The

ANALOGUE SIMULATION

of a

FUSION REACTOR

A thesis presented for the

DEGREE of DOCTOR of PHILOSOPHY

of the

UNIVERSITY of ASTON in BIRMINGHAM

AWARDED THE DEGREE OF M.Phil.

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Summary

Electronic simulation is common in training courses for control of aircraft, army tanks and fission reactors. A limited version of a fusion reactor simulator has been constructed. It was designed using a Solartron Space 30 analogue computer and from this design a hybrid simulator using mostly solid state amplifiers was built.

The fusion reactor uses the nuclear fusion reactions which occur in fully ionised gases - in this case deuterium and tritium - at very high temperatures and in the form known as a plasma. The plasma must be heated to some 100 million ^{o}K, maintained at this temperature for as long as possible and contained within a magnetic field. Electrical energy provides initial heating of the plasma supplemented by an injection of energetic neutral hydrogen atoms and internal heating from alpha-particles created in the nuclear reactions and reabsorbed in the plasma. Energy losses of many kinds occur.

Mathematical formulae govern the processes of heating plasma, loss of energy by radiation, production of energy in the nuclear reactions and the interaction of parameters. In particular, the plasma temperature is of great importance. In building the simulator these formulae were accepted and solved by analogue methods using operational amplifiers. Most parameters are used in log form so that addition and subtraction replace the more difficult analogue multiplication and division processes.

The simulator behaves basically as expected but the checking of its results awaits the building of the first critical fusion reactor.

It is a simplified representation of a fusion reactor for only the principal energy sources and losses have been incorporated. As such it is for training purposes only and accuracy and potential for training are discussed.

Key words:-

Fusion Simulator Electronics Plasma Training

Acknowledgements

Few scientific experiments or developments can be made these days in isolation. Indeed it is to the benefit of the experiment to be otherwise and to invite discussion on its purpose, method and progress.

It is with gratitude therefore that the author acknowledges the many helpful discussions with Dr. P.N.Cooper, supervisor for the project, who has many times returned the development to its rightful direction ; also to Mr. S.MacManus, electronics technician, for maintaining the equipment and for frequent talks about electronic techniques.

To Professor S.E. Hunt, Head of the Physics Department are due my sincere thanks for making the development facilities available and for being so tolerant of delays in progress in difficult circumstances.

R.R. Osborne

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CHAPTER 1

Introduction.

Not so many years ago, the operation of machines was passed on to apprentices while ' on the job ' by skilled and experienced personnel. With the rapid growth of technology and advanced machinery this technique fails since even the skilled operator soon finds his machine to be obsolete and due to be replaced by another of more advanced technology. Where then will he learn the new skill required to operate this advanced machine? To allow him, now as unskilled, to operate and learn on the new machine is to invite the risk of break-downs, accidents and not least, expensive running costs. It now becomes the job of the scientist, the engineer and the designers initially to give instruction to the new operator.

Simulators fit into this instruction pattern. They are devices which are programmed to behave in similar manner to the advanced machine when its various parameters are changed. The operator can control the simulator with its many variables and gain experience of its reactions to his control.

Although no more can be obtained from the simulator than is programmed into it, yet it allows rapid investigation of the effects of combinations of parameters some of which may not usually be realised on the actual machine. For later design improvement the designer may also incorporate in the simulator variable parameters which may be fixed in the machine. This will allow some limited upgrading of the machine design and set limits to the many parameters to avoid damage to the real machine. The form which damage to the machine might take can also be displayed. That is, the simulator may be operated outside the design limits of the actual machine.

Simulators have many forms, mechanical, electronic optical. Generally speaking, they are electronic, this type being more flexible for operation and for the insertion of modifications. Electronic simulators have developed since the late 1940's and are based on the D.C.Amplifier(1). They are specialised forms of analogue computers. The digital computer, developed alongside the analogue computer has been used principally as a calculating device, but is now being programmed, in digital form for simulator work. In these pages it is the analogue type which has been developed to a fusion reactor simulator. One distinct difference between the two types of computer should be noted. The digital computer is a 'serial' machine, responding to a series of commands from the program inserted. The analogue machine is a 'parallel' device, all operations in the system occuring virtually simultaneously. Thus the analogue computer has, generally, been faster than the digital computer though this advantage is being lost as the latter become very fast indeed. But whereas the digital computer responds to its program instructions with a 'go' or 'no go' operation (leaving no room for doubt) the analogue computer responds to its instructions with a D.C.(or A.C.) voltage, the accuracy of which depends on the accuracy and stability of its components. But the parameters in an analogue simulator can be changed during operation, whereas in general, the digital simulator would need such changes to be preset in the program. The immediate and visual response of the analogue simulator to these changes gives a good physical appreciation of the machine behaviour.

In devising this fusion simulator the plan of work has been as follows. A large general purpose analogue computer, the Solartron 'Space 30' was available. This is a machine using thermionic valves in all its many units and is in consequence large physically, consumes much electricity and needs frequent maintenance. It was however very flexible in use; controls were readily to hand and changes to the simulator were easily made via a patch panel and interlinking cords. This machine was used for the general design of the simulator and when this had been developed to an adequate extent, a new system to a similar design was built using solid state components wherever possible, thereby reducing the physical dimensions of the simulator by a factor of about 10 times linear. This has less power consumption and increased reliability by reducing the number of sliding contacts (plugs and sockets, switches etc) in favour of soldered joints.

A few of the results obtained with the 'Space 30' are given but the majority of the results are from the solid state simulator. Where they are available, experimental results from actual operational fusion reactors - though sub-critical - are quoted for comparison. It should be noted however that at this time of writing only a few fusion reactors are known to operate but none has gone 'critical', that is, have not yielded 'saleable' power(American term) or more power out than was put in. This simulator project may therefore be said to be looking well into the future in that it seeks to show how the critical fusion reactor will behave and operate though at present there is no such reactor to simulate. The Joint European Torus (JET)[(2)] reactor is the next probable step forward. It is to be built at Culham (England) but its scheduled completion date is about 1983. A fuller description of a fusion reactor is given in chapter 3.

Fission simulators have been in use since the early 1950's and many years experience of building and operating these machines has been acquired. As far as is known no other fusion simulator has been built and new ground is being broken in this project.

The fission and fusion processes will be discussed in more detail later. Here a brief note on their differences will show up the variations in circuitry used in their respective simulators. In a fission reactor a supercritical mass of uranium fuel is assembled and will immediately of its own accord start a chain reaction by reason of the neutrons produced. Control is exercised by inserting neutron absorbing rods into the mass of fuel. By contrast, the fusion reactor contains at any instant comparatively little of the tritium and deuterium fuels but it has to be supplied with a large amount of electrical energy to raise the fuel temperature sufficiently high to separate the electrons from the hydrogen nuclei and produce a mixture of positive and negative ions called a plasma. The temperature must then be raised even higher to initiate nuclear reactions which will release more energy than has been put into the system. Control is obtained by varying the fuel content, the energy put in or the frequency of operation.

In both types of reactor there are positive and negative feedbacks. These are processes in which the output of the system reacts to affect the input to the system. Where a rise in the output of the system increases the input and hence raises the output still further, the feedback is termed positive. Conversely, where the rise in output would decrease the input there is a negative feedback. A positive feedback makes a system expand in power while a negative feedback tries to shut down the system. In each type of reactor simulator there is a central unit which determines the energy output of the system and this is affected by both positive and negative feedbacks.

Thus, referring to Fig. 1(a)p5, A is the central unit in a fission simulator, its output, in the form of a voltage signal, indicates the energy production. This is

Fig. 1a

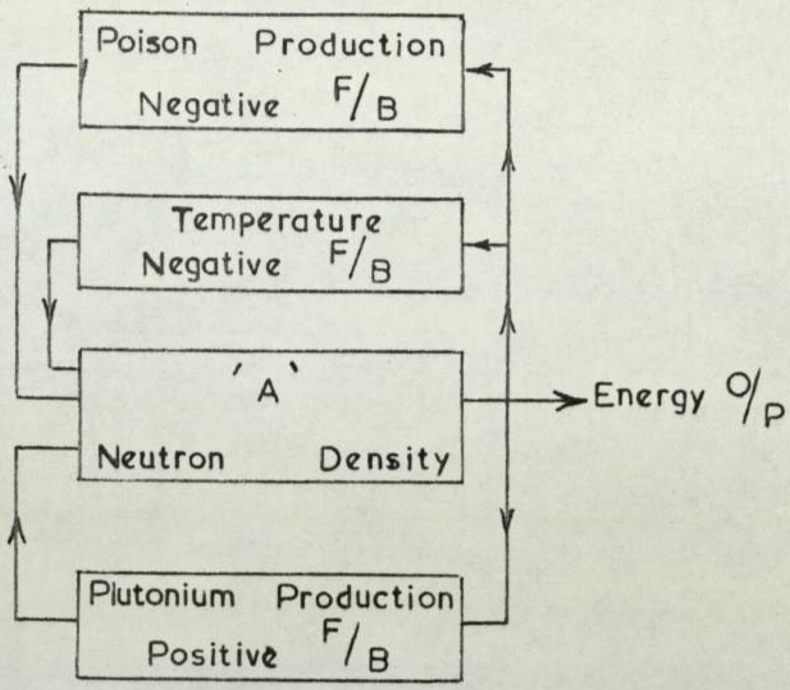
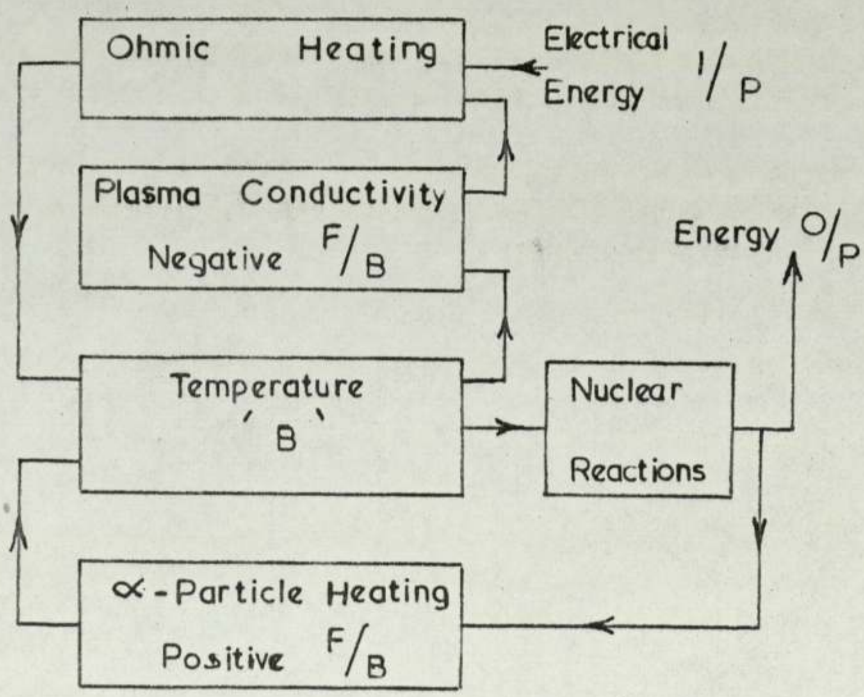

Poison Production
Negative F/B
Temperature
Negative F/B
'A'
Neutron Density
Energy O/P
Plutonium Production
Positive F/B

Fig. 1b


Ohmic Heating
Electrical Energy I/P
Plasma Conductivity
Negative F/B
Energy O/P
Temperature
'B'
Nuclear Reactions
∝-Particle Heating
Positive F/B

adversely affected by an excessive rise in temperature and the production of nuclear poisons (strong neutron absorbers) e.g. Xe-135, both of which are negative feedbacks. The production of plutonium from neutron absorption in uranium-238 is a production of more fuel and this is obviously a positive feedback.

In Fig. 1(b) p5, B is the central unit in a fusion simulator, its output indicating the temperature reached in the reactor. Temperature is raised by electrical heating of the tritium-deuterium mixture, converting it to a plasma; but as the temperature rises the plasma conduction increases giving less ohmic heating. This is a negative feedback. The high temperature initiates nuclear reactions, one product of these being energetic alpha-particles which dissipate their energy in the plasma and contribute to its heating, this is a positive feedback.

There are many more feedbacks than indicated in Fig.1, in both fusion and fission simulators. The complexity of the simulator increases as more feedbacks are added; so does the cost, the realism and the value of the simulator as a training machine. Hence any simulator must be a compromise and the number of feedbacks to be incorporated must be limited. This limit may be drawn by considering the importance of a particular feedback, that is, its contribution to an increase or decrease of the energy output. These feedbacks are discussed in more detail in Chapter 3.

Both fission and fusion simulators have a common limitation. In each type of reactor there is a variation of conditions across the fuel chamber. In the fission reactor temperature and neutron density both vary vertically and radially across the fuel core. This necessitates some 'gagging' of selected fuel channels to obtain a correct cooling gas flow pattern for the more uniform release and removal of heat in the core. The fusion reactor of the Tokamak type with a 'doughnut' shaped annular fuel chamber has a temperature variation across its minor radius together with a variation of the poloidal magnetic field.

This variation of conditions means that, in theory, an infinite number of coupled simulators would be needed fully to represent a single reactor of either type. Obviously this is not a very practical system and the majority of simulators are built to represent an average set of conditions in the reactor being simulated. These are then termed 'point simulators'.

Another problem, common to simulators of both fission and fusion reactors is the wide range of power or temperature to be simulated. The fission reactor power may change from as little as $^1/4$ watt to 1000 megawatts, that is, over 10 decades. Temperatures in the fusion reactor vary from room temperature (0.025 ev) to 300,000,000^{o}K (25Kev) or higher, that is, over 6 decades. These wide ranges are outside the limits of the D.C.Amplifiers used (currently about 3 decades) and recourse is made to the use of 'Log' quantities. Thus log (Temperature) in the fusion simulator now varies from -4.6 to +1.4, a range which the D.C.Amplifiers can handle. But this technique involves the conversion of linear quantities to log quantities and vice-versa and these processes need the function generators and other devices described in Chapter 6. Further advantage arises from the use of log quantities; the multiplication of factors in linear equations is replaced by addition processes which are easily performed with D.C.Amplifiers.

Fission reactors give a smoothed output of power. Smoothed, since although individual atoms fission to give bursts of energy, the immense number involved appear on a macroscopic scale to give a continuous energy output.

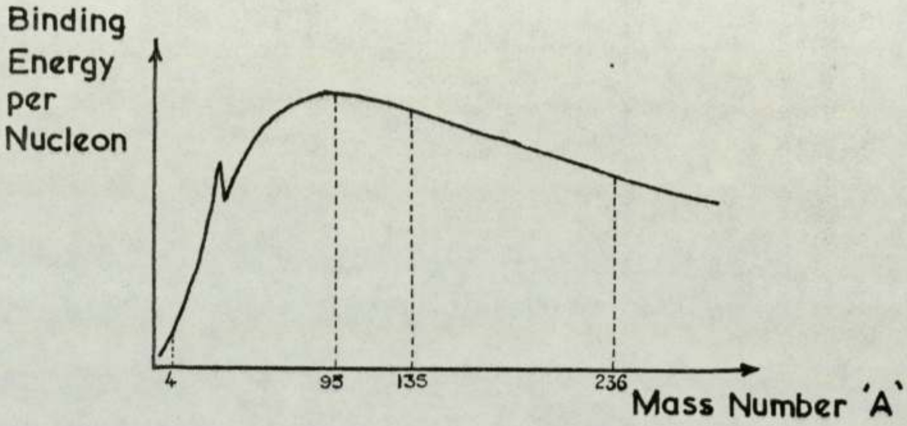
Fusion reactors of the present Tokamak design give bursts of energy lasting for a few milliseconds only, that is, the time during which the plasma is above the 'ignition temperature' and which is limited by the duration of the input of electrical power, usually from the discharge of a capacitor bank. This operational period is followed by a period for recharging the capacitors and refuelling the reactor. The average 'saleable' power from the fusion reactor is therefore partly dependent on this recharging period. The fusion simulator must allow for this and must be programmed for repetition at a variable rate and with means for averaging out the bursts of input and output energies to arrive at a mean power output.

For training purposes the student operator should be aware how various fusion quantities, e.g. temperature, ohmic heating, alpha heating etc., behave as he changes the control parameters, i.e. tritrium-deuterium ratios and densities, input current magnitude and waveform, etc. This requires much metering. Even so a power cycle time of milliseconds gives little time for recording. It is an advantage of the analogue simulator that its time scale can be lengthened or shortened by increasing or decreasing respectively the time constant of the integrating amplifiers. With a lengthened time scale and chart recorders a fairly complete picture of the power cycle is obtained.

CHAPTER 2

Fission and Fusion Processes

Although this work is not primarily concerned with fission, it will be of help to compare the processes of fission and fusion. Such a comparison will show why the control of fusion is being so strongly pursued in several countries and also the differences which simulators of fission and fusion reactors have to show.



There is some degree of similarity between the two processes. Both seek the release of nuclear energy by exploiting the relationship between the binding energy of the nucleus and the mass number. This relationship is shown above. Where a nucleus contains Z protons and N neutrons, its binding energy is " defined as the difference between the sum of the masses of the Z protons and N neutrons in the free state and the mass of the nucleus containing $A = (Z + N)$ nucleons". (3)

Example (3) :- The Lithium isotope $^{7}Li_{3}$ has 3 protons $^{1}H_{1}$ plus 4 neutrons $^{1}n_{o}$

In the free state

$$4 \times {}^{1}n_{o} = 4 \times 1.008665 = 4.034660 \text{ atomic mass units}$$

$$3 \times {}^{1}H_{1} = 3 \times 1.007276 = 3.021828 \quad " \quad " \quad "$$

Total mass in free state = $4 \times {}^{1}n_{o} - 3 \times {}^{1}H_{1}$ = 7.056488 a.m.u. s

Mass of ${}^{7}Li_{3}$ nucleus ${}^{7}Li_{3}$ = 7.014358 "

Loss of mass on formation = 0.042130 "

≡ 39.23 Mev.

i.e. The Binding Energy of the ${}^{7}Li_{3}$ isotope is 39.23 Mev.

The form of the B.E. per nucleon v Mass number graph indicates that if a Uranium- 236 nucleus is split to form two products each of mass 118 these will have greater binding energies than the Uranium nucleus and the loss of mass is converted to energy released as kinetic energy. This is the fission process. Similarly, if two protons and two neutrons are combined to form a Helium nucleus there is an increase in binding energy and again a release of energy. This is the fusion process. Neither reaction is quite so simple as this.

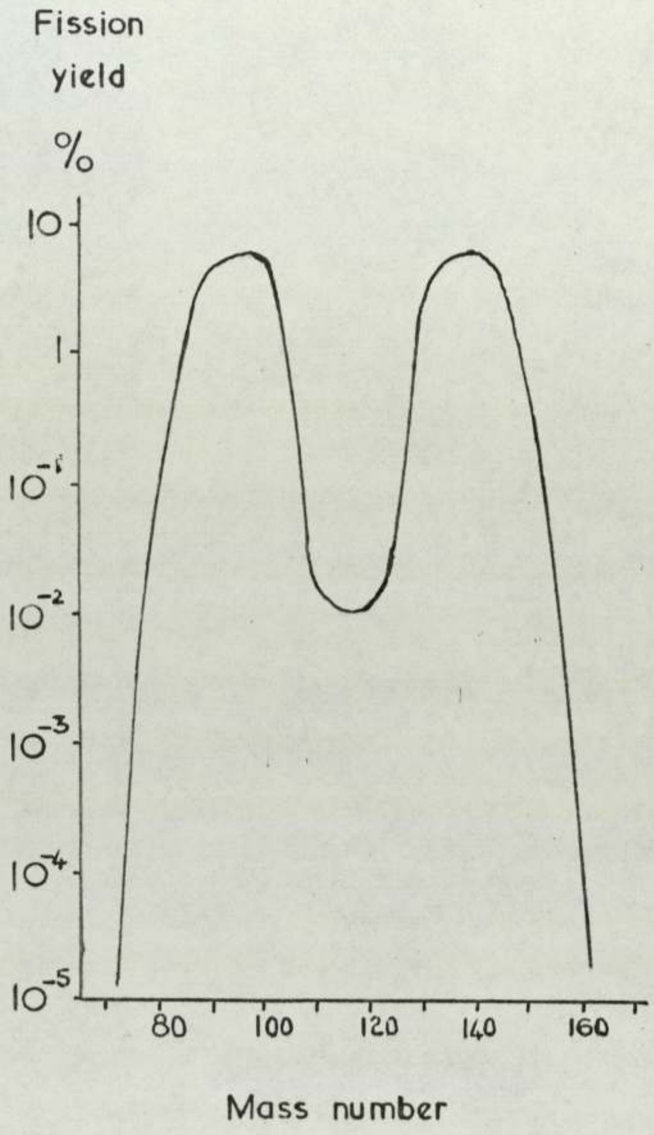
The fission reaction is

$$^{235}U_{92} + {}^{1}n_{o} \longrightarrow {}^{236}U_{92} \longrightarrow A + B + n's + \gamma's + 200 \text{ Mev}$$

In this reaction,a neutron, having no charge, enters a U-235 nucleus with comparative ease, the coulomb forces being ineffective. Being bound into the Uranium nucleus its binding energy causes instability and the Uranium nucleus splits up into parts A and B plus some neutrons and gamma photons and with kinetic energy given to the products.

A and B are isotopes of medium weight nuclei but vary in mass number from one reaction to another. The percentage distribution of the mass numbers of A and B is shown in Fig. 2 p.11 Statistically, mass numbers 95 and 135 are favoured. Very occasionally three products have been detected. An average of 2.5 neutrons and 6 to 7 gamma photons are obtained from each fission reaction of Uranium. These figures differ with other fissile material. The whole process is erratic and the figure of 200 Mev of energy released is also an average value

Fig.2



Fission yields of products from U-235

(ex Glasstone and Edlund) [4]

shared between the several products. About 5% of the energy is given to the neutrons and gamma photons and the remainder is kinetic energy to the products A and B. These products A and B are usually unstable and radioactive and a further energy release occurs with their decay.

It should be noticed that the reaction is initiated by a neutron and that further neutrons are produced. These are available to renew the reaction and to form a chain reaction. The product neutrons are fast and energetic but the reaction prefers a slower neutron (i.e. the cross section for the reaction is greater for slow neutrons). A thermal reactor therefore employs a moderating medium (e.g. graphite or water) to slow down the fast neutrons. Basically the thermal fission reactor has a core of moderating medium in which are located at specific spacings the rods of uranium fuels surrounded by channels carrying the cooling fluid to heat exchangers. In any reactor core there is a loss of neutrons and the chain reaction will only be sustained if at least one neutron from each generation is retained to cause further fission in the next generation.

The fusion process is more complex. Two neutrons and two protons have to be fused together. It is very unlikely that the four particles can simultaneously be brought together so an intermediate step is used by employing deuterium and tritium isotopes of hydrogen in which some neutrons and protons have already been fused together. The nuclear reactions are

(a) ${}^{2}D_{1} + {}^{2}D_{1} = ({}^{3}T_{1} + 1.0\ \text{Mev}) + ({}^{1}p_{1} + 3.00\ \text{Mev})$

(b) ${}^{2}D_{1} + {}^{2}D_{1} = ({}^{3}He_{2} + 0.8\ \text{Mev}) + ({}^{1}n_{o} + 2.45\ \text{Mev})$

(c) ${}^{2}D_{1} + {}^{3}T_{1} = ({}^{4}He_{2} + 3.52\text{Mev}) + ({}^{1}n_{o} + 14.06\ \text{Mev})$

(d) ${}^{2}D_{1} + {}^{3}He_{2} = ({}^{4}He_{2} + 3.67\text{Mev}) + ({}^{1}p_{1} + 14.67\ \text{Mev})$

(e) ${}^{1}n_{o} + {}^{6}Li_{3} = {}^{4}He_{2} + {}^{3}T_{1}$

Reactions (a) and (b) are alternatives of about the same probability neither yielding as much energy as reaction (c) but producing tritium and charged particles. Although reaction (d) produces slightly more energy than reaction (c) its cross section is lower and consequently reaction (c) is the starting point for the fusion reactor with fuel gases deuterium and tritium. Reaction (e) is useful as a contribution to the renewal of the tritium fuel. Its cross-section is low but the reaction takes place in a blanket of Lithium surrounding the fuel chamber where the concentration of Lithium is high. By processing,the blanket is thus a source of the primary fuel tritium.

By comparison with the fission reaction the energy release in a fusion reaction is low but on a basis of energy release per unit mass of fuel involved, then the fusion process yields some four times as much energy. Further, the products of the fusion reaction have little radioactivity, though some radioactivity will be produced in structural materials by neutron bombardment. The high activity of fission products is a big disadvantage of the fission reactor and a highly contentious public issue at the present time.

Fuel for the fission reactor is mined from randomsited deposits and already the continued supply of uranium ore of adequate quality is questioned. The inventory of hundreds of tonnes of uranium per power reactor core has also raised questions of safety.

The fusion reactor can draw all its fuel from sea water. Deuterium is the heavy hydrogen isotope in heavy water forming 0.02% of water. Tritium is obtainable via reaction (e) from Lithium of which there are immense quantities in the oceans and in terrestial deposits. Hancox[(5)], in a general description of a 2500 Mw(e) reactor estimates the tritium inventory at about 5 Kilograms. Further, at room temperature the fuel is electrically neutral and safe.

A fission research reactor may go 'critical' with a few kilograms of Uranium-235. Unfortunately the fusion reactor needs a high input of electrical power and is unlikely to go 'critical' until it is very large both physically and electrically. Commercial fusion reactors are expected initially to be useful power generators only when above the 4000 to 5000 Megawatt output range. Until it is built there is no certainty of success.

The fusion reactions are between nuclei and the cross-sections for the reactions are small, around 10^{-2} barn compared with the fission cross-sections of around 500 barns.

Consequently to obtain fusion reactions the following conditions appear to be necessary.

(a) The deuterium and tritium atoms must be stripped of their electrons by

(1) ohmic heating - the passage of huge electric currents through the gases

(2) bombardment with high energy hydrogen atoms injected from an external source

(3) bombardment with energetic alpha particles generated internally at the highest temperatures.

The energy required to strip the single electron from the hydrogen atom is 13.6 ev, equivalent to a temperature of about $160,000^{o}K$. In such a state the nuclei form a plasma of charged particles mutually repulsive.

(b) The plasma particles must be accelerated by further heating and bombardment to acquire energies sufficient to overcome the repulsive forces between them. This requires heating the plasma to temperatures around $300,000,000^{o}K$ (25Kev)

(c) At these temperatures the plasma must be contained for a long enough period for sufficient fusion reactions to occur to release a profitable amount of energy. This period is of the order of seconds for the D-D reactions and shorter times for the D-T reactions.

Figure 3 p.16 shows how the cross sections for the reactions indicated in (a), (b) and (c) vary with the energies of the particles and in Figure 4 p.16 the averaged quantity (σv) has been derived and plotted against temperature assuming a Maxwell distribution of velocities among the plasma particles. At around 75 Kev of energy the cross-section for the D-T reaction is some 400 times that of the D-D reaction so that the latter reaction is not considered seriously for fusion purposes.

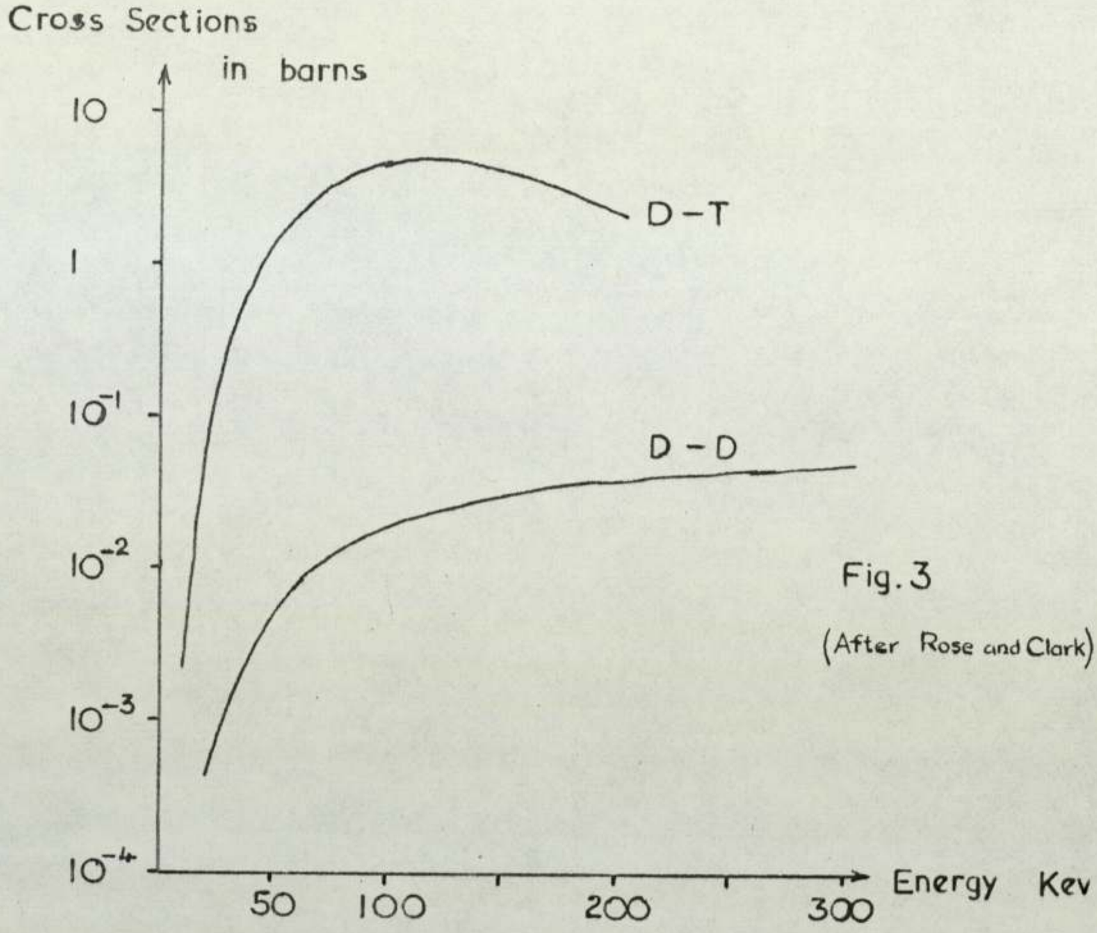


Fig. 3

(After Rose and Clark)

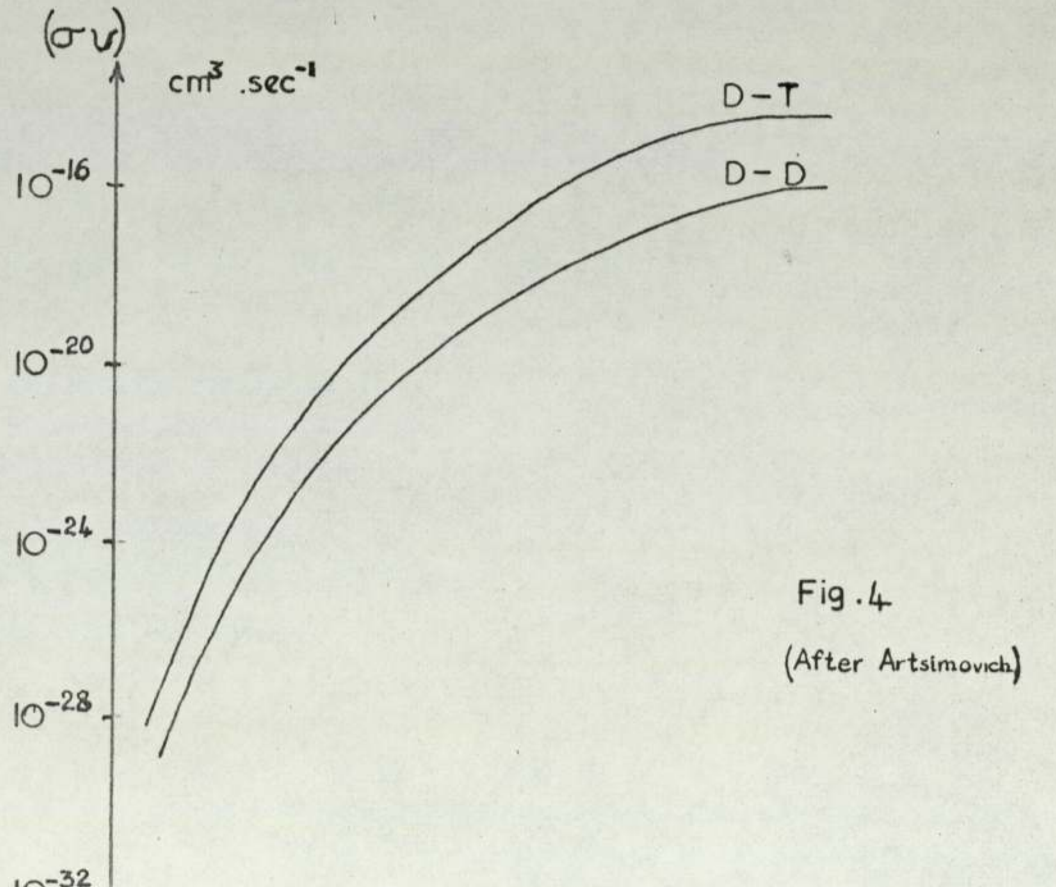


Fig. 4

(After Artsimovich)

CHAPTER 3

The Fusion Reactor

The anticipated form of a practical fusion reactor to realise the conditions previously stipulated can now be discussed. This discussion will show the principal features to be incorporated in the simulator.

Early work in the fusion field was carried out with plasma formed in a straight or linear tube with end electrodes. This soon encountered the difficulties of

(a) loss of heat to the electrodes

(b) instabilities in the discharge.

The loss of heat and hence a fall of temperature with a deterioration of the plasma was removed by bending the tube to a 'torus' form, otherwise called a dough-nut (American style). Provided the torus vessel was non-conducting the plasma could be used as the single turn secondary of a huge transformer and an electrodeless discharge created within the plasma. This is the form now favoured.

Instabilities in a linear discharge were of two forms

(a) kinks

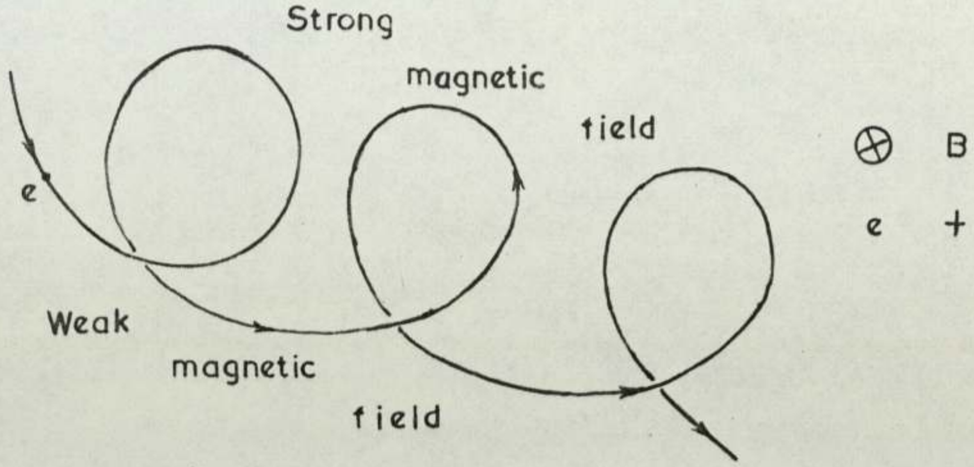
(b) necking or 'sausage' form

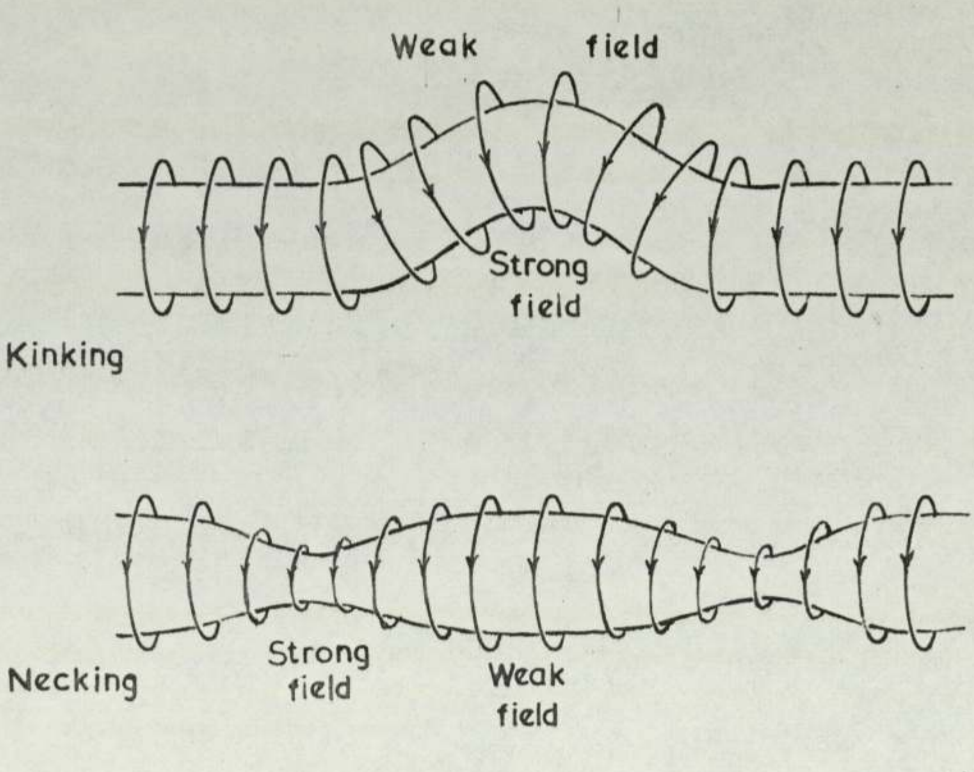
The plasma in a torus is invariably heated electrically and the current therein creates its own concentric magnetic field. Its behaviour can be considered in two ways.

The charged particles of the plasma will, in the magnetic field created make circular motion. In a uniform magnetic field this would be a truly circular motion. But in the non-uniform field of the plasma current the motion is not perfectly circular and results in a drift of the particles across the fields to its weaker regions as in Fig. 5 p.18. Alternatively, taking a macroscopic aspect, the plasma shows

Fig. 5

Ion trajectory





Plasma instabilities

Fig. 6

diamagnetic properties and may be said to be drawn towards a weaker field. By either consideration a slight disturbance of the plasma off its axis results in a weaker field to the convex side of the disturbance and the plasma is attracted to that region, aggrevating the effect and enhancing the disturbance or kink.

Where the plasma suffers a slight decrease in cross section the current density and the magnetic field at the surface of the plasma will both increase. The plasma will flow away from this region forming a neck in the plasma and if several necks are formed the condition is a 'sausage'form of instability. See Fig. 6 p.18.

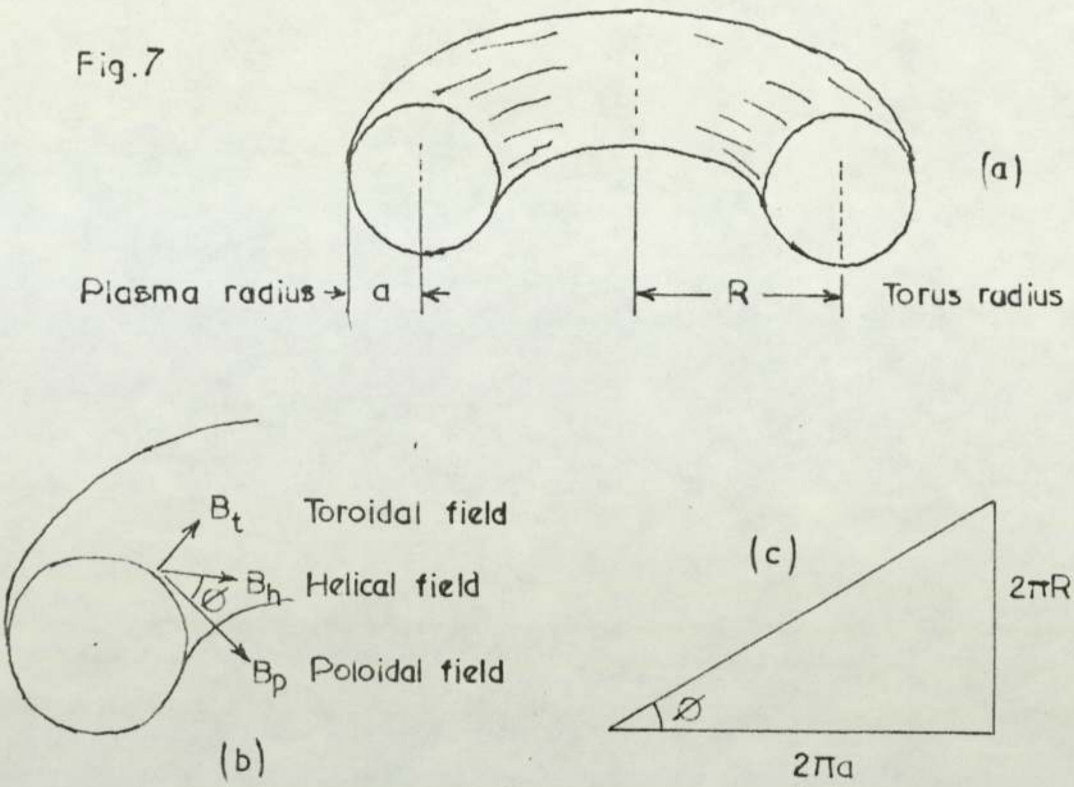
In extreme cases the kink or the bulge of plasma may expand to touch the walls of the vessel, causing a cooling of the plasma and/or the removal of some wall material and contamination of the fuel gases.

It was soon found that a toroidal magnetic field applied along the axis of the plasma discharge would aid stability and the field was supplied by current through a coil winding on the torus vessel itself. The toroidal field also assisted the natural 'pinching' action of the plasma current to confine the plasma within a small radius and away from the walls of the vessel. A succession of machines with various patterns and strengths of toroidal field were developed in attempts to overcome instability. The mirror machines and stellarators in the U.S.A., Zeta in Britain and the Tokamaks in the U.S.S.R. are examples. Of these the Tokamak design is most promising and the Joint European Torus machine (JET) to be built at Culham follows its pattern. The simulator is based on a Tokamak design.

A series of Tokamaks has been designed and Tokamak III is well described in Golovin's (6) paper, "Tokamak as a possible fusion reactor". In common with other 'torus' machines, the tritium-deuterium fuel mixture is contained in the torus vessel and forms the single turn secondary of a step-down transformer. The primary winding carries the discharge, when initiated, of a bank of capacitors. Currents of the order of millions of amperes are created in the plasma when the discharge occurs. The torus is formed of insulated sections so that there is no parallel path to that of the plasma and carries the external windings to obtain the toroidal field. For extremely high fields these windings may be super-cooled to make use of superconductivity in certain metals, e.g. niobium. Surrounding the torus is a blanket of layers of lithium, graphite and thermal insulation. The graphite moderates the fast neutrons generated in the nuclear reactions and gives neutron radiation shielding; the lithium is an absorber of neutrons and breeder of tritium as already mentioned and thermal insulation reduces loss of heat to the surroundings. Cooling pipes are laid throughout the blanket to transfer heat to the steam raising plant.

One limitation to the heating of the plasma has already been mentioned, that is, the increase of electrical conductivity and a consequent fall in heating as the plasma temperature rises . Another limitation follows from a relationship between toroidal field, plasma current and the onset of instability in the plasma. Kruskel [(16)] showed that the toroidal field with the poloidal field due to the plasma current produced a helical field around the torus. The direction of this field relative to the plasma axis depends on the ratio of the poloidal and toroidal fields. See Fig. 7 p.21.

Fig. 7



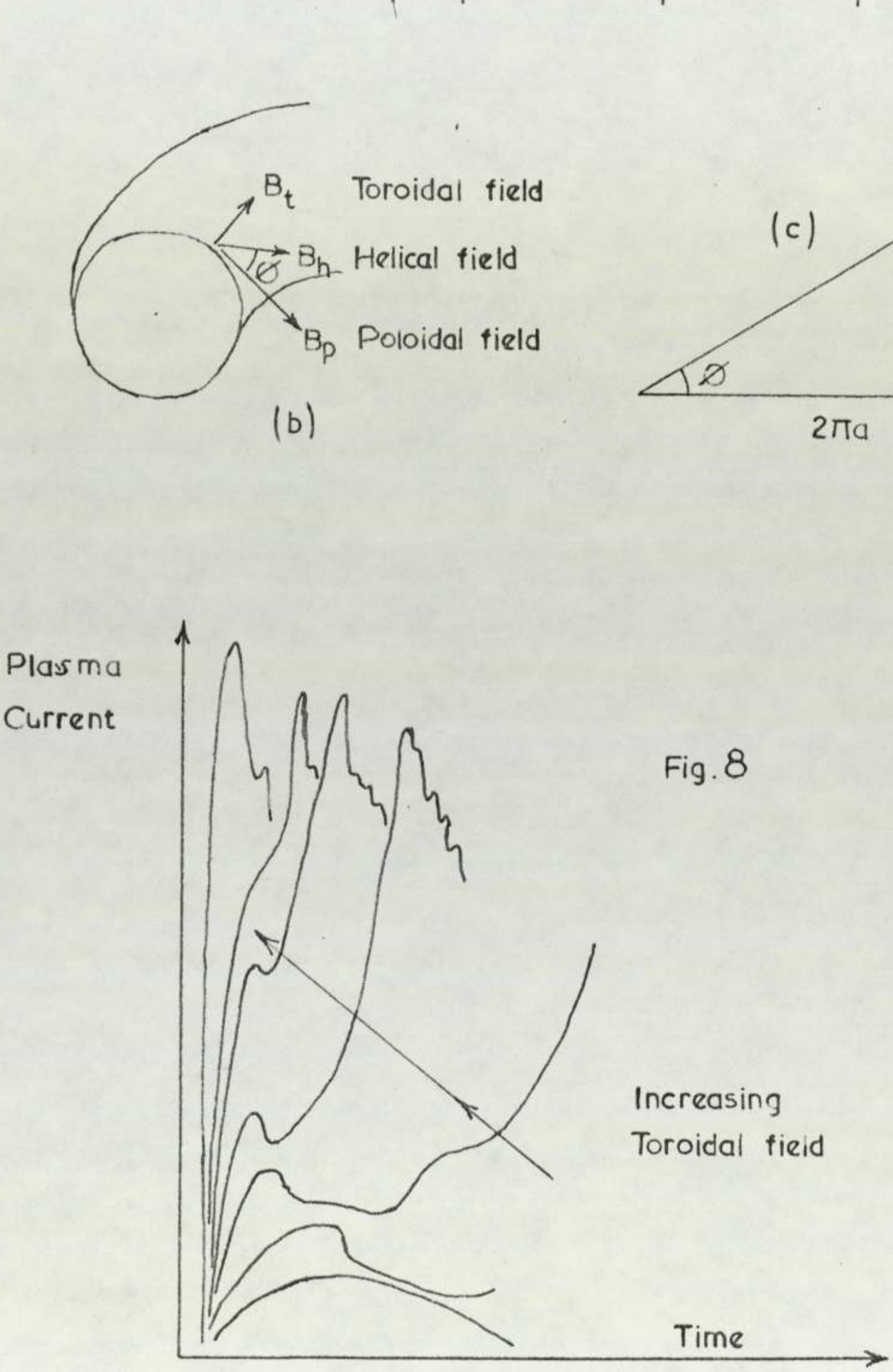


Fig. 8

(After, Rose and Clark. fig 16.14)

If the helical field makes a complete rotation around the torus, and plasma, in one traverse of the torus circumference then instabilities can be expected. The onset of instability limits the plasma current which can then only be increased by a corresponding increase in the toroidal field. If the helical field needs two traverses of the torus circumference to make one rotation of the plasma then the stability is greater and the stability margin is said to be q = 2. Fig. 8 p.21 (not to scale) follows that of Rose and Clark [7] (fig. 16.14) to illustrate Kruskel's criterion.

With limitations to the toroidal field and the plasma the ohmic heating becomes insufficient to raise the plasma temperature to ignition point and must be augmented. The methods available are

(a) alpha particle heating

(b) neutral injection heating

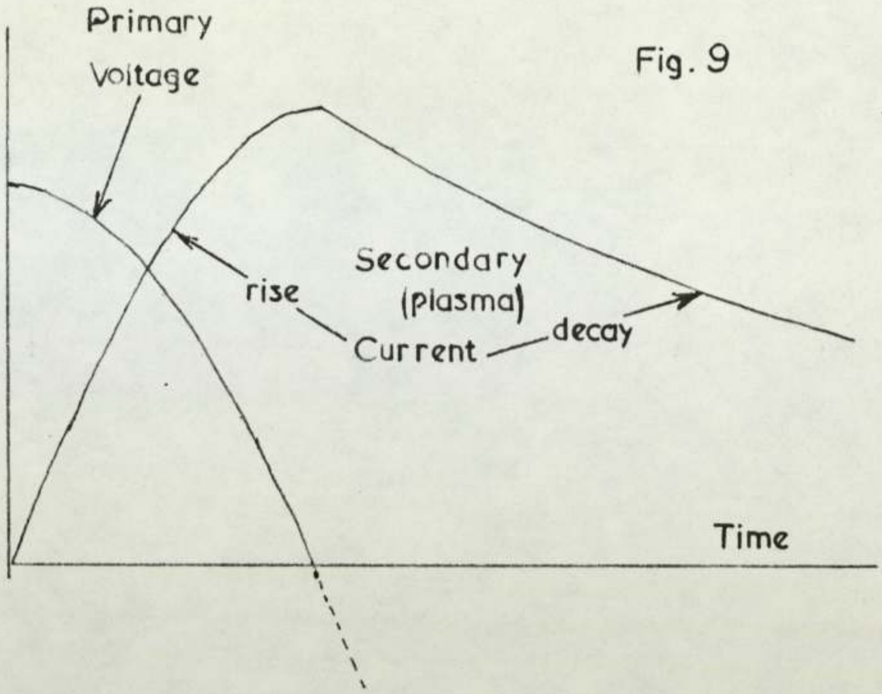
(c) radio frequency heating

When nuclear reactions occur in the plasma then alpha-particles with 3.52 Mev of energy are released. These travel comparatively slowly and give up their energy to the plasma ions before escaping from the plasma or capturing electrons and becoming neutral helium atoms. However, the alpha particles are not generated in sufficient numbers until the ignition temperature is reached. To bridge the gap between ohmic heating and alpha heating neutral injection heating is used. The entry of charged particles into the plasma is opposed by the electric and magnetic fields there present. Therefore, in an exterior unit hydrogen is first ionised and the positive ions accelerated to energies of the order of 50 to 100 Kev (higher energies are projected in future machines). The positive hydrogen ions are passed through a neutralising chamber to acquire the neutralising electrons.

These neutral hydrogen atoms of high energy can now enter the plasma region without difficulty and by collisions with the plasma ions can give these an additional 50 or more Kev.

Radio frequency heating [8] appears to have received less development than neutral injection heating. The principle of the method is to establish a travelling wave on the surface of the plasma by using two or more sets of conductors, around the plasma, fed with currents with a suitable phase difference. The travelling wave produces a ripple on the plasma surface which is alternately expanded and compressed to give a heating.

The sequence of operations is briefly as follows. The transformer core is first given reverse magnetism to permit a large change in flux. Then a radio frequency discharge through the fuel gases makes these initially conducting. A bank of capacitors of some 3000 Farads, charged to some 25,000 volts is discharged through the primary winding of the transformer. The discharge is oscillatory and the plasma current rises in an approximate sine mode. To avoid a draining back of energy to the capacitors the primary discharge is cut off (crowbarred) at the instant when the primary voltage has fallen to zero. From this instant the plasma starts to decay exponentially. See Fig. 9 p.24. Ohmic heating follows the plasma current rise and fall and at some point in the operational period neutral injection heating must be introduced. The extent of this auxilliary heating will depend on how much further temperature rise is required. Should ignition temperature be reached it is anticipated that nuclear reactions will continue until the fuel gases are weakened or the densities too low for maintenance of an adequate supply of alpha particles for heating. When the temperature falls below ignition the operational period ends with the removal of the toroidal field and is followed by a recharging period for recharging the


Primary
Voltage
Fig. 9
rise
Secondary
(plasma)
Current
decay
Time

capacitors and refuelling the torus.

The self-sustaining nuclear reactions above the ignition temperature are expected to be achieved in the mid 1980's. The conditions for this include the Lawson criteria that

$$n \times \tau_E > 3 \times 10^{14}$$

where n is the ion density (No. per millilitre)

τ_E is an energy replacement time

and this applies for temperatures above about 10 Kev.

Inevitably there are energy losses from the plasma. Energy is lost from the system by

(a) Bremsstrahlung radiation from the slowing down of electrons in collisions with ions, in which collisions the electron is accelerated in the coulomb field of the ion. This is electromagnetic radiation in the X - ray region.

(b) Cyclotron radiation from charged particles describing circular paths in the magnetic field and hence subject to continuous acceleration.

(c) A drift of charged particles towards the walls of the torus due to non-uniform magnetic fields.

(d) The presence of impurities of high atomic number which have high ionising energies and exert a cooling effect on the plasma.

(e) Thermal conduction through the blanket.

(f) Black body radiation according to Stefan's Law.

(g) Escape of neutrons through the Lithium blanket into the graphite and external biological shield, the neutrons not being contained by the magnetic fields.

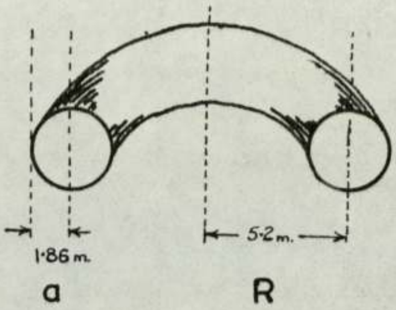
Calculations in Appendix 2. show the relative magnitudes of these losses. These show also that (a) and (b) are the most important and the simulator has been limited to the inclusion of these two negative feedbacks only.

CHAPTER 4

The Fusion Simulator Equations.

In the block diagram of Fig. 10 the various 'boxes' represent D.C. Amplifiers, either singly or in groups. The equations now to be considered determine the several inputs to these amplifiers, any multiplication of the signal needed, constants to be added or subtracted and the polarity of the signal to be passed to the next 'box'. The magnitude of some signals will depend on the reactor being simulated.

The reactor to be simulated is assumed to have a major torus radius of 5.2 metres a minor torus radius of 1.86 metres as per Golovin's[6] paper (Table I, p.15) and estimated by him to provide 5000 Megawatts of thermal power.



The power dissipated P_{Ω} in the plasma at constant temperature by ohmic heating is

$$P_{\Omega} = I^2 \mathcal{R}$$ where I is the instantaneous plasma current

$$= \frac{I^2 . 2\pi R . \rho}{a^2 \pi}$$ $\mathcal{R}$ is the resistance of the plasma

a is the minor torus radius

$$P_{\Omega} = \frac{I^2 , 2R . \rho}{a^2}$$ R is the major torus radius

ρ is the resistivity of the plasma

But the conductivity depends on the temperature of the plasma according to the Spitzer formula

$$\frac{1}{\rho} = \frac{1}{\rho_o} . T_e^{3/2}$$ where T_e is the electron temperature

$$= 12 . T_e^{3/2}$$ according to Golovin [6]

Hence

$$P_{\Omega} = \frac{I^2 . 2R .}{a^2 . 12 . T_e^{3/2}} = I^2 . \frac{R .}{6a^2} T^{-3/2}$$

and as $\frac{R}{6a^2} = 0.0025 \text{ cm}^{-1}$

and $\log_{10}(0.0025) = \bar{3}.398 = -2.602$

converting the equation to log form gives

$$\log(P_\Omega) = 2.\log(I) - (1.5)\log(T_e) + \text{constant}$$

or $$\log(P_\Omega) = 2.\log(I) - (1.5)\log(T_e) - 2.602$$

It should be noted that as this is a 'point' simulator, both temperature and conductivity are assumed constant throughout the plasma.

The energy put into the plasma in one cycle will be the sum of the powers supplied from external sources by ohmic heating and neutral injection heating plus the alpha particle heating from internal generation less the losses due to Bremsstrahlung and cyclotron radiation.

Hence

$$E = \oint (P_\Omega + P_\alpha + P_{NIH} - P_B - P_c).\,dt$$ taken over a whole cycle

where P_Ω = Ohmic heating power (watts)

P_α = Alpha particle power (watts)

P_{NIH} = NIH power (watts)

P_B = Bremsstrahlung power loss (watts)

P_c = Cyclotron power loss (watts)

t = time (seconds)

E = Energy given to plasma (joules)

It should be noted that linear powers are being integrated. If log forms were used then the powers would be multiplied together, which is not so.

The energy E is next converted to log (E) by a log amplifier.

The relation between the energy supplied to the plasma and the temperature reached is

$E = 3n.k.T.$ (per millilitre) where n = No. of ions per millilitre

k = Boltzmann's constant

$= 1.60 \times 10^{-16}$ joules/Kev

T = temperature in Kev.

Hence

$$\log(T) = \log(E) - \log(n) - \log(k)$$

and as $\log(k) = \log(1.60 \times 10^{-16}) = \overline{16}.2041 = -15.8$

$$\underline{\log(T) = \log(E) - \log(n) + 15.8}$$

Golovin gives the Bremsstrahlung power loss as

$$P_B = 2.2(\pi^2) \cdot 10^{-32} \cdot n^2 \cdot R.a^2 \cdot T^{\frac{1}{2}} \text{ watts (total)}$$

where T is in ev.

or $P_B = 1.25 \times 10^{-22} \cdot n^2 . T^{\frac{1}{2}}$ where T is in Kev

hence

$$\underline{\log(P_B) = 2.\log(n) + (0.5)\log(T) - 21.9}$$

Log (P_B), is converted to linear P_B and fed back to the 'E into plasma' box.

Golovin gives the cyclotron power loss as

$$P_c = 6.2 \times 10^{-20} \cdot (\pi^2) . B^2 . n.T.R.a^2 . K_\alpha \text{ watts (total)}$$

where B is the toroidal magnetic field (Tesla)

K_α is an absoption factor of the plasma for the cyclotron radiation

Rose and Clark[7] give K_α as between 0.1 and 0.002 depending on the electron velocities and therefore on temperature. At temperatures below 25 Kev, K changes only slowly with temperature and a constant value of 0.05 will be assumed. Golovin's design for the 5,000 megawatt thermal output reactor assumes a value for the magnetic field B of 4 Tesla.

Therefore

$$P_c = 1.101 \times 10^{-11} \times n.T.B^2$$

and $\underline{\log(P_C) = 2.\log(B) + \log(n) + \log(T) - 10.96}$

Log (P_c) is converted to linear P_c and fed back to the 'E into plasma' box.

The reaction rate for nuclear reactions in the plasma is

Reaction rate $= (\sigma v) . n_D . n_T \quad cm^{-3}.sec^{-1}$

No of reactions per operational period $= (\sigma v) . n_D . n_T . t \quad cm^{-3}$

Energy release per operational period $= (\sigma v) . n_D . n_T . t.Q$ joules. cm^{-3}

Average power per cycle $= (\sigma v) . n_D . n_T . t.Q/\tau$ watts.cm^{-3}

Average power per cycle (total) $= (\sigma v) . n_D . n_T . t. Q.2\pi^2 R.a^2/\tau$ watts

$P_o = (\sigma v) . n_D . n_T .(1.295.10^{-3}. t/\tau$ watts

where t = duration of operational period

τ = duration of cycle including recharging period

Q = energy release in the D-T reaction

Hence

$$\log(P_o) = \log(n_D) + \log(n_T) + \log(\sigma v) + \log(t/\tau) - 2.89$$

The averaged quantity (σv) is a function of temperature but is not a simple function. It is $\log(\sigma v)$ which is required and this is given empirically by

$$\log(\sigma v) = 5.75 \log [\log(T)] - 16.56$$

As shown in Fig 37 the calculated values for log (σv) from this expression agree with those from Golovin's quoted values of (σv) to within 1% over the range of temperatures 2 Kev to 40 Kev.

Hence

$$\log(P_o) = \log(n_D) + \log(n_T) + 5.75\log [\log(T)] + \log(t/\tau) - 19.45$$

Using a function generator, log (P_o) is converted to linear P_o which can be integrated to give linear E_o, the energy produced by nuclear reactions.

CHAPTER 5

The Fusion Reactor Simulator

A block diagram of the simulator is shown in Fig. 10 p.31. For simplification potentiometers controlling input parameters and potentiometers introducing constants have been omitted. These details can be found on the full simulator circuit.

The diagram has a central chain of boxes starting at E_{IN} and continuing to E_o when it splits to give two outputs, one showing the efficiency of the system and if 'saleable' power is available; the other to show the average power output over an operational period, a full cycle or a number of cycles. At positions along the chain parameters are introduced and from other positions positive and negative feedbacks are returned to the start of the chain. The initial input point is shown.

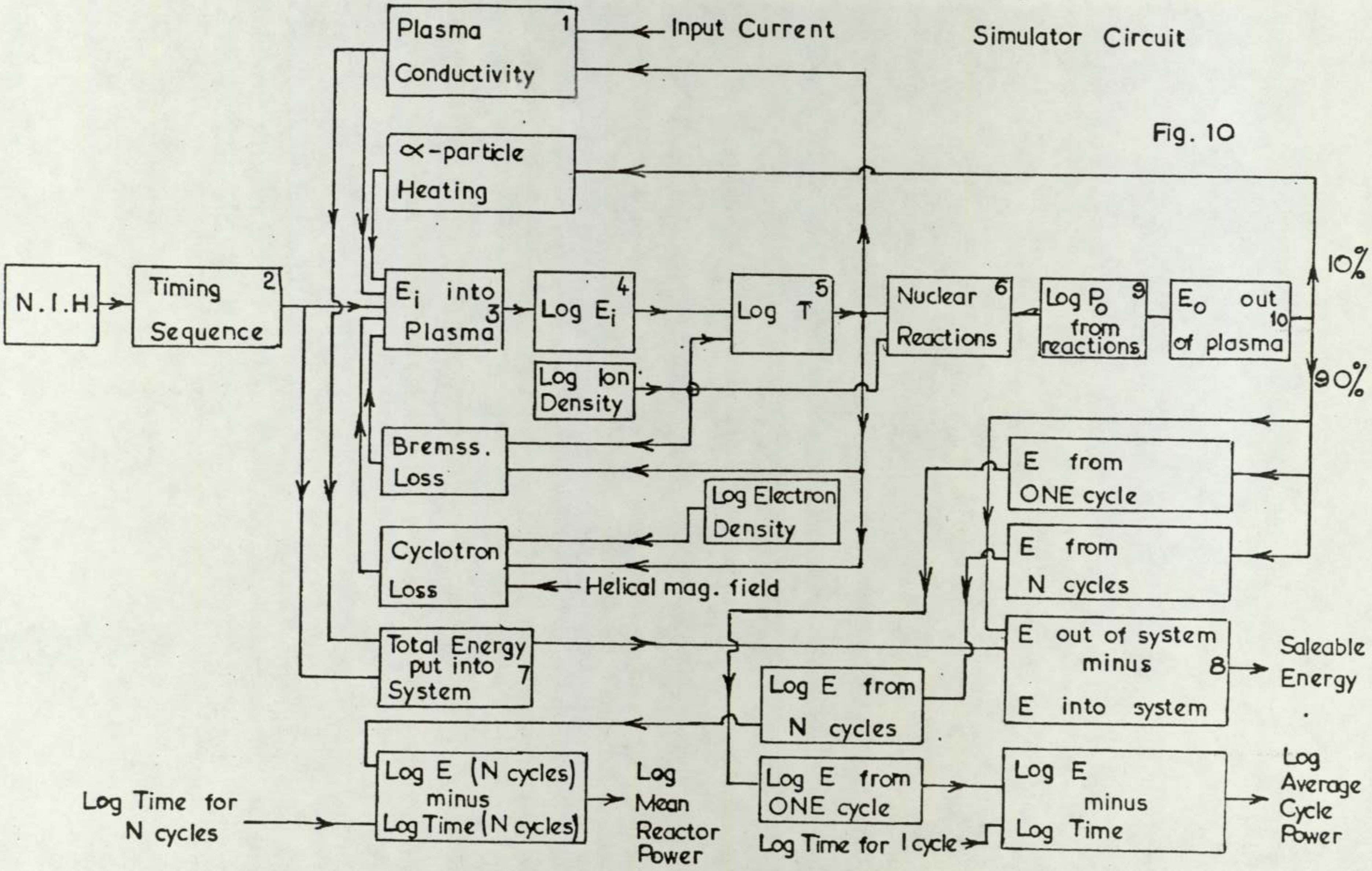
The discharge current in the plasma, reaching the order of several million amperes will have a particular waveform depending on the circuit impedances. An approximation to this waveform is simulated and its representative signal voltage is fed in log form into No. 1 box (plasma conductivity). A log (temperature) signal modifies the log (current) which is then converted to linear (current) and fed to the No.3 box. The neutral injection signal in linear form is passed through No. 2 box (timing sequence) which determines its duration and position in the reactor cycle. This signal also passes into No. 3 box.

These two signals, linear (current) and NIH are separately integrated together to produce a summation of the energy put into the plasma from external sources in No. 7 box.

Signals affecting the energy into the plasma need to be linear by reason of difficulties in summing and integrating log quantities. The linear E_{IN} output from No. 3 box is

Block Diagram of main Simulator Circuit

Fig. 10



converted to log (E_{IN}), in No. 4 box and is then combined with log (ion density) to give log (temperature) from No. 5 box. Log (temperature) and log (ion density) together with a constant determine the log (Bremsstrahlung loss) which is converted to linear (Brem. loss) and fed back to No. 3 box out of phase with the ohmic heating and NIH signals, i.e. as a negative feedback. The cyclotron loss depends additionally on the toroidal magnetic field on the plasma axis as well as the temperature and the electron density. Like the Bremsstrahlung loss signal, it is obtained in log form, is linearised and fed back to No. 3 box also as a negative feedback.

The cross-sections for nuclear reactions in the plasma depend on the particle velocities and hence on temperature. The output of No. 5 box (log(T)) is operated on by No.s 6 & 9 boxes to give log (E) i.e. the energy produced by the nuclear reactions. This quantity is linearised and integrated to give linear (E) from No. 10 box. About 10% of this energy is taken away by the alpha particles formed in the reactions and is fed back to No. 3 box as a positive feedback producing additional heating of the plasma. The remaining 90% of the energy E is useable energy. To see if the reactor is commercially viable this energy must be compared with that put in from external sources. This is done in No. 8 box which subtracts the output of No. 7 box, i.e. energy put into the system from exteranl sources, from E_s the useable or saleable energy. Initially the output of No. 8 box is negative becoming positive when there is a gain of energy. This can be displayed on a centre zero 'power' meter.

One cycle is obviously inadequate for average power measurement. The simulator will repeat the cycle automatically and both the saleable energy and the elapsed time can be integrated and divided by logging to give the mean power over n cycles. This will not be the same as the average cycle power due to the recharging periods between operational periods.

CHAPTER 6

Simulator Circuitry.

This chapter will consider first some of the less familiar units used in the simulator circuitry and then proceed to see in more detail how the circuit is assembled.

Note. Owing to their frequent usage certain electrical terms will from this point be abbreviated where appropriate and particularly when followed by a reference number. e.g.

Potentiometer - Pot.P6 Diode Function Generator - DFG 2

Amplifier - Amp. 4 Input - $^{I}/_{P}$.

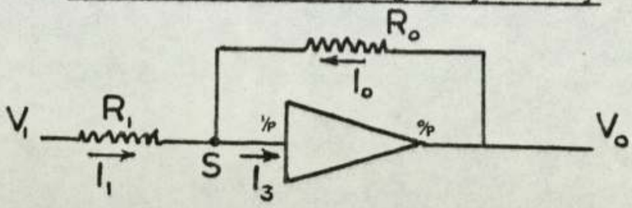
Integrator - INT. 3 Output- $^{O}/_{P}$

The principal unit in the simulator circuitry is the D.C.Amplifier. This may be interpreted as 'direct current' amplifier or as a 'directly coupled' amplifier, the noteworthy feature being an absence of capacitors in the signal path, i.e. in the interstage couplings.

A principal requirement of the D.C.Amplifier is a very high gain on open circuit. In earlier days amplifiers employing up to seven or eight valves had gains around 3×10^7 . Modern transistorised amplifiers have gains around 10^5 to 10^6 . These high gains are rarely used in the simulator circuitry since negative feedback is incorporated and restricts the overall gain to about 100 maximum. Valve amplifiers operate with signal inputs in the range of 0.1 to 100 volts and outputs not exceeding 100 volts of either polarity. Transistorised D.C. Amplifiers now usually obtained as integrated encapsulated units operate with signal imputs between 0.01 and 10 volts and output signals up to 10 volts. Most amplifiers tend to drift i.e. for their $^{O}/_{P}$ voltage to build up even in the absence of an $^{I}/_{P}$ signal. For correction, the drift voltage is 'chopped', amplified by a small A.C. Amplifier, rectified and returned to the Input of the D.C. Amplifier with the correct phase to nullify the drift voltage. Without drift correction amplifiers used for integrating give large errors.

The amplifier is used in the simulator in several modes. It is indicated by a triangle with I/P and O/P.

(a) As an invertor of signal polarity



With the resistors, voltages and currents as shown, Kirchoff's Law can be applied to the currents at S

$$I_1 + I_o + I_3 = 0$$

Since the gain of the amplifier is, say, 10^7, and the output voltage is limited to 100 volts, the input voltage to the amplifier alone must not exceed 10^{-5} volt. The input current to the amplifier (I_3) is therefore very small indeed and can be neglected.

$$I_1 + I_o \doteq 0$$

$$\frac{V_1}{R_1} + \frac{V_o}{R_o} = 0$$

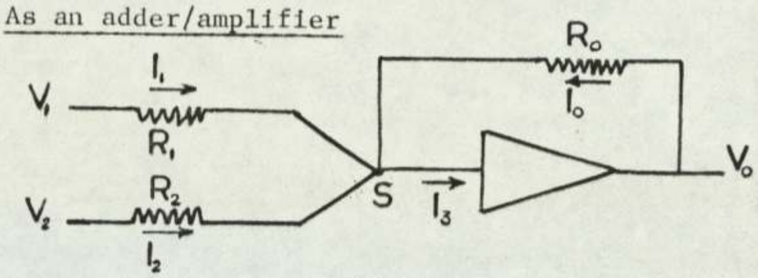
or $$V_o = \frac{-R_o}{R_1} . V_1$$

and if $R_o = R_1$, the signal input voltage has been inverted as shown by the negative sign,

(b) As an amplifier

By making $R_o \gg R_1$, a gain of signal voltage is obtained.

(c) As an adder/amplifier



Again applying Kirchoff's Law to the currents at S and as before neglecting I_3.

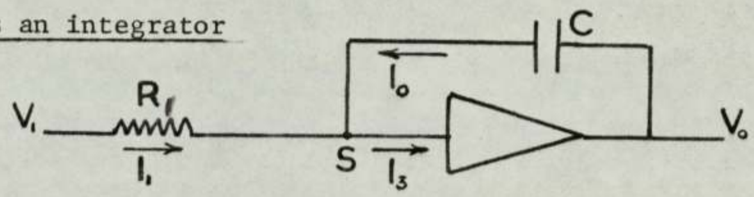
$$I_1 + I_2 + I_o = 0$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_o}{R_o} = 0$$

$$V_o = -\frac{R_o}{R_1} . V_1 + \frac{R_o}{R_2} . V_2$$

If $R_1 = R_2 = R_o$, there is straightforward addition or the signal voltages can be individually amplified and added.

(d) As an integrator



Applying the previous method at S and neglecting I_3

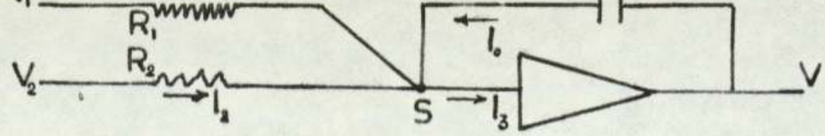
$$I_1 + I_o = 0$$

$$\frac{V_1}{R_1} + \frac{C.dVo}{dt} = 0$$

$$\frac{dVo}{dt} = -\frac{I}{R_1C} . V_1$$

$$V_o = -\frac{I}{R_1C}\int V_1 . dt$$

Similarly several input signals can be simultaneously integrated, amplified and added.

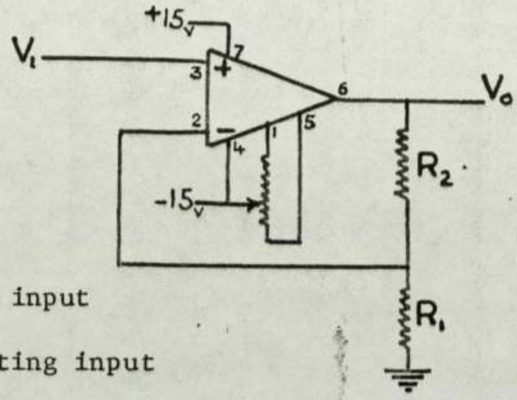


$$V_o = -\int_0^t \frac{V_1}{R_1C} . dt - \int_0^t \frac{V_2}{R_2C} . dt = -\frac{1}{R_1C}\left[\int_0^t V_1 . dt - \frac{R_1}{R_2}\int_0^t V_2 . dt\right]$$

So that one signal may be amplified relative to another, both integrated with respect to time and added.

The above uses of the D.C. Amplifier apply to both valve(Type MEC100) and transistorised (Type 741) amplifiers except that the 741 amplifier, not being drift corrected, is not a reliable integrator over the long periods used in the simulator. The 741 amplifier however has an additional facility, a non-inverting input. This uses a circuit :-

(e)



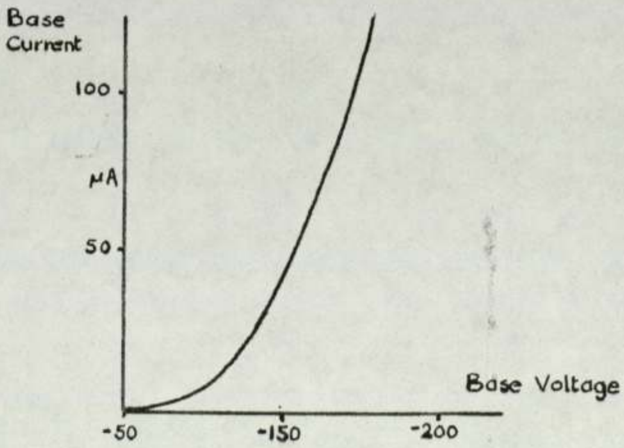
− Is the inverting input

+ Is the non-inverting input

V_o and V_1 have the same polarity and the gain of the circuit is

$$\frac{V_o}{V_1} = 1 + \frac{R_2}{R_1} \qquad \text{or } G = 1 + \frac{R_2}{R_1}$$

(f) <u>The conversion of linear signals to log form</u>



units?

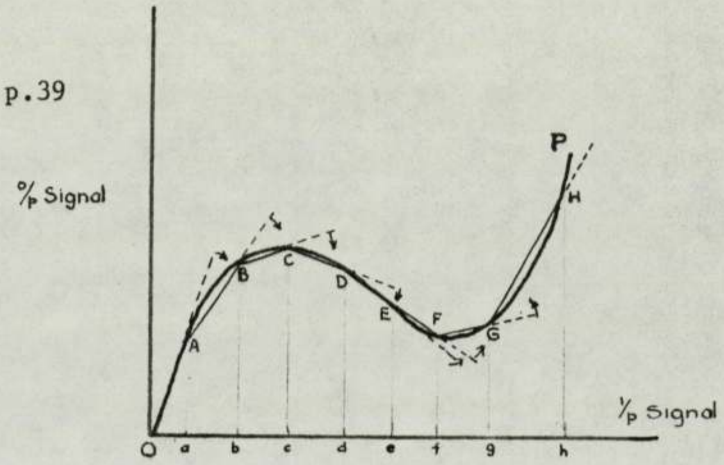
The characteristic of a transistor, base current versus base voltage is approximately exponential as shown. This characteristic is used in transistorised log amplifiers which operate over a small input signal range and with a small output signal. Typical ranges are, 10^{-3} to 1.0 volt input with an output signal of 0 to 1.0 volt.

(g) Function Generators

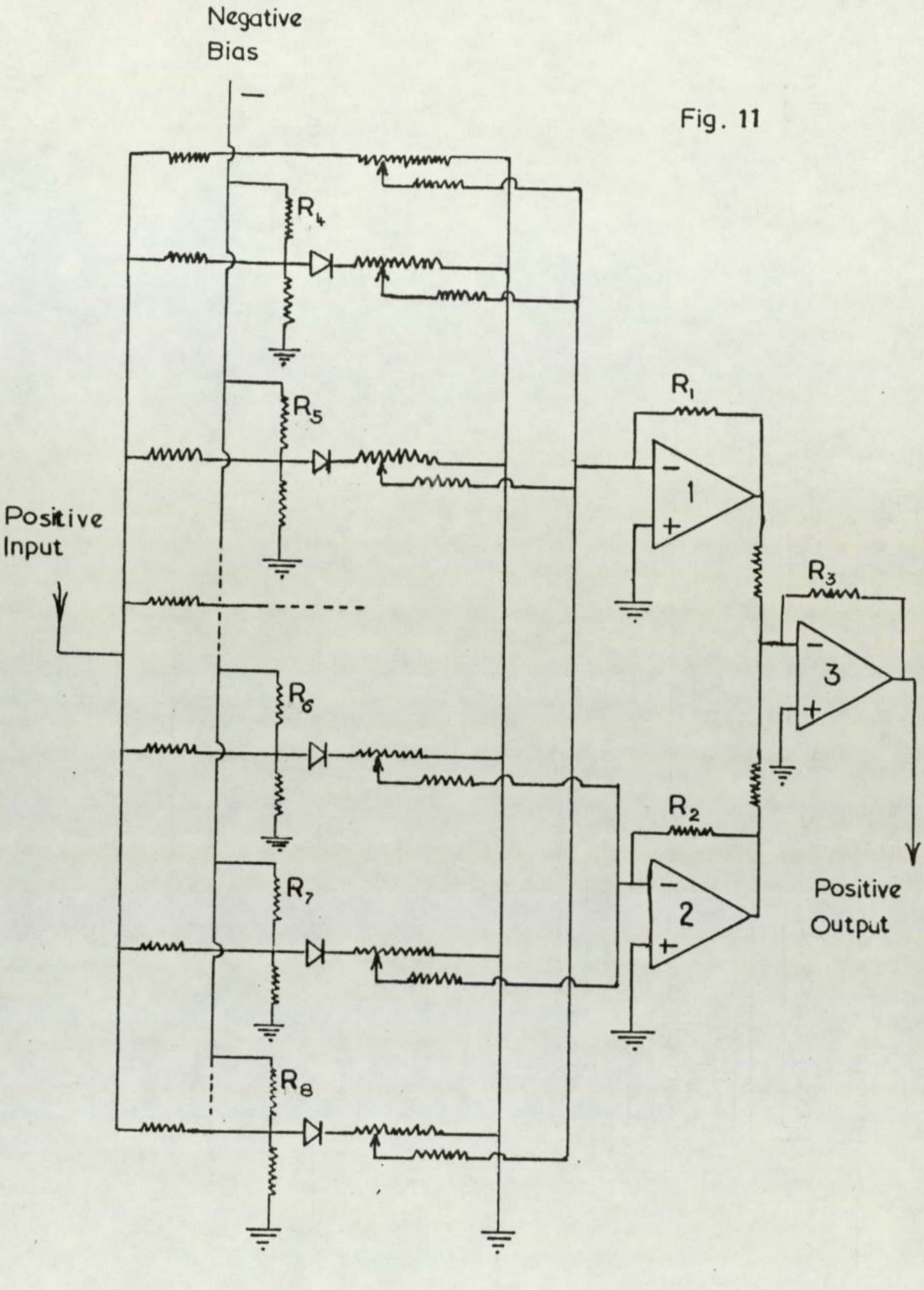
These play an important part in the simulator circuitry, principally as a means of converting log signals to linear signals, that is, they act as antilog devices. Several designs of function generator have been tested and much time and work has been expended in attempts to make them work satisfactorily. Before the integrated log amplifiers were available function generators were tried as linear to log converters but the results were very disappointing.

The circuit of the function generator finally used is shown in Fig. 11 p.38. The principle of the function generator is shown here.

See also Fig.11a p.39



A functional curve O to P can be assumed to be assumed to be made up of straight segments, OA, AB, BC, etc. A linearly rising voltage is fed to the function generator input. Via a potentiometer a part of the input signal is passed on directly to the D.C. Amplifier and the output voltage rises along OA. Suppose this is a positive input signal. At an input signal Oa a biassed diode in series with another potentiometer starts to conduct and passes a part of a negative version of the signal to the amplifier and, reduces the rate of rise of the output signal along AB. Similar events occur at input signals Ob, Oc, Od but at input Oe the conducting diode passes a positive signal to the amplifier. This causes the output to slow its downward trend and with more

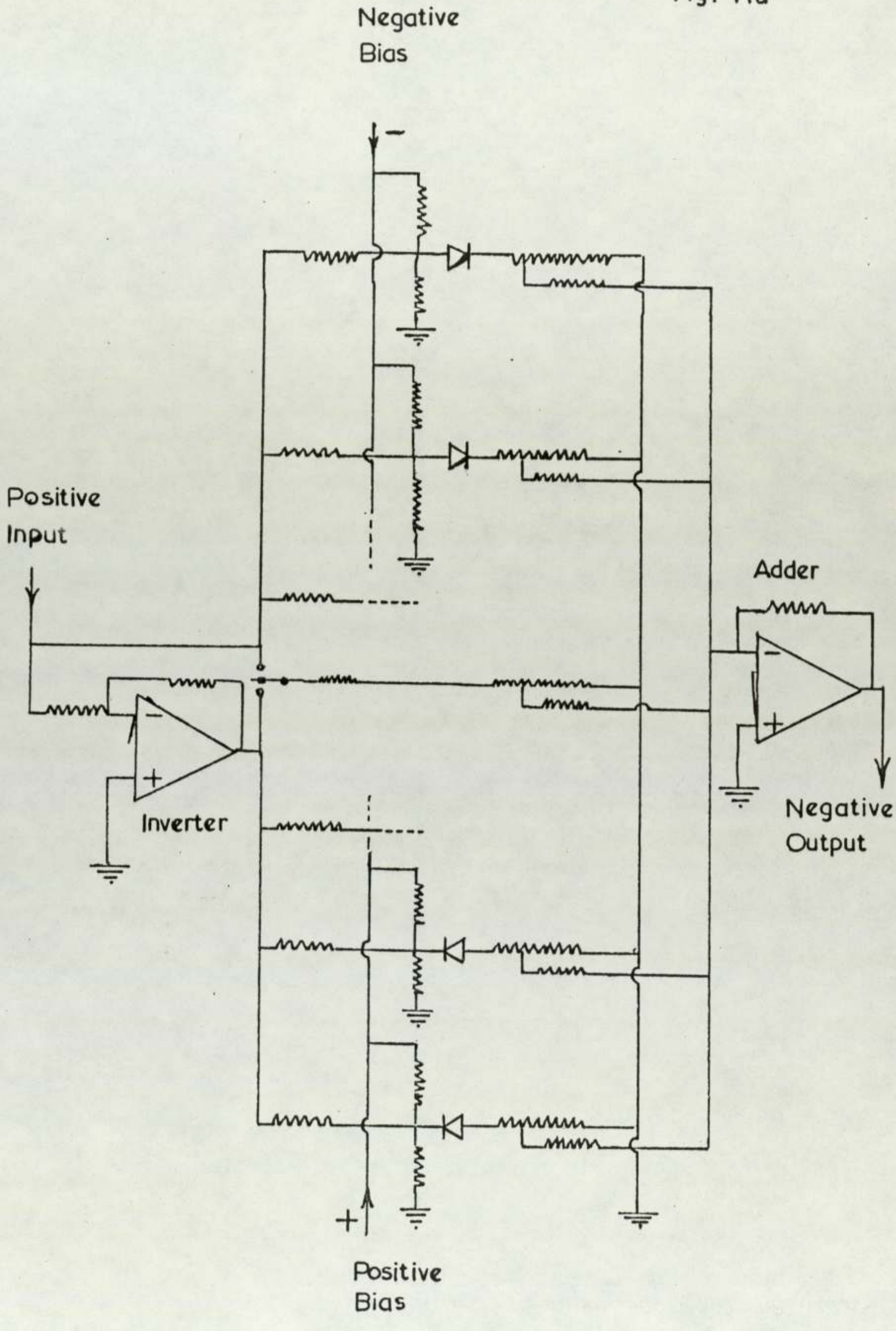


D.F.G. with extra gain on two elements

Suitable for a continuously increasing function

e.g. x v log x

Fig. 11a



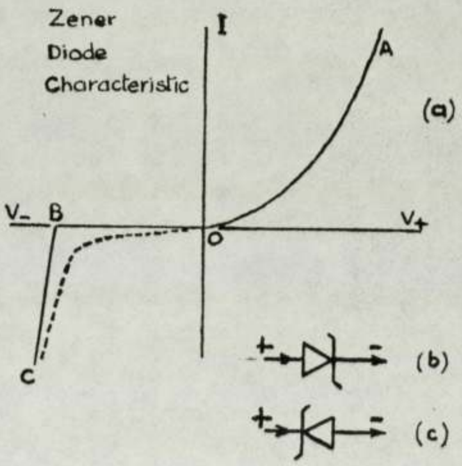
Diode Function Generator for General Use positive signals at higher inputs to rise along FG, GH etc.

The potentiometer settings determine the slopes of the segments; the bias on the diodes sets the 'break points', a, b, c, etc.

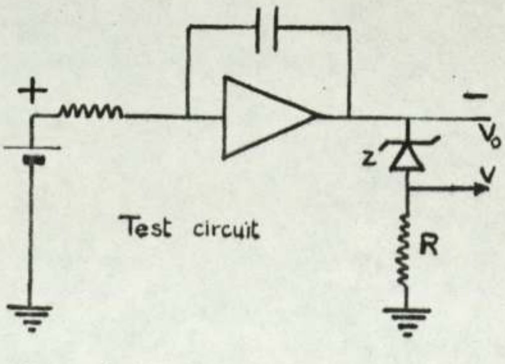
Obviously the accuracy of representation of the simulated function depends on the number of segments, that is, the number of biassed diode elements used and, of course, on the complexity of the functional curve.

In the early simulator design stages, log amplifiers to work with an input of 0 to 100 volts were not available and attempts were made to build function generators for linear to log conversion using Zener diodes rather than biassed diodes. Zener diodes are self-biassed and their use would simplify the circuitry by avoiding the introduction of a biassing supply.

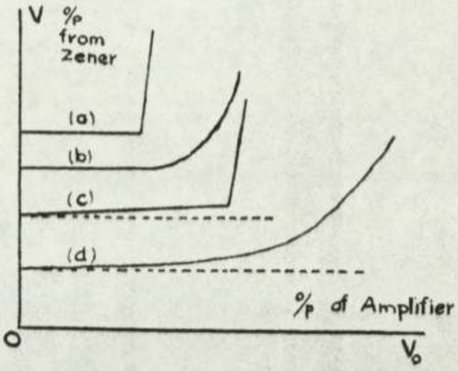
The Zener diode has a characteristic shown here at (a). OA is the usual characteristic when a voltage is applied across the diode as in (b). OBC is the characteristic when the voltage polarity is reversed as in (c). OB is the self-bias. In a good diode OB lies along the -V axis and the change to BC is very sharp. A poor diode has the dotted characteristic, the corner at B being rounded.



The zener diodes were tested in the circuit shown here. The amplifier in integrating mode gives a rising negative voltage at its output and hence across the zener diode and resistor R. The voltage V across R was passed to the Y motion of an X - Y



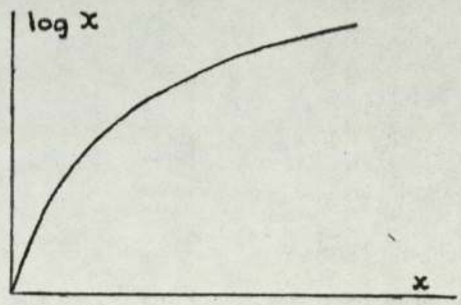
plotter, the X movement being obtained directly from the output of the amplifier.

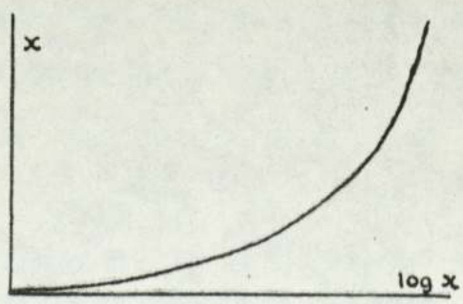


A large number of diodes was examined in this way and gave graphs as shown. Only those diodes with a well defined bias and a characteristic like (a) were acceptable. Generally, low biassed diodes (up to 10 volts) were unsatisfactory.

The function generator circuitry with zener diodes is shown in Fig. 12 p.42. Basically it is a simpler circuit than that of Fig. 11 but with the limitation that the break points are not variable and are set by the diode manufacturer. However, a range of biassing voltages is available and intermediate values can be obtained by series coupling diodes. Again, the potentiometers P_1, P_2 , etc set the slopes of the segments.

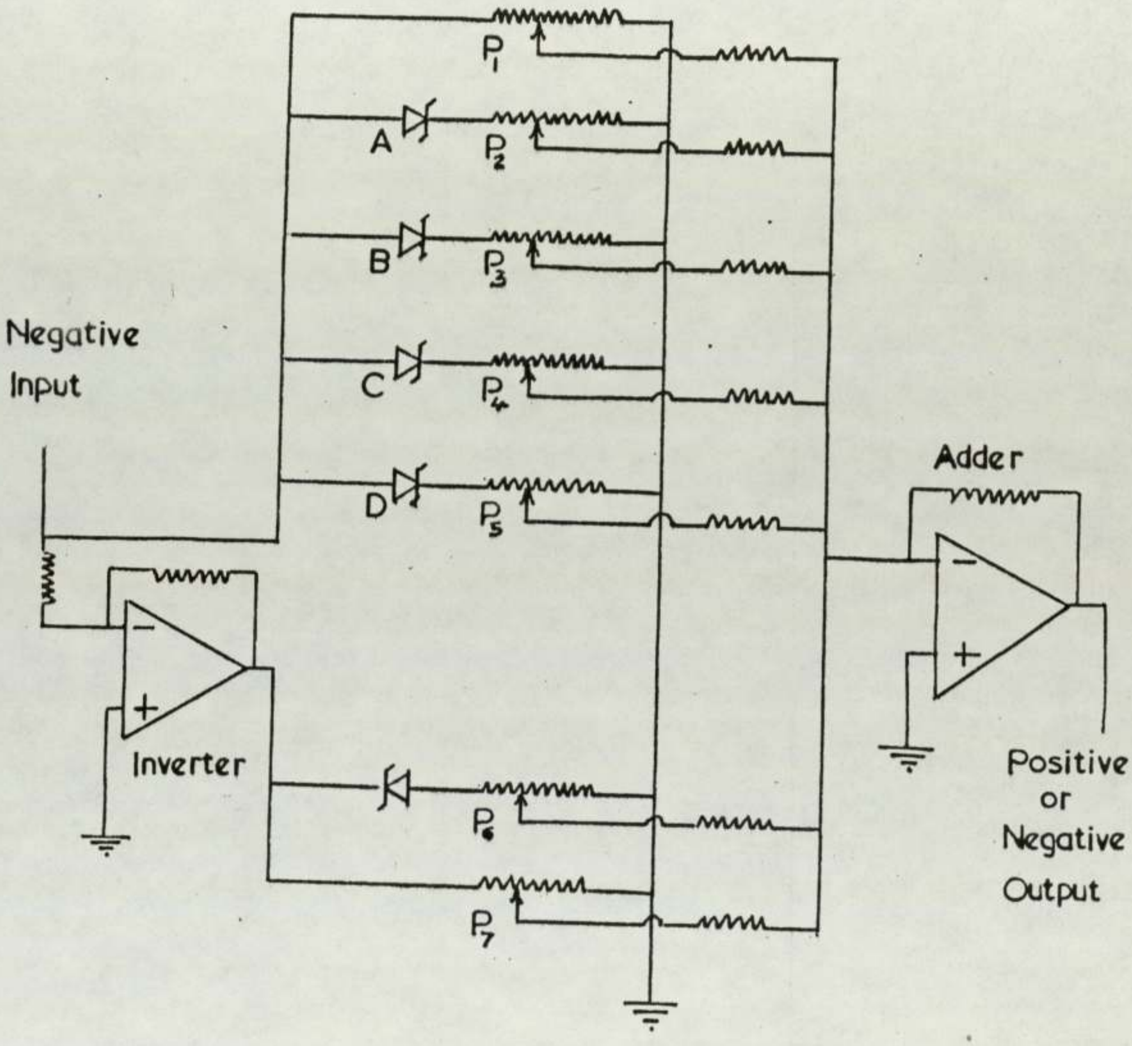
The curve of log x against x is shown here. x is the input signal and log x the output from the summing amplifier. There are frequent changes to be made to the slopes when x is small. This calls for a large number of segments and many break points close together. But this is the very region in which the zener diodes are least reliable, having characteristics like (b), (c) and (d) above. It was noted that, supposing A, B, and C diodes (Fig.12) were satisfactory and had been adjusted to give segments fitting the log x curve, then if diode D had a characteristic like (d) above, then on





Pots. P_6 and P_7 set initial slope positive or negative

Fig. 12



Diode Function Generator, with self-biassed zener diodes.

adjusting Pot.P5, previous adjustments were completely upset. In the end this system as a means for linear to log conversion was abandoned.

However, in the case of log to linear conversion the curve, as shown, is almost linear for small values of x. Consequently low voltage zener diodes were not required and the higher voltage zeners, being more reliable and with sharper 'corners', the system proved satisfactory for this conversion.

These comments apply to the early design stages working in the range 0 to 100 volts with the 'Space 30' computer. When the design was transistorised, log amplifiers were available for the linear to log conversion, but for the log to linear conversion in the 0 to 10 volt range the range of biassing voltages was too restricted and resource was made to the circuit of Fig.11.

It may be noted that

(a) An integrating amplifier used as the feedback for a D.C. amplifier gives a differentiating system.

(b) A differentiating amplifier used as the feedback for a D.C. amplifier gives an integrating system.

(c) A log amplifier used as the feedback for a D.C. amplifier gives an antilogging system.

The integrated log amplifier requires two additional integrated D.C. amplifiers to perform its normal linear to log conversion. To set this as a feedback as in (c) above would be rather complex and it was judged simpler to use a function generator as in Fig. 11 to make this conversion.

Before proceeding to explain the simulator circuitry in detail, it should be mentioned that the D.C. amplifiers used for summation, inversion and multiplying are of the type 'Texas 741'. These have frequency correction built in and use an external potentiometer for correcting offset voltage.

The supply voltages to this type are $\pm$ 18 volts maximum and this limits the output signal to around $\pm$ 12 volts, say $\pm$ 10 volts in use. This type 741 however, has no drift correction and for the comparatively long cycle periods of up to 3 minutes, is unsatisfactory for integration purposes. For integration a valve amplifier 'MEC 100' has been used. The final simulator is thus a hybrid.

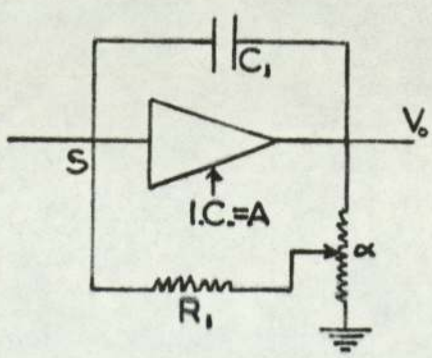
The simulator has been built into a standard 19" (48.3cms) rack occupying about 1½ metres of vertical space. Apart from the $\pm$ 300 volt power supplies for the valve amplifiers at the top and the meter panel at the bottom, the remainder is contained in small units 7" x 2¾" (17.8 x 7.0 cms) fitted into three 'nests'. These units approximately 10" (25cms) in depth, carry the valve amplifiers for integration, control circuits, diode function generators and power supplies for the integrated solid state amplifiers. See Fig. 17 p. 79.

The main simulator circuit of Fig.33, at the end of this work, will be considered next in this chapter and the control circuits in a following chapter.

The simulator circuit is built on four boards in a single unit, though the integrators and function generators are in separate units.

<u>Current Waveform Generation</u>

The current waveform is generated by the use of amplifiers 1, 2 and 3 and uses amplifier 4, to introduce the effect of temperature on the plasma conductivity and hence on the current waveform. The circuitry for Amp.1 and Amp.2 is shown here.



At S

$$C_1 \cdot \frac{dV_o}{dt} + \frac{\alpha V_o}{R_1} = 0$$

Hence V_o = A.exp(- t/R C)

where α = fractional setting of the potentiometer

A = initial condition (I.C.) constant

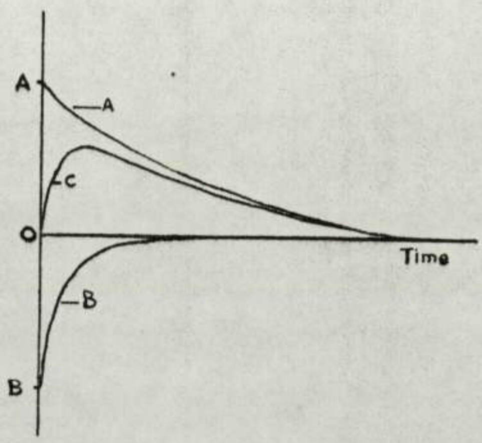
A similar circuit for Amp.2 yields an output voltage V_o^1

V_o^1 = B.exp(- t/R C)

where β = fractional setting of the potentiometer

B = initial condition constant

When integration occurs in the operational period the outputs of the amplifiers 1 & 2 are 'decaying exponentials' as shown. The constants A and B can be made equal but of opposite polarity and $R_1C_1 > R_2C_2$. The two outputs are added in Amp.3 and the combined output is as shown by curve OC. This curve OC simulates approximately the variation of



E.M.F. in the plasma representing the build up of E.M.F. and its subsequent decay. If the plasma has constant conductivity then the current waveform will be similar but will be changed by the effect of temperature on the plasma conductivity. The waveform OC can be changed by an alteration to any of the variables α, β , R_1, R_2, C_1, C_2.

Originally the log amplifier LA 1 was to receive the waveform from Amp.3 and convert it to log form but as discussed more fully in Chapter 9 (p.67) this was discarded and Amp.3 now sends its output direct to Pot.P9 and thence by the input resistor R.11 to Amp.4. The output of Amp.3, now assumed to be a near approximation to log I, is combined in Amp.4 with log T and a constant as in the equation

$$\log (P_n) \doteq 2.\log(I) - (1.5)\log(T) - 2.602$$

The output of Amp.4 therefore represents log (P_n)

N.B. P is just one of five power signals to be integrated to give the the total energy, less losses, to be dissipated in the plasma.

The requirement is

$$E = \int P_{\Omega} .dt + \int P_{\alpha} .dt + \int P_{NIH} .dt - \int P_{B} .dt - \int P_{c} .dt$$

$$E = \int (P_{\Omega} + P_{\alpha} + P_{NIH} - P_B - P_c).dt$$

This is obviously not the same as

$$E = \int (\log(P_{\Omega}) + \log(P_{NIH}) + \log(P_{\alpha}) - \log(P_B) - \log(P_c)).dt$$
$$= \int \left[\log(P_{\Omega}.P_{\alpha}.P_{NIH}/P_B.P_c)\right].dt$$

Hence the power gains (i.e. P_{Ω}, P_{α}, & P_{NIH}) and losses (i.e. P_B & P_c) need to be in the linear form. The conversion, where necessary, is made with function generators.

Temperature

Looking further along the amplifier chain, polarity problems arise. As the temperature T rises from 2.5×10^{-5} Kev (Room Temperature) to 25Kev (29×10^{6} °K), log (T) changes from negative (-4.6) to positive (1.4). When temperature is high and log (T) positive this must increase plasma conductivity and also reduce the ohmic heating P . Amp.12 is an inverter and gives -log (T) output. Hence the output of Amp.3 must be positive which is ensured by making the constant A a positive voltage and $R_1C_1 > R_2C_2$. The diode function generator (DFG) 2 receives a negative signal from Amp.4 and sends out a negative signal for integration by INT.1. In line with P_{Ω}, P_{α} & P_{NIH} must also be negative signals entering INT.1 while P_B & P_c representing losses must be positive signals.

The output of INT.1 now gives a positive signal representing E_{IN} , the energy available to heat the plasma. This signal passes through the log amplifier system LA.2 giving $\log(E_{IN})$.

Log(Temperature) Generation

For Amp.7 the equation is

$$\text{Log}(T) = \log(E_{IN}) - \log(n_e) - 15.8$$

Remembering that Amp.7 inverts, Pot.P17 feeds in the constant voltage of -15.8 volts, Pot.P18 supplies a controlable signal, representing $\log(n_e)$ of between +11 and +16 volts. As $\log(T)$, the output of Amp.7 varies between -4.6 and +1.4 volts, the third input signal representing the $\log(E_{IN})$ contribution from Amp.6 must vary between +9.4 and -1.6 volts, as $\log(n_e)$ increases (See Appendix 2). This means that for zero input of energy E_{IN} to the system the input voltage to Amp.6 is related linearly to $\log(n_e)$ thus :-

$\log(n_e)$	11	12	13	14	15	16
$^{i}/_{p}$ volts needed	9.4	8.4	7.4	6.4	5.4	4.4

and for a maximum $\log(E_{IN})$ input of 6 volts to Amp.6 to make $\log(T)$ = +1.4, the relationship is :-

$\log(n_e)$	11	12	13	14	15	16
$^{i}/_{p}$ volts needed	3.4	2.4	1.4	0.4	-0.6	-1.6

Resetting the input voltage to Amp.6 for each value of $\log(n_e)$ would be tiresome. The relationships show that Amp.6 can be supplied with a constant input of -20.4 volts made up from Pot.16 and the $\log(n_e)$ setting from Pot.P18. Amp.5 is inserted to increase the $\log(E_{IN})$ signal without inversion.

Losses

Energy losses from the plasma which reduce its heating are listed in Chapter 3,p.25 and estimated in Appendix 1. In this first version of the simulator only two are being considered. For the Bremsstrahlung loss

$$\log(P_B) = 2.\log(n_e) + \tfrac{1}{2}.\log(T) - 21.9$$

This requires a constant input of +21.9 volts from a potentiometer which is only supplied with 15 volts. By writing the equation

$$\log(P_B) = 2.\log(n_e) + \tfrac{1}{2}.\log(T) - 4 \times 5.47$$

the constant can be inserted into Amp.8 by setting Pot.P30 to 5.47 volts and $R._{60} = \frac{1}{4} \times R._{64}$. This ruse is not infrequently used and is discussed more fully in Chapter 8. The output of Amp.8 is a negative going log signal which is then converted by DFG 2 to a negative going linear (P_B) signal. But the Bremsstrahlung radiation is a loss and must be fed back to the INT 1 as a negative feedback. Amp.9 inverts the signal from DFG 2 and Pot.P 31 sets the magnitude of the feedback

Similarly for the cyclotron loss

$$\log(P_c) = \log(n_e) + \log(T) + 2.\log(B\ ) - 10.96$$

As before, signals representing $\log(n_e)$ and $\log(T)$ are readily available. The log(B) signal is obtained from Pot.P 32 and the constant, from Pot.P 33.

The chain of amplifiers 10 & 11 with DFG 3 follows the pattern as for the Bremsstrahlung loss.

Nuclear Energy Release

Log(T) varies between -4.6 and +1.4 volts. At log(T) = 0, T = 1 Kev, i.e. 11,600,000 ^{o}K. At this temperature very little energy will be released as the cross-section for the D - T reaction is so small. This means that negative values of log(T) can be neglected and barred from the rest of the system by the diode D_1 . Positive values of the log(T) signals are passed on through the log amplifier system LA 3 to produce a log(log(T)) signal at the output of Amp.A2LA3. The equation for Amp.13 is

$$\log(P_o) = \log(n_D) + \log(n_T) + (5.75) \log\left[\log(T)\right] - 19.45$$

so that the loglog signal is combined with signals from the potentiometers 22 & 22A and a constant from Pot.P 21 to give an output from Amp. 13 representing $\log(P_o)$. The separation here between n_D and n_T introduces the latent possibility of showing the effect of fuel burn-up. It would not be too difficult to link the ratio of n_D to n_T to the number of cycles that the system has made.

The $\log(P_o)$ signal is next converted to linear P_o and then inverted in polarity by Amp. 14 to give a positive output. This output is split between two potentiometers, 23 and 24, the first to take 10% to be returned through Amp. 15 and Pot.P 13 as the positive feedback of alpha-particle heating. Amp. 15 is merely an inverter. The signal from the second potentiometer is the remaining 90% and after passing through the integrator INT 2 gives the nuclear energy produced in the plasma for useful purposes.

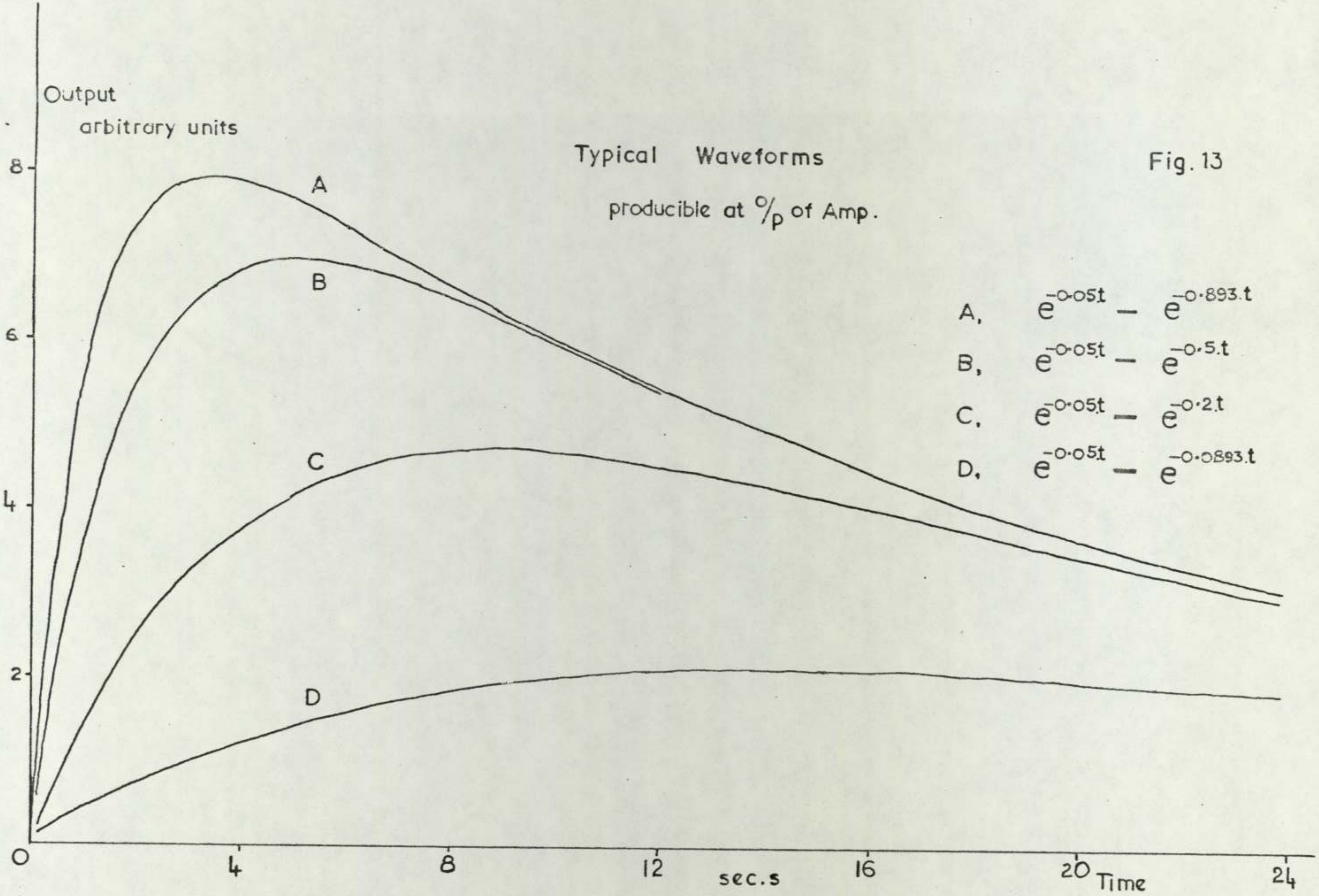
Unlike the fission reactor, which merely receives an initial load of uranium, the fusion reactor requires a substantial and initial input of electrical energy with which the reactor's energy output must be compared. The P_{Ω} and P_{NIH} signals are integrated in INT. 3 to give the total energy put into the plasma from external sources. This quantity is then compared in Amp. 16 with the linear E_o from INT. 2. Amp. 16 feeds a centre zero meter which moves to the positive side when the system is producing more than the input of energy and vice-versa.

Power production

The average power in a cycle or in a series of cycles, as distinct from the instantaneous power indicated at DFG 4 is obtained by dividing the energy from the plasma (i.e. INT 2 $^o/_p$) by the duration of the cycle(s). Division is not a simple process electronically and it is easier to add algebraically $\log(E_o)$ and log(time). INT 2 output supplies linear E_o and this is converted to $-\log(E_o)$ by passing through Amp. 17, log amplifier system LA4 and amplifier 18. The time involved here is that which elapses since the simulator was switched to 'RUN' and may be a part operational period, a full operational period, include a part or full delay period or extend over several reactor cycles. Another integrating amplifier B, in the control section, is required to be continuously integrating at the same ratio as amplifier A even when the amplifier has been switched to the 'delay condition'. Integrating amplifier B returns to intial condition only when the simulator is switched back to 'RESET'. The output of this amplifier is proportional to time elapsed and is passed through the log amplifier system LA5 to give a log(time) signal at the output of Amp.A2LA5. This signal is now combined with the $-\log(E_o)$ signal in Amp. 19. The output of Amp. 19 is then

$$\log(E_o) - \log(\text{time}) = \log \frac{E_o}{\text{time}} = \log(\text{average power})$$

It should be noted that the average power in an operational period will not be the same as that in a full cycle.



Typical Waveforms producible at O/p of Amp.

Fig. 13

CHAPTER 7

The Control System

The circuitry for this system is shown in Fig. 33
The system is required to

(a) produce a repetition of the operating and recharging periods

(b) count the number of such cycles

(c) vary the operating period

(d) vary the recharging period and hence the ratio of operating period to recharging period

(e) provide for a single operating period

(f) give an indication of the state of the 'reactor', that is operating or recharging

(g) provide HOLD and RESET facilities

(h) vary the integrating rates, that is, to give slow or fast simulation

In Fig.33 a small voltage is fed to a MEC 100 integrating amplifier 'A' and the output of this amplifier 'A' is passed through a dropping Pot.P29 to the inverting input of Amp (17), which is a 741 type amplifier without feedback. The non-inverting I/P of the Amp(17) is supplied with either of two small voltages from Pot.P27 or Pot.P28. These Pot's feed alternate contacts of a Post Office type rotary selector switch, the wiper of which connects to the non-inverting input of Amp(17).

Suppose these two voltages are 0.8 and 0.5 volts and let it be the 0.8 volt which is applied to the non-inverting input of Amp(18). Without feedback the amplifier output is driven to saturate positively or negatively depending on the voltage applied to the inverting input. When this voltage to the inverting input exceeds the 0.8 volt, then Amp(17) output flops over to the opposite polarity. If the change is from negative to positive polarity this signal triggers the Thyratron EN91 which discharges the large capacitor C through the relay coils RL1 and RL2. The discharge through RL2 momentarily closes its contacts RL2/1 which resets the integrator output to zero. At the same time RL1 which is the coil of the P.O. selector, switches the wiper on to the next contact and puts the 0.5 volt potential on to the non-inverting input of Amp(17). The integrator having reset, the system reverts to its initial condition, the thyratron is extinguished and the capacitor C recharges through R.103.

The duration of the two periods, the operational and recharging periods depend on the times the integrator output takes to reach the voltage on the non-inverting input of Amp(17). Thus, supposing the integrator output is rising at 0.5 volt per second and that the voltage at the wiper of Pot.P29 is rising at 0.005 volt per second, then assuming that the voltage on the non-inverting input of Amp(17) is 0.8 volt the time required to trigger the thyratron and so terminate the operating period is

$$^{0.8}/_{0.005} = 160 \text{ seconds}$$

Similarly the recharging period would be

$$^{0.5}/_{0.005} = 100 \text{ seconds}$$

During the operational period the whole simulator circuit must integrate and must be followed by a shut down during the recharging period. The P.O selector has a second bank of contacts; alternate contacts of this bank are connected together and to the RESET relays. These relays are connected in parallel and their contacts, which are normally closed, are individually connected across the integrators in the main simulator circuit. When the wiper of the selector first bank is setting an operating period, the wiper of the second band switches a 30 volt supply to the RESET relays to open their contacts and allow integration to occur. This is the start of the reactor cycle. In the recharging period the second wiper is off the selector RESET contacts so that the integrators are shorted and out of operation.

A RED lamp in parallel with the RESET relays indicates the operational period and these periods (or cycles) are counted by a resettable electromagnetic counter also in parallel with the red lamp.

The other alternate contacts on the selector second bank are also joined together and to a GREEN lamp which comes on during the recharging period.

A HOLD relay is associated with each integrator. The contacts of this relay are normally closed and are in the input circuit of the integrating amplifier. The HOLD relay coils are in parallel and can be energised at any instant by a manually operated switch (SW1). This isolates the integrators, integration stopping at that point in the cycle.

Each integrator has a choice of two integrating rates by switching their feedbacks to be 1.0 μF or 0.091μF.

This control system does actually satisfy the requirements listed at the start of this chapter. It has in fact 'just grown' as the requirements have appeared. Given adequate time and specialised attention it could most probably be much simplified. As in the main simulator circuit the use of valve amplifiers for integration and their power supplies makes unwanted bulk. The type 741 amplifiers were unsatisfactory as integrators over the periods of minutes due to their high and uncorrected drift rates.

CHAPTER 8

Scaling

The frequent changes between log and linear forms of the parameters in the simulator circuit call for a careful adjustment of the settings of the potentiometers which provide the constants involved in the equations of Chapter 4. Other potentiometers control the amplitude of signals into the operational amplifiers, to avoid overloading these amplifiers regard must also be had to the polarity of signals and constants.

The heart of the simulator system is the log(temp) i.e. the O/P of Amp(7). This therefore is a convenient starting point from which to work backward to the external energy inputs and the positive and negative feedbacks and to work forward to the nuclear reactions, the saleable energy and the power levels developed.

As indicated before a temperature range from room temperature to +25 Kev is assumed and this sets the range of log(temperature) between -4.6 and +1.4. Each amplifier will now be considered individually.

Amplifier 7.

For this amplifier, $\log(T) = \log(E_{IN}) - \log(n_e) + 15.8$ so that Pot.P 17 and Pot.P18 must supply voltages of the opposite ~~same~~ polarity and these must negative and be positive respectively because of the inversion in the amplifier. The electron density is assumed to be between 10^{11} and 10^{16} per millilitre, so that Pot.P18 will need to be adjustable between +11 and +16 volts, while Pot.P17 provide the constant of +15.8. But neither Pot. can provide these voltages fully, being supplied with 15 volts only. However as indicated on page 47, the potentiometer settings just mentioned can be halved if the ratios R.34/R.32 and R.34/R.33 are each equal to 2. Hence, with Pot.P17 set at - 7.9 volts and Pot.P18 set to provide between + 5.5 and + 8.0 volts the output of Amp.6 to give a required output from Amp.7 can be calculated.

The extremes of temperature postulated, that is, for log(T) to vary from - 4.6 (Room temperature) to + 1.4 (25 Kev), for values of $\log(n_e)$ between 11.0 and 16.0 lead to a range of outputs from Amp.6 of + 9.4 to - 1.6 volts. Since these outputs are within the capability of the '741' amplifier, the ratio R.34/R.31 is unity. See also Appendix 3 pp 136-136a.

Amplifier 6.

For zero E_{IN} and $n_e = 10^{11} cm^{-3}$, Amp.6 must have an output of + 9.4 volts and for maximum E_{IN} an output of + 3.4 volts, that is, a range of 6.0 volts. Similarly when $n_e = 10^{16}$ cm^{-3}, the output of Amp.6 also has a range of 6.0 volts between + 4.4 and - 1.6 volts. If now Pot.P16 is set to give - 9.4 volts input to Amp.6 via R.28 and the output of Amp.5 changes between 0 and 6.0 volts then the output of Amp.6 will change between + 9.4 and + 3.4 volts for zero E_{IN} to maximum E_{IN}, with $n_e = 10^{11}$ cm^{-3}.

When n_e is increased to 10^{16} cm^{-3} a similar consideration shows that the setting of Pot.P16 must be altered to - 4.4 volts, a change of 5.0 volts. Resetting Pot.P16 for each value of n_e is inconvenient. In changing n_e from 10^{11} to 10^{16} Pot.P18 changes by 2.5 volts. By making the ratio R.30/R.29 equal to 2 this change can be doubled and added to the input of Amp.6. The setting of Pot.P16 would now have to be - 20.4 volts but by making the ratio R.30/R.28 also equal to 2 the setting of Pot.P16 is reduced to - 10.2 volts.

This setting will remain unchanged, for as n_e is increased or decreased so the 'non-signal' input to Amp.6 will be adjusted automatically. Since the output of Amp.5 has a maximum of + 6.0 volts, the ratio R.30/R.27 is unity.

Amplifier 5.

Amp.5 is used in the non-inverting mode to give a gain of (1 + R.26/R.26a) = 6 from an input of 0 to 1 volt. The ratio R.26/R.26a is therefore 5 to provide this gain of 6.

Log amplifier LA 2.

According to the manufacturer this log amplifier accepts input signals in the range 0 to 1 volt with a similar range of outputs. A measured characteristic of output v input is shown in Fig. 13a, p 58. The integrator INT 1 can operate up to an output of 100 volts. R.122 and R.123 reduce this sufficiently for input to LA 2.

Integrator INT 1.

With the maximum input to the log Amp.LA 2 set at 1 volt for maximum E_{IN} which gives log(T) of + 1.4 from Amp.7 the output of INT 1 can be allowed to rise to 100 volts. Assuming the longest operational period to be 100 secs., the output of INT 1 will rise at the rate of 1 volt/sec. This means that with the feedback capacitor of the integrator being 1μF and the input resistors R.16, 19, 67, 75 and 95 all equal to 1 Megohm, the combined signal from the five inputs to INT 1 must not exceed 1volt. The percentage which each input contributes to the 1 volt has now to be found.

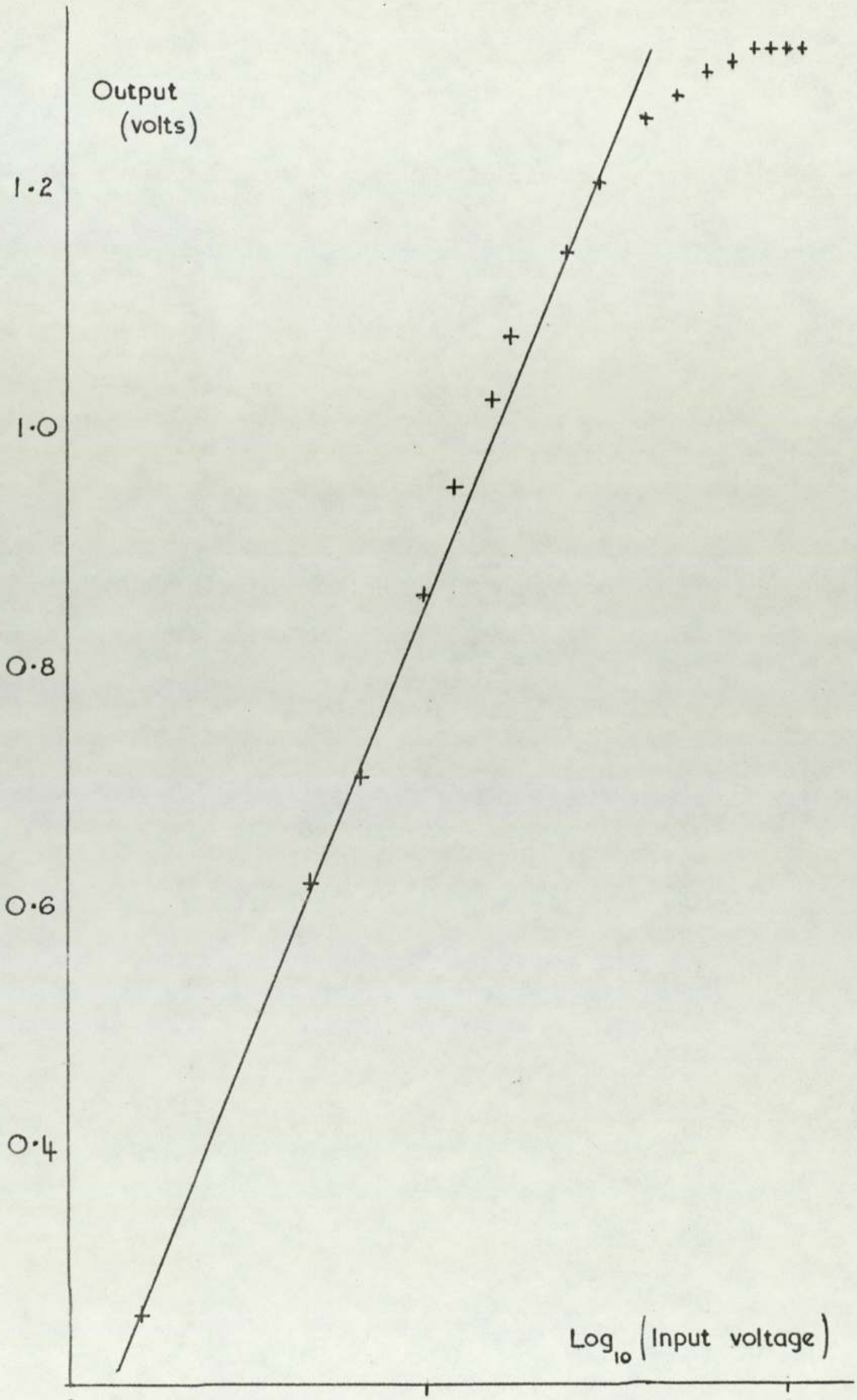
This statement can be expressed thus

$$\int_0^{t_1} P_{\Omega}.dt + \int_{t_2}^{t_3} P_{\alpha}.dt + \int_{t_4}^{t_5} P_{NIH}.dt - \int_0^{t_6} P_{B}.dt - \int_0^{t_7} P_{C}.dt = 100 \text{ volts (Max)}$$

Log Amplifier, type, TL441CN (Texas)

characteristic

Fig. 13a



In this expression only P_{NIH} can be assumed constant. P_{Ω} rises and falls and may have fallen to zero in the time t_1 , which may be very much less than the operational period. t_2 and t_3 are the times when the plasma temperature rises above and subsequently falls below the ignition temperature and in which interval energetic alpha particles are produced. t_4 and t_5 are the times between which neutral injection heating is used and in this simulator these are under the control of the operator.. t_6 and t_7 are the times over which the Bremsstrahlung and cyclotron losses occur. These times are not necessarily the same and will vary with temperature, but the expression assumes that these losses begin almost immediately at the start of the operational period.

The approximate calculations in Appendix 1 show that Bremsstrahlung and cyclotron radiations cause energy losses from the plasma of 1.1% and 0.6% respectively, at a temperature of 20 Kev. Alpha particle energy contributes about 10% of the nuclear energy developed to heating the plasma and the rest of the input of energy to the plasma comes from the external sources, i.e. the neutral injection heating and the ohmic heating. Since the two terms

$$\int_{o}^{t6} P_B.dt \qquad \text{and} \quad \int_{o}^{t7} P_C.dt$$

are deductions, the other three terms

$$\int_{o}^{t1} P_{\Omega}.dt \quad , \int_{t4}^{t5} P_{NIH}.dt \quad \text{and} \int_{t2}^{t3} P_{\alpha}.dt$$

may together exceed 100 volts.

In the absence of more detailed knowledge and as a starting point, to be modified later after experience with the simulator, let it be assumed that P_{Ω} , P_{α} , P_{NIH}, P_B, and P_C , all act at constant value throughout the operational period. Then it can be estimated that

(a) P_B signal input will be 0.011 volt

(b) P_C signal input will be 0.006 volt

(c) P_α signal input will be 0.100 volt

(d) P_Ω signal input will be 0.600 volt

(e) P_{NIH} signal input will be 0.300 volt

The contributions (d) and (e) are arbitrary values with a sum of 0.9 volt. These are the contributions to make E_{IN} a maximum and produce a log(Temperature) value of 20 Kev. There still remains the problem of the settings of Pot.P11, Pot.P13, Pot.P31 and Pot.P34 since the inputs to these potentiometers are variable. Pot.P12 has a constant input of 15 volts and its setting can be calculated.

To calculate or estimate the settings of the first four potentiometers the behaviour of the feedback loops involving P_B , P_C, P_Ω , and P_α must next be considered.

Amplifier 8

The feedback loop for P_B includes Amp 8, DFG 1 and Amp. 9. DFG 1 is designed to accept up to 10 volts maximum imput and this is therefore the maximum output of Amp. 8. The equation for Amp. 8 is

$$\log(P_B) = 2.\log(n_e) + (0.5)\log(T) - 21.90$$

The constant -21.90 is too large to be supplied by Pot.P30 but can be reduced to -5.47(5) volts and R.64/R.60 made equal to 4 to compensate. Similarly, since $2.\log(n_e)$ would have values between +22.0 and +32.0 volts the ratio R.64/R.62 is also made equal to 4. Since the term log(T) will only vary between -4.6 and -1.4 volts the ratio R.64/R.61 is 0.5. For the variations of log(T) and $\log(n_e)$ these ratios give an output from Amp. 8 of -10.8 volts to -2.2 volts, which range is just acceptable, the -10.8 volts being the extreme case. Since the DFG 1 accepts only negative input signals the diode D_2 blocks positive input signals. The range of outputs from DFG 1 is then, by design of the DFG, 0 volts to -10 volts.

Amplifier 9

The output of DFG 1 is negative and hence Amp. 9 is used to invert this polarity so that this P_B feedback loop feeds a positive signal to the integrator INT 1, i.e. a signal which is out of phase with P_{Ω} , P_{α} and P_{NIH} and which therefore represents a loss of energy by Bremsstrahlung radiation. Amp.9 may also provide some signal gain.
The lowest value of n_e (10^{11} ions/ml) is likely to yield the highest temperature with log(T) equal to +1.4 and these combined with the constant give an output from Amp 8 of 0.8 volt. Within the DFG 1 the input of 0.8 volt is effectively reduced by a factor of 10 and then antilogged to provide an output of 1.20(2) volts which goes to the Pot.P31. The requirement of making a contribution of 0.011 volt to INT 1 is then met by setting Pot.P31 to 0.91%.

Amplifier 10

The feedback loop for P_C includes Amp. 10 , DFG 3 and Amp. 11. An additional term is that which represents the effect of the toroidal magnetic field (B). This term is adjusted by Pot.P34 in the Potentiometer Unit. Thereafter this loop behaves similarly to that for the feedback of the Bremsstrahlung loss.

The equation of the cyclotron loss is

$\log(P_C) = 2.\log(B) + \log(n_e) + \log(T) - 10.96$

The toroidal magnetic field is assumed to be variable about a value of 4 tesla, so that the term 2.log(B) has a median value of 1.2, obtained from Pot.P32. The ratio R.72/R.70 is made 2 to compensate for the half values of $\log(n_e)$ supplied by Pot.P18. For the log(T) input the ratio R.72/R.69 is unity since log(T) has a small range -4.6 to 1.4 volts. The constant of 10.96 volts is kept at full value and the ratio at unity. The variations of $\log(n_e)$ and log(T) cause the O/P of Amp. 10 to range between 1.15 volts and 12.15 volts, or even higher if the magnetic field is increased above 4 teslà. However, if R.72 is reduced to its half value the O/P of Amp. 10 is halved to 6.07(5) at its maximum and can be accepted by DFG 3. Again the O/P of DFG 3 is adjusted by Amp. 11 to provide Pot.P34 with a maximum input of 10 volts and this potentiometer set at 0.33% to send a maximum signal of 0.006 volt through R.75 to INT 1.

Amplifier 4

The equation for this amplifier is

$$\log(P_\Omega) = 2.\log(I) - (1.5)\log(T) - 2.60$$

in which the maximum plasma current is as yet undetermined. By the Kruskal stability criterion, the maximum poloidal magnetic field due to the plasma current, before the onset of instability is given by

$$\frac{\text{Toroidal field}}{\text{Poloidal field}} \geqq \frac{q.R}{a}$$ where q is the stability margin

Golovin quotes q = 1 for his design and with R = 5.2m, a = 1.86m and the toroidal field of 4 tesla, the poloidal field is 1.43 tesla which requires a plasma current of 13 x 10^6 amperes for its production. Hence log(I) = 7.12 and $\log(P_\Omega) \neq 9.54$ which is acceptable by DFG 2. With this input DFG 2 gives an output of 9.0 volts to Pot.P11. This Pot., set at 6.7% sends 0.6 volt to INT 1.

Since R.99 and R.98 are equal, Pot.P10 receives -log(T). R.13 is 2/3 of R.14 to multiply -log(T) by 1.5. R.100 and R.14 are equal and Pot.P35 is then set at 2.60 volts. R.11 is 1/4 of R.14 and thus the maximum output to be taken from the wiper of Pot.P9 is 7.12/4 = 1.78 volts .

Amplifier 3.

This amplifier was originally intended to feed an output signal of 0 to 1 volt to the log amplifier LA 1. As explained in Chapter 9 p.67, the output of Amp.3 was taken direct to the top of Pot.P9.

Amplifiers 1 and 2.

These two amplifiers behave similarly, each producing an exponential decay of an initial voltage at the amplifier output. Amp. 1 has a negative output and Amp. 2 has a positive output. Pots. P1 and P2 set the initial output voltages and the rates of decay are determined by R_1, R_2, C_1 and C_2 and by the settings of Pots. P3 and P4. The two outputs are combined in Amp.3. To make the waveform start from zero, Pots. P4 and P5 are so adjusted that the two inputs to Amp.3 initially cancel. These same Pots. also give the peak output from Amp.3 to exceed 3.56 volts.

Amplifier 12.

This amplifier is an inverter for the sign of the log(T) feedback. Resistors R.99 and R.98 are equal and the degree of log(T) feedback is adjusted by Pot.P10.

Diode Function Generator DFG 2.

After its initial setting up, whereby the O/P of this DFG is related to the antilog of the input signal, no controls are provided except for the Pot.P11 to adjust the magnitude of the P signal to INT.1 and INT.3.

Log Amplifier LA 3.

This amplifier with its associated amplifiers A1LA3 and A2LA3 is used to produce an O/P signal from Amp.A2LA3 proportional to $\log\left[\log(T)\right]$. For temperatures between 2 and 40 Kev the quantity

$\log(\sigma v)$ is empirically found to be given by the expression

$$\log(\sigma v) = (5.75).\log\left[\log(T)\right] - 16.56$$

Since the simulator is concerned with power generation in the temperature region where log(T) is positive, the diode D_1 ensures that only positive values of log(T) pass on to Amp.A1LA3.

Amplifier 13.

This amplifier is required to produce an output related to log(Power from nuclear reactions, P_o). The equation for the amplifier is

$$\log(P_o) = \log(\tfrac{1}{2}n_D) + \log(\tfrac{1}{2}n_T) + (5.75)\log\left[\log(T)\right] - 19.45$$

The simulator is designed for a maximum value of log(T) = +1.4 so that the term $(5.75)\log\left[\log(T)\right]$, has a maximum of 0.84 which is within the O/P range of 0 to 1 volt from Amp A2LA3. The resistors R.43 and R.46 are therefore equal. The Pot.P21 supplies the constant terms in the equation and should be adjusted for any change in the operational period. However, $\log(^t/\tau)$ is only about 0.5% of the constant term 19.45 and the adjustment is omitted from this Mk. 1 simulator. Pot. P21 is set to 9.72 volts and R.42 is made half of R.46 to compensate.

Similarly, R.44 and R.45 are each made half of R.46 and the potentiometers Pot.P22 and Pot.P22A adjusted to the values of $\log(\tfrac{1}{2}n_D)$ and $\log(\tfrac{1}{2}n_T)$ respectively.

The output of Amp 13 with maximum value of n_D and n_T and log(T) is now about 12 volts and with lower values of n_D and n_T the output is acceptable by the DFG 4.

Diode Function Generator 4.

Like other DFG's after an initial setting up DFG 4 has no controls and delivers a signal proportional to linear P_o within the range 0 to 10 volts. An O/P of 10 volts represents a linear power of 5,500 MW at log(T) = 1.4 and $n_D = n_T = 1.5 \times 10^{14}$ ions per millilitre.

Amplifier 14.

This amplifier inverts the polarity of the DFG 4 O/P signal, gives unit gain and feeds two potentiometers Pot.P23 and Pot.P24 which are in parallel. Pot.P23 is set to feed back to INT 1, via Amp.15 and Pot.P13, that fraction of power produced by nuclear reactions which is returned to the plasma by the alpha particles, Pot.P24 is set to pass the remainder of the power to the INT 2. Hence Pot.P23 is set at 10% and Pot.P24 at 90%.

Integrator 2.

The O/P from Pot.P24 may reach 9 volts and is proportionally reduced by resistors R.49 and R.49A to provide a suitable I/P to INT 2 so that its O/P does not exceed 100 volts in the longest operational period. This O/P is then reduced 10 times by resistors R.120 and R.121 to feed Amplifiers 16 and 17.

Amplifier 15.

This inverting amplifier provides the positive feedback to represent the alpha particle heating to augment the ohmic heating and at temperatures above critical to sustain the nuclear reactions.

Integrator 3.

External power for a fusion reactor is supplied by ohmic heating and neutral injection heating. In the simulator these two quantities are integrated together in INT 3 to give an O/P signal representing the external power supplied. This output signal could rise to 100 volts but is reduced by R.120 and R.121 to a maximum of 10 volts to be fed into Amp. 16.

Amplifier 16.

Both signals into Amp. 16 represent linear energies. That from INT 3 is the external energy supplied and is positive; that from INT 2 is the nuclear energy available and is negative. Amp. 16 sums these two amounts of energy, and its output, when shown on a centre zero meter, if positive indicates a gain of energy from the system and if negative a loss of energy. INT 2 O/P into R.81 has a maximum of 10 volts. INT 3 with a maximum of 100 volts is reduced 10 times by resistors R.101 and R.102 and further scaling by Pot.P36 is introduced so that Amp. 16 O/P is zero at an agreed ignition temperature.

Amplifier 17.

The reduced output of INT 2 is fed into Amp 17 to give an integrated positive signal to be passed to the log amplifier system LA 4.

Log Amplifier LA 4.

The log amplifier LA 4 together with the amplifiers A1LA 4 and A2LA 4 produces an output signal proportional to $\log(E_o)$ as part of the process of determining the average power in an operational period, a full cycle or over a number of cycles.

Amplifier 18.

This amplifier with Pot.P37 is used to invert the polarity of the $\log(E_o)$ signal and to provide any gain or reduction required. Its O/P is fed to amplifier 19.

Amplifier MEC 100 B.

This amplifier integrates at the same rate as Amp MEC 100 A when the switch SW2a is in position 1. By means of SW2b the amplifier is switched to the I/P of the log amplifier LA5. Since amplifier MEC 100 B integrates at a steady rate its O/P is proportional to the time elapsed since SW2a was moved to position 1.

Log Amplifier LA 5.

The O/P of this system from amplifier A2LA2 is proportional to log(time). When SW2 is in position 1, the O/P is log(total time elapsed since integration started). When SW2 is in position 2 the O/P is log(time of operational period). The O/P in each case is taken to amplifier 19.

Amplifier 19.

The signals into Amp. 19 are of opposite polarity. Consequently the O/P of this amplifier is

$$\log(E_o) - \log(\text{time}) = \log\left[E_o/\ \text{time}\right] = \log\ (\text{average power})$$

and this average can be displayed on a meter, X-Y plotter of chart recorder.

CHAPTER 9

Accuracy of Simulation.

The test of any simulator will be its ability to reproduce the same behaviour as that of the actual machine. As indicated in an earlier chapter this is an ideal to be aimed at, it is not a practical reality since a simulator of any kind is a compromise between complexity and cost. Yet, if, to improve simulation, complexity is increased, so more errors are introduced by the approximations so necessary to make one set of apparatus behave like an entirely different set.

In more specific terms, the laws governing the behaviour of an electrical circuit have to be 'bent' to conform to those of, say, a mechanical structure such as an aircraft wing. The behaviour of the wing under set conditions can be observed experimentally and there is then a direct comparison of the electrical simulation with experimental results. Discrepancies in the simulation lead to modifications in the electrical circuitry and hence to closer and better simulation.

Fission reactor simulators are of long standing and the degree of simulation has been tested against the actual reactor through the design stages to the critical state and power producing plant.

The position of the fusion simulator is very different. Small reactors have been built but have not reached the critical state of yielding more power than is put into the system. Simulation therefore can only be tested against reality part way to the critical state. Beyond this point simulation, at present, can only be tested against theory and theoretical predictions of the simulation. If the simulation is good up to the limits of experiments, then beyond those limits is the reactor likely to follow the predictions of simulator or of theory ? In brief terms there is a question, how can a simulator be judged against a reactor that does not exist ?

Consider the waveform of Log(plasma current) which is to be combined with Log(temperature) in Amplifier 4.

Amplifier 1. gives an output voltage

$$V = A.\exp\left(^{-\alpha t}/_{R_1C_1}\right)$$

Amplifier 2. gives an output voltage

$$V = A.\exp\left(^{-\beta t}/_{R_2C_2}\right)$$

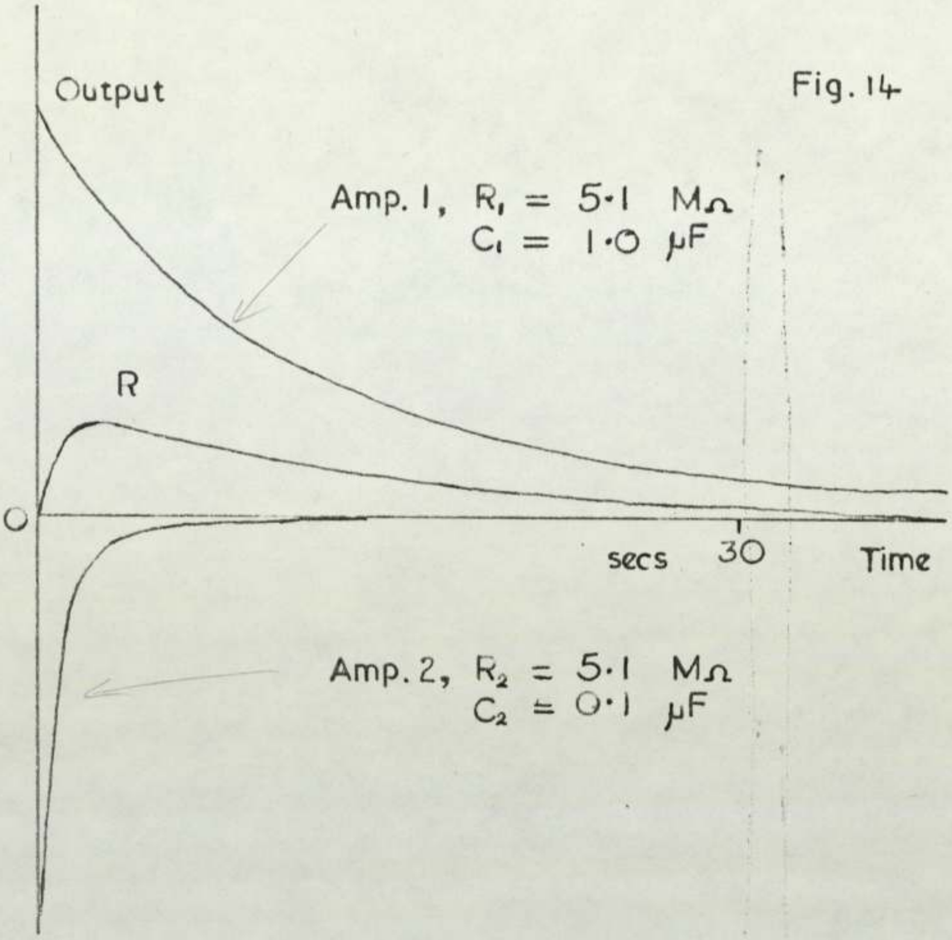
and the two outputs are combined in Amplifier 3. to give an output $V = A.\left[\exp\left(^{-\alpha t}/_{R_1C_1}\right) - \exp\left(^{-\beta t}/_{R_2C_2}\right)\right]$ and this output is calculated and plotted against time in Fig. 14 for several sets of the constants.

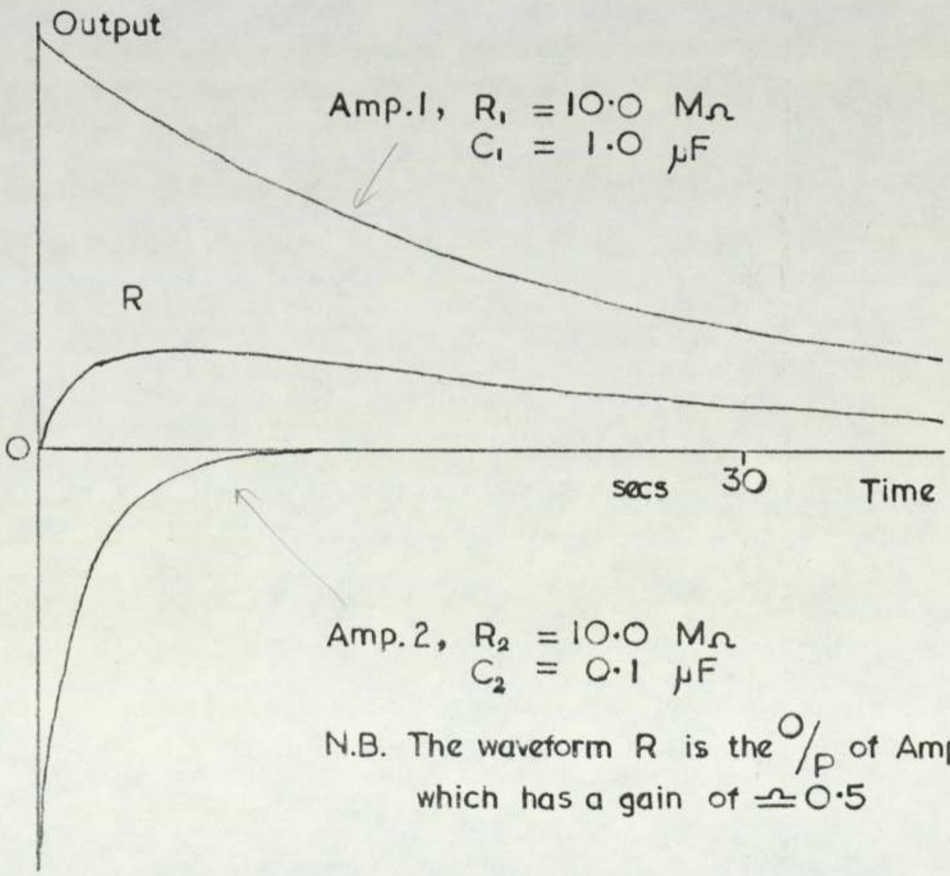
Fig. 14 p.69. shows how the output of Amplifier 3. can compare with the theoretical change of plasma current during the operational period, that is a rise of current in a sine mode and a decay in an exponential mode. However it is log(plasma current) which is required for insertion into Amplifier 4. Fig. 15 p.70 shows how the calculated log (V) compares with lin(V).; the graphs are of similar form.

Fig.16 p.71 shows some typical and experimental oscillographs of the plasma current waveform in actual reactors. These cannot be said to reproduce the theoretical prediction of a sine rise and exponential decay (see Fig.9 p24). In the early designs of the simulator the output of Amplifier 3 was to be converted to a log quantity by a log amplifier LA 1. Since however, the actual current waveforms are so far from theory, the linear form (from Amplifier 3) is as close to reality as the log form. Log amplifier LA 1 has been discarded and the output of Amplifier 3 taken direct to the top of Pot.P9. This obviously is an approximation but does avoid errors in the log amplifier and there is a reproducable waveform available.

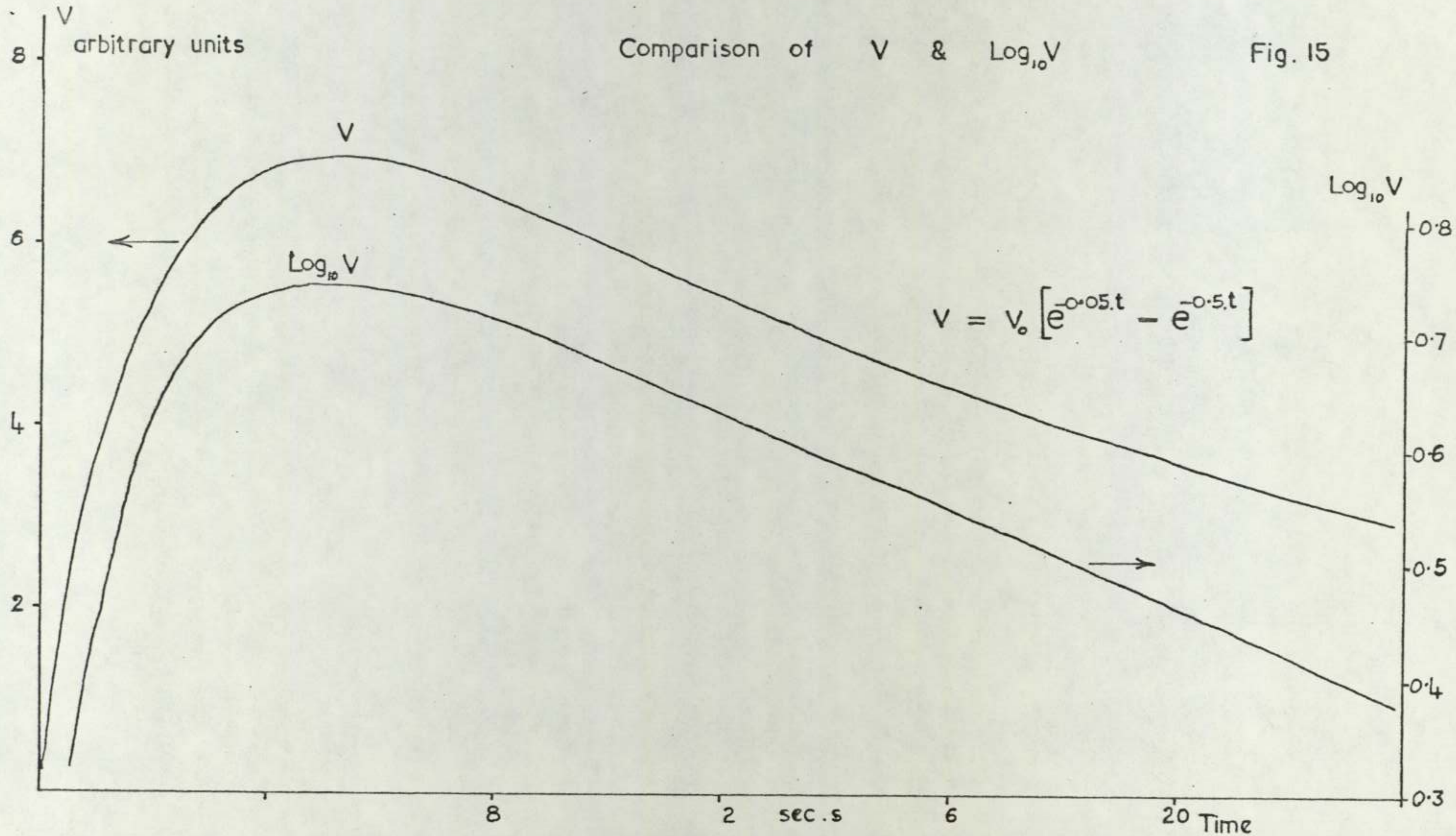
Current Waveforms — experimental

Fig. 14





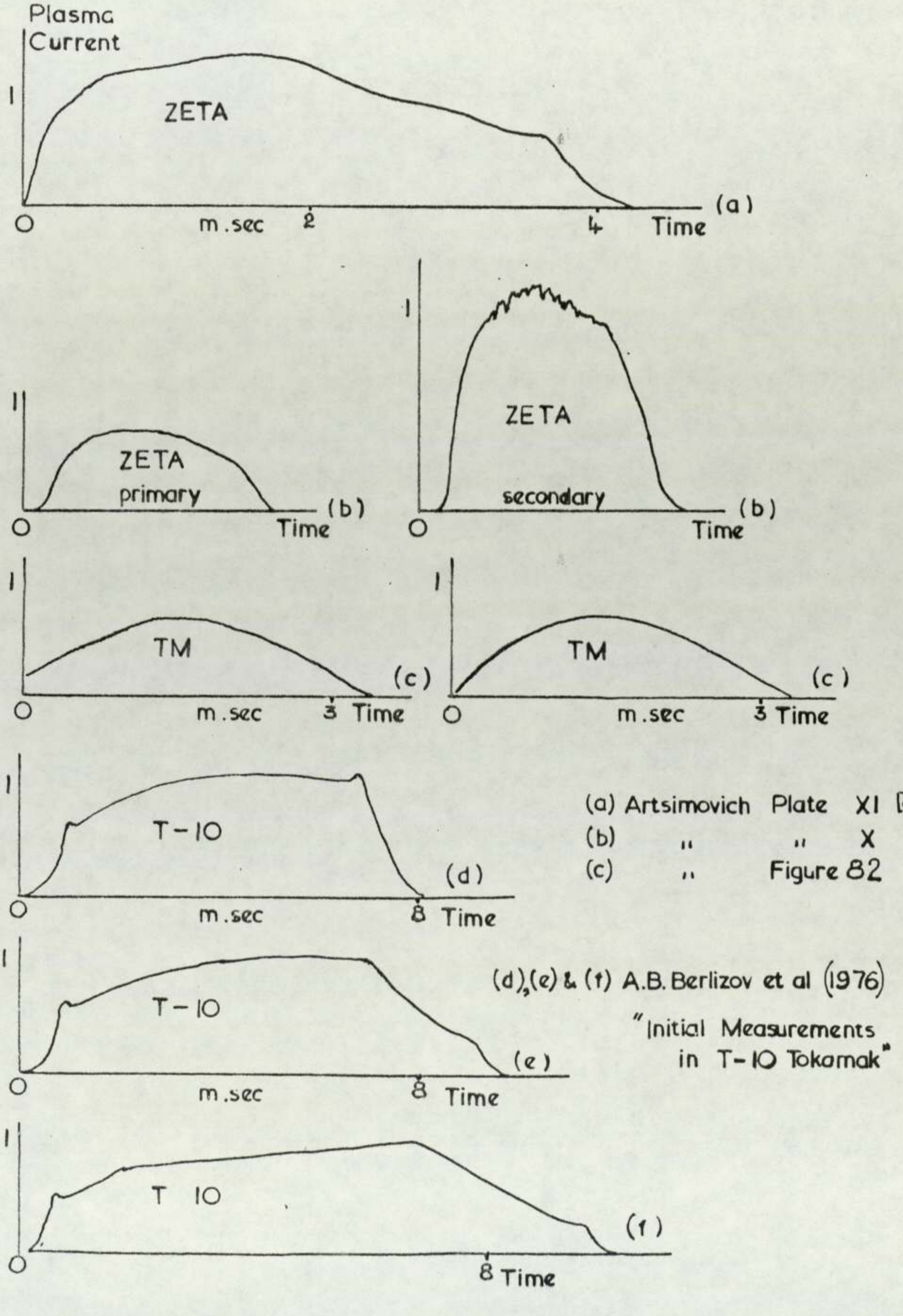
N.B. The waveform R is the O/P of Amp. 3 which has a gain of ≏ 0·5



Comparison of V & $Log_{10}V$ Fig. 15

Plasma Current Oscillograms

Fig. 16



(a) Artsimovich Plate XI [8]
(b) " " X
(c) " Figure 82

(d), (e) & (f) A.B. Berlizov et al (1976) "Initial Measurements in T-10 Tokamak"

The output of Amplifier 4, modified by the log(temperature) feedback passes to the DFG 2 for conversion to a linear quantity.

The following general remarks on the accuracy of diode function generators apply to all those used in this simulator, since they are all used to produce an output voltage related to the antilog of the input signal. Since, in Fig.11 the feedback resistors R_1, R_2, R_3, can be adjusted to produce gain or loss in the Amplifiers 1, 2, 3, the output signal may be greater than the input signal, but the input signal must lie within the range for which the DFG was designed. In these cases the range is 0 to 10 volts. The ability of the DFG to produce accurately a given function from a linearly increasing input depends on the number of elements employed i.e. the number of segments into which the function curve may be divided, and the distribution of those segments along the curve. If the segments are long where the curvature of the curve is high the errors can be large e.g. 20%. Elements should therefore be concentrated in regions of high curvature and this is done by adjusting the bias resistors (Fig.11) R_4, R_5, etc to be close together in the upper part of the range of these particular DFG's. Fig.16a p.73 shows a typical DFG output curve in comparison with a theoretical curve of x v log(x). It shows how the error changes over the range of input voltages.

Next in the chain of simulation, the integrating amplifier INT,1 receives five inputs, three of which come from DFG's. All five inputs enter INT 1 through input resistors. The accuracy of the integrator itself depends on the product of its input resistor (10%) and feedback capacitor (1%).

The output of INT 1 represents the energy input to the plasma and this signal is passed on to the log amplifier LA 2 for conversion to Log (E_{IN}). Fig.16b p.74 shows how the output of the logging system, taken from Amplifier A2LA2 compares with

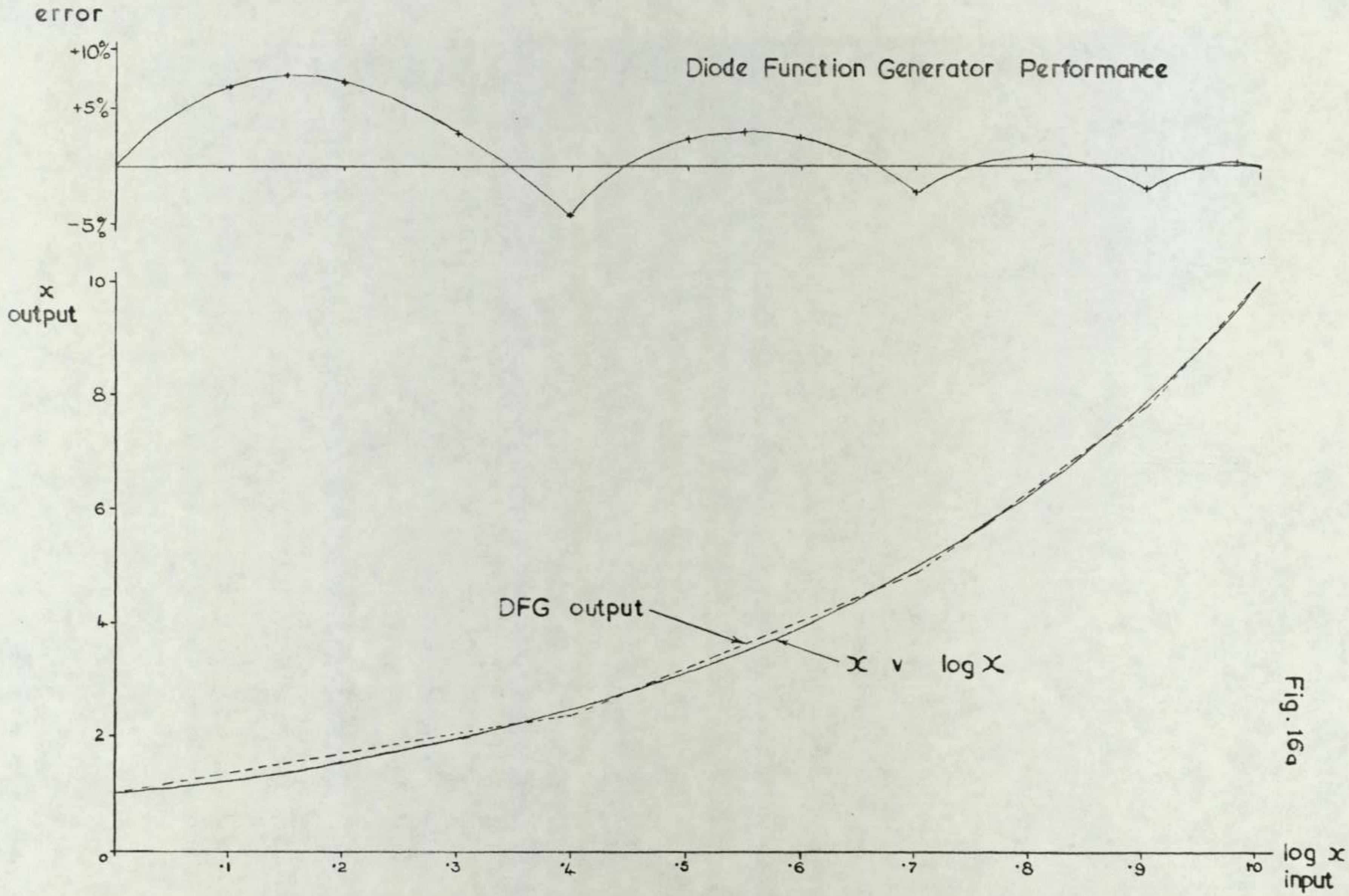

Diode Function Generator Performance
error
+10%
+5%
-5%
x
output
10
8
6
4
2
0
·1
·2
·3
·4
·5
·6
·7
·8
·9
1·0
log x
input
DFG output
x v log x

Fig. 16a

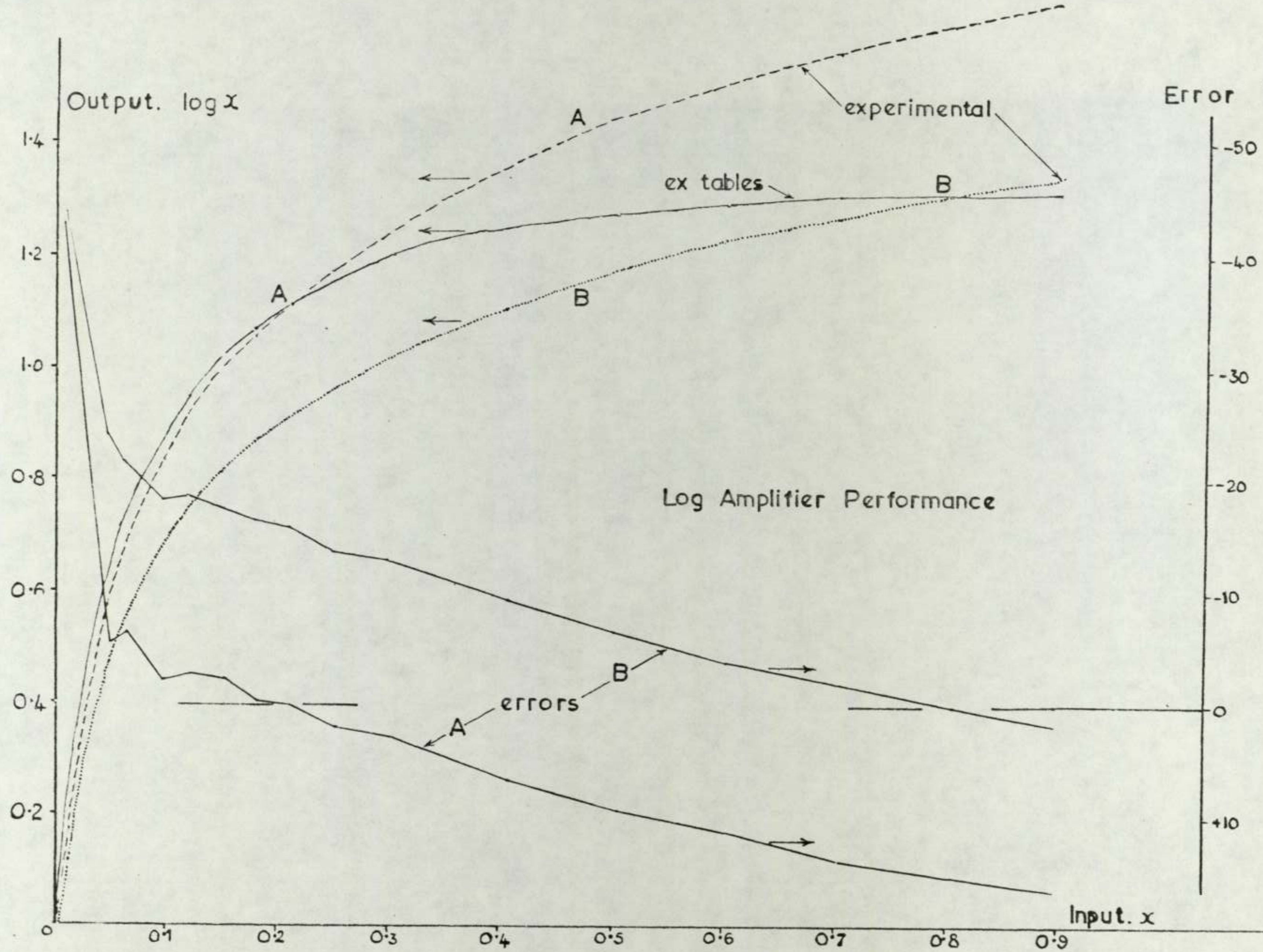

Output. log x
Error %
Input. x
Log Amplifier Performance
experimental
ex tables
A
B
errors
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
-50
-40
-30
-20
-10
+10

Fig. 16b

Table

Experimental Measurements Input (A)	Output (B)	A.100 (C)	Log C (D)	D/1.18 (E)	Error B-E	Error % Curve A	D/1.45 (F)	Error B-F	Error % Curve B
0.016 volt	0.26 volt	1.6	0.204	0.17	0.09	44	0.14	0.12	46
0.048	0.62	4.8	0.681	0.58	0.04	5.8	0.47	0.15	24
0.061	0.71	6.1	0.785	0.66	0.05	6.3	0.54	0.17	21.7
0.098	0.86	9.8	0.991	0.84	0.02	2.0	0.68	0.18	18.2
0.121	0.95	12.1	1.083	0.92	0.03	2.8	0.75	0.20	18.5
0.153	1.02	15.3	1.185	1.00	0.02	2.1	0.82	0.20	17.3
0.181	1.07	18.1	1.258	1.07	0.00	0.4	0.87	0.20	16.2
0.212	1.12	21.2	1.326	1.12	0.00	0.0	0.91	0.21	15.8
0.249	1.15	24.9	1.396	1.18	0.03	2.1	0.96	0.19	13.6
0.303	1.21	30.3	1.481	1.25	0.04	2.7	1.02	0.19	12.8
0.409	1.26	40.9	1.612	1.37	0.11	6.8	1.11	0.15	9.3
0.504	1.28	50.4	1.702	1.44	0.16	9.4	1.17	0.11	6.4
0.604	1.30	60.4	1.781	1.51	0.21	11.8	1.23	0.07	3.9
0.705	1.31	70.5	1.848	1.57	0.26	14.1	1.27	0.04	2.1
0.815	1.32	81.5	1.911	1.62	0.30	15.7	1.32	0.00	0.0
0.907	1.32	90.7	1.958	1.66	0.34	17.0	1.35	0.03	1.5

the calculated values of log(x). Within the input range of 0 to 1 volt (the manufacturer's range) the output is related to the log of the input over a much smaller range. Errors are present up to 20%. Since the output of INT 1 may attain 100 volts it must be followed by a potentiometer circuit to reduce this output to a maximum of 1 volt. The log amplifier system has four adjustments. Both amplifiers A1LA2 and A2LA2 have to be corrected for offset voltages by their attached potentiometers, shown on page 36, but not shown in the main circuit. Additionally in the 'no input signal' state the output of amplifier A2LA2 is zero-ed by adjusting potentiometer P.15 which balances the two inputs of the amplifier to earth. VR_2 is an adjustable feedback resistor for amplifier A2LA2 and partly determines the output signal magnitude.

Single Amplifiers

It is assumed that single amplifiers elsewhere in the chain of the simulator will operate without serious error provided that any offset voltages in the 'no signal' mode are nullified by the associated potentiometers and that the input signals and constant voltage inputs are kept low enough to limit the amplifier outputs to well below the amplifier supply voltages ($\pm$15v) say to $\pm$ 10v.

Single '741' type amplifiers are only used as adders or inverters employing input and feedback resistors and no capacitors. With 10% tolerance resistors there are possible errors on the nominal gain of about 20%. Fortunately, most input or outputs to amplifiers are controlled by potentiometers and these allow corrections for any 'off normal' gain of the amplifier.

As a specific example consider amplifier 4. The equation for this amplifier is

$$\log(P_n) = 2.\log(I) - (1.5).\mathrm{Log}(T) - 2.60$$

The constant (2.60) is obtained from Potentiometer P.35. If the nominal gain of the amplifier has risen by 20% then the setting of P.35 could be reduced to 0.9 volt. This can be checked practically by earthing the outer ends of the input resistors R_{11} and R_{13} and measuring the output of amplifier 4. This can be repeated for the remaining inputs since the gains on these differ in accordance with the above equation

Overall Accuracy

The previous discussion of errors raises the problem of how to assess the overall accuracy of the simulator, if indeed it can be ascertained at all. If in the conventional way the errors are added the total (3 INT's @11% - 33%, 4 DFG's @ 10% = 40% and 4 log amp's @ 5% = 20%) is about 100%. This estimate does not include single amplifiers so the picture is very gloomy.

What is of more importance is whether the simulator behaves qualitatively as theory predicts. For example, does the output of amplifier 16 pass from negative to positive as log(T) reaches 1 volt positive (this corresponds to a temperature above which 'saleable power' is expected) ? Does log(T) rise more rapidly as the plasma current is increased ? Does an increase of log(ion density) lower log(T), etc etc ? Answers to these and similar questions are given in Chapter 11 on results with the simulator and discussions thereon.

CHAPTER 10

Construction

The objective of this project was the production of a training simulator of a fission reactor. Its initial design using the Solartron Space 30 Analogue Computer gave rise to a very large machine since all units employed thermionic valves. It occupied some 3 $metres^2$ of floor space and a volume of about 4.5 $metres^3$ but more inconveniently tied up a general purpose analogue to one specific job. Hence the decision to transistorise the design and reduce the simulator dimensions to occupy less than 0.4 $metres^2$ of floor area and a volume of under 0.6 $metres^3$.

A very brief outline of the arrangement was given in Chapter 5 and in Fig. 17 p.79.

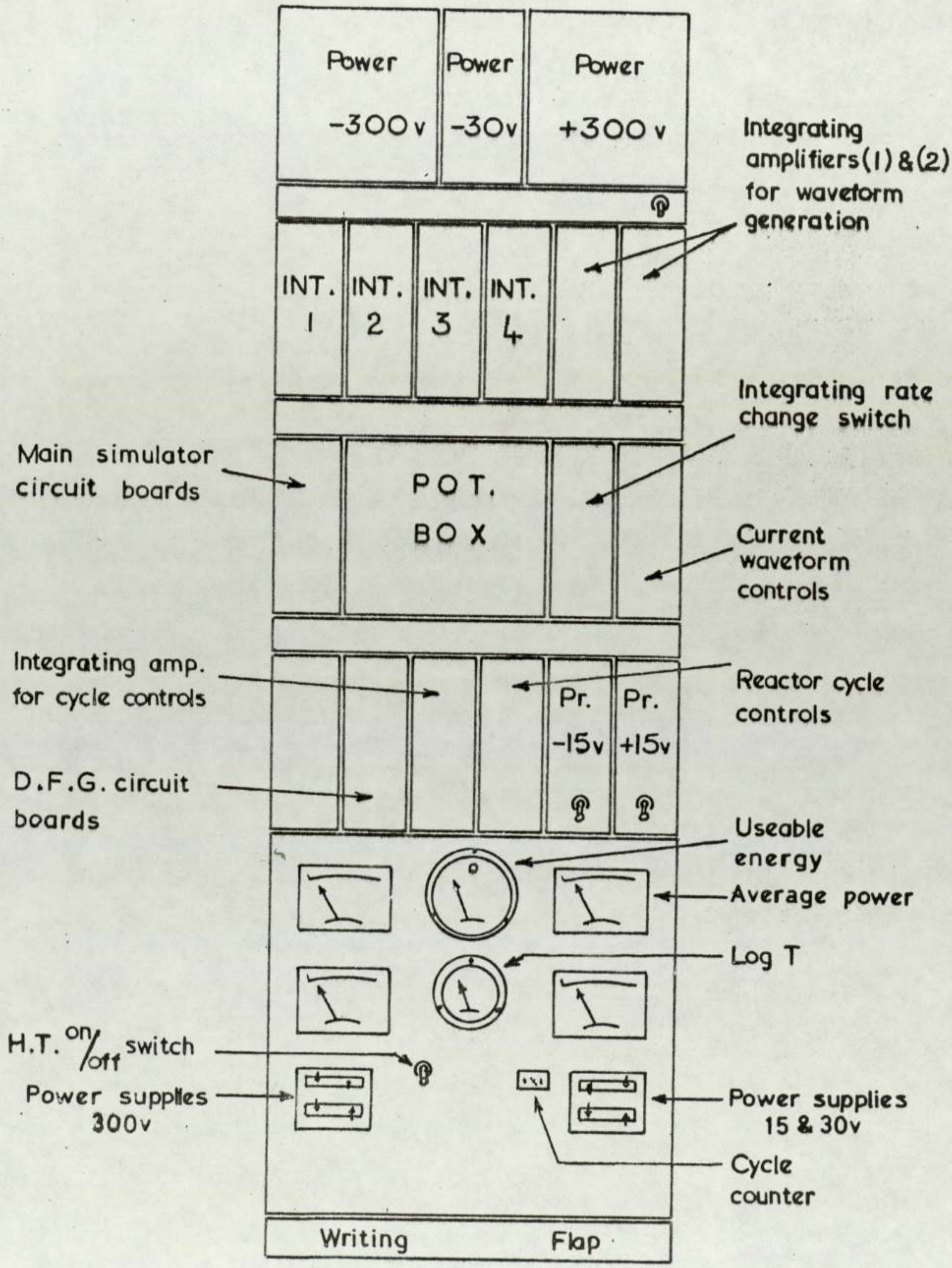
The power supplies of $\pm$ 300 volts are obtained from two ex-Harwell units providing up to 220mA output each. They are hybrid units with stabilising circuits but the circuits are not available. They are mounted at the top of the simulator to reduce the effect of their heat output on the transistorised units. In the same nest is a -30 volt supply to operate the relays in the control system. Heater supplies to the MEC 100 valve amplifiers come from 6.3v $^{o}/_{p}$ transformers mounted outside the simulator system.

The type 741 transistorised operational amplifiers are fed with $\pm$15 volts from two Farnell power units with a variable output of 15 to 30 volts at 500 mA maximum output. These are well stabilised with a ripple less than one millivolt r.m.s. They also supply the potentiometers which provide the 'constant' voltages into the 741 amplifiers.

As far as is possible the amplifiers, MEC 100's used as integrators, and the blocks of 741 amplifiers in the main

Lay-out of Simulator Units in 19" Rack

Fig. 17



simulator unit have been placed to minimise the leads between them and reduce noise pick-up. These leads are screened.

Meters have been placed in the lower parts of the simulator corresponding to eye level when seated at the pull-out writing flap. The number of meters provided is in excess of actual requirement allowing for observation of any other selected amplifier output.

Internally, apart from the MEC 100 amplifiers and the power units, the circuitry is mounted on perforated matrix boards. Four of these boards are fitted into each of two units which are ex-chassis of the MEC 100 amplifiers. One unit carries the main simulator circuitry with the 741 amplifiers and the log amplifiers on its four boards and the other unit carries the four DFG circuits. The locations of the boards and components in the simulator unit are shown in Figs. 19, 20, 21, 22 and 23 pp83/86.

All units built into an ex-chassis of the MEC 100 amplifier can be serviced and preset potentiometers adjusted by the use of an extension arm which brings the unit forward beyond the front of the simulator as in Fig. 18 p.81. Further, by removing two screws at the top and ends of the chassis the boards can be opened sideways for access to the internal wiring as in Fig.19 p.82. A large number of test points are provided throughout the simulator as befits its experimental nature.

Test points on the front panel of the main simulator unit are detailed in Fig.34 p.96. 36 points are available; not all are at present being used.

Extension arm for test and adjustment purposes

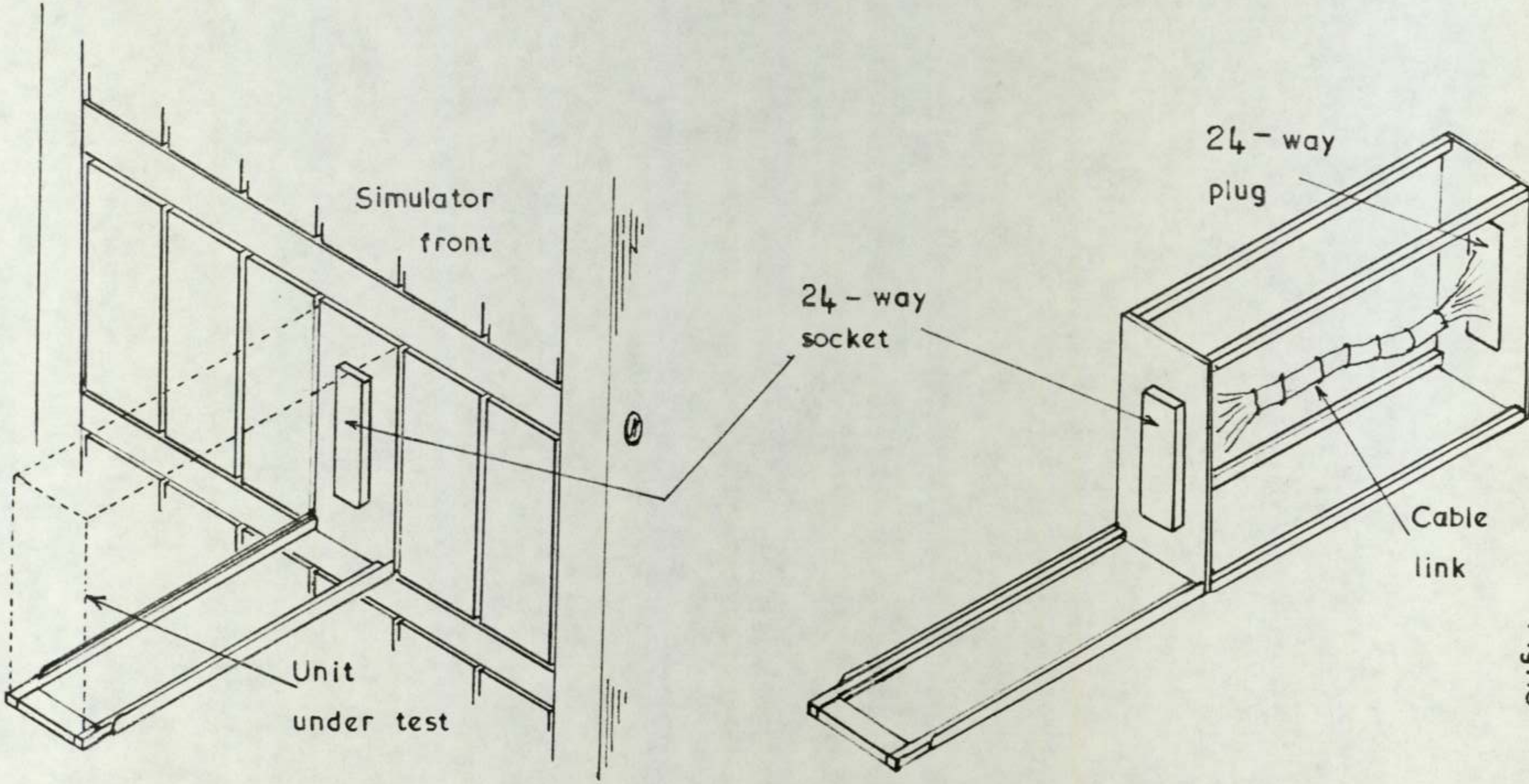
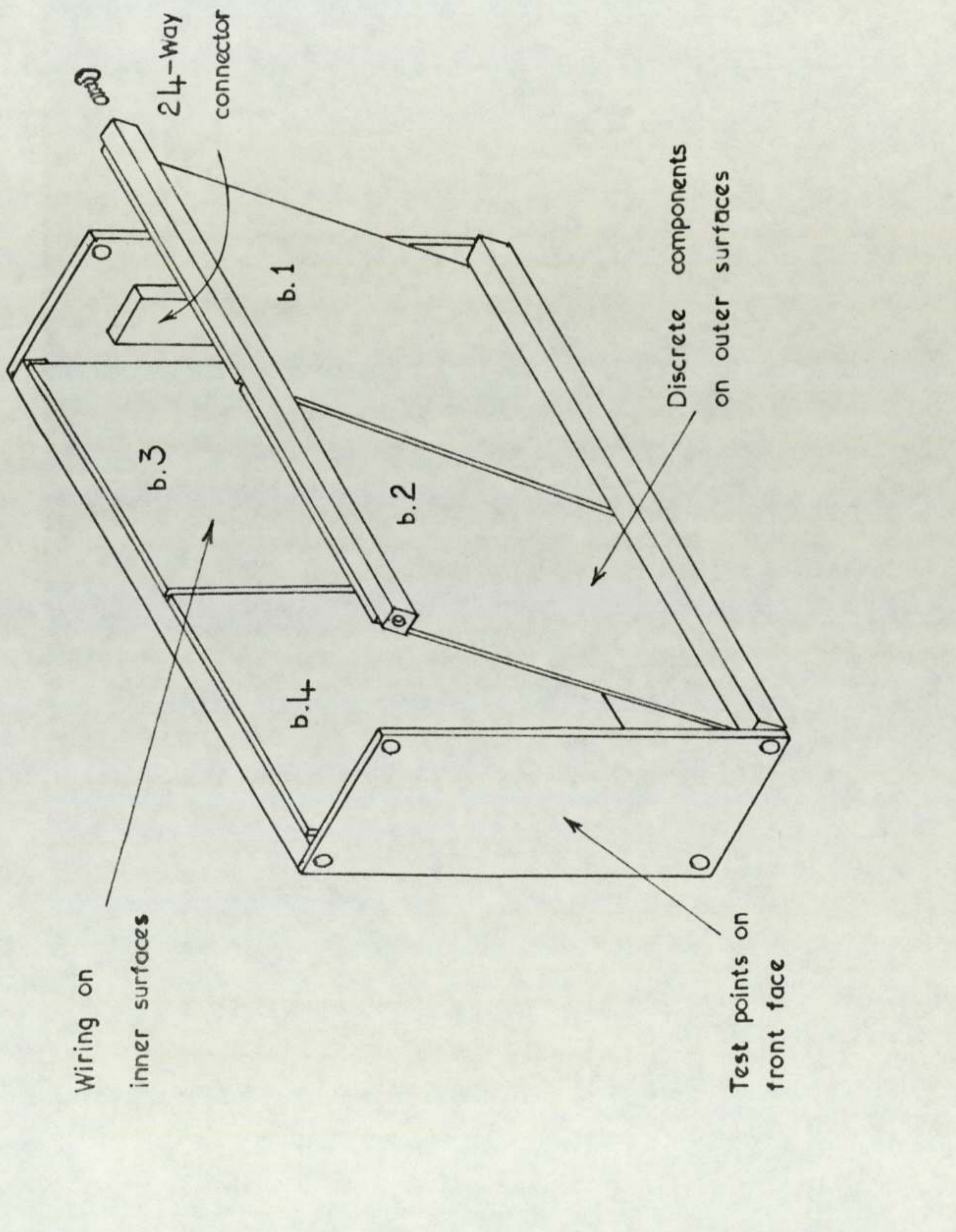


Fig.18

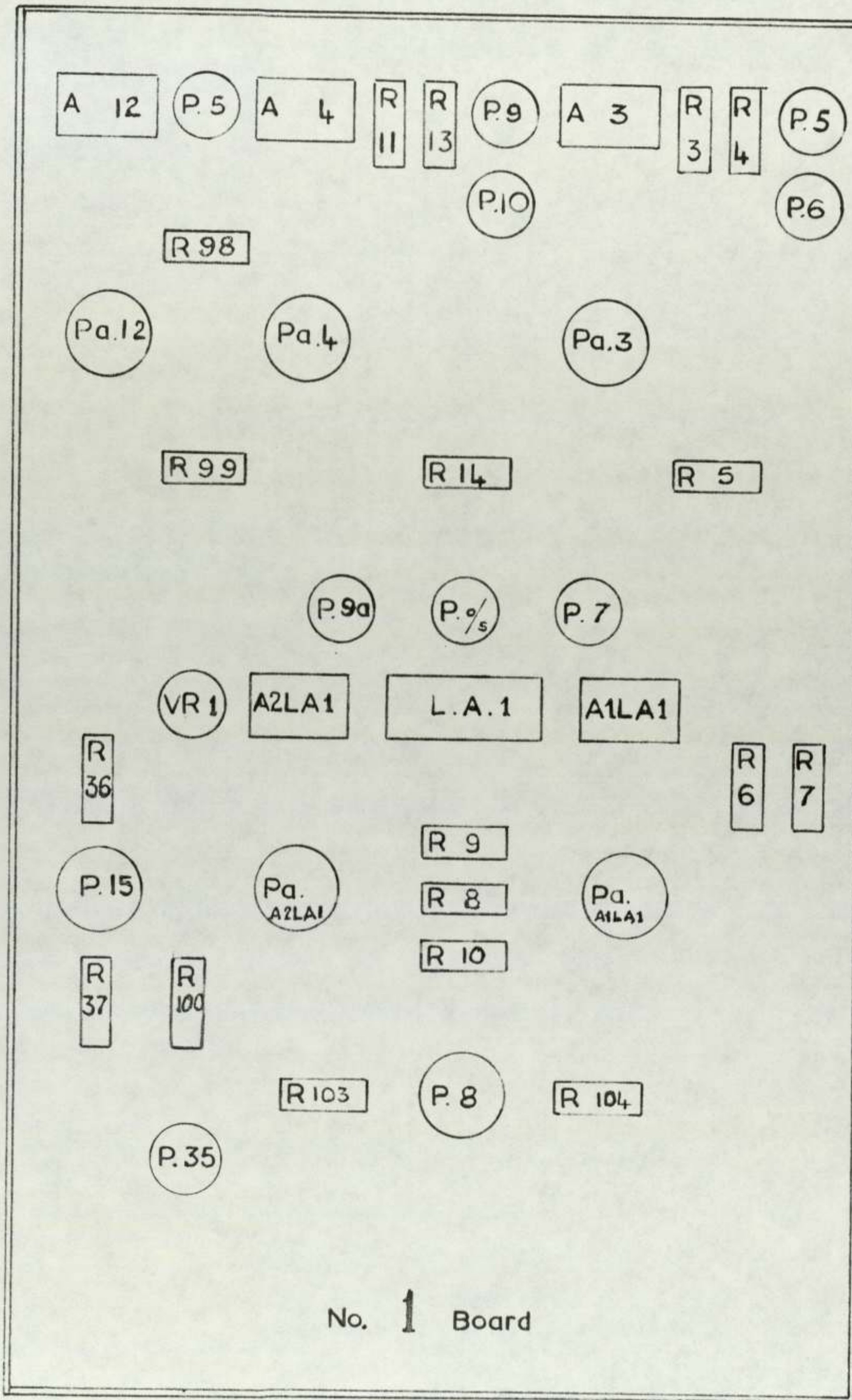
Construction — Location of boards in
Main Simulator Unit Fig. 19



Construction —Location of components

Main Simulator Unit

Fig. 20

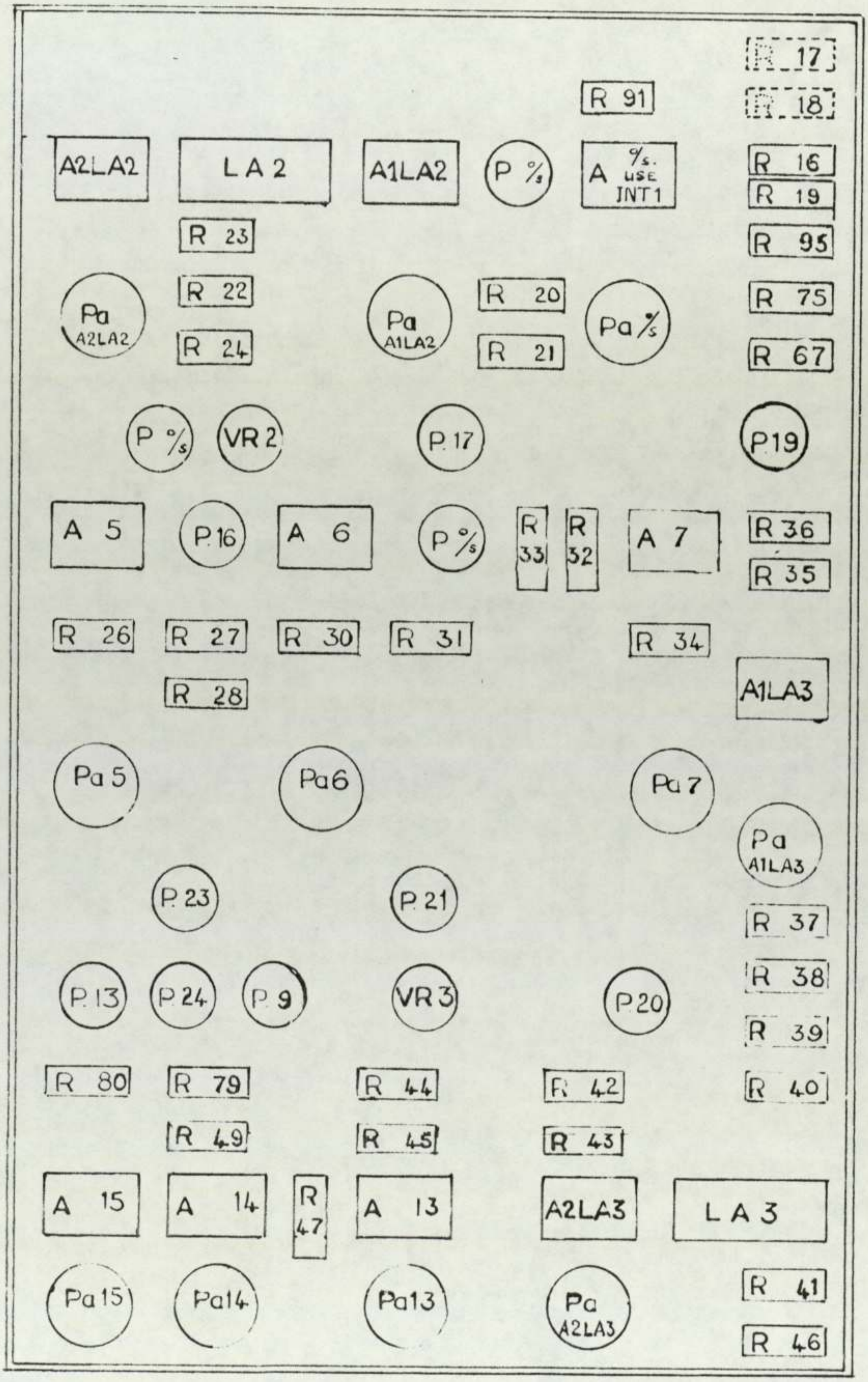


Key:- (Pa) Amp. offset adjustment (P) Circuit pot.s [R] Resistor o/s out-of-service

Construction — Location of components

Main Simulator Unit

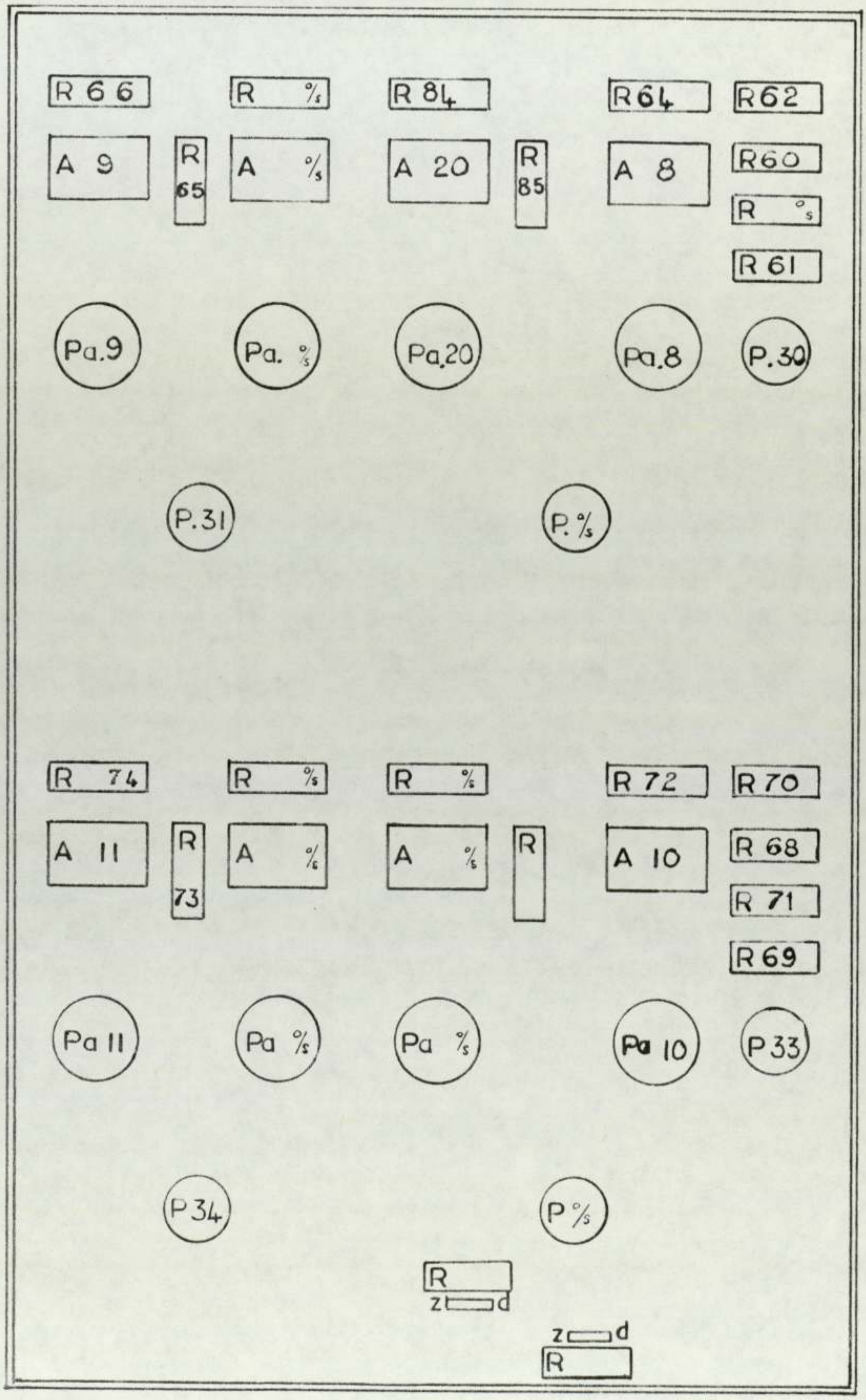
Fig.21



No. 2 Board

Construction — Location of components

Main Simulator Unit Fig.22

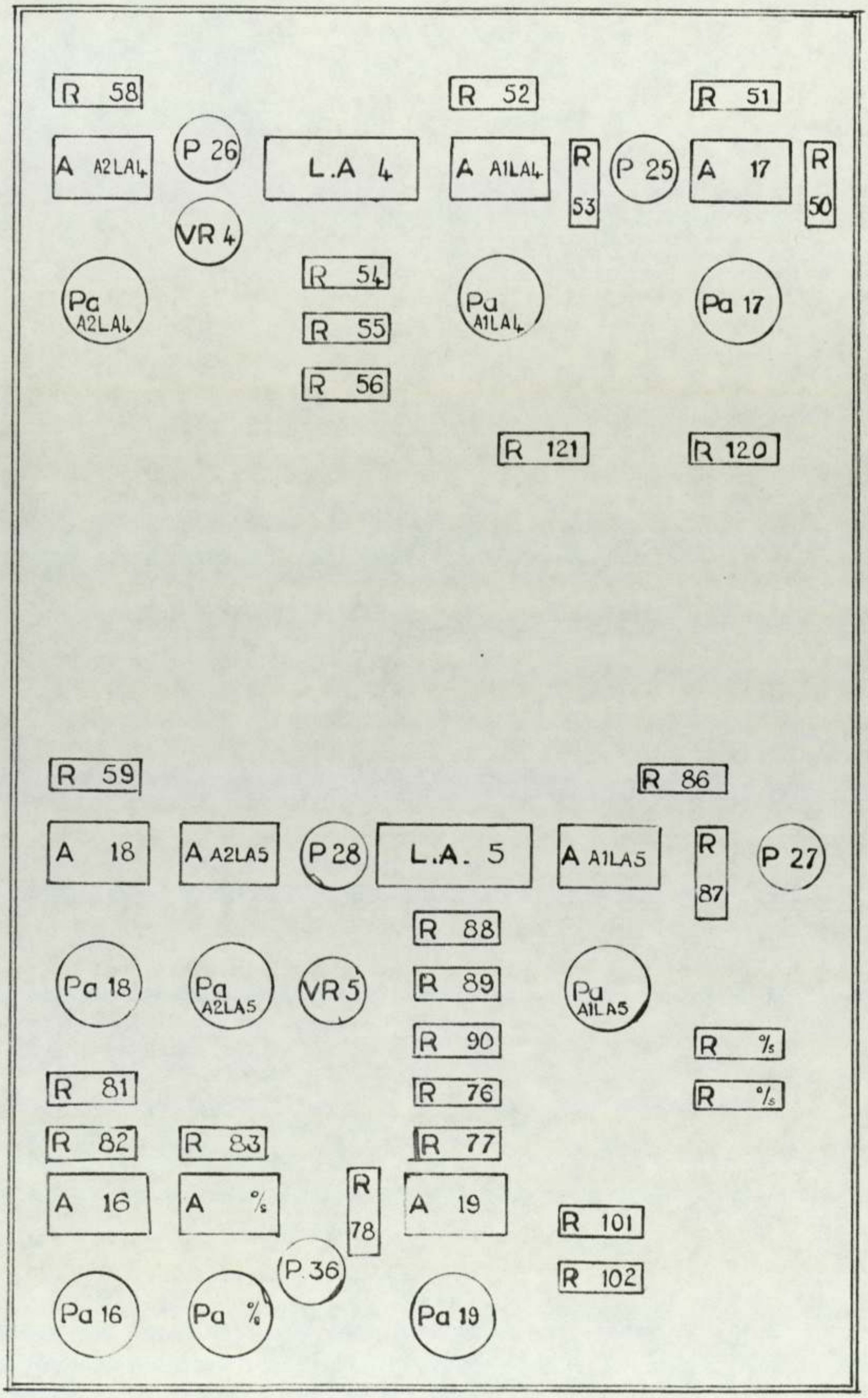


z▭d zener diode

No. 3 Board

Construction — Location of components

Main Simulator Unit Fig.23



No. 4 Board

Inter Unit Wiring

Main Simulator Unit Fig.24

Pin	Connected externally to		Pin	Co[illegible]ed externally to	
1	Pot. Unit log B	P3	13		
2	Amp. 2 waveform	P20	14	Amp. 1 waveform	P20
3	Log T meter		15	Pot. Unit log n_e	P7
4	Pot. Unit N.I.H.	P2	16	Pot. Unit log n_t	P9
5	I/P of Integrator 3		17	Pot. Unit log n_d	P8
6	I/P of Integrator 2		18	Pot. Unit linear I	P1
7	O/P of Integrator 3		19	Pot. Unit linear I	P3
8	'Saleable Power' meter		20	Farnel 2 P.S.U. −ve pot. supply	P24
9			21	Farnel 1 P.S.U. +ve pot. supply	P12
10	I/P of Integrator		22	I/P of integrator	
11	O/P of Integrator		23	O/P of Integrator	
12	−15v. Farnel P.S.U. 2	P24	24	+15v. Farnel P.S.U. 1	P12

earth connection via chassis

16-way 'flying' connector

Pin	Connected externally to		Pin	Connected externally to
1	D.F.G. Unit	P	9	
2	" "	P	10	
3	" "	P	11	
4	" "	P	12	
5	" "	P	13	
6	" "	P	14	
7	" "	P	15	
8	" "	P	16	

Inter – Unit Wiring

Fig.25

Potentiometer Unit (Box)

Pin	Connected externally to	Pin	Connected externally to
1	Main Simulator Unit P1	13	Main Simulator Unit P19
2	" " " P4	14	Farnel(2) P.S.U. P24
3	" " " P1	15	Farnel(2) P.S.U. P24
4		16	
5		17	
6		18	
7	Main Simulator Unit P15	19	Farnel(2) P.S.U. P24
8	" " " P17	20	Farnel(1) P.S.U. P12
9	" " " P16	21	Farnel(1) P.S.U. P12
10		22	
11		23	
12		24	

Inter - Unit Wiring

Fig. 26

Farnel (1) P.S.U. positive o/p

Pin	Connected externally to	Pin	Connected externally to
1	A.C. Mains	13	
2		14	
3	A.C. Mains	15	
4		16	
5		17	
6		18	
7		19	
8		20	
9		21	
10		22	
11		23	
12	+15v o/p	24	Earth

Inter – Unit Wiring

Fig.27

Farnel (2) P.S.U. negative o/p

Pin	Connected externally to	Pin	Connected externally to
1	A.C. Mains	13	
2		14	
3	A.C. Mains	15	
4		16	
5		17	
6		18	
7		19	
8		20	
9		21	
10		22	
11		23	
12	Earth	24	−15v o/p

Inter – Unit Wiring

Fig.28

Diode Function Generators Unit

Pin	Connected externally to		Pin	Connected externally to	
1	16-pin connector (mauve/red)	P1	13	16-pin connector (black)	P8
2	16-pin connector (white/red)	P2	14	16-pin connector (red/blue)	P7
3	16-pin connector (red/green)	P3	15	16-pin connector (pink/black)	P6
4	16-pin connector (red/black)	P4	16	16-pin connector (yellow/red)	P5
5			17		
6			18		
7			19		
8			20		
9			21		
10			22		
11			23		
12			24		

Inter – Unit Wiring

Fig.29

Control Unit

Pin	Connected externally to		Pin	Connected externally to	
1	Via 2·2 MΩ to Amp. A. of Control Circuitry	P22	13	6·3 v Heaters of ext. trans.	
2	NC		14	6·3 v Heaters of ext. trans.	
3	INT 4		15	INT 4	
4	+300v. P.S.U.	P3	16	−30 v. P.S.U.	P7
5	Earth		17	NC	
6	−15v. Farnel(2) P.S.U.	P24	18	NC	
7	−30 v. P.S.U.	P7	19	NC	
8	NC		20	RESET Relays	
9	HOLD Relays		21	NC	
10	NC		22	Amp A of Control Circuitry	P20
11	Amp. A. of Control Circuitry	P22	23	+15v. Farnel(1) P.S.U.	P12
12	Amp. A. of Control Circuitry	P20	24	−15v. Farnel(2) PSU	P24

Inter – Unit Wiring

Fig.30

Current Waveform Control Unit

Pin	Connected externally to		Pin	Connected externally to	
1	Input of Amp.1	P22	13	Input of Amp.2	P22
2	NC		14	NC	
3	Via 56 KΩ to earth. Via 56 KΩ to O/p of Amp.1	P20	15	Via 56 KΩ to earth. Via 56 KΩ to O/p of Amp.2	P20
4	NC		16	NC	
5	NC		17	NC	
6	RESET Relays		18	−15v. Farnel(2) P.S.U.	P24
7	NC		19	NC	
8	+15v. Farnel(1) P.S.U.	P12	20	−15v Farnel(2) P.S.U.	P24
9	NC		21	NC	
10	O/p of Amp.1	P20	22	O/p of Amp.2	P20
11	NC		23	NC	
12	I/p of Amp.1	P22	24	I/p of Amp.2	P22

Inter – Unit Wiring

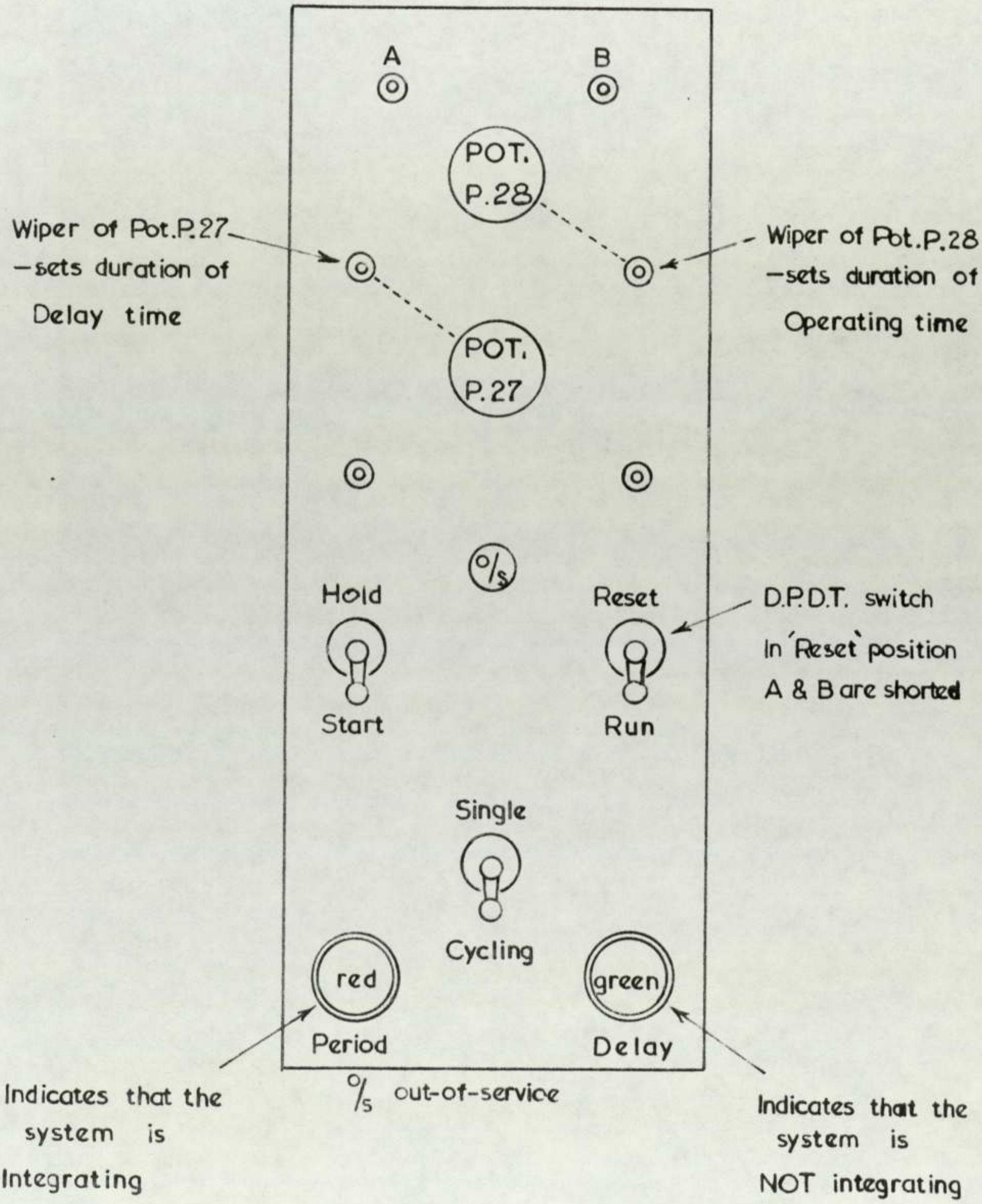
Fig.31

Integrating Rate Change Unit

Pin	Connected externally to	Pin	Connected externally to
1	/p of Integrator	13	NC
2	NC	14	/p of Integrator
3	NC	15	NC
4	/p of Integrator	16	NC
5	NC	17	/p of Integrator
6	NC	18	NC
7	/p of Integrator	19	NC
8	NC	20	/p of Integrator
9	NC	21	NC
10	/p of Integrator	22	NC
11	NC	23	/p of Integrator
12	NC	24	NC

Control Panel

Fig. 32



Test points
on
Main simulator unit front panel

Fig.34

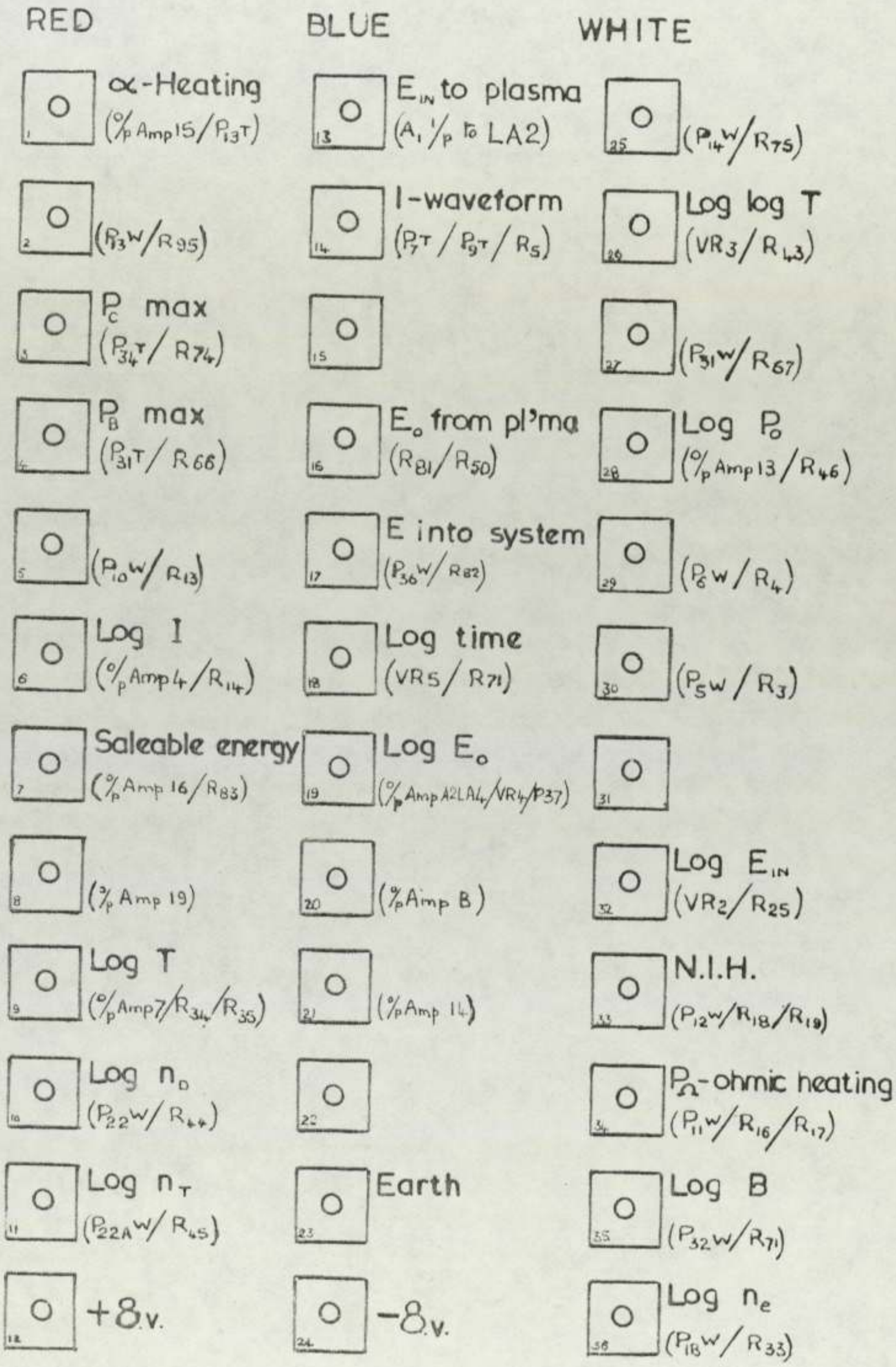
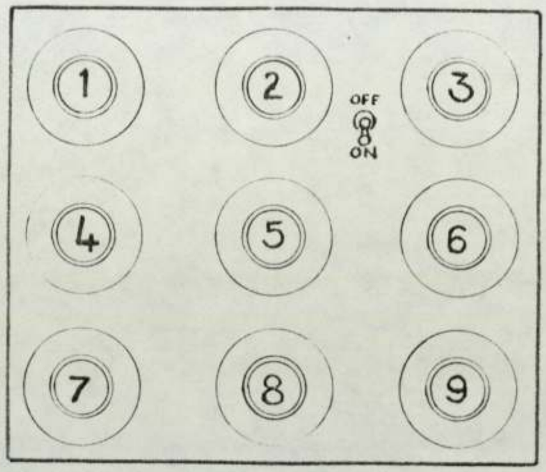


Fig.36

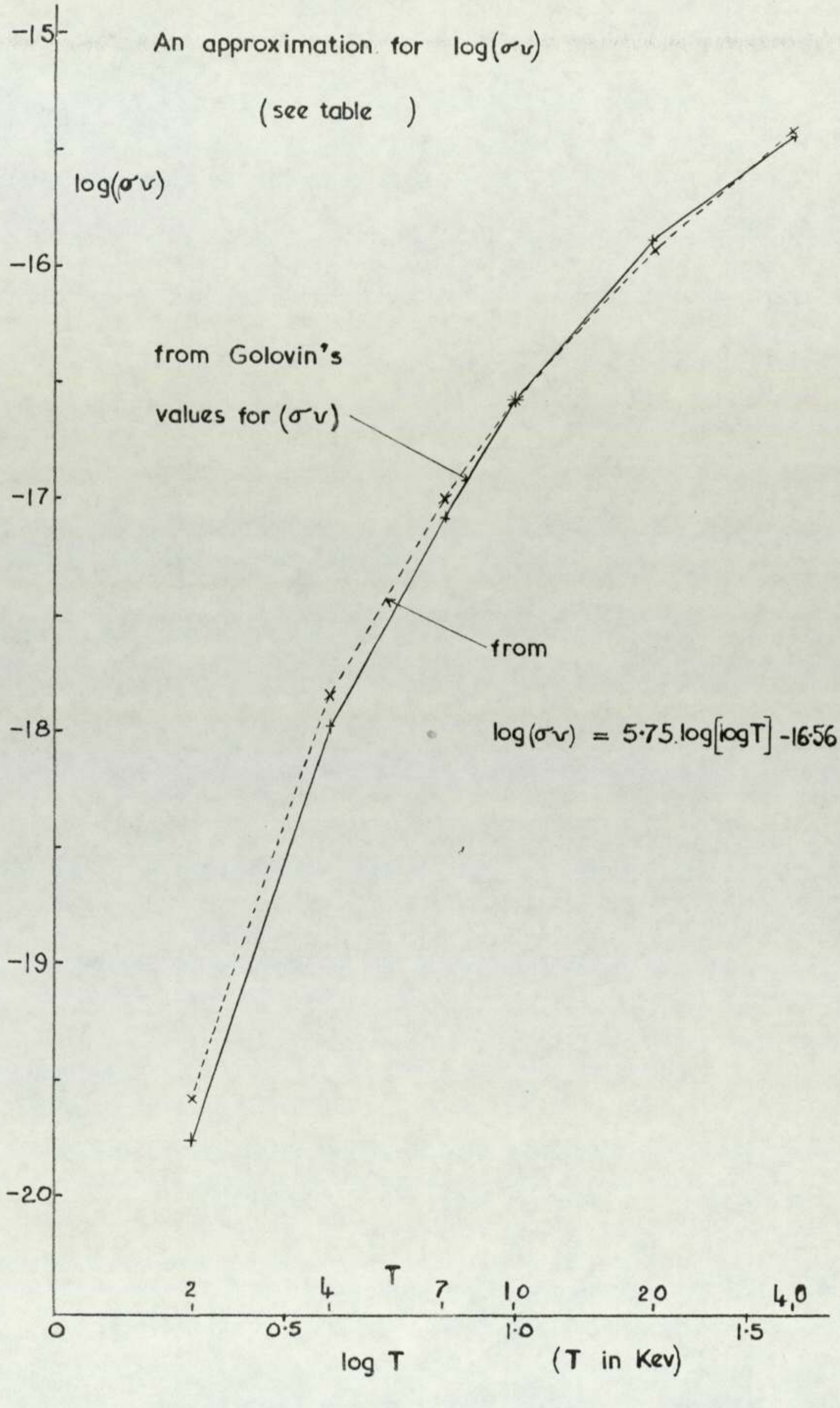
Potentiometer Unit



Pot.No. above	Circuit No.	Purpose
1.	P.11	Log I
2.	P.12	N.I.H.
3.	P.32	Log B
4.		Spare
5.		Spare
6.		Spare
7.	P.18	Log n_e
8.	P.22	Log n_D
9.	P.22A	Log n_T

ON / OFF switch for N.I.H.

Fig. 37


An approximation for log(σv)
(see table)
log(σv)
-15
-16
-17
-18
-19
-20
from Golovin's
values for (σv)
from
$\log(\sigma v) = 5{\cdot}75.\log[\log T] - 16{\cdot}56$
2
4
T
7
10
20
40
0
0·5
1·0
1·5
log T
(T in Kev)

CHAPTER 11

Results

General comment

It was pointed out in Chapter 1 that there is as yet no critical fusion reactor against whose performance that of the simulator can be compared. Sub-critical reactors exist but their performance does not reach into the regions in which the simulator tries to investigate, it being remembered that the simulator is designed to a concept of a power producing system envisaged by Golovin. At this time of writing, the press have just released news from Princeton University of an achievement of 60M^{o}K (5.2 Kev) but technical papers are awaited.

In the present design of simulator there are the following variables :-

(1) Magnitude of heating current

(2) Waveform and duration of this heating current

(3) Magnitude and duration of neutral injection heating

(4) Starting point of neutral injection heating

(5) Magnitude of toroidal magnetic field

(6) Ion density

(7) Duration of operational period

(8) Duration of reactor cycle

Additionally the following are under pre-set control :-

(1) Degree of Bremsstrahlung loss

(2) Degree of cyclotron loss

(3) Degree of temperature effect on plasma conductivity

(4) Degree of alpha-particle heating

Normally these four parameters would be fixed in any real reactor. Here they can be varied for training purposes.

If only the first list of eight is considered, then each quantity can be varied as each of the remaining seven takes on an infinite number of values within its own range. Obviously this leads to an infinite number of experimental results, way beyond time or ability to be carried out. If each of the eight variables were allotted four values only the combinations of these would be 65,536 ! A selection of results is given showing

(1) Effect of temperature on current waveform

(2) Effect of N.I.H. insertion point on temperature

(3) Effect of alpha-particle heating on temperature

(4) Effect of ohmic heating on 'saleable energy'

In the figures in this chapter the effects are shown qualitatively only, except in the case of the time axis, since the magnitude of the signal being examined depends upon so many other parameter settings. In setting up the system to show the interdependence of two parameters other parameters are optimised to enhance the effect to be demonstrated, but throughout the traces of that particular effect these optimised parameters are retained constant. Thus, for example, in Fig.40p.105, $\log(n_e)$ has been chosed so that trace A does not reach positive values of log(T) but will do so when N.I.H. is applied.

In the various traces the dependent variable is traced against a linear time scale and variations are shown as differences between the traces as an independent variable is changed. In some cases such a change can be made from cycle to cycle, but in others a series of cycles is required to show changes in the dependent variable.

In regions above the ignition temperature the traces obtained can only be accepted for the present and any assumptions as to a reactor's behaviour in these regions can only be proved by events at a future date. But in all those traces which cannot be checked against an actual reactor there is always the possibility that peculiarities may be due to some obscure fault in the circuitry, e.g. an amplifier being operated above its rated input or output. The safeguard against such faults can only be the use of test points to gauge signal magnitudes at strategic points in the circuitry plus a rigorous asking "Is the result reasonable ?".

Further work on the simulator is continuing, to improve the predictions of reactor behaviour.

Conclusions

1. Effect of temperature feedback on current waveform.

Fig.38 p.102 shows traces of the formation of current waveform from the two decaying exponential outputs of Amp.1 and Amp.2 and also how this passes through Amp.4 with only a phase inversion. This, by itself alone, produces log(T) changes which show a sudden lowering of temperature followed by a rise to positive values of log(T) as the heating current peaks, and then a slow decline towards initial log(T) values. When log(T) is allowed to affect the current waveform from Amp.3, there is an approximate reflection of log(T) in the current waveform which shows a sudden rise in current followed by a fall to a minimum and then a rise, remembering that Amp.4 has also produced inversion and its positive output signal has a reducing effect upon log(T).

The initial increase of the negative value of log(T) is not expected and judged to be unreasonable. It can be ascribed to a positive voltage on the input of integrator INT. which is not operative until the cycle starts.

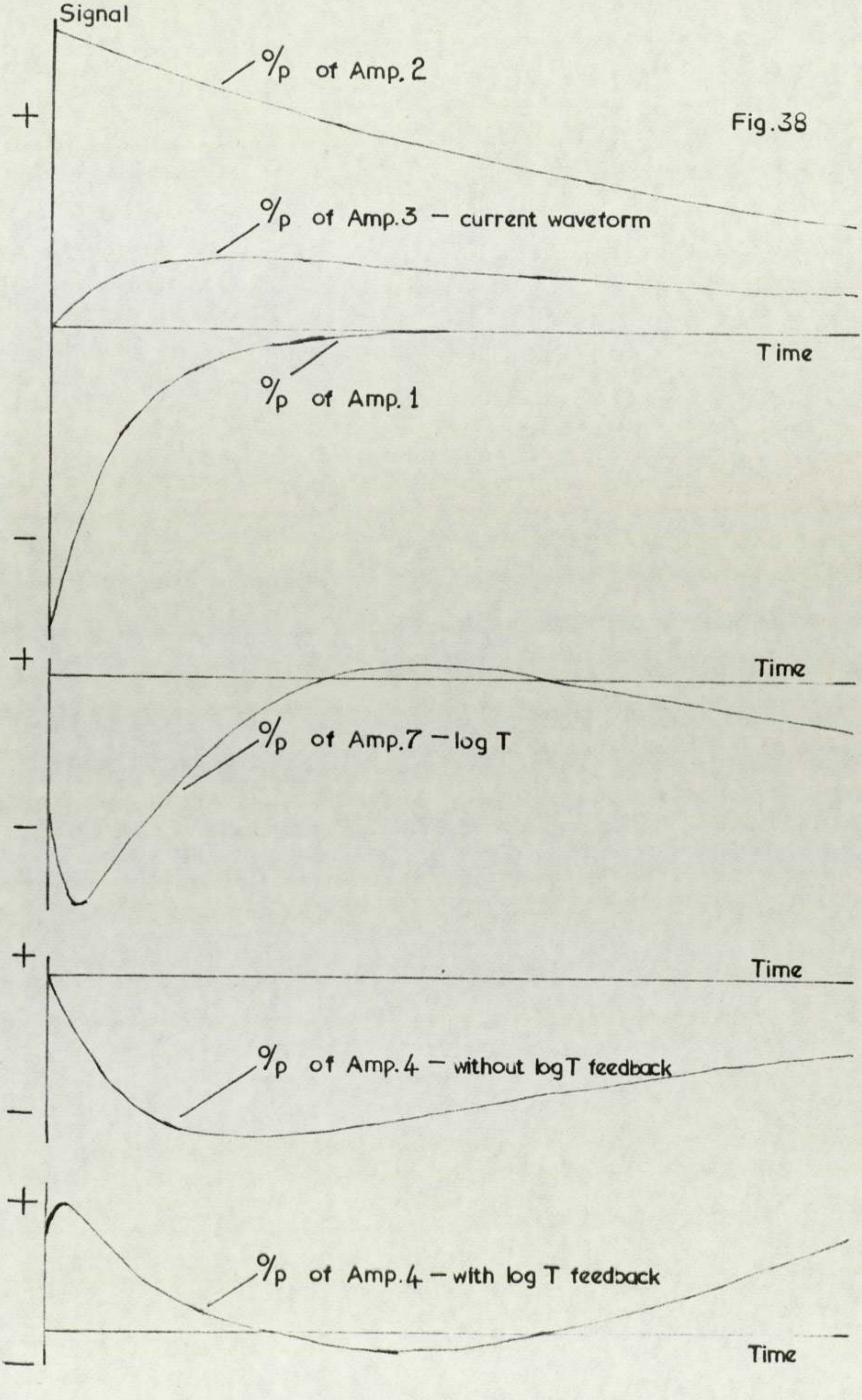

Signal
%p of Amp. 2
%p of Amp. 3 – current waveform
Time
%p of Amp. 1
Time
%p of Amp. 7 – log T
Time
%p of Amp. 4 – without log T feedback
%p of Amp. 4 – with log T feedback
Time
+
–

Fig. 38

2. Effect of N.I.H. insertion point on temperature.

These effects are shown in figures 39, 40 and 41.

In Fig.39 p.104 the operational period during which the temperature may rise has been extended without limit. N.I.H. of fixed magnitude and duration has been introduced at particular times from the start of the operational period. This figure is a combination of several traces made possible since the individual traces all departed from and returned to the same basic log(T) trace obtained when N.I.H. was absent.

If the area above the zero log(T) line is taken as a measure of the nuclear energy developed, then the figure indicates that N.I.H. applied around the maximum temperature will lead to the highest peak temperature and greatest amount of nuclear energy, as might be expected.

The duration of the N.I.H. effect, i.e. both rise and decay remains constant and independent of the point of entry.

Fig.40p.105 shows the effect of both duration and point of entry of N.I.H. in a series of non-consecutive operational periods in which some fixed amount of alpha-particle heating and feedback has been introduced. The P_{α} does not become effective until temperature reaches an ignition value, taken here as log(T) = 0 (i.e. T = 1 Kev)

In trace A the ohmic heating, P_{Ω} , raises the temperature which does not however reach the ignition value and log(T) decays as P_{Ω} decays. The succeeding traces show log(T) being raised above ignition temperature by N.I.H. applied at various points of time in the operational period. Temperatures rise above the ignition value at rates set by the N.I.H. value and when this ceases, the log(T) rise continues at a rate set by the P_{α} feedback. It should be noted that a linear log(T) rise indicates an exponential rise of temperature, Effect of N.I.H. insertion point on temperature

(Extended operational period)

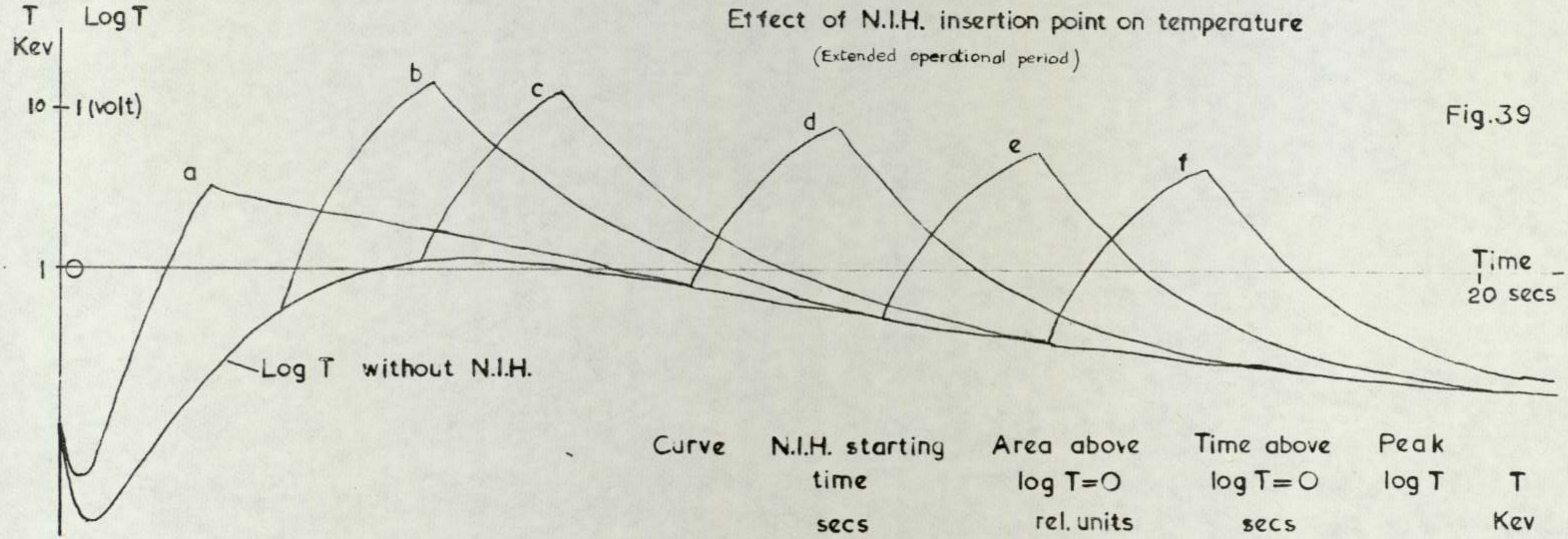
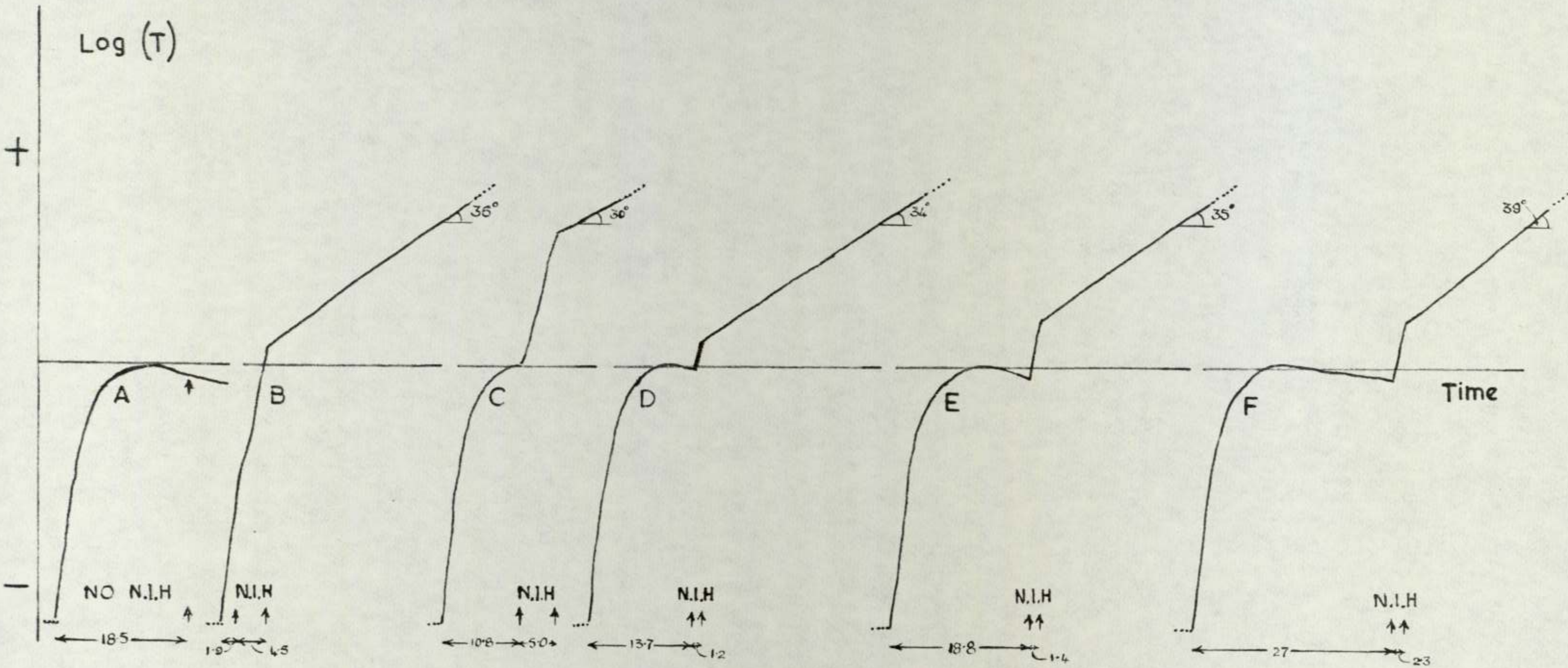


Fig.39

N I H duration ≈ 2 secs

Curve	N.I.H. starting time secs	Area above log T=O rel. units	Time above log T=O secs	Peak log T	T Kev
a	0	94	6·6	·52	3·3
b	3·1	172	6·0	1·18	15·1
c	5·1	150	5·8	1·11	12·9
d	8·9	103	6·8	·90	8·0
e	11·6	75	6·2	·74	5·5
f	13·9	50	5·5	·59	3·9



Interval times in seconds.

Fig.40

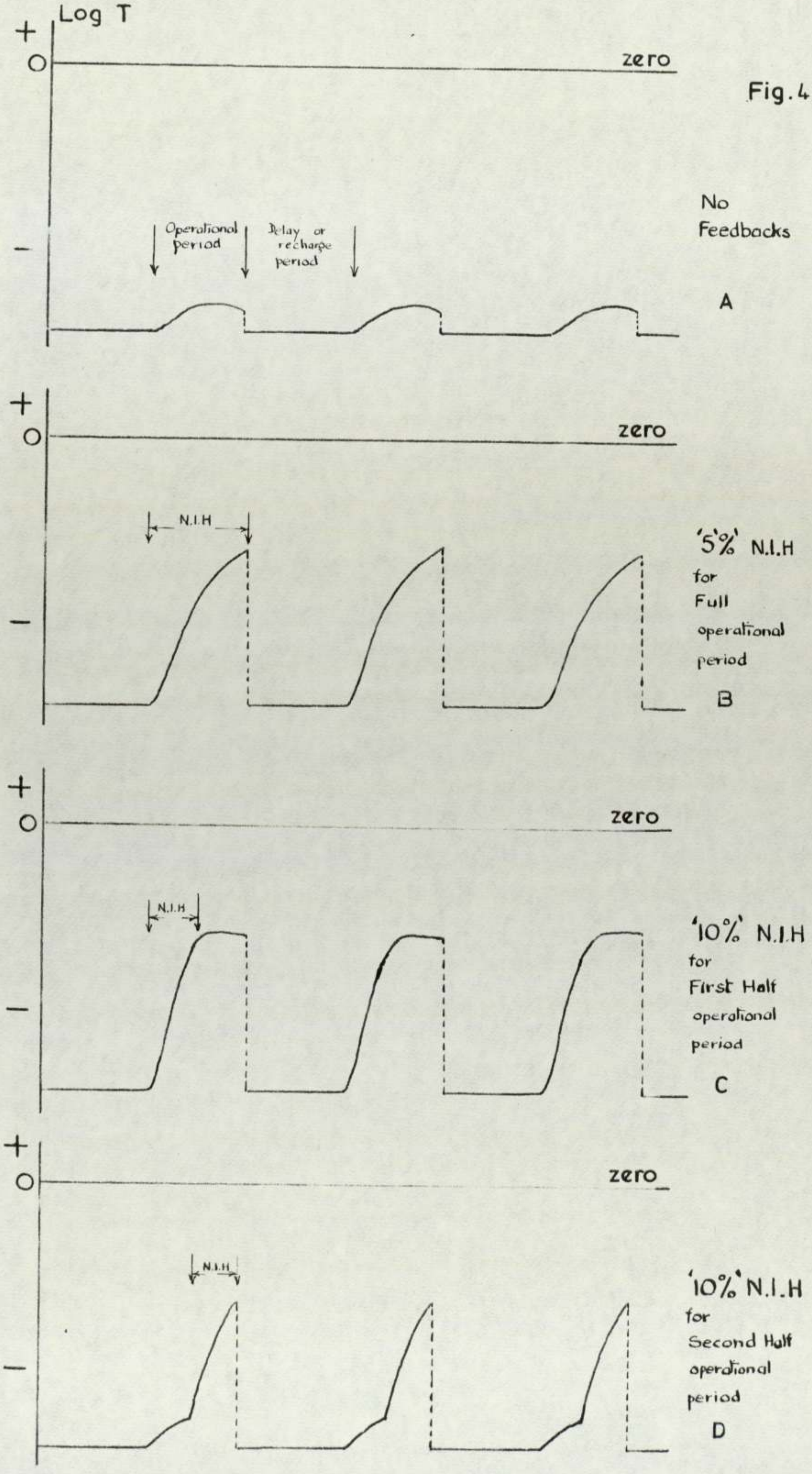

Log T
+
O
zero
-
Operational period
Delay or recharge period
No Feedbacks
A
N.I.H
'5%' N.I.H for Full operational period
B
'10%' N.I.H for First Half operational period
C
'10%' N.I.H for Second Half operational period
D

Fig. 41

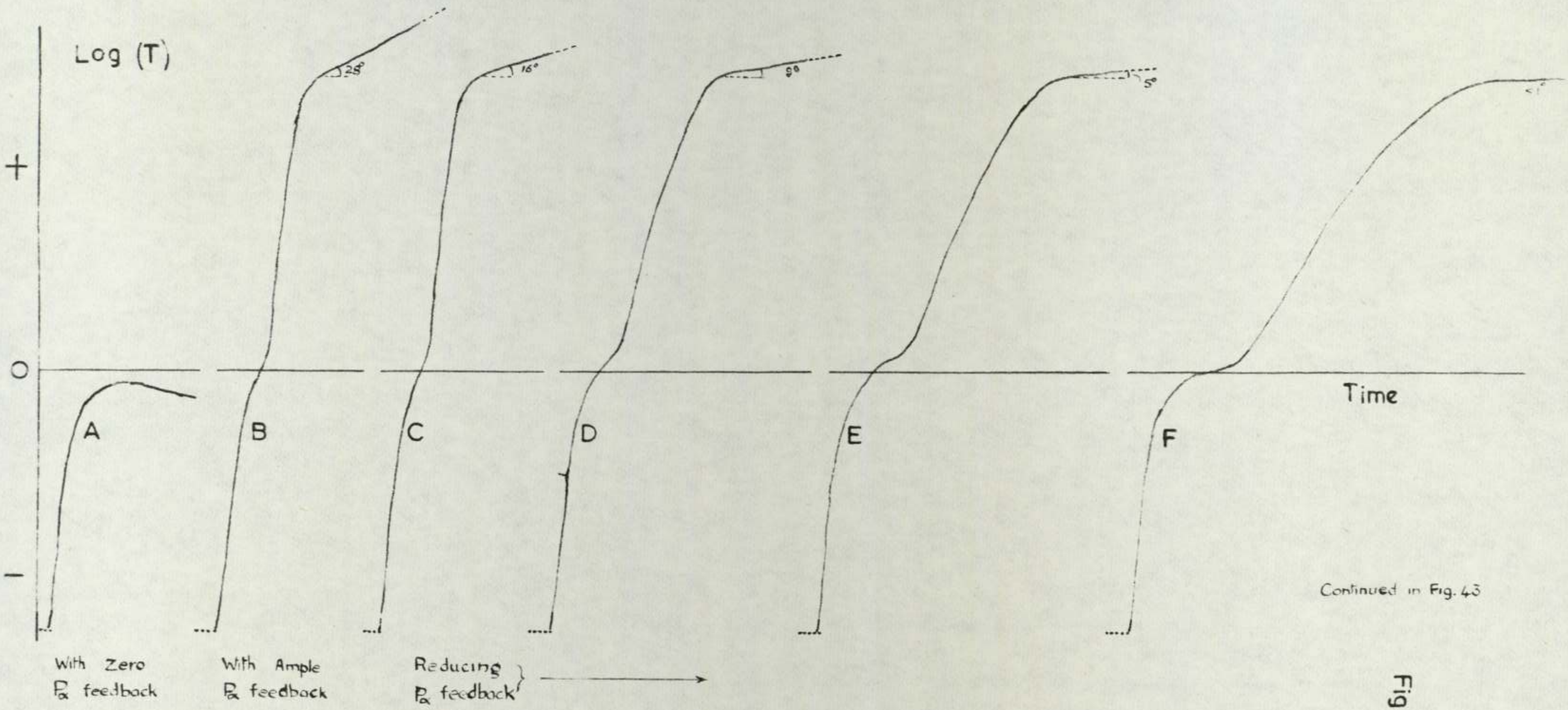
Fig.41 p.106 shows in another way how the same N.I.H. energy affects log(T) according to how and when it is inserted. In trace C the N.I.H. concentrated into the first half of the operational cycle is shown to be more effective in raising and sustaining log(T) than being concentrated in the second half of the period (trace D) or spread over the full period (trace B).

3. Effect of alpha-particle heating on temperature.

These effects are shown in figures 42, p.108 and 43, p.109, under zero N.I.H. conditions. In trace A there is also zero alpha-particle heating and log(T) with only ohmic heating cannot reach ignition value and so falls off as does P_{Ω}. (this is similar to trace A of Fig.40). In trace B the maximum P_{α} feedback available is provided. This appears to assist the log(T) rise even below the ignition value and above this value the log(T) rise quickens to a common value and then still continues to rise but at a slower rate.

This pattern is reproduced as the P_{α} feedback is progressively reduced down to a limiting value indicated in trace G. There are differences; as the P_{α} feedback decreases, the assistance to log(T) when near the ignition value weakens until in trace H the ignition value is not reached. Trace J indicates a slight improvement in log(T) with a small increase in P_{α} feedback.

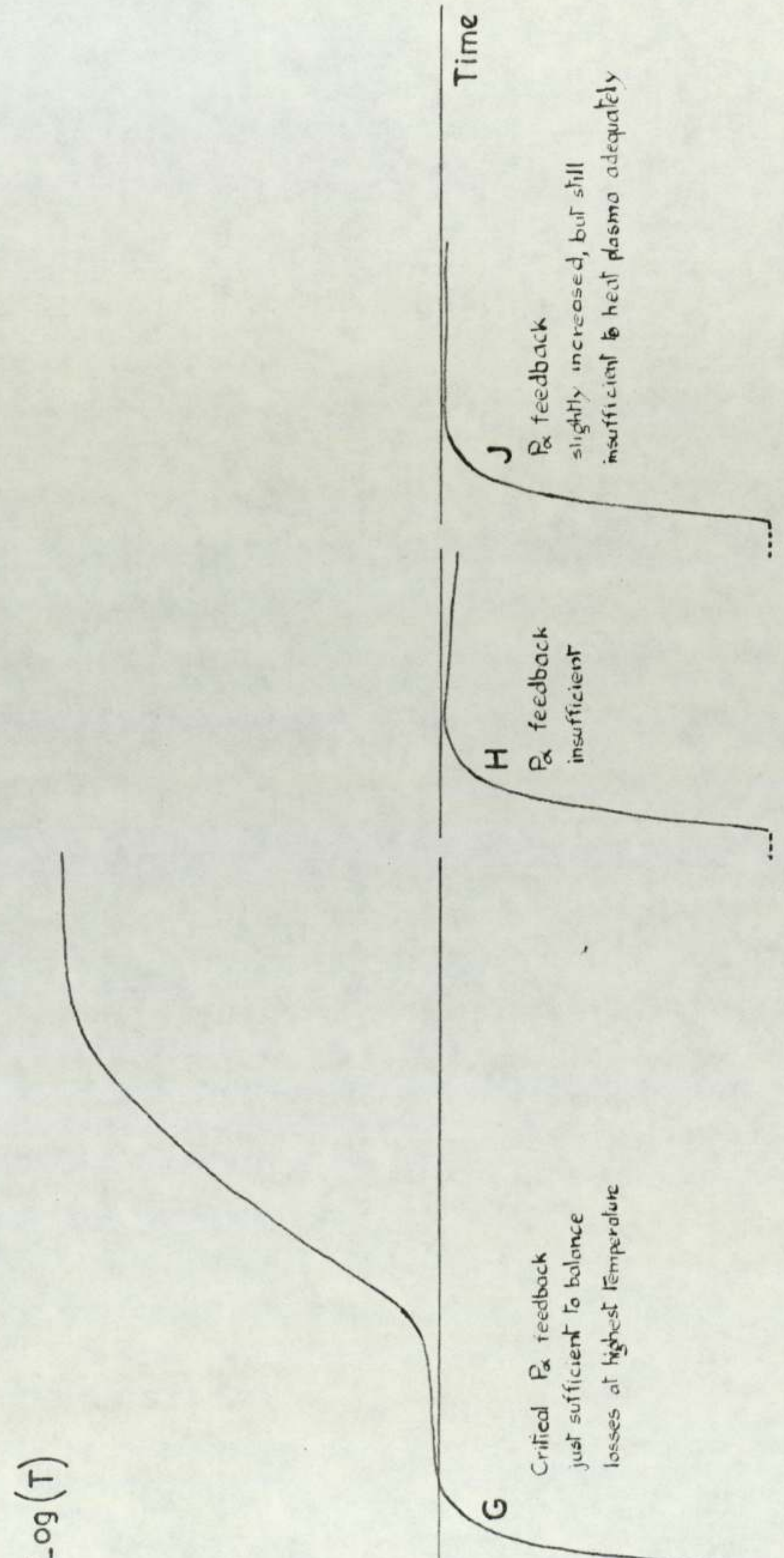
As might be expected the rate of rise of log(T) above ignition value decreases as the P_{α} feedback decreases. Above the common value reached by log(T) the steady rate of rise also shows a continuous decrease until in trace G it has been reduced to zero. Presumably, at this condition the P_{α} feedback just balances the losses by Bremsstrahlung and cyclotron radiations and in an actual reactor by thermal and nuclear radiations and by thermal conductivity through the walls.

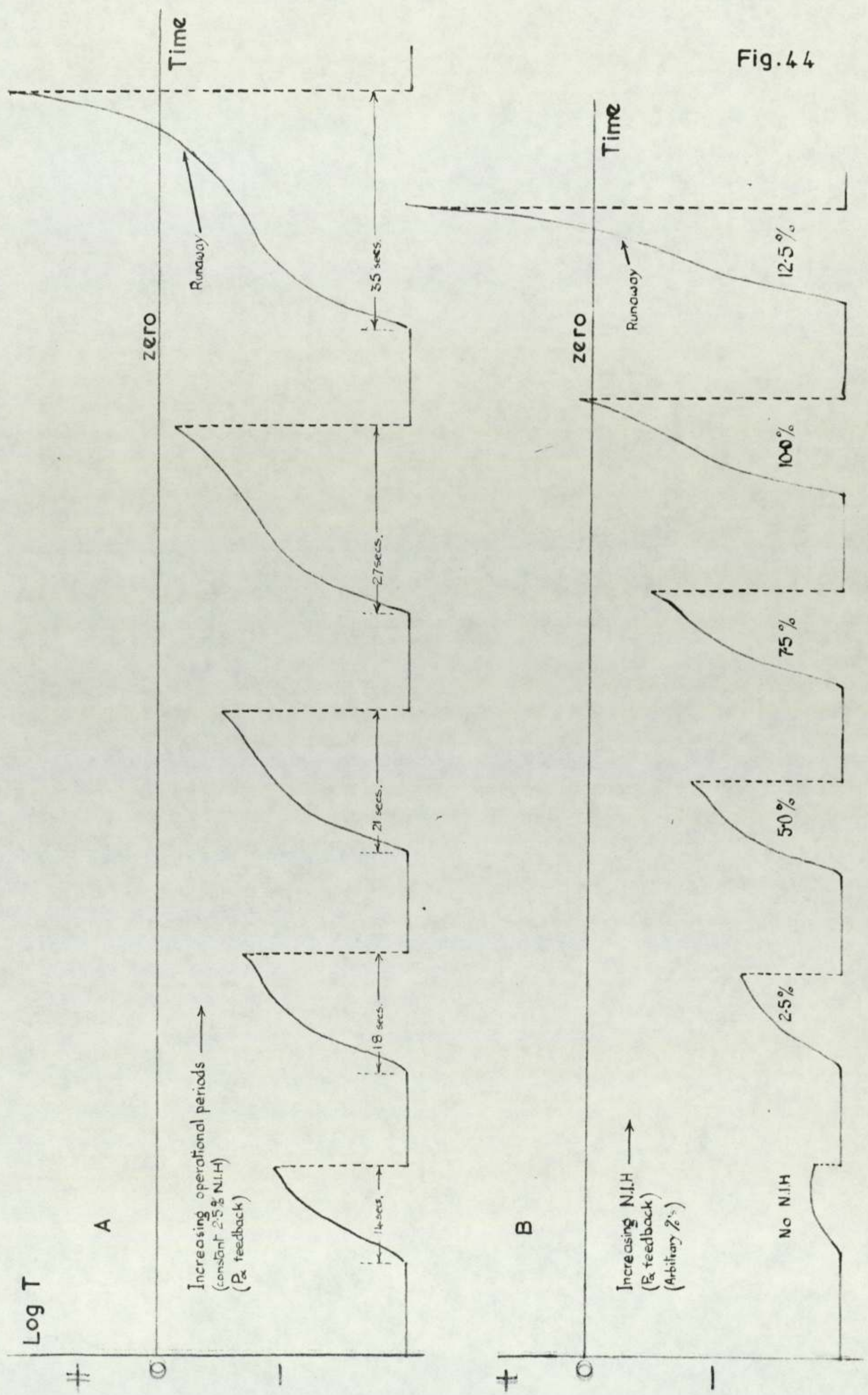


Continued in Fig. 43

Fig.42

Fig.43


Log(T)
+
0
-
Time
G
Critical P_α feedback
just sufficient to balance
losses at highest temperature
H
P_α feedback
insufficient
J
P_α feedback
slightly increased, but still
insufficient to heat plasma adequately



Log T
+
0
-
A
Increasing operational periods ⟶
(constant 2·5% N.I.H)
(Pα feedback)
14 secs.
18 secs.
21 secs.
27 secs.
35 secs.
Runaway
zero
Time
B
Increasing N.I.H ⟶
(Pα feedback)
(Arbitrary %'s)
No N.I.H
2·5%
5·0%
7·5%
10·0%
12·5%
Runaway
zero
Time

Fig. 44

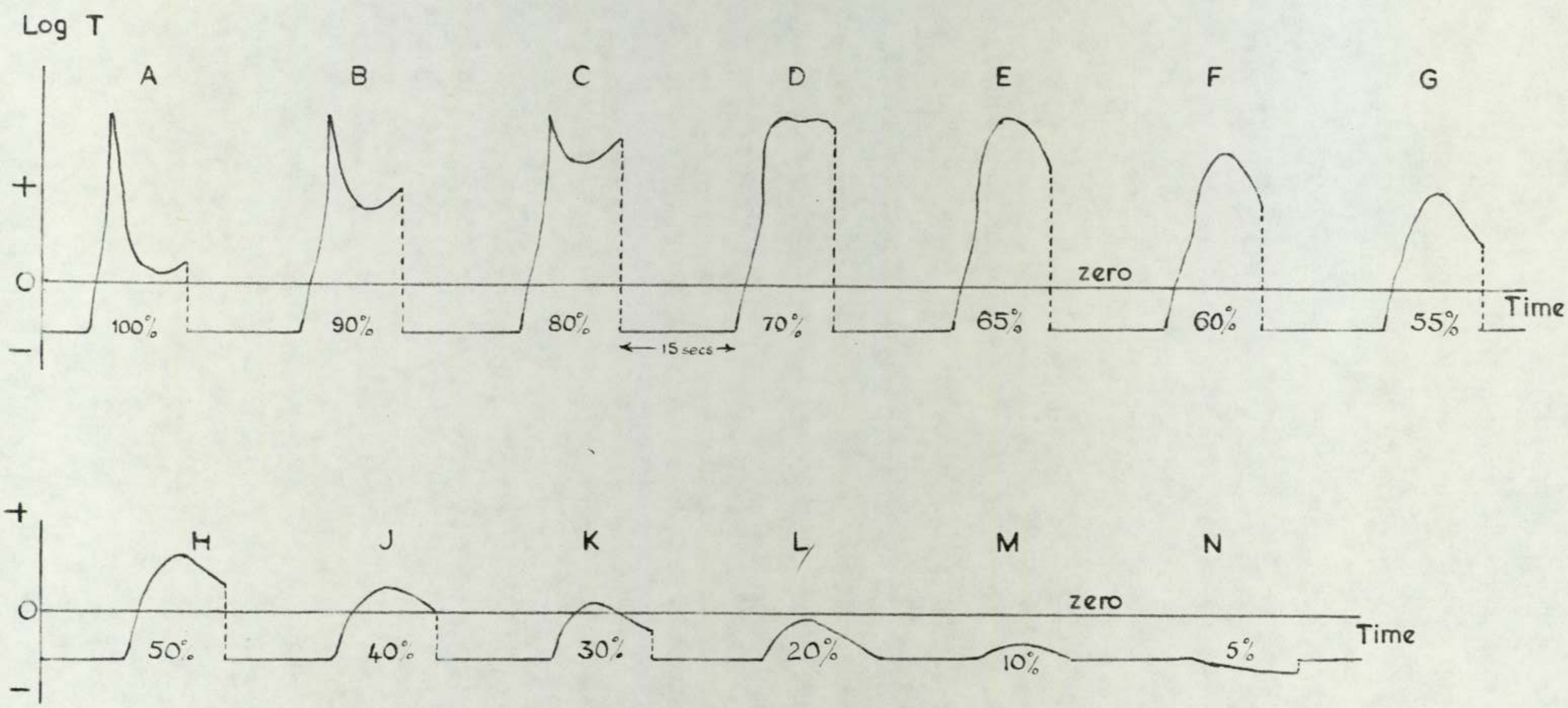
The common value which log(T) reaches in traces B to C may possibly mark the end of the ohmic heating period and the change over to heating by P_α alone. Alternatively there may be some limitation in the circuitry not yet apparent.

Fig.44 p.110 illustrates how, given the opportunity, alpha-particle heating can be effective in raising log(T). In trace A the decay periods are constant but the operational period increases from one cycle to the next. In this expected trace the lengthening operational period gives more time for log(T) to rise, eventually reaching a runaway situation. Similarly, in trace B with increasing N.I.H. giving more and more assistance to the heating of the plasma a runaway situation is again reached even in cycles of constant duration.

4. Effect of ohmic heating on saleable energy.

A series of traces in Fig.45 p.112 shows the effect of decreasing the amount of ohmic heating upon log(T) with some log(T) feedback to affect the degree of ohmic heating by changes to the plasma conductivity.

The peak values of log(T) show, as might be expected, a continuing decrease as the ohmic heating is reduced, eventually failing to reach the ignition temperature and therefore unable to excite P_α heating. Less predictable are the sharp initial peaks of log(T) in traces A,B,C, and D followed by a minimum and a rise again. It is a suggestion only that these traces show the onset of "hunting" or oscillations of log(T) which are cut short by the limited operational period. This oscillation decreases in amplitude as P_Ω reduces to the arbitrary value of 70% and then the decay of log(T) follows the decay of ohmic heating. It is perhaps possible that the oscillation is showing the form of instability due to the Kruskal limitation of plasma current for a given toroidal magnetic field. The effect of the toroidal field



Log T v Time
for
decreasing percentages of maximum P_{Ω}

Fig.4.5

strength on instability in the simulator has yet to be investigated.

The apparent onset of this instability has been investigated with the results shown in figures 47 and 48. Two methods were used. In Fig.47 p.116 the maximum ohmic heating was maintained constant and the toroidal magnetic field was progressively reduced from its maximum. The traces show that the instability, as measured by the initial variations of log(T), increases as the field decreases, particularly below half its maximum. The oscillation period also increases, though the period is not uniform, while the amplitude tends to swing about the zero value of log(T). In Fig.48 p.117 the toroidal field was kept constant at half its maximum value and the ohmic heating was increased in steps up to its maximum. The instability can be seen to commence at about 90% of the maximum heating.

These effects appear to follow the pattern of Fig.8 p.21. In that figure instability arises with high currents in high fields and in the early part of an operational period. In low fields instability would appear to be less violent with the smaller currents and to occupy a longer period of time.

The production of saleable energy is the prime purpose of a fusion reactor. Fig.46 p.115 shows interesting changes of cycle as the amount of ohmic heating is reduced. The traces display the balance of energy between the integrated amounts of nuclear energy generated after allowing for losses and the energy put into the system from external sources; positive values indicating a gain of energy and negative values a loss. The overall picture is of small energy gains with the greatest ohmic heating, heavy losses of energy with lower ohmic heating, followed by huge energy gains at still lower ohmic heating and both gains and losses tending to zero as ohmic heating reduces to zero. This is difficult to interpret, and correlation with log(T) in Fig.45 does not appear. Assuming that the circuitry is satisfactory, it might be suggested that the initial small gains of energy are due to initial rapid rise of temperature which is not sustained since the high temperature decreases the ohmic heating. When this heating lessens the losses predominate. The build up of energy may be due to steadier conditions below the Kruskal limit but the trend to zero gain or loss is not expected since the saleable energy is the difference of two separately integrated amounts of energy and there is no reason for these to finally balance equally. More work is necessary to check these suggestions.

As mentioned earlier the simulator is intended for the qualitative demonstration of the basic behaviour of a fusion reactor, rather than for design work. It provides 'open ended' experimental training in this field and there is discussion on this in a following chapter.

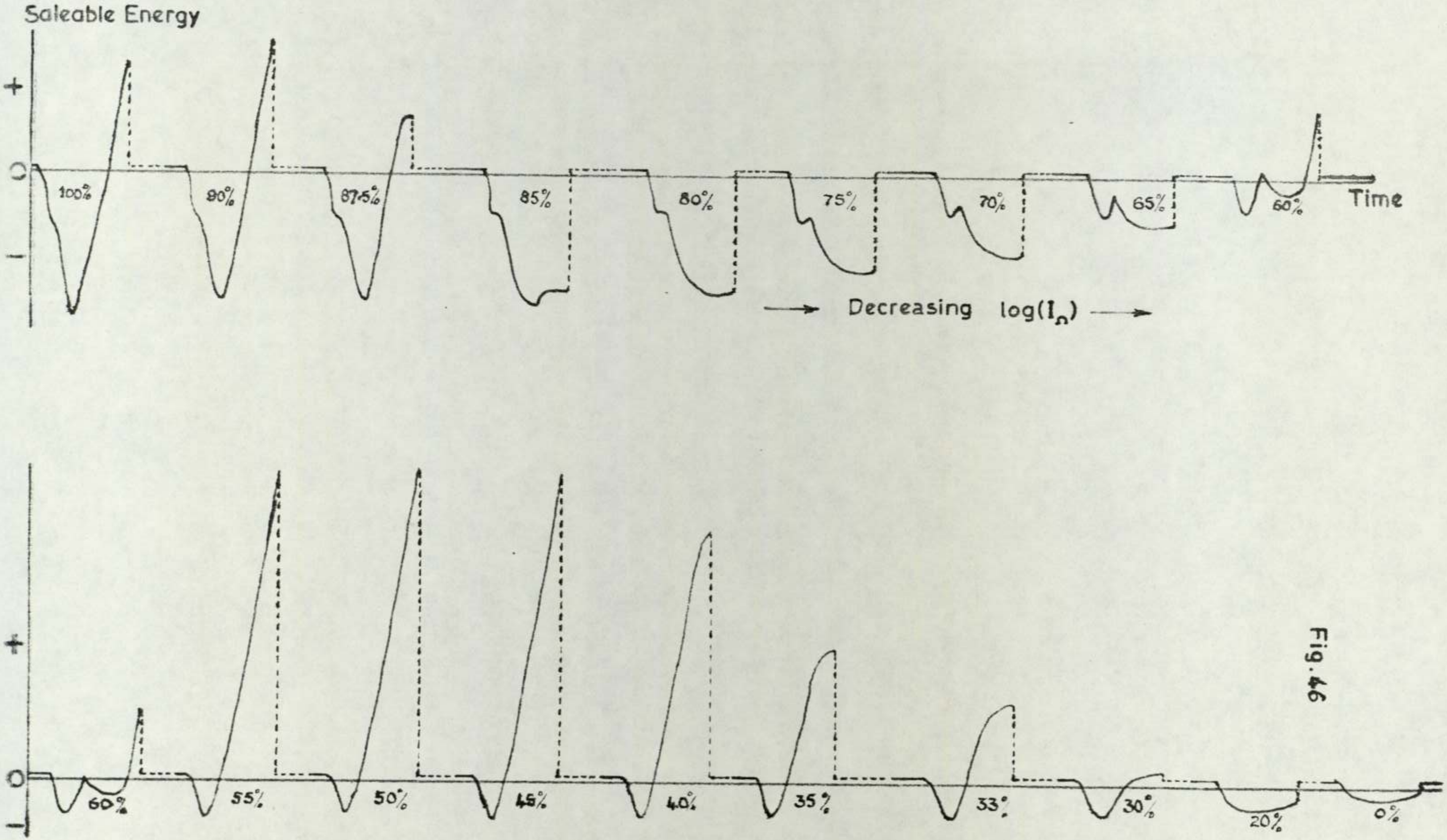

Saleable Energy
+
0
-
100%
90%
87.5%
85%
80%
75%
70%
65%
60%
Time
Decreasing log(In)
+
0
-
60%
55%
50%
45%
40%
35%
33%
30%
20%
0%

Fig. 46

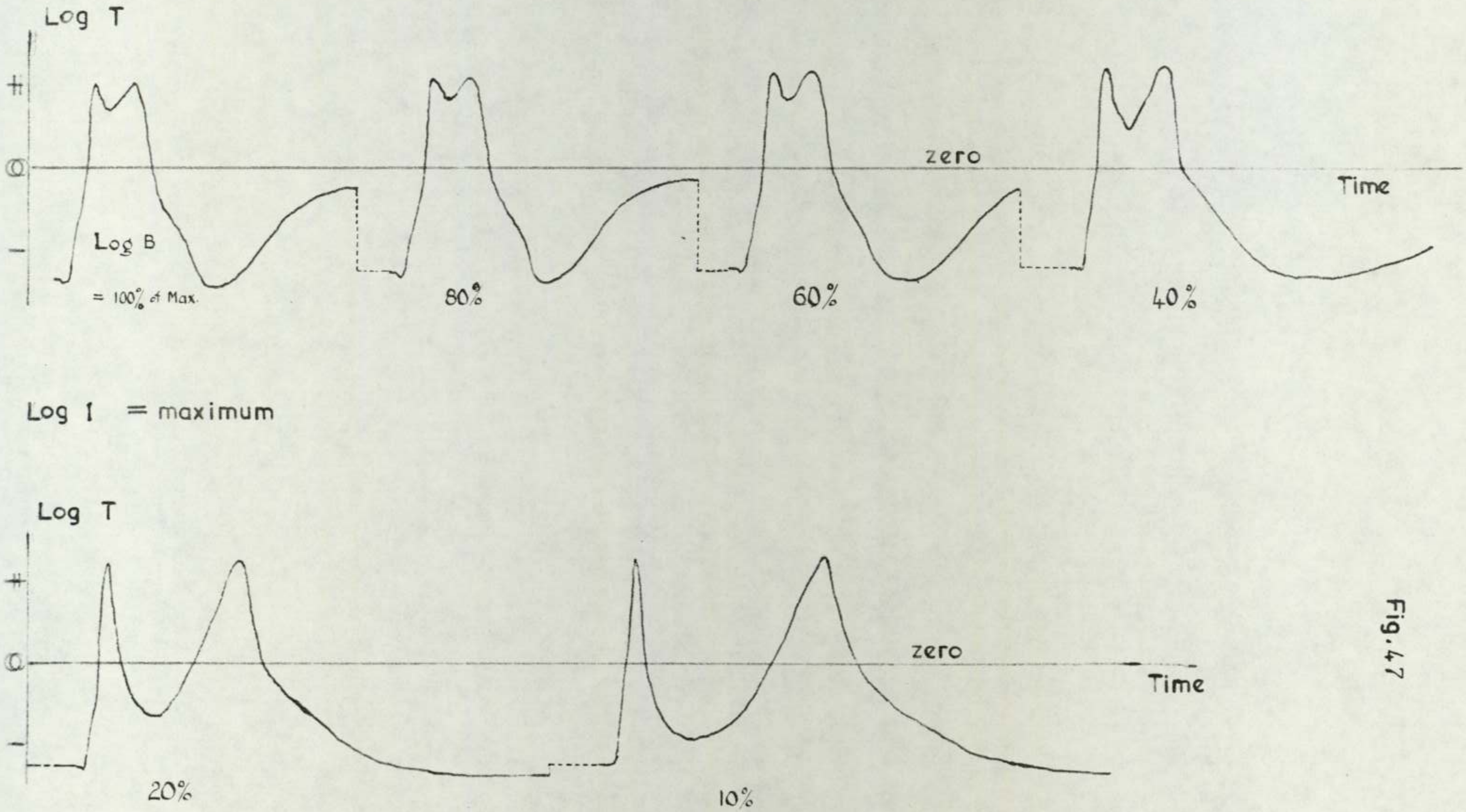
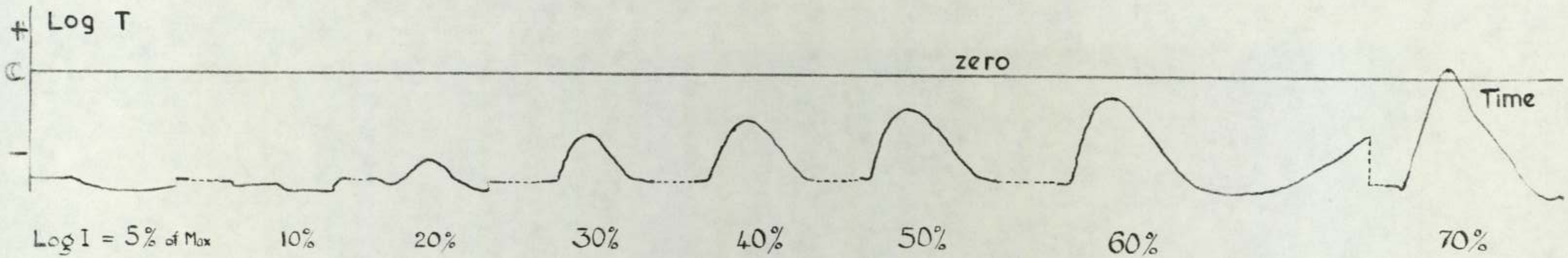

Log T
+
0
-
zero
Time
Log B
= 100% of Max.
80%
60%
40%
Log I = maximum
Log T
+
0
-
zero
Time
20%
10%

Fig. 47



Log B = 50% of maximum

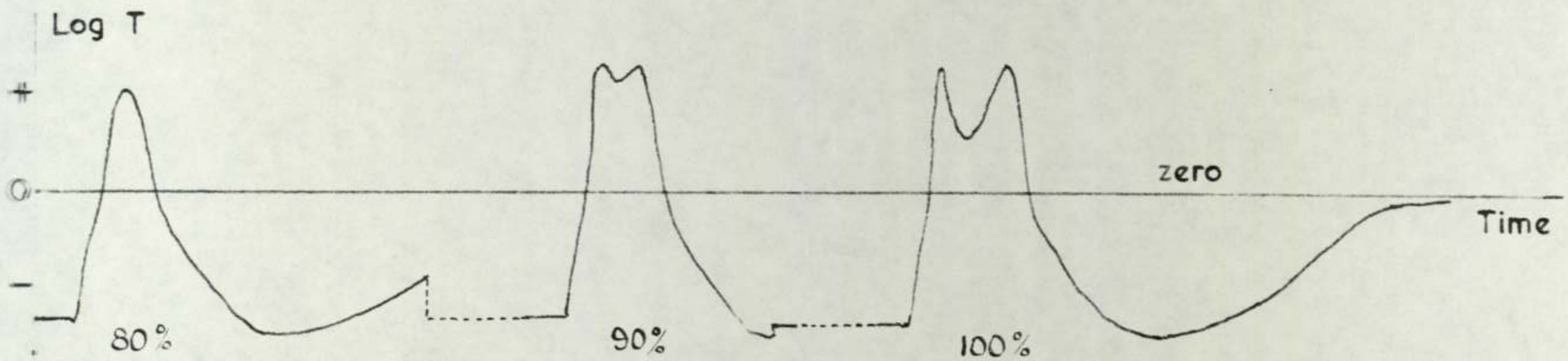


Fig.48

Simultaneous 5-Channel Recording with Single Pen X-Y Recorder

(from 'Space 30' Records)

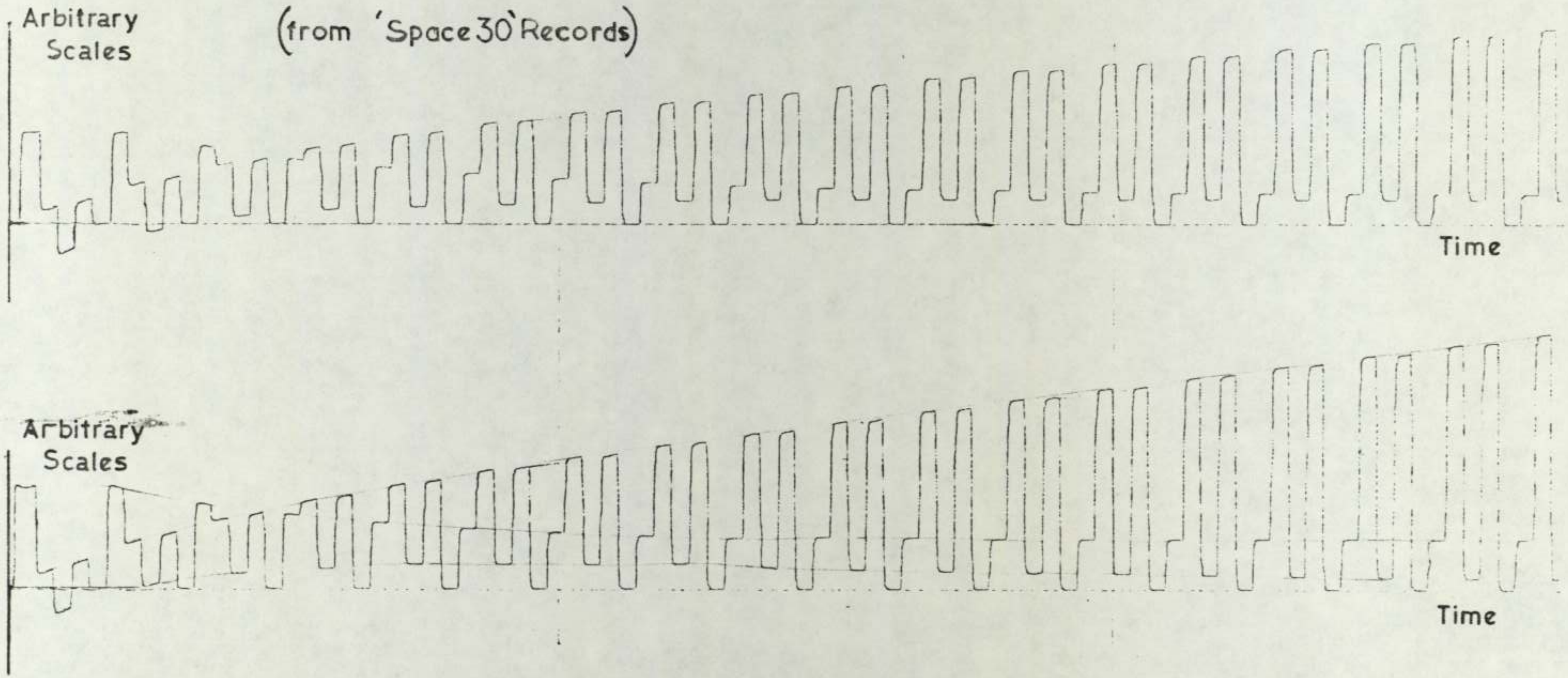


Fig.49

CHAPTER 12

Training Potential of Simulator

This is a look into the future, to anticipate what may be required of the simulator. The present simulator is only a first step towards simulation and training experience may well indicate modifications to the circuitry, particularly to the feedback loops.

When fusion reactors are built in any quantity for commercial use, technical operators will be needed. There will be two classes of users both of simulators and the actual reactors. First, the technicians who will operate the reactors to a fixed schedule and secondly, the technologists and scientists for whom the reactor is a test bed. The former group will, in essence, require only to know the controls to operate the reactor at steady power, the 'start-up' and 'shut+down' procedure and the emergency drill. "Their's not to reason why, their's but to do and die"(10). The technologists and scientists will wish to vary the normal running conditions, to operate the reactor, under safeguards, beyond its design limits and to modify it with a view to improving the design. The simulator can be of great initial use to all these workers.

In current simulators of all types, e.g. flight and tank simulators, the technicians are faced with a control console similar to that actually employed in the aircraft or tank. The controls, meters and recorders are placed in familiar places. This similarity is not possible with this present simulator since such a commercial console is not yet in existance.

The present simulator is therefore principally of use to the trainee technologist and scientist and needs to be liberally equipped with read-out meters and recorders for the vital parameters.

It has been provided with means for :-

(a) changing the plasma current waveform and its magnitude.

(b) varying the toroidal magnetic field

(c) varying the magnitude and duration of neutral injection heating and its moment of introduction

(d) varying the densities of the fuel gases

(e) controlling the various feedbacks

(f) varying the operational and recharging periods and their ratio

(g) averaging the power over a single operational period or over several cycles of operation and recharge.

It is not claimed that the simulator is for design assistance. It is purely to show the effects of changes in parameters. Other advantages are incidental.

Experience in using the simulator has shown that

(a) values of the stability margin 'q' can be obtained by varying the peak plasma current and the toroidal magnetic field.

(b) values of the ratio (β) of kinetic gas pressure to magnetic field pressure ($nkT / \frac{B^2}{8\pi}$) can be obtained by varying ion density and/or toroidal field B.

The critical or ignition temperature is that at which the nuclear reactions become self sustaining. That is, taking into account the various losses from the system, the nuclear reactions produce an amount of energy equal to or greater than the energy required to heat the plasma to that temperature. In Appendix 3 it is shown that by assuming that at the critical temperature the power input to the system just balances the power losses there exists a simplified relationship

$$n.t_r = \frac{1}{293} \cdot \frac{T}{(\sigma v)}$$

where t_r is the length of the operational period necessary to replace the energy losses.

When the quantity $n.t_r$ is plotted against the temperature T a minimum is shown. Now temperature varies with different profiles across the plasma; likewise the quantity (σv). Hence the minimum values of $n.t_r$ vary. According to Gibson these minimum values are around 2 to 3 x 10^{14} with temperatures between 25Kev and 60Kev. The Lawson criterion therefore implies that to obtain a self sustaining reactor

$$n.t_r \geqq 2 \text{ to } 3 \times 10^{14} \text{ sec. cm}^{-3}$$

This is interpreted as

Number Density x Containment Time $\geqq$ 2 to 3 x 10^{14}

In the simulator, both n and t_r are variable and their product can be raised to find the value at which saleable power is obtained continuously, that is when Amp. 16 O/P passes through zero. However, as the $n.t_r$ product is raised more energy input will be needed and I/P P_Ω will have to be increased.

The control system is such that a continuous period of operation can be simulated but within this period the P_Ω will decay to zero leaving only P_α as a continuous supply (supposing P_Ω to have terminated). Passing the Lawson criterion will be indicated by the O/P of Amp. 16 remaining above zero.

As shown earlier in this work, the heart of the simulator is Amp 7 whose O/P indicated the temperature reached in the plasma. Most of the formal experiments for students are therefore concerned to show how log(T) varies with changes in those parameters which control the energy inputs and losses. Other experiments concern the effects of log(T) upon the nuclear energy output and the average power developed.

For their adequate control reactors must be fully instrumented but not all instruments need be under continuous observation. A teaching simulator will require even fuller instrumentation for observation of those quantities which are self-regulating in an actual reactor, e.g. losses due to Bremsstrahlung and cyclotron radiation and also waveforms of plasma currents which are set by the electrical constants of the circuits. A list of meters provided and the potentiometers which are under the operator's control are shown in Figs. 35 and 36 respectively.

The training potential of any simulator develops with time and in doing so brings its own special problems. Students cannot be turned loose even on a simulator and some instruction must be given. Initially, instructions for a few obvious experiments or exercises will be written up and a group of trainees may experience all these simulator exercises in sub-groups of 2 or 3 students. As the simulator becomes more familiar to the instructor more exercises are developed, written up and the process is self-defeating, since to complete the increased number of exercises, each sub-group takes longer and fewer students can obtain the simulator experience within the duration of the course. In fact the

$$\text{N}^{\circ}\text{ of students trained} \propto (\text{N}^{\circ}\text{ of exercises})^{-1}$$

It is not an easy problem to solve.

Students at the level for simulator exercises are mainly interested in the immediate reaction of the machine or simulator to changes of control parameters. The process of reading meters and plotting graphs is, at this stage, a waste of simulator time and a slowing up of the student throughput. Recorders, X - Y and/or time chart instruments are essential. These, preferably should be multi-channel for recording simultaneously from several points in the simulator circuitry, unless the system reproduces very faithfully.

In this work initially in design with the Space 30 computer a single channel X - Y recorder was used to record five channels throughout a single cycle by switching each of the five channels in turn to the Y input for a duration of about one second, the duration being determined by the slew rate of the recorder. An example of this record is in Fig. 49

In a large group of students, each sub-group could be limited to a few initial exercises on the simulator. Unfortunately this leaves a feeling that the simulator is not being fully exploited. An alternative is for each sub-group to do different exercises. This is unsatisfactory from a teaching aspect since vital exercises will be missed by some sub-groups.

A possible way around this problem of more fully training more students on the simulator is the following suggestion, so far untried(11). The simulator is usually regarded as a slowing down device so that students and/or chart recorders which are comparatively slow acting have time to make their records. But the simulator may also be speeded up, making it approach the operational speed of the reactor itself. The operator will now need to preset the parameters he requires in a program to be passed to a small digital computer which will control the high-speed simulator and then receive back and record its signals. During the slower print out of the results and subsequent analysis by the operating group, the high-speed simulator could be switched to a second digital computer group. Even more computer groups might use the system, cost permitting! In theory the number of students being trained simultaneously could be very high. If the simulator is switched on a cycle of the digital computers each computer group may have several opportunities to reprogramme the simulator.

A particular advantage of the slow simulator is the facility for testing emergency procedure. It is comparatively easy for an instructor, from a remote control centre, to introduce a fault into the simulator such as a loss of toroidal field, and subsequently to assess the operator's reaction and suitability for reactor control.

Conclusions

The feasibility of constructing a fusion simulator based on the point reactor model has been demonstrated. Although computer control of fusion reactors is certain to be employed for routine operation, as in many fission reactors, manual intervention may prove necessary under fault conditions and such a simulator could therefore be useful to illustrate the consequences of faults and the remedial action necessary to render the system safe.

If such a simulator is to be used for meaningful studies of fusion reactor behaviour then much greater accuracy in the response of amplifiers and particularly logarithmic amplifiers and antilog function generators will be needed (see Figures 16a and 16b). Such errors could account for the slight initial drop in T noted in Figure 39 since the log amplifiers exhibit their greatest error at lowest inputs. The present system has been constructed with very low cost components and considerable home construction so substantial increases in accuracy could probably be made with commercially designed units or possibly by a complete redesign involving a hybrid system containing both analogue and digital components interconnected.

Appendix 1

Operational Procedures

This chapter deals with the run-up of the simulator to the point of switching on for operation and recording of its behaviour.

Power supplies.

1. The simulator operates from a 13 amp. 240 V AC supply.
2. All toggle switches should be OFF, i.e. in the UP position.
3. Switching on the AC mains supply immediately provides the 6.3 volt heater voltage to the valves of the MEC 100 amplifiers and the ±15 volts from the Farnel PSU's.
4. The right hand switch just below the +300 volt unit switches AC power to both 300 volt units, the -30 volt central unit and the neon on the left hand side.
5. The -30 volt supply is ON when either the RED or GREEN lamp on the control panel is alight.
6. The 300 volt supplies require about 2 minutes to heat up and will be available when their separate neons glow. Each unit contains several internal fuses and a cut-out. If the front neon does not glow one of these may have gone open-circuit although the front panel fuse is intact.
7. All DC power supplies can be monitored on their front panels at this stage.
8. Switch the ±15 volt supplies to the '741' amplifiers by switching on the Farnel PSU's front panels.
9. The log amplifiers in the main simulator unit require supply voltages of ±8 volts. These can be monitored at the lowest test points on the main simulator unit front panel.

10. Switch on the 300 volt supplies to the MEC 100 amplifiers by the HT switch on the meter panel. Neons on these amplifiers should glow for a short period only. A continuing glow indicates a fault in the amplifier.

Control Panel.

1. Switches are initially in the UP position and potentiometers just off zero.
2. Switch to START.
3. Switch to CYCLING.
4. Switch to RUN.
5. The RED and GREEN lamps should now light alternately, changing at approcimately 20 second intervals.
6. If a continuous operational period is required, switch to SINGLE when the RED lamp is alight.
7. Switch to RESET.
8. The RESET / RUN also controls INT 4. In the RESET position a resistor across the integrator holds its output voltage at a fraction of the small input voltage provided for integration. In the RUN position the resistor is removed and the integrator integrates continuously. Its output therefore provides (a) a voltage for the X - motion of an X - Y plotter and (b) a voltage proportional to time with which to obtain the average power delivered by the reactor/ simulator.
9. If the simulator is to cycle switch to CYCLING and adjust the two potentiometers on the control panel to give the required periods for 'operation' and 'delay'.

Operation.

1. All the '741' amplifiers will need setting from time to time to correct the output offset voltage. These corrections, to make the output zero are made with each input earthed, by adjusting the associated potentiometer marked Pa 3 or Pa 4 etc in Fig.s 20 to 23. Although this may earth the output of a previous '741' according to the manufacturer it is not detrimental.
2. It will now be assumed that these corrections have been made and preset potentiometers in the main simulator circuit adjusted according the Chapter 8 on Scaling.
3. Set the potentiometers in the potentiometer unit to the values required, that is, for $\log(n_e)$, $\log(n_D)$, $\log(n_T)$, log(B), linear I and NIH.
4. Check the current waveform with a time /chart or X - Y recorder.
5. Connect the output of INT 4 to the X motion of the X - Y plotter.
6. Adjust the X movement to be adequate in the duration of the experiment.
7. Connect the Y input of the plotter to the selected test point on the main simulator unit front panel.
8. Check that the RED lamp on the control panel is alight and switch to SINGLE or CYCLING as required.
9. Switch to RUN.
10. Return to RESET at the end of the experiment.

Appendix 2

Calculation of various losses from a Tokamak

Reactor having the following

parameters

Major reactor radius	5.20 metres
Minor reactor radius	1.86 metres
Toroidal field strength	4.0 tesla
Plasma density	3×10^{20} m^{-3}
Containment time	0.7 sec
Thermal power	5×10^{9} watts

Volume of torus $= \pi.(1.86)^2.2.\pi.5.20 \ m^3.$

$= 364.5 \ m^3$

Area of walls $= 2.\pi(1.86).2.\pi.5.20 \ m^2$

$= 3.818 \times 10^2 \ m^2$

Total gas ions $= 364.5 \times 3 \times 10^{20}$

$= 1.0935 \times 10^{23}$

Energy produced per cycle per cubic metre

$= \frac{n^2}{4}.(\sigma v).Q$ where $n = 3 \times 10^{20} \ m^{-3}$

$Q = 3.6 \times 10^{-12}$ joules

at T = 15 Kev

$(\sigma v) = 1 \times 10^{-22} \ m^3 sec^{-1}$

at T = 20 Kev

$(\sigma v) = 1.4 \times 10^{-22} \ m^3 sec^{-1}$

Total energy produced per cycle

$= \frac{(3 \times 10^{20})^2}{4} \times 10^{-22} \times 3.6 \times 10^{-12} \times 364.5$ joules

$= \underline{\underline{2.952 \times 10^9 \text{ joules}}}$

Average power $= \frac{2.952 \times 10^9}{0.7}$ watts

$= \underline{\underline{4.22 \times 10^9}}$ watts at T = 15 Kev

Average power $= 5.90 \times 10^9$ watts at T = 20 Kev

Bremsstrahlung Loss

Several authors give formulae for the Bremsstrahlung power loss which differ in form or in the value of a constant used. Some calculations based on these formulae follow. The units of the various quantities are those used in the derivation of the formulae by the respective authors to keep the same numerical constants.

Simon[12], "An introduction to thermonuclear research" p.18, eqn. 2.12

$$P_B = \frac{64}{3\sqrt{2\pi}} \cdot \frac{e^6 Z^3 n^2}{mc^3 \hbar}\sqrt{\frac{kT}{m}} \quad \text{ergs.cm}^3\text{.sec}^{-1}$$

where

$e = 4.803 \times 10^{-10}$ e.s.u.
$Z = 1$
$c = 3 \times 10^{10}$ cms.sec^{-1}
$k = 1.38 \times 10^{-16}$ erg.$^oK^{-1}$
$m = 9.1 \times 10^{-28}$ gram
$\frac{h}{2\pi} = \hbar = 1.0522 \times 10^{-27}$ erg.sec
$T = 20$ Kev
$n = 3 \times 10^{14}$ cm^{-3}

$= \underline{112 \times 10^6}$ watts (total)

as a percentage of the thermal power this is

$= \underline{1.90\%}$

Golovin, "Tokamak as a possible fusion reactor". p.16, eqn. 7.4

$$P_B = (2.2)\pi^2.10^{-32}.R.a^2.n^2.T^{\frac{1}{2}} \quad \text{watts (total)}$$

where

$R = 520$ cm
$a = 186$ cm
$n = 3 \times 10^{14}$ cm^{-3}
$T = 20 \times 10^3$ ev

$= \underline{50 \times 10^6}$ watts

as a percentage of the thermal power this is

$= \underline{0.85\%}$

Sweetman[13], "Ignition condition in Tokamak". p.164 (appen.), eqn. 15

$$P_B = (3.3).10^{-31}.n^2.(^a/_R)^2.R^3.T^{\frac{1}{2}}.E_B$$

where

$R = 520$ cm
$a = 186$ cm
$n = 3 \times 10^{14}$ cm^{-3}
$T = 20$ Kev
$E_B = 0.49$ (a correcting factor)

$= \underline{37 \times 10^6}$ watts

as a percentage of the thermal power this is

$= \underline{0.63\%}$

Saxe,[14] "Approaches to thermonuclear power". p.7, eqn.1.4

$$P_B = (0.54).10^{-30}.Z^2.n^2.T^{\frac{1}{2}} \text{ watts.cm}^{-3}$$

where $Z = 1$
$n = 3 \times 10^{14}$ cm^{-3}
$T = 20$ Kev

$$= 79 \times 10^6 \text{ watts (total)}$$

as a percentage of the thermal

power this is

= 1.34%

Rose and Clark, "Plasmas and controlled fusion". p.233, eqn.11.17

$$P_B = (4.8).10^{-37}.Z^2.n_i.n_e.T^{\frac{1}{2}} \text{ watts.m}^{-3}$$

where $Z = 1$
$T = 20$ Kev
$n_e = 3 \times 10^{20}$ m^{-3}

$$= 70 \times 10^6 \text{ watts (total)} \quad n_i = n_e$$

as a percentage of the thermal

power this is

= 1.19%

These results are simulated at the end of this appendix.

2. Cyclotron Losses

These are more difficult to estimate due to

(a) only of importance in the very high temperature range

(b) uncertainty of electron temperature, electron velocity and frequency

(c) uncertainty of plasma absorption for electron frequency and harmonics.

Some estimates of these losses by various authors now follow.

Trubnikov. ex Gibson,[(15)] "Parameters required for plasma in a toroidal reactor". sec. 2.4

$P_c = (o.7).10^{-24}.n.B^2.T.K_{\mathcal{L}}$ where $n = 3 \times 10^{14}$ cm^{-3}

$B = 4 \times 10^4$ gauss

$= \underline{49 \times 10^6}$ watts (total) $T = 20$ Kev

$K_{\mathcal{L}}$ = a plasma transparency factor taken as 0.02

as a percentage of the thermal power this is

$= \underline{0.83\%}$

Rose and Clark, "Plasmas and controlled fusion".p.251, eqn.11.83

$P_c = (6.2).10^{-17}.B^2.n.T.(1 + {}^T/204 +...)$ watts.m^{-3} where

$B = 4$ $webers.m^{-2}$

$n = 3 \times 10^{20}$ m^{-3}

$T = 20$ Kev

$= \underline{6.55 \times 10^6}$ watts.m^{-3}

This is a figure for the radiation generated, not all of which escapes. Rose and Clark quote a factor of 0.02 for the absorption in the plasma and the radiation then escaping through the surface of the plasma is

$P_c = 6.55 \times 10^6 \times 0.02 \times 3.645 \times 10^2$

$= \underline{48 \times 10^6}$ watts (total)

As a percentage of the thermal power this is

$= \underline{0.81\%}$

Artsimovich,"Controlled thermonuclear reactions". p.282, eqn.7.65

$$P_c = \frac{4.e^2.n.V.}{3c}\left(\frac{eH}{mc}\right)^2\frac{kT}{mc^2}$$

where

e =	4.8	e.s.u.
m =	9.1×10^{-28}	gram
c =	3×10^{10}	$cm.sec^{-1}$
k =	1.38 c 10^{-16}	$erg.^oK^{-1}$
H =	4×10^4	gauss
n =	3×10^{14}	cm^{-3}
T =	2.32×10^8 (≡ 20 Kev)	^oK

$= 22 \times 10^6$ watts (total)

as a percentage of the thermal power this is

$= \underline{0.4\%}$

Thermal Conduction Losses

Both ions and electrons contribute to these losses and estimates of their magnitudes are given below.

Simon" Introduction to thermonuclear research". p.32

$$P_{cond} = \frac{n.k.\lambda.v.(T_c - T_o)}{(1 + (W\tau)^2).\ell^2}$$

where
- n is particle density
- λ is particle m.f. path
- v is particle velocity
- W is particle frequency
- τ is time between collisions
- ℓ is plasma radius
- T_c is temperature at centre
- T_o is temperature at walls

For the ion, v, λ, W have to be calculated

$$v = \sqrt{\frac{3kT}{M}}$$

where $T = 2.32 \times 10^8$ ^oK
$M = 3.4 \times 10^{-24}$ gram
$k = 1.38 \times 10^{-16}$ erg.$^oK^{-1}$

$$= 1.681 \times 10^8 \text{ cm.sec}^{-1}$$

Cross-section for 90^o scattering

$$\sigma = \frac{80\,.\pi.\,e^4}{M^2\ v^4}$$

where $e = 4.8 \times 10^{-10}$ e.s.u.

$$= 1.447 \times 10^{-21} \text{ cm}^2$$

$$\lambda = \frac{1}{n\sigma} = 2.304 \times 10^6 \text{ cm}$$

$$\tau = \frac{\lambda}{v} = 1.371 \times 10^{-2} \text{ sec}$$

$$W = \frac{eB}{Mc} = 1.882 \times 10^8 \text{ sec}^{-1}$$

$$w\tau = 1.882 \text{ c } 10^8 \times 1.371 \times 10^{-2}$$

$$= 2.557 \times 10^6$$

$$P_{cond} = \frac{5.602 \times 10^8}{2}$$ and taking ℓ = 186 cm

P_{cond} = $\underline{5.9 \times 10^5}$ watts (total)

As a percentage of the thermal power this is

= 0.01%

For the electron, v, λ, W, and τ have to be calculated

$$v = \sqrt{\frac{3kT}{m}} \quad \text{where} \quad m = 9.1 \times 10^{-28} \text{ gram}, \quad T = 2.32 \times 10^{8} \ {}^{o}K \ (\equiv 20 \text{ Kev})$$

$$= 1.0274 \times 10^{10} \text{ cm.sec}^{-1}$$

Cross-section for 90^{o} scattering

$$\sigma = \frac{80. \quad .e^{4}}{m^{2} \ v^{4}} \quad \text{where} \quad e = 4.8 \times 10^{-10} \text{ e.s.u.}$$

$$= 1.447 \times 10^{-21} \text{ cm}^{2}$$

$$\lambda = \frac{1}{n\sigma} = 2.305 \times 10^{6} \text{ cm}$$

$$\tau = \frac{\lambda}{v} = 2.243 \times 10^{-4} \text{ sec}$$

$$W = \frac{e.B}{mc} = 7.033 \times 10^{11} \text{ sec}^{-1}$$

$$W\tau = 7.033 \times 10^{11} \times 2.243 \times 10^{-4}$$

$$= 1.578 \times 10^{8}$$

$P_{cond} = 7.946 \times 10^{8}$ and taking ℓ =186 cm

(electron)

$$= 2.297 \times 10^{4} \text{ ergs.cm}^{-3}.\text{sec}^{-1}$$

$$P_{cond} = 2.297 \times 10^{4} \times 3.645 \times 10^{8}$$

(electrons)

$$= \underline{8.372 \times 10^{5}} \text{ watts}$$

As a percentage of the thermal power this is

= <u>0.014%</u>

Impurities

These arise from contamination of the fuel gases and also from contact of these with the walls of the torus. By collisions with electrons and ions they give rise to multiply charged ions, which absorb more energy for ionisation or excitation from the electrons than do the fuel atoms and thus exert a cooling effect on the plasma.

Golovin,[6] "Tokamak as a possible fusion reactor".p.18, eqn. 8.1 quotes Kogan et al, that the power taken away from the plasma in this cooling effect is

$$P_{mci} = \left[(8).10^{-30}.Z^6.T^{-3/2} + (6).10^{-31}.Z^4.T^{-\frac{1}{2}}\right]n^2\xi \quad \text{watts. cm}^{-3}$$

where Z is nuclear charge of the impurity ion

ξ is the concentration of the impurity ions

T is the electron temperature in ev

$$= \frac{Z^4.10^{-30}.n^2\xi}{T^{\frac{1}{2}}}\left[\frac{8Z^2}{T} + 0.6\right]$$

Obviously P_{mci} decreases with rising temperature

Let $Z = 4$, $n = 3 \times 10^{14}\text{cm}^{-3}$, $\xi = 1\% = 0.01$

When T = 10ev

$P_{mci} = 356 \times 10^6$ watts $\equiv$ 6% of thermal power (5900 Mw)

When T = 1000 ev

$P_{mci} = 193 \times 10^6$ watts $\equiv$ 3.3% " " "

When T = 3 Kev

$P_{mci} = 0.93 \times 10^6$ watts $\equiv$ 0.016% " " "

When T = 20 Kev

$P_{mci} = 0.36 \times 10^6$ watts $\equiv$ 0.006% " " "

As the simulator is discarding operations at temperatures below 1 Kev and as the P_{mci} is falling rapidly above this temperature, the effect of impurities has been omitted from the simulator circuitry.

Summary of some losses from the plasma

(calculated at T = 20 Kev)

Bremsstrahlung radiation		1.1%
Cyclotron radiation		0.6%
Thermal conductivity	(a) electrons	0.014%
	(b) ions	0.01 %
Impurities (Z = 4, conc. of ions 1.0%)		0.006%

Appendix 3.

Detailed scaling of Amplifiers 5, 6 & 7.

Four extreme cases are considered

(a) $\log(n_e) = 11.0$ with $\log(T) = -4.6$

(b) $\log(n_e) = 11.0$ with $\log(T) = +1.4$

(c) $\log(n_e) = 16.0$ with $\log(T) = -4.6$

(d) $\log(n_e) = 16.0$ with $\log(T) = +1.4$

(a) Referring to the attached Fig.50, for an output from Amp.7 of -4.6 volts, the input signals must total + 4.6 v

Hence, including the $\log(E_{IN})$ signal from Amp.6

$$\log(E_{IN}) - 2 \times 7.9 + 2 \times 5.5 = + 4.6$$

$$\therefore \log(E_{IN}) = 4.6 + 15.8 - 11 = \underline{+ 9.4 \text{ v}} = \text{\% of Amp.6}$$

The input signals to Amp.6 must total - 9.4 v

Hence with the $\log(E_{IN})$ signal from Amp.5

$$\log(E_{IN}) - 2 \times 10.2 + 2 \times 5.5 = - 9.4$$

$$\therefore \log(E_{IN}) = 20.4 - 11.0 - 9.4 = 0 \quad \text{as expected.}$$

Similar calculations show for :-

(b) output of Amp.6 = + 3.4 v : output of Amp.5 =+6 volts

(c) output of Amp.6 = + 4.4 v : output of Amp.5 = 0 volts

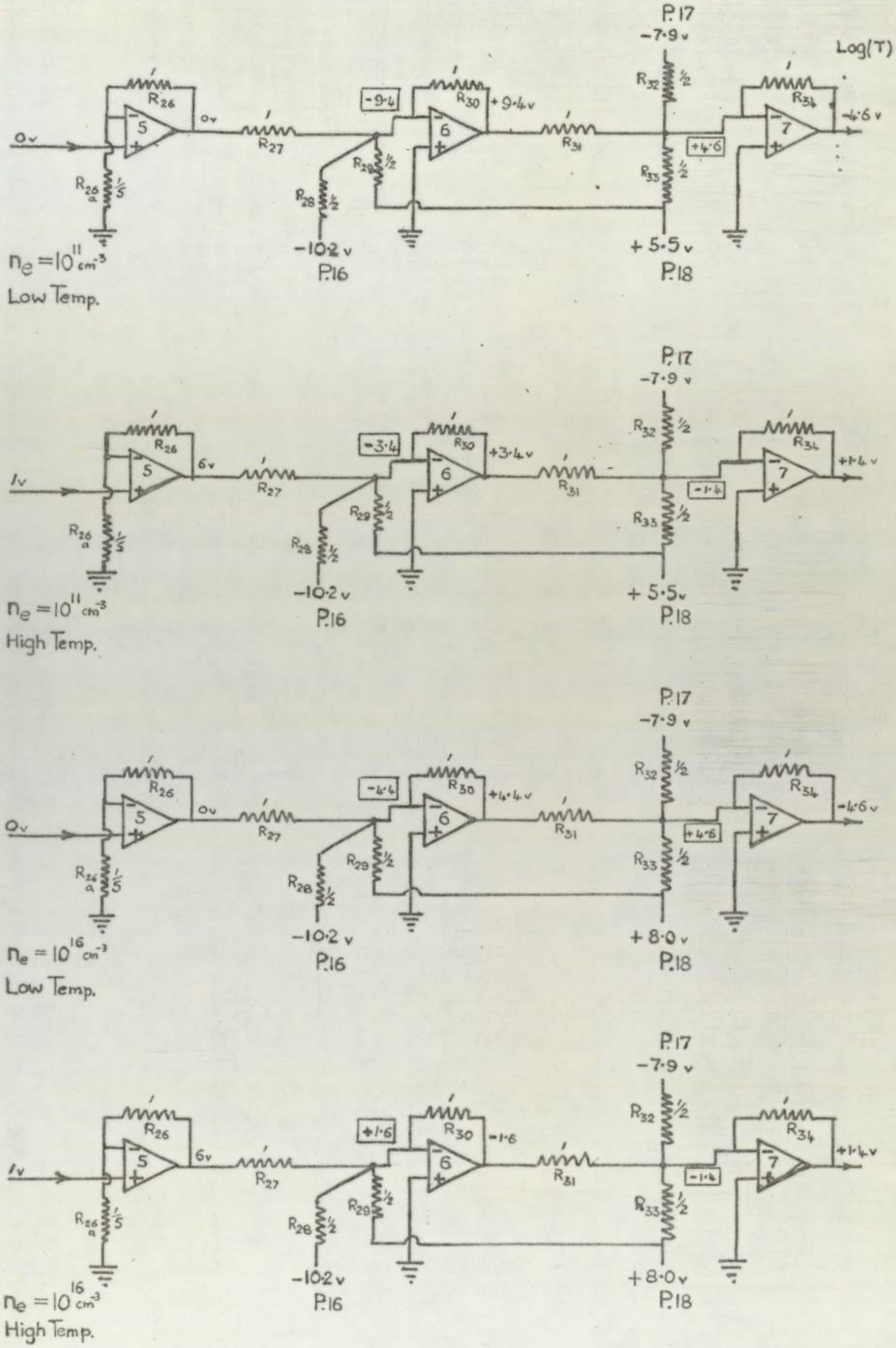
(d) output of Amp.6 = - 1.6 v : output of Amp.5 =+6 volts

Amp.5 is used in the non-inverting mode and its inputs are for

(a)	0 volt	i.e. zero	energy	in	to	system
(b)	+1 volt	" Max.	"	"	"	"
(c)	0 volt	" zero	"	"	"	"
(d)	+1 volt	" Max.	"	"	"	"

Fig. 50

Detailed scaling of Amplifiers 5, 6 and 7



Appendix 4.

The Lawson Criterion

The energy of a gas ion at a temperature T is given by

$$E = {}^{3}/_{2}\ kT$$

Hence

$E = 3nkT$ per unit volume, wher n is the ion density

Where there is a just self-sustaining reaction this energy gain from all sources will balance the losses.

If P_i is the loss rate (i.e. power loss) per unit volume then the energy loss is

$P_i \times \tau_E$ where τ_E is the time during which the power loss operates to remove the energy supplied

$P_i \times \tau_E = {}^{3}/_{2}\ n.k.T$ and τ_E is called an 'energy replacement time'

$$P_i = 3\ \frac{n.k.T}{\tau_E}$$

In the simplest case, for a D - T reaction the products are $^{4}He_{2}$ and $^{1}n_{o}$ and the neutrons, being uncharged can leave the system immediately while alpha-particles remain to give up 3.52 Mev of energy to the plasma (i.e. Q_{CH} for charged products is 3.52 Mev)

Hence the energy into the self-sustaining system is that due to the alpha-particles whose formation rate is the nuclear reaction rate which is

$n_D.n_T.(\sigma v).Q_{CH}$ per unit volume assuming that n_D and n_T differ

If there are equal numbers of n_D and n_T then

$$P_{IN} = \frac{n^2}{4}.(\sigma v).Q$$

But (σv) is a function of temperature and therefore of radial position in the plasma. The radial position can be expressed as $^{r}/_{a}$ where r is the radial position in the plasma and where a is the radius of the plasma

and if $^{r}/_{a}$ is denoted by x then (σv) is a function of x

Hence the energy from the alpha-particles is

$$= Q_{CH}\int_{x=0}^{x=1} \frac{n^2}{4} \cdot (\sigma v)\ .dx$$

This leads to

$$n_o \tau_o = \frac{12\,kT_o \int_o^1 \frac{n}{n_o} \cdot \frac{T}{T_o}\ .x.dx}{Q_{CH}\int_o^1 (\frac{n}{n_o})^2 (\sigma v)\, x.dx}$$

and if n and T are constant the expression simplifies to

$$n\tau = \frac{12kT}{(\sigma v).Q_{CH}} = \frac{12}{Q_{CH}}k\,\frac{T}{(\sigma v)} = \frac{1}{293}\,\frac{T}{(\sigma v)} \quad (T \text{ in KeV})$$

$\frac{T}{(\sigma v)}$ plotted against T shows a minimum. In so far as the values of (σv) vary slightly from one author to another and also that T varies with different profiles across the plasma, so the minimum varies in value and temperature. According to Gibson[15] this range may be from about 25 Kev to around 60 Kev but with minimum values of $n\tau$ fairly close to 2 to 3 x 10^{14}

The conclusion then is that to obtain a self-sustaining reactor

$$n\tau > 2 \text{ to } 3 \times 10^{14}\ \text{sec.cm}^{-3}$$

or

number density x containment time > 2 to 3 x 10^{14}

This is known as the Lawson Criterion

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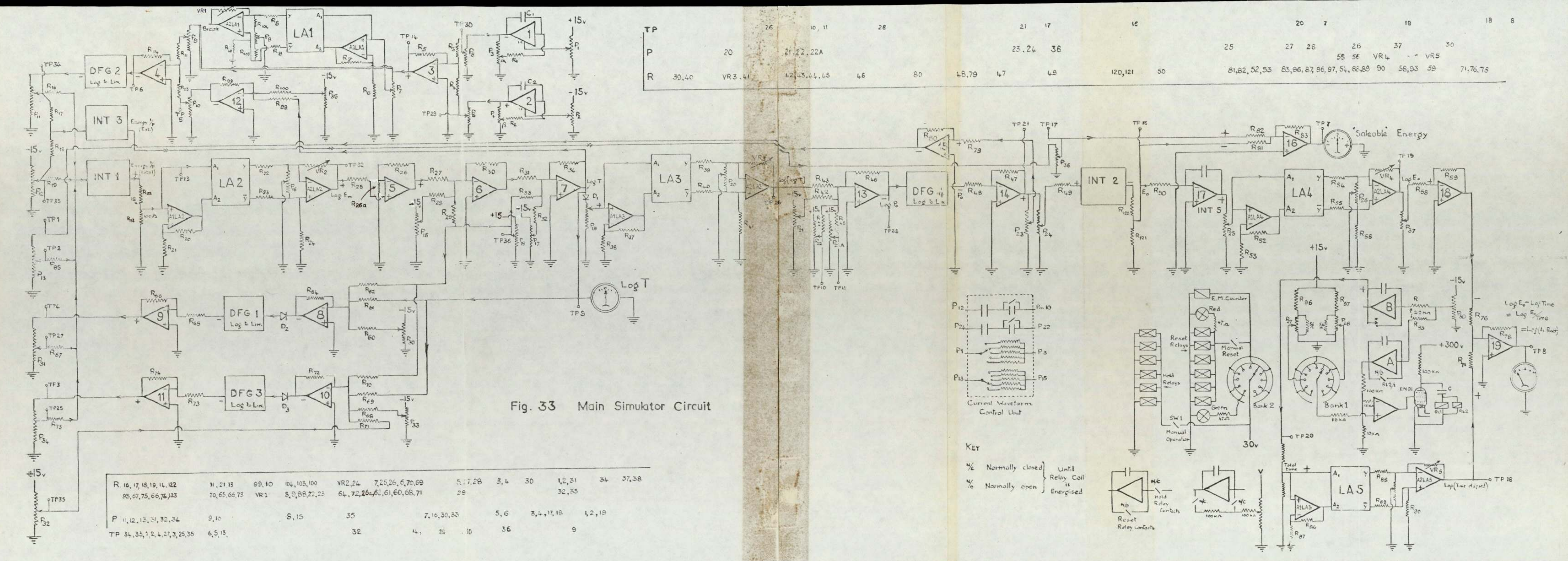

Fig. 33 Main Simulator Circuit