00  2016.00     0.79874     0.00322     0.00617     0.01345     0.04036
 500000.00  2016.00     0.79887     0.00217     0.00421     0.01345     0.04036



          B.L.E.V.E FIREBALL RESULTS:
         ******************************


          METHANE BLEVE FIREBALL RESULTS:
         ==================================

     MASS      TEMP       H/DC      F21-HUMAN  F21-ANIM  F21-BUILD    F21-PROCESS
  ---------------------------------------------------------------------------------
   1000.00  1482.00     0.50000     0.03484     0.06418     0.04607     0.13820
   5000.00  1482.00     0.50000     0.02349     0.04385     0.04607     0.13820
  10000.00  1482.00     0.50000     0.01982     0.03722     0.04607     0.13820
  25000.00  1482.00     0.50000     0.01583     0.02996     0.04607     0.13820
  50000.00  1482.00     0.50000     0.01336     0.02543     0.04607     0.13820
  75000.00  1482.00     0.50000     0.01210     0.02310     0.04607     0.13820
 100000.00  1482.00     0.50000     0.01127     0.02158     0.04607     0.13820
 500000.00  1482.00     0.50000     0.00760     0.01475     0.04607     0.13820


          ETHANE BLEVE FIREBALL RESULTS:
         ==================================

     MASS      TEMP       H/DC      F21-HUMAN  F21-ANIM  F21-BUILD    F21-PROCESS
  ---------------------------------------------------------------------------------
   1000.00  1642.00     0.50000     0.02697     0.04942     0.03057     0.09171
   5000.00  1642.00     0.50000     0.01818     0.03377     0.03057     0.09171
  10000.00  1642.00     0.50000     0.01534     0.02866     0.03057     0.09171
  25000.00  1642.00     0.50000     0.01226     0.02307     0.03057     0.09171
  50000.00  1642.00     0.50000     0.01034     0.01958     0.03057     0.09171
  75000.00  1642.00     0.50000     0.00936     0.01779     0.03057     0.09171
 100000.00  1642.00     0.50000     0.00873     0.01662     0.03057     0.09171
 500000.00  1642.00     0.50000     0.00588     0.01136     0.03057     0.09171


          PROPANE BLEVE FIREBALL RESULTS:
         ==================================

     MASS      TEMP       H/DC      F21-HUMAN  F21-ANIM  F21-BUILD    F21-PROCESS
  ---------------------------------------------------------------------------------
```

```
    1000.00  1740.00    0.50000    0.02349    0.04291    0.02424    0.07273
    5000.00  1740.00    0.50000    0.01584    0.02932    0.02424    0.07273
   10000.00  1740.00    0.50000    0.01336    0.02488    0.02424    0.07273
   25000.00  1740.00    0.50000    0.01068    0.02003    0.02424    0.07273
   50000.00  1740.00    0.50000    0.00901    0.01700    0.02424    0.07273
   75000.00  1740.00    0.50000    0.00816    0.01545    0.02424    0.07273
  100000.00  1740.00    0.50000    0.00760    0.01443    0.02424    0.07273
  500000.00  1740.00    0.50000    0.00512    0.00986    0.02424    0.07273


            BUTANE BLEVE FIREBALL RESULTS:
            ======================================

     MASS       TEMP      H/DC     F21-HUMAN  F21-ANIM  F21-BUILD   F21-PROCESS
 ------------------------------------------------------------------------------
    1000.00  1818.00    0.50000    0.02109    0.03844    0.02034    0.06103
    5000.00  1818.00    0.50000    0.01422    0.02626    0.02034    0.06103
   10000.00  1818.00    0.50000    0.01200    0.02229    0.02034    0.06103
   25000.00  1818.00    0.50000    0.00959    0.01794    0.02034    0.06103
   50000.00  1818.00    0.50000    0.00809    0.01523    0.02034    0.06103
   75000.00  1818.00    0.50000    0.00732    0.01384    0.02034    0.06103
  100000.00  1818.00    0.50000    0.00683    0.01293    0.02034    0.06103
  500000.00  1818.00    0.50000    0.00460    0.00883    0.02034    0.06103


            PENTANE BLEVE FIREBALL RESULTS:
            ======================================

     MASS       TEMP      H/DC     F21-HUMAN  F21-ANIM  F21-BUILD   F21-PROCESS
 ------------------------------------------------------------------------------
    1000.00  1884.00    0.50000    0.01928    0.03508    0.01764    0.05292
    5000.00  1884.00    0.50000    0.01300    0.02397    0.01764    0.05292
   10000.00  1884.00    0.50000    0.01097    0.02034    0.01764    0.05292
   25000.00  1884.00    0.50000    0.00876    0.01638    0.01764    0.05292
   50000.00  1884.00    0.50000    0.00739    0.01390    0.01764    0.05292
   75000.00  1884.00    0.50000    0.00670    0.01263    0.01764    0.05292
  100000.00  1884.00    0.50000    0.00624    0.01180    0.01764    0.05292
  500000.00  1884.00    0.50000    0.00421    0.00806    0.01764    0.05292
```

```
          VIEW FACTOR AND (H/DS) RESULTS:
          -------------------------------

          (FOR THERMODYNAMIC FIREBALL TEMPERATURES)
          *****************************************


     FIREBALL RESULTS USING PREVIOUS WORK EQUATIONS & PARAMETERS:
     ============================================================


        USING GAYLE PARAMETERS (A,AS,B & BS)
        =====================================


         METHANE FIREBALL RESULTS:
        **************************

    MASS      TEMP      H/DS  F21-HUMAN    F21-ANIM  F21-BUILD  F21-PROCESS
  -------------------------------------------------------------------------
   1000.00  2014.47   0.81906   0.02925   0.02536   0.01349   0.04048
   5000.00  2014.47   0.85958   0.01897   0.01688   0.01349   0.04048
  10000.00  2014.47   0.87764   0.01574   0.01417   0.01349   0.04048
  25000.00  2014.47   0.90210   0.01230   0.01124   0.01349   0.04048
  50000.00  2014.47   0.92106   0.01021   0.00943   0.01349   0.04048
  75000.00  2014.47   0.93233   0.00915   0.00852   0.01349   0.04048
 100000.00  2014.47   0.94041   0.00847   0.00792   0.01349   0.04048
 500000.00  2014.47   0.98693   0.00549   0.00527   0.01349   0.04048



         ETHANE FIREBALL RESULTS:
        **************************

    MASS     TEMP       H/DS   F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
  -------------------------------------------------------------------------
   1000.00  2092.95   0.81906   0.01194   0.02177   0.01158   0.03474
   5000.00  2092.95   0.85958   0.00784   0.01449   0.01158   0.03474
  10000.00  2092.95   0.87764   0.00654   0.01216   0.01158   0.03474
  25000.00  2092.95   0.90210   0.00514   0.00965   0.01158   0.03474
  50000.00  2092.95   0.92106   0.00429   0.00810   0.01158   0.03474
  75000.00  2092.95   0.93233   0.00386   0.00731   0.01158   0.03474
 100000.00  2092.95   0.94041   0.00358   0.00680   0.01158   0.03474
 500000.00  2092.95   0.98693   0.00235   0.00452   0.01158   0.03474



        PROPANE FIREBALL RESULTS:
        ************************
```

```
      MASS    TEMP      H/DS    F21-HUMAN F21-ANIM  F21-BULID  F21-PROCESS
-------------------------------------------------------------------------
   1000.00  2113.34   0.81906   0.01149   0.02094   0.01114   0.03342
   5000.00  2113.34   0.85958   0.00754   0.01394   0.01114   0.03342
  10000.00  2113.34   0.87764   0.00629   0.01170   0.01114   0.03342
  25000.00  2113.34   0.90210   0.00495   0.00928   0.01114   0.03342
  50000.00  2113.34   0.92106   0.00413   0.00779   0.01114   0.03342
  75000.00  2113.34   0.93233   0.00371   0.00703   0.01114   0.03342
 100000.00  2113.34   0.94041   0.00344   0.00654   0.01114   0.03342
 500000.00  2113.34   0.98693   0.00226   0.00435   0.01114   0.03342



          BUTANE FIREBALL RESULTS:
          *************************

     MASS    TEMP      H/DS   F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
-------------------------------------------------------------------------
   1000.00  2120.31   0.81906   0.01134   0.02066   0.01099   0.03298
   5000.00  2120.31   0.85958   0.00744   0.01376   0.01099   0.03298
  10000.00  2120.31   0.87764   0.00621   0.01155   0.01099   0.03298
  25000.00  2120.31   0.90210   0.00488   0.00916   0.01099   0.03298
  50000.00  2120.31   0.92106   0.00407   0.00769   0.01099   0.03298
  75000.00  2120.31   0.93233   0.00366   0.00694   0.01099   0.03298
 100000.00  2120.31   0.94041   0.00340   0.00645   0.01099   0.03298
 500000.00  2120.31   0.98693   0.00223   0.00430   0.01099   0.03298



          PENTANE FIREBALL RESULTS:
          **************************

     MASS      TEMP      H/DS  F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
-------------------------------------------------------------------------
   1000.00  2127.22   0.81906   0.01119   0.02040   0.01085   0.03256
   5000.00  2127.22   0.85958   0.00734   0.01358   0.01085   0.03256
  10000.00  2127.22   0.87764   0.00613   0.01140   0.01085   0.03256
  25000.00  2127.22   0.90210   0.00482   0.00904   0.01085   0.03256
  50000.00  2127.22   0.92106   0.00402   0.00759   0.01085   0.03256
  75000.00  2127.22   0.93233   0.00362   0.00685   0.01085   0.03256
 100000.00  2127.22   0.94041   0.00335   0.00637   0.01085   0.03256
 500000.00  2127.22   0.98693   0.00220   0.00424   0.01085   0.03256



          USING BRASIE PARAMETERS (A,AS,B & BS)
          =====================================


          METHANE FIREBALL RESULTS:
```

```
         **************************

   MASS      TEMP      H/DS  F21-HUMAN   F21-ANIM  F21-BUILD  F21-PROCESS
---------------------------------------------------------------------------
   1000.00  2014.47  0.78947  0.02830   0.02459   0.01349   0.04048
   5000.00  2014.47  0.78947  0.01887   0.01681   0.01349   0.04048
  10000.00  2014.47  0.78947  0.01585   0.01426   0.01349   0.04048
  25000.00  2014.47  0.78947  0.01259   0.01149   0.01349   0.04048
  50000.00  2014.47  0.78947  0.01057   0.00975   0.01349   0.04048
  75000.00  2014.47  0.78947  0.00954   0.00886   0.01349   0.04048
 100000.00  2014.47  0.78947  0.00888   0.00828   0.01349   0.04048
 500000.00  2014.47  0.78947  0.00592   0.00566   0.01349   0.04048


          ETHANE FIREBALL RESULTS:
         **************************

   MASS     TEMP      H/DS   F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
---------------------------------------------------------------------------
   1000.00  2092.95   0.78947  0.01156   0.02110   0.01158   0.03474
   5000.00  2092.95   0.78947  0.00780   0.01442   0.01158   0.03474
  10000.00  2092.95   0.78947  0.00658   0.01224   0.01158   0.03474
  25000.00  2092.95   0.78947  0.00526   0.00986   0.01158   0.03474
  50000.00  2092.95   0.78947  0.00444   0.00837   0.01158   0.03474
  75000.00  2092.95   0.78947  0.00402   0.00760   0.01158   0.03474
 100000.00  2092.95   0.78947  0.00375   0.00710   0.01158   0.03474
 500000.00  2092.95   0.78947  0.00253   0.00485   0.01158   0.03474


          PROPANE FIREBALL RESULTS:
         ************************

   MASS     TEMP      H/DS    F21-HUMAN F21-ANIM   F21-BULID  F21-PROCESS
---------------------------------------------------------------------------
   1000.00  2113.34  0.78947  0.01112   0.02030   0.01114   0.03342
   5000.00  2113.34  0.78947  0.00750   0.01387   0.01114   0.03342
  10000.00  2113.34  0.78947  0.00633   0.01178   0.01114   0.03342
  25000.00  2113.34  0.78947  0.00506   0.00948   0.01114   0.03342
  50000.00  2113.34  0.78947  0.00427   0.00805   0.01114   0.03342
  75000.00  2113.34  0.78947  0.00387   0.00731   0.01114   0.03342
 100000.00  2113.34  0.78947  0.00360   0.00683   0.01114   0.03342
 500000.00  2113.34  0.78947  0.00243   0.00467   0.01114   0.03342


          BUTANE FIREBALL RESULTS:
         *************************

   MASS     TEMP      H/DS   F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
```

```
------------------------------------------------------------------------------
   1000.00  2120.31   0.78947   0.01098   0.02003   0.01099   0.03298
   5000.00  2120.31   0.78947   0.00740   0.01369   0.01099   0.03298
  10000.00  2120.31   0.78947   0.00625   0.01162   0.01099   0.03298
  25000.00  2120.31   0.78947   0.00499   0.00936   0.01099   0.03298
  50000.00  2120.31   0.78947   0.00421   0.00794   0.01099   0.03298
  75000.00  2120.31   0.78947   0.00382   0.00722   0.01099   0.03298
 100000.00  2120.31   0.78947   0.00356   0.00674   0.01099   0.03298
 500000.00  2120.31   0.78947   0.00240   0.00461   0.01099   0.03298


          PENTANE FIREBALL RESULTS:
          *************************

      MASS      TEMP      H/DS  F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
------------------------------------------------------------------------------
   1000.00  2127.22   0.78947   0.01084   0.01977   0.01085   0.03256
   5000.00  2127.22   0.78947   0.00731   0.01352   0.01085   0.03256
  10000.00  2127.22   0.78947   0.00617   0.01147   0.01085   0.03256
  25000.00  2127.22   0.78947   0.00493   0.00924   0.01085   0.03256
  50000.00  2127.22   0.78947   0.00416   0.00784   0.01085   0.03256
  75000.00  2127.22   0.78947   0.00377   0.00712   0.01085   0.03256
 100000.00  2127.22   0.78947   0.00351   0.00666   0.01085   0.03256
 500000.00  2127.22   0.78947   0.00237   0.00455   0.01085   0.03256


          USING MARSHALL PARAMETERS (A,AS,B & BS):
          ========================================


          METHANE FIREBALL RESULTS:
          *************************

      MASS      TEMP      H/DS  F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
------------------------------------------------------------------------------
   1000.00  2014.47   0.69091   0.02367   0.02079   0.01349   0.04048
   5000.00  2014.47   0.69091   0.01578   0.01421   0.01349   0.04048
  10000.00  2014.47   0.69091   0.01326   0.01206   0.01349   0.04048
  25000.00  2014.47   0.69091   0.01053   0.00971   0.01349   0.04048
  50000.00  2014.47   0.69091   0.00884   0.00824   0.01349   0.04048
  75000.00  2014.47   0.69091   0.00798   0.00749   0.01349   0.04048
 100000.00  2014.47   0.69091   0.00742   0.00700   0.01349   0.04048
 500000.00  2014.47   0.69091   0.00495   0.00478   0.01349   0.04048


          ETHANE FIREBALL RESULTS:
          *************************
```

```
     MASS      TEMP        H/DS    F21-HUMAN   F21-ANIM   F21-BUILD   F21-PROCESS
----------------------------------------------------------------------------------
   1000.00   2092.95     0.69091    0.00972    0.01784    0.01158     0.03474
   5000.00   2092.95     0.69091    0.00655    0.01219    0.01158     0.03474
  10000.00   2092.95     0.69091    0.00553    0.01035    0.01158     0.03474
  25000.00   2092.95     0.69091    0.00442    0.00833    0.01158     0.03474
  50000.00   2092.95     0.69091    0.00373    0.00707    0.01158     0.03474
  75000.00   2092.95     0.69091    0.00338    0.00643    0.01158     0.03474
 100000.00   2092.95     0.69091    0.00315    0.00601    0.01158     0.03474
 500000.00   2092.95     0.69091    0.00212    0.00410    0.01158     0.03474



             PROPANE FIREBALL RESULTS:
             *************************

     MASS      TEMP        H/DS    F21-HUMAN F21-ANIM    F21-BULID   F21-PROCESS
----------------------------------------------------------------------------------
   1000.00   2113.34     0.69091    0.00935    0.01716    0.01114     0.03342
   5000.00   2113.34     0.69091    0.00631    0.01173    0.01114     0.03342
  10000.00   2113.34     0.69091    0.00532    0.00996    0.01114     0.03342
  25000.00   2113.34     0.69091    0.00425    0.00802    0.01114     0.03342
  50000.00   2113.34     0.69091    0.00359    0.00681    0.01114     0.03342
  75000.00   2113.34     0.69091    0.00325    0.00618    0.01114     0.03342
 100000.00   2113.34     0.69091    0.00303    0.00578    0.01114     0.03342
 500000.00   2113.34     0.69091    0.00204    0.00395    0.01114     0.03342



             BUTANE FIREBALL RESULTS:
             **************************

     MASS      TEMP        H/DS    F21-HUMAN   F21-ANIM   F21-BUILD   F21-PROCESS
----------------------------------------------------------------------------------
   1000.00   2120.31     0.69091    0.00923    0.01694    0.01099     0.03298
   5000.00   2120.31     0.69091    0.00622    0.01158    0.01099     0.03298
  10000.00   2120.31     0.69091    0.00525    0.00983    0.01099     0.03298
  25000.00   2120.31     0.69091    0.00420    0.00791    0.01099     0.03298
  50000.00   2120.31     0.69091    0.00354    0.00672    0.01099     0.03298
  75000.00   2120.31     0.69091    0.00321    0.00610    0.01099     0.03298
 100000.00   2120.31     0.69091    0.00299    0.00570    0.01099     0.03298
 500000.00   2120.31     0.69091    0.00202    0.00390    0.01099     0.03298



             PENTANE FIREBALL RESULTS:
             ***************************

     MASS        TEMP      H/DS  F21-HUMAN   F21-ANIM   F21-BUILD   F21-PROCESS
----------------------------------------------------------------------------------
   1000.00   2127.22     0.78947    0.01084    0.01977    0.01085     0.03256
```

```
   5000.00  2127.22   0.78947   0.00731   0.01352   0.01085   0.03256
  10000.00  2127.22   0.78947   0.00617   0.01147   0.01085   0.03256
  25000.00  2127.22   0.78947   0.00493   0.00924   0.01085   0.03256
  50000.00  2127.22   0.78947   0.00416   0.00784   0.01085   0.03256
  75000.00  2127.22   0.78947   0.00377   0.00712   0.01085   0.03256
 100000.00  2127.22   0.78947   0.00351   0.00666   0.01085   0.03256
 500000.00  2127.22   0.78947   0.00237   0.00455   0.01085   0.03256



          USING ROBERTS PARAMETERS (A,AS,B & BS):
          =========================================


          METHANE FIREBALL RESULTS:
          **************************

     MASS      TEMP      H/DS  F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
 -----------------------------------------------------------------------
   1000.00  2014.47   0.77586   0.02083   0.01844   0.01349   0.04048
   5000.00  2014.47   0.77586   0.01389   0.01260   0.01349   0.04048
  10000.00  2014.47   0.77586   0.01167   0.01070   0.01349   0.04048
  25000.00  2014.47   0.77586   0.00926   0.00861   0.01349   0.04048
  50000.00  2014.47   0.77586   0.00778   0.00731   0.01349   0.04048
  75000.00  2014.47   0.77586   0.00702   0.00664   0.01349   0.04048
 100000.00  2014.47   0.77586   0.00653   0.00621   0.01349   0.04048
 500000.00  2014.47   0.77586   0.00436   0.00424   0.01349   0.04048


          ETHANE FIREBALL RESULTS:
          **************************

     MASS     TEMP      H/DS   F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
 -----------------------------------------------------------------------
   1000.00  2092.95   0.77586   0.00858   0.01582   0.01158   0.03474
   5000.00  2092.95   0.77586   0.00579   0.01081   0.01158   0.03474
  10000.00  2092.95   0.77586   0.00489   0.00918   0.01158   0.03474
  25000.00  2092.95   0.77586   0.00390   0.00739   0.01158   0.03474
  50000.00  2092.95   0.77586   0.00329   0.00627   0.01158   0.03474
  75000.00  2092.95   0.77586   0.00298   0.00570   0.01158   0.03474
 100000.00  2092.95   0.77586   0.00278   0.00533   0.01158   0.03474
 500000.00  2092.95   0.77586   0.00188   0.00364   0.01158   0.03474


          PROPANE FIREBALL RESULTS:
          ************************

     MASS     TEMP      H/DS   F21-HUMAN F21-ANIM  F21-BULID  F21-PROCESS
```

```
-------------------------------------------------------------------------------
  1000.00  2113.34   0.77586   0.00826   0.01522   0.01114   0.03342
  5000.00  2113.34   0.77586   0.00557   0.01040   0.01114   0.03342
 10000.00  2113.34   0.77586   0.00470   0.00883   0.01114   0.03342
 25000.00  2113.34   0.77586   0.00376   0.00711   0.01114   0.03342
 50000.00  2113.34   0.77586   0.00317   0.00604   0.01114   0.03342
 75000.00  2113.34   0.77586   0.00287   0.00548   0.01114   0.03342
100000.00  2113.34   0.77586   0.00267   0.00512   0.01114   0.03342
500000.00  2113.34   0.77586   0.00180   0.00350   0.01114   0.03342



          BUTANE FIREBALL RESULTS:
          *************************

    MASS     TEMP     H/DS   F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
-------------------------------------------------------------------------------
  1000.00  2120.31   0.77586   0.00815   0.01502   0.01099   0.03298
  5000.00  2120.31   0.77586   0.00550   0.01027   0.01099   0.03298
 10000.00  2120.31   0.77586   0.00464   0.00872   0.01099   0.03298
 25000.00  2120.31   0.77586   0.00371   0.00702   0.01099   0.03298
 50000.00  2120.31   0.77586   0.00313   0.00596   0.01099   0.03298
 75000.00  2120.31   0.77586   0.00283   0.00541   0.01099   0.03298
100000.00  2120.31   0.77586   0.00264   0.00506   0.01099   0.03298
500000.00  2120.31   0.77586   0.00178   0.00346   0.01099   0.03298



          PENTANE FIREBALL RESULTS:
          **************************

    MASS      TEMP      H/DS  F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
-------------------------------------------------------------------------------
  1000.00  2127.22   0.77586   0.00804   0.01483   0.01085   0.03256
  5000.00  2127.22   0.77586   0.00542   0.01013   0.01085   0.03256
 10000.00  2127.22   0.77586   0.00458   0.00860   0.01085   0.03256
 25000.00  2127.22   0.77586   0.00366   0.00693   0.01085   0.03256
 50000.00  2127.22   0.77586   0.00309   0.00588   0.01085   0.03256
 75000.00  2127.22   0.77586   0.00280   0.00534   0.01085   0.03256
100000.00  2127.22   0.77586   0.00261   0.00499   0.01085   0.03256
500000.00  2127.22   0.77586   0.00176   0.00341   0.01085   0.03256



          USING HOT SHELL-COLD CORE MODEL:
          ================================


          METHANE RESULTS OF HOT SHELL-COLD CORE MODEL:
          *********************************************
```

```
    MASS      TEMP     H/DS    F21-HUMAN  F21-ANIM  F21-BUILD  F21-PROCESS
---------------------------------------------------------------------------
   1000.00  1500.00   0.79645   0.01024   0.02010   0.08779    0.26337
   5000.00  1500.00   0.79645   0.00690   0.01373   0.08779    0.26337
  10000.00  1500.00   0.79645   0.00582   0.01165   0.08779    0.26337
  25000.00  1500.00   0.79645   0.00465   0.00938   0.08779    0.26337
  50000.00  1500.00   0.79645   0.00392   0.00796   0.08779    0.26337
  75000.00  1500.00   0.79645   0.00355   0.00723   0.08779    0.26337
 100000.00  1500.00   0.79645   0.00331   0.00676   0.08779    0.26337
 500000.00  1500.00   0.79645   0.00223   0.00462   0.08779    0.26337


          BUTANE RESULTS OF HOT SHELL-COLD CORE MODEL:
          *********************************************


         THE VALUE OF F1 =       0.007

    MASS        TEMP   H/DS     F21-HUMAN  F21-ANIM F21-BUILD  F21-PROCESS
---------------------------------------------------------------------------
   1000.00  1300.00   9.97053   0.00047   0.00102   0.07781    0.23342
   5000.00  1300.00   9.98992   0.00014   0.00032   0.07781    0.23342
  10000.00  1300.00   9.99365   0.00009   0.00020   0.07781    0.23342
  25000.00  1300.00   9.99655   0.00004   0.00010   0.07781    0.23342
  50000.00  1300.00   9.99783   0.00003   0.00006   0.07781    0.23342
  75000.00  1300.00   9.99834   0.00002   0.00005   0.07781    0.23342
 100000.00  1300.00   9.99863   0.00002   0.00004   0.07781    0.23342
 500000.00  1300.00   9.99953   0.00000   0.00001   0.07781    0.23342

         THE VALUE OF H/DS =       9.971


     THE VALUE OF F21 BECOMES VERY SMALL AND THAT MEAN
     THE VALUE OF F21 APPROACHES ZERO.
     THEN THIS MODEL MUST NOT USED IN THESE CONDITIONS.


         USING ISO-THERMAL MODEL:
         =======================


         METANE RESULTS OF ISO-THERMAL MODEL:
         ====================================

    MASS      TEMP        H/DC   F21-HUMAN    F21-ANIM  F21-BUILD   F21-PROCESS
------------------------------------------------------------------------------
   1000.00  2014.47    0.76321    0.00998    0.01840    0.01349    0.04048
   5000.00  2014.47    0.76333    0.00673    0.01257    0.01349    0.04048
  10000.00  2014.47    0.76338    0.00568    0.01067    0.01349    0.04048
  25000.00  2014.47    0.76345    0.00454    0.00859    0.01349    0.04048
  50000.00  2014.47    0.76350    0.00383    0.00729    0.01349    0.04048
  75000.00  2014.47    0.76354    0.00346    0.00662    0.01349    0.04048
```

```
100000.00  2014.47    0.76356    0.00323    0.00619    0.01349    0.04048
500000.00  2014.47    0.76368    0.00218    0.00423    0.01349    0.04048


          ETHANE RESULTS OF ISO-THERMAL MODEL:
          ===================================

    MASS      TEMP       H/DC   F21-HUMAN   F21-ANIM  F21-BUILD  F21-PROCESS
-------------------------------------------------------------------------------
   1000.00  2092.95    0.77356    0.00857    0.01579    0.01158    0.03474
   5000.00  2092.95    0.77369    0.00577    0.01079    0.01158    0.03474
  10000.00  2092.95    0.77374    0.00487    0.00916    0.01158    0.03474
  25000.00  2092.95    0.77381    0.00389    0.00737    0.01158    0.03474
  50000.00  2092.95    0.77386    0.00328    0.00626    0.01158    0.03474
  75000.00  2092.95    0.77390    0.00297    0.00568    0.01158    0.03474
 100000.00  2092.95    0.77392    0.00277    0.00531    0.01158    0.03474
 500000.00  2092.95    0.77404    0.00187    0.00363    0.01158    0.03474


          PROPANE RESULTS OF ISO-THERMAL MODEL:
          ====================================

    MASS      TEMP       H/DC   F21-HUMAN   F21-ANIM  F21-BUILD  F21-PROCESS
-------------------------------------------------------------------------------
   1000.00  2113.34    0.77903    0.00824    0.01519    0.01114    0.03342
   5000.00  2113.34    0.77916    0.00555    0.01038    0.01114    0.03342
  10000.00  2113.34    0.77921    0.00469    0.00881    0.01114    0.03342
  25000.00  2113.34    0.77928    0.00374    0.00709    0.01114    0.03342
  50000.00  2113.34    0.77934    0.00316    0.00602    0.01114    0.03342
  75000.00  2113.34    0.77937    0.00286    0.00547    0.01114    0.03342
 100000.00  2113.34    0.77939    0.00267    0.00511    0.01114    0.03342
 500000.00  2113.34    0.77952    0.00180    0.00349    0.01114    0.03342


          BUTANE RESULTS OF ISO-THERMAL MODEL:
          ===================================

    MASS      TEMP       H/DC   F21-HUMAN   F21-ANIM  F21-BUILD  F21-PROCESS
-------------------------------------------------------------------------------
   1000.00  2120.31    0.78239    0.00813    0.01499    0.01099    0.03298
   5000.00  2120.31    0.78252    0.00548    0.01024    0.01099    0.03298
  10000.00  2120.31    0.78257    0.00463    0.00869    0.01099    0.03298
  25000.00  2120.31    0.78264    0.00370    0.00700    0.01099    0.03298
  50000.00  2120.31    0.78270    0.00312    0.00594    0.01099    0.03298
  75000.00  2120.31    0.78273    0.00282    0.00540    0.01099    0.03298
 100000.00  2120.31    0.78275    0.00263    0.00504    0.01099    0.03298
 500000.00  2120.31    0.78288    0.00177    0.00344    0.01099    0.03298


          PENTANE RESULTS OF ISO-THERMAL MODDEL:
          ===================================

    MASS      TEMP       H/DC   F21-HUMAN   F21-ANIM  F21-BUILD  F21-PROCESS
-------------------------------------------------------------------------------
```

```
   1000.00  2127.22    0.78421    0.00803    0.01480    0.01085    0.03256
   5000.00  2127.22    0.78433    0.00541    0.01011    0.01085    0.03256
  10000.00  2127.22    0.78439    0.00457    0.00858    0.01085    0.03256
  25000.00  2127.22    0.78446    0.00365    0.00691    0.01085    0.03256
  50000.00  2127.22    0.78451    0.00308    0.00586    0.01085    0.03256
  75000.00  2127.22    0.78455    0.00279    0.00533    0.01085    0.03256
 100000.00  2127.22    0.78457    0.00260    0.00497    0.01085    0.03256
 500000.00  2127.22    0.78469    0.00175    0.00340    0.01085    0.03256



          B.L.E.V.E FIREBALL RESULTS:
          ****************************


          METHANE BLEVE FIREBALL RESULTS:
          ================================

     MASS     TEMP      H/DC     F21-HUMAN  F21-ANIM  F21-BUILD   F21-PROCESS
-------------------------------------------------------------------------------
   1000.00  1207.65    0.50000    0.07901    0.14555    0.10448    0.31343
   5000.00  1207.65    0.50000    0.05326    0.09945    0.10448    0.31343
  10000.00  1207.65    0.50000    0.04495    0.08440    0.10448    0.31343
  25000.00  1207.65    0.50000    0.03591    0.06795    0.10448    0.31343
  50000.00  1207.65    0.50000    0.03030    0.05767    0.10448    0.31343
  75000.00  1207.65    0.50000    0.02744    0.05239    0.10448    0.31343
 100000.00  1207.65    0.50000    0.02557    0.04895    0.10448    0.31343
 500000.00  1207.65    0.50000    0.01724    0.03344    0.10448    0.31343


          ETHANE BLEVE FIREBALL RESULTS:
          ================================

     MASS     TEMP      H/DC     F21-HUMAN  F21-ANIM  F21-BUILD   F21-PROCESS
-------------------------------------------------------------------------------
   1000.00  1219.64    0.50000    0.08859    0.16235    0.10043    0.30129
   5000.00  1219.64    0.50000    0.05972    0.11093    0.10043    0.30129
  10000.00  1219.64    0.50000    0.05040    0.09415    0.10043    0.30129
  25000.00  1219.64    0.50000    0.04026    0.07579    0.10043    0.30129
  50000.00  1219.64    0.50000    0.03398    0.06433    0.10043    0.30129
  75000.00  1219.64    0.50000    0.03076    0.05844    0.10043    0.30129
 100000.00  1219.64    0.50000    0.02867    0.05460    0.10043    0.30129
 500000.00  1219.64    0.50000    0.01933    0.03730    0.10043    0.30129


          PROPANE BLEVE FIREBALL RESULTS:
          ================================

     MASS     TEMP      H/DC     F21-HUMAN  F21-ANIM  F21-BUILD   F21-PROCESS
-------------------------------------------------------------------------------
```

```
  1000.00  1220.49    0.50000    0.09703    0.17726    0.10015    0.30045
  5000.00  1220.49    0.50000    0.06542    0.12111    0.10015    0.30045
 10000.00  1220.49    0.50000    0.05520    0.10279    0.10015    0.30045
 25000.00  1220.49    0.50000    0.04410    0.08275    0.10015    0.30045
 50000.00  1220.49    0.50000    0.03721    0.07023    0.10015    0.30045
 75000.00  1220.49    0.50000    0.03370    0.06381    0.10015    0.30045
100000.00  1220.49    0.50000    0.03140    0.05961    0.10015    0.30045
500000.00  1220.49    0.50000    0.02117    0.04073    0.10015    0.30045


           BUTANE BLEVE FIREBALL RESULTS:
           ==============================

    MASS     TEMP      H/DC     F21-HUMAN  F21-ANIM  F21-BUILD   F21-PROCESS
   -------------------------------------------------------------------------
  1000.00  1220.02    0.50000    0.10399    0.18952    0.10030    0.30091
  5000.00  1220.02    0.50000    0.07010    0.12949    0.10030    0.30091
 10000.00  1220.02    0.50000    0.05916    0.10990    0.10030    0.30091
 25000.00  1220.02    0.50000    0.04726    0.08848    0.10030    0.30091
 50000.00  1220.02    0.50000    0.03988    0.07509    0.10030    0.30091
 75000.00  1220.02    0.50000    0.03611    0.06822    0.10030    0.30091
100000.00  1220.02    0.50000    0.03365    0.06373    0.10030    0.30091
500000.00  1220.02    0.50000    0.02269    0.04355    0.10030    0.30091


           PENTANE BLEVE FIREBALL RESULTS:
           ===============================

    MASS     TEMP      H/DC     F21-HUMAN  F21-ANIM  F21-BUILD   F21-PROCESS
   -------------------------------------------------------------------------
  1000.00  1220.51    0.50000    0.10947    0.19915    0.10014    0.30043
  5000.00  1220.51    0.50000    0.07380    0.13607    0.10014    0.30043
 10000.00  1220.51    0.50000    0.06227    0.11549    0.10014    0.30043
 25000.00  1220.51    0.50000    0.04975    0.09298    0.10014    0.30043
 50000.00  1220.51    0.50000    0.04198    0.07891    0.10014    0.30043
 75000.00  1220.51    0.50000    0.03801    0.07169    0.10014    0.30043
100000.00  1220.51    0.50000    0.03543    0.06697    0.10014    0.30043
500000.00  1220.51    0.50000    0.02388    0.04576    0.10014    0.30043
```

```
C
C
C
C
C    PROGRAM FOR EVALUATION OF THE FIREBALL DIAMETER AND HAZARD RANGE
C    ****************************************************************
C    USING AUTHOR'S PARAMETERS,HOTSHELL-COLD CORE ,ISOTHERMAL & BLEVE MODELS:
C    ***********************************************************************
C
C
C
C
      DIMENSION W(10)
C
C
C
            READ *,N
         READ *,(W(I),I=1,N)
C
      PRINT 777
 777  FORMAT(//12X,'FIREBALL DIMENSIONS AND HAZARD RANGES RESULSTS:',
     @/12X,48('=')//)
C
C
C
      PRINT 13
 13   FORMAT(5X,'THE PREDICATION OF FIREBALL DIMENSIONS & ',
     @'HAZARD RANGES',/,5X,55('*')/5X,'USING PREVIOUS WORK',
     @' EQUATIONS & PARAMETERS:',/5X,44('*')//)
C
C
C
C
C    CALCULATION OF FIREBALL DIMENSIONS BY USING PREVIOUS WORK.
C    ----------------------------------------------------------
C
C
C
C
C
      READ *,THETA,V,V2,V3,V4,V5,GN,GN2,GN3,GN4,GN5,FC,FC2,
     @FC3,FC4,FC5,WTM,WTM2,WTM3,WTM4,WTM5
C
      PRINT 19
 19   FORMAT(10X,'USING GAYLE PARAMETERS (A,AS,B & BS)',/,10X,36('=')//)
C
       READ *,SECMA,TEMS1,TEMS2,TEMS3,TEMS4,TEMS5
C
C
      READ *,A,AS,B,BS,A2,AS2,B2,BS2,A3,AS3,B3,BS3,A4,AS4,B4,BS4
     @,A5,AS5,B5,BS5
C
      CALL FIRBAL(N,W,THETA,V,V2,V3,GN,GN2,GN3,FC,FC2,FC3,WTM,WTM2
     +,WTM3,A,A2,A3,AS,AS2,AS3,B,B2,B3,BS,BS2,BS3,A4,AS4,B4,BS4,
```

```
     @A5,AS5,B5,BS5,SECMA,V4,GN4,FC4,WTM4,V5,GN5,FC5,WTM5,
     @TEMS1,TEMS2,TEMS3,TEMS4,TEMS5)
C
C
C
      PRINT 21
  21   FORMAT(10X,'USING BRASIE PARAMETERS (A,AS,B & BS)',/,10X,
     +40('=')//)
C
        READ *,SECMA,TEMS1,TEMS2,TEMS3,TEMS4,TEMS5
C
C
      READ *,A,AS,B,BS,A2,AS2,B2,BS2,A3,AS3,B3,BS3,A4,AS4,B4,BS4
     @,A5,AS5,B5,BS5
      CALL FIRBAL(N,W,THETA,V,V2,V3,GN,GN2,GN3,FC,FC2,FC3,WTM,WTM2,
     @WTM3,A,A2,A3,AS,AS2,AS3,B,B2,B3,BS,BS2,BS3,A4,AS4,B4,BS4,
     @A5,AS5,B5,BS5,SECMA,V4,GN4,FC4,WTM4,V5,GN5,FC5,WTM5,
     @TEMS1,TEMS2,TEMS3,TEMS4,TEMS5)
C
C
C
      PRINT 22
 22   FORMAT(10X,'USING MARSHALL PARAMETERS (A,AS,B & BS):',/,10X,
     @40('=')//)
C
        READ *,SECMA,TEMS1,TEMS2,TEMS3,TEMS4,TEMS5
C
C
      READ *,A,AS,B,BS,A2,AS2,B2,BS2,A3,AS3,B3,BS3,A4,AS4,B4,BS4
      CALL FIRBAL(N,W,THETA,V,V2,V3,GN,GN2,GN3,FC,FC2,FC3,WTM,WTM2,
     @WTM3,A,A2,A3,AS,AS2,AS3,B,B2,B3,BS,BS2,BS3,A4,AS4,B4,BS4,
     @A5,AS5,B5,BS5,SECMA,V4,GN4,FC4,WTM4,V5,GN5,FC5,WTM5
     @,TEMS1,TEMS2,TEMS3,TEMS4,TEMS5)
C
C
C
      PRINT 23
 23   FORMAT(10X,'USING ROBERTS PARAMETERS (A,AS,B & BS):',/,10X,
     @40('=')//)
C
C
        READ *,SECMA,TEMS1,TEMS2,TEMS3,TEMS4,TEMS5
C
      READ *,A,AS,B,BS,A2,AS2,B2,BS2,A3,AS3,B3,BS3,A4,AS4,B4,BS4
     @,A5,AS5,B5,BS5
      CALL FIRBAL(N,W,THETA,V,V2,V3,GN,GN2,GN3,FC,FC2,FC3,WTM,WTM2,
     @WTM3,A,A2,A3,AS,AS2,AS3,B,B2,B3,BS,BS2,BS3,A4,AS4,B4,BS4,
     @A5,AS5,B5,BS5,SECMA,V4,GN4,FC4,WTM4,V5,GN5,FC5,WTM5,
     @TEMS1,TEMS2,TEMS3,TEMS4,TEMS5)
C
C
C
      PRINT 31
 31   FORMAT(10X,'USING HOT SHELL-COLD CORE MODEL:',/,10X,
```

```
     @35('=')//)
C
C
      PRINT 201
 201  FORMAT(10X,' METHANE RESULTS OF HOT SHELL-COLD CORE MODEL:',
     @/,10X,46('*')/)
C
C
C
       CALL HOTMET(N,W,THETA)
C
C
      PRINT 203
 203  FORMAT(10X,' BUTANE RESULTS OF HOT SHELL-COLD CORE MODEL:',
     @/,10X,46('*')/)
C
      CALL HOTSHE(N,W,THETA,SECMA)
C
C
C
      PRINT 32
  32  FORMAT(10X,'USING ISO-THERMAL MODEL:',/,10X,23('=')//)
C
C
C
      PRINT 204
 204  FORMAT(10X,' METANE RESULTS OF ISO-THERMAL MODEL:',
     @/,10X,37('=')/)
C
      READ *,SECMA5,V5,GN5,WTM5,FC5,TEMS11
      CALL ISOTHR(N,W,THETA,SECMA5,V5,GN5,WTM5,FC5,TEMS11)
C
C
      PRINT 2001
 2001 FORMAT(10X,'ETHANE RESULTS OF ISO-THERMAL MODEL:',
     @/,10X,39('=')/)
C
      READ *,SECMA26,V26,GN26,WTM26,FC26,TEMS26
      CALL ISOTHR(N,W,THETA,SECMA26,V26,GN26,WTM26,FC26,TEMS26)
C
C
      PRINT 206
 206  FORMAT(10X,' PROPANE RESULTS OF ISO-THERMAL MODEL:',
     @/,10X,39('=')/)
C
      READ *,SECMA6,V6,GN6,WTM6,FC6,TEMS12
      CALL ISOTHR(N,W,THETA,SECMA6,V6,GN6,WTM6,FC6,TEMS12)
C
C
      PRINT 207
 207  FORMAT(10X,' BUTANE RESULTS OF ISO-THERMAL MODEL:',
     @/,10X,38('=')/)
C
      READ *,SECMA7,V7,GN7,WTM7,FC7,TEMS13
```

```
      CALL ISOTHR(N,W,THETA,SECMA7,V7,GN7,WTM7,FC7,TEMS13)
C
C
      PRINT 208
  208 FORMAT(10X,' PENTANE RESULTS OF ISO-THERMAL MODDEL:',
     @/,10X,37('=')/)
C
      READ *,SECMA8,V8,GN8,WTM8,FC8,TEMS14
      CALL ISOTHR(N,W,THETA,SECMA8,V8,GN8,WTM8,FC8,TEMS14)
C
C
C
      PRINT 901
  901 FORMAT(10X,' B.L.E.V.E FIREBALL RESULTS:',/,10X,30('*')//)
C
C
C
      PRINT 902
  902 FORMAT(10X,' METHANE BLEVE FIREBALL RESULTS:',/,10X,35('=')/)
C
C
      READ *,SECMA,WTM,TEMS6
      CALL BLEVE(N,W,THETA,SECMA,TEMS6,WTM)
C
C
      PRINT 926
  926 FORMAT(10X,'ETHANE BLEVE FIREBALL RESULTS:',/,10X,35('=')/)
C
       READ *,SECMA,WTM,TEMS26
       CALL BLEVE(N,W,THETA,SECMA,TEMS26,WTM)
C
C
      PRINT 903
  903 FORMAT(10X,'PROPANE BLEVE FIREBALL RESULTS:',/,10X,35('=')/)
C
      READ *,SECMA,WTM,TEMS7
      CALL BLEVE(N,W,THETA,SECMA,TEMS7,WTM)
C
C
      PRINT 904
  904 FORMAT(10X,' BUTANE BLEVE FIREBALL RESULTS:',/10X,35('=')/)
C
      READ *,SECMA,WTM,TEMS8
      CALL BLEVE(N,W,THETA,SECMA,TEMS8,WTM)
C
C
      PRINT 906
  906 FORMAT(10X,' PENTANE BLEVE FIREBALL RESULTS:',/,10X,35('=')/)
C
      READ *,SECMA,WTM,TEMS9
      CALL BLEVE(N,W,THETA,SECMA,TEMS9,WTM)
  913  FORMAT(2X,100('*'))
C
C
```

```
C
                  STOP
                   END
C
C
C
C
C
C
C
C
C
C  THIS SUBROUTINE PROGRAM FOR CALCULATION OF TC,DC,HIGHT,F21,RANGE
C  ================================================================
C  Q1,Q2PIG,TEMP.OF FIREBALL SURFACE,DISTANCE OF THE TARGETS,TAW,Q2.
C  ===================================================================
C  BY USING PREVIOUS WORK:
C  =======================
C
C
C
       SUBROUTINE FIRBAL(II,W,THETA,V,V2,V3,GN,GN2,GN3,FC,FC2,FC3,
      +WTM,WTM2,WTM3,A1,A2,A3,AS1,AS2,AS3,B1,B2,B3,BS1,BS2,BS3,
      @A4,AS4,B4,BS4,A5,AS5,B5,BS5,SECMA,V4,GN4,FC4,WTM4,
      @V5,GN5,FC5,WTM5,TEMS1,TEMS2,TEMS3,TEMS4,TEMS5)
C
C
C
C
C
C
C
       DIMENSION Q1(10),RTAPIG(10),F21(10),Y(10),DS(10),
      @Q2HUM(10),X(10),TC(10),RTAHUM(10),RTAB(10),RTAPE(10),
      @W(10),Q2PIG(10),TAW(10),RHUM(10),RPIG(10),RB(10),RPE(10)
C
C
            QB=12.6
            QPE=37.8
C
C
C
C   CALCULATION OF METHANE FIREBALL DIMENSIONS & HAZARDS
C   ================================================
C
C
          PRINT 11
 11       FORMAT(10X,' METHANE FIREBALL RESULTS:',/,10X,26('*')/)
C
C
C
C
           READ *,(RTAHUM(LL),LL=1,II)
          READ *,(RTAPIG(LL),LL=1,II)
```

```
      READ *,(RTAB(MM),MM=1,II)
      READ *,(RTAPE(KK),KK=1,II)
C
C
C
C
       DO 5 I=1,II
       TC(I)=A1*(W(I)**AS1)
       DS(I)=B1*(W(I)**BS1)
       Y(I)=10*TC(I)
      RHUM(I)=DS(I)*RTAHUM(I)
     RPIG(I)=DS(I)*RTAPIG(I)
      RB(I)=DS(I)*RTAB(I)
      RPE(I)=DS(I)*RTAPE(I)
      Q1(I)=SECMA*THETA*(TEMS1**4.0)
      Q2HUM(I)=28.16/(TC(I)**0.735)
       Q2PIG(I)=50.0/(TC(I)**0.71)
       F21(I)=((Y(I)/DS(I))+0.5)/(4.0*(((Y(I)/DS(I)+0.5)**2.0)
     @+(RHUM(I)/DS(I))**2.0)**1.5)
      X(I)=DS(I)*((((((Y(I)/DS(I)+0.5)**2.0)+(RHUM(I)/DS(I))**2.0))
     @**0.5)-0.5)
       TAW(I)=EXP(-0.0007*X(I))
  5       CONTINUE
C
      PRINT 1001,TEMS1
 1001 FORMAT(/10X,'AT FIREBALL SURFACE TEMPERATUE =',F10.3,/10X,
     @30('-')/)
C
C
     PRINT 100
 100 FORMAT(1X,
     @'   MASS      TIME    DIAMETER  HEIGHT   HUMAN R. ANIMAL R.',
     @'BULID.R. PR.EQ.R.',
     @/1X,74('-'))
C
     DO 6 N=1,II
     PRINT 105,W(N),TC(N),DS(N),Y(N),RHUM(N),RPIG(N),RB(N),RPE(N)
 105   FORMAT(8F9.2)
C
C
  6     CONTINUE
C
C
C
C
C  CALCULATION OF ETHANE FIREBALL DIMENSIONS & HAZARDS:
C  ===================================================
C
       PRINT 3333
 3333    FORMAT(10X,///)
C
C
     PRINT 261
 261 FORMAT(10X,' ETHANE FIREBALL RESULTS:',/,10X,26('*')/)
```

```
C
C
C
      READ *,(RTAHUM(JJ),JJ=1,II)
      READ *,(RTAPIG(KK),KK=1,II)
      READ *,(RTAB(MM),MM=1,II)
      READ *,(RTAPE(NN),NN=1,II)
C
C
C
       DO 51 J=1,II
      TC(J)=A2*(W(J)**AS2)
      DS(J)=B2*(W(J)**BS2)
      Y(J)=10*TC(J)
      RHUM(J)=DS(J)*RTAHUM(J)
      RPIG(J)=DS(J)*RTAPIG(J)
      RB(J)=DS(J)*RTAB(J)
      RPE(J)=DS(J)*RTAPE(J)
      Q1(J)=SECMA*THETA*(TEMS2**4.0)
      Q2HUM(J)=28.16/(TC(J)**0.735)
      Q2PIG(J)=50.0/(TC(J)**0.71)
      F21(J)=((Y(J)/DS(J))+0.5)/(4.0*(((Y(J)/DS(J)+0.5)**2.0)
     @+(RHUM(J)/DS(J))**2.0)**1.5)
      X(J)=DS(J)*((((((Y(J)/DS(J)+0.5)**2.0)+(RHUM(J)/DS(J))**2.0))
     @**0.5)-0.5)
C
      TAW(J)=EXP(-0.0007*X(J))
C
  51    CONTINUE
C
       PRINT 1002,TEMS2
 1002  FORMAT(/10X,'FIREBALL SURFACE TEMPERATUER =',F10.3,/10X,
     @30('-')/)
C
C
C
     PRINT 500
 500 FORMAT(1X,
     @'   MASS     TIME   DIAMETER  HEIGHT    HUMAN R.  ANIMAL R. ',
     @'BULID.R. PR.EQ.R',
     @/,1X,74('-'))
C
C
       DO 76 M=1,II
     PRINT 1051,W(M),TC(M),DS(M),Y(M),RHUM(M),RPIG(M),RB(M),RPE(M)
 1051 FORMAT(8F9.2)
C
  76    CONTINUE
C
C
C
C
C
C  CALCULATION OF PROPANE FIREBALL DIMENSIONS & HAZARDS:
```

```
C =====================================================
      PRINT 260
 260  FORMAT(10X,///)
C
      PRINT 150
 150   FORMAT(10X,'PROPANE FIREBALL RESULTS:',/,10X,24('*'))
C
        READ *,(RTAHUM(MM),MM=1,II)
      READ *,(RTAPIG(LL),LL=1,II)
       READ *,(RTAB(L),L=1,II)
       READ *,(RTAPE(K),K=1,II)
C
C
      DO 10 M=1,II
      TC(M)=A3*(W(M)**AS3)
      DS(M)=B3*(W(M)**BS3)
      Y(M)=10*TC(M)
      RHUM(M)=DS(M)*RTAHUM(M)
      RPIG(M)=DS(M)*RTAPIG(M)
     RB(M)=DS(M)*RTAB(M)
     RPE(M)=DS(M)*RTAPE(M)
C
     Q1(M)=SECMA*THETA*(TEMS3**4.0)
      Q2HUM(M)=28.16/(TC(M)**0.735)
      Q2PIG(M)=50.0/(TC(M)**0.71)
     F21(M)=((Y(M)/DS(M))+0.5)/(4.0*(((Y(M)/DS(M)+0.5)**2.0)
    @+(RHUM(M)/DS(M))**2.0)**1.5)
     X(M)=DS(M)*((((((Y(M)/DS(M)+0.5)**2.0)+(RHUM(M)/DS(M))**2.0))
    @**0.5)-0.5)
     TAW(M)=EXP(-0.0007*X(M))
 10    CONTINUE
C
     PRINT 1003,TEMS3
 1003 FORMAT(/10X,'FIREBALL SURFACE TEMPERATURE =',F10.3,/10X,
    @30('-')/)
C
C
C
C
      PRINT 200
 200 FORMAT(1X,
    @' MASS     TIME    DIAMETER   HEIGHT  HUMAN R.  ANIMAL R. ',
    @'BULID.R. PR.EQ.R',
    @/1X,74('-'))
       DO 15 MM=1,II
      PRINT 210,W(MM),TC(MM),DS(MM),Y(MM),RHUM(MM),RPIG(MM),
    @RB(MM),RPE(MM)
 210    FORMAT(8F9.2)
  15    CONTINUE
C
C
C
C   CALCULATION OF BUTANE FIREBALL DIMENSIONS & HAZARDS:
C   ====================================================
```

```
C
C
C
       PRINT 360
 360   FORMAT(2X,///)
C
        PRINT 255
 255    FORMAT(10X,'BUTANE FIREBALL RESULTS:',/,10X,25('*'))
C
C
         READ *,(RTAHUM(JJ),JJ=1,II)
          READ *,(RTAPIG(MM),MM=1,II)
       READ *,(RTAB(LL),LL=1,II)
       READ *,(RTAPE(KK),KK=1,II)
C
C
C
C
C
        DO 20 J=1,II
       TC(J)=A4*(W(J)**AS4)
       DS(J)=B4*(W(J)**BS4)
       Y(J)=10.0*TC(J)
      Q1(J)=SECMA*THETA*(TEMS4**4.0)
       RHUM(J)=DS(J)*RTAHUM(J)
       RPIG(J)=DS(J)*RTAPIG(J)
      RB(J)=DS(J)*RTAB(J)
      RPE(J)=DS(J)*RTAPE(J)
        Q2HUM(J)=28.16/(TC(J)**0.735)
       Q2PIG(J)=50.0/(TC(J)**0.71)
       F21(J)=((Y(J)/DS(J)+0.5)/(4.0*(((Y(J)/DS(J)+0.5)**2.0)
     @+(RHUM(J)/DS(J)+0.5))**2.0)**1.5)
      X(J)=DS(J)*((((((Y(J)/DS(J)+0.5)**2.0)+(RHUM(J)/DS(J))**2.0))
     @**0.5)-0.5)
      TAW(J)=EXP(-0.0007*X(J))
 20      CONTINUE
C
      PRINT 1004,TEMS4
 1004 FORMAT(/10X,'FIREBALL SURFACE TEMPERATURE =',F10.3,/10X,
     @30('-')/)
C
C
C
C
      PRINT 300
 300 FORMAT(1X,
     @'   MASS   TIME    DIAMETER   HEIGHT  HUMAN R.   ANIMAL R.   ',
     @'BULID.R. PR.EQ.R',
     @/1X,74('-'))
C
        DO 25 L=1,II
      PRINT 320,W(L),TC(L),DS(L),Y(L),RHUM(L),RPIG(L),RB(L),RPE(L)
  320   FORMAT(8F9.2)
C
```

```
   25     CONTINUE
C
C
C
          PRINT 811
 811      FORMAT(5X,///)
C
C
C
C  CALCULATION OF PENTANE FIREBALL DIMENSIONS & HAZARDS:
C  ======================================================
C
         READ *,(RTAHUM(I),I=1,II)
         READ *,(RTAPIG(KK),KK=1,II)
         READ *,(RTAB(J),J=1,II)
         READ *,(RTAPE(K),K=1,II)
C
C
      PRINT 301
 301  FORMAT(10X,'PENTANE FIREBALL RESULTS:',/,10X,26('*')/)
C
C
      DO 77 L=1,II
      TC(L)=A5*(W(L)**AS5)
      DS(L)=B5*(W(L)**BS5)
      Y(L)=10.0*TC(L)
       Q1(L)=SECMA*THETA*(TEMS5**4.0)
      RHUM(L)=DS(L)*RTAHUM(L)
      RPIG(L)=DS(L)*RTAPIG(L)
      RB(L)=DS(L)*RTAB(L)
      RPE(L)=DS(L)*RTAPE(L)
       Q2HUM(L)=28.16/(TC(L)**0.735)
      Q2PIG(L)=50.0/(TC(L)**0.71)
      F21(L)=((Y(L)/DS(L)+0.5)/(4.0*(((Y(L)/DS(L)+0.5)**2.0)
     @+(RHUM(L)/DS(L)+0.5))**2.0)**1.5)
      X(L)=DS(L)*((((((Y(L)/DS(L)+0.5)**2.0)+(RHUM(L)/DS(L))**2.0))
     @**0.5)-0.5)
      TAW(L)=EXP(-0.0007*X(L))
  77    CONTINUE
C
      PRINT 1005,TEMS5
 1005 FORMAT(/10X,'FIREBALL SURFACE TEMPERATURE =',F10.3,/10X,
     @30('-')/)
C
C
C
C
      PRINT 303
 303  FORMAT(1X,
     @'   MASS     TIME      DIAMETER  HEIGHT   HUMAN R.  ANIMAL R. ',
     @'BULID.R. PR.EQ.R',
     @/1X,74('-'))
C
C
```

```
      DO 27 K=1,II
       PRINT 306,W(K),TC(K),DS(K),Y(K),RHUM(K),RPIG(K),RB(K),RPE(K)
C
C
  306    FORMAT(8F9.2)
C
  27  CONTINUE
C
C
           PRINT 99
  99    FORMAT(10X,////)
C
            RETURN
             END
C
C
C
C SUBROUTINE FOR METHANE ONLY (USING HOT SHELL-COLD CORE MODEL):
C ****************************************************************
C
C
C
       SUBROUTINE HOTMET(M,W,THETA)
       DIMENSION Q1(25),Y(25),DC(25),RTAPE(25),RTAB(25),RB(25),RPE(25),
     @TC(25),W(25),DO(25),Q2PIG(25),RHUM(25),F21(25),X(25),
     @Q2HUM(25),RPIG(25),RTAPIG(25),RTAHUM(25),TAW(25),DSH(25)
C
C
       SECMA=0.5
       QB=12.6
       QPE=37.8
C
            READ *,WTM,TEMS,ZH
C
C
       READ *,(RTAHUM(J),J=1,M)
       READ *,(RTAPIG(K),K=1,M)
       READ *,(RTAB(I),I=1,M)
       READ *,(RTAPE(N),N=1,M)
C
C
       DO 140 I=1,M
       Q1(I)=SECMA*THETA*(TEMS**4.0)
       DO(I)=1.42*(W(I)**0.3334)
       DC(I)=DO(I)*((((273.0*WTM*ZH)/(44.8*290*Q1(I)))+1.0)**0.3334)
       TC(I)=(DC(I)-DO(I))/1.0
       Y(I)=1.0*TC(I)
       RHUM(I)=DC(I)*RTAHUM(I)
       RPIG(I)=DC(I)*RTAPIG(I)
       RB(I)=DC(I)*RTAB(I)
       RPE(I)=DC(I)*RTAPE(I)
        Q2HUM(I)=28.16/(TC(I)**0.735)
       Q2PIG(I)=50.0/(TC(I)**0.71)
       F21(I)=((Y(I)/DC(I)+0.5)/(4.0*(((Y(I)/DC(I)+0.5)**2.0)
```

```
     @+(RHUM(I)/DC(I)+0.5))**2.0)**1.5)
      X(I)=DC(I)*((((((Y(I)/DC(I)+0.5)**2.0)+(RHUM(I)/DC(I)+0.5)**2.0))
     @**0.5)-0.5)
      TAW(I)=EXP(-0.0007*X(I))
      DSH(I)=Y(I)/DC(I)
 140  CONTINUE
C
      PRINT 1006,TEMS
 1006 FORMAT(/10X,'FIREBALL SURFACE TEMPERATURE =',F10.3,/10X,
     @30('-')/)
C
C
C
      PRINT 1421
 1421 FORMAT(1X,
     @'  MASS    TIME     DIAMETER  HEIGHT   HUMAN R.  ANIMAL R.',
     @' BULID.R. PR.EQ.R',
     @/1X,74('-'))
C
C
      DO 145 J=1,M
      PRINT 1400,W(J),TC(J),DC(J),Y(J),
     @RHUM(J),RPIG(J),RB(J),RPE(J)
 1400  FORMAT(8F9.2)
  145    CONTINUE
C
C
        PRINT 5600
 5600   FORMAT(10X,///)
C
C
        RETURN
         END
C
C
C
C
C
C    SUBROUTINE FOR CALCULATION OF FIREBALL
C    ==========================================
C    DIMENSIONS USING HOT SHELL-COLD CORE MODEL:
C    ==================================================
C
C
       SUBROUTINE HOTSHE(MM,W,THETA,SECMA)
C
C
C
       DIMENSION Q1(25),Y(25),DC(25),RTAB(25),RTAPE(25),RB(25),RPE(25)
     @,F21(25),DSH(25),RTAHUM(25),TC(25),D0(25),Q2PIG(25),D1(25)
     @,W(25),Q2HUM(25),RHUM(25),RPIG(25),RTAPIG(25),X(25),TAW(25)
C
C
C
```

```
C     CALCULATION OF FIREBALL BY USING HOT SHELL-COLD CORE MODEL:
C     ---------------------------------------------------------------
C
C
C
        QB=12.6
        QPE=37.8
C
C
        READ *,TEMS,WTM,C,RS,ZH
C
C
C
       READ *,(RTAHUM(J),J=1,MM)
       READ *,(RTAPIG(JJ),JJ=1,MM)
       READ *,(RTAB(L),L=1,MM)
       READ *,(RTAPE(J),J=1,MM)
C
C
C
      F1=((1.0-(29.0/WTM))*(93.05*SECMA*((TEMS/1000.0)**4.0)))/(ZH
     @-RS*C*(TEMS-290.0)-93.05*SECMA*((TEMS/1000.0)**4.0)*RS)
C
C
C
      PRINT *,'      THE VALUE OF F1=',F1
C
C
       IF(F1.LT.0.0) THEN
       PRINT 1222
 1222  FORMAT(//,5X,'THIS MODEL SHOUD NOT USED IN THESE CONDITIONS',
     @/,5X,'BECAUSE F1 VALUE IS NEGATIVE & IT MUST BE POSTIVE',//)
C
C
C
              ELSE
C
C
C
        DO 40 K=1,MM
      Q1(K)=SECMA*THETA*(TEMS**4.0)
C
      D1(K)=(1.567*(1.0+(RS*F1))*W(K))*0.3334
      DO(K)=3.57*((W(K)/WTM)**0.3334)
      DC(K)=((((273.0*ZH*(1.0-F1))/(448.0*Q1(K)*(1.0+RS*F1)))
     @+1.0)**0.3334)*D1(K)
C
       TC(K)=(DC(K)-DO(K))/1.0
C
C
C
        RHUM(K)=DC(K)*RTAHUM(K)
        RPIG(K)=DC(K)*RTAPIG(K)
      RB(K)=DC(K)*RTAB(K)
```

```
      RPE(K)=DC(K)*RTAPE(K)
        Y(K)=10.0*TC(K)
        Q2HUM(K)=28.16/(TC(K)**0.735)
        Q2PIG(K)=50.0/(TC(K)**0.71)
      F21(K)=((Y(K)/DC(K)+0.5)/(4.0*(((Y(K)/DC(K)+0.5)**2.0)
     @+(RHUM(K)/DC(K)+0.5))**2.0)**1.5)
      X(K)=DC(K)*((((((Y(K)/DC(K)+0.5)**2.0)+(RHUM(K)/DC(K))**2.0))
     @**0.5)-0.5)
       TAW(K)=EXP(-0.0007*X(K))
C
            DSH(K)=Y(K)/DC(K)
C
 40     CONTINUE
C
      PRINT 1007,TEMS
 1007 FORMAT(/10X,'FIREBALL SURFACE TEMPERATURE =',F10.3,/10X,
     @30('-')/)
C
C
C
C
      PRINT 421
 421  FORMAT(1X,
     @'   MASS    TIME  DIAMETER  HEIGHT  HUMAN R.  ANIMAL R.    ',
     @'BULID.R. PR.EQ.R',
     @/1X,74('-'))
C
         DO 45 KI=1,MM
        PRINT 493,W(KI),TC(KI),DC(KI),Y(KI),
    @RHUM(KI),RPIG(KI),RB(KI),RPE(KI)
 493    FORMAT(8E9.2)
C
  45    CONTINUE
C
C
C
      IF(DSH(1).GT.2.5) THEN
C
        PRINT 5601,DSH(1)
 5601      FORMAT(/,10X,'THE VALUE OF H/DS =',F10.3,/)
C
C
C
      PRINT 1223
 1223 FORMAT(/,5X,'THE VALUE OF F21 BECOMES VERY SMALL AND THAT MEAN',
     @/,5X,'THE VALUE OF F21 APPROACHES ZERO.',
     @/,5X,'THEN THIS MODEL MUST NOT USED IN THESE CONDITIONS.',///)
C
C
C
         ELSE
C
C
          PRINT 29
```

```
 29     FORMAT(3X,76('*')////)
C
                ENDIF
                  ENDIF
C
C
C
        RETURN
        END
C
C
C
C
C    SUBROUTINE PROGRAM FOR CALCULATION OF FIREBALL
C    USING ISO-THERMAL MODEL EQUATIONS:
C    ====================================
C
C
C
      SUBROUTINE ISOTHR(LL,W,THETA,SECMA,V,GN,WTM,FC,TEMS)
C
C
      DIMENSION W(25),RTAHUM(25),TC(25),DC(25),DO(25),
     @RHUM(25),RB(25),RPE(25),Y(25),Q1(25),Q2PIG(25),RTAB(25),
     @RPIG(25),RTAPIG(25),Q2HUM(25),RTAPE(25),F21(25),TAW(25),X(25)
C
C
C
        READ *,(RTAHUM(J),J=1,LL)
        READ *,(RTAPIG(KK),KK=1,LL)
            READ *,(RTAB(K),K=1,LL)
            READ *,(RTAPE(N),N=1,LL)
C
C
C
C    CALCULATION OF FIREBALL USING ISOTHERMAL MODEL:
C    -------------------------------------------------
        QB=12.6
        QPE=37.8
C
C
C
C
C
       DO 50 L=1,LL
       DO(L)=0.539*((290.0*W(L)/WTM)**0.3333)
       DC(L)=0.539*((V+(GN+1.0)*FC)**0.3333)*((TEMS*W(L)/WTM)**0.3333)
       TC(L)=0.45*(W(L)**0.3334)
C
       RHUM(L)=DC(L)*RTAHUM(L)
       RPIG(L)=DC(L)*RTAPIG(L)
     RB(L)=RTAB(L)*DC(L)
     RPE(L)=RTAPE(L)*DC(L)
       Y(L)=10.0*TC(L)
```

```
        Q1(L)=SECMA*THETA*(TEMS**4.0)
        Q2HUM(L)=28.16/(TC(L)**0.735)
         Q2PIG(L)=50.0/(TC(L)**0.71)
      F21(L)=((Y(L)/DC(L)+0.5)/(4.0*(((Y(L)/DC(L)+0.5)**2.0)
     @+(RHUM(L)/DC(L)+0.5))**2.00)**1.5)
      X(L)=DC(L)*((((((Y(L)/DC(L)+0.5)**2.0)+(RHUM(L)/DC(L))**2.0))
     @**0.5)-0.5)
      TAW(L)=EXP(-0.0007*X(L))
C
C
 50       CONTINUE
C
      PRINT 1008,TEMS
 1008 FORMAT(/10X,'FIREBALL SURFACE TEMPERATURE =',F10.3,/10X,
     @30('-')/)
C
C
C
      PRINT 752
 752  FORMAT(1X,
     @'   MASS    TIME    DIAMETER  HEIGHT    HUMAN R. ANIMAL R.',
     @' BULID.R PR.EQ.R',
     @/1X,74('-'))
C
C
C
      DO 55 N=1,LL
      PRINT 500,W(N),TC(N),DC(N),Y(N),RHUM(N),RPIG(N),RB(N),RPE(N)
 500    FORMAT(8F9.2)
 55     CONTINUE
C
       PRINT 43
 43    FORMAT(2X,65('*')////)
C
               RETURN
                END
C
C
C
C
C
C  SUBROUTINE TO CALCULATE B.L.E.V.E. FIREBALL
C  ==============================================
C  DIMENSIONS AND PROPERTIES:
C  ===========================
C
C
C
C
      SUBROUTINE BLEVE(M,W,THETA,SECMA,TEMS,WTM)
C
C
C
      DIMENSION W(25),RTAHUM(25),TC(25),DC(25),RB(25),RPE(25),
```

```
     @Y(25),Q1BL(25),RTAB(25),RTAPE(25),F21BL(25),TAW(25),X(25)
     @,RHUM(25),RPIG(25),RTAPIG(25),Q2PIG(25),Q2HUM(25)
C
C
C
       QB=12.6
       QPE=37.8
C
C
C
       READ *,(RTAHUM(I),I=1,M)
       READ *,(RTAPIG(J),J=1,M)
      READ *,(RTAB(K),K=1,M)
      READ *,(RTAPE(J),J=1,M)
C
C
C
      DO 83 N=1,M
      TC(N)=0.31*((44.8*W(N)/WTM)**0.3333)
      DC(N)=3.44*((44.8*W(N)/WTM)**0.3333)
C
      Y(N)=0.5*DC(N)
      Q1BL(N)=SECMA*THETA*(TEMS**4.0)
        Q2HUM(N)=28.16/(TC(N)**0.735)
        Q2PIG(N)=50.0/(TC(N)**0.71)
        RHUM(N)=RTAHUM(N)*DC(N)
        RPIG(N)=RTAPIG(N)*DC(N)
        RB(N)=RTAB(N)*DC(N)
        RPE(N)=RTAPE(N)*DC(N)
      F21BL(N)=((Y(N)/DC(N)+0.5)/(4.0*(((Y(N)/DC(N)+0.5)**2.0)
    @+(RHUM(N)/DC(N)+0.5))**2.0)**1.5)
      X(N)=DC(N)*((((((Y(N)/DC(N)+0.5)**2.0)+(RHUM(N)/DC(N))**2.0))
    @**0.5)-0.5)
      TAW(N)=EXP(-0.0007*X(N))
C
  83   CONTINUE
C
      PRINT 1009,TEMS
 1009 FORMAT(/10X,'FIREBALL SURFACE TEMPERATURE =',F10.3,/10X,
     @30('-')/)
C
C
C
      PRINT 703
 703  FORMAT(1X,
     @'    MASS     TIME    DIAMETER  HEIGHT    HUMAN R.  ANIMAL R.',
     @'  BULID.R.  PR.EQ.R',
     @/1X,74('-'))
C
C
      DO 87 K=1,M
      PRINT 808,W(K),TC(K),DC(K),Y(K),RHUM(K),RPIG(K),RB(K),RPE(K)
 808    FORMAT(8F9.2)
C
```

```
 87        CONTINUE
C
C
        PRINT 819
 819      FORMAT(2X,//)
C
             RETURN
              END
C
C
C
```

```
          FIREBALL DIMENSIONS AND HAZARD RANGES RESULSTS:
          ===============================================

          (FOR ISOTHERMAL FIREBALL TEMPERATURES)
          **************************************



    THE PREDICATION OF FIREBALL DIMENSIONS & HAZARD RANGES
    ******************************************************
    USING PREVIOUS WORK EQUATIONS & PARAMETERS:
    *******************************************


        USING GAYLE PARAMETERS (A,AS,B & BS)
        ====================================


         METHANE FIREBALL RESULTS:
        **************************


        AT FIREBALL SURFACE TEMPERATUE =  2138.000
        ------------------------------

   MASS      TIME    DIAMETER  HEIGHT    HUMAN R.  ANIMAL R.BULID.R. PR.EQ.R.
 ----------------------------------------------------------------------------
   1000.00    2.87    34.98     28.65     76.96     78.71    89.20     59.47
   5000.00    5.08    59.12     50.82    156.66    153.70   150.75    100.50
  10000.00    6.50    74.11     65.04    211.20    200.08   192.67    129.68
  25000.00    9.01    99.90     90.12    309.70    294.71   259.75    174.83
  50000.00   11.53   125.23    115.35    407.00    394.48   331.86    225.42
  75000.00   13.33   142.93    133.26    478.81    464.52   378.76    257.27
 100000.00   14.76   156.98    147.63    541.59    533.74   423.85    290.42
 500000.00   26.18   265.28    261.82    941.76    955.02   716.27    490.78



         ETHANE FIREBALL RESULTS:
        **************************


        FIREBALL SURFACE TEMPERATUER =  2182.000
        ------------------------------

   MASS     TIME   DIAMETER  HEIGHT     HUMAN R.   ANIMAL R. BULID.R. PR.EQ.R
 ----------------------------------------------------------------------------
   1000.00    2.87    34.98     28.65     94.45     78.71    94.45     62.97
   5000.00    5.08    59.12     50.82    168.48    156.66   159.62    106.41
  10000.00    6.50    74.11     65.04    218.61    211.20   203.79    137.09
  25000.00    9.01    99.90     90.12    314.69    313.69   274.73    184.82
```

```
  50000.00     11.53    125.23    115.35    413.26    419.52    350.65    237.94
  75000.00     13.33    142.93    133.26    493.10    500.25    400.20    271.56
 100000.00     14.76    156.98    147.63    557.28    572.98    447.40    306.11
 500000.00     26.18    265.28    261.82    981.55   1008.08    756.06    517.30


          PROPANE FIREBALL RESULTS:
          *************************

          FIREBALL SURFACE TEMPERATURE =  2188.000
          ---------------------------------

    MASS     TIME    DIAMETER    HEIGHT  HUMAN R.   ANIMAL R.  BULID.R.  PR.EQ.R
-------------------------------------------------------------------------------------
   1000.00      2.87     34.98     28.65     89.20     80.46     94.45     61.22
   5000.00      5.08     59.12     50.82    162.57    156.66    159.62    103.45
  10000.00      6.50     74.11     65.04    218.61    214.90    203.79    133.39
  25000.00      9.01     99.90     90.12    314.69    309.70    274.73    179.82
  50000.00     11.53    125.23    115.35    413.26    407.00    350.65    231.68
  75000.00     13.33    142.93    133.26    493.10    485.96    400.20    264.42
 100000.00     14.76    156.98    147.63    572.98    549.43    447.40    298.26
 500000.00     26.18    265.28    261.82    994.82    955.02    756.06    504.04


          BUTANE FIREBALL RESULTS:
          *************************

          FIREBALL SURFACE TEMPERATURE =  2188.000
          ---------------------------------

    MASS     TIME    DIAMETER    HEIGHT  HUMAN R.   ANIMAL R.  BULID.R.  PR.EQ.R
-------------------------------------------------------------------------------------
   1000.00      2.87     34.98     28.65     85.71     82.21     96.20     61.22
   5000.00      5.08     59.12     50.82    162.57    156.66    162.57    103.45
  10000.00      6.50     74.11     65.04    218.61    214.90    207.49    133.39
  25000.00      9.01     99.90     90.12    324.68    309.70    279.73    179.82
  50000.00     11.53    125.23    115.35    425.79    407.00    356.91    231.68
  75000.00     13.33    142.93    133.26    507.39    485.96    407.35    264.42
 100000.00     14.76    156.98    147.63    572.98    549.43    455.25    298.26
 500000.00     26.18    265.28    261.82   1021.35    955.02    769.33    504.04


          PENTANE FIREBALL RESULTS:
          **************************


          FIREBALL SURFACE TEMPERATURE =  2190.000
          ---------------------------------
```

```
  MASS      TIME     DIAMETER  HEIGHT    HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
-----------------------------------------------------------------------------
  1000.00     2.87     34.98     28.65     87.46     80.46     96.20     61.22
  5000.00     5.08     59.12     50.82    162.57    156.66    162.57    103.45
 10000.00     6.50     74.11     65.04    218.61    214.90    207.49    133.39
 25000.00     9.01     99.90     90.12    324.68    309.70    279.73    179.82
 50000.00    11.53    125.23    115.35    432.05    407.00    356.91    231.68
 75000.00    13.33    142.93    133.26    514.54    485.96    407.35    264.42
100000.00    14.76    156.98    147.63    596.53    549.43    455.25    298.26
500000.00    26.18    265.28    261.82   1034.61    955.02    769.33    504.04


          USING BRASIE PARAMETERS (A,AS,B & BS)
          =====================================


           METHANE FIREBALL RESULTS:
          *************************


          AT FIREBALL SURFACE TEMPERATUE =  2086.000
          ------------------------------

  MASS      TIME     DIAMETER  HEIGHT    HUMAN R.  ANIMAL R.BULID.R.  PR.EQ.R.
-----------------------------------------------------------------------------
  1000.00     2.99     37.91     29.93    104.26     83.41    104.26     60.66
  5000.00     5.12     64.79     51.15    184.67    155.51    178.19    103.67
 10000.00     6.44     81.62     64.43    248.93    224.45    228.53    130.59
 25000.00     8.74    110.74     87.42    359.90    332.21    310.07    177.18
 50000.00    11.01    139.49    110.12    481.24    439.39    397.54    230.16
 75000.00    12.60    159.65    126.04    582.74    526.86    455.01    263.43
100000.00    13.87    175.70    138.71    676.46    597.40    509.54    289.91
500000.00    23.71    300.29    237.07   1186.14   1051.01    870.84    495.48


           ETHANE FIREBALL RESULTS:
          *************************


          FIREBALL SURFACE TEMPERATUER =  2126.000
          ------------------------------

  MASS      TIME     DIAMETER  HEIGHT    HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
-----------------------------------------------------------------------------
  1000.00     2.99     37.91     29.93    104.26     83.41    104.26     64.45
  5000.00     5.12     64.79     51.15    191.14    158.75    178.19    110.15
 10000.00     6.44     81.62     64.43    257.10    228.53    228.53    138.75
 25000.00     8.74    110.74     87.42    370.97    332.21    310.07    188.26
 50000.00    11.01    139.49    110.12    495.19    446.37    397.54    237.13
```

```
 75000.00    12.60   159.65   126.04   598.70   534.84   455.01   271.41
100000.00    13.87   175.70   138.71   676.46   606.18   509.54   298.70
500000.00    23.71   300.29   237.07  1216.17  1066.03   870.84   510.49
```

```
           PROPANE FIREBALL RESULTS:
           ************************

           FIREBALL SURFACE TEMPERATURE =  2132.000
           --------------------------------

   MASS    TIME    DIAMETER    HEIGHT  HUMAN R.  ANIMAL R.  BULID.R.  PR.EQ.R
-----------------------------------------------------------------------------
  1000.00     2.99    37.91    29.93   106.16    85.30   102.36    64.45
  5000.00     5.12    64.79    51.15   194.38   161.99   174.95   110.15
 10000.00     6.44    81.62    64.43   261.18   228.53   220.37   138.75
 25000.00     8.74   110.74    87.42   376.51   337.75   298.99   188.26
 50000.00    11.01   139.49   110.12   502.16   453.34   376.62   237.13
 75000.00    12.60   159.65   126.04   606.68   542.82   431.07   271.41
100000.00    13.87   175.70   138.71   685.25   614.97   474.40   298.70
500000.00    23.71   300.29   237.07  1231.19  1081.04   810.78   510.49
```

```
           BUTANE FIREBALL RESULTS:
           *************************

           FIREBALL SURFACE TEMPERATURE =  2132.000
           --------------------------------

   MASS    TIME    DIAMETER    HEIGHT  HUMAN R.  ANIMAL R.  BULID.R.  PR.EQ.R
-----------------------------------------------------------------------------
  1000.00     2.99    37.91    29.93   106.16    85.30   102.36    64.45
  5000.00     5.12    64.79    51.15   194.38   161.99   174.95   110.15
 10000.00     6.44    81.62    64.43   265.26   228.53   220.37   138.75
 25000.00     8.74   110.74    87.42   382.05   337.75   298.99   188.26
 50000.00    11.01   139.49   110.12   509.14   453.34   376.62   237.13
 75000.00    12.60   159.65   126.04   614.67   542.82   431.07   271.41
100000.00    13.87   175.70   138.71   694.03   614.97   474.40   298.70
500000.00    23.71   300.29   237.07  1246.20  1081.04   810.78   510.49
```

```
           PENTANE FIREBALL RESULTS:
           **************************


           FIREBALL SURFACE TEMPERATURE =  2134.000
           --------------------------------
```

```
     MASS      TIME      DIAMETER  HEIGHT    HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
-------------------------------------------------------------------------------------
   1000.00      2.99      37.91     29.93     106.16     85.30    102.36     64.45
   5000.00      5.12      64.79     51.15     194.38    161.99    174.95    110.15
  10000.00      6.44      81.62     64.43     269.34    228.53    220.37    138.75
  25000.00      8.74     110.74     87.42     387.58    337.75    298.99    188.26
  50000.00     11.01     139.49    110.12     516.11    453.34    376.62    237.13
  75000.00     12.60     159.65    126.04     622.65    542.82    431.07    271.41
 100000.00     13.87     175.70    138.71     702.82    614.97    474.40    298.70
 500000.00     23.71     300.29    237.07    1261.22   1081.04    810.78    510.49



                USING MARSHALL PARAMETERS (A,AS,B & BS):
                ========================================


                 METHANE FIREBALL RESULTS:
                ***************************


                AT FIREBALL SURFACE TEMPERATUE =  2024.000
                ------------------------------

     MASS      TIME      DIAMETER  HEIGHT    HUMAN R. ANIMAL R.BULID.R. PR.EQ.R.
-------------------------------------------------------------------------------------
   1000.00      3.79      54.87     37.91     150.90    117.98    137.18     82.31
   5000.00      6.48      93.78     64.79     276.66    239.14    234.46    140.67
  10000.00      8.16     118.13     81.62     360.30    324.86    295.33    177.20
  25000.00     11.07     160.28    110.74     512.89    472.82    400.70    240.42
  50000.00     13.95     201.89    139.49     686.43    615.77    504.73    302.84
  75000.00     15.97     231.08    159.65     843.43    762.56    577.69    346.62
 100000.00     17.57     254.31    175.70     953.66    877.37    635.77    381.46
 500000.00     30.03     434.63    300.29    1673.33   1564.67   1086.58    651.95


                 ETHANE FIREBALL RESULTS:
                ***************************


                FIREBALL SURFACE TEMPERATUER =  2060.000
                ------------------------------

     MASS      TIME    DIAMETER  HEIGHT     HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
-------------------------------------------------------------------------------------
   1000.00      3.79      54.87     37.91     150.90    120.72    142.67     87.80
   5000.00      6.48      93.78     64.79     276.66    243.83    243.83    150.05
  10000.00      8.16     118.13     81.62     366.21    330.77    307.14    189.01
  25000.00     11.07     160.28    110.74     520.91    480.84    416.73    256.45
  50000.00     13.95     201.89    139.49     696.53    625.87    524.92    323.03
```

```
 75000.00    15.97   231.08   159.65   854.99   762.56   600.80   369.72
100000.00    17.57   254.31   175.70   966.38   890.08   661.20   406.90
500000.00    30.03   434.63   300.29  1695.06  1586.40  1130.04   695.41


           PROPANE FIREBALL RESULTS:
           ************************

           FIREBALL SURFACE TEMPERATURE =  2064.000
           --------------------------------

   MASS    TIME    DIAMETER   HEIGHT  HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
--------------------------------------------------------------------------
  1000.00    3.79    54.87    37.91   153.65   126.21   142.67    87.80
  5000.00    6.48    93.78    64.79   276.66   243.83   243.83   150.05
 10000.00    8.16   118.13    81.62   372.11   330.77   307.14   189.01
 25000.00   11.07   160.28   110.74   520.91   480.84   416.73   256.45
 50000.00   13.95   201.89   139.49   706.62   635.96   524.92   323.03
 75000.00   15.97   231.08   159.65   866.54   762.56   600.80   369.72
100000.00   17.57   254.31   175.70   979.09   877.37   661.20   406.90
500000.00   30.03   434.63   300.29  1716.79  1586.40  1130.04   695.41


           BUTANE FIREBALL RESULTS:
           *************************

           FIREBALL SURFACE TEMPERATURE =  2064.000
           --------------------------------

   MASS    TIME    DIAMETER   HEIGHT  HUMAN R.  ANIMAL R.  BULID.R. PR.EQ.R
---------------------------------------------------------------------------
  1000.00    3.79    54.87    37.91   156.39   126.21   142.67    87.80
  5000.00    6.48    93.78    64.79   276.66   243.83   243.83   150.05
 10000.00    8.16   118.13    81.62   378.02   330.77   307.14   189.01
 25000.00   11.07   160.28   110.74   528.92   480.84   416.73   256.45
 50000.00   13.95   201.89   139.49   726.81   635.96   524.92   323.03
 75000.00   15.97   231.08   159.65   889.65   762.56   600.80   369.72
100000.00   17.57   254.31   175.70  1004.52   877.37   661.20   406.90
500000.00   30.03   434.63   300.29  1781.98  1586.40  1130.04   695.41


           PENTANE FIREBALL RESULTS:
           **************************


           FIREBALL SURFACE TEMPERATURE =  2066.000
           --------------------------------
```

```
    MASS      TIME     DIAMETER  HEIGHT    HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
--------------------------------------------------------------------------------
   1000.00     2.99     37.91    29.93     108.05     87.20     98.57    60.66
   5000.00     5.12     64.79    51.15     194.38    168.47    168.47   103.67
  10000.00     6.44     81.62    64.43     261.18    228.53    212.21   130.59
  25000.00     8.74    110.74    87.42     370.97    332.21    287.92   177.18
  50000.00    11.01    139.49   110.12     502.16    439.39    362.67   223.18
  75000.00    12.60    159.65   126.04     614.67    526.86    415.10   255.45
 100000.00    13.87    175.70   138.71     694.03    606.18    456.83   281.13
 500000.00    23.71    300.29   237.07    1246.20   1096.06    780.75   480.46



                USING ROBERTS PARAMETERS (A,AS,B & BS):
                =======================================


                 METHANE FIREBALL RESULTS:
                *************************


                AT FIREBALL SURFACE TEMPERATUE =   1980.000
                ------------------------------

    MASS       TIME     DIAMETER  HEIGHT    HUMAN R. ANIMAL R.BULID.R. PR.EQ.R.
--------------------------------------------------------------------------------
   1000.00     4.49     57.87    44.90     150.45    144.67    138.88    81.01
   5000.00     7.67     98.90    76.73     291.75    271.97    237.35   138.46
  10000.00     9.67    124.57    96.65     386.18    367.49    298.98   174.40
  25000.00    13.11    169.02   131.14     549.32    523.97    405.65   236.63
  50000.00    16.52    212.90   165.18     723.88    681.29    510.97   298.07
  75000.00    18.91    243.68   189.06     865.07    804.15    584.84   341.15
 100000.00    20.81    268.18   208.07    1019.09    911.82    643.63   375.45
 500000.00    35.56    458.34   355.61    1810.43   1627.10   1100.01   641.67



                 ETHANE FIREBALL RESULTS:
                *************************


                FIREBALL SURFACE TEMPERATUER =   2012.000
                ------------------------------

    MASS      TIME    DIAMETER  HEIGHT     HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
--------------------------------------------------------------------------------
   1000.00     4.49     57.87    44.90     147.56    130.20    144.67    86.80
   5000.00     7.67     98.90    76.73     291.75    247.24    247.24   148.35
  10000.00     9.67    124.57    96.65     392.41    348.81    311.44   186.86
  25000.00    13.11    169.02   131.14     549.32    490.16    422.55   253.53
  50000.00    16.52    212.90   165.18     734.52    660.00    532.26   319.36
```

```
  75000.00     18.91    243.68    189.06    877.26    791.97    609.20    365.52
 100000.00     20.81    268.18    208.07   1019.09    911.82    670.45    402.27
 500000.00     35.56    458.34    355.61   1833.35   1650.01   1145.84    687.51


           PROPANE FIREBALL RESULTS:
           *************************

           FIREBALL SURFACE TEMPERATURE =  2016.000
           -------------------------------------

     MASS     TIME     DIAMETER    HEIGHT  HUMAN R.   ANIMAL R.  BULID.R. PR.EQ.R
---------------------------------------------------------------------------------
   1000.00      4.49     57.87     44.90    150.45    133.09    150.45     89.69
   5000.00      7.67     98.90     76.73    286.80    247.24    257.13    153.29
  10000.00      9.67    124.57     96.65    398.64    348.81    323.89    193.09
  25000.00     13.11    169.02    131.14    557.77    498.61    439.46    261.98
  50000.00     16.52    212.90    165.18    745.17    670.65    553.55    330.00
  75000.00     18.91    243.68    189.06    889.44    816.33    633.57    377.71
 100000.00     20.81    268.18    208.07   1019.09    925.22    697.27    415.68
 500000.00     35.56    458.34    355.61   1856.27   1672.93   1191.68    710.42


           BUTANE FIREBALL RESULTS:
           *************************

           FIREBALL SURFACE TEMPERATURE =  2016.000
           -------------------------------------

     MASS     TIME     DIAMETER    HEIGHT  HUMAN R.   ANIMAL R.  BULID.R. PR.EQ.R
---------------------------------------------------------------------------------
   1000.00      4.49     57.87     44.90    153.35    144.67    150.45     89.69
   5000.00      7.67     98.90     76.73    291.75    276.91    257.13    153.29
  10000.00      9.67    124.57     96.65    404.87    367.49    323.89    193.09
  25000.00     13.11    169.02    131.14    574.67    532.42    439.46    261.98
  50000.00     16.52    212.90    165.18    755.81    702.59    553.55    330.00
  75000.00     18.91    243.68    189.06    913.81    840.70    633.57    377.71
 100000.00     20.81    268.18    208.07   1032.50    952.04    697.27    415.68
 500000.00     35.56    458.34    355.61   1879.18   1695.85   1191.68    710.42


           PENTANE FIREBALL RESULTS:
           *************************


           FIREBALL SURFACE TEMPERATURE =  2016.000
           -------------------------------------
```

```
  MASS      TIME      DIAMETER  HEIGHT    HUMAN R.  ANIMAL R.  BULID.R.  PR.EQ.R
-------------------------------------------------------------------------------
  1000.00     4.49     57.87     44.90    156.24    150.45    150.45     86.80
  5000.00     7.67     98.90     76.73    301.64    281.86    257.13    148.35
 10000.00     9.67    124.57     96.65    411.09    373.72    323.89    186.86
 25000.00    13.11    169.02    131.14    591.58    540.87    439.46    253.53
 50000.00    16.52    212.90    165.18    787.75    713.23    553.55    319.36
 75000.00    18.91    243.68    189.06    938.18    852.89    633.57    365.52
100000.00    20.81    268.18    208.07   1086.13    978.86    697.27    402.27
500000.00    35.56    458.34    355.61   1925.02   1764.60   1191.68    687.51


          USING HOT SHELL-COLD CORE MODEL:
          ================================


           METHANE RESULTS OF HOT SHELL-COLD CORE MODEL:
          **********************************************


          FIREBALL SURFACE TEMPERATURE =  1500.000
          ------------------------------

  MASS    TIME     DIAMETER  HEIGHT    HUMAN R.  ANIMAL R.  BULID.R.  PR.EQ.R
-------------------------------------------------------------------------------
  1000.00    55.59     69.80     55.59    157.04    153.55    202.41    125.63
  5000.00    95.07    119.36     95.07    310.34    298.40    346.15    214.85
 10000.00   119.78    150.39    119.78    421.10    413.58    436.14    270.71
 25000.00   162.58    204.13    162.58    632.79    612.38    591.97    367.43
 50000.00   204.84    257.19    204.84    835.88    810.16    745.87    462.95
 75000.00   234.49    294.42    234.49   1001.04    956.87    853.83    529.96
100000.00   258.10    324.06    258.10   1150.41   1085.60    939.77    583.31
500000.00   441.39    554.19    441.39   2050.52   1939.68   1607.16    997.55


           BUTANE RESULTS OF HOT SHELL-COLD CORE MODEL:
          **********************************************

      THE VALUE OF F1=    7.14186E-03

          FIREBALL SURFACE TEMPERATURE =  1300.000
          ------------------------------

  MASS     TIME  DIAMETER  HEIGHT  HUMAN R.  ANIMAL R.   BULID.R.  PR.EQ.R
-------------------------------------------------------------------------------
 0.10E+04 0.31E+04 0.31E+04 0.31E+05 0.00E+01 0.00E+01 0.00E+01 0.00E+01
 0.50E+04 0.16E+05 0.16E+05 0.16E+06 0.00E+01 0.00E+01 0.00E+01 0.00E+01
 0.10E+05 0.31E+05 0.31E+05 0.31E+06 0.00E+01 0.00E+01 0.00E+01 0.00E+01
 0.25E+05 0.78E+05 0.78E+05 0.78E+06 0.00E+01 0.00E+01 0.00E+01 0.00E+01
```

```
0.50E+05 0.16E+06 0.16E+06 0.16E+07 0.00E+01 0.00E+01 0.00E+01 0.00E+01
0.75E+05 0.23E+06 0.23E+06 0.23E+07 0.00E+01 0.00E+01 0.00E+01 0.00E+01
0.10E+06 0.31E+06 0.31E+06 0.31E+07 0.00E+01 0.00E+01 0.00E+01 0.00E+01
0.50E+06 0.16E+07 0.16E+07 0.16E+08 0.00E+01 0.00E+01 0.00E+01 0.00E+01

        THE VALUE OF H/DS =      9.971


    THE VALUE OF F21 BECOMES VERY SMALL AND THAT MEAN
    THE VALUE OF F21 APPROACHES ZERO.
    THEN THIS MODEL MUST NOT USED IN THESE CONDITIONS.


        USING ISO-THERMAL MODEL:
        ========================


         METANE RESULTS OF ISO-THERMAL MODEL:
        ========================================


        FIREBALL SURFACE TEMPERATURE =  1980.000
        --------------------------------

   MASS     TIME    DIAMETER  HEIGHT    HUMAN R. ANIMAL R. BULID.R PR.EQ.R
--------------------------------------------------------------------------------
   1000.00    4.50    58.65    45.02   155.42   149.56   140.76    82.11
   5000.00    7.70   100.29    76.99   280.80   270.77   240.69   140.40
  10000.00    9.70   126.35    97.01   379.05   379.05   303.24   176.89
  25000.00   13.17   171.48   131.67   548.73   548.73   411.55   240.07
  50000.00   16.59   216.04   165.90   723.74   723.74   518.50   302.46
  75000.00   18.99   247.30   189.91   877.93   853.20   593.53   346.23
 100000.00   20.90   272.19   209.03  1020.71   966.28   653.26   381.07
 500000.00   35.75   465.41   357.48  1791.84  1722.03  1116.99   651.58
***************************************************************************


        ETHANE RESULTS OF ISO-THERMAL MODEL:
        ========================================


        FIREBALL SURFACE TEMPERATURE =  2012.000
        --------------------------------

   MASS     TIME    DIAMETER  HEIGHT    HUMAN R. ANIMAL R. BULID.R PR.EQ.R
--------------------------------------------------------------------------------
   1000.00    4.50    57.44    45.02   149.34   134.98   143.60    86.16
   5000.00    7.70    98.21    76.99   270.09   270.09   245.54   147.32
  10000.00    9.70   123.74    97.01   365.03   377.40   309.35   185.61
  25000.00   13.17   167.93   131.67   529.00   537.39   419.84   251.90
  50000.00   16.59   211.58   165.90   687.63   708.79   528.95   317.37
```

```
  75000.00     18.99    242.20    189.91    835.57    847.68    605.49    363.29
 100000.00     20.90    266.57    209.03    986.30    972.97    666.42    399.85
 500000.00     35.75    455.80    357.48   1777.62   1709.25   1139.50    683.70
 ****************************************************************


                  PROPANE RESULTS OF ISO-THERMAL MODEL:
                  ======================================


                  FIREBALL SURFACE TEMPERATURE =  2016.000
                  ------------------------------

      MASS      TIME     DIAMETER  HEIGHT     HUMAN R. ANIMAL R. BULID.R PR.EQ.R
 ------------------------------------------------------------------------------
   1000.00      4.50     56.89     45.02    139.38    136.53    142.22     85.33
   5000.00      7.70     97.27     76.99    262.64    252.91    243.19    145.91
  10000.00      9.70    122.56     97.01    355.41    337.03    306.39    183.83
  25000.00     13.17    166.33    131.67    515.62    498.98    415.82    249.49
  50000.00     16.59    209.56    165.90    691.53    670.58    523.89    314.33
  75000.00     18.99    239.88    189.91    839.57    803.59    599.69    359.82
 100000.00     20.90    264.02    209.03    976.86    924.06    660.04    396.03
 500000.00     35.75    451.44    357.48   1738.04   1647.75   1128.60    677.16
 ****************************************************************


                  BUTANE RESULTS OF ISO-THERMAL MODEL:
                  =====================================


                  FIREBALL SURFACE TEMPERATURE =  2016.000
                  ------------------------------

      MASS      TIME     DIAMETER  HEIGHT     HUMAN R. ANIMAL R. BULID.R PR.EQ.R
 ------------------------------------------------------------------------------
   1000.00      4.50     56.58     45.02    144.29    135.80    141.46     84.87
   5000.00      7.70     96.75     76.99    261.23    251.55    241.88    145.13
  10000.00      9.70    121.90     97.01    347.40    341.31    304.74    182.84
  25000.00     13.17    165.43    131.67    512.84    512.84    413.58    248.15
  50000.00     16.59    208.43    165.90    687.81    687.81    521.07    312.64
  75000.00     18.99    238.59    189.91    835.05    823.12    596.46    357.88
 100000.00     20.90    262.59    209.03    958.47    945.34    656.49    393.89
 500000.00     35.75    449.01    357.48   1706.22   1683.77   1122.52    673.51
 ****************************************************************


                  PENTANE RESULTS OF ISO-THERMAL MODDEL:
                  ====================================
```

```
          FIREBALL SURFACE TEMPERATURE =  2016.000
          ---------------------------------

    MASS     TIME     DIAMETER  HEIGHT     HUMAN R. ANIMAL R. BULID.R PR.EQ.R
--------------------------------------------------------------------------------
   1000.00     4.50     56.39     45.02   140.98    132.52    140.98    84.59
   5000.00     7.70     96.42     76.99   260.34    250.70    241.05   144.63
  10000.00     9.70    121.48     97.01   346.22    334.07    303.70   182.22
  25000.00    13.17    164.87    131.67   494.61    511.10    412.18   247.31
  50000.00    16.59    207.72    165.90   664.70    675.09    519.30   311.58
  75000.00    18.99    237.78    189.91   808.44    808.44    594.44   356.66
 100000.00    20.90    261.70    209.03   929.05    915.96    654.26   392.55
 500000.00    35.75    447.48    357.48  1678.06   1633.31   1118.70   671.22
  ************************************************************************


           B.L.E.V.E FIREBALL RESULTS:
          *******************************


           METHANE BLEVE FIREBALL RESULTS:
          ======================================


          FIREBALL SURFACE TEMPERATURE =  1482.000
          ---------------------------------

    MASS     TIME     DIAMETER  HEIGHT     HUMAN R. ANIMAL R.  BULID.R. PR.EQ.R
--------------------------------------------------------------------------------
   1000.00     4.37     48.47     24.24    60.59     60.59     67.86    33.93
   5000.00     7.47     82.88     41.44   124.32    116.04    116.04    58.02
  10000.00     9.41    104.42     52.21   177.52    167.08    146.19    73.10
  25000.00    12.77    141.72     70.86   269.27    255.10    198.41    99.20
  50000.00    16.09    178.55     89.28   366.03    357.10    249.97   124.99
  75000.00    18.42    204.39    102.19   439.43    429.21    286.14   143.07
 100000.00    20.27    224.96    112.48   562.39    506.15    314.94   157.47
 500000.00    34.66    384.65    192.32  1019.32    961.62    538.51   269.25


          ETHANE BLEVE FIREBALL RESULTS:
          ======================================


          FIREBALL SURFACE TEMPERATURE =  1642.000
          ---------------------------------

    MASS     TIME     DIAMETER  HEIGHT     HUMAN R. ANIMAL R.  BULID.R. PR.EQ.R
--------------------------------------------------------------------------------
   1000.00     3.54     39.31     19.66    55.03     55.03     70.76    35.38
   5000.00     6.06     67.22     33.61   107.55    114.27    120.99    60.49
  10000.00     7.63     84.68     42.34   148.20    156.67    152.43    76.22
```

```
 25000.00    10.36    114.93     57.47    229.86    241.36    206.88    103.44
 50000.00    13.05    144.80     72.40    318.56    333.04    260.64    130.32
 75000.00    14.94    165.75     82.88    397.81    414.38    298.36    149.18
100000.00    16.44    182.43     91.22    465.21    483.45    328.38    164.19
500000.00    28.11    311.94    155.97    873.43    873.43    561.49    280.75


           PROPANE BLEVE FIREBALL RESULTS:
           =====================================


           FIREBALL SURFACE TEMPERATURE =  1740.000
           --------------------------------

    MASS      TIME    DIAMETER  HEIGHT    HUMAN R.  ANIMAL R.  BULID.R.  PR.EQ.R
--------------------------------------------------------------------------------
  1000.00     3.12     34.60     17.30     51.90     51.90     69.20     38.06
  5000.00     5.33     59.16     29.58    100.57    103.53    118.32     65.08
 10000.00     6.72     74.54     37.27    141.62    149.07    149.07     81.99
 25000.00     9.12    101.16     50.58    212.43    222.55    202.32    111.27
 50000.00    11.49    127.45     63.72    293.13    305.88    254.90    140.19
 75000.00    13.15    145.89     72.94    364.72    372.02    291.78    160.48
100000.00    14.47    160.57     80.29    433.54    425.51    321.14    176.63
500000.00    24.74    274.56    137.28    782.49    782.49    549.12    302.01


           BUTANE BLEVE FIREBALL RESULTS:
           =====================================


           FIREBALL SURFACE TEMPERATURE =  1818.000
           --------------------------------

    MASS      TIME    DIAMETER  HEIGHT    HUMAN R.  ANIMAL R.  BULID.R.  PR.EQ.R
--------------------------------------------------------------------------------
  1000.00     2.84     31.56     15.78     47.33     50.49     69.42     37.87
  5000.00     4.86     53.96     26.98     94.42     99.82    118.70     64.75
 10000.00     6.13     67.98     33.99    132.56    139.36    149.56     81.58
 25000.00     8.31     92.26     46.13    193.75    202.97    202.97    110.71
 50000.00    10.47    116.24     58.12    267.35    278.97    255.72    139.48
 75000.00    11.99    133.06     66.53    332.64    345.95    292.72    159.67
100000.00    13.20    146.45     73.22    388.08    402.73    322.18    175.74
500000.00    22.57    250.41    125.20    713.66    726.18    550.89    300.49


           PENTANE BLEVE FIREBALL RESULTS:
           =====================================


           FIREBALL SURFACE TEMPERATURE =  1884.000
           --------------------------------
```

MASS	TIME	DIAMETER	HEIGHT	HUMAN R.	ANIMAL R.	BULID.R.	PR.EQ.R
1000.00	2.65	29.36	14.68	46.98	49.91	67.53	38.17
5000.00	4.52	50.21	25.10	90.37	102.92	115.47	65.27
10000.00	5.70	63.25	31.63	129.67	142.32	145.48	82.23
25000.00	7.74	85.84	42.92	188.86	210.32	197.44	111.60
50000.00	9.75	108.16	54.08	259.57	286.61	248.76	140.60
75000.00	11.16	123.81	61.90	321.89	352.84	284.75	160.95
100000.00	12.28	136.26	68.13	374.73	401.98	313.41	177.14
500000.00	21.00	233.00	116.50	675.69	722.29	535.89	302.89

```
              FIREBALL DIMENSIONS AND HAZARD RANGES RESULSTS:
              ===============================================

               (FOR THERMODYNAMIC FIREBALL TEMPERATURES)
               *****************************************


         THE PREDICATION OF FIREBALL DIMENSIONS & HAZARD RANGES
         *******************************************************
         USING PREVIOUS WORK EQUATIONS & PARAMETERS:
         *******************************************


            USING GAYLE PARAMETERS (A,AS,B & BS)
            ====================================

             METHANE FIREBALL RESULTS:
            **************************

            AT FIREBALL SURFACE TEMPERATUE =  2014.468
            ------------------------------

      MASS       TIME    DIAMETER  HEIGHT    HUMAN R.  ANIMAL R.BULID.R.  PR.EQ.R.
   -------------------------------------------------------------------------------
     1000.00     2.87     34.98     28.65     69.96     76.96     87.46     52.47
     5000.00     5.08     59.12     50.82    133.01    144.84    147.79     88.68
    10000.00     6.50     74.11     65.04    192.67    192.67    185.26    111.16
    25000.00     9.01     99.90     90.12    274.73    289.72    249.76    149.85
    50000.00    11.53    125.23    115.35    369.43    394.48    313.08    187.85
    75000.00    13.33    142.93    133.26    450.22    471.66    357.32    214.39
   100000.00    14.76    156.98    147.63    518.04    541.59    392.45    235.47
   500000.00    26.18    265.28    261.82    915.23    941.76    663.21    397.93


             ETHANE FIREBALL RESULTS:
            **************************

            FIREBALL SURFACE TEMPERATUER =  2092.953
            ------------------------------

      MASS      TIME   DIAMETER  HEIGHT     HUMAN R.  ANIMAL R. BULID.R.  PR.EQ.R
   -------------------------------------------------------------------------------
     1000.00     2.87     34.98     28.65     90.95     69.96     94.45     55.97
     5000.00     5.08     59.12     50.82    165.53    135.97    159.62     94.59
    10000.00     6.50     74.11     65.04    218.61    188.97    200.08    118.57
    25000.00     9.01     99.90     90.12    314.69    264.74    269.74    159.84
```

```
  50000.00     11.53    125.23    115.35    419.52    375.69    338.12    200.37
  75000.00     13.33    142.93    133.26    500.25    464.52    385.91    228.69
 100000.00     14.76    156.98    147.63    565.13    533.74    423.85    251.17
 500000.00     26.18    265.28    261.82    981.55    941.76    716.27    424.46


          PROPANE FIREBALL RESULTS:
          *************************

          FIREBALL SURFACE TEMPERATURE =  2113.337
          ------------------------------------

    MASS     TIME    DIAMETER   HEIGHT  HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
-------------------------------------------------------------------------------
   1000.00      2.87     34.98     28.65     83.96     80.46     94.45     59.47
   5000.00      5.08     59.12     50.82    156.66    147.79    159.62    100.50
  10000.00      6.50     74.11     65.04    218.61    200.08    200.08    125.98
  25000.00      9.01     99.90     90.12    309.70    299.71    269.74    169.83
  50000.00     11.53    125.23    115.35    407.00    394.48    338.12    212.89
  75000.00     13.33    142.93    133.26    485.96    464.52    385.91    242.98
 100000.00     14.76    156.98    147.63    557.28    525.89    423.85    266.87
 500000.00     26.18    265.28    261.82    968.29    941.76    716.27    450.98


          BUTANE FIREBALL RESULTS:
          ***************************

          FIREBALL SURFACE TEMPERATURE =  2120.308
          ------------------------------------

    MASS     TIME    DIAMETER   HEIGHT  HUMAN R.  ANIMAL R.  BULID.R. PR.EQ.R
-------------------------------------------------------------------------------
   1000.00      2.87     34.98     28.65     82.21     76.96     94.45     59.47
   5000.00      5.08     59.12     50.82    156.66    147.79    159.62    100.50
  10000.00      6.50     74.11     65.04    211.20    200.08    200.08    125.98
  25000.00      9.01     99.90     90.12    314.69    299.71    269.74    169.83
  50000.00     11.53    125.23    115.35    419.52    388.22    338.12    212.89
  75000.00     13.33    142.93    133.26    493.10    471.66    385.91    242.98
 100000.00     14.76    156.98    147.63    557.28    533.74    423.85    266.87
 500000.00     26.18    265.28    261.82    968.29    941.76    716.27    450.98


          PENTANE FIREBALL RESULTS:
          ***************************


          FIREBALL SURFACE TEMPERATURE =  2127.224
          ------------------------------------
```

```
     MASS      TIME      DIAMETER  HEIGHT     HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
  ------------------------------------------------------------------------------
    1000.00     2.87      34.98     28.65     89.20     87.46     94.45     59.47
    5000.00     5.08      59.12     50.82    162.57    159.62    159.62    100.50
   10000.00     6.50      74.11     65.04    222.32    222.32    200.08    125.98
   25000.00     9.01      99.90     90.12    314.69    314.69    269.74    169.83
   50000.00    11.53     125.23    115.35    407.00    407.00    338.12    212.89
   75000.00    13.33     142.93    133.26    500.25    493.10    385.91    242.98
  100000.00    14.76     156.98    147.63    588.68    557.28    423.85    266.87
  500000.00    26.18     265.28    261.82   1034.61    968.29    716.27    450.98


             USING BRASIE PARAMETERS (A,AS,B & BS)
             ======================================


              METHANE FIREBALL RESULTS:
             **************************


             AT FIREBALL SURFACE TEMPERATUE =  2014.468
             ------------------------------

     MASS      TIME      DIAMETER  HEIGHT     HUMAN R. ANIMAL R.BULID.R.  PR.EQ.R.
  ------------------------------------------------------------------------------
    1000.00     2.99      37.91     29.93     98.57     90.99     94.78     56.87
    5000.00     5.12      64.79     51.15    178.19    165.23    161.99     97.19
   10000.00     6.44      81.62     64.43    240.77    224.45    204.04    122.43
   25000.00     8.74     110.74     87.42    337.75    326.68    276.85    166.11
   50000.00    11.01     139.49    110.12    453.34    432.42    348.72    209.23
   75000.00    12.60     159.65    126.04    550.81    510.89    399.13    239.48
  100000.00    13.87     175.70    138.71    623.75    579.83    439.26    263.56
  500000.00    23.71     300.29    237.07   1096.06   1036.00    750.72    450.43


              ETHANE FIREBALL RESULTS:
             **************************


             FIREBALL SURFACE TEMPERATUER =  2092.953
             ------------------------------

     MASS      TIME   DIAMETER  HEIGHT      HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
  ------------------------------------------------------------------------------
    1000.00     2.99     37.91     29.93     98.57     92.89    102.36     64.45
    5000.00     5.12     64.79     51.15    178.19    168.47    174.95    110.15
   10000.00     6.44     81.62     64.43    240.77    232.61    220.37    138.75
   25000.00     8.74    110.74     87.42    348.83    332.21    298.99    188.26
   50000.00    11.01    139.49    110.12    467.29    439.39    376.62    237.13
```

```
  75000.00    12.60   159.65   126.04   566.77   518.87   431.07   271.41
 100000.00    13.87   175.70   138.71   641.32   597.40   474.40   298.70
 500000.00    23.71   300.29   237.07  1141.10  1066.03   810.78   510.49


           PROPANE FIREBALL RESULTS:
           *************************

           FIREBALL SURFACE TEMPERATURE =  2113.337
           ------------------------------

    MASS     TIME    DIAMETER  HEIGHT  HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
---------------------------------------------------------------------------
   1000.00     2.99    37.91    29.93   102.36    94.78   106.16    64.45
   5000.00     5.12    64.79    51.15   187.91   174.95   181.43   110.15
  10000.00     6.44    81.62    64.43   253.01   236.69   228.53   138.75
  25000.00     8.74   110.74    87.42   365.44   343.29   310.07   188.26
  50000.00    11.01   139.49   110.12   481.24   453.34   390.57   237.13
  75000.00    12.60   159.65   126.04   566.77   534.84   447.03   271.41
 100000.00    13.87   175.70   138.71   641.32   614.97   491.97   298.70
 500000.00    23.71   300.29   237.07  1141.10  1111.07   840.81   510.49


           BUTANE FIREBALL RESULTS:
           **************************

           FIREBALL SURFACE TEMPERATURE =  2120.308
           ------------------------------

    MASS     TIME    DIAMETER  HEIGHT  HUMAN R.  ANIMAL R.  BULID.R. PR.EQ.R
---------------------------------------------------------------------------
   1000.00     2.99    37.91    29.93    89.09    94.78   106.16    64.45
   5000.00     5.12    64.79    51.15   165.23   174.95   181.43   110.15
  10000.00     6.44    81.62    64.43   228.53   236.69   228.53   138.75
  25000.00     8.74   110.74    87.42   332.21   343.29   310.07   188.26
  50000.00    11.01   139.49   110.12   439.39   453.34   390.57   237.13
  75000.00    12.60   159.65   126.04   534.84   542.82   447.03   271.41
 100000.00    13.87   175.70   138.71   606.18   623.75   491.97   298.70
 500000.00    23.71   300.29   237.07  1096.06  1096.06   840.81   510.49


           PENTANE FIREBALL RESULTS:
           ***************************


           FIREBALL SURFACE TEMPERATURE =  2127.224
           ------------------------------
```

```
   MASS      TIME      DIAMETER  HEIGHT    HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
 ------------------------------------------------------------------------------
   1000.00     2.99     37.91     29.93    102.36     94.78    106.16    64.45
   5000.00     5.12     64.79     51.15    187.91    174.95    181.43   110.15
  10000.00     6.44     81.62     64.43    253.01    236.69    228.53   138.75
  25000.00     8.74    110.74     87.42    365.44    343.29    310.07   188.26
  50000.00    11.01    139.49    110.12    488.21    453.34    390.57   237.13
  75000.00    12.60    159.65    126.04    590.72    534.84    447.03   271.41
 100000.00    13.87    175.70    138.71    676.46    606.18    491.97   298.70
 500000.00    23.71    300.29    237.07   1231.19   1081.04    840.81   510.49


             USING MARSHALL PARAMETERS (A,AS,B & BS):
             ========================================


              METHANE FIREBALL RESULTS:
             **************************


             AT FIREBALL SURFACE TEMPERATUE =  2014.468
             ------------------------------

   MASS      TIME      DIAMETER  HEIGHT    HUMAN R.  ANIMAL R.BULID.R. PR.EQ.R.
 ------------------------------------------------------------------------------
   1000.00     3.79     54.87     37.91    153.65    131.70    137.18    82.31
   5000.00     6.48     93.78     64.79    281.35    253.21    234.46   140.67
  10000.00     8.16    118.13     81.62    372.11    342.58    295.33   177.20
  25000.00    11.07    160.28    110.74    520.91    488.85    400.70   240.42
  50000.00    13.95    201.89    139.49    706.62    646.06    504.73   302.84
  75000.00    15.97    231.08    159.65    854.99    762.56    577.69   346.62
 100000.00    17.57    254.31    175.70    979.09    877.37    635.77   381.46
 500000.00    30.03    434.63    300.29   1716.79   1586.40   1086.58   651.95


              ETHANE FIREBALL RESULTS:
             **************************


             FIREBALL SURFACE TEMPERATUER =  2092.953
             ------------------------------

   MASS      TIME    DIAMETER  HEIGHT      HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
 ------------------------------------------------------------------------------
   1000.00     3.79     54.87     37.91    153.65    142.67    148.16    93.28
   5000.00     6.48     93.78     64.79    276.66    257.90    253.21   159.43
  10000.00     8.16    118.13     81.62    372.11    348.49    318.95   200.82
  25000.00    11.07    160.28    110.74    528.92    496.87    432.75   272.47
  50000.00    13.95    201.89    139.49    706.62    646.06    545.11   343.22
```

```
  75000.00    15.97   231.08   159.65   854.99   774.11   623.91   392.83
 100000.00    17.57   254.31   175.70   979.09   877.37   686.64   432.33
 500000.00    30.03   434.63   300.29  1738.52  1564.67  1173.50   738.87


           PROPANE FIREBALL RESULTS:
           *************************

           FIREBALL SURFACE TEMPERATURE =  2113.337
           ---------------------------------

     MASS    TIME   DIAMETER   HEIGHT  HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
---------------------------------------------------------------------------
   1000.00     3.79    54.87    37.91   153.65   137.18   148.16    87.80
   5000.00     6.48    93.78    64.79   276.66   253.21   253.21   150.05
  10000.00     8.16   118.13    81.62   372.11   354.39   318.95   189.01
  25000.00    11.07   160.28   110.74   520.91   504.88   432.75   256.45
  50000.00    13.95   201.89   139.49   706.62   666.24   545.11   323.03
  75000.00    15.97   231.08   159.65   866.54   785.66   623.91   369.72
 100000.00    17.57   254.31   175.70   991.81   902.80   686.64   406.90
 500000.00    30.03   434.63   300.29  1738.52  1586.40  1173.50   695.41


           BUTANE FIREBALL RESULTS:
           ************************

           FIREBALL SURFACE TEMPERATURE =  2120.308
           ---------------------------------

     MASS    TIME   DIAMETER   HEIGHT  HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
---------------------------------------------------------------------------
   1000.00     3.79    54.87    37.91   156.39   131.70   148.16    90.54
   5000.00     6.48    93.78    64.79   281.35   253.21   253.21   154.74
  10000.00     8.16   118.13    81.62   378.02   336.67   318.95   194.92
  25000.00    11.07   160.28   110.74   528.92   488.85   432.75   264.46
  50000.00    13.95   201.89   139.49   726.81   646.06   545.11   333.12
  75000.00    15.97   231.08   159.65   889.65   774.11   623.91   381.28
 100000.00    17.57   254.31   175.70  1004.52   890.08   686.64   419.61
 500000.00    30.03   434.63   300.29  1803.71  1608.13  1173.50   717.14


           PENTANE FIREBALL RESULTS:
           *************************


           FIREBALL SURFACE TEMPERATURE =  2127.224
           ---------------------------------
```

```
   MASS      TIME     DIAMETER  HEIGHT    HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
------------------------------------------------------------------------------
  1000.00     2.99     37.91     29.93    108.05     92.89    102.36    62.56
  5000.00     5.12     64.79     51.15    197.62    178.19    174.95   106.91
 10000.00     6.44     81.62     64.43    265.26    236.69    220.37   134.67
 25000.00     8.74    110.74     87.42    376.51    343.29    298.99   182.72
 50000.00    11.01    139.49    110.12    502.16    460.31    376.62   230.16
 75000.00    12.60    159.65    126.04    614.67    558.79    431.07   263.43
100000.00    13.87    175.70    138.71    711.60    641.32    474.40   289.91
500000.00    23.71    300.29    237.07   1261.22   1141.10    810.78   495.48


               USING ROBERTS PARAMETERS (A,AS,B & BS):
               =======================================


                METHANE FIREBALL RESULTS:
               **************************


               AT FIREBALL SURFACE TEMPERATUE =  2014.468
               ------------------------------

   MASS      TIME     DIAMETER  HEIGHT    HUMAN R. ANIMAL R.BULID.R. PR.EQ.R.
------------------------------------------------------------------------------
  1000.00     4.49     57.87     44.90    153.35    144.67    144.67    86.80
  5000.00     7.67     98.90     76.73    291.75    276.91    247.24   148.35
 10000.00     9.67    124.57     96.65    392.41    379.95    311.44   186.86
 25000.00    13.11    169.02    131.14    549.32    540.87    422.55   253.53
 50000.00    16.52    212.90    165.18    723.88    723.88    532.26   319.36
 75000.00    18.91    243.68    189.06    877.26    877.26    609.20   365.52
100000.00    20.81    268.18    208.07   1019.09   1005.68    670.45   402.27
500000.00    35.56    458.34    355.61   1833.35   1764.60   1145.84   687.51


                ETHANE FIREBALL RESULTS:
               **************************


               FIREBALL SURFACE TEMPERATUER =  2092.953
               ------------------------------

   MASS      TIME   DIAMETER  HEIGHT      HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
------------------------------------------------------------------------------
  1000.00     4.49     57.87     44.90    147.56    141.77    159.13    95.48
  5000.00     7.67     98.90     76.73    291.75    262.08    271.97   163.18
 10000.00     9.67    124.57     96.65    392.41    367.49    342.58   205.55
 25000.00    13.11    169.02    131.14    557.77    532.42    464.81   278.89
 50000.00    16.52    212.90    165.18    745.17    702.59    585.49   351.29
```

```
  75000.00    18.91   243.68   189.06   889.44   840.70   670.13   402.08
 100000.00    20.81   268.18   208.07  1019.09   965.45   737.50   442.50
 500000.00    35.56   458.34   355.61  1856.27  1718.76  1260.43   756.26


          PROPANE FIREBALL RESULTS:
          *************************

          FIREBALL SURFACE TEMPERATURE =  2113.337
          ------------------------------

   MASS    TIME    DIAMETER   HEIGHT  HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
---------------------------------------------------------------------------
   1000.00    4.49    57.87    44.90   153.35   144.67   162.03    98.37
   5000.00    7.67    98.90    76.73   291.75   267.02   276.91   168.13
  10000.00    9.67   124.57    96.65   398.64   373.72   348.81   211.78
  25000.00   13.11   169.02   131.14   574.67   532.42   473.26   287.34
  50000.00   16.52   212.90   165.18   766.46   702.59   596.13   361.94
  75000.00   18.91   243.68   189.06   901.62   840.70   682.31   414.26
 100000.00   20.81   268.18   208.07  1032.50   965.45   750.91   455.91
 500000.00   35.56   458.34   355.61  1879.18  1695.85  1283.34   779.17


          BUTANE FIREBALL RESULTS:
          ************************

          FIREBALL SURFACE TEMPERATURE =  2120.308
          ------------------------------

   MASS    TIME    DIAMETER   HEIGHT  HUMAN R.  ANIMAL R.  BULID.R. PR.EQ.R
---------------------------------------------------------------------------
   1000.00    4.49    57.87    44.90   156.24   147.56   162.03    98.37
   5000.00    7.67    98.90    76.73   291.75   276.91   276.91   168.13
  10000.00    9.67   124.57    96.65   392.41   373.72   348.81   211.78
  25000.00   13.11   169.02   131.14   566.22   540.87   473.26   287.34
  50000.00   16.52   212.90   165.18   755.81   723.88   596.13   361.94
  75000.00   18.91   243.68   189.06   913.81   852.89   682.31   414.26
 100000.00   20.81   268.18   208.07  1045.91   992.27   750.91   455.91
 500000.00   35.56   458.34   355.61  1879.18  1764.60  1283.34   779.17


          PENTANE FIREBALL RESULTS:
          *************************


          FIREBALL SURFACE TEMPERATURE =  2127.224
          ------------------------------
```

```
   MASS      TIME      DIAMETER  HEIGHT    HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
-------------------------------------------------------------------------------
  1000.00      4.49     57.87     44.90    162.03    150.45    159.13    98.37
  5000.00      7.67     98.90     76.73    296.69    271.97    271.97   168.13
 10000.00      9.67    124.57     96.65    404.87    373.72    342.58   211.78
 25000.00     13.11    169.02    131.14    591.58    540.87    464.81   287.34
 50000.00     16.52    212.90    165.18    798.39    723.88    585.49   361.94
 75000.00     18.91    243.68    189.06    950.36    852.89    670.13   414.26
100000.00     20.81    268.18    208.07   1099.54    965.45    737.50   455.91
500000.00     35.56    458.34    355.61   1947.93   1718.76   1260.43   779.17



            USING HOT SHELL-COLD CORE MODEL:
            ================================


             METHANE RESULTS OF HOT SHELL-COLD CORE MODEL:
             *********************************************


            FIREBALL SURFACE TEMPERATURE =  1500.000
            ------------------------------

   MASS     TIME     DIAMETER  HEIGHT     HUMAN R.  ANIMAL R. BULID.R. PR.EQ.R
-------------------------------------------------------------------------------
  1000.00    55.59    69.80     55.59     153.55    150.06    209.39   136.10
  5000.00    95.07   119.36     95.07     298.40    298.40    358.08   232.75
 10000.00   119.78   150.39    119.78     406.06    406.06    451.18   293.27
 25000.00   162.58   204.13    162.58     591.97    591.97    612.38   398.05
 50000.00   204.84   257.19    204.84     797.30    784.44    771.58   501.53
 75000.00   234.49   294.42    234.49     956.87    927.43    883.27   574.12
100000.00   258.10   324.06    258.10    1085.60   1036.99    972.18   631.92
500000.00   441.39   554.19    441.39    1911.97   1856.55   1662.58  1080.68



             BUTANE RESULTS OF HOT SHELL-COLD CORE MODEL:
             ********************************************

         THE VALUE OF F1=   7.14186E-03

            FIREBALL SURFACE TEMPERATURE =  1300.000
            ------------------------------

   MASS    TIME  DIAMETER  HEIGHT  HUMAN R.  ANIMAL R.   BULID.R. PR.EQ.R
-------------------------------------------------------------------------------
0.10E+04 0.31E+04 0.31E+04 0.31E+05 0.00E+01 0.00E+01 0.00E+01 0.00E+01
0.50E+04 0.16E+05 0.16E+05 0.16E+06 0.00E+01 0.00E+01 0.00E+01 0.00E+01
0.10E+05 0.31E+05 0.31E+05 0.31E+06 0.00E+01 0.00E+01 0.00E+01 0.00E+01
0.25E+05 0.78E+05 0.78E+05 0.78E+06 0.00E+01 0.00E+01 0.00E+01 0.00E+01
```

```
0.50E+05 0.16E+06 0.16E+06 0.16E+07 0.00E+01 0.00E+01 0.00E+01 0.00E+01
0.75E+05 0.23E+06 0.23E+06 0.23E+07 0.00E+01 0.00E+01 0.00E+01 0.00E+01
0.10E+06 0.31E+06 0.31E+06 0.31E+07 0.00E+01 0.00E+01 0.00E+01 0.00E+01
0.50E+06 0.16E+07 0.16E+07 0.16E+08 0.00E+01 0.00E+01 0.00E+01 0.00E+01

        THE VALUE OF H/DS =     9.971


     THE VALUE OF F21 BECOMES VERY SMALL AND THAT MEAN
     THE VALUE OF F21 APPROACHES ZERO.
     THEN THIS MODEL MUST NOT USED IN THESE CONDITIONS.


        USING ISO-THERMAL MODEL:
        ========================


        METANE RESULTS OF ISO-THERMAL MODEL:
        ====================================


        FIREBALL SURFACE TEMPERATURE =  2014.468
        ----------------------------

   MASS     TIME    DIAMETER  HEIGHT    HUMAN R. ANIMAL R. BULID.R PR.EQ.R
-------------------------------------------------------------------------
   1000.00   4.50    58.99     45.02    159.27   150.42   147.47    97.33
   5000.00   7.70   100.86     76.99    287.46   287.46   252.16   166.43
  10000.00   9.70   127.08     97.01    393.94   387.59   317.70   209.68
  25000.00  13.17   172.47    131.67    560.52   543.27   431.17   284.57
  50000.00  16.59   217.29    165.90    749.65   717.05   543.22   358.53
  75000.00  18.99   248.73    189.91    895.43   858.12   621.83   410.41
 100000.00  20.90   273.76    209.03   1040.29   999.23   684.40   451.70
 500000.00  35.75   468.10    357.48   1848.99  1778.78  1170.25   772.36
 *****************************************************************


        ETHANE RESULTS OF ISO-THERMAL MODEL:
        ====================================


        FIREBALL SURFACE TEMPERATURE =  2092.953
        ----------------------------

   MASS     TIME    DIAMETER  HEIGHT    HUMAN R. ANIMAL R. BULID.R PR.EQ.R
-------------------------------------------------------------------------
   1000.00   4.50    58.20     45.02    154.23   148.41   157.14    98.94
   5000.00   7.70    99.51     76.99    278.64   283.61   268.69   169.17
  10000.00   9.70   125.38     97.01    376.13   382.40   338.52   213.14
  25000.00  13.17   170.16    131.67    544.50   553.01   459.43   289.27
  50000.00  16.59   214.38    165.90    718.17   718.17   578.83   364.45
```

```
  75000.00     18.99   245.40    189.91   871.17    846.63    662.58    417.18
 100000.00     20.90   270.10    209.03  1012.86    958.84    729.26    459.16
 500000.00     35.75   461.83    357.48  1824.24   1731.87   1246.95    785.11
   ****************************************************************************


                 PROPANE RESULTS OF ISO-THERMAL MODEL:
                 ==========================================


                FIREBALL SURFACE TEMPERATURE =  2113.337
                ---------------------------------

     MASS      TIME     DIAMETER  HEIGHT     HUMAN R. ANIMAL R. BULID.R PR.EQ.R
   ------------------------------------------------------------------------------
    1000.00     4.50     57.79     45.02   147.37    150.26    161.81     98.24
    5000.00     7.70     98.82     76.99   281.62    281.62    276.68    167.99
   10000.00     9.70    124.50     97.01   379.71    392.16    348.59    211.64
   25000.00    13.17    168.96    131.67   532.23    549.13    473.10    287.24
   50000.00    16.59    212.87    165.90   691.84    734.42    596.05    361.89
   75000.00    18.99    243.68    189.91   840.69    865.06    682.30    414.25
  100000.00    20.90    268.20    209.03   965.52   1005.75    750.96    455.94
  500000.00    35.75    458.59    357.48  1765.57   1765.57   1284.05    779.60
   ****************************************************************************


                 BUTANE RESULTS OF ISO-THERMAL MODEL:
                 ==========================================


                FIREBALL SURFACE TEMPERATURE =  2120.308
                ---------------------------------

     MASS      TIME     DIAMETER  HEIGHT     HUMAN R. ANIMAL R. BULID.R PR.EQ.R
   ------------------------------------------------------------------------------
    1000.00     4.50     57.54     45.02   149.61    143.86    155.36     97.82
    5000.00     7.70     98.39     76.99   275.49    260.74    265.66    167.26
   10000.00     9.70    123.96     97.01   359.49    365.69    334.70    210.74
   25000.00    13.17    168.24    131.67   529.95    521.53    454.24    286.00
   50000.00    16.59    211.96    165.90   710.07    688.87    572.29    360.33
   75000.00    18.99    242.63    189.91   861.34    824.94    655.10    412.47
  100000.00    20.90    267.05    209.03   988.07    948.02    721.03    453.98
  500000.00    35.75    456.62    357.48  1757.99   1666.66   1232.87    776.25
   ****************************************************************************


                 PENTANE RESULTS OF ISO-THERMAL MODDEL:
                 ==========================================
```

```
        FIREBALL SURFACE TEMPERATURE =  2127.224
        ------------------------------

   MASS      TIME    DIAMETER  HEIGHT    HUMAN R. ANIMAL R. BULID.R PR.EQ.R
---------------------------------------------------------------------------
  1000.00     4.50     57.41     45.02    149.26    149.26   155.00    97.60
  5000.00     7.70     98.16     76.99    279.77    274.86   265.04   166.88
 10000.00     9.70    123.68     97.01    383.39    371.03   333.92   210.25
 25000.00    13.17    167.85    131.67    537.11    528.72   453.19   285.34
 50000.00    16.59    211.47    165.90    708.42    687.28   570.97   359.50
 75000.00    18.99    242.07    189.91    835.14    823.04   653.59   411.52
100000.00    20.90    266.43    209.03    945.82    932.50   719.36   452.93
500000.00    35.75    455.56    357.48   1685.58   1662.81  1230.02   774.46
*************************************************************


        B.L.E.V.E FIREBALL RESULTS:
        ******************************


        METHANE BLEVE FIREBALL RESULTS:
        ===================================


        FIREBALL SURFACE TEMPERATURE =  1207.654
        ------------------------------

   MASS      TIME    DIAMETER  HEIGHT    HUMAN R. ANIMAL R.  BULID.R.  PR.EQ.R
------------------------------------------------------------------------------
  1000.00     4.37     48.47     24.24     53.32     55.74     43.63      2.42
  5000.00     7.47     82.88     41.44    103.60    107.75     74.59      4.14
 10000.00     9.41    104.42     52.21    140.97    146.19     93.98      5.22
 25000.00    12.77    141.72     70.86    205.49    212.58    127.55      7.09
 50000.00    16.09    178.55     89.28    276.75    294.61    160.70      8.93
 75000.00    18.42    204.39    102.19    337.24    357.68    183.95     10.22
100000.00    20.27    224.96    112.48    393.67    416.17    202.46     11.25
500000.00    34.66    384.65    192.32    711.60    769.30    346.18     19.23


        ETHANE BLEVE FIREBALL RESULTS:
        ===================================


        FIREBALL SURFACE TEMPERATURE =  1219.642
        ------------------------------

   MASS      TIME    DIAMETER  HEIGHT    HUMAN R. ANIMAL R.  BULID.R.  PR.EQ.R
------------------------------------------------------------------------------
  1000.00     3.54     39.31     19.66     39.31     41.28     35.38      1.97
  5000.00     6.06     67.22     33.61     77.30     80.66     60.49      3.36
 10000.00     7.63     84.68     42.34    105.86    110.09     76.22      4.23
```

```
  25000.00     10.36    114.93     57.47    155.16    160.90    103.44      5.75
  50000.00     13.05    144.80     72.40    209.96    217.20    130.32      7.24
  75000.00     14.94    165.75     82.88    256.92    265.21    149.18      8.29
 100000.00     16.44    182.43     91.22    301.02    319.26    164.19      9.12
 500000.00     28.11    311.94    155.97    577.09    592.69    280.75     15.60


               PROPANE BLEVE FIREBALL RESULTS:
               =======================================


               FIREBALL SURFACE TEMPERATURE =  1220.490
               ---------------------------------

     MASS      TIME     DIAMETER  HEIGHT    HUMAN R.  ANIMAL R.   BULID.R.  PR.EQ.R
 ---------------------------------------------------------------------------------
   1000.00      3.12     34.60     17.30     36.33     38.06     31.14      1.73
   5000.00      5.33     59.16     29.58     68.03     70.99     53.24      2.96
  10000.00      6.72     74.54     37.27     93.17     96.90     67.08      3.73
  25000.00      9.12    101.16     50.58    136.56    141.62     91.04      5.06
  50000.00     11.49    127.45     63.72    184.80    191.17    114.70      6.37
  75000.00     13.15    145.89     72.94    226.13    233.42    131.30      7.29
 100000.00     14.47    160.57     80.29    264.94    272.97    144.51      8.03
 500000.00     24.74    274.56    137.28    480.48    494.20    247.10     13.73


               BUTANE BLEVE FIREBALL RESULTS:
               =======================================


               FIREBALL SURFACE TEMPERATURE =  1220.024
               ---------------------------------

     MASS      TIME     DIAMETER  HEIGHT    HUMAN R.  ANIMAL R.   BULID.R.  PR.EQ.R
 ---------------------------------------------------------------------------------
   1000.00      2.84     31.56     15.78     33.13     33.13     28.40      1.58
   5000.00      4.86     53.96     26.98     62.05     62.05     48.56      2.70
  10000.00      6.13     67.98     33.99     84.97     88.37     61.18      3.40
  25000.00      8.31     92.26     46.13    124.55    129.16     83.03      4.61
  50000.00     10.47    116.24     58.12    168.54    174.36    104.61      5.81
  75000.00     11.99    133.06     66.53    206.24    212.89    119.75      6.65
 100000.00     13.20    146.45     73.22    241.64    248.96    131.80      7.32
 500000.00     22.57    250.41    125.20    425.69    438.21    225.37     12.52


               PENTANE BLEVE FIREBALL RESULTS:
               =======================================


               FIREBALL SURFACE TEMPERATURE =  1220.514
               ---------------------------------
```

MASS	TIME	DIAMETER	HEIGHT	HUMAN R.	ANIMAL R.	BULID.R.	PR.EQ.R
1000.00	2.65	29.36	14.68	29.36	27.89	26.43	1.47
5000.00	4.52	50.21	25.10	55.23	52.72	45.18	2.51
10000.00	5.70	63.25	31.63	75.90	72.74	56.93	3.16
25000.00	7.74	85.84	42.92	111.60	107.31	77.26	4.29
50000.00	9.75	108.16	54.08	151.42	146.01	97.34	5.41
75000.00	11.16	123.81	61.90	185.71	179.52	111.42	6.19
100000.00	12.28	136.26	68.13	218.02	211.21	122.64	6.81
500000.00	21.00	233.00	116.50	384.44	384.44	209.70	11.65

APPENDIX H

Computer program for evaluation of BLEVE's fireball diameter and duration using different authors' parameters

```
C
C PROGRAM FOR EVALUATION OF BLEVE FIREBALL
C ========================================
C USING MAURER,TNO,CRAWLEY,AND LIHOU EQUATIONS:
C ==============================================
C
C
C
      DIMENSION W(30),DM(30),DT(30),DC(30),DL(30),TM(30),TT(30),TL(30)
C
       READ *,NN
C
      READ *,(W(II),II=1,NN)
C
      DO 3 I=1,NN
       DM(I)=3.51*(W(I)**0.333)
       DT(I)=6.48*(W(I)**0.325)
       DC(I)=105.0*((W(I)/(1000.0*44.0))**0.333)
       DL(I)=3.44*((44.8*W(I)/44.0)**0.333)
       TM(I)=0.32*(W(I)**0.333)
       TT(I)=0.85*(W(I)**0.26)
       TL(I)=0.31*((44.8*W(I)/44.0)**0.333)
C
  3       CONTINUE
C
C
      PRINT 100
 100  FORMAT(//10X,'BLEVE PROPANE FIREBALL DIAMETER & DURATION:',/10X,
     @43('-')//)
C
C
        PRINT 200
 200  FORMAT(11X,'MASS       FIREBALL DIAMETER       FIREBALL DURATION ',
     @/,11X,'(KG)  MAURER  TNO   CRAWLEY  LIHOU  MAURER TNO     LIHOU ',
     @/,10X,55('-'))
C
C
      DO 5 J=1,NN
      PRINT 300,W(J),DM(J),DT(J),DC(J),DL(J),TM(J),TT(J),TL(J)
 300  FORMAT(5X,F9.1,7(F6.1,1X))
  5     CONTINUE
C
C
        STOP
        END
```

BLEVE PROPANE FIREBALL DIAMETER & DURATION:

MASS	FIREBALL DIAMETER				FIREBALL DURATION		
(KG)	MAURER	TNO	CRAWLEY	LIHOU	MAURER	TNO	LIHOU
0.1	1.6	3.1	1.4	1.6	0.1	0.5	0.1
1.0	3.5	6.5	3.0	3.5	0.3	0.9	0.3
5.0	6.0	10.9	5.1	5.9	0.5	1.3	0.5
10.0	7.6	13.7	6.4	7.5	0.7	1.5	0.7
20.0	9.5	17.2	8.1	9.4	0.9	1.9	0.8
50.0	12.9	23.1	11.0	12.7	1.2	2.4	1.1
75.0	14.8	26.4	12.6	14.6	1.3	2.6	1.3
100.0	16.3	28.9	13.8	16.0	1.5	2.8	1.4
250.0	22.1	39.0	18.8	21.8	2.0	3.6	2.0
500.0	27.8	48.8	23.6	27.4	2.5	4.3	2.5
1000.0	35.0	61.2	29.8	34.5	3.2	5.1	3.1
5000.0	59.9	103.2	50.9	59.0	5.5	7.8	5.3
10000.0	75.4	129.3	64.1	74.3	6.9	9.3	6.7
25000.0	102.3	174.1	87.0	100.9	9.3	11.8	9.1
50000.0	128.8	218.1	109.6	127.0	11.7	14.2	11.4
75000.0	147.5	248.9	125.4	145.4	13.4	15.7	13.1
100000.0	162.3	273.3	138.0	160.0	14.8	17.0	14.4
250000.0	220.2	368.0	187.3	217.1	20.1	21.5	19.6
500000.0	277.4	461.0	235.9	273.5	25.3	25.8	24.6
1000000.0	349.4	577.5	297.1	344.5	31.9	30.9	31.0

APPENDIX I

Computer program for calculation of pool fires on vertical cylinders

```
C
C
C PROGRAM FOR CALCULATION OF POOL FIRES ON VERTICAL CYLINDERS:
C ==========================================================
C
C
C
      DIMENSION RLD(99),WR(99),E(99),DS(99),Q1(99),
     @R(99),AREA(99),Q(99),Q2(99),DSH(99),DSB(99),DSPE(99)
C
C
      READ *,FC,SECMA,THETA
C
      PRINT 100
 100  FORMAT(//10X,'POOL FIRE HAZARD DISTANCES RESULTS:',/,10X,
     @35('-')/)
C
C
      PRINT 110
 110  FORMAT(10X,'PROPANE RESULTS:',/,10X,16('-'))
C
      CALL VERT(FC,SECMA,THETA,E,DS,Q1,Q2)
C
C
      PRINT 120
 120  FORMAT(10X,'BUTANE RESULTS:',/,10X,16('-')/)
C
      CALL VERT(FC,SECMA,THETA,E,DS,Q1,Q2)
C
C
C
         STOP
          END
C
C
C
C
C SUBROUTINE FOR CALCULATION OF POOL FIRE ON VERTICAL CYLINDER.
C ----------------------------------------------------------
C
C
      SUBROUTINE VERT(F,SECMA,THETA,E,DS,Q1,Q2)
C
      DIMENSION RLD(99),WR(99),RAT(99),DS(99),E(99),Q1(99)
     @,AREA(99),Q(99),R(99),Q2(99),DSH(99),DSB(99),DSPE(99)
C
C
          Q2H=4.7
          Q2B=12.6
          Q2PE=37.8
C
       READ *,J,N
       READ *,(DS(NN),NN=1,J)
       READ *,(RLD(II),II=1,N)
```

```
        READ *,TEMP,HC,TRW,CP
C
          PRINT 105,TEMP
  105     FORMAT(//10X,'AT FLAME TEMPERATURE =',F10.3,/10X,22('-'))
C
C
C
      DO 5 M=1,J
      PRINT 220,M,DS(M)
 220  FORMAT(//,10X,'DIAMETER OF VERTICAL CYLINDER(',I2,')=',F10.3,/,
     @10X,34('-')//)
C
C
      PRINT 210
 210  FORMAT(1X,'   L/D    HUMAN DIST.  BULID.DIST.',
     @'  PROCESS DSIT.  WATER RATE',/3X,60('-'))
C
C
      DO 3 I=1,N
      E(I)=SECMA*THETA*(TEMP**4.0)
      R(I)=(E(I)/(F*HC))*(1.0+(4.0*RLD(I)))
      Q1(I)=F*HC*R(I)*(RLD(I)*(DS(M)**2.0))
      DSH(I)=(Q1(I)/(4.0*3.14159*Q2H))**0.5
      DSB(I)=(Q1(I)/(4.0*3.14159*Q2B))**0.5
      DSPE(I)=(Q1(I)/(4.0*3.14159*Q2PE))**0.5
      AREA(I)=(RLD(I)*(DS(M)**2.0)*3.14159)/2.0
      Q(I)=Q1(I)*AREA(I)
      WR(I)=Q(I)/(CP*TRW*60.0)
      PRINT 200,RLD(I),DSH(I),DSB(I),DSPE(I),WR(I)
 200    FORMAT(F8.2,1X,3(F10.3,2X),6X,F10.2)
C
  3    CONTINUE
  5      CONTINUE
C
           PRINT 250
 250      FORMAT(10X,//)
         RETURN
          END
```

```
        POOL FIRE HAZARD DISTANCES RESULTS:
        ------------------------------------

        PROPANE RESULTS:
        ----------------

        AT FLAME TEMPERATURE =  2113.000
        ----------------------

        DIAMETER OF VERTICAL CYLINDER( 1)=      1.000
        ----------------------------------

L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
-------------------------------------------------------------
1.00       9.782        5.974        3.449           0.50
1.20      11.541        7.049        4.070           0.84
1.40      13.298        8.122        4.689           1.30
1.60      15.053        9.193        5.308           1.91
1.80      16.807       10.265        5.926           2.68
2.00      18.560       11.335        6.544           3.63
2.20      20.312       12.406        7.162           4.78
2.40      22.065       13.476        7.780           6.16
2.60      23.816       14.546        8.398           7.77
2.80      25.568       15.616        9.016           9.65
3.00      27.319       16.685        9.633          11.80

        DIAMETER OF VERTICAL CYLINDER( 2)=      2.000
        ----------------------------------

L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
-------------------------------------------------------------
1.00      19.564       11.949        6.899           8.07
1.20      23.082       14.097        8.139          13.48
1.40      26.595       16.243        9.378          20.88
1.60      30.105       18.387       10.616          30.57
1.80      33.613       20.529       11.853          42.88
2.00      37.120       22.671       13.089          58.10
2.20      40.625       24.812       14.325          76.55
2.40      44.129       26.952       15.561          98.53
2.60      47.633       29.092       16.796         124.37
2.80      51.136       31.231       18.031         154.36
3.00      54.639       33.371       19.266         188.82

        DIAMETER OF VERTICAL CYLINDER( 3)=      3.000
        ----------------------------------
```

```
L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
------------------------------------------------------------
1.00      29.346      17.923       10.348           40.85
1.20      34.623      21.146       12.209           68.24
1.40      39.893      24.365       14.067          105.69
1.60      45.158      27.580       15.923          154.77
1.80      50.420      30.794       17.779          217.06
2.00      55.679      34.006       19.633          294.12
2.20      60.937      37.217       21.487          387.52
2.40      66.194      40.428       23.341          498.82
2.60      71.449      43.638       25.194          629.61
2.80      76.704      46.847       27.047          781.44
3.00      81.958      50.056       28.900          955.88

      DIAMETER OF VERTICAL CYLINDER( 4)=      4.000
      -------------------------------------

L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
------------------------------------------------------------
1.00      39.127      23.897       13.797          129.11
1.20      46.164      28.195       16.278          215.66
1.40      53.190      32.486       18.756          334.02
1.60      60.211      36.774       21.231          489.15
1.80      67.226      41.059       23.705          686.01
2.00      74.239      45.342       26.178          929.56
2.20      81.250      49.623       28.650         1224.74
2.40      88.258      53.904       31.121         1576.53
2.60      95.266      58.183       33.592         1989.87
2.80     102.272      62.463       36.063         2469.73
3.00     109.277      66.741       38.533         3021.06

      DIAMETER OF VERTICAL CYLINDER( 5)=      5.000
      -------------------------------------

L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
------------------------------------------------------------
1.00      48.909      29.871       17.246          315.20
1.20      57.705      35.243       20.348          526.51
1.40      66.488      40.608       23.445          815.48
1.60      75.263      45.967       26.539         1194.22
1.80      84.033      51.323       29.631         1674.84
2.00      92.799      56.677       32.722         2269.43
2.20     101.562      62.029       35.812         2990.10
2.40     110.323      67.380       38.902         3848.95
2.60     119.082      72.729       41.990         4858.09
2.80     127.840      78.078       45.078         6029.61
3.00     136.596      83.426       48.166         7375.64

      DIAMETER OF VERTICAL CYLINDER( 6)=      6.000
```

L/D	HUMAN DIST.	BULID.DIST.	PROCESS DSIT.	WATER RATE
1.00	58.691	35.846	20.696	653.59
1.20	69.246	42.292	24.417	1091.76
1.40	79.786	48.729	28.134	1690.98
1.60	90.316	55.160	31.847	2476.34
1.80	100.840	61.588	35.558	3472.94
2.00	111.359	68.012	39.267	4705.88
2.20	121.874	74.435	42.975	6200.26
2.40	132.387	80.856	46.682	7981.18
2.60	142.898	87.275	50.388	10073.73
2.80	153.408	93.694	54.094	12503.01
3.00	163.916	100.112	57.799	15294.12

DIAMETER OF VERTICAL CYLINDER(7)= 7.000

L/D	HUMAN DIST.	BULID.DIST.	PROCESS DSIT.	WATER RATE
1.00	68.473	41.820	24.145	1210.87
1.20	80.787	49.340	28.487	2022.63
1.40	93.083	56.851	32.823	3132.75
1.60	105.368	64.354	37.155	4587.73
1.80	117.646	71.852	41.484	6434.05
2.00	129.919	79.348	45.811	8718.23
2.20	142.187	86.841	50.137	11486.75
2.40	154.452	94.332	54.462	14786.12
2.60	166.715	101.821	58.786	18662.82
2.80	178.976	109.309	63.110	23163.37
3.00	191.235	116.797	67.433	28334.24

DIAMETER OF VERTICAL CYLINDER(8)= 8.000

L/D	HUMAN DIST.	BULID.DIST.	PROCESS DSIT.	WATER RATE
1.00	78.255	47.794	27.594	2065.68
1.20	92.328	56.389	32.556	3450.52
1.40	106.381	64.972	37.512	5344.33
1.60	120.421	73.547	42.463	7826.46
1.80	134.453	82.117	47.410	10976.21
2.00	148.478	90.683	52.356	14872.91
2.20	162.499	99.246	57.300	19595.89
2.40	176.517	107.808	62.243	25224.46
2.60	190.531	116.367	67.184	31837.95
2.80	204.544	124.925	72.125	39515.68
3.00	218.554	133.482	77.066	48336.97

```
        DIAMETER OF VERTICAL CYLINDER( 9)=      9.000
        ------------------------------------

 L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
 -------------------------------------------------------------
 1.00      88.037       53.769      31.043         3308.82
 1.20     103.869       63.438      36.626         5527.06
 1.40     119.678       73.094      42.201         8560.59
 1.60     135.474       82.741      47.770        12536.47
 1.80     151.259       92.382      53.337        17581.77
 2.00     167.038      102.019      58.900        23823.53
 2.20     182.812      111.652      64.462        31388.83
 2.40     198.581      121.283      70.023        40404.71
 2.60     214.348      130.913      75.583        50998.24
 2.80     230.111      140.541      81.141        63296.48
 3.00     245.873      150.167      86.699        77426.48

        DIAMETER OF VERTICAL CYLINDER(10)=     10.000
        ------------------------------------

 L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
 -------------------------------------------------------------
 1.00      97.819       59.743      34.493         5043.17
 1.20     115.409       70.486      40.695         8424.11
 1.40     132.976       81.215      46.890        13047.69
 1.60     150.526       91.934      53.078        19107.56
 1.80     168.066      102.646      59.263        26797.39
 2.00     185.598      113.354      65.445        36310.82
 2.20     203.124      124.058      71.625        47841.53
 2.40     220.646      134.759      77.803        61583.16
 2.60     238.164      145.459      83.981        77729.37
 2.80     255.679      156.156      90.157        96473.83
 3.00     273.193      166.853      96.332       118010.18


        BUTANE RESULTS:
        ----------------


        AT FLAME TEMPERATURE =  2120.000
        ----------------------

        DIAMETER OF VERTICAL CYLINDER( 1)=      1.000
        ------------------------------------

 L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
 -------------------------------------------------------------
```

```
1.00      9.847       6.014       3.472            0.51
1.20     11.618       7.095       4.097            0.85
1.40     13.386       8.175       4.720            1.32
1.60     15.153       9.254       5.343            1.94
1.80     16.918      10.333       5.966            2.72
2.00     18.683      11.411       6.588            3.68
2.20     20.447      12.488       7.210            4.85
2.40     22.211      13.565       7.832            6.24
2.60     23.974      14.642       8.454            7.88
2.80     25.738      15.719       9.076            9.78
3.00     27.501      16.796       9.697           11.96


          DIAMETER OF VERTICAL CYLINDER( 2)=      2.000
          ----------------------------------


L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
------------------------------------------------------------
1.00     19.694      12.028       6.944            8.18
1.20     23.235      14.191       8.193           13.66
1.40     26.772      16.351       9.440           21.15
1.60     30.305      18.509      10.686           30.98
1.80     33.836      20.666      11.931           43.45
2.00     37.366      22.821      13.176           58.87
2.20     40.894      24.976      14.420           77.57
2.40     44.422      27.131      15.664           99.85
2.60     47.949      29.285      16.908          126.02
2.80     51.475      31.439      18.151          156.41
3.00     55.001      33.592      19.394          191.33


          DIAMETER OF VERTICAL CYLINDER( 3)=      3.000
          ----------------------------------


L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
------------------------------------------------------------
1.00     29.540      18.042      10.416           41.39
1.20     34.853      21.286      12.290           69.14
1.40     40.158      24.526      14.160          107.09
1.60     45.458      27.763      16.029          156.83
1.80     50.754      30.998      17.897          219.95
2.00     56.049      34.232      19.764          298.03
2.20     61.342      37.464      21.630          392.68
2.40     66.633      40.696      23.496          505.47
2.60     71.923      43.927      25.361          637.99
2.80     77.213      47.158      27.227          791.84
3.00     82.502      50.388      29.092          968.61


          DIAMETER OF VERTICAL CYLINDER( 4)=      4.000
          ----------------------------------
```

```
L/D    HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
-----------------------------------------------------------
1.00     39.387       24.056       13.889          130.82
1.20     46.470       28.382       16.386          218.53
1.40     53.543       32.702       18.880          338.47
1.60     60.610       37.018       21.372          495.67
1.80     67.673       41.331       23.862          695.15
2.00     74.732       45.643       26.352          941.94
2.20     81.789       49.953       28.840         1241.05
2.40     88.844       54.261       31.328         1597.52
2.60     95.898       58.570       33.815         2016.37
2.80    102.951       62.877       36.302         2502.62
3.00    110.002       67.184       38.789         3061.29

       DIAMETER OF VERTICAL CYLINDER( 5)=      5.000
       ---------------------------------

L/D    HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
-----------------------------------------------------------
1.00     49.234       30.070       17.361          319.40
1.20     58.088       35.477       20.483          533.52
1.40     66.929       40.877       23.600          826.34
1.60     75.763       46.272       26.715         1210.13
1.80     84.591       51.664       29.828         1697.14
2.00     93.415       57.053       32.940         2299.65
2.20    102.236       62.441       36.050         3029.92
2.40    111.055       67.827       39.160         3900.20
2.60    119.872       73.212       42.269         4922.78
2.80    128.688       78.596       45.378         6109.91
3.00    137.503       83.980       48.486         7473.86

       DIAMETER OF VERTICAL CYLINDER( 6)=      6.000
       ---------------------------------

L/D    HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
-----------------------------------------------------------
1.00     59.081       36.084       20.833          662.30
1.20     69.705       42.572       24.579         1106.30
1.40     80.315       49.052       28.320         1713.50
1.60     90.915       55.527       32.058         2509.32
1.80    101.509       61.997       35.794         3519.19
2.00    112.098       68.464       39.528         4768.55
2.20    122.683       74.929       43.260         6282.83
2.40    133.266       81.392       46.992         8087.46
2.60    143.847       87.854       50.723        10207.88
2.80    154.426       94.316       54.453        12669.51
3.00    165.003      100.776       58.183        15497.80

       DIAMETER OF VERTICAL CYLINDER( 7)=      7.000
```

```
        ------------------------------

L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
-----------------------------------------------------------
1.00      68.928       42.097       24.305         1226.99
1.20      81.323       49.668       28.676         2049.57
1.40      93.701       57.228       33.041         3174.47
1.60     106.068       64.781       37.401         4648.82
1.80     118.427       72.329       41.759         6519.74
2.00     130.781       79.874       46.115         8834.33
2.20     143.130       87.417       50.470        11639.72
2.40     155.477       94.958       54.824        14983.03
2.60     167.821      102.497       59.177        18911.36
2.80     180.163      110.035       63.529        23471.84
3.00     192.504      117.572       67.880        28711.58

        DIAMETER OF VERTICAL CYLINDER( 8)=     8.000
        ------------------------------

L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
-----------------------------------------------------------
1.00      78.774       48.111       27.777         2093.19
1.20      92.940       56.763       32.772         3496.47
1.40     107.087       65.403       37.761         5415.51
1.60     121.220       74.035       42.744         7930.68
1.80     135.345       82.662       47.725        11122.38
2.00     149.464       91.285       52.703        15070.98
2.20     163.578       99.905       57.680        19856.85
2.40     177.688      108.523       62.656        25560.38
2.60     191.796      117.139       67.630        32261.95
2.80     205.901      125.754       72.604        40041.92
3.00     220.005      134.368       77.577        48980.69

        DIAMETER OF VERTICAL CYLINDER( 9)=     9.000
        ------------------------------

L/D     HUMAN DIST.  BULID.DIST.  PROCESS DSIT.  WATER RATE
-----------------------------------------------------------
1.00      88.621       54.125       31.249         3352.89
1.20     104.558       63.859       36.869         5600.66
1.40     120.473       73.579       42.481         8674.59
1.60     136.373       83.290       48.087        12703.42
1.80     152.263       92.995       53.691        17815.91
2.00     168.147      102.696       59.291        24140.80
2.20     184.025      112.393       64.890        31806.84
2.40     199.899      122.088       70.488        40942.79
2.60     215.770      131.782       76.084        51677.40
2.80     231.639      141.473       81.680        64139.41
3.00     247.505      151.164       87.275        78457.59
```

```
         DIAMETER OF VERTICAL CYLINDER(10)=     10.000
         ----------------------------------

  L/D     HUMAN DIST.   BULID.DIST.   PROCESS DSIT.   WATER RATE
 ------------------------------------------------------------------
  1.00      98.468        60.139        34.721          5110.33
  1.20     116.175        70.954        40.965          8536.30
  1.40     133.858        81.754        47.201         13221.45
  1.60     151.525        92.544        53.430         19362.02
  1.80     169.181       103.328        59.656         27154.26
  2.00     186.830       114.106        65.879         36794.39
  2.20     204.472       124.881        72.100         48478.65
  2.40     222.110       135.654        78.320         62403.28
  2.60     239.745       146.424        84.538         78764.52
  2.80     257.376       157.193        90.755         97758.60
  3.00     275.006       167.960        96.972        119581.76
```

APPENDIX J

Computer program for calculation of spacing distance using TNT equivalent model (Jarrett's equation)

```
C
C
C PROGRAM FOR CALCULATION OF SPACING DISTANCE
C ============================================
C USING T.N.T. EQUIVALENT MODEL (JARRETT'S EQUATION)
C ===================================================
C
      PRINT 333
 333  FORMAT(//15X,'JARRETT EQUATION RESULTS:',/15X,25('*')//)
C
C
      PRINT 20
 20   FORMAT(10X,'METHANE RESULTS:',/,10X,15('*')//)
C
      READ *,CH4
      CALL PR(CH4)
C
      PRINT 25
 25   FORMAT(///,10X,'PROPANE RESULTS:',/,10X,15('*')//)
C
      READ *,CH8
      CALL PR(CH8)
C
C
      PRINT 30
 30   FORMAT(///,10X,'BUTANE RESULTS:',/,10X,15('*')//)
C
       READ *,CH10
       CALL PR(CH10)
C
C
         STOP
         END
C
C
C
       SUBROUTINE PR(C)
C
C
C
      DIMENSION W(99),CH(99),R(99),TNT(99),FK(99),Y(99)
C
C
      READ *,(CH(II),II=1,6)
      READ *,(FK(NN),NN=1,15)
      READ *,(Y(JJ),JJ=1,3)
C
C
       DO 5 J=1,3
C
      PRINT 100,J,Y(J)
 100  FORMAT(10X,'EXPLOSION YIELD FACTOR(',I2,')=',F10.3,'%',
     */,10X,26('-')///)
C
```

```
           TNT(J)=(1100.0*100.0)/(C*Y(J))
C
        PRINT 150,J,TNT(J)
 150  FORMAT(10X,'TNT EQUIVALENT VALUE (',I2,')=',F10.4//)
C
C
        DO 10 N=1,15
C
      PRINT 200,N,FK(N)
 200  FORMAT(10X,'CONSTANT OF JARRETT EQUATION (',I2,')=',F10.3,
     */,10X,33('-')/)
C
      PRINT 300
 300  FORMAT(10X,'W.OF H.C.   W.OF TNT   DISTANCE',/
     @,10X,'  TONS         TONS        METERS',/,10X,32('='))
C
C
C
          DO 15 I=1,6
      W(I)=CH(I)/TNT(J)
      R(I)=0.3048*(FK(N)*((W(I)*2200.0)**0.333))/
     @((1.0+((6996.0/(W(I)*2200.0))**2.0))**0.1667)
C
      PRINT 400,CH(I),W(I),R(I)
 400  FORMAT(8X,3F10.3)
C
  15    CONTINUE
C
       PRINT 500
 500   FORMAT(8X,35('*')///)
  10    CONTINUE
C
   5    CONTINUE
C
          RETURN
          END
C
```

```
        JARRETT EQUATION RESULTS:
        *************************


    METHANE RESULTS:
    ***************


    EXPLOSION YIELD FACTOR( 1)=      2.000%
    --------------------------



    TNT EQUIVALENT VALUE ( 1)=    4.5891

    CONSTANT OF JARRETT EQUATION ( 1)=      3.000
    ---------------------------------

    W.OF H.C.   W.OF TNT    DISTANCE
      TONS        TONS       METERS
    ================================
       5.000      1.090       8.384
      10.000      2.179      12.712
      20.000      4.358      18.036
      30.000      6.537      21.395
      40.000      8.716      23.892
      50.000     10.895      25.921
  ***********************************


    CONSTANT OF JARRETT EQUATION ( 2)=      9.000
    ---------------------------------

    W.OF H.C.   W.OF TNT    DISTANCE
      TONS        TONS       METERS
    ================================
       5.000      1.090      25.151
      10.000      2.179      38.136
      20.000      4.358      54.109
      30.000      6.537      64.185
      40.000      8.716      71.675
      50.000     10.895      77.762
  ***********************************


    CONSTANT OF JARRETT EQUATION ( 3)=     10.050
    ---------------------------------

    W.OF H.C.   W.OF TNT    DISTANCE
```

```
   TONS         TONS       METERS
=================================
   5.000       1.090      28.086
  10.000       2.179      42.585
  20.000       4.358      60.422
  30.000       6.537      71.674
  40.000       8.716      80.037
  50.000      10.895      86.834
***********************************


 CONSTANT OF JARRETT EQUATION ( 4)=     13.900
 ----------------------------------

 W.OF H.C.   W.OF TNT    DISTANCE
   TONS        TONS       METERS
=================================
   5.000       1.090      38.845
  10.000       2.179      58.898
  20.000       4.358      83.569
  30.000       6.537      99.131
  40.000       8.716     110.698
  50.000      10.895     120.099
***********************************


 CONSTANT OF JARRETT EQUATION ( 5)=     16.300
 ----------------------------------

 W.OF H.C.   W.OF TNT    DISTANCE
   TONS        TONS       METERS
=================================
   5.000       1.090      45.552
  10.000       2.179      69.068
  20.000       4.358      97.998
  30.000       6.537     116.247
  40.000       8.716     129.812
  50.000      10.895     140.836
***********************************


 CONSTANT OF JARRETT EQUATION ( 6)=     18.500
 ----------------------------------

 W.OF H.C.   W.OF TNT    DISTANCE
   TONS        TONS       METERS
=================================
   5.000       1.090      51.700
  10.000       2.179      78.390
  20.000       4.358     111.224
  30.000       6.537     131.936
```

```
    40.000     8.716   147.332
    50.000    10.895   159.844
***********************************


   CONSTANT OF JARRETT EQUATION ( 7)=     19.800
   ---------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ================================
     5.000      1.090     55.333
    10.000      2.179     83.898
    20.000      4.358    119.040
    30.000      6.537    141.208
    40.000      8.716    157.686
    50.000     10.895    171.077
***********************************


   CONSTANT OF JARRETT EQUATION ( 8)=     21.600
   ---------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ================================
     5.000      1.090     60.363
    10.000      2.179     91.526
    20.000      4.358    129.862
    30.000      6.537    154.045
    40.000      8.716    172.021
    50.000     10.895    186.629
***********************************


   CONSTANT OF JARRETT EQUATION ( 9)=     22.800
   ---------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ================================
     5.000      1.090     63.716
    10.000      2.179     96.610
    20.000      4.358    137.077
    30.000      6.537    162.603
    40.000      8.716    181.577
    50.000     10.895    196.998
***********************************
```

```
   CONSTANT OF JARRETT EQUATION (10)=     25.500
   ------------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ==================================
      5.000      1.090     71.262
     10.000      2.179    108.051
     20.000      4.358    153.309
     30.000      6.537    181.858
     40.000      8.716    203.080
     50.000     10.895    220.326
*************************************


   CONSTANT OF JARRETT EQUATION (11)=     37.000
   ------------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ==================================
      5.000      1.090    103.400
     10.000      2.179    156.780
     20.000      4.358    222.449
     30.000      6.537    263.873
     40.000      8.716    294.665
     50.000     10.895    319.689
*************************************


   CONSTANT OF JARRETT EQUATION (12)=     51.500
   ------------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ==================================
      5.000      1.090    143.921
     10.000      2.179    218.221
     20.000      4.358    309.625
     30.000      6.537    367.282
     40.000      8.716    410.142
     50.000     10.895    444.972
*************************************


   CONSTANT OF JARRETT EQUATION (13)=     61.400
   ------------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ==================================
```

```
     5.000      1.090   171.587
    10.000      2.179   260.170
    20.000      4.358   369.145
    30.000      6.537   437.886
    40.000      8.716   488.984
    50.000     10.895   530.511
***********************************


  CONSTANT OF JARRETT EQUATION (14)=     72.000
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  =================================
     5.000      1.090   201.210
    10.000      2.179   305.085
    20.000      4.358   432.874
    30.000      6.537   513.482
    40.000      8.716   573.402
    50.000     10.895   622.097
***********************************


  CONSTANT OF JARRETT EQUATION (15)=     99.000
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  =================================
     5.000      1.090   276.664
    10.000      2.179   419.492
    20.000      4.358   595.201
    30.000      6.537   706.038
    40.000      8.716   788.428
    50.000     10.895   855.384
***********************************


  EXPLOSION YIELD FACTOR( 2)=      5.000%
  -------------------------


  TNT EQUIVALENT VALUE ( 2)=    1.8356


  CONSTANT OF JARRETT EQUATION ( 1)=      3.000
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
```

```
   TONS        TONS       METERS
  ===============================
   5.000       2.724      14.349
  10.000       5.448      19.865
  20.000      10.895      25.921
  30.000      16.343      29.889
  40.000      21.791      32.982
  50.000      27.239      35.571
**********************************


  CONSTANT OF JARRETT EQUATION ( 2)=      9.000
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS       METERS
  ===============================
   5.000       2.724      43.047
  10.000       5.448      59.596
  20.000      10.895      77.762
  30.000      16.343      89.667
  40.000      21.791      98.947
  50.000      27.239     106.714
**********************************


  CONSTANT OF JARRETT EQUATION ( 3)=     10.050
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS       METERS
  ===============================
   5.000       2.724      48.069
  10.000       5.448      66.549
  20.000      10.895      86.834
  30.000      16.343     100.129
  40.000      21.791     110.491
  50.000      27.239     119.164
**********************************


  CONSTANT OF JARRETT EQUATION ( 4)=     13.900
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS       METERS
  ===============================
   5.000       2.724      66.484
  10.000       5.448      92.042
  20.000      10.895     120.099
  30.000      16.343     138.486
```

```
   40.000    21.791   152.819
   50.000    27.239   164.814
*********************************


  CONSTANT OF JARRETT EQUATION ( 5)=     16.300
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000     2.724     77.963
    10.000     5.448    107.935
    20.000    10.895    140.836
    30.000    16.343    162.398
    40.000    21.791    179.205
    50.000    27.239    193.271
*********************************


  CONSTANT OF JARRETT EQUATION ( 6)=     18.500
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000     2.724     88.486
    10.000     5.448    122.502
    20.000    10.895    159.844
    30.000    16.343    184.317
    40.000    21.791    203.392
    50.000    27.239    219.356
*********************************


  CONSTANT OF JARRETT EQUATION ( 7)=     19.800
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000     2.724     94.704
    10.000     5.448    131.111
    20.000    10.895    171.077
    30.000    16.343    197.268
    40.000    21.791    217.684
    50.000    27.239    234.771
*********************************
```

```
CONSTANT OF JARRETT EQUATION ( 8)=      21.600
----------------------------------

W.OF H.C.   W.OF TNT   DISTANCE
  TONS        TONS      METERS
================================
   5.000      2.724    103.313
  10.000      5.448    143.030
  20.000     10.895    186.629
  30.000     16.343    215.202
  40.000     21.791    237.474
  50.000     27.239    256.113
***********************************


CONSTANT OF JARRETT EQUATION ( 9)=      22.800
----------------------------------

W.OF H.C.   W.OF TNT   DISTANCE
  TONS        TONS      METERS
================================
   5.000      2.724    109.053
  10.000      5.448    150.976
  20.000     10.895    196.998
  30.000     16.343    227.158
  40.000     21.791    250.667
  50.000     27.239    270.342
***********************************


CONSTANT OF JARRETT EQUATION (10)=      25.500
----------------------------------

W.OF H.C.   W.OF TNT   DISTANCE
  TONS        TONS      METERS
================================
   5.000      2.724    121.967
  10.000      5.448    168.855
  20.000     10.895    220.326
  30.000     16.343    254.058
  40.000     21.791    280.351
  50.000     27.239    302.356
***********************************


CONSTANT OF JARRETT EQUATION (11)=      37.000
----------------------------------

W.OF H.C.   W.OF TNT   DISTANCE
  TONS        TONS      METERS
================================
```

```
     5.000      2.724    176.972
    10.000      5.448    245.005
    20.000     10.895    319.689
    30.000     16.343    368.633
    40.000     21.791    406.784
    50.000     27.239    438.713
**********************************


   CONSTANT OF JARRETT EQUATION (12)=      51.500
   ------------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ================================
     5.000      2.724    246.326
    10.000      5.448    341.020
    20.000     10.895    444.972
    30.000     16.343    513.097
    40.000     21.791    566.199
    50.000     27.239    610.640
**********************************


   CONSTANT OF JARRETT EQUATION (13)=      61.400
   ------------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ================================
     5.000      2.724    293.678
    10.000      5.448    406.576
    20.000     10.895    530.511
    30.000     16.343    611.732
    40.000     21.791    675.041
    50.000     27.239    728.026
**********************************


   CONSTANT OF JARRETT EQUATION (14)=      72.000
   ------------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ================================
     5.000      2.724    344.378
    10.000      5.448    476.766
    20.000     10.895    622.097
    30.000     16.343    717.340
    40.000     21.791    791.579
    50.000     27.239    853.711
```

```
***********************************


  CONSTANT OF JARRETT EQUATION (15)=     99.000
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  =================================
     5.000      2.724   473.520
    10.000      5.448   655.554
    20.000     10.895   855.384
    30.000     16.343   986.342
    40.000     21.791  1088.421
    50.000     27.239  1173.853
***********************************


  EXPLOSION YIELD FACTOR( 3)=    10.000%
  --------------------------


  TNT EQUIVALENT VALUE ( 3)=    0.9178

  CONSTANT OF JARRETT EQUATION ( 1)=      3.000
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  =================================
     5.000      5.448     19.865
    10.000     10.895     25.921
    20.000     21.791     32.982
    30.000     32.686     37.824
    40.000     43.582     41.655
    50.000     54.477     44.882
***********************************


  CONSTANT OF JARRETT EQUATION ( 2)=      9.000
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  =================================
     5.000      5.448     59.596
    10.000     10.895     77.762
    20.000     21.791     98.947
    30.000     32.686    113.471
```

```
     40.000    43.582   124.965
     50.000    54.477   134.647
***********************************


  CONSTANT OF JARRETT EQUATION ( 3)=     10.050
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
      5.000     5.448    66.549
     10.000    10.895    86.834
     20.000    21.791   110.491
     30.000    32.686   126.710
     40.000    43.582   139.544
     50.000    54.477   150.356
***********************************


  CONSTANT OF JARRETT EQUATION ( 4)=     13.900
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
      5.000     5.448    92.042
     10.000    10.895   120.099
     20.000    21.791   152.819
     30.000    32.686   175.250
     40.000    43.582   193.002
     50.000    54.477   207.955
***********************************


  CONSTANT OF JARRETT EQUATION ( 5)=     16.300
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
      5.000     5.448   107.935
     10.000    10.895   140.836
     20.000    21.791   179.205
     30.000    32.686   205.509
     40.000    43.582   226.326
     50.000    54.477   243.861
***********************************
```

```
   CONSTANT OF JARRETT EQUATION ( 6)=     18.500
   -----------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS       TONS       METERS
   ==================================
      5.000     5.448    122.502
     10.000    10.895    159.844
     20.000    21.791    203.392
     30.000    32.686    233.247
     40.000    43.582    256.873
     50.000    54.477    276.775
***********************************


   CONSTANT OF JARRETT EQUATION ( 7)=     19.800
   -----------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS       TONS       METERS
   ==================================
      5.000     5.448    131.111
     10.000    10.895    171.077
     20.000    21.791    217.684
     30.000    32.686    249.637
     40.000    43.582    274.923
     50.000    54.477    296.224
***********************************


   CONSTANT OF JARRETT EQUATION ( 8)=     21.600
   -----------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS       TONS       METERS
   ==================================
      5.000     5.448    143.030
     10.000    10.895    186.629
     20.000    21.791    237.474
     30.000    32.686    272.331
     40.000    43.582    299.916
     50.000    54.477    323.154
***********************************


   CONSTANT OF JARRETT EQUATION ( 9)=     22.800
   -----------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS       TONS       METERS
   ==================================
```

```
     5.000     5.448   150.976
    10.000    10.895   196.998
    20.000    21.791   250.667
    30.000    32.686   287.461
    40.000    43.582   316.578
    50.000    54.477   341.107
***********************************


  CONSTANT OF JARRETT EQUATION (10)=     25.500
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000     5.448   168.855
    10.000    10.895   220.326
    20.000    21.791   280.351
    30.000    32.686   321.502
    40.000    43.582   354.068
    50.000    54.477   381.501
***********************************


  CONSTANT OF JARRETT EQUATION (11)=     37.000
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000     5.448   245.005
    10.000    10.895   319.689
    20.000    21.791   406.784
    30.000    32.686   466.493
    40.000    43.582   513.745
    50.000    54.477   553.550
***********************************


  CONSTANT OF JARRETT EQUATION (12)=     51.500
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000     5.448   341.020
    10.000    10.895   444.972
    20.000    21.791   566.199
    30.000    32.686   649.308
    40.000    43.582   715.078
    50.000    54.477   770.482
```

```
***********************************


 CONSTANT OF JARRETT EQUATION (13)=     61.400
 ----------------------------------

 W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS      METERS
 =================================
    5.000      5.448   406.576
   10.000     10.895   530.511
   20.000     21.791   675.041
   30.000     32.686   774.127
   40.000     43.582   852.539
   50.000     54.477   918.594
***********************************


 CONSTANT OF JARRETT EQUATION (14)=     72.000
 ----------------------------------

 W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS      METERS
 =================================
    5.000      5.448   476.766
   10.000     10.895   622.097
   20.000     21.791   791.579
   30.000     32.686   907.771
   40.000     43.582   999.720
   50.000     54.477  1077.178
***********************************


 CONSTANT OF JARRETT EQUATION (15)=     99.000
 ----------------------------------

 W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS      METERS
 =================================
    5.000      5.448   655.554
   10.000     10.895   855.384
   20.000     21.791  1088.421
   30.000     32.686  1248.185
   40.000     43.582  1374.615
   50.000     54.477  1481.120
***********************************
```

```
  PROPANE RESULTS:
  ***************


  EXPLOSION YIELD FACTOR( 1)=     2.000%
  ----------------------------



  TNT EQUIVALENT VALUE ( 1)=    4.9541

  CONSTANT OF JARRETT EQUATION ( 1)=      3.000
  -------------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS       TONS      METERS
  ==================================
     5.000      1.009      7.987
    10.000      2.019     12.174
    20.000      4.037     17.420
    30.000      6.056     20.749
    40.000      8.074     23.216
    50.000     10.093     25.214
*************************************


  CONSTANT OF JARRETT EQUATION ( 2)=      9.000
  -------------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS       TONS      METERS
  ==================================
     5.000      1.009     23.961
    10.000      2.019     36.521
    20.000      4.037     52.259
    30.000      6.056     62.246
    40.000      8.074     69.648
    50.000     10.093     75.643
*************************************


  CONSTANT OF JARRETT EQUATION ( 3)=     10.050
  -------------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS       TONS      METERS
  ==================================
     5.000      1.009     26.756
    10.000      2.019     40.782
    20.000      4.037     58.355
    30.000      6.056     69.508
```

```
     40.000      8.074    77.774
     50.000     10.093    84.468
***********************************


  CONSTANT OF JARRETT EQUATION ( 4)=     13.900
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS       METERS
  ================================
      5.000      1.009    37.006
     10.000      2.019    56.405
     20.000      4.037    80.711
     30.000      6.056    96.136
     40.000      8.074   107.567
     50.000     10.093   116.826
***********************************


  CONSTANT OF JARRETT EQUATION ( 5)=     16.300
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS       METERS
  ================================
      5.000      1.009    43.395
     10.000      2.019    66.144
     20.000      4.037    94.646
     30.000      6.056   112.734
     40.000      8.074   126.140
     50.000     10.093   136.997
***********************************


  CONSTANT OF JARRETT EQUATION ( 6)=     18.500
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS       METERS
  ================================
      5.000      1.009    49.252
     10.000      2.019    75.071
     20.000      4.037   107.421
     30.000      6.056   127.950
     40.000      8.074   143.165
     50.000     10.093   155.488
***********************************
```

```
 CONSTANT OF JARRETT EQUATION ( 7)=     19.800
 -----------------------------------

 W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS      METERS
 =================================
    5.000      1.009     52.713
   10.000      2.019     80.346
   20.000      4.037    114.969
   30.000      6.056    136.941
   40.000      8.074    153.225
   50.000     10.093    166.414
***********************************


 CONSTANT OF JARRETT EQUATION ( 8)=     21.600
 -----------------------------------

 W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS      METERS
 =================================
    5.000      1.009     57.505
   10.000      2.019     87.650
   20.000      4.037    125.421
   30.000      6.056    149.390
   40.000      8.074    167.155
   50.000     10.093    181.542
***********************************


 CONSTANT OF JARRETT EQUATION ( 9)=     22.800
 -----------------------------------

 W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS      METERS
 =================================
    5.000      1.009     60.700
   10.000      2.019     92.520
   20.000      4.037    132.389
   30.000      6.056    157.690
   40.000      8.074    176.441
   50.000     10.093    191.628
***********************************


 CONSTANT OF JARRETT EQUATION (10)=     25.500
 -----------------------------------

 W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS      METERS
 =================================
```

```
     5.000      1.009    67.888
    10.000      2.019   103.476
    20.000      4.037   148.066
    30.000      6.056   176.364
    40.000      8.074   197.336
    50.000     10.093   214.321
***********************************


  CONSTANT OF JARRETT EQUATION (11)=     37.000
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      1.009    98.505
    10.000      2.019   150.142
    20.000      4.037   214.841
    30.000      6.056   255.900
    40.000      8.074   286.330
    50.000     10.093   310.975
***********************************


  CONSTANT OF JARRETT EQUATION (12)=     51.500
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      1.009   137.108
    10.000      2.019   208.981
    20.000      4.037   299.036
    30.000      6.056   356.186
    40.000      8.074   398.541
    50.000     10.093   432.844
***********************************


  CONSTANT OF JARRETT EQUATION (13)=     61.400
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      1.009   163.465
    10.000      2.019   249.154
    20.000      4.037   356.520
    30.000      6.056   424.656
    40.000      8.074   475.154
    50.000     10.093   516.051
```

```
***********************************


  CONSTANT OF JARRETT EQUATION (14)=     72.000
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      1.009    191.685
    10.000      2.019    292.168
    20.000      4.037    418.069
    30.000      6.056    497.968
    40.000      8.074    557.184
    50.000     10.093    605.141
***********************************


  CONSTANT OF JARRETT EQUATION (15)=     99.000
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      1.009    263.567
    10.000      2.019    401.731
    20.000      4.037    574.845
    30.000      6.056    684.706
    40.000      8.074    766.127
    50.000     10.093    832.069
***********************************


  EXPLOSION YIELD FACTOR( 2)=      5.000%
  --------------------------


  TNT EQUIVALENT VALUE ( 2)=    1.9816

  CONSTANT OF JARRETT EQUATION ( 1)=      3.000
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      2.523     13.777
    10.000      5.046     19.233
    20.000     10.093     25.214
    30.000     15.139     29.108
```

```
    40.000     20.185     32.134
    50.000     25.232     34.663
***********************************


  CONSTANT OF JARRETT EQUATION ( 2)=       9.000
  ---------------------------------

  W.OF H.C.    W.OF TNT    DISTANCE
    TONS         TONS       METERS
  ================================
     5.000      2.523     41.331
    10.000      5.046     57.699
    20.000     10.093     75.643
    30.000     15.139     87.324
    40.000     20.185     96.402
    50.000     25.232    103.990
***********************************


  CONSTANT OF JARRETT EQUATION ( 3)=      10.050
  ---------------------------------

  W.OF H.C.    W.OF TNT    DISTANCE
    TONS         TONS       METERS
  ================================
     5.000      2.523     46.153
    10.000      5.046     64.430
    20.000     10.093     84.468
    30.000     15.139     97.511
    40.000     20.185    107.649
    50.000     25.232    116.122
***********************************


  CONSTANT OF JARRETT EQUATION ( 4)=      13.900
  ---------------------------------

  W.OF H.C.    W.OF TNT    DISTANCE
    TONS         TONS       METERS
  ================================
     5.000      2.523     63.834
    10.000      5.046     89.113
    20.000     10.093    116.826
    30.000     15.139    134.866
    40.000     20.185    148.888
    50.000     25.232    160.607
***********************************
```

```
  CONSTANT OF JARRETT EQUATION ( 5)=     16.300
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ==================================
     5.000      2.523     74.856
    10.000      5.046    104.499
    20.000     10.093    136.997
    30.000     15.139    158.153
    40.000     20.185    174.595
    50.000     25.232    188.338
***********************************


  CONSTANT OF JARRETT EQUATION ( 6)=     18.500
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ==================================
     5.000      2.523     84.959
    10.000      5.046    118.603
    20.000     10.093    155.488
    30.000     15.139    179.499
    40.000     20.185    198.160
    50.000     25.232    213.758
***********************************


  CONSTANT OF JARRETT EQUATION ( 7)=     19.800
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ==================================
     5.000      2.523     90.929
    10.000      5.046    126.937
    20.000     10.093    166.414
    30.000     15.139    192.112
    40.000     20.185    212.085
    50.000     25.232    228.778
***********************************


  CONSTANT OF JARRETT EQUATION ( 8)=     21.600
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ==================================
```

```
      5.000      2.523     99.196
     10.000      5.046    138.477
     20.000     10.093    181.542
     30.000     15.139    209.577
     40.000     20.185    231.365
     50.000     25.232    249.576
***********************************


   CONSTANT OF JARRETT EQUATION ( 9)=     22.800
   ---------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   =================================
      5.000      2.523    104.706
     10.000      5.046    146.170
     20.000     10.093    191.628
     30.000     15.139    221.220
     40.000     20.185    244.219
     50.000     25.232    263.442
***********************************


   CONSTANT OF JARRETT EQUATION (10)=     25.500
   ---------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   =================================
      5.000      2.523    117.106
     10.000      5.046    163.480
     20.000     10.093    214.321
     30.000     15.139    247.417
     40.000     20.185    273.140
     50.000     25.232    294.639
***********************************


   CONSTANT OF JARRETT EQUATION (11)=     37.000
   ---------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   =================================
      5.000      2.523    169.918
     10.000      5.046    237.206
     20.000     10.093    310.975
     30.000     15.139    358.997
     40.000     20.185    396.320
     50.000     25.232    427.515
```

```
***********************************


  CONSTANT OF JARRETT EQUATION (12)=    51.500
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      2.523   236.508
    10.000      5.046   330.165
    20.000     10.093   432.844
    30.000     15.139   499.685
    40.000     20.185   551.635
    50.000     25.232   595.055
***********************************


  CONSTANT OF JARRETT EQUATION (13)=    61.400
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      2.523   281.973
    10.000      5.046   393.634
    20.000     10.093   516.051
    30.000     15.139   595.741
    40.000     20.185   657.678
    50.000     25.232   709.444
***********************************


  CONSTANT OF JARRETT EQUATION (14)=    72.000
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      2.523   330.652
    10.000      5.046   461.590
    20.000     10.093   605.141
    30.000     15.139   698.589
    40.000     20.185   771.218
    50.000     25.232   831.921
***********************************


  CONSTANT OF JARRETT EQUATION (15)=    99.000
  ---------------------------------
```

```
  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ==================================
     5.000      2.523    454.646
    10.000      5.046    634.687
    20.000     10.093    832.069
    30.000     15.139    960.560
    40.000     20.185   1060.425
    50.000     25.232   1143.892
************************************


  EXPLOSION YIELD FACTOR( 3)=     10.000%
  ---------------------------


  TNT EQUIVALENT VALUE ( 3)=    0.9908

  CONSTANT OF JARRETT EQUATION ( 1)=      3.000
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ==================================
     5.000      5.046     19.233
    10.000     10.093     25.214
    20.000     20.185     32.134
    30.000     30.278     36.863
    40.000     40.371     40.601
    50.000     50.464     43.749
************************************


  CONSTANT OF JARRETT EQUATION ( 2)=      9.000
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ==================================
     5.000      5.046     57.699
    10.000     10.093     75.643
    20.000     20.185     96.402
    30.000     30.278    110.588
    40.000     40.371    121.803
    50.000     50.464    131.247
************************************


  CONSTANT OF JARRETT EQUATION ( 3)=     10.050
```

```
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      5.046     64.430
    10.000     10.093     84.468
    20.000     20.185    107.649
    30.000     30.278    123.489
    40.000     40.371    136.013
    50.000     50.464    146.559
**********************************


  CONSTANT OF JARRETT EQUATION ( 4)=     13.900
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      5.046     89.113
    10.000     10.093    116.826
    20.000     20.185    148.888
    30.000     30.278    170.796
    40.000     40.371    188.118
    50.000     50.464    202.704
**********************************


  CONSTANT OF JARRETT EQUATION ( 5)=     16.300
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      5.046    104.499
    10.000     10.093    136.997
    20.000     20.185    174.595
    30.000     30.278    200.286
    40.000     40.371    220.598
    50.000     50.464    237.703
**********************************


  CONSTANT OF JARRETT EQUATION ( 6)=     18.500
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      5.046    118.603
```

```
     10.000     10.093    155.488
     20.000     20.185    198.160
     30.000     30.278    227.319
     40.000     40.371    250.372
     50.000     50.464    269.785
**********************************


   CONSTANT OF JARRETT EQUATION ( 7)=     19.800
   --------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ================================
      5.000      5.046    126.937
     10.000     10.093    166.414
     20.000     20.185    212.085
     30.000     30.278    243.293
     40.000     40.371    267.966
     50.000     50.464    288.743
**********************************


   CONSTANT OF JARRETT EQUATION ( 8)=     21.600
   --------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ================================
      5.000      5.046    138.477
     10.000     10.093    181.542
     20.000     20.185    231.365
     30.000     30.278    265.410
     40.000     40.371    292.327
     50.000     50.464    314.993
**********************************


   CONSTANT OF JARRETT EQUATION ( 9)=     22.800
   --------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ================================
      5.000      5.046    146.170
     10.000     10.093    191.628
     20.000     20.185    244.219
     30.000     30.278    280.155
     40.000     40.371    308.567
     50.000     50.464    332.492
**********************************
```

```
CONSTANT OF JARRETT EQUATION (10)=     25.500
-----------------------------------

W.OF H.C.   W.OF TNT   DISTANCE
  TONS        TONS      METERS
=================================
   5.000      5.046    163.480
  10.000     10.093    214.321
  20.000     20.185    273.140
  30.000     30.278    313.331
  40.000     40.371    345.108
  50.000     50.464    371.866
***********************************


CONSTANT OF JARRETT EQUATION (11)=     37.000
-----------------------------------

W.OF H.C.   W.OF TNT   DISTANCE
  TONS        TONS      METERS
=================================
   5.000      5.046    237.206
  10.000     10.093    310.975
  20.000     20.185    396.320
  30.000     30.278    454.638
  40.000     40.371    500.745
  50.000     50.464    539.571
***********************************


CONSTANT OF JARRETT EQUATION (12)=     51.500
-----------------------------------

W.OF H.C.   W.OF TNT   DISTANCE
  TONS        TONS      METERS
=================================
   5.000      5.046    330.165
  10.000     10.093    432.844
  20.000     20.185    551.635
  30.000     30.278    632.807
  40.000     40.371    696.983
  50.000     50.464    751.024
***********************************


CONSTANT OF JARRETT EQUATION (13)=     61.400
-----------------------------------

W.OF H.C.   W.OF TNT   DISTANCE
  TONS        TONS      METERS
=================================
```

```
    5.000      5.046    393.634
   10.000     10.093    516.051
   20.000     20.185    657.678
   30.000     30.278    754.453
   40.000     40.371    830.966
   50.000     50.464    895.396
***********************************


  CONSTANT OF JARRETT EQUATION (14)=      72.000
  ---------------------------------

  W.OF H.C.    W.OF TNT    DISTANCE
    TONS         TONS       METERS
  =================================
    5.000      5.046    461.590
   10.000     10.093    605.141
   20.000     20.185    771.218
   30.000     30.278    884.700
   40.000     40.371    974.422
   50.000     50.464   1049.976
***********************************


  CONSTANT OF JARRETT EQUATION (15)=      99.000
  ---------------------------------

  W.OF H.C.    W.OF TNT    DISTANCE
    TONS         TONS       METERS
  =================================
    5.000      5.046    634.687
   10.000     10.093    832.069
   20.000     20.185   1060.425
   30.000     30.278   1216.463
   40.000     40.371   1339.831
   50.000     50.464   1443.716
***********************************



  BUTANE RESULTS:
  ***************


  EXPLOSION YIELD FACTOR( 1)=      2.000%
  --------------------------
```

```
TNT EQUIVALENT VALUE ( 1)=     5.0237


CONSTANT OF JARRETT EQUATION ( 1)=      3.000
-----------------------------------

W.OF H.C.   W.OF TNT   DISTANCE
  TONS        TONS      METERS
=================================
   5.000     0.995      7.916
  10.000     1.991     12.077
  20.000     3.981     17.308
  30.000     5.972     20.631
  40.000     7.962     23.094
  50.000     9.953     25.087
***********************************


CONSTANT OF JARRETT EQUATION ( 2)=      9.000
-----------------------------------

W.OF H.C.   W.OF TNT   DISTANCE
  TONS        TONS      METERS
=================================
   5.000     0.995     23.749
  10.000     1.991     36.231
  20.000     3.981     51.923
  30.000     5.972     61.894
  40.000     7.962     69.281
  50.000     9.953     75.260
***********************************


CONSTANT OF JARRETT EQUATION ( 3)=     10.050
-----------------------------------

W.OF H.C.   W.OF TNT   DISTANCE
  TONS        TONS      METERS
=================================
   5.000     0.995     26.519
  10.000     1.991     40.457
  20.000     3.981     57.980
  30.000     5.972     69.115
  40.000     7.962     77.364
  50.000     9.953     84.040
***********************************


CONSTANT OF JARRETT EQUATION ( 4)=     13.900
-----------------------------------
```

```
  W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS       METERS
  ================================
    5.000      0.995      36.678
   10.000      1.991      55.956
   20.000      3.981      80.192
   30.000      5.972      95.592
   40.000      7.962     107.000
   50.000      9.953     116.234
**********************************


  CONSTANT OF JARRETT EQUATION ( 5)=     16.300
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS       METERS
  ================================
    5.000      0.995      43.011
   10.000      1.991      65.618
   20.000      3.981      94.038
   30.000      5.972     112.097
   40.000      7.962     125.475
   50.000      9.953     136.303
**********************************


  CONSTANT OF JARRETT EQUATION ( 6)=     18.500
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS       METERS
  ================================
    5.000      0.995      48.817
   10.000      1.991      74.474
   20.000      3.981     106.730
   30.000      5.972     127.227
   40.000      7.962     142.411
   50.000      9.953     154.700
**********************************


  CONSTANT OF JARRETT EQUATION ( 7)=     19.800
  ---------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
   TONS        TONS       METERS
  ================================
    5.000      0.995      52.247
   10.000      1.991      79.707
   20.000      3.981     114.230
```

```
    30.000      5.972   136.167
    40.000      7.962   152.418
    50.000      9.953   165.571
**********************************


  CONSTANT OF JARRETT EQUATION ( 8)=     21.600
  --------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      0.995     56.997
    10.000      1.991     86.953
    20.000      3.981    124.614
    30.000      5.972    148.546
    40.000      7.962    166.274
    50.000      9.953    180.623
**********************************


  CONSTANT OF JARRETT EQUATION ( 9)=     22.800
  --------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      0.995     60.163
    10.000      1.991     91.784
    20.000      3.981    131.537
    30.000      5.972    156.798
    40.000      7.962    175.511
    50.000      9.953    190.657
**********************************


  CONSTANT OF JARRETT EQUATION (10)=     25.500
  --------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ================================
     5.000      0.995     67.288
    10.000      1.991    102.653
    20.000      3.981    147.114
    30.000      5.972    175.367
    40.000      7.962    196.296
    50.000      9.953    213.235
**********************************
```

```
  CONSTANT OF JARRETT EQUATION (11)=     37.000
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ==================================
     5.000      0.995     97.633
    10.000      1.991    148.948
    20.000      3.981    213.460
    30.000      5.972    254.454
    40.000      7.962    284.821
    50.000      9.953    309.400
************************************


  CONSTANT OF JARRETT EQUATION (12)=     51.500
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ==================================
     5.000      0.995    135.895
    10.000      1.991    207.319
    20.000      3.981    297.113
    30.000      5.972    354.172
    40.000      7.962    396.440
    50.000      9.953    430.652
************************************


  CONSTANT OF JARRETT EQUATION (13)=     61.400
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ==================================
     5.000      0.995    162.018
    10.000      1.991    247.173
    20.000      3.981    354.228
    30.000      5.972    422.256
    40.000      7.962    472.649
    50.000      9.953    513.437
************************************


  CONSTANT OF JARRETT EQUATION (14)=     72.000
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS      METERS
  ==================================
```

```
      5.000       0.995    189.989
     10.000       1.991    289.844
     20.000       3.981    415.381
     30.000       5.972    495.153
     40.000       7.962    554.247
     50.000       9.953    602.076
***********************************


   CONSTANT OF JARRETT EQUATION (15)=      99.000
   ---------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ================================
      5.000       0.995    261.235
     10.000       1.991    398.536
     20.000       3.981    571.149
     30.000       5.972    680.835
     40.000       7.962    762.089
     50.000       9.953    827.855
***********************************


   EXPLOSION YIELD FACTOR( 2)=      5.000%
   --------------------------


   TNT EQUIVALENT VALUE ( 2)=    2.0095

   CONSTANT OF JARRETT EQUATION ( 1)=       3.000
   ---------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
     TONS        TONS      METERS
   ================================
      5.000       2.488     13.674
     10.000       4.976     19.118
     20.000       9.953     25.087
     30.000      14.929     28.967
     40.000      19.905     31.981
     50.000      24.882     34.500
***********************************


   CONSTANT OF JARRETT EQUATION ( 2)=       9.000
   ---------------------------------

   W.OF H.C.   W.OF TNT   DISTANCE
```

```
    TONS        TONS       METERS
  ==================================
     5.000      2.488      41.022
    10.000      4.976      57.354
    20.000      9.953      75.260
    30.000     14.929      86.901
    40.000     19.905      95.944
    50.000     24.882     103.500
***********************************


  CONSTANT OF JARRETT EQUATION ( 3)=     10.050
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS       METERS
  ==================================
     5.000      2.488      45.808
    10.000      4.976      64.046
    20.000      9.953      84.040
    30.000     14.929      97.039
    40.000     19.905     107.137
    50.000     24.882     115.575
***********************************


  CONSTANT OF JARRETT EQUATION ( 4)=     13.900
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS       METERS
  ==================================
     5.000      2.488      63.356
    10.000      4.976      88.581
    20.000      9.953     116.234
    30.000     14.929     134.214
    40.000     19.905     148.180
    50.000     24.882     159.850
***********************************


  CONSTANT OF JARRETT EQUATION ( 5)=     16.300
  ----------------------------------

  W.OF H.C.   W.OF TNT   DISTANCE
    TONS        TONS       METERS
  ==================================
     5.000      2.488      74.295
    10.000      4.976     103.875
    20.000      9.953     136.303
    30.000     14.929     157.387
```

```
    40.000     19.905    173.765
    50.000     24.882    187.450
***********************************


   CONSTANT OF JARRETT EQUATION ( 6)=      18.500
   ---------------------------------

   W.OF H.C.    W.OF TNT    DISTANCE
     TONS         TONS       METERS
   =================================
     5.000       2.488      84.322
    10.000       4.976     117.895
    20.000       9.953     154.700
    30.000      14.929     178.630
    40.000      19.905     197.218
    50.000      24.882     212.750
***********************************


   CONSTANT OF JARRETT EQUATION ( 7)=      19.800
   ---------------------------------

   W.OF H.C.    W.OF TNT    DISTANCE
     TONS         TONS       METERS
   =================================
     5.000       2.488      90.248
    10.000       4.976     126.179
    20.000       9.953     165.571
    30.000      14.929     191.182
    40.000      19.905     211.077
    50.000      24.882     227.700
***********************************


   CONSTANT OF JARRETT EQUATION ( 8)=      21.600
   ---------------------------------

   W.OF H.C.    W.OF TNT    DISTANCE
     TONS         TONS       METERS
   =================================
     5.000       2.488      98.452
    10.000       4.976     137.650
    20.000       9.953     180.623
    30.000      14.929     208.562
    40.000      19.905     230.265
    50.000      24.882     248.400
***********************************
```

APPENDIX K

Computer program for calculation of spacing distance using TNT equivalent model (Hopkinson's Law)

```
C
C
C PROGRAM FOR CALCULATION OF SPACING DISTANCE USING
C ===============================================
C T.N.T. EQUIVALENT MODEL (HOPKINSON'S LAW)
C =====================================
C
C
C
      DIMENSION W(100),Y(30),TNT(100),PR(100),DS(100),SD(100)
C
C
        READ *,M,N
         READ *,ER
        READ *,(Y(JI),JI=1,3)
        READ *,(W(II),II=1,M)
        READ *,(PR(JJ),JJ=1,N)
        READ *,(SD(KK),KK=1,N)
C
C
       PRINT 111
  111  FORMAT(//15X,'HOPKINSON S LAW RESULTS:',/,15X,22('*')//)
C
C
        PRINT 124
  124   FORMAT(//,10X,'PROPANE RESULTS:',/,10X,16('*'))
C
        DO 5 K=1,3
C
       PRINT 127,K,Y(K)
   127 FORMAT(///10X,'EXPLOSION YIELD FACTOR(',I1,')=',F10.3,
     @/9X,27('-'))
C
C
C
       DO 2 J=1,M
C
      PRINT 25,J,W(J)
   25 FORMAT(///,7X,'MASS OF LIQUEFIED PROPANE(',I1,')=',F10.2,/,
     *7X,29('-'),//)
C
C
      TNT(J)=W(J)*ER*Y(K)
C
      PRINT 35,J,TNT(J)
   35  FORMAT(7X,'TNT EQUIVALENT (',I1,')=',F10.3,/,7X,19('-')//)
C
C
      PRINT 55
 55    FORMAT(6X,'RESULTS OF TNT MODEL (HOPKINSON S LAW)',/,
     @6X,36('=')/)
C
C
     PRINT 105
```

```
  105 FORMAT(6X,'PR.WAVE  SCALE DIST.',
     @' HAZARD RANGE',/6X,' (PSI)                          (METERS)',/5X,35('-'))
C
        DO 3 I=1,N
        DS(I)=SD(I)*((TNT(J)*1000.0)**0.3333)
C
        PRINT 200,PR(I),SD(I),DS(I)
  200   FORMAT(2X,3(F10.3,2X))
C
C
  3         CONTINUE
C
  2       CONTINUE
C
  5       CONTINUE
C
C
            STOP
             END
```

```
          HOPKINSON S LAW RESULTS:
          ************************


      PROPANE RESULTS:
      ****************


      EXPLOSION YIELD FACTOR(1)=      0.020
     ------------------------------


    MASS OF LIQUEFIED PROPANE(1)=      1.00
    --------------------------------


    TNT EQUIVALENT (1)=     0.200
    --------------------


   RESULTS OF TNT MODEL (HOPKINSON S LAW)
   ======================================

   PR.WAVE  SCALE DIST. HAZARD RANGE
    (PSI)                (METERS)
  ---------------------------------------
   10.000       4.000     23.388
    7.250       4.800     28.066
    7.000       5.000     29.235
    6.080       5.500     32.159
    5.000       6.000     35.082
    3.470       7.500     43.853
    3.000       8.500     49.700
    2.500       9.400     54.962
    2.300       9.900     57.885
    2.000      11.000     64.317
    1.500      14.000     81.858
    1.000      18.000    105.246
    0.690      24.000    140.328
    0.400      35.000    204.645
    0.290      46.000    268.962
    0.140      78.000    456.066
    0.100     100.000    584.700


   MASS OF LIQUEFIED PROPANE(2)=      5.00
   --------------------------------
```

```
  TNT EQUIVALENT (2)=       1.000
  -------------------


 RESULTS OF TNT MODEL (HOPKINSON S LAW)
 ======================================

 PR.WAVE  SCALE DIST. HAZARD RANGE
  (PSI)                 (METERS)
-------------------------------------
 10.000        4.000       39.991
  7.250        4.800       47.989
  7.000        5.000       49.988
  6.080        5.500       54.987
  5.000        6.000       59.986
  3.470        7.500       74.983
  3.000        8.500       84.980
  2.500        9.400       93.978
  2.300        9.900       98.977
  2.000       11.000      109.975
  1.500       14.000      139.968
  1.000       18.000      179.959
  0.690       24.000      239.945
  0.400       35.000      349.919
  0.290       46.000      459.894
  0.140       78.000      779.820
  0.100      100.000      999.770


  MASS OF LIQUEFIED PROPANE(3)=      10.00
  -----------------------------


  TNT EQUIVALENT (3)=       2.000
  -------------------


 RESULTS OF TNT MODEL (HOPKINSON S LAW)
 ======================================

 PR.WAVE  SCALE DIST. HAZARD RANGE
  (PSI)                 (METERS)
-------------------------------------
 10.000        4.000       50.384
  7.250        4.800       60.461
  7.000        5.000       62.980
  6.080        5.500       69.278
  5.000        6.000       75.576
  3.470        7.500       94.470
  3.000        8.500      107.066
  2.500        9.400      118.403
  2.300        9.900      124.701
  2.000       11.000      138.556
```

```
 1.500       14.000      176.344
 1.000       18.000      226.728
 0.690       24.000      302.304
 0.400       35.000      440.861
 0.290       46.000      579.417
 0.140       78.000      982.489
 0.100      100.000     1259.602


 MASS OF LIQUEFIED PROPANE(4)=      20.00
 ----------------------------


 TNT EQUIVALENT (4)=      4.000
 -------------------


 RESULTS OF TNT MODEL (HOPKINSON S LAW)
 ======================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                (METERS)
---------------------------------
10.000        4.000       63.478
 7.250        4.800       76.174
 7.000        5.000       79.348
 6.080        5.500       87.283
 5.000        6.000       95.218
 3.470        7.500      119.022
 3.000        8.500      134.892
 2.500        9.400      149.174
 2.300        9.900      157.109
 2.000       11.000      174.566
 1.500       14.000      222.175
 1.000       18.000      285.653
 0.690       24.000      380.871
 0.400       35.000      555.437
 0.290       46.000      730.003
 0.140       78.000     1237.831
 0.100      100.000     1586.962


 MASS OF LIQUEFIED PROPANE(5)=      30.00
 ----------------------------


 TNT EQUIVALENT (5)=      6.000
 -------------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
======================================
```

```
PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                 (METERS)
-----------------------------------
10.000       4.000      72.664
 7.250       4.800      87.197
 7.000       5.000      90.830
 6.080       5.500      99.913
 5.000       6.000     108.996
 3.470       7.500     136.245
 3.000       8.500     154.410
 2.500       9.400     170.760
 2.300       9.900     179.843
 2.000      11.000     199.825
 1.500      14.000     254.323
 1.000      18.000     326.987
 0.690      24.000     435.983
 0.400      35.000     635.808
 0.290      46.000     835.633
 0.140      78.000    1416.943
 0.100     100.000    1816.594


 MASS OF LIQUEFIED PROPANE(6)=       40.00
 -----------------------------


 TNT EQUIVALENT (6)=        8.000
 ------------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
======================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                 (METERS)
-----------------------------------
10.000       4.000      79.976
 7.250       4.800      95.971
 7.000       5.000      99.970
 6.080       5.500     109.967
 5.000       6.000     119.964
 3.470       7.500     149.955
 3.000       8.500     169.949
 2.500       9.400     187.944
 2.300       9.900     197.941
 2.000      11.000     219.934
 1.500      14.000     279.916
 1.000      18.000     359.892
 0.690      24.000     479.856
 0.400      35.000     699.790
 0.290      46.000     919.724
 0.140      78.000    1559.533
 0.100     100.000    1999.401
```

```
MASS OF LIQUEFIED PROPANE(7)=       50.00
-------------------------------


TNT EQUIVALENT (7)=     10.000
-------------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
======================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                 (METERS)
------------------------------------
10.000        4.000       86.151
 7.250        4.800      103.381
 7.000        5.000      107.689
 6.080        5.500      118.458
 5.000        6.000      129.226
 3.470        7.500      161.533
 3.000        8.500      183.071
 2.500        9.400      202.455
 2.300        9.900      213.224
 2.000       11.000      236.915
 1.500       14.000      301.528
 1.000       18.000      387.679
 0.690       24.000      516.906
 0.400       35.000      753.821
 0.290       46.000      990.736
 0.140       78.000     1679.943
 0.100      100.000     2153.774


    EXPLOSION YIELD FACTOR(2)=       0.050
  ----------------------------


MASS OF LIQUEFIED PROPANE(1)=        1.00
-------------------------------


TNT EQUIVALENT (1)=      0.500
-------------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
======================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                 (METERS)
------------------------------------
10.000        4.000       31.741
```

```
   7.250       4.800      38.090
   7.000       5.000      39.677
   6.080       5.500      43.644
   5.000       6.000      47.612
   3.470       7.500      59.515
   3.000       8.500      67.451
   2.500       9.400      74.592
   2.300       9.900      78.560
   2.000      11.000      87.289
   1.500      14.000     111.095
   1.000      18.000     142.837
   0.690      24.000     190.449
   0.400      35.000     277.738
   0.290      46.000     365.027
   0.140      78.000     618.958
   0.100     100.000     793.536


   MASS OF LIQUEFIED PROPANE(2)=       5.00
   ------------------------------


   TNT EQUIVALENT (2)=      2.500
   -------------------


  RESULTS OF TNT MODEL (HOPKINSON S LAW)
  ======================================

  PR.WAVE   SCALE DIST.  HAZARD RANGE
   (PSI)                   (METERS)
  ------------------------------------
  10.000       4.000      54.274
   7.250       4.800      65.129
   7.000       5.000      67.843
   6.080       5.500      74.627
   5.000       6.000      81.411
   3.470       7.500     101.764
   3.000       8.500     115.333
   2.500       9.400     127.544
   2.300       9.900     134.329
   2.000      11.000     149.254
   1.500      14.000     189.960
   1.000      18.000     244.234
   0.690      24.000     325.645
   0.400      35.000     474.899
   0.290      46.000     624.153
   0.140      78.000    1058.347
   0.100     100.000    1356.855


  MASS OF LIQUEFIED PROPANE(3)=      10.00
```

```
--------------------------------


TNT EQUIVALENT (3)=      5.000
--------------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
======================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                 (METERS)
--------------------------------------
10.000        4.000       68.380
 7.250        4.800       82.056
 7.000        5.000       85.475
 6.080        5.500       94.022
 5.000        6.000      102.569
 3.470        7.500      128.212
 3.000        8.500      145.307
 2.500        9.400      160.692
 2.300        9.900      169.240
 2.000       11.000      188.044
 1.500       14.000      239.329
 1.000       18.000      307.708
 0.690       24.000      410.278
 0.400       35.000      598.322
 0.290       46.000      786.366
 0.140       78.000     1333.403
 0.100      100.000     1709.491


MASS OF LIQUEFIED PROPANE(4)=       20.00
------------------------------


TNT EQUIVALENT (4)=      10.000
--------------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
======================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                 (METERS)
--------------------------------------
10.000        4.000       86.151
 7.250        4.800      103.381
 7.000        5.000      107.689
 6.080        5.500      118.458
 5.000        6.000      129.226
 3.470        7.500      161.533
 3.000        8.500      183.071
```

```
  2.500        9.400      202.455
  2.300        9.900      213.224
  2.000       11.000      236.915
  1.500       14.000      301.528
  1.000       18.000      387.679
  0.690       24.000      516.906
  0.400       35.000      753.821
  0.290       46.000      990.736
  0.140       78.000     1679.943
  0.100      100.000     2153.774


  MASS OF LIQUEFIED PROPANE(5)=        30.00
  -----------------------------


  TNT EQUIVALENT (5)=     15.000
  ------------------


 RESULTS OF TNT MODEL (HOPKINSON S LAW)
 ======================================

 PR.WAVE   SCALE DIST.  HAZARD RANGE
  (PSI)                   (METERS)
 ------------------------------------
 10.000        4.000       98.617
  7.250        4.800      118.340
  7.000        5.000      123.271
  6.080        5.500      135.598
  5.000        6.000      147.925
  3.470        7.500      184.907
  3.000        8.500      209.561
  2.500        9.400      231.750
  2.300        9.900      244.077
  2.000       11.000      271.196
  1.500       14.000      345.159
  1.000       18.000      443.776
  0.690       24.000      591.701
  0.400       35.000      862.898
  0.290       46.000     1134.094
  0.140       78.000     1923.029
  0.100      100.000     2465.422


  MASS OF LIQUEFIED PROPANE(6)=        40.00
  -----------------------------


  TNT EQUIVALENT (6)=     20.000
  ------------------
```

```
RESULTS OF TNT MODEL (HOPKINSON S LAW)
======================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                (METERS)
--------------------------------------
10.000      4.000      108.541
 7.250      4.800      130.249
 7.000      5.000      135.676
 6.080      5.500      149.244
 5.000      6.000      162.811
 3.470      7.500      203.514
 3.000      8.500      230.649
 2.500      9.400      255.071
 2.300      9.900      268.639
 2.000     11.000      298.487
 1.500     14.000      379.893
 1.000     18.000      488.434
 0.690     24.000      651.245
 0.400     35.000      949.733
 0.290     46.000     1248.220
 0.140     78.000     2116.547
 0.100    100.000     2713.522


 MASS OF LIQUEFIED PROPANE(7)=      50.00
 -----------------------------


 TNT EQUIVALENT (7)=     25.000
 -------------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
======================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                (METERS)
--------------------------------------
10.000      4.000      116.921
 7.250      4.800      140.305
 7.000      5.000      146.152
 6.080      5.500      160.767
 5.000      6.000      175.382
 3.470      7.500      219.227
 3.000      8.500      248.458
 2.500      9.400      274.765
 2.300      9.900      289.380
 2.000     11.000      321.533
 1.500     14.000      409.224
 1.000     18.000      526.146
 0.690     24.000      701.527
 0.400     35.000     1023.061
```

```
0.290        46.000     1344.594
0.140        78.000     2279.964
0.100       100.000     2923.031


    EXPLOSION YIELD FACTOR(3)=        0.100
   ------------------------------


MASS OF LIQUEFIED PROPANE(1)=        1.00
----------------------------------


TNT EQUIVALENT (1)=        1.000
---------------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
=======================================

PR.WAVE  SCALE DIST.  HAZARD RANGE
 (PSI)                  (METERS)
----------------------------------------
10.000       4.000        39.991
 7.250       4.800        47.989
 7.000       5.000        49.988
 6.080       5.500        54.987
 5.000       6.000        59.986
 3.470       7.500        74.983
 3.000       8.500        84.980
 2.500       9.400        93.978
 2.300       9.900        98.977
 2.000      11.000       109.975
 1.500      14.000       139.968
 1.000      18.000       179.959
 0.690      24.000       239.945
 0.400      35.000       349.919
 0.290      46.000       459.894
 0.140      78.000       779.820
 0.100     100.000       999.770


MASS OF LIQUEFIED PROPANE(2)=        5.00
----------------------------------


TNT EQUIVALENT (2)=        5.000
---------------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
```

```
=====================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                 (METERS)
-----------------------------------
10.000      4.000        68.380
 7.250      4.800        82.056
 7.000      5.000        85.475
 6.080      5.500        94.022
 5.000      6.000       102.569
 3.470      7.500       128.212
 3.000      8.500       145.307
 2.500      9.400       160.692
 2.300      9.900       169.240
 2.000     11.000       188.044
 1.500     14.000       239.329
 1.000     18.000       307.708
 0.690     24.000       410.278
 0.400     35.000       598.322
 0.290     46.000       786.366
 0.140     78.000      1333.403
 0.100    100.000      1709.491


 MASS OF LIQUEFIED PROPANE(3)=      10.00
 ----------------------------


 TNT EQUIVALENT (3)=    10.000
 -----------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
=====================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                 (METERS)
-----------------------------------
10.000      4.000        86.151
 7.250      4.800       103.381
 7.000      5.000       107.689
 6.080      5.500       118.458
 5.000      6.000       129.226
 3.470      7.500       161.533
 3.000      8.500       183.071
 2.500      9.400       202.455
 2.300      9.900       213.224
 2.000     11.000       236.915
 1.500     14.000       301.528
 1.000     18.000       387.679
 0.690     24.000       516.906
 0.400     35.000       753.821
 0.290     46.000       990.736
```

```
 0.140        78.000    1679.943
 0.100       100.000    2153.774


 MASS OF LIQUEFIED PROPANE(4)=        20.00
 ------------------------------


 TNT EQUIVALENT (4)=     20.000
 --------------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
======================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                 (METERS)
-----------------------------------
10.000        4.000      108.541
 7.250        4.800      130.249
 7.000        5.000      135.676
 6.080        5.500      149.244
 5.000        6.000      162.811
 3.470        7.500      203.514
 3.000        8.500      230.649
 2.500        9.400      255.071
 2.300        9.900      268.639
 2.000       11.000      298.487
 1.500       14.000      379.893
 1.000       18.000      488.434
 0.690       24.000      651.245
 0.400       35.000      949.733
 0.290       46.000     1248.220
 0.140       78.000     2116.547
 0.100      100.000     2713.522


 MASS OF LIQUEFIED PROPANE(5)=        30.00
 ------------------------------


 TNT EQUIVALENT (5)=     30.000
 --------------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
======================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                 (METERS)
-----------------------------------
10.000        4.000      124.247
```

```
 7.250       4.800     149.096
 7.000       5.000     155.308
 6.080       5.500     170.839
 5.000       6.000     186.370
 3.470       7.500     232.962
 3.000       8.500     264.024
 2.500       9.400     291.980
 2.300       9.900     307.510
 2.000      11.000     341.678
 1.500      14.000     434.863
 1.000      18.000     559.110
 0.690      24.000     745.480
 0.400      35.000    1087.158
 0.290      46.000    1428.836
 0.140      78.000    2422.809
 0.100     100.000    3106.165


 MASS OF LIQUEFIED PROPANE(6)=      40.00
 ------------------------------


 TNT EQUIVALENT (6)=    40.000
 -------------------


RESULTS OF TNT MODEL (HOPKINSON S LAW)
======================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                 (METERS)
----------------------------------------
10.000       4.000     136.750
 7.250       4.800     164.100
 7.000       5.000     170.937
 6.080       5.500     188.031
 5.000       6.000     205.125
 3.470       7.500     256.406
 3.000       8.500     290.593
 2.500       9.400     321.362
 2.300       9.900     338.456
 2.000      11.000     376.062
 1.500      14.000     478.624
 1.000      18.000     615.374
 0.690      24.000     820.499
 0.400      35.000    1196.561
 0.290      46.000    1572.622
 0.140      78.000    2666.621
 0.100     100.000    3418.745


MASS OF LIQUEFIED PROPANE(7)=      50.00
```

```
 ----------------------------

 TNT EQUIVALENT (7)=    50.000
 -------------------

RESULTS OF TNT MODEL (HOPKINSON S LAW)
======================================

PR.WAVE  SCALE DIST. HAZARD RANGE
 (PSI)                 (METERS)
------------------------------------
10.000       4.000     147.308
 7.250       4.800     176.770
 7.000       5.000     184.135
 6.080       5.500     202.549
 5.000       6.000     220.962
 3.470       7.500     276.203
 3.000       8.500     313.030
 2.500       9.400     346.174
 2.300       9.900     364.588
 2.000      11.000     405.097
 1.500      14.000     515.578
 1.000      18.000     662.887
 0.690      24.000     883.849
 0.400      35.000    1288.946
 0.290      46.000    1694.043
 0.140      78.000    2872.508
 0.100     100.000    3682.703
```

APPENDIX L

Computer program for calculation of spacing distance using Gugan's Model

```
C
C
C
C PROGRAM FOR CALCULATION OF SPACING DISTANCE USING GUGAN MODEL.
C ================================================================
C
C
C
       DIMENSION W(100),PS(100),EO(100),PC(100),D(100),R(100),
     @N(100),E(100),RS(100),T(100),WTM(100),AN(100),EOR(100),V(100)
C
C
        READ *,A
C
        READ *,(W(II),II=1,7)
        READ *,(PS(JJ),JJ=1,18)
          READ *,(N(KK),E(KK),AN(KK),WTM(KK),KK=1,4)
C
C
      PRINT 333
 333  FORMAT(//15X,'GUGAN S MODEL RESULTS:',/15X,21('*')//)
C
C
      DO 3 I=1,7
C
      PRINT 100,I,W(I)
 100  FORMAT(10X,'MASS OF FLAMMABLE GAS IN THE CLOUD(',I2,')=',F9.1,
     @/10X,40('-')//)
C
      DO 5 K=1,18
C
      PRINT 110,K,PS(K)
 110  FORMAT(10X,'OVER PRESSURE(',I2,')=',F10.3,/10X,15('-')//)
C
C
C
      PRINT 150
 150  FORMAT(3X,' COMPONENT      V        D          TO       EO    ',
     @'   PC       RS         R ',/,5X,71('-'))
C
C
C
      DO 8 J=1,4
C
      V(J)=(22.4*AN(J)*W(I))/WTM(J)
      D(J)=((12.0*V(J))/3.14159)**0.3333
      T(J)=D(J)/A
      EO(J)=E(J)*W(I)
      PC(J)=(EO(J)*A*1000000.0)/(0.57*(D(J)**4.0))
      G=4.95E+07
      RS(J)=G/PC(J)
      R(J)=(37.86*(EO(J)**0.5)/PS(K))**0.6667
      EOR(J)=(EO(J)**0.333)/R(J)
C
```

```
C
      PRINT 200,N(J),V(J),D(J),T(J),EO(J),PC(J),RS(J),R(J)
 200   FORMAT(7X,'C',I1,5X,7(1PE8.2,1X))
C
  8    CONTINUE
C
       PRINT 220
 220   FORMAT(10X,///)
C
  5     CONTINUE
C
        PRINT 230
 230    FORMAT(10X,///)
C
  3     CONTINUE
C
         STOP
        END
```

```
          GUGAN S MODEL RESULTS:
          *********************


      MASS OF FLAMMABLE GAS IN THE CLOUD( 1)=   1000.0
      -----------------------------------------


      OVER PRESSURE( 1)=    69.000
      ----------------


COMPONENT    V         D          TO        EO         PC        RS        R
------------------------------------------------------------------------------------
   C1     1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 2.47E+01
   C2     1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 2.43E+01
   C3     1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 2.41E+01
   C4     1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 2.40E+01


      OVER PRESSURE( 2)=    50.000
      ----------------


COMPONENT    V         D          TO        EO         PC        RS        R
------------------------------------------------------------------------------------
   C1     1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 3.06E+01
   C2     1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 3.01E+01
   C3     1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 2.99E+01
   C4     1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 2.97E+01


      OVER PRESSURE( 3)=    48.300
      ----------------


COMPONENT    V         D          TO        EO         PC        RS        R
------------------------------------------------------------------------------------
   C1     1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 3.14E+01
   C2     1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 3.08E+01
   C3     1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 3.06E+01
   C4     1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 3.04E+01


      OVER PRESSURE( 4)=    42.000
      ----------------
```

```
COMPONENT    V          D          TO         EO         PC         RS         R
-----------------------------------------------------------------------------------------
   C1      1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 3.44E+01
   C2      1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 3.38E+01
   C3      1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 3.35E+01
   C4      1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 3.34E+01


        OVER PRESSURE( 5)=     34.500
        ---------------

COMPONENT    V          D          TO         EO         PC         RS         R
-----------------------------------------------------------------------------------------
   C1      1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 3.92E+01
   C2      1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 3.86E+01
   C3      1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 3.83E+01
   C4      1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 3.81E+01


        OVER PRESSURE( 6)=     24.000
        ---------------

COMPONENT    V          D          TO         EO         PC         RS         R
-----------------------------------------------------------------------------------------
   C1      1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 5.00E+01
   C2      1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 4.91E+01
   C3      1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 4.87E+01
   C4      1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 4.85E+01


        OVER PRESSURE( 7)=     20.700
        ---------------

COMPONENT    V          D          TO         EO         PC         RS         R
-----------------------------------------------------------------------------------------
   C1      1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 5.52E+01
   C2      1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 5.42E+01
   C3      1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 5.38E+01
   C4      1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 5.35E+01


        OVER PRESSURE( 8)=     17.300
        ---------------
```

```
COMPONENT    V         D          TO        EO        PC        RS        R
-------------------------------------------------------------------------------
  C1      1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 6.22E+01
  C2      1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 6.11E+01
  C3      1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 6.06E+01
  C4      1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 6.03E+01


     OVER PRESSURE( 9)=     15.900
     ---------------

COMPONENT    V         D          TO        EO        PC        RS        R
-------------------------------------------------------------------------------
  C1      1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 6.58E+01
  C2      1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 6.46E+01
  C3      1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 6.41E+01
  C4      1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 6.38E+01


     OVER PRESSURE(10)=     13.800
     ---------------

COMPONENT    V         D          TO        EO        PC        RS        R
-------------------------------------------------------------------------------
  C1      1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 7.23E+01
  C2      1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 7.10E+01
  C3      1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 7.05E+01
  C4      1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 7.01E+01


     OVER PRESSURE(11)=     10.350
     ---------------

COMPONENT    V         D          TO        EO        PC        RS        R
-------------------------------------------------------------------------------
  C1      1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 8.76E+01
  C2      1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 8.61E+01
  C3      1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 8.54E+01
  C4      1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 8.50E+01


     OVER PRESSURE(12)=     6.900
     ---------------
```

```
COMPONENT     V        D          TO        EO        PC        RS        R
-------------------------------------------------------------------------------
   C1      1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 1.15E+02
   C2      1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 1.13E+02
   C3      1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 1.12E+02
   C4      1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 1.11E+02


       OVER PRESSURE(13)=      4.800
       -----------------

COMPONENT     V        D          TO        EO        PC        RS        R
-------------------------------------------------------------------------------
   C1      1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 1.46E+02
   C2      1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 1.44E+02
   C3      1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 1.42E+02
   C4      1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 1.42E+02


       OVER PRESSURE(14)=      2.760
       -----------------

COMPONENT     V        D          TO        EO        PC        RS        R
-------------------------------------------------------------------------------
   C1      1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 2.11E+02
   C2      1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 2.08E+02
   C3      1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 2.06E+02
   C4      1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 2.05E+02


       OVER PRESSURE(15)=      2.000
       -----------------

COMPONENT     V        D          TO        EO        PC        RS        R
-------------------------------------------------------------------------------
   C1      1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 2.62E+02
   C2      1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 2.57E+02
   C3      1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 2.55E+02
   C4      1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 2.54E+02


       OVER PRESSURE(16)=      1.000
       -----------------
```

```
COMPONENT     V          D          TO         EO         PC         RS         R
---------------------------------------------------------------------------------------
  C1       1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 4.16E+02
  C2       1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 4.09E+02
  C3       1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 4.05E+02
  C4       1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 4.04E+02


      OVER PRESSURE(17)=      0.700
      -----------------

COMPONENT     V          D          TO         EO         PC         RS         R
---------------------------------------------------------------------------------------
  C1       1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 5.28E+02
  C2       1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 5.18E+02
  C3       1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 5.14E+02
  C4       1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 5.12E+02


      OVER PRESSURE(18)=      0.200
      -----------------

COMPONENT     V          D          TO         EO         PC         RS         R
---------------------------------------------------------------------------------------
  C1       1.47E+04 3.83E+01 1.16E-01 5.01E+04 1.35E+07 3.67E+00 1.22E+03
  C2       1.32E+04 3.69E+01 1.12E-01 4.76E+04 1.48E+07 3.34E+00 1.20E+03
  C3       1.26E+04 3.64E+01 1.10E-01 4.64E+04 1.53E+07 3.23E+00 1.19E+03
  C4       1.23E+04 3.61E+01 1.09E-01 4.58E+04 1.56E+07 3.17E+00 1.18E+03




      MASS OF FLAMMABLE GAS IN THE CLOUD( 2)=    5000.0
      ------------------------------------------


      OVER PRESSURE( 1)=    69.000
      -----------------

COMPONENT     V          D          TO         EO         PC         RS         R
---------------------------------------------------------------------------------------
  C1       7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 4.23E+01
  C2       6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 4.15E+01
```

```
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 4.12E+01
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 4.10E+01


         OVER PRESSURE( 2)=      50.000
         ---------------

COMPONENT     V        D          TO       EO        PC       RS       R
----------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 5.24E+01
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 5.15E+01
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 5.11E+01
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 5.08E+01


         OVER PRESSURE( 3)=      48.300
         ---------------

COMPONENT     V        D          TO       EO        PC       RS       R
----------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 5.36E+01
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 5.27E+01
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 5.23E+01
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 5.20E+01


         OVER PRESSURE( 4)=      42.000
         ---------------

COMPONENT     V        D          TO       EO        PC       RS       R
----------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 5.89E+01
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 5.78E+01
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 5.74E+01
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 5.71E+01


         OVER PRESSURE( 5)=      34.500
         ---------------

COMPONENT     V        D          TO       EO        PC       RS       R
----------------------------------------------------------------------------
```

```
    C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 6.71E+01
    C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 6.59E+01
    C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 6.54E+01
    C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 6.51E+01


        OVER PRESSURE( 6)=     24.000
        ----------------

COMPONENT     V          D          TO        EO        PC        RS         R
-------------------------------------------------------------------------------
    C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 8.55E+01
    C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 8.40E+01
    C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 8.33E+01
    C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 8.29E+01


        OVER PRESSURE( 7)=     20.700
        ----------------

COMPONENT     V          D          TO        EO        PC        RS         R
-------------------------------------------------------------------------------
    C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 9.43E+01
    C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 9.27E+01
    C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 9.20E+01
    C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 9.15E+01


        OVER PRESSURE( 8)=     17.300
        ----------------

COMPONENT     V          D          TO        EO        PC        RS         R
-------------------------------------------------------------------------------
    C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 1.06E+02
    C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 1.04E+02
    C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 1.04E+02
    C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 1.03E+02


        OVER PRESSURE( 9)=     15.900
        ----------------
```

```
COMPONENT     V         D            TO        EO         PC        RS         R
-------------------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 1.12E+02
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 1.11E+02
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 1.10E+02
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 1.09E+02


      OVER PRESSURE(10)=     13.800
      ----------------

COMPONENT     V         D            TO        EO         PC        RS         R
-------------------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 1.24E+02
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 1.21E+02
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 1.20E+02
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 1.20E+02


      OVER PRESSURE(11)=     10.350
      ----------------

COMPONENT     V         D            TO        EO         PC        RS         R
-------------------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 1.50E+02
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 1.47E+02
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 1.46E+02
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 1.45E+02


      OVER PRESSURE(12)=     6.900
      ----------------

COMPONENT     V         D            TO        EO         PC        RS         R
-------------------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 1.96E+02
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 1.93E+02
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 1.91E+02
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 1.90E+02


      OVER PRESSURE(13)=     4.800
      ----------------
```

```
COMPONENT     V          D            TO         EO          PC          RS           R
------------------------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 2.50E+02
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 2.46E+02
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 2.44E+02
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 2.42E+02


       OVER PRESSURE(14)=      2.760
       -----------------

COMPONENT     V          D            TO         EO          PC          RS           R
------------------------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 3.61E+02
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 3.55E+02
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 3.52E+02
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 3.51E+02


       OVER PRESSURE(15)=      2.000
       -----------------

COMPONENT     V          D            TO         EO          PC          RS           R
------------------------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 4.48E+02
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 4.40E+02
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 4.37E+02
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 4.35E+02


       OVER PRESSURE(16)=      1.000
       -----------------

COMPONENT     V          D            TO         EO          PC          RS           R
------------------------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 7.11E+02
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 6.99E+02
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 6.93E+02
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 6.90E+02


       OVER PRESSURE(17)=      0.700
       -----------------
```

```
COMPONENT     V          D          TO         EO         PC         RS         R
------------------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 9.02E+02
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 8.87E+02
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 8.79E+02
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 8.75E+02


      OVER PRESSURE(18)=     0.200
      -----------------

COMPONENT     V          D          TO         EO         PC         RS         R
------------------------------------------------------------------------------------
   C1      7.36E+04 6.55E+01 1.98E-01 2.51E+05 7.89E+06 6.27E+00 2.08E+03
   C2      6.59E+04 6.31E+01 1.91E-01 2.38E+05 8.68E+06 5.70E+00 2.04E+03
   C3      6.31E+04 6.22E+01 1.89E-01 2.32E+05 8.97E+06 5.52E+00 2.03E+03
   C4      6.17E+04 6.17E+01 1.87E-01 2.29E+05 9.12E+06 5.43E+00 2.02E+03



      MASS OF FLAMMABLE GAS IN THE CLOUD( 3)=  10000.0
      -------------------------------------------

      OVER PRESSURE( 1)=     69.000
      -----------------

COMPONENT     V          D          TO         EO         PC         RS         R
------------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 5.33E+01
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 5.23E+01
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 5.19E+01
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 5.17E+01


      OVER PRESSURE( 2)=     50.000
      -----------------

COMPONENT     V          D          TO         EO         PC         RS         R
------------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 6.60E+01
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 6.49E+01
```

```
  C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 6.44E+01
  C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 6.41E+01


     OVER PRESSURE( 3)=     48.300
     ---------------

COMPONENT     V        D          TO        EO        PC        RS        R
--------------------------------------------------------------------------------
  C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 6.76E+01
  C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 6.64E+01
  C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 6.59E+01
  C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 6.55E+01


     OVER PRESSURE( 4)=     42.000
     ---------------

COMPONENT     V        D          TO        EO        PC        RS        R
--------------------------------------------------------------------------------
  C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 7.42E+01
  C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 7.29E+01
  C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 7.23E+01
  C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 7.19E+01


     OVER PRESSURE( 5)=     34.500
     ---------------

COMPONENT     V        D          TO        EO        PC        RS        R
--------------------------------------------------------------------------------
  C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 8.45E+01
  C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 8.31E+01
  C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 8.24E+01
  C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 8.20E+01


     OVER PRESSURE( 6)=     24.000
     ---------------

COMPONENT     V        D          TO        EO        PC        RS        R
--------------------------------------------------------------------------------
```

```
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 1.08E+02
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 1.06E+02
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 1.05E+02
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 1.04E+02



       OVER PRESSURE( 7)=     20.700
       ---------------

COMPONENT      V         D           TO        EO        PC        RS        R
-----------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 1.19E+02
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 1.17E+02
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 1.16E+02
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 1.15E+02



       OVER PRESSURE( 8)=     17.300
       ---------------

COMPONENT      V         D           TO        EO        PC        RS        R
-----------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 1.34E+02
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 1.32E+02
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 1.31E+02
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 1.30E+02



       OVER PRESSURE( 9)=     15.900
       ---------------

COMPONENT      V         D           TO        EO        PC        RS        R
-----------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 1.42E+02
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 1.39E+02
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 1.38E+02
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 1.37E+02



       OVER PRESSURE(10)=     13.800
       ---------------
```

```
COMPONENT     V          D           TO         EO         PC         RS         R
------------------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 1.56E+02
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 1.53E+02
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 1.52E+02
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 1.51E+02


      OVER PRESSURE(11)=     10.350
      ------------------

COMPONENT     V          D           TO         EO         PC         RS         R
------------------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 1.89E+02
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 1.85E+02
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 1.84E+02
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 1.83E+02


      OVER PRESSURE(12)=     6.900
      ------------------

COMPONENT     V          D           TO         EO         PC         RS         R
------------------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 2.47E+02
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 2.43E+02
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 2.41E+02
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 2.40E+02


      OVER PRESSURE(13)=     4.800
      ------------------

COMPONENT     V          D           TO         EO         PC         RS         R
------------------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 3.15E+02
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 3.09E+02
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 3.07E+02
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 3.06E+02


      OVER PRESSURE(14)=     2.760
      ------------------
```

```
COMPONENT     V          D           TO        EO          PC        RS         R
------------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 4.55E+02
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 4.48E+02
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 4.44E+02
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 4.42E+02


      OVER PRESSURE(15)=       2.000
      -----------------

COMPONENT     V          D           TO        EO          PC        RS         R
------------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 5.64E+02
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 5.55E+02
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 5.50E+02
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 5.48E+02


      OVER PRESSURE(16)=       1.000
      -----------------

COMPONENT     V          D           TO        EO          PC        RS         R
------------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 8.96E+02
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 8.81E+02
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 8.73E+02
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 8.69E+02


      OVER PRESSURE(17)=       0.700
      -----------------

COMPONENT     V          D           TO        EO          PC        RS         R
------------------------------------------------------------------------------------
   C1      1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 1.14E+03
   C2      1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 1.12E+03
   C3      1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 1.11E+03
   C4      1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 1.10E+03


      OVER PRESSURE(18)=       0.200
      -----------------
```

```
COMPONENT     V          D          TO         EO         PC         RS         R
------------------------------------------------------------------------------------
  C1       1.47E+05 8.25E+01 2.50E-01 5.01E+05 6.26E+06 7.90E+00 2.62E+03
  C2       1.32E+05 7.95E+01 2.41E-01 4.76E+05 6.89E+06 7.19E+00 2.58E+03
  C3       1.26E+05 7.84E+01 2.38E-01 4.64E+05 7.12E+06 6.95E+00 2.55E+03
  C4       1.23E+05 7.78E+01 2.36E-01 4.58E+05 7.24E+06 6.83E+00 2.54E+03




      MASS OF FLAMMABLE GAS IN THE CLOUD( 4)=  20000.0
      ------------------------------------------


      OVER PRESSURE( 1)=     69.000
      ----------------


COMPONENT     V          D          TO         EO         PC         RS         R
------------------------------------------------------------------------------------
  C1       2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 6.71E+01
  C2       2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 6.59E+01
  C3       2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 6.54E+01
  C4       2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 6.51E+01


      OVER PRESSURE( 2)=     50.000
      ----------------


COMPONENT     V          D          TO         EO         PC         RS         R
------------------------------------------------------------------------------------
  C1       2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 8.32E+01
  C2       2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 8.17E+01
  C3       2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 8.11E+01
  C4       2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 8.07E+01


      OVER PRESSURE( 3)=     48.300
      ----------------


COMPONENT     V          D          TO         EO         PC         RS         R
------------------------------------------------------------------------------------
  C1       2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 8.51E+01
  C2       2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 8.36E+01
```

```
      C3      2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 8.30E+01
      C4      2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 8.26E+01


        OVER PRESSURE( 4)=     42.000
        ---------------

 COMPONENT     V          D          TO        EO         PC        RS         R
 --------------------------------------------------------------------------------
      C1      2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 9.34E+01
      C2      2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 9.18E+01
      C3      2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 9.11E+01
      C4      2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 9.07E+01


        OVER PRESSURE( 5)=     34.500
        ---------------

 COMPONENT     V          D          TO        EO         PC        RS         R
 --------------------------------------------------------------------------------
      C1      2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 1.07E+02
      C2      2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 1.05E+02
      C3      2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 1.04E+02
      C4      2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 1.03E+02


        OVER PRESSURE( 6)=     24.000
        ---------------

 COMPONENT     V          D          TO        EO         PC        RS         R
 --------------------------------------------------------------------------------
      C1      2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 1.36E+02
      C2      2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 1.33E+02
      C3      2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 1.32E+02
      C4      2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 1.32E+02


        OVER PRESSURE( 7)=     20.700
        ---------------

 COMPONENT     V          D          TO        EO         PC        RS         R
 --------------------------------------------------------------------------------
```

```
    C1      2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 1.50E+02
    C2      2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 1.47E+02
    C3      2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 1.46E+02
    C4      2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 1.45E+02


        OVER PRESSURE( 8)=     17.300
        ---------------


COMPONENT     V         D          TO         EO        PC        RS        R
-------------------------------------------------------------------------------
    C1      2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 1.69E+02
    C2      2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 1.66E+02
    C3      2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 1.65E+02
    C4      2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 1.64E+02


        OVER PRESSURE( 9)=     15.900
        ---------------


COMPONENT     V         D          TO         EO        PC        RS        R
-------------------------------------------------------------------------------
    C1      2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 1.79E+02
    C2      2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 1.75E+02
    C3      2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 1.74E+02
    C4      2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 1.73E+02


        OVER PRESSURE(10)=     13.800
        ---------------


COMPONENT     V         D          TO         EO        PC        RS        R
-------------------------------------------------------------------------------
    C1      2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 1.96E+02
    C2      2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 1.93E+02
    C3      2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 1.91E+02
    C4      2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 1.90E+02


        OVER PRESSURE(11)=     10.350
        ---------------
```

```
COMPONENT     V          D            TO         EO         PC         RS         R
---------------------------------------------------------------------------------------
   C1     2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 2.38E+02
   C2     2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 2.34E+02
   C3     2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 2.32E+02
   C4     2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 2.31E+02


       OVER PRESSURE(12)=      6.900
       -----------------

COMPONENT     V          D            TO         EO         PC         RS         R
---------------------------------------------------------------------------------------
   C1     2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 3.11E+02
   C2     2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 3.06E+02
   C3     2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 3.04E+02
   C4     2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 3.02E+02


       OVER PRESSURE(13)=      4.800
       -----------------

COMPONENT     V          D            TO         EO         PC         RS         R
---------------------------------------------------------------------------------------
   C1     2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 3.97E+02
   C2     2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 3.90E+02
   C3     2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 3.87E+02
   C4     2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 3.85E+02


       OVER PRESSURE(14)=      2.760
       -----------------

COMPONENT     V          D            TO         EO         PC         RS         R
---------------------------------------------------------------------------------------
   C1     2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 5.74E+02
   C2     2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 5.64E+02
   C3     2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 5.59E+02
   C4     2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 5.57E+02


       OVER PRESSURE(15)=      2.000
       -----------------
```

```
COMPONENT     V          D            TO          EO           PC          RS           R
-----------------------------------------------------------------------------------------------
   C1      2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 7.11E+02
   C2      2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 6.99E+02
   C3      2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 6.93E+02
   C4      2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 6.90E+02


        OVER PRESSURE(16)=      1.000
        -----------------

COMPONENT     V          D            TO          EO           PC          RS           R
-----------------------------------------------------------------------------------------------
   C1      2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 1.13E+03
   C2      2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 1.11E+03
   C3      2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 1.10E+03
   C4      2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 1.10E+03


        OVER PRESSURE(17)=      0.700
        -----------------

COMPONENT     V          D            TO          EO           PC          RS           R
-----------------------------------------------------------------------------------------------
   C1      2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 1.43E+03
   C2      2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 1.41E+03
   C3      2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 1.40E+03
   C4      2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 1.39E+03


        OVER PRESSURE(18)=      0.200
        -----------------

COMPONENT     V          D            TO          EO           PC          RS           R
-----------------------------------------------------------------------------------------------
   C1      2.95E+05 1.04E+02 3.15E-01 1.00E+06 4.97E+06 9.96E+00 3.30E+03
   C2      2.64E+05 1.00E+02 3.04E-01 9.52E+05 5.47E+06 9.05E+00 3.24E+03
   C3      2.53E+05 9.88E+01 2.99E-01 9.29E+05 5.65E+06 8.75E+00 3.22E+03
   C4      2.47E+05 9.80E+01 2.97E-01 9.16E+05 5.75E+06 8.61E+00 3.20E+03
```

```
      MASS OF FLAMMABLE GAS IN THE CLOUD( 5)=  30000.0
      ---------------------------------------------


      OVER PRESSURE( 1)=     69.000
      ---------------


COMPONENT     V         D          TO        EO        PC        RS        R
----------------------------------------------------------------------------------
  C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 7.68E+01
  C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 7.55E+01
  C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 7.49E+01
  C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 7.45E+01


      OVER PRESSURE( 2)=     50.000
      ---------------


COMPONENT     V         D          TO        EO        PC        RS        R
----------------------------------------------------------------------------------
  C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 9.52E+01
  C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 9.36E+01
  C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 9.28E+01
  C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 9.24E+01


      OVER PRESSURE( 3)=     48.300
      ---------------


COMPONENT     V         D          TO        EO        PC        RS        R
----------------------------------------------------------------------------------
  C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 9.74E+01
  C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 9.58E+01
  C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 9.50E+01
  C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 9.45E+01


      OVER PRESSURE( 4)=     42.000
      ---------------


COMPONENT     V         D          TO        EO        PC        RS        R
----------------------------------------------------------------------------------
  C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 1.07E+02
  C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 1.05E+02
```

```
   C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 1.04E+02
   C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 1.04E+02


      OVER PRESSURE( 5)=    34.500
      ---------------


COMPONENT    V        D          TO       EO       PC       RS       R
-------------------------------------------------------------------------
   C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 1.22E+02
   C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 1.20E+02
   C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 1.19E+02
   C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 1.18E+02


      OVER PRESSURE( 6)=    24.000
      ---------------


COMPONENT    V        D          TO       EO       PC       RS       R
-------------------------------------------------------------------------
   C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 1.55E+02
   C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 1.53E+02
   C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 1.51E+02
   C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 1.51E+02


      OVER PRESSURE( 7)=    20.700
      ---------------


COMPONENT    V        D          TO       EO       PC       RS       R
-------------------------------------------------------------------------
   C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 1.71E+02
   C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 1.68E+02
   C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 1.67E+02
   C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 1.66E+02


      OVER PRESSURE( 8)=    17.300
      ---------------


COMPONENT    V        D          TO       EO       PC       RS       R
-------------------------------------------------------------------------
```

```
   C1     4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 1.93E+02
   C2     3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 1.90E+02
   C3     3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 1.88E+02
   C4     3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 1.87E+02



      OVER PRESSURE( 9)=     15.900
      ----------------

COMPONENT     V         D         TO        EO        PC        RS        R
-------------------------------------------------------------------------------
   C1     4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 2.04E+02
   C2     3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 2.01E+02
   C3     3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 1.99E+02
   C4     3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 1.98E+02



      OVER PRESSURE(10)=     13.800
      ----------------

COMPONENT     V         D         TO        EO        PC        RS        R
-------------------------------------------------------------------------------
   C1     4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 2.25E+02
   C2     3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 2.21E+02
   C3     3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 2.19E+02
   C4     3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 2.18E+02



      OVER PRESSURE(11)=     10.350
      ----------------

COMPONENT     V         D         TO        EO        PC        RS        R
-------------------------------------------------------------------------------
   C1     4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 2.72E+02
   C2     3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 2.67E+02
   C3     3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 2.65E+02
   C4     3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 2.64E+02



      OVER PRESSURE(12)=     6.900
      ----------------
```

```
COMPONENT     V          D              TO        EO          PC         RS         R
-----------------------------------------------------------------------------------------
  C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 3.57E+02
  C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 3.50E+02
  C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 3.48E+02
  C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 3.46E+02


      OVER PRESSURE(13)=       4.800
      ---------------

COMPONENT     V          D              TO        EO          PC         RS         R
-----------------------------------------------------------------------------------------
  C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 4.54E+02
  C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 4.46E+02
  C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 4.43E+02
  C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 4.41E+02


      OVER PRESSURE(14)=       2.760
      ---------------

COMPONENT     V          D              TO        EO          PC         RS         R
-----------------------------------------------------------------------------------------
  C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 6.57E+02
  C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 6.45E+02
  C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 6.40E+02
  C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 6.37E+02


      OVER PRESSURE(15)=       2.000
      ---------------

COMPONENT     V          D              TO        EO          PC         RS         R
-----------------------------------------------------------------------------------------
  C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 8.14E+02
  C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 8.00E+02
  C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 7.94E+02
  C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 7.90E+02


      OVER PRESSURE(16)=       1.000
      ---------------
```

```
COMPONENT     V          D          TO         EO         PC         RS         R
-------------------------------------------------------------------------------------
  C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 1.29E+03
  C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 1.27E+03
  C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 1.26E+03
  C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 1.25E+03


     OVER PRESSURE(17)=     0.700
     -----------------

COMPONENT     V          D          TO         EO         PC         RS         R
-------------------------------------------------------------------------------------
  C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 1.64E+03
  C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 1.61E+03
  C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 1.60E+03
  C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 1.59E+03


     OVER PRESSURE(18)=     0.200
     -----------------

COMPONENT     V          D          TO         EO         PC         RS         R
-------------------------------------------------------------------------------------
  C1      4.42E+05 1.19E+02 3.61E-01 1.50E+06 4.34E+06 1.14E+01 3.78E+03
  C2      3.96E+05 1.15E+02 3.48E-01 1.43E+06 4.78E+06 1.04E+01 3.71E+03
  C3      3.79E+05 1.13E+02 3.43E-01 1.39E+06 4.94E+06 1.00E+01 3.68E+03
  C4      3.70E+05 1.12E+02 3.40E-01 1.37E+06 5.02E+06 9.86E+00 3.67E+03




     MASS OF FLAMMABLE GAS IN THE CLOUD( 6)=  40000.0
     ---------------------------------------


     OVER PRESSURE( 1)=    69.000
     -----------------

COMPONENT     V          D          TO         EO         PC         RS         R
-------------------------------------------------------------------------------------
  C1      5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 8.45E+01
  C2      5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 8.31E+01
```

```
    C3       5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 8.24E+01
    C4       4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 8.20E+01


       OVER PRESSURE( 2)=     50.000
       -----------------

COMPONENT      V         D           TO        EO         PC        RS         R
----------------------------------------------------------------------------------
    C1       5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 1.05E+02
    C2       5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 1.03E+02
    C3       5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 1.02E+02
    C4       4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 1.02E+02


       OVER PRESSURE( 3)=     48.300
       -----------------

COMPONENT      V         D           TO        EO         PC        RS         R
----------------------------------------------------------------------------------
    C1       5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 1.07E+02
    C2       5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 1.05E+02
    C3       5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 1.05E+02
    C4       4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 1.04E+02


       OVER PRESSURE( 4)=     42.000
       -----------------

COMPONENT      V         D           TO        EO         PC        RS         R
----------------------------------------------------------------------------------
    C1       5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 1.18E+02
    C2       5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 1.16E+02
    C3       5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 1.15E+02
    C4       4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 1.14E+02


       OVER PRESSURE( 5)=     34.500
       -----------------

COMPONENT      V         D           TO        EO         PC        RS         R
----------------------------------------------------------------------------------
```

```
  C1     5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 1.34E+02
  C2     5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 1.32E+02
  C3     5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 1.31E+02
  C4     4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 1.30E+02


       OVER PRESSURE( 6)=    24.000
       ---------------

COMPONENT    V        D          TO       EO        PC       RS       R
------------------------------------------------------------------------
  C1     5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 1.71E+02
  C2     5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 1.68E+02
  C3     5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 1.67E+02
  C4     4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 1.66E+02


       OVER PRESSURE( 7)=    20.700
       ---------------

COMPONENT    V        D          TO       EO        PC       RS       R
------------------------------------------------------------------------
  C1     5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 1.89E+02
  C2     5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 1.85E+02
  C3     5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 1.84E+02
  C4     4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 1.83E+02


       OVER PRESSURE( 8)=    17.300
       ---------------

COMPONENT    V        D          TO       EO        PC       RS       R
------------------------------------------------------------------------
  C1     5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 2.13E+02
  C2     5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 2.09E+02
  C3     5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 2.07E+02
  C4     4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 2.06E+02


       OVER PRESSURE( 9)=    15.900
       ---------------
```

```
COMPONENT     V          D              TO        EO          PC          RS          R
-------------------------------------------------------------------------------------------
   C1      5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 2.25E+02
   C2      5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 2.21E+02
   C3      5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 2.19E+02
   C4      4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 2.18E+02


      OVER PRESSURE(10)=      13.800
      ------------------

COMPONENT     V          D              TO        EO          PC          RS          R
-------------------------------------------------------------------------------------------
   C1      5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 2.47E+02
   C2      5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 2.43E+02
   C3      5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 2.41E+02
   C4      4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 2.40E+02


      OVER PRESSURE(11)=      10.350
      ------------------

COMPONENT     V          D              TO        EO          PC          RS          R
-------------------------------------------------------------------------------------------
   C1      5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 2.99E+02
   C2      5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 2.94E+02
   C3      5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 2.92E+02
   C4      4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 2.91E+02


      OVER PRESSURE(12)=      6.900
      ------------------

COMPONENT     V          D              TO        EO          PC          RS          R
-------------------------------------------------------------------------------------------
   C1      5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 3.92E+02
   C2      5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 3.86E+02
   C3      5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 3.83E+02
   C4      4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 3.81E+02


      OVER PRESSURE(13)=      4.800
      ------------------
```

```
COMPONENT     V          D            TO          EO         PC         RS         R
--------------------------------------------------------------------------------------
   C1     5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 5.00E+02
   C2     5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 4.91E+02
   C3     5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 4.87E+02
   C4     4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 4.85E+02


      OVER PRESSURE(14)=      2.760
      ---------------

COMPONENT     V          D            TO          EO         PC         RS         R
--------------------------------------------------------------------------------------
   C1     5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 7.23E+02
   C2     5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 7.10E+02
   C3     5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 7.05E+02
   C4     4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 7.01E+02


      OVER PRESSURE(15)=      2.000
      ---------------

COMPONENT     V          D            TO          EO         PC         RS         R
--------------------------------------------------------------------------------------
   C1     5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 8.96E+02
   C2     5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 8.81E+02
   C3     5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 8.73E+02
   C4     4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 8.69E+02


      OVER PRESSURE(16)=      1.000
      ---------------

COMPONENT     V          D            TO          EO         PC         RS         R
--------------------------------------------------------------------------------------
   C1     5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 1.42E+03
   C2     5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 1.40E+03
   C3     5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 1.39E+03
   C4     4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 1.38E+03


      OVER PRESSURE(17)=      0.700
      ---------------
```

```
COMPONENT     V          D           TO         EO         PC         RS         R
-------------------------------------------------------------------------------------
   C1     5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 1.80E+03
   C2     5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 1.77E+03
   C3     5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 1.76E+03
   C4     4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 1.75E+03


      OVER PRESSURE(18)=      0.200
      -----------------

COMPONENT     V          D           TO         EO         PC         RS         R
-------------------------------------------------------------------------------------
   C1     5.89E+05 1.31E+02 3.97E-01 2.01E+06 3.95E+06 1.25E+01 4.16E+03
   C2     5.27E+05 1.26E+02 3.83E-01 1.90E+06 4.34E+06 1.14E+01 4.09E+03
   C3     5.05E+05 1.24E+02 3.77E-01 1.86E+06 4.49E+06 1.10E+01 4.05E+03
   C4     4.94E+05 1.23E+02 3.74E-01 1.83E+06 4.56E+06 1.08E+01 4.04E+03




      MASS OF FLAMMABLE GAS IN THE CLOUD( 7)=  50000.0
      -----------------------------------------

      OVER PRESSURE( 1)=     69.000
      -----------------

COMPONENT     V          D           TO         EO         PC         RS         R
-------------------------------------------------------------------------------------
   C1     7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 9.11E+01
   C2     6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 8.95E+01
   C3     6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 8.88E+01
   C4     6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 8.84E+01


      OVER PRESSURE( 2)=     50.000
      -----------------

COMPONENT     V          D           TO         EO         PC         RS         R
-------------------------------------------------------------------------------------
   C1     7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 1.13E+02
   C2     6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 1.11E+02
```

```
   C3      6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 1.10E+02
   C4      6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 1.10E+02



       OVER PRESSURE( 3)=    48.300
       ----------------

COMPONENT     V         D           TO       EO        PC       RS        R
-----------------------------------------------------------------------------
   C1      7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 1.16E+02
   C2      6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 1.14E+02
   C3      6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 1.13E+02
   C4      6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 1.12E+02



       OVER PRESSURE( 4)=    42.000
       ----------------

COMPONENT     V         D           TO       EO        PC       RS        R
-----------------------------------------------------------------------------
   C1      7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 1.27E+02
   C2      6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 1.25E+02
   C3      6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 1.24E+02
   C4      6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 1.23E+02



       OVER PRESSURE( 5)=    34.500
       ----------------

COMPONENT     V         D           TO       EO        PC       RS        R
-----------------------------------------------------------------------------
   C1      7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 1.45E+02
   C2      6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 1.42E+02
   C3      6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 1.41E+02
   C4      6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 1.40E+02



       OVER PRESSURE( 6)=    24.000
       ----------------

COMPONENT     V         D           TO       EO        PC       RS        R
-----------------------------------------------------------------------------
```

```
C1        7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 1.84E+02
C2        6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 1.81E+02
C3        6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 1.80E+02
C4        6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 1.79E+02


     OVER PRESSURE( 7)=     20.700
     ---------------

COMPONENT     V          D          TO        EO        PC        RS        R
-------------------------------------------------------------------------------
  C1      7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 2.03E+02
  C2      6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 2.00E+02
  C3      6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 1.98E+02
  C4      6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 1.97E+02


     OVER PRESSURE( 8)=     17.300
     ---------------

COMPONENT     V          D          TO        EO        PC        RS        R
-------------------------------------------------------------------------------
  C1      7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 2.29E+02
  C2      6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 2.25E+02
  C3      6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 2.23E+02
  C4      6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 2.22E+02


     OVER PRESSURE( 9)=     15.900
     ---------------

COMPONENT     V          D          TO        EO        PC        RS        R
-------------------------------------------------------------------------------
  C1      7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 2.42E+02
  C2      6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 2.38E+02
  C3      6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 2.36E+02
  C4      6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 2.35E+02


     OVER PRESSURE(10)=     13.800
     ---------------
```

```
COMPONENT     V          D           TO          EO          PC         RS          R
-----------------------------------------------------------------------------------------
   C1     7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 2.66E+02
   C2     6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 2.62E+02
   C3     6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 2.60E+02
   C4     6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 2.58E+02



        OVER PRESSURE(11)=     10.350
        ---------------

COMPONENT     V          D           TO          EO          PC         RS          R
-----------------------------------------------------------------------------------------
   C1     7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 3.23E+02
   C2     6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 3.17E+02
   C3     6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 3.14E+02
   C4     6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 3.13E+02



        OVER PRESSURE(12)=     6.900
        ---------------

COMPONENT     V          D           TO          EO          PC         RS          R
-----------------------------------------------------------------------------------------
   C1     7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 4.23E+02
   C2     6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 4.15E+02
   C3     6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 4.12E+02
   C4     6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 4.10E+02



        OVER PRESSURE(13)=     4.800
        ---------------

COMPONENT     V          D           TO          EO          PC         RS          R
-----------------------------------------------------------------------------------------
   C1     7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 5.38E+02
   C2     6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 5.29E+02
   C3     6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 5.25E+02
   C4     6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 5.22E+02



        OVER PRESSURE(14)=     2.760
        ---------------
```

```
COMPONENT     V          D           TO         EO         PC         RS         R
------------------------------------------------------------------------------------------
  C1      7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 7.79E+02
  C2      6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 7.65E+02
  C3      6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 7.59E+02
  C4      6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 7.56E+02


      OVER PRESSURE(15)=      2.000
      ---------------

COMPONENT     V          D           TO         EO         PC         RS         R
------------------------------------------------------------------------------------------
  C1      7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 9.65E+02
  C2      6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 9.49E+02
  C3      6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 9.41E+02
  C4      6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 9.37E+02


      OVER PRESSURE(16)=      1.000
      ---------------

COMPONENT     V          D           TO         EO         PC         RS         R
------------------------------------------------------------------------------------------
  C1      7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 1.53E+03
  C2      6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 1.51E+03
  C3      6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 1.49E+03
  C4      6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 1.49E+03


      OVER PRESSURE(17)=      0.700
      ---------------

COMPONENT     V          D           TO         EO         PC         RS         R
------------------------------------------------------------------------------------------
  C1      7.36E+05 1.41E+02 4.28E-01 2.51E+06 3.66E+06 1.35E+01 1.94E+03
  C2      6.59E+05 1.36E+02 4.12E-01 2.38E+06 4.03E+06 1.23E+01 1.91E+03
  C3      6.31E+05 1.34E+02 4.06E-01 2.32E+06 4.17E+06 1.19E+01 1.89E+03
  C4      6.17E+05 1.33E+02 4.03E-01 2.29E+06 4.24E+06 1.17E+01 1.89E+03


      OVER PRESSURE(18)=      0.200
      ---------------
```

COMPONENT	V	D	TO	EO	PC	RS	R
C1	7.36E+05	1.41E+02	4.28E-01	2.51E+06	3.66E+06	1.35E+01	4.48E+03
C2	6.59E+05	1.36E+02	4.12E-01	2.38E+06	4.03E+06	1.23E+01	4.40E+03
C3	6.31E+05	1.34E+02	4.06E-01	2.32E+06	4.17E+06	1.19E+01	4.37E+03
C4	6.17E+05	1.33E+02	4.03E-01	2.29E+06	4.24E+06	1.17E+01	4.35E+03

APPENDIX M

Computer program for calculation of spacing distance using Clancey's model

```
C
C
C
C PROGRAM FOR CALCULATION OF SPACING DISTANCE USING CLANCEY MODEL.
C ================================================================
C
C
C
C
      DIMENSION W(100),F1(100),F2(100),C1(100),C2(100),QM(100),
     @RS(100),R(100),N(100),X(100),R1(100),RE(100),WTM(100)
C
C
       READ *,T
C
      PRINT 222
 222  FORMAT(//15X,'CLANCEY S MODEL RESULTS:'/,15X,23('*')//)
C
C
       READ *,(W(II),II=1,7)
       READ *,(RS(NN),NN=1,18)
C
         READ *,(N(KK),F1(KK),F2(KK),WTM(KK),KK=1,4)
C
C
      DO 3 I=1,7
C
      PRINT 100,I,W(I)
 100  FORMAT(10X,'MASS OF FLAMMABLE GAS IN THE CLOUD(',I2,')=',F9.1,
     @/10X,40('-')//)
C
C
      DO 6 L=1,18
C
       PRINT 155,L,RS(L)
 155  FORMAT(10X,'SCALED RANGE (',I2,')=',F10.3,/,10X,16('-'))
C
      PRINT 150
 150  FORMAT(3X,' COMPONENT     C1       C2        QM      X      ',
     @'   R1        RE          R',/,4X,72('-'))
C
C
C
      DO 8 J=1,4
C
      C1(J)=(12.187*F1(J)*WTM(J))/T
      C2(J)=(12.187*F2(J)*WTM(J))/T
      QM(J)=0.5*((W(I)/C2(J))**0.333)
      X(J)=(10.0*QM(J))**1.14
      R1(J)=0.71*((W(I)/C2(J))**0.333)*((ALOG(C2(J)/C1(J)))**0.5)
      RE(J)=2.0*R1(J)
       R(J)=(RE(J)*RS(L))/0.48
C
C
```

```
      PRINT 200,N(J),C1(J),C2(J),QM(J),X(J),R1(J),RE(J),R(J)
 200  FORMAT(7X,'C',I1,5X,7(F8.2,1X))
C
  8    CONTINUE
C
       PRINT 220
 220   FORMAT(10X,///)
C
  6     CONTINUE
C
         PRINT 230
 230   FORMAT(10X,///)
C
C
  3     CONTINUE
C
         STOP
        END
```

```
          CLANCEY S MODEL RESULTS:
          ***********************


      MASS OF FLAMMABLE GAS IN THE CLOUD( 1)=    1000.0
      ----------------------------------------


      SCALED RANGE ( 1)=      0.480
      ----------------
COMPONENT     C1        C2         QM       X          R1        RE        R
-------------------------------------------------------------------------------
   C1        0.03      0.10      10.75    206.82     15.99     31.99     31.99
   C2        0.04      0.16       9.26    174.59     15.35     30.70     30.70
   C3        0.04      0.17       8.93    167.54     14.88     29.76     29.76
   C4        0.05      0.20       8.49    158.07     14.70     29.39     29.39


      SCALED RANGE ( 2)=      0.660
      ----------------
COMPONENT     C1        C2         QM       X          R1        RE        R
-------------------------------------------------------------------------------
   C1        0.03      0.10      10.75    206.82     15.99     31.99     43.98
   C2        0.04      0.16       9.26    174.59     15.35     30.70     42.22
   C3        0.04      0.17       8.93    167.54     14.88     29.76     40.92
   C4        0.05      0.20       8.49    158.07     14.70     29.39     40.41


      SCALED RANGE ( 3)=      0.670
      ----------------
COMPONENT     C1        C2         QM       X          R1        RE        R
-------------------------------------------------------------------------------
   C1        0.03      0.10      10.75    206.82     15.99     31.99     44.65
   C2        0.04      0.16       9.26    174.59     15.35     30.70     42.86
   C3        0.04      0.17       8.93    167.54     14.88     29.76     41.54
   C4        0.05      0.20       8.49    158.07     14.70     29.39     41.02


      SCALED RANGE ( 4)=      0.700
      ----------------
COMPONENT     C1        C2         QM       X          R1        RE        R
-------------------------------------------------------------------------------
   C1        0.03      0.10      10.75    206.82     15.99     31.99     46.65
   C2        0.04      0.16       9.26    174.59     15.35     30.70     44.78
   C3        0.04      0.17       8.93    167.54     14.88     29.76     43.39
   C4        0.05      0.20       8.49    158.07     14.70     29.39     42.86
```

```
     SCALED RANGE ( 5)=      0.750
     ----------------
COMPONENT      C1        C2        QM        X         R1        RE        R
-------------------------------------------------------------------------------
   C1         0.03      0.10     10.75    206.82     15.99     31.99     49.98
   C2         0.04      0.16      9.26    174.59     15.35     30.70     47.97
   C3         0.04      0.17      8.93    167.54     14.88     29.76     46.49
   C4         0.05      0.20      8.49    158.07     14.70     29.39     45.92


     SCALED RANGE ( 6)=      0.900
     ----------------
COMPONENT      C1        C2        QM        X         R1        RE        R
-------------------------------------------------------------------------------
   C1         0.03      0.10     10.75    206.82     15.99     31.99     59.97
   C2         0.04      0.16      9.26    174.59     15.35     30.70     57.57
   C3         0.04      0.17      8.93    167.54     14.88     29.76     55.79
   C4         0.05      0.20      8.49    158.07     14.70     29.39     55.11


     SCALED RANGE ( 7)=      0.980
     ----------------
COMPONENT      C1        C2        QM        X         R1        RE        R
-------------------------------------------------------------------------------
   C1         0.03      0.10     10.75    206.82     15.99     31.99     65.31
   C2         0.04      0.16      9.26    174.59     15.35     30.70     62.69
   C3         0.04      0.17      8.93    167.54     14.88     29.76     60.75
   C4         0.05      0.20      8.49    158.07     14.70     29.39     60.01


     SCALED RANGE ( 8)=      1.090
     ----------------
COMPONENT      C1        C2        QM        X         R1        RE        R
-------------------------------------------------------------------------------
   C1         0.03      0.10     10.75    206.82     15.99     31.99     72.64
   C2         0.04      0.16      9.26    174.59     15.35     30.70     69.72
   C3         0.04      0.17      8.93    167.54     14.88     29.76     67.57
   C4         0.05      0.20      8.49    158.07     14.70     29.39     66.74


     SCALED RANGE ( 9)=      1.120
     ----------------
COMPONENT      C1        C2        QM        X         R1        RE        R
-------------------------------------------------------------------------------
   C1         0.03      0.10     10.75    206.82     15.99     31.99     74.63
   C2         0.04      0.16      9.26    174.59     15.35     30.70     71.64
```

C3	0.04	0.17	8.93	167.54	14.88	29.76	69.43
C4	0.05	0.20	8.49	158.07	14.70	29.39	68.58

SCALED RANGE (10)= 1.210

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	10.75	206.82	15.99	31.99	80.63
C2	0.04	0.16	9.26	174.59	15.35	30.70	77.40
C3	0.04	0.17	8.93	167.54	14.88	29.76	75.01
C4	0.05	0.20	8.49	158.07	14.70	29.39	74.09

SCALED RANGE (11)= 1.530

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	10.75	206.82	15.99	31.99	101.96
C2	0.04	0.16	9.26	174.59	15.35	30.70	97.87
C3	0.04	0.17	8.93	167.54	14.88	29.76	94.85
C4	0.05	0.20	8.49	158.07	14.70	29.39	93.68

SCALED RANGE (12)= 2.100

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	10.75	206.82	15.99	31.99	139.94
C2	0.04	0.16	9.26	174.59	15.35	30.70	134.33
C3	0.04	0.17	8.93	167.54	14.88	29.76	130.18
C4	0.05	0.20	8.49	158.07	14.70	29.39	128.58

SCALED RANGE (13)= 2.800

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	10.75	206.82	15.99	31.99	186.59
C2	0.04	0.16	9.26	174.59	15.35	30.70	179.10
C3	0.04	0.17	8.93	167.54	14.88	29.76	173.58
C4	0.05	0.20	8.49	158.07	14.70	29.39	171.45

```
        SCALED RANGE (14)=      4.300
        -----------------
COMPONENT     C1        C2        QM        X         R1        RE        R
-------------------------------------------------------------------------------
    C1        0.03      0.10      10.75     206.82    15.99     31.99     286.54
    C2        0.04      0.16       9.26     174.59    15.35     30.70     275.05
    C3        0.04      0.17       8.93     167.54    14.88     29.76     266.57
    C4        0.05      0.20       8.49     158.07    14.70     29.39     263.29


        SCALED RANGE (15)=      5.600
        -----------------
COMPONENT     C1        C2        QM        X         R1        RE        R
-------------------------------------------------------------------------------
    C1        0.03      0.10      10.75     206.82    15.99     31.99     373.17
    C2        0.04      0.16       9.26     174.59    15.35     30.70     358.20
    C3        0.04      0.17       8.93     167.54    14.88     29.76     347.16
    C4        0.05      0.20       8.49     158.07    14.70     29.39     342.89


        SCALED RANGE (16)=      9.600
        -----------------
COMPONENT     C1        C2        QM        X         R1        RE        R
-------------------------------------------------------------------------------
    C1        0.03      0.10      10.75     206.82    15.99     31.99     639.73
    C2        0.04      0.16       9.26     174.59    15.35     30.70     614.06
    C3        0.04      0.17       8.93     167.54    14.88     29.76     595.13
    C4        0.05      0.20       8.49     158.07    14.70     29.39     587.81


        SCALED RANGE (17)=     13.000
        -----------------
COMPONENT     C1        C2        QM        X         R1        RE        R
-------------------------------------------------------------------------------
    C1        0.03      0.10      10.75     206.82    15.99     31.99     866.29
    C2        0.04      0.16       9.26     174.59    15.35     30.70     831.54
    C3        0.04      0.17       8.93     167.54    14.88     29.76     805.90
    C4        0.05      0.20       8.49     158.07    14.70     29.39     796.00


        SCALED RANGE (18)=     34.000
        -----------------
COMPONENT     C1        C2        QM        X         R1        RE        R
-------------------------------------------------------------------------------
    C1        0.03      0.10      10.75     206.82    15.99     31.99    2265.69
    C2        0.04      0.16       9.26     174.59    15.35     30.70    2174.79
```

```
    C3          0.04     0.17      8.93   167.54     14.88     29.76  2107.75
    C4          0.05     0.20      8.49   158.07     14.70     29.39  2081.84




       MASS OF FLAMMABLE GAS IN THE CLOUD( 2)=   5000.0
       -----------------------------------------------

       SCALED RANGE ( 1)=     0.480
       ------------------
COMPONENT       C1        C2        QM       X         R1        RE         R
-------------------------------------------------------------------------------
    C1          0.03     0.10     18.36   381.01     27.33     54.67     54.67
    C2          0.04     0.16     15.83   321.63     26.24     52.47     52.47
    C3          0.04     0.17     15.27   308.65     25.43     50.86     50.86
    C4          0.05     0.20     14.51   291.21     25.12     50.23     50.23


       SCALED RANGE ( 2)=     0.660
       ------------------
COMPONENT       C1        C2        QM       X         R1        RE         R
-------------------------------------------------------------------------------
    C1          0.03     0.10     18.36   381.01     27.33     54.67     75.17
    C2          0.04     0.16     15.83   321.63     26.24     52.47     72.15
    C3          0.04     0.17     15.27   308.65     25.43     50.86     69.93
    C4          0.05     0.20     14.51   291.21     25.12     50.23     69.07


       SCALED RANGE ( 3)=     0.670
       ------------------
COMPONENT       C1        C2        QM       X         R1        RE         R
-------------------------------------------------------------------------------
    C1          0.03     0.10     18.36   381.01     27.33     54.67     76.31
    C2          0.04     0.16     15.83   321.63     26.24     52.47     73.24
    C3          0.04     0.17     15.27   308.65     25.43     50.86     70.99
    C4          0.05     0.20     14.51   291.21     25.12     50.23     70.11


       SCALED RANGE ( 4)=     0.700
       ------------------
COMPONENT       C1        C2        QM       X         R1        RE         R
-------------------------------------------------------------------------------
```

C1	0.03	0.10	18.36	381.01	27.33	54.67	79.72
C2	0.04	0.16	15.83	321.63	26.24	52.47	76.52
C3	0.04	0.17	15.27	308.65	25.43	50.86	74.16
C4	0.05	0.20	14.51	291.21	25.12	50.23	73.25

SCALED RANGE (5)= 0.750

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	85.42
C2	0.04	0.16	15.83	321.63	26.24	52.47	81.99
C3	0.04	0.17	15.27	308.65	25.43	50.86	79.46
C4	0.05	0.20	14.51	291.21	25.12	50.23	78.49

SCALED RANGE (6)= 0.900

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	102.50
C2	0.04	0.16	15.83	321.63	26.24	52.47	98.39
C3	0.04	0.17	15.27	308.65	25.43	50.86	95.35
C4	0.05	0.20	14.51	291.21	25.12	50.23	94.18

SCALED RANGE (7)= 0.980

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	111.61
C2	0.04	0.16	15.83	321.63	26.24	52.47	107.13
C3	0.04	0.17	15.27	308.65	25.43	50.86	103.83
C4	0.05	0.20	14.51	291.21	25.12	50.23	102.55

SCALED RANGE (8)= 1.090

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	124.14
C2	0.04	0.16	15.83	321.63	26.24	52.47	119.16
C3	0.04	0.17	15.27	308.65	25.43	50.86	115.48
C4	0.05	0.20	14.51	291.21	25.12	50.23	114.06

SCALED RANGE (9)= 1.120

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	127.55
C2	0.04	0.16	15.83	321.63	26.24	52.47	122.44
C3	0.04	0.17	15.27	308.65	25.43	50.86	118.66
C4	0.05	0.20	14.51	291.21	25.12	50.23	117.20

SCALED RANGE (10)= 1.210

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	137.80
C2	0.04	0.16	15.83	321.63	26.24	52.47	132.28
C3	0.04	0.17	15.27	308.65	25.43	50.86	128.20
C4	0.05	0.20	14.51	291.21	25.12	50.23	126.62

SCALED RANGE (11)= 1.530

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	174.25
C2	0.04	0.16	15.83	321.63	26.24	52.47	167.26
C3	0.04	0.17	15.27	308.65	25.43	50.86	162.10
C4	0.05	0.20	14.51	291.21	25.12	50.23	160.11

SCALED RANGE (12)= 2.100

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	239.17
C2	0.04	0.16	15.83	321.63	26.24	52.47	229.57
C3	0.04	0.17	15.27	308.65	25.43	50.86	222.49
C4	0.05	0.20	14.51	291.21	25.12	50.23	219.76

SCALED RANGE (13)= 2.800

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	318.89
C2	0.04	0.16	15.83	321.63	26.24	52.47	306.09

C3	0.04	0.17	15.27	308.65	25.43	50.86	296.66
C4	0.05	0.20	14.51	291.21	25.12	50.23	293.01

SCALED RANGE (14)= 4.300

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	489.72
C2	0.04	0.16	15.83	321.63	26.24	52.47	470.07
C3	0.04	0.17	15.27	308.65	25.43	50.86	455.58
C4	0.05	0.20	14.51	291.21	25.12	50.23	449.98

SCALED RANGE (15)= 5.600

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	637.77
C2	0.04	0.16	15.83	321.63	26.24	52.47	612.19
C3	0.04	0.17	15.27	308.65	25.43	50.86	593.31
C4	0.05	0.20	14.51	291.21	25.12	50.23	586.02

SCALED RANGE (16)= 9.600

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	1093.33
C2	0.04	0.16	15.83	321.63	26.24	52.47	1049.46
C3	0.04	0.17	15.27	308.65	25.43	50.86	1017.11
C4	0.05	0.20	14.51	291.21	25.12	50.23	1004.61

SCALED RANGE (17)= 13.000

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	18.36	381.01	27.33	54.67	1480.55
C2	0.04	0.16	15.83	321.63	26.24	52.47	1421.15
C3	0.04	0.17	15.27	308.65	25.43	50.86	1377.34
C4	0.05	0.20	14.51	291.21	25.12	50.23	1360.41

```
        SCALED RANGE (18)=     34.000
        ----------------
COMPONENT        C1         C2          QM        X          R1         RE         R
--------------------------------------------------------------------------------------
   C1           0.03       0.10       18.36     381.01      27.33      54.67   3872.20
   C2           0.04       0.16       15.83     321.63      26.24      52.47   3716.85
   C3           0.04       0.17       15.27     308.65      25.43      50.86   3602.27
   C4           0.05       0.20       14.51     291.21      25.12      50.23   3557.99




        MASS OF FLAMMABLE GAS IN THE CLOUD( 3)=  10000.0
        ------------------------------------------------


        SCALED RANGE ( 1)=     0.480
        ----------------
COMPONENT        C1         C2          QM        X          R1         RE         R
--------------------------------------------------------------------------------------
   C1           0.03       0.10       23.13     495.69      34.43      68.86     68.86
   C2           0.04       0.16       19.94     418.44      33.05      66.10     66.10
   C3           0.04       0.17       19.23     401.55      32.03      64.06     64.06
   C4           0.05       0.20       18.27     378.86      31.64      63.27     63.27


        SCALED RANGE ( 2)=     0.660
        ----------------
COMPONENT        C1         C2          QM        X          R1         RE         R
--------------------------------------------------------------------------------------
   C1           0.03       0.10       23.13     495.69      34.43      68.86     94.68
   C2           0.04       0.16       19.94     418.44      33.05      66.10     90.88
   C3           0.04       0.17       19.23     401.55      32.03      64.06     88.08
   C4           0.05       0.20       18.27     378.86      31.64      63.27     87.00


        SCALED RANGE ( 3)=     0.670
        ----------------
COMPONENT        C1         C2          QM        X          R1         RE         R
--------------------------------------------------------------------------------------
   C1           0.03       0.10       23.13     495.69      34.43      68.86     96.12
   C2           0.04       0.16       19.94     418.44      33.05      66.10     92.26
   C3           0.04       0.17       19.23     401.55      32.03      64.06     89.42
   C4           0.05       0.20       18.27     378.86      31.64      63.27     88.32
```

SCALED RANGE (4)= 0.700

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	23.13	495.69	34.43	68.86	100.42
C2	0.04	0.16	19.94	418.44	33.05	66.10	96.39
C3	0.04	0.17	19.23	401.55	32.03	64.06	93.42
C4	0.05	0.20	18.27	378.86	31.64	63.27	92.27

SCALED RANGE (5)= 0.750

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	23.13	495.69	34.43	68.86	107.59
C2	0.04	0.16	19.94	418.44	33.05	66.10	103.28
C3	0.04	0.17	19.23	401.55	32.03	64.06	100.09
C4	0.05	0.20	18.27	378.86	31.64	63.27	98.86

SCALED RANGE (6)= 0.900

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	23.13	495.69	34.43	68.86	129.11
C2	0.04	0.16	19.94	418.44	33.05	66.10	123.93
C3	0.04	0.17	19.23	401.55	32.03	64.06	120.11
C4	0.05	0.20	18.27	378.86	31.64	63.27	118.63

SCALED RANGE (7)= 0.980

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	23.13	495.69	34.43	68.86	140.59
C2	0.04	0.16	19.94	418.44	33.05	66.10	134.95
C3	0.04	0.17	19.23	401.55	32.03	64.06	130.79
C4	0.05	0.20	18.27	378.86	31.64	63.27	129.18

SCALED RANGE (8)= 1.090

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	23.13	495.69	34.43	68.86	156.37
C2	0.04	0.16	19.94	418.44	33.05	66.10	150.09

C3	0.04	0.17	19.23	401.55	32.03	64.06	145.47
C4	0.05	0.20	18.27	378.86	31.64	63.27	143.68

SCALED RANGE (9)= 1.120

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	23.13	495.69	34.43	68.86	160.67
C2	0.04	0.16	19.94	418.44	33.05	66.10	154.23
C3	0.04	0.17	19.23	401.55	32.03	64.06	149.47
C4	0.05	0.20	18.27	378.86	31.64	63.27	147.63

SCALED RANGE (10)= 1.210

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	23.13	495.69	34.43	68.86	173.58
C2	0.04	0.16	19.94	418.44	33.05	66.10	166.62
C3	0.04	0.17	19.23	401.55	32.03	64.06	161.48
C4	0.05	0.20	18.27	378.86	31.64	63.27	159.50

SCALED RANGE (11)= 1.530

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	23.13	495.69	34.43	68.86	219.49
C2	0.04	0.16	19.94	418.44	33.05	66.10	210.68
C3	0.04	0.17	19.23	401.55	32.03	64.06	204.19
C4	0.05	0.20	18.27	378.86	31.64	63.27	201.68

SCALED RANGE (12)= 2.100

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	23.13	495.69	34.43	68.86	301.26
C2	0.04	0.16	19.94	418.44	33.05	66.10	289.17
C3	0.04	0.17	19.23	401.55	32.03	64.06	280.26
C4	0.05	0.20	18.27	378.86	31.64	63.27	276.81

```
        SCALED RANGE (13)=       2.800
        -----------------
COMPONENT      C1        C2         QM        X         R1        RE        R
--------------------------------------------------------------------------------
   C1         0.03      0.10      23.13    495.69     34.43     68.86    401.68
   C2         0.04      0.16      19.94    418.44     33.05     66.10    385.56
   C3         0.04      0.17      19.23    401.55     32.03     64.06    373.68
   C4         0.05      0.20      18.27    378.86     31.64     63.27    369.09


        SCALED RANGE (14)=       4.300
        -----------------
COMPONENT      C1        C2         QM        X         R1        RE        R
--------------------------------------------------------------------------------
   C1         0.03      0.10      23.13    495.69     34.43     68.86    616.87
   C2         0.04      0.16      19.94    418.44     33.05     66.10    592.12
   C3         0.04      0.17      19.23    401.55     32.03     64.06    573.86
   C4         0.05      0.20      18.27    378.86     31.64     63.27    566.81


        SCALED RANGE (15)=       5.600
        -----------------
COMPONENT      C1        C2         QM        X         R1        RE        R
--------------------------------------------------------------------------------
   C1         0.03      0.10      23.13    495.69     34.43     68.86    803.36
   C2         0.04      0.16      19.94    418.44     33.05     66.10    771.13
   C3         0.04      0.17      19.23    401.55     32.03     64.06    747.36
   C4         0.05      0.20      18.27    378.86     31.64     63.27    738.17


        SCALED RANGE (16)=       9.600
        -----------------
COMPONENT      C1        C2         QM        X         R1        RE        R
--------------------------------------------------------------------------------
   C1         0.03      0.10      23.13    495.69     34.43     68.86   1377.19
   C2         0.04      0.16      19.94    418.44     33.05     66.10   1321.93
   C3         0.04      0.17      19.23    401.55     32.03     64.06   1281.18
   C4         0.05      0.20      18.27    378.86     31.64     63.27   1265.43


        SCALED RANGE (17)=      13.000
        -----------------
COMPONENT      C1        C2         QM        X         R1        RE        R
--------------------------------------------------------------------------------
   C1         0.03      0.10      23.13    495.69     34.43     68.86   1864.94
   C2         0.04      0.16      19.94    418.44     33.05     66.10   1790.12
```

```
     C3          0.04      0.17     19.23    401.55     32.03     64.06  1734.94
     C4          0.05      0.20     18.27    378.86     31.64     63.27  1713.61


          SCALED RANGE (18)=      34.000
          ----------------
COMPONENT        C1        C2         QM        X         R1        RE        R
-------------------------------------------------------------------------------
     C1          0.03      0.10     23.13    495.69     34.43     68.86  4877.54
     C2          0.04      0.16     19.94    418.44     33.05     66.10  4681.85
     C3          0.04      0.17     19.23    401.55     32.03     64.06  4537.52
     C4          0.05      0.20     18.27    378.86     31.64     63.27  4481.75




          MASS OF FLAMMABLE GAS IN THE CLOUD( 4)=  20000.0
          -------------------------------------------


          SCALED RANGE ( 1)=       0.480
          ----------------
COMPONENT        C1        C2         QM        X         R1        RE        R
-------------------------------------------------------------------------------
     C1          0.03      0.10     29.14    644.90     43.37     86.74     86.74
     C2          0.04      0.16     25.11    544.39     41.63     83.26     83.26
     C3          0.04      0.17     24.22    522.42     40.35     80.69     80.69
     C4          0.05      0.20     23.02    492.90     39.85     79.70     79.70


          SCALED RANGE ( 2)=       0.660
          ----------------
COMPONENT        C1        C2         QM        X         R1        RE        R
-------------------------------------------------------------------------------
     C1          0.03      0.10     29.14    644.90     43.37     86.74    119.26
     C2          0.04      0.16     25.11    544.39     41.63     83.26    114.48
     C3          0.04      0.17     24.22    522.42     40.35     80.69    110.95
     C4          0.05      0.20     23.02    492.90     39.85     79.70    109.59


          SCALED RANGE ( 3)=       0.670
          ----------------
COMPONENT        C1        C2         QM        X         R1        RE        R
-------------------------------------------------------------------------------
```

C1	0.03	0.10	29.14	644.90	43.37	86.74	121.07
C2	0.04	0.16	25.11	544.39	41.63	83.26	116.21
C3	0.04	0.17	24.22	522.42	40.35	80.69	112.63
C4	0.05	0.20	23.02	492.90	39.85	79.70	111.25

SCALED RANGE (4)= 0.700

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	126.49
C2	0.04	0.16	25.11	544.39	41.63	83.26	121.42
C3	0.04	0.17	24.22	522.42	40.35	80.69	117.67
C4	0.05	0.20	23.02	492.90	39.85	79.70	116.23

SCALED RANGE (5)= 0.750

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	135.53
C2	0.04	0.16	25.11	544.39	41.63	83.26	130.09
C3	0.04	0.17	24.22	522.42	40.35	80.69	126.08
C4	0.05	0.20	23.02	492.90	39.85	79.70	124.53

SCALED RANGE (6)= 0.900

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	162.63
C2	0.04	0.16	25.11	544.39	41.63	83.26	156.11
C3	0.04	0.17	24.22	522.42	40.35	80.69	151.30
C4	0.05	0.20	23.02	492.90	39.85	79.70	149.44

SCALED RANGE (7)= 0.980

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	177.09
C2	0.04	0.16	25.11	544.39	41.63	83.26	169.98
C3	0.04	0.17	24.22	522.42	40.35	80.69	164.74
C4	0.05	0.20	23.02	492.90	39.85	79.70	162.72

SCALED RANGE (8)= 1.090

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	196.97
C2	0.04	0.16	25.11	544.39	41.63	83.26	189.06
C3	0.04	0.17	24.22	522.42	40.35	80.69	183.24
C4	0.05	0.20	23.02	492.90	39.85	79.70	180.98

SCALED RANGE (9)= 1.120

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	202.39
C2	0.04	0.16	25.11	544.39	41.63	83.26	194.27
C3	0.04	0.17	24.22	522.42	40.35	80.69	188.28
C4	0.05	0.20	23.02	492.90	39.85	79.70	185.96

SCALED RANGE (10)= 1.210

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	218.65
C2	0.04	0.16	25.11	544.39	41.63	83.26	209.88
C3	0.04	0.17	24.22	522.42	40.35	80.69	203.41
C4	0.05	0.20	23.02	492.90	39.85	79.70	200.91

SCALED RANGE (11)= 1.530

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	276.48
C2	0.04	0.16	25.11	544.39	41.63	83.26	265.38
C3	0.04	0.17	24.22	522.42	40.35	80.69	257.20
C4	0.05	0.20	23.02	492.90	39.85	79.70	254.04

SCALED RANGE (12)= 2.100

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	379.48
C2	0.04	0.16	25.11	544.39	41.63	83.26	364.25

C3	0.04	0.17	24.22	522.42	40.35	80.69	353.02
C4	0.05	0.20	23.02	492.90	39.85	79.70	348.68

SCALED RANGE (13)= 2.800

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	505.97
C2	0.04	0.16	25.11	544.39	41.63	83.26	485.67
C3	0.04	0.17	24.22	522.42	40.35	80.69	470.70
C4	0.05	0.20	23.02	492.90	39.85	79.70	464.91

SCALED RANGE (14)= 4.300

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	777.02
C2	0.04	0.16	25.11	544.39	41.63	83.26	745.85
C3	0.04	0.17	24.22	522.42	40.35	80.69	722.86
C4	0.05	0.20	23.02	492.90	39.85	79.70	713.97

SCALED RANGE (15)= 5.600

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	1011.94
C2	0.04	0.16	25.11	544.39	41.63	83.26	971.34
C3	0.04	0.17	24.22	522.42	40.35	80.69	941.39
C4	0.05	0.20	23.02	492.90	39.85	79.70	929.82

SCALED RANGE (16)= 9.600

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	29.14	644.90	43.37	86.74	1734.75
C2	0.04	0.16	25.11	544.39	41.63	83.26	1665.15
C3	0.04	0.17	24.22	522.42	40.35	80.69	1613.82
C4	0.05	0.20	23.02	492.90	39.85	79.70	1593.98

```
      SCALED RANGE (17)=     13.000
      ---------------
COMPONENT      C1       C2        QM       X        R1       RE        R
---------------------------------------------------------------------------
   C1         0.03     0.10     29.14    644.90    43.37    86.74   2349.14
   C2         0.04     0.16     25.11    544.39    41.63    83.26   2254.89
   C3         0.04     0.17     24.22    522.42    40.35    80.69   2185.38
   C4         0.05     0.20     23.02    492.90    39.85    79.70   2158.51


      SCALED RANGE (18)=     34.000
      ---------------
COMPONENT      C1       C2        QM       X        R1       RE        R
---------------------------------------------------------------------------
   C1         0.03     0.10     29.14    644.90    43.37    86.74   6143.90
   C2         0.04     0.16     25.11    544.39    41.63    83.26   5897.40
   C3         0.04     0.17     24.22    522.42    40.35    80.69   5715.60
   C4         0.05     0.20     23.02    492.90    39.85    79.70   5645.34



      MASS OF FLAMMABLE GAS IN THE CLOUD( 5)=  30000.0
      ----------------------------------------


      SCALED RANGE ( 1)=      0.480
      ---------------
COMPONENT      C1       C2        QM       X        R1       RE        R
---------------------------------------------------------------------------
   C1         0.03     0.10     33.35    752.21    49.64    99.28     99.28
   C2         0.04     0.16     28.74    634.98    47.65    95.29     95.29
   C3         0.04     0.17     27.72    609.35    46.18    92.36     92.36
   C4         0.05     0.20     26.35    574.92    45.61    91.22     91.22


      SCALED RANGE ( 2)=      0.660
      ---------------
COMPONENT      C1       C2        QM       X        R1       RE        R
---------------------------------------------------------------------------
   C1         0.03     0.10     33.35    752.21    49.64    99.28    136.50
   C2         0.04     0.16     28.74    634.98    47.65    95.29    131.03
   C3         0.04     0.17     27.72    609.35    46.18    92.36    126.99
   C4         0.05     0.20     26.35    574.92    45.61    91.22    125.43
```

SCALED RANGE (3)= 0.670

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	33.35	752.21	49.64	99.28	138.57
C2	0.04	0.16	28.74	634.98	47.65	95.29	133.01
C3	0.04	0.17	27.72	609.35	46.18	92.36	128.91
C4	0.05	0.20	26.35	574.92	45.61	91.22	127.33

SCALED RANGE (4)= 0.700

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	33.35	752.21	49.64	99.28	144.78
C2	0.04	0.16	28.74	634.98	47.65	95.29	138.97
C3	0.04	0.17	27.72	609.35	46.18	92.36	134.69
C4	0.05	0.20	26.35	574.92	45.61	91.22	133.03

SCALED RANGE (5)= 0.750

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	33.35	752.21	49.64	99.28	155.12
C2	0.04	0.16	28.74	634.98	47.65	95.29	148.90
C3	0.04	0.17	27.72	609.35	46.18	92.36	144.31
C4	0.05	0.20	26.35	574.92	45.61	91.22	142.53

SCALED RANGE (6)= 0.900

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	33.35	752.21	49.64	99.28	186.14
C2	0.04	0.16	28.74	634.98	47.65	95.29	178.67
C3	0.04	0.17	27.72	609.35	46.18	92.36	173.17
C4	0.05	0.20	26.35	574.92	45.61	91.22	171.04

SCALED RANGE (7)= 0.980

COMPONENT	C1	C2	QM	X	R1	RE	R
C1	0.03	0.10	33.35	752.21	49.64	99.28	202.69
C2	0.04	0.16	28.74	634.98	47.65	95.29	194.56

```
      C3          0.04     0.17    27.72   609.35    46.18    92.36   188.56
      C4          0.05     0.20    26.35   574.92    45.61    91.22   186.24



         SCALED RANGE ( 8)=       1.090
         ----------------
COMPONENT         C1       C2         QM      X        R1       RE        R
-----------------------------------------------------------------------------
      C1          0.03     0.10    33.35   752.21    49.64    99.28   225.44
      C2          0.04     0.16    28.74   634.98    47.65    95.29   216.39
      C3          0.04     0.17    27.72   609.35    46.18    92.36   209.72
      C4          0.05     0.20    26.35   574.92    45.61    91.22   207.15



         SCALED RANGE ( 9)=       1.120
         ----------------
COMPONENT         C1       C2         QM      X        R1       RE        R
-----------------------------------------------------------------------------
      C1          0.03     0.10    33.35   752.21    49.64    99.28   231.64
      C2          0.04     0.16    28.74   634.98    47.65    95.29   222.35
      C3          0.04     0.17    27.72   609.35    46.18    92.36   215.50
      C4          0.05     0.20    26.35   574.92    45.61    91.22   212.85



         SCALED RANGE (10)=       1.210
         ----------------
COMPONENT         C1       C2         QM      X        R1       RE        R
-----------------------------------------------------------------------------
      C1          0.03     0.10    33.35   752.21    49.64    99.28   250.26
      C2          0.04     0.16    28.74   634.98    47.65    95.29   240.22
      C3          0.04     0.17    27.72   609.35    46.18    92.36   232.81
      C4          0.05     0.20    26.35   574.92    45.61    91.22   229.95



         SCALED RANGE (11)=       1.530
         ----------------
COMPONENT         C1       C2         QM      X        R1       RE        R
-----------------------------------------------------------------------------
      C1          0.03     0.10    33.35   752.21    49.64    99.28   316.44
      C2          0.04     0.16    28.74   634.98    47.65    95.29   303.75
      C3          0.04     0.17    27.72   609.35    46.18    92.36   294.38
      C4          0.05     0.20    26.35   574.92    45.61    91.22   290.76
```

```
      SCALED RANGE (12)=      2.100
      ---------------
COMPONENT      C1        C2        QM       X         R1        RE        R
-------------------------------------------------------------------------------
   C1         0.03      0.10     33.35    752.21     49.64     99.28    434.33
   C2         0.04      0.16     28.74    634.98     47.65     95.29    416.91
   C3         0.04      0.17     27.72    609.35     46.18     92.36    404.06
   C4         0.05      0.20     26.35    574.92     45.61     91.22    399.09


      SCALED RANGE (13)=      2.800
      ---------------
COMPONENT      C1        C2        QM       X         R1        RE        R
-------------------------------------------------------------------------------
   C1         0.03      0.10     33.35    752.21     49.64     99.28    579.11
   C2         0.04      0.16     28.74    634.98     47.65     95.29    555.88
   C3         0.04      0.17     27.72    609.35     46.18     92.36    538.74
   C4         0.05      0.20     26.35    574.92     45.61     91.22    532.12


      SCALED RANGE (14)=      4.300
      ---------------
COMPONENT      C1        C2        QM       X         R1        RE        R
-------------------------------------------------------------------------------
   C1         0.03      0.10     33.35    752.21     49.64     99.28    889.35
   C2         0.04      0.16     28.74    634.98     47.65     95.29    853.67
   C3         0.04      0.17     27.72    609.35     46.18     92.36    827.35
   C4         0.05      0.20     26.35    574.92     45.61     91.22    817.18


      SCALED RANGE (15)=      5.600
      ---------------
COMPONENT      C1        C2        QM       X         R1        RE        R
-------------------------------------------------------------------------------
   C1         0.03      0.10     33.35    752.21     49.64     99.28   1158.22
   C2         0.04      0.16     28.74    634.98     47.65     95.29   1111.75
   C3         0.04      0.17     27.72    609.35     46.18     92.36   1077.48
   C4         0.05      0.20     26.35    574.92     45.61     91.22   1064.24


      SCALED RANGE (16)=      9.600
      ---------------
COMPONENT      C1        C2        QM       X         R1        RE        R
-------------------------------------------------------------------------------
   C1         0.03      0.10     33.35    752.21     49.64     99.28   1985.52
   C2         0.04      0.16     28.74    634.98     47.65     95.29   1905.86
```

```
    C3          0.04     0.17     27.72   609.35     46.18     92.36  1847.11
    C4          0.05     0.20     26.35   574.92     45.61     91.22  1824.40



       SCALED RANGE (17)=     13.000
       ----------------
COMPONENT       C1       C2         QM       X         R1        RE         R
-------------------------------------------------------------------------------
    C1          0.03     0.10     33.35   752.21     49.64     99.28  2688.73
    C2          0.04     0.16     28.74   634.98     47.65     95.29  2580.85
    C3          0.04     0.17     27.72   609.35     46.18     92.36  2501.29
    C4          0.05     0.20     26.35   574.92     45.61     91.22  2470.55



       SCALED RANGE (18)=     34.000
       ----------------
COMPONENT       C1       C2         QM       X         R1        RE         R
-------------------------------------------------------------------------------
    C1          0.03     0.10     33.35   752.21     49.64     99.28  7032.06
    C2          0.04     0.16     28.74   634.98     47.65     95.29  6749.93
    C3          0.04     0.17     27.72   609.35     46.18     92.36  6541.85
    C4          0.05     0.20     26.35   574.92     45.61     91.22  6461.43




       MASS OF FLAMMABLE GAS IN THE CLOUD( 6)=  40000.0
       ------------------------------------------------


       SCALED RANGE ( 1)=      0.480
       ----------------
COMPONENT       C1       C2         QM       X         R1        RE         R
-------------------------------------------------------------------------------
    C1          0.03     0.10     36.70   839.01     54.63    109.26    109.26
    C2          0.04     0.16     31.63   708.26     52.44    104.87    104.87
    C3          0.04     0.17     30.51   679.66     50.82    101.64    101.64
    C4          0.05     0.20     28.99   641.26     50.20    100.39    100.39



       SCALED RANGE ( 2)=      0.660
       ----------------
COMPONENT       C1       C2         QM       X         R1        RE         R
-------------------------------------------------------------------------------
```

```
     C1          0.03      0.10     36.70    839.01     54.63    109.26    150.23
     C2          0.04      0.16     31.63    708.26     52.44    104.87    144.20
     C3          0.04      0.17     30.51    679.66     50.82    101.64    139.76
     C4          0.05      0.20     28.99    641.26     50.20    100.39    138.04


        SCALED RANGE ( 3)=      0.670
        ------------------
COMPONENT        C1        C2          QM        X         R1        RE          R
-----------------------------------------------------------------------------------
     C1          0.03      0.10     36.70    839.01     54.63    109.26    152.50
     C2          0.04      0.16     31.63    708.26     52.44    104.87    146.39
     C3          0.04      0.17     30.51    679.66     50.82    101.64    141.87
     C4          0.05      0.20     28.99    641.26     50.20    100.39    140.13


        SCALED RANGE ( 4)=      0.700
        ------------------
COMPONENT        C1        C2          QM        X         R1        RE          R
-----------------------------------------------------------------------------------
     C1          0.03      0.10     36.70    839.01     54.63    109.26    159.33
     C2          0.04      0.16     31.63    708.26     52.44    104.87    152.94
     C3          0.04      0.17     30.51    679.66     50.82    101.64    148.23
     C4          0.05      0.20     28.99    641.26     50.20    100.39    146.40


        SCALED RANGE ( 5)=      0.750
        ------------------
COMPONENT        C1        C2          QM        X         R1        RE          R
-----------------------------------------------------------------------------------
     C1          0.03      0.10     36.70    839.01     54.63    109.26    170.71
     C2          0.04      0.16     31.63    708.26     52.44    104.87    163.86
     C3          0.04      0.17     30.51    679.66     50.82    101.64    158.81
     C4          0.05      0.20     28.99    641.26     50.20    100.39    156.86


        SCALED RANGE ( 6)=      0.900
        ------------------
COMPONENT        C1        C2          QM        X         R1        RE          R
-----------------------------------------------------------------------------------
     C1          0.03      0.10     36.70    839.01     54.63    109.26    204.86
     C2          0.04      0.16     31.63    708.26     52.44    104.87    196.64
     C3          0.04      0.17     30.51    679.66     50.82    101.64    190.58
     C4          0.05      0.20     28.99    641.26     50.20    100.39    188.23
```

```
        SCALED RANGE ( 7)=      0.980
        ----------------
COMPONENT      C1        C2        QM       X          R1        RE        R
--------------------------------------------------------------------------------
   C1         0.03      0.10     36.70    839.01     54.63    109.26    223.07
   C2         0.04      0.16     31.63    708.26     52.44    104.87    214.12
   C3         0.04      0.17     30.51    679.66     50.82    101.64    207.52
   C4         0.05      0.20     28.99    641.26     50.20    100.39    204.97


        SCALED RANGE ( 8)=      1.090
        ----------------
COMPONENT      C1        C2        QM       X          R1        RE        R
--------------------------------------------------------------------------------
   C1         0.03      0.10     36.70    839.01     54.63    109.26    248.10
   C2         0.04      0.16     31.63    708.26     52.44    104.87    238.15
   C3         0.04      0.17     30.51    679.66     50.82    101.64    230.81
   C4         0.05      0.20     28.99    641.26     50.20    100.39    227.97


        SCALED RANGE ( 9)=      1.120
        ----------------
COMPONENT      C1        C2        QM       X          R1        RE        R
--------------------------------------------------------------------------------
   C1         0.03      0.10     36.70    839.01     54.63    109.26    254.93
   C2         0.04      0.16     31.63    708.26     52.44    104.87    244.70
   C3         0.04      0.17     30.51    679.66     50.82    101.64    237.16
   C4         0.05      0.20     28.99    641.26     50.20    100.39    234.25


        SCALED RANGE (10)=      1.210
        ----------------
COMPONENT      C1        C2        QM       X          R1        RE        R
--------------------------------------------------------------------------------
   C1         0.03      0.10     36.70    839.01     54.63    109.26    275.42
   C2         0.04      0.16     31.63    708.26     52.44    104.87    264.37
   C3         0.04      0.17     30.51    679.66     50.82    101.64    256.22
   C4         0.05      0.20     28.99    641.26     50.20    100.39    253.07


        SCALED RANGE (11)=      1.530
        ----------------
COMPONENT      C1        C2        QM       X          R1        RE        R
--------------------------------------------------------------------------------
   C1         0.03      0.10     36.70    839.01     54.63    109.26    348.26
   C2         0.04      0.16     31.63    708.26     52.44    104.87    334.28
```

NOMENCLATURE

a	numerical exponent
a	sonic velocity in air (m/sec), equation 7.6
a_o	sonic velocity in air at the instant of vessel rupture (m/sec)
a_2	sonic velocity in the sphere at the instant of vessel rupture (m/sec)
A	numerical constant
A	surface area of pool (m^2), equation 6.73
b	numerical exponent
B	numercial constant
C	specific heat of combustion products (kJ/kg K)
C	calorific value of liquid (kJ/kg), equation 6.69
Ca	specific heat of air (kJ/kg K)
Cp_m	mean specific heat of combustion products (kJ/kg K)
$C(r)$	vapour concentration at distance r from centre (g/m^3)
C_o	vapour concentration at centre of cloud (g/m3)
C_1	concentration at lower flammable limit (g/m^3)
C_2	concentration at upper flammable limit (g/m^3)
d	distance from tank to receiver (m)
D	equivalent spherical diameter of fireball (m)
D	diameter of pool (m) equation 6.73
D_c	equivalent spherical diameter at completion of combustion (m)
D_c	the initial hemispherical diameter of the cloud at NTP (m), equation 7.6
D_1	equivalent spherical diameter at neutral buoyancy (m)
D_o	equivalent spherical diameter of gas cloud (m)
D_s	equivalent spherical diameter of hot shell (m)
$(dD/dt)_c$	constant rate of increase of diameter during combustion (m/sec)
E	flame surface emissive power (kW/m^2), equation 6.73
E_1	the effective energy stored in a pressurised sphere of ideal gas (J)
E_o	total combustion energy released (MJ)

ΔE	Isentropic expansion energy (J)
f	fraction of fuel burnt
f	fraction of heat of combustion of fuel which is radiated, equation 6.72
f_c	fraction of fuel burnt at the end of combustion
f_1	fraction of fuel burnt to produce neutral buoyancy
F_{21}	view factor from target to the fireball surface
h	net calorific value of fuel (kJ/kg)
H	elevation of bottom of fireball above ground (m)
H_c	heat of combustion (kJ/kg), equation 6.72
ΔH	the enthalpy change
$\Delta H^{\circ}{}_c$	standard heat of combustion (cal/g mole)
$\Delta H^{\circ}{}_p$	the enthalpy change of the products
k	constant, equation 6.69
k	constant appropriate to various degrees of damage, equation 7.1
L	distance from surface of fireball to target (m)
L	length of flame (m), equation 6.73
m	mass of fuel in cloud initially (kg)
m_1	mass of water required to remove the heat (kg)
m	fuel burning rate (kg/m^2.sec)
M	molecular weight of the flammable material
M	mean molecular weight of stoichiometric combustion products
n	increase in total number of moles per mole of flammable gas burnt stoichiometrically
n	number of moles, equation 6.63
P_c°	rate of pressure rise at the centre of the initial explosion
P_f	final absolute pressure (N/m^2)
P_o	initial absolute pressure (N/m^2)
P_o	ambient atmospheric pressure (N/m^2), equation 5.1
P_2	initial absolute pressure in the sphere at the instant of burst (kN/m^2), equation 5.1
P_2	dimensionless overpressure in the sphere
P_s	shock overpressure KN/m^2
P_s	shock overpressure (kN/m^2), equation 7.2
P_s	dimensionless shock overpressure
P_{so}	initial reduced shock overpressure

q	radiation intensity (kW/m^2)
q_1	emitted flux density from fireball surface (kW/m^2)
q_2	incident flux density from a fireball surface (kW/m^2)
Q	heat flux density function (kW/m^2)
Q_1	quantity of heat radiated (kW)
Q_2	radiant flux intensity (kW/m^2)
r	mass ratio of combustion products per unit mass of flammable gas, from stoichiometric combustion
r	liquid burning rate (m/sec), equation 6.69
r	radius (m), equation 7.8
r_1	radius at which the concentration is at the lower flammable limit (m)
r_o	initial radius of sphere (m)
R	distance radially along the ground from the centre-line of a fireball (m)
R	distance from the explosion (ft), equation 7.1
R	radial distance from centre of explosion (m), equation 7.2
R_e	radius when the flame front reaches the periphery (m)
R_o	scaling radius based on energy (m)
R_s	radial distance at shock front condition
R_s	dimensionless shock radius
R_{so}	scaled shock front radius at the instant of failure
R_s	radius at which blast wave becomes shock wave (m), equation 7.4
t	time since ignition (sec)
t_c	duration of combustion (sec)
t_e	exposure time (sec)
t_o	duration of explosive release of energy (sec)
t_s	time taken for a pressure wave to transform into a shock wave (sec)
t	theoretical flame temperature (c)
T	absolute temperature (k)
T_c	isothermal temperature of fireball (k)
T_f	flame surface temperature (k)
T_s	temperature of hot shell (k)
ΔT	temperature rise of the water (k)
U	average radial velocity of air through the hot shell (m/sec)
V	volumetric rate of flow of air into fireball (m^3/sec)

V	volume of sphere (m^3)
v_1	water capacity of vessel (litres)
V_o	original volume (m^3)
V_o	original volume of sphere (m^3), equation 5.5
W_1	maximum permitted LPG fill by weight (kg)
W	weight of TNT (lb), equation 7.1
W	total quantity of vapour in cloud (g), equation 7.16
Z	percent of damage

Greek Letters

τ	atmospheric transmissivity
α	absorptivity
ε	emissivity
θ	Stefan-Boltzmann constant (kW/m^2K^4)
υ	stoichiometric molar ratio of air to flammable gas
σ	standard deviation of concentration distribution (m)
σ_m	standard deviation when cloud is at maximum potential (m)
γ	ratio of specific heats
γ_o	specific heat ratio of air
γ_1	specific heat ratio of stored gas
ρ	density (kg/m^3)
ρ_{ref}	relative density of LPG at the reference temperature for filling ratio

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