DECISION MAKING IN NUCLEAR WASTE MANAGEMENT

The Use Of The Synoptic Approach

RACHEL ELIZABETH JOY WESTERN

Doctor of Philosophy

THE UNIVERSITY OF ASTON IN BIRMINGHAM

June 1993

The University of Aston in Birmingham

DECISION MAKING IN NUCLEAR WASTE MANAGEMENT

The Use Of The Synoptic Approach

Rachel Elizabeth Joy Western

Doctor of Philosophy

1993

This thesis is concerned with the use of the synoptic approach within decision making concerning nuclear waste management. The synoptic approach to decision making refers to an approach to rational decision making that assumes as an ideal, comprehensiveness of information and analysis. Two case studies are examined in which a high degree of synoptic analysis has been used within the decision making process. The case studies examined are the Windscale Inquiry into the decision to build the THORP reprocessing plant and the Nirex safety assessment of nuclear waste disposal. The case studies are used to test Lindblom's hypothesis that a synoptic approach to decision making is not achievable.

In the first case study Lindblom's hypothesis is tested through the evaluation of the decision to build the THORP plant, taken following the Windscale Inquiry. It is concluded that the incongruity of this decision supports Lindblom's hypothesis. However, it has been argued that the Inquiry should be seen as a legitimisation exercise for a decision that was effectively predetermined, rather than a rigourous synoptic analysis. Therefore, the Windscale Inquiry does not provide a robust test of the synoptic method. It was concluded that a methodology was required, that allowed robust conclusions to be drawn, despite the ambiguity of the role of the synoptic method in decision making. Thus, the methodology adopted for the second case study was modified. In this case study the synoptic method was evaluated directly. This was achieved through the analysis of the cogency of the Nirex safety assessment. It was concluded that the failure of Nirex to provide a cogent synoptic analysis supported Lindblom's criticism of the synoptic method. Moreover, it was found that the synoptic method failed in the way that Lindblom predicted that it would.

Key word: Incremental

ACKNOWLEDGEMENTS

A number of individuals and organisations have provided assistance and information during the compilation of this thesis. I would particularly like to thank the following:

Dr. Margaret Adams, Lorna Arnold, Jane Bufton, John Black, Dr. Bush, Dave Collingridge, Ben Cooper, Nick Cassidy, Neil Chapman, Ray Dodds, the staff at the Department of the Environment library, Tim McEwen, Pad Green, IBC, Gabriel Lindsay, Sue Meagher, Dr. Miles, Dominic Palfreman, Walt Patterson and his family, Dr. Pilkington, Simon Roberts, Anna Stanford, Charles Tanner, the late Gordon Watkins, Fiona Weightman, Matilda Western, John Whiteley and Vanessa Winter.

CONTENTS

ABBREVIATIONS

AEA	Atomic Energy Authority
AGR	Advanced Gas-cooled Reactor
BGS	British Geological Survey
BNFL	British Nuclear Fuels Plc
CEC	Commission of the European Communities
CEGB	Central Electricity Generating Board
CFR	Commercial-scale Fast Reactor
CHEQMATE	Chemical Equilibrium with Migration and Transport Equations
DoE	Department of the Environment
FBR	Fast Breeder Reactor
HATCHES	Harwell/Nirex Thermodynamic Database for Chemical Equilibrium Studies
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ILW	Intermediate Level Waste
K	Chemical Equilibrium Constant
LIPAS	Laser Induced Photoacoustic Spectroscopy
M	Unit of Chemical Concentration
MOX	Mixed Oxide Fuel
mSv	Milli-sievert
NEA	Nuclear Energy Agency
NII	Nuclear Installations Inspectorate
Nirex	Nuclear Industry Radioactive Waste Executive
NRPB	National Radiological Protection Board
OECD	Organisation for Economic Cooperation and Development
PERA	Preliminary Environmental and Radiological Assessment
PHREEQE	pH Redox Equilibrium Equations
REDOX	Reduction/Oxidation Reactions
RWMAC	Radioactive Waste Management Advisory Committee
SCV	Site Characterisation and Validation
SGHW	Steam Generating Heavy Water Reactor
SSEB	South of Scotland Electricity Board
TBq	Terabecquerel
THORP	Thermal Oxide Reprocessing Plant
UKAEA	United Kingdom Atomic Energy Authority
US-NRC	US National Research Council
WAGR	Windscale Advanced Gas-cooled Reactor
WHO	World Health Organisation

1. DECISION MAKING IN NUCLEAR WASTE MANAGEMENT
THE USE OF THE SYNOPTIC APPROACH

1.1. INTRODUCTION

This thesis is concerned with the use of the synoptic approach within decision making concerning the management of nuclear waste. The synoptic approach to decision making refers to an approach to rational decision making that assumes as an ideal, comprehensiveness of information and analysis concerning a given problem [1] in order that the 'correct' decision may be identified. Two particular examples of decision making concerning nuclear waste management are considered, in which a high degree of synoptic analysis is used within the decision making process. The two case studies examined are the Windscale Public Inquiry into the decision to build the THORP reprocessing plant, and the Nirex safety assessment of nuclear waste disposal. The synoptic approach to decision making may be compared to the incremental approach outlined by Lindblom, under which policy is developed through incremental changes to existing policy, rather than through synoptic analysis. Lindblom argues that synoptic analysis is not a credible approach to decision making. In this thesis, the performance of the synoptic analyses undertaken in the case studies are used to test the synoptic approach. It is found that Lindblom's criticism of the synoptic approach is vindicated. However, due to the ambiguous role that synoptic analysis may play in decision making, this conclusion must be qualified.

---

1 Braybrooke (1970) pp 40,41

1.2. THE SYNOPTIC APPROACH

The synoptic approach to decision making aims to generate 'correct' decisions through comprehensive analysis. In order that the correct decision may be identified, the objectives to be achieved must be identified and prioritised: methods for achieving the objectives must be identified, evaluated and compared; and finally the best out of all of the possible solutions must be chosen. Lindblom [2] has identified the following four steps in synoptic decision making: prioritisation of objectives, identification of possible solutions, identification of consequences, and final choice. These four steps are described in more detail below.

1. Prioritisation of Objectives

   The objectives to be met in the solution of a problem must be identified. Having identified the objectives to be achieved by problem solving, the objectives and the values they encompass, must be scrutinized in order to prioritise the objectives and thus obtain criteria by which to govern the choice between possible solutions.

2. Identification of Possible Solutions

   All of the possible means of achieving the values identified must also be identified. If some options were not considered it is possible that the best means of achieving the values identified would be excluded. The wisdom of a choice will depend on

---

2 Lindblom (1965) pp 137-138

whether the best choice has been made; [*3*] therefore all the alternative means of achieving a particular set of objectives should be identified. [*4*]

3. Identification of Consequences

Each of the possible solutions to the problem must be examined exhaustively in order to identify the probable consequences of adopting each of the solutions. If the solutions were not examined exhaustively it is possible that unforeseen benefits, or disbenefits, would be neglected. Unsought consequences are as important as desired objectives when alternative strategies are evaluated. [*5*]

4. Final Choice

The final choice must be made between each of the possible solutions in order to enable the decision maker to achieve the optimal result, given the criteria identified in (1) above. The advantages and disadvantages of all of the possible options must be weighed up and used to identify the best strategy.

Under the synoptic approach the task of rational decision making is to select that one of the possible options which will lead to the preferred set of consequences. Thus the synoptic approach aims to achieve the *best* decision. This may be compared to the provisionally optimal decision which is aimed for under the incremental approach. Given that the synoptic approach aims for the best

---

3 Simon (1976) p65
4 Simon (1976) p67
5 Simon (1976) p65

decision, all of the consequences that follow from the chosen strategy are relevant to the evaluation of its correctness, not simply those consequences that were anticipated. [*6*] Furthermore, the synoptic approach does not allow for the fact that the subsequent outturn of events may present a better strategy. These considerations, and other problems with the synoptic approach are discussed below.

1.2.1. Problems With The Synoptic Approach

The synoptic approach to decision making suffers from a number of fundamental deficiencies which have been extensively discussed in the literature (see for example [*7*] [*8*] [*9*] [*10*] [*11*] [*12*]). These limitations are outlined below:

1. The limitations of human intellectual capacity. [*13*]

   The synoptic ideal insists on comprehensiveness of analysis. [*14*] The structure of the problem, all the relevant facts and values, the relationship between the decision and possible future decisions and future information that may become available in the future must all be understood in great detail. [*15*] This is not a credible requirement.

---

6 Simon (1976) p67
7 Braybrooke (1970) pp 48-57, p113
8 Lindblom (1965) pp 138-143
9 Quinn (1980)
10 Collingridge (1982) pp 21-33
11 Wildavsky (1979) pp 6-8
12 Simon (1976) pp 65-69,81-82,197
13 Lindblom (1965) p138
14 Braybrooke (1970) p50
15 Collingridge (1982) p21

2. Limitations on the information available. [*16*]

The raw data available to achieve comprehensive policy analysis is not available.

3. Limitations on the resources available for problem analysis. [*17*]

A problem requires a solution within a finite amount of time and within a limited budget allocation, the indefinite commitment of time and resources required in order to identify the optimum solution is not a viable option.

4. Prioritisation difficulties. [*18*]

The identification of the objectives to be met through a given solution; the quantification of the benefits and disbenefits obtained; and the amalgamation of this information to allow the prioritisation of potential solutions to a given problem is not feasible. There are a number of intrinsic difficulties which invalidate a quantitative approach to objective prioritisation. [*19*] For example, a given solution will incorporate a number of different social values which cannot be compared and contrasted to the values incorporated within other solutions without a detailed knowledge of the context. [*20*] In addition, social values change over time. [*21*] More

---

16 Braybrooke (1970) p50
17 Braybrooke (1970) p50
18 Braybrooke (1970) p51
19 Braybrooke (1970) pp 23-36
20 Braybrooke (1970) pp 23-26, 29-33
21 Braybrooke (1970) pp 26-29

importantly, there will be social disagreement on the relative importance of different social values. [22]

5. Fact and value are related. [23]

The decision analyst will not know which values are relevant to the prioritisation process until the consequences of the possible problem solutions has been identified. This demands an iterative approach between the analysis of desired objectives and possible outcomes. [24]

6. The synoptic ideal is not able to contend with the openness of the system of variables.

In actual policy making situations it will not always be possible to identify a closed system of variables that is of sufficient size to encompass all of the information required for the problem. [25] Braybrooke and Lindblom have commented:

"the analyst is therefore left with an open analytical system mirroring the far-reaching interactions that his analytical system is designed to encompass." [26]

7. The synoptic ideal is not adapted to the analyst's need for strategic sequences of analytical moves. [27]

The synoptic ideal demands that the decision maker achieves a

---

22 Braybrooke (1970) pp 33-36
23 Braybrooke (1970) p52
24 Lindblom (1965) p142
25 Braybrooke (1970) p53
26 Braybrooke (1970) p53
27 Braybrooke (1970) p53

comprehensiveness of information and understanding, but it does not provide the decision maker with any guidance on how to achieve this ideal. Thus, Braybrooke and Lindblom have stated that the synoptic approach does not:

"specify the details of a dynamic process in such a way as to convert an impossible task into a feasible one." [*28*]

The synoptic approach does not allow prioritisation of the welter of information that will inundate the decision maker. Work in one area of investigations will have repercussions in another area. However, the synoptic approach does provide the decision maker with a strategy to contend with this constant feedback situation.

8. The synoptic ideal is not adapted to the variety of forms in which policy problems actually arise. [*29*]

The concept of a policy problem as a detached conundrum requiring a solution algorithm does not adequately adhere to the variety of evolving situations that require policy adoption and modification in the real world. For example, many decisions are triggered by the suggestion of a new proposal rather than the identification a particular problem - which turns the synoptic ideal "upside down". [*30*]

Moreover, the satisfactory resolution of a given situation will not only be dependent on the extant circumstances, but also on those that will arise in the future. [*31*]

---

28 Braybrooke (1970) p53
29 Braybrooke (1970) p54
30 Braybrooke (1970) p56
31 Braybrooke (1970) p55

1.3. INCREMENTALISM

A contemporary formulation of the incremental approach to decision making has been presented by Braybrooke and Lindblom, who present the thesis that decision makers do not actually use the synoptic approach. Instead, they argue that decision makers have developed a much more sophisticated system that is able to by-pass the problems of the synoptic approach. They argue that decision makers:

> "have in fact hit upon a mutually reinforcing and defensible set of evaluative practices that, if clearly understood, would raise great doubts in their own minds as to whether the received ideals are worth aspiring to even as ideals." [*32*]

The name that they assigned to the strategy identified was "disjointed incrementalism". [*33*] The principles of this strategy are outlined below.

1. Incremental Evaluation. [*34*]

    The policy options chosen for analysis by the decision maker are only marginally different from the status quo. [*35*] Policy analysts do not start from nothing, but have an idea of present conditions, policies and objectives. [*36*] In order to identify possible improvements the alternatives that they consider focus on incremental alteration of the existing position, and information is derived from historical and contemporary experience. [*37*]

---

32 Braybrooke (1970) p23
33 Braybrooke (1970) p61
34 Braybrooke (1970) pp 83-88
35 Braybrooke (1970) p84
36 Braybrooke (1970) p83
37 Braybrooke (1970) p84

2. Limitation on the Number of Alternatives Considered. [*38*]

The consideration of only incremental changes immediately limits the number of alternatives considered. In addition, discontinuities in the adjustments by which the possible increments are varied also limits the number of policy alternatives that are considered. [*39*]

3. Limitation on the Number of Possible Consequences Considered. [*40*]

Analysts neglect the analysis of consequences that they consider to be unimportant, but in addition consequences which are uninteresting to the analyst, remote, imponderable, intangible and poorly understood are also neglected - no matter how important. [*41*] It is inevitable that inadvertently important consequences may be omitted. [*42*]

4. Objectives Adjusted to Policies Available. [*43*]

There is a fundamental sense in which the proximate ends of policy are governed by the means available. [*44*] Outcomes established as policy objectives are derived in large part from the range of means which are actually available. [*45*]

---

38 Braybrooke (1970) pp 88-90
39 Braybrooke (1970) p88
40 Braybrooke (1970) pp 90-93
41 Braybrooke (1970) p90
42 Braybrooke (1970) p90
43 Braybrooke (1970) pp 93-98
44 Braybrooke (1970) p93
45 Braybrooke (1970) p93

5. Reconstructive Treatment of Data. [*46*]

Understanding, objectives and options change over time. This alters the conception of the problem and it becomes reconstructed. The strategy is not rigidly bound to treat problems in their original form [*47*]

6. Serial Analysis and Evaluation. [*48*]

Policy making proceeds through a long chain of policy steps [*49*] - it is not a once and for all accomplishment. Analysts return time after time to approximately the same objectives; the same incremental policy change options and the same analytic context, [*50*] in order to move iteratively towards desired objectives.

7. Remedial Orientation of Analysis and Evaluation. [*51*]

The characteristics of the strategy - serial, incremental and exploratory - lead the decision maker to seek to avoid or move away from disagreeable situations rather than to choose as the desired objective a move *towards*, a particular goal. [52] Under the strategy the decision maker is less concerned with pursuing a better world than avoiding a worse. [*53*]

---

46 Braybrooke (1970) pp 98-99
47 Braybrooke (1970) p98
48 Braybrooke (1970) pp 99-102
49 Braybrooke (1970) p99
50 Braybrooke (1970) p100
51 Braybrooke (1970) pp 102-104
52 Braybrooke (1970) p102
53 Braybrooke (1970) p104

8. Social Fragmentation of Analysis and Evaluation. [*54*]

It is integral to the strategy that analysis and evaluation are undertaken by a wide spectrum of society. [*55*] The social fragmentation of decision making and the mechanism of disjointed incrementalism are further elucidated by Lindblom in "The Intelligence of Democracy". [*56*] Lindblom introduces the term "partisan decision maker" to describe a decision maker who makes decisions calculated to serve his own goals. [*57*] These decisions are adjusted to the context arising from the decisions from the other partisans. Lindblom identifies a variety of different methods of adjustment including "parametric", [*58*] "deferential", [*59*] "calculated" [*60*], and negotiated [*61*]. The analysis of various aspects of policy at different points in society with no apparent coordination led Braybrooke and Lindblom to use the term "disjointed" in the name of the strategy. [*62*] (The term also refers to the remedial rather than comprehensive approach to decision making. [*63*])

In response to possible criticisms of the lack of completeness and co-ordination that the strategy engenders Braybrooke and Lindblom comment:

---

54 Braybrooke (1970) pp 104-106
55 Braybrooke (1970) p104
56 Lindblom (1965)
57 Lindblom (1965) p29
58 Lindblom (1965) p37
59 Lindblom (1965) p44
60 Lindblom (1965) p52
61 Lindblom (1965) pp 54-84
62 Braybrooke (1970) p105
63 Braybrooke (1970) p106

> "Disjointedness has its advantages - the virtues of its defects - chief among them the advantage of preserving a rich variety of impressions and insights that are liable to be "co-ordinated" out of sight by hasty and inappropriate demands for a common plan of attack." [*64*]

Incrementalists argue that the limitation of possible policy options considered and the involvement of a large spectrum of society in decision making under the strategy of disjointed incrementalism overcomes the major failings of the synoptic approach that arise due to the limitations of analysis and the problems of incorporating value.

1.3.1. Incrementalism in Business Decision Making

The work of Braybrooke and Lindblom was largely concerned with decision making in public policy. However, Quinn has extended to their work to decision making in business. [*65*] Following a study of the way that companies arrived at strategic changes, [*66*] Quinn concluded that managers in major enterprises consciously and proactively move forward incrementally. [*67*] Quinn commented:

> "The most effective strategies of major enterprises tend to emerge step by step from an iterative process in which the organisation probes the future, experiments and learns from a series of partial (incremental) commitments rather than through global formulations of total strategies." [*68*]

Although Quinn considered that, compared to the public policy decisions considered by Braybrooke and Lindblom, business executives took a more proactive approach and consciously surveyed a wider departure from the status

---

64 Braybrooke (1970) p106
65 Quinn (1980)
66 Quinn (1980) p2
67 Quinn (1980) p(x)
68 Quinn (1980) p58

quo; [*69*] the central conclusion, that it is literally impossible to predict all the events and forces that will shape the future, [*70*] and that actual strategies evolve over time, [*71*] remained unchanged. Quinn argued that the essence of strategy is to achieve a posture that is sufficiently strong and flexible that goals may be achieved despite the unforeseeable ways external forces may actually interact when the time comes. [*72*] The importance of flexibility is emphasised in Quinn's definition of "logical incrementalism":

> "it is logical that one proceed flexibly and experimentally from broad concepts toward specific commitments, making the latter concrete as late as possible in order to narrow the bands of uncertainty and to benefit from the best available information. This is the process of *logical incrementalism.*" [*73*] (Author's emphasis)

1.3.2. Incrementalism in Technology Policy

The ideas of Braybrooke and Lindblom are extended to decisions concerning technology policy by Collingridge. (See [*74*] [*75*] [*76*] [*77*] [*78*] [*79*] [*80*]) It is concluded that in order to be able to meet the prescriptions of partisan mutual adjustment a technology must be flexible. [*81*] An inflexible technology is indicated by four physical properties: long lead time, large unit size, capital intensity and the need for a supporting infrastructure. [*82*] Although the involvement of a large number of partisans in the decision making process may allay the problems that arise due to a lack of knowledge and understanding -

---

69 Quinn (1980) p100
70 Quinn (1980) p53
71 Quinn (1980) p43
72 Quinn (1980) p164
73 Quinn (1980) p56
74 Collingridge (1980)
75 Collingridge (1982)
76 Collingridge (1983)
77 Collingridge (1989)
78 Collingridge (1990)
79 Collingridge (1992)
80 Collingridge (1994)
81 Collingridge (1983) p229
82 Collingridge (1990) p181

which is especially acute for decision making in technology policy - this will be ineffective if the decision is inflexible and not open to meliorative actions. Thus the system outlined by Braybrooke and Lindblom for redressing the errors of previous decisions - through serial attack and socially fragmented analysis - becomes futile unless the decision is flexible. [*83*] Collingridge has concluded that all inflexible technologies perform badly. [*84*]

1.4. THE CASE STUDIES

This thesis is concerned with the use of the synoptic method within decision making concerning nuclear waste management in the UK. Two particular case studies are considered. Firstly, the Windscale Public Inquiry into the decision to build the THORP reprocessing plant, and secondly the Nirex safety assessment of nuclear waste disposal. Much work has already been undertaken on decision making in nuclear waste management (see for example [*85*] [*86*] [*87*] [*88*] [*89*] [*90*] [*91*] [*92*] [*93*]) and the particular approach taken within this thesis has been chosen in order to avoid replicating previous studies. Both of the decisions studied display an extraordinarily high level of inflexibility and, overtly, an overwhelming reliance on synoptic techniques. This will be explored below.

---

83 Moreover, decisions to develop inflexible technologies are expected to display certain characteristics which reduce the amount of criticism to which the decision is exposed. [Collingridge (1990) p182]
84 Collingridge (1990) p182
85 TCPA (1978)
86 Breach (1978)
87 Pearce (1979)
88 Williams (1980)
89 Wynne (1980)
90 Wynne (1982)
91 Berkhout (1991)
92 Blowers (1991)
93 Kemp (1992)

1.4.1. THORP

In 1992, BNFL (British Nuclear Fuels) completed construction of a £1.8 billion plutonium separation facility known as THORP, the Thermal Oxide Reprocessing Plant. The decision to build this plant was very controversial and was the subject of a 100 day Public Inquiry in 1977. Overtly, the Windscale Inquiry was an extraordinary example of synoptic analysis. Pearce has described the Inquiry process as:

> "a quasijudicial process in an administrative framework, designed to bring all the relevant evidence to light in order to apprise the Secretary of State of the fullest information possible for him to make a reasonable decision on the issue." [*94*]

One commentator remarked:

> "several million words were poured into the ear of Mr Justice Parker, sitting as planning inspector, and almost as many more were offered for insertion through the eyes in the form of books, pamphlets, and research papers. And not only words but equations, and orders of magnitude, and readings from radiation-sensitive instruments, and calculations in micro-curies and millirems, and measurements of actinides in porphyra and of transuranic isotopes in molluscs and sediments, and hopes of abundant energy, and fears of barbarian collapse, and visions of what the world will be like in fifty years time." [*95*]

Peter Shore, the then Secretary of State for the Environment stated that:

> "In handling Windscale ... I wanted to ensure as thorough an investigation as I could devise. I needed it for my own purposes as Secretary of State, in order to ensure a fully reasoned and informed decision - a decision that was in all the circumstances and with due allowance for human fallibility - right!" [*96*]

Following the Inquiry, the Inspector recommended that THORP should be built. However, the case for reprocessing has since collapsed. In March 1993, the decision to allow THORP to operate was the subject of three Governmental

---

94 Pearce (1979) p92
95 Taylor in Guardian (1977) p(v)
96 Shore (1979) p232

reviews, [97] and the possibility of abandoning the plant, post-construction. was under consideration. It is therefore argued that the synoptic analysis undertaken at the Windscale Inquiry was not successful. The incongruity of the Windscale decision is considered within the thesis and it is concluded that the Windscale Public Inquiry vindicates the position of the incrementalist - the attempt to arrive at a rational decision through a synoptic approach was a failure. However, given the context in which the Windscale Public Inquiry was undertaken this conclusion must be qualified. Although, overtly, the decision to build THORP was made as a result of the synoptic analysis undertaken at the Windscale Inquiry, it has been argued that the decision was effectively predetermined by the historical context in which the decision arose. [98] [99] [100] For example, Wynne has argued that:

> "The Windscale Inquiry was a ceremonial of collective self-delusion with the judiciary left to plug the authority gap between the belief in objective control and the reality of *ad hoc* historical developments. ... in the nuclear issue, even in the age of participation, we have so far seen in Britain only unwitting rituals". [101]

The role of synoptic analysis as a legitimisation exercise for controversial decisions has been further considered elsewhere (see for example [102]) and will not be considered here. However, the ambiguity of the role of the Windscale Inquiry has important implications for the use of this case study as a test of the synoptic model. The historical development of the decision to build THORP is discussed in the thesis. It is concluded that the 'decision' to build THORP emerged over time, and was effectively determined prior to the Windscale Public Inquiry. Therefore, the use of the Windscale Inquiry as a test of the synoptic method is not robust.

---

97 Marshall (1993) 15 March 1993 pp 8,9
98 Wynne (1982) p33
99 Williams (1980) pp 316-317
100 Wynne (1980) p166
101 Wynne (1982) p176
102 O'Riordan (1988) pp 80-81,383

The lessons from this case study are used to ensure that the second study does provide a robust test of the synoptic method. In order to achieve a robust examination of the viability of the synoptic method as a decision making tool, the conclusions that are drawn must be independent of the political constraints faced by the decision makers. Therefore, in the second case study a different method of testing the synoptic approach is adopted.

1.4.2. Nirex

In order to achieve a robust examination of the viability of the synoptic method as a decision making tool, this case study adopts an approach which is independent of the political constraints faced by the decision makers. Nirex, the Nuclear Industry Radioactive Waste Executive, propose to dispose of nuclear waste in an underground repository. In order to obtain regulatory approval to dispose of nuclear waste, Nirex are required to prepare a radiological safety assessment of the long term behaviour of the disposed waste. This requirement is equivalent to the third stage of the synoptic method which requires the exhaustive examination of the consequences of a proposed policy. In order for the synoptic method to offer the decision maker a viable approach to decision making, each one of the four stages must be achievable. Under Lindblom's hypothesis, it is predicted that, due to the overwhelming information demands of the synoptic method, the safety assessment work undertaken by Nirex will fail to provide a cogent analysis of the radiological safety of the proposed disposal facility. The analysis of the cogency of the safety assessment, independently of the decisions taken concerning nuclear waste disposal, overcomes the problem highlighted in the first case study.

It is in Nirex's interest to prepare a safety assessment which is cogent, comprehensive and coherent and they are spending £6 million per year on a research programme involving 14 universities and 11 other research organisations. [*103*] In 1989, Nirex commented that:

> "by gaining a fundamental understanding of the processes concerned, descriptive mathematical models can be formulated which, together with measured data, can be used to make confident predictions about the distant future" [*104*]

Under Lindblom's hypothesis, it is predicted that the attempt by Nirex to make "confident predictions" [*105*] will fail. Most of this thesis is concerned with an analysis of the safety assessment reports which have been published by Nirex, in order to justify their claim that they are able to predict the radiological impact of the proposed repository. It is argued that the inconsistencies, inadequacies, and absurdities found within these documents demonstrate that Nirex are not able to provide a synoptic analysis of the consequences of nuclear waste disposal. Moreover, it is found that the synoptic method fails in the way that Lindblom predicts that it would. Thus, the problems found in the safety assessment are seen to arise due to lack of understanding, lack of data, lack of resources, and the open-endedness of the analysis required. This poses a particular problem for Nirex as it is found that work in one area of investigation often has repercussions in another area. However, the synoptic approach does not provide Nirex with a strategy to contend with this constant feedback. It is therefore argued that, given that it is not possible to provide a synoptic assessment of the safety of nuclear waste disposal, this case study vindicates Lindblom's criticism of the synoptic method. [*106*]

---

103 Nirex (1992) Safety Assessment
104 Nirex (1989) Deep Repository Project, pH1
105 Nirex (1989) Deep Repository Project, pH1
106 This conclusion may be compared to the Collingridge (1984) study of the the use of expert advice in the control of environmental lead which also vindicates Lindblom's criticism of the synoptic method.

1.5. SUMMARY

Two synoptic analyses undertaken within the nuclear waste decision making process are considered within this thesis, the Windscale Public Inquiry and the Nirex safety assessment of nuclear waste disposal. In these case studies an extensive effort has been expended in order to attempt to achieve a comprehensive understanding of the decisions taken. Such an approach to decision making has been termed 'synoptic' by Lindblom, due to the high degree of synopsis, or comprehensiveness of view the decision maker attempts to achieve. [*107*] The synoptic approach has been widely criticised and Lindblom has argued that such an approach to decision making is not achievable. [*108*] Lindblom argues that it is not possible to identify 'correct' decisions through comprehensive analysis. Instead, he suggests that decision making should be seen as a process, rather than a one-off event. Under this approach the fundamental importance of flexibility is stressed.

In the first case study, the success of a decision taken following a Public Inquiry was used to test Lindblom's hypothesis that the synoptic approach to decision making is not achievable. The decision to construct the THORP plant was the subject of a Public Inquiry held in 1977. Overtly, the Inquiry was held in order to provide the Secretary of State for the Environment with the information required in order to allow him to make the "right" [*109*] decision concerning the construction of the plant. This thesis briefly evaluates the success of the decision taken following the Inquiry. It is concluded that the incongruity of the Windscale decision vindicates the position of the incrementalist. However, due to the

107 Lindblom (1965) p138
108 Lindblom (1965) p138
109 Shore (1979) p232

ambiguous role of the synoptic analysis undertaken at the Inquiry it is important to qualify this conclusion.

Given the context in which the Windscale Inquiry was held, it will be argued that the outcome of the Inquiry was constrained by the development of the decision that had already taken place. Therefore, the Inquiry should be seen as a legitimisation exercise, rather than a rigourous synoptic analysis. Consequently, the Windscale Inquiry does not provide a rigourous test of the synoptic method. It was concluded that a methodology was required, that allowed robust conclusions to be drawn, despite the ambiguity introduced by the political constraints faced by decision makers.

In order to obtain a robust test of the synoptic method, a methodology was adopted for the second case study which is robust to the criticism that the synoptic method plays a political role and is peripheral to the decision making process. In the second case study the viability of the synoptic method was evaluated directly. In order to obtain regulatory approval to dispose of nuclear waste, Nirex are required to prepare a radiological safety assessment of the proposed repository. It is in Nirex's interest to prepare a safety case which is cogent, comprehensive and coherent, and they are spending £6 million per year on a safety assessment research programme. The requirement to provide a safety assessment is equivalent to the requirement in synoptic decision making to undertake an exhaustive examination of the consequences of a proposed policy. The analysis of the safety assessment, independently of the decisions taken overcomes the problem highlighted in the first case study. Most of the thesis is concerned with an analysis of the Nirex safety assessment research programme. It is concluded that the failure of this programme to achieve a cogent synoptic analysis of the long-term behaviour of the proposed repository supports Lindblom's criticism of the synoptic approach.

2. THE SYNOPTIC ANALYSIS OF THE DECISION TO BUILD THORP

2.1. INTRODUCTION

In 1977 a Public Inquiry, the Windscale Public Inquiry, [1] [2] [3] [4] [5] [6] [7] was held to consider the proposal by British Nuclear Fuels (BNFL) to build THORP, the Thermal Oxide Reprocessing Plant. [8] Ostensibly, the Inquiry was held in order to provide the Secretary of State for the Environment with the "fullest information possible", [9] in order to allow him to make the "right" [10] decision concerning the construction of the plant. Within this chapter the Windscale Inquiry is treated as an attempt at a synoptic approach to decision making and is used to test Lindblom's hypothesis that a synoptic approach is not achievable.

2.2. THE CASE FOR THORP

Reprocessing achieves the separation of spent nuclear fuel, removed from a nuclear reactor, into plutonium, uranium and wastes. BNFL's case for reprocessing put forward at the Windscale Inquiry as follows:

---

1 TCPA (1978)
2 Breach (1978)
3 Pearce (1979)
4 Williams (1980)
5 Wynne (1980)
6 Wynne (1982)
7 Parker (1978)
8 Parker (1978) vol I, p1
9 Pearce (1979) p92
10 Shore (1979) p232

> "The justification for reprocessing irradiated fuel is that it enables the recovery and reuse of the valuable uranium and plutonium which it contains. This represents an economically attractive and very substantial contribution towards energy conservation. Such recycling accords with sound waste management principles" [*11*]

These three factors, plutonium recovery, uranium recovery, and waste management will be considered below. The alternative to reprocessing, spent fuel storage, will also be considered.

2.2.1. Plutonium Recovery and Reuse

From the very early days of the nuclear industry, it was recognised that nuclear power would be more expensive than electricity generated by coal-fired stations. [*12*] However, it was argued that the value of the plutonium, produced as a by-product of the generation of nuclear electricity and extracted by reprocessing, would make up for short-term losses. [*13*] This was accounted for in the finances of the early nuclear power stations with the so-called 'plutonium credit' Thus, when the UK nuclear power programme was announced in 1955 plutonium was valued at "many thousands of pounds a kilogram". [*14*] Inclusion of this credit brought the cost of nuclear power down to roughly the same cost as coal fired electricity. For example, the White Paper "A Programme of Nuclear Power" forecast:

> "the cost of electricity from the first commercial nuclear stations comes to about 0.6d. a unit. This is about the same as the probable future cost of electricity generated by new coal-fired power stations ... . If no credit were allowed for the plutonium the cost of nuclear power would be substantially more than 0.6d. a unit." [*15*]

---

11 BNFL (1977) p7
12 Cmd. 9389 (1955) p5
13 Cmd. 9389 (1955) p5
14 Cmd. 9389 (1955) p5
15 Cmd. 9389 (1955) p5

The reason that plutonium was considered so valuable was its potential use in fast breeder reactors or FBRs. [*16*] In a fast breeder reactor, "fast" neutrons, which travel at a greater speed than in an ordinary reactor, are fired at plutonium which is surrounded by uranium. This releases heat and, in addition, more neutrons which may be captured by the uranium to generate more plutonium (hence the term "breeder"). [*17*] [*18*] The FBR is theoretically able to make much more efficient use of fuel. In the early days of nuclear power it was thought that shortage of uranium fuel for ordinary "thermal" nuclear reactors would be the limiting factor in the development of nuclear electricity. [*19*] It was therefore argued that the FBR was essential to the maintenance of a long-term UK nuclear power programme. The UK has been developing the FBR since the early 1950s and has spent over £4 billion on its development. [*20*] However, despite this degree of investment the FBR has not proved to be economic. The operation of the prototype fast breeder complex at Dounreay in Scotland costs about £60 million per year. [*21*] Yet, the electricity the reactor produces is worth only £12 to £14 million per year. [*22*] In 1988, the Government announced that the reactor would not be funded after 1994. [*23*] Moreover, despite the initial projections and the vast amounts of money spent on the FBR programme, the predicted uranium scarcity it was designed to relieve has not transpired. The House of Commons Energy Committee wrote in 1990:

> "The fast reactor is therefore an insurance policy against a problem (uranium scarcity) which *might* happen in the first half of the 21st century (perhaps 2020-2030) but which equally might not occur until the 22nd century, or not at all" [*24*]

---

16 Cmd. 9389 (1955) pp 4,5
17 Energy Committee (1990) 4 July 1990, vol I, p(ix)
18 Cmnd. 6618 (1976) pp 41,43
19 Energy Committee (1990) 4 July 1990, vol I, p(xi)
20 Department of Energy (1991) p60
21 Department of Energy (1991) p61
22 Department of Energy (1991) p61
23 Energy Committee (1990) 4 July 1990, vol I, p(ix)
24 Energy Committee (1990) 4 July 1990, vol I, p(xviii)

Apart from use in FBR reactors it is also possible to use plutonium in 'ordinary' reactors. However, due to the difficulties of handling plutonium it is much more expensive to fabricate plutonium, or mixed oxide (MOX), fuel than uranium fuel. [*25*] In addition, there is also evidence that MOX fuel is more expensive to manage than standard fuel when it leaves the reactor. [*26*] For safety reasons, it is currently only possible to use one third MOX in a reactor. [*27*] Over all, the cost benefits of using MOX instead of standard fuel would be only 5-10%. [*28*] However this "saving" is calculated on the basis that the plutonium is a by product of reprocessing and is provided at zero cost. [*29*] The cost of reprocessing is neglected. Ironically, MOX fuel is not suitable for use in the Magnox [*30*] and AGR [*31*] reactors used by existing nuclear power stations in the UK.

The separation of plutonium for which there is no use presents significant problems. In 1990, Britain's stockpile of plutonium totalled nearly 30 tonnes. [*32*] Plutonium is very expensive to store, requiring safeguards against terrorism and protection against radioactivity. Plutonium storage costs are generally considered to be in the region of $1000 to $2000 per kg per year [*33*] [*34*] which is equivalent to $30-60M/year for the UK stockpile. The absurdity of the current situation is illustrated by the fact that although the rationale for reprocessing spent fuel and building up a plutonium stockpile was to breed yet more plutonium in FBRs, fast reactors are now increasingly seen as a way of attempting to eliminate rather than breed plutonium. [*35*] John Collier, former Chairman of the Atomic Energy Authority [*36*] which was responsible for the development of the breeder reactor,

---

25 Williams (1990) p2
26 CEGB in Energy Committee (1989) p(xv)
27 CEGB in Energy Committee (1989) p(xv)
28 CEGB in Energy Committee (1989) p(xv)
29 BNFL in Energy Committee (1989) p(xiii)
30 Williams (1990) p5
31 BNFL in Energy Committee (1989) p(xiii)
32 Energy Committee (1990) 4 July 1990, vol I, p(xix)
33 Nuclear Energy Agency (1985) p58
34 Nuclear Energy Agency (1989) p64
35 Energy Committee (1990) 4 July 1990, vol I, p(xix)
36 Shaw (1990) p6

has now suggested that the design of the FBR should be modified in order to make an attempt at destroying plutonium. [*37*]

2.2.2. Uranium Recovery and Reuse

In addition to plutonium, unused uranium is also separated through reprocessing and it is possible to reuse this in a reactor. However, the uranium recovered from spent fuel is contaminated with radioactive uranium 'isotopes'. Although these isotopes have the same chemical properties as natural uranium, they have different nuclear properties. This results in additional costs at each stage of fuel manufacture and lower fuel efficiency. [*38*] The isotopes 'U-232' and 'U-236', which do not occur naturally, [*39*] present particular problems. U-232 breaks down to a product that emits gamma rays. A contamination level of just 2 parts per billion of U-232 will increase the gamma dose rate to a level 10 times that from fresh uranium after two years. [*40*] The isotope 'U-236' reduces the fuels effective reactivity by absorbing neutrons that would otherwise initiate a release of energy. [*41*]

As was the case for plutonium, any "savings" calculated due to the use of uranium separated during reprocessing assume that the cost of reprocessing is ignored. [*42*] Neglecting the cost of reprocessing is dubious as reprocessing imposes an enormous financial burden on nuclear power station operators. In their 1991-92 accounts, Nuclear Electric included provisions of nearly £8 billion to allow for reprocessing and waste management costs incurred by BNFL. [*43*] John Collier,

37 Collier (1991) Fast Reactors, p3
38 Williams (1990) p2
39 Paleit (1987) p520
40 Williams (1990) p3
41 Williams (1990) p2
42 Gresley (1989) p14
43 Nuclear Electric (1992) p49

the Chairman of Nuclear Electric, commented in January 1991 that between a quarter and a third of Nuclear Electric's total revenue went "straight out the door" to BNFL. [*44*] Reprocessing costs are so high that in 1989 the South of Scotland Electricity Board (SSEB) announced the closure of Hunterston A nuclear power station largely due to the rapidly increasing cost of Magnox reprocessing [*45*] [*46*] although it was the best performing Magnox reactor in the UK. [*47*] The alternative method of spent fuel management, storage, would halve the cost of dealing with spent fuel. [*48*]

2.2.3. Waste Management

BNFL argued at the Windscale Inquiry that reprocessing "accords with sound waste management principles". [*49*] In fact, the disturbance of spent fuel elements through reprocessing considerably exacerbates waste management problems. Large volumes of additional wastes are created through contamination and a considerable amount of radioactivity is discharged directly to the environment. Before the Inquiry took place, the Royal Commission on Environmental Pollution commented:

> "many of the most troublesome problems of radioactive waste management arise as a result of the reprocessing operation". [*50*]

Similarly, Lord Marshall, former Chairman of the CEGB, [*51*] has stated that Britain's nuclear programme has probably generated more nuclear waste than

---

44 Collier (1991) Straight Talking, p6
45 SSEB (1989) p1
46 SSEB in Energy Committee (1990) 7 June 1990, vol II, p79
47 Howles (1990) p14
48 RWMAC (1990) Eleventh Annual Report, p43
49 BNFL (1977) p7
50 Cmnd. 6618 (1976) p143
51 Energy Committee (1990) 7 June 1990, vol II, p1

those of the rest of the world put together. [*52*] Most of this volume of waste has arisen due to reprocessing undertaken by BNFL. [*53*] Disposing of all of the nuclear waste produced in the UK would require a cavity as large as the Channel Tunnel. [*54*] [*55*] Nearly 60% of this waste will be produced at Sellafield. [*56*] [*57*] The impact that reprocessing has on waste volumes may be illustrated by the example of Magnox fuel reprocessing. The volume of waste to be handled is increased over seventy-fold if Magnox fuel is reprocessed. [*58*] [*59*] This figure does not include the uranium and plutonium stocks that must be managed, the decommissioning wastes, or the radioactivity that is discharged to the environment. In contrast, if the fuel is not reprocessed but instead disassembled and packaged for long term storage, the volume of waste to be managed would be reduced by 30%. [*60*]

In addition to increasing the volume of waste to be handled, reprocessing also makes the wastes more difficult to handle. During reprocessing spent fuel is dissolved in nitric acid and sent through a complex plant to separate out the plutonium and uranium. As a result radioactivity originally held in the fuel rod is dispersed throughout the plant, miscellaneous material becomes contaminated and the most highly active waste is left as an intensely radioactive acid liquid. Liquids present intrinsic problems and in 1986 the Nuclear Installations Inspectorate (NII) commented:

> "So long as waste remains in liquid form and therefore dispersable, it presents a hazard to those who work there, and potentially to the public or the environment." [*61*]

---

52 Lord Marshall in Energy Committee (1990) 7 June 1990, vol II, p165
53 CEGB in Environment Committee (1986) First Report, vol II, pp 74,75,77
54 Beale (1988) p13
55 Barker (1992) p40
56 Electrowatt (1990) Table 4.2b
57 Electrowatt (1992) pp 74,75
58 CEGB in Environment Committee (1986) vol II, p74
59 Department of the Environment in Environment Committee (1986) vol II, p554
60 Department of the Environment in Environment Committee (1986) vol II, p554
61 Health and Safety Executive (1986) vol I, pp 1,4

Thus, the waste must be returned to solid form - as it was before it was reprocessed. It is planned to use the vitrification process which involves heating the intensely radioactive material and mixing it with glass frit to produce molten glass. The machinery becomes intensely radioactive and must be operated remotely. [*62*] The process is not straightforward and in September 1991, just seven months after the vitrification plant at Sellafield was opened it had to be closed due to failure of the shielding. Following the incident the NII considered legal action against BNFL. [*63*] In February 1993, BNFL were convicted following a second incident associated with the vitrification plant. [*64*]

Reprocessing introduces other complications to radioactive waste management. For example, the reprocessing plant becomes contaminated with plutonium, which is highly radioactive [*65*] and extremely toxic [*66*] - inhalation of just a few milligrams is sufficient to cause massive fibrosis of the lungs and death. [*67*] The Magnox [*68*] [*69*] [*70*] or zirconium [*71*] cladding removed from the spent fuel before it is dissolved is liable to combust. Furthermore, the intermediate and low level waste streams generated by reprocessing may be contaminated with plutonium which presents a long-term hazard. [*72*] [*73*] In addition, the mixing of other miscellaneous materials, such as lab-coats, paper towels and gloves, with the waste introduces materials which make the chemical behaviour of the waste difficult to predict over the huge timescales for which containment must be guaranteed. These materials could, for example, react to make the waste more

---

62 Anon (1990) March 1990, p44
63 Health and Safety Executive (1992) p4
64 Marshall (1993) 4 March 1993, pp 8-9
65 Bairiot (1989) p72
66 Wakerley (1989) pp 9,10
67 Cmnd. 6618 (1976) p126
68 Cmnd. 6618 (1976) p140
69 Charlesworth (1981) p36
70 O'Tallamhain (1986) p36
71 James (1989) p101
72 Tasker (1990) p461
73 Nirex (1989) Deep Repository Project, Table 2.3

soluble [*74*] and so increase the speed that the radioactivity escapes back to the human environment after disposal. Additionally, the decay of these materials could lead to a build up of potentially explosive gases. [*75*] [*76*]

The liquid and gaseous wastes arising from reprocessing, that are directly discharged into the environment, must also be considered. As a result of its reprocessing operations at Sellafield, BNFL is responsible for the largest radiological exposure in the whole of Europe from the routine operation of any civil nuclear installation. The National Radiological Protection Board (NRPB) has stated:

> "the main contribution to population exposure in both the UK and Europe as a result of discharges from civil nuclear installations has arisen from the Sellafield effluent discharges into the Irish Sea." [*77*]

There is a continuing excess of childhood leukaemias in the village of Seascale near Sellafield. [*78*] [*79*] [*80*] The cause of this excess is the subject of considerable controversy and is currently the subject of action in the High Court. [*81*]

Ironically, the most hazardous waste stream produced by reprocessing is the separated plutonium. Britain's stockpile of plutonium is about 30 tonnes and is expected to rise to about 65 tonnes by 2005. [*82*] By comparison, the minimum amount of plutonium required to make a nuclear explosive device is just 8 kg. [*83*] In 1976, the Royal Commission on Environmental Pollution commented extensively on the risks that arise due to the separation of plutonium and

74 Atkinson (1988) p153
75 Lever (1988) p117
76 Billington (1990) p277
77 NRPB in Select Committee on the European Communities (1988) p15
78 Gardner (1990) pp 423-9
79 Marshall (1993) 21 January 1993 pp 1-2
80 Black (1984)
81 Gibb (1992)
82 Energy Committee (1990) 4 July 1990, vol I, p(xix)
83 Berkhout (1990) p523

concluded that it would be possible for a terrorist group to construct a nuclear weapon. Such a device would be lethal over a range of several hundred metres. [*84*] The commission commented:

> "plutonium appears to offer unique and terrifying potential for threat and blackmail against society." [*85*]

In 1992, William Dircks, deputy-director of the International Atomic Energy Agency (IAEA) commented:

> "as a result of nuclear fuel reprocessing ... the supply of plutonium will far exceed the industrial capacity to absorb it into peaceful, commercial nuclear industrial activities ... the excess of isolated fissible plutonium from civilian nuclear programmes is going to pose a major political and security problem worldwide." [*86*]

2.2.4. The Storage of Spent Fuel

The alternative to reprocessing is to leave spent fuel intact and to store it in specially designed facilities. If fuel is stored the radiological impact - the amount of radioactivity directly released to the human environment - is much lower than if the fuel is reprocessed. [*87*] [*88*] In addition, the volume of the waste to be managed would be considerably reduced. [*89*] Although spent fuel storage is an established technology that is used in many countries it has been argued that it is not appropriate to the UK because different types of fuel are used (known as Magnox and AGR fuel). In particular, Magnox fuel is liable to corrode and it has been argued that it is essential that it is reprocessed. However, these corrosion problems may be avoided if the fuel is not stored in ponds, but instead in dry storage. In 1987 Lord Marshall, Chairman of the CEGB, commented:

---

84 Cmnd. 6618 (1976) p126
85 Cmnd. 6618 (1976) p81
86 Dircks (1992) pp 4,5
87 Martin (1983) p18
88 U.S. Department of Energy (1989) pI-98
89 Department of the Environment in Environment Committee (1986) vol II, pp 553,554

> "...we are under attack from environmentalists and our critics for storing Magnox fuel in water. The attack is difficult for us to answer because it is basically correct. The early pioneers who initiated the policy of storing spent Magnox fuel in water made a mistake." [*90*]

It is possible to build dry stores for this fuel, as has been done at Wylfa in Anglesey since 1971. [*91*] Indeed, research prepared for the Department of the Environment (DoE) has concluded that long-term storage of Magnox fuel in such stores would be feasible. [*92*] Magnox fuel that has already been wet stored presents difficulties. Following a recommendation of the Environment Committee in 1986, the CEGB investigated the problem and concluded that it would be possible to dry this fuel and place it in long term dry storage. [*93*] [*94*] However, very little subsequent research has been carried out on this subject.

AGR fuel is much easier to store than Magnox fuel. In 1989 a second DoE report specifically considered long term management of AGR fuel and found that storage would be viable. [*95*] Moreover, the report commented that storage was "environmentally cleaner than the reprocessing route". [*96*]

In addition to the environmental advantages of storage, it is also considerably cheaper than the reprocessing option. Scottish Nuclear propose to construct dry stores for the fuel from their AGR reactors at Torness and Hunterston [*97*] and they have estimated that this will save £40M/year. [*98*] [*99*] Similarly, German utilities, who also currently have reprocessing contracts with BNFL, are

---

90 Bell (1989) 24 May 1989, p13
91 NNC in Environment Committee (1986) vol III, p611
92 Kempe (1980) pp 5,71
93 CEGB/SSEB (1986) p18
94 O'Tallamhain (1986) p28
95 Angell (1989) p20
96 Angell (1989) p20
97 Marshall (1992) 23 July 1992, p5
98 Marshall (1992) 23 July 1992, p5
99 Marshall (1993) 18 February 1993, p15

considering the adoption of storage rather than reprocessing in order to reduce waste management costs. [*100*] [*101*] [*102*] [*103*] [*104*]

2.3. THE SUCCESS OF THE WINDSCALE INQUIRY

After 100 days of hearings, and consideration of 1,500 documents [*105*] the Inspector at the Windscale Inquiry accepted BNFL's case and, in 1978, recommended that BNFL should be granted permission to construct THORP. [*106*] However, just three years later in 1981, Brian Mummery head of Nuclear Operations at the CEGB wrote:

> "Are we reprocessing: a) to recover the plutonium for fast reactors; b) to recycle the uranium; c) to permit safe storage/disposal of fission products?
>
> These arguments were made at the Windscale Inquiry but BNFL's performance and current estimates of likely reprocessing costs must cause us to reexamine the issue. I believe that:
>
> 1. We do not *need* the plutonium, at least on a timescale which requires reprocessing in the next 15 years.
> 2. Recycling the uranium by costly reprocessing is uneconomic.
> 3. Dry storage is very satisfactory, as an interim measure, of dealing with fission products.
> ... I believe that consideration of the above leads to the conclusion that we would now prefer dry storage to reprocessing". [*107*]

In 1989, when construction of THORP was largely complete, [*108*] Alan Johnson, a Director of BNFL, commented:

> "Reprocessing is not necessary. In fact one or two of our important customers would love to cancel their contracts. At the drop of a hat they'd cancel their contracts." [*109*]

---

100 Hibbs (1992) 6 July 1992, p5
101 Hibbs (1992) 20 July 1992, p7
102 Hibbs (1992) 13 August 1992, p13
103 Hibbs (1993) 4 January 1993, p9
104 Hibbs (1993) 14 January 1993, p12
105 Parker (1978) vol I, p1
106 Parker (1978) vol I, p83
107 Bell (1989) 31 May 1989, pp 10-11
108 BNFL (1991) Annual Report, p17
109 Johnson (1989)

It may therefore be concluded that the decision of the Windscale Inquiry Inspector, to accept BNFL's case, was erroneous. Therefore, the Windscale Inquiry supports Lindblom's hypothesis that a synoptic approach to decision making is not achievable. However, due to the historical context in which the Windscale Inquiry arose, it has been argued that the outcome of the Inquiry was effectively predetermined. The historical context of the Windscale Inquiry, and its implications for conclusions concerning this case study will be considered in the following chapter.

2.4. SUMMARY

The case for reprocessing put forward by BNFL at the Windscale Inquiry was based on the value of the plutonium and the uranium separated by reprocessing, and the role of reprocessing in waste management. This case has collapsed. The collapse of the case for reprocessing, after it had been accepted by the Inspector at the Inquiry, supports Lindblom's hypothesis that the synoptic approach to decision making is not viable. However, this conclusion assumes that it is valid to view the outcome of the Windscale Inquiry as the result of synoptic analysis. This assumption is open to criticism, as it has been argued that the decision to build THORP was effectively predetermined by the historical context in which the decision arose. In the following chapter the historical context of the Windscale Inquiry and its implications for conclusions concerning this case study will be considered.

3. THE HISTORICAL DEVELOPMENT OF THE DECISION TO BUILD THORP

3.1. INTRODUCTION

In the previous chapter, the Windscale Inquiry was considered as an attempt at a synoptic approach to decision making. If the Windscale Inquiry is considered in this way, the incongruity of the decision to build THORP may be viewed as vindication of Lindblom's hypothesis that a synoptic approach to decision making is not viable. However, this conclusion is not robust if it is not appropriate to consider the Inquiry as an attempt to achieve synoptic decision making. Given the historical context in which the Windscale decision arose, it has been argued that the outcome of the Inquiry was virtually inevitable. [*1*] [*2*] [*3*] This chapter traces the historical development of the decision to build THORP [*4*][*5*] from the original plutonium separation work undertaken in the United States in the 1940s, to BNFL's expansion plans of the early 1970s. It is concluded that the 'decision' to build THORP emerged over time and that the outcome of the Inquiry was effectively predetermined. Therefore, the Windscale Inquiry does not provide a robust test of the synoptic method. However, lessons drawn from this case study may be used to ensure that the conclusions drawn from the second case study are robust.

---

1 Wynne (1982) p33
2 Williams (1980) p317
3 Wynne (1980) p166
4 see also Wynne (1982) pp 33-51
5 Internal Documents used in this chapter were presented as supplementary documents to the Windscale Inquiry. [See Windscale Transcript (1977) Day 16, p78, see also Parker (1978) vol II]

3.2. THE ORIGIN OF REPROCESSING

On Thursday August 20 1942, Glenn Seaborg wrote:

> "Perhaps today was the most exciting and thrilling day I have experienced since coming to the Met Lab. Our microchemists isolated element 94 for the first time!
>
> It is the first time element 94 (or any synthetic element, for that matter) has been beheld by the eye of man. I'm sure my feelings were akin to those of a new father who has been engrossed in the development of his offspring since conception. Counting from the time that uranium oxide was first bombarded by deuterons on December 14, 1940, to produce the 50-year 94 isotope, the gestation period has been 20 months. Not everyone shares Fermi's confidence that the pile will chain-react and produce 94. Without a working pile, we will never be able to produce 94 in much greater yields than with the cyclotron, and it would probably remain a novelty for years to come. Without a pile, the dream of atomic power plants will come to naught. And without 94, the only possibility of producing a bomb will be to use an isotope of uranium." [*6*]

Element 94 is plutonium.

On 2 December 1942, the first self-sustaining nuclear chain reaction was realised. [*7*] Seaborg wrote:

> "Fermi has demonstrated that we now have a means of manufacturing 94-239 in copious amounts, it is the responsibility of chemists to show that the 94 can be extracted and purified to the degree required for a working bomb." [*8*]

The plutonium produced in a nuclear reactor is locked inside the uranium rod and mixed with intensely radioactive fission products. The fission products are isotopes of elements ranging in atomic number from 30 (zinc) to 66 (dysprosium). [*9*] Most of them are radioactive and their half-lives range from less than a second to thousands of years. [*10*] This radioactivity is the major source of the

---

6 Seaborg (1992) p9
7 Farmelo (1992) p3
8 Seaborg (1992) p10
9 Bebbington (1976) p30
10 Bebbington (1976) p30

heat and radiation from spent fuel. [*11*] Therefore, in addition to the chemical problem presented by the large number of chemical elements in the fuel. the difficulties of plutonium separation are exacerbated by the fact that the chemical operations must be carried out by remote control behind thick concrete walls. [*12*] The designers of the plutonium separation plants for the atomic bomb programme, recognized that the technological innovations required were demanding enough without attempting to optimise the process. [*13*]

The technique which was chosen for the separation plants was a simple batch operation which had been developed by Seaborg for working with microgram amounts of plutonium. [*14*] The uranium rods were dissolved in acid to produce an extremely dilute solution of plutonium. [*15*] Bismuth and lanthanum were added as "carriers", so that when bismuth phosphate and lanthanum fluoride were subsequently precipitated out, plutonium phosphate and plutonium fluoride would also be precipitated out. [*16*] Repeated dissolutions and precipitations allowed the plutonium to be separated from the uranium and the fission products. [*17*] Uranium was not separated and the volume of waste was large because of the lanthanum fluoride and bismuth phosphate that was added. [*18*]

Barely two and a half years after the onset of large scale plutonium production in a nuclear reactor on 2 December 1942, sufficient plutonium was separated to make the first nuclear bomb which was tested in the New Mexico desert on 16

---

11 Bebbington (1976) p30
12 Bebbington (1976) p30
13 Bebbington (1976) p30
14 Bebbington (1976) p30
15 Bebbington (1976) p30
16 Bebbington (1976) pp 30,32
17 Bebbington (1976) p32
18 Bebbington (1976) p32

July 1945. [19] [20] Three weeks later on 9 August 1945 a plutonium bomb was dropped on Nagasaki. [21]

3.3. THE DEVELOPMENT OF REPROCESSING IN THE UK

At the end of 1946, a British Chemistry team working in Canada was asked to develop by September 1947 a plutonium separation process for the British weapons programme. [22] Rather than simply use the American process which had already been demonstrated, it was decided that a process was required which also extracted the uranium which was very scarce. [23] The American precipitation technique did not separate out the uranium. [24] As early as 1942 Seaborg's work had identified that it would be possible to use organic solvents to separate plutonium. [25] Although the precipitation technique was finally chosen in 1944, one of the chemist's who had worked with Seaborg, Goldschmidt, went back to the solvent extraction process in the course of work carried out by the Chemistry Division of the Anglo-Canadian Atomic Energy Group. [26] The team concentrated on solvent extraction because it had greater promise for the future. [27] However, the process that was developed also did not separate out the uranium. [28]

The British chemistry team in Canada, headed by Robert Spence, consisted of twelve chemists and chemical engineers and five assistants. [29] Using just 20

---

19 Bebbington (1976) p32
20 Goldschmidt (1982) p20
21 Goldschmidt (1982) p22
22 Gowing (1974) vol II, p405
23 Gowing (1974) vol II, p403
24 Gowing (1974) vol II, p404
25 Goldschmidt (1956) p492
26 Goldschmidt (1956) p492
27 Gowing (1974) vol II, p404
28 Gowing (1974) vol II, p405
29 Gowing (1974) vol II, p405

milligrams of plutonium (just enough to cover a pinhead) they reviewed all the possible methods of separation - precipitation, distillation, adsorption and solvent extraction. [*30*] Solvent extraction was chosen - both because it would be more efficient and because more information was available about it. [*31*] Although it was not the most certain process and its adoption was a gamble, [*32*] its modification to include uranium extraction [*33*] was felt to be the best long-term solution. [*34*] Using a rack of seven special test tubes together with pipettes, rubber bulb stoppers and mechanical shakers, [*35*] and the 20 mg of plutonium available to them, [*36*] Spence's team produced their eight part report precisely to time. [*37*]

Due to the poor knowledge of plutonium chemistry it was extremely difficult to produce the data required to the level of precision necessary to design a delicately balanced flow sheet for an efficient separation plant. [*38*] Nevertheless, the decision was taken to adopt the solvent extraction process recommended in the report. [*39*] The decision to base a large expensive and hazardous plant on experiments with 20 milligrams of plutonium was alarming. [*40*] No one was known to have designed solvent extraction plant of this type before. [*41*] Having accepted the process based on the report produced in September 1947 it was decided that the flowsheets should be available by the end of 1947. [*42*] No major

30 Gowing (1974) vol II, p405
31 Gowing (1974) vol II, p405
32 Gowing (1974) vol II, p404
33 Gowing (1974) vol II, pp 405-6
34 Gowing (1974) vol II, p404
35 Gowing (1974) vol II, p406
36 Gowing (1974) vol II, p405
37 Gowing (1974) vol II, p406
38 Gowing (1974) vol II, p405
39 Gowing (1974) vol II, p407
40 Gowing (1974) vol II, p407
41 Gowing (1974) vol II, p407
42 Gowing (1974) vol II, p408

alteration was to be allowed after April 1948. [*43*] The separation plant was due to be ready for inactive operation by July 1950. [*44*]

Solvent extraction is very complicated. In order for the separation to work properly, the flows of the various streams in and out and up and down the extraction columns in the plant and through the neutralising, oxidising and reducing vessels, had to be correctly foreseen. [*45*] In addition, the quantities of the aqueous liquors, the solvent and the reagents had to be correctly balanced and the height of the columns correctly estimated. [*46*] The magnitude of the quantity of information required may be appreciated by the fact that the column height for uranium extraction was based on one set of results from a one inch column. [*47*] The inadequacy of the information on plutonium and the fission products made it difficult to even plan the ancillary plants for purification of the separated plutonium and uranium. [*48*]

The research requirements were analysed into sixty items [*49*] and a chemistry division had to be built up. [*50*] The flowsheets were constantly revised as new information arrived and the final version was numbered Mark 9. [*51*] Pilot plants were constructed at Springfields, Widnes, Harwell and at Chalk River in Canada. [*52*] Although the Americans were also working on a continuous solvent extraction system to replace the precipitation process, differences in the details of their process meant that it was impossible to check the UK data against the American information. [*53*]

---

43 Gowing (1974) vol II, p408
44 Gowing (1974) vol II, p408
45 Gowing (1974) vol II, p408
46 Gowing (1974) vol II, p408
47 Gowing (1974) vol II, p408
48 Gowing (1974) vol II, p409
49 Gowing (1974) vol II, p409
50 Gowing (1974) vol II, p409
51 Gowing (1974) vol II, p410
52 Gowing (1974) vol II, p410
53 Gowing (1974) vol II, pp 410-1

ICI, who were responsible for the flowsheets, warned in 1948 that there would be a nine to eighteen month delay in the programme. [*54*] Much of the design for the chemical separation plant had to go ahead based on guess-work. [*55*] In 1949. ICI had serious doubts that the plant would work and urged that the whole concept of the plant be changed from columns to air mixers. [*56*] A high level meeting was held, but it was decided that as so much work had been put into the design of the plant, it would be inexpedient on psychological grounds alone to stop it. [*57*] The plant was to go ahead on the understanding that no promises could be made about its performance. [*58*] Subsequently results from the Chalk River pilot plant indicated that the predictions of the Spence report from 1947 were correct. [*59*] However, just three weeks before the first inactive run of the plant was due to start the plant had to be hastily modified in order to avoid an explosion risk with the solvent. [*60*]

The plant was completed in April 1951 and the first inactive run took place in June 1951. [*61*] On 25 February 1952, fully active material was fed into the separation plant [*62*] and the first billet of plutonium was made on 31 March 1952. [*63*] On 3rd October 1952, the first British atomic weapon was tested at the Monte Bello Islands off Western Australia. [*64*]

---

54 Gowing (1974) vol II, p410
55 Gowing (1974) vol II, p411
56 Gowing (1974) vol II, p412
57 Gowing (1974) vol II, p413
58 Gowing (1974) vol II, p413
59 Gowing (1974) vol II, p413
60 Gowing (1974) vol II, pp 416-7
61 Gowing (1974) vol II, p419
62 Gowing (1974) vol II, p419
63 Gowing (1974) vol II, p422
64 Gowing (1974) vol II, pp 443,474,529

3.3.1. Reprocessing for the Nuclear Power Programme

In February 1955, the White Paper "A Programme of Nuclear Power" was presented to Parliament. [*65*] This proposed that by 1965 nuclear power stations should be used to produce electricity at a rate equivalent to the burning of 5 to 6 million tons of coal a year. [*66*] This would be achieved through the construction of 12 nuclear power stations with a combined capacity of about 1500 to 2000 megawatts. [*67*] In addition to electricity, these power stations would produce plutonium. In fact, the chart shown in the White Paper to illustrate the principles of nuclear power presents plutonium as the main product and electricity as a side product. [*68*]

Plutonium production was intrinsic to the rationale for nuclear power presented in the 1955 White Paper. It was stated that without the plutonium it would not be possible to build up a system of nuclear power stations of steadily advancing efficiency. [*69*] [*70*] It was argued that the plutonium produced was potentially very valuable [*71*] and it had already been decided to build a full-scale experimental "fast breeder" reactor [*72*] which would use plutonium-based fuel. [*73*] It was thought that this would be a major advance in the economic use of nuclear materials. [*74*] Although it was not obvious what would be the correct value to ascribe to the plutonium to be produced in the nuclear power stations, [*75*] it was decided to allow for the plutonium at a rate of many thousands of

---

65 Cmd. 9389 (1955)
66 Cmd. 9389 (1955) p6
67 Cmd. 9389 (1955) p6
68 Cmd. 9389 (1955) p16
69 Cmd. 9389 (1955) p4
70 Plutonium was also the subject of a barter agreement with the US, see O'Riordan (1988) pp 240-249
71 Cmd. 9389 (1955) p2
72 Cmd. 9389 (1955) p2
73 Cmd. 9389 (1955) p17
74 Cmd. 9389 (1955) p17
75 Cmd. 9389 (1955) p4

pounds per kilogram. [*76*] Using this assumed value for the plutonium stockpile, that would be generated by the production of electricity in nuclear power stations, the cost of the electricity produced was calculated to be 0.6d per unit. [*77*] This was approximately the same as the cost of electricity generated from a new coal-fired power station. [*78*] The plutonium from the early reactors was expected to begin to become available in 1964 at the rate of several hundred kilograms a year. [*79*] By the late 1960s, the early reactors were expected to be producing plutonium in quantity. [*80*] It was anticipated that a new chemical separation plant would be required. [*81*]

3.3.1.1. The Construction of the Second Plant

The Windscale Plant Design Office, Risley and the Chemical Plant Development Group, Windscale were commissioned to develop and design the process and plant for plutonium separation from the spent fuel arising from the nuclear power stations. [*82*] Although, the decision on the technology to use for the first reprocessing plant [*83*] had been limited due to the sparse background of fundamental knowledge, and due to the fact that only 20mg of plutonium was available for experimental work, [*84*] considerably more information was available when the second plant was designed. In 1955, Culler of Oak Ridge National Laboratory in the United States noted that:

> "A survey of the reprocessing technology of irradiated reactor fuel elements by solvent extraction must cover the work of hundreds of people and data contained in thousands of detailed reports." [*85*]

---

76 Cmd. 9389 (1955) p5
77 Cmd. 9389 (1955) p5
78 Cmd. 9389 (1955) p5
79 Cmd. 9389 (1955) p7
80 Cmd. 9389 (1955) p8
81 Cmd. 9389 (1955) p7
82 Warner (1964) p224
83 Gowing (1974) vol II, pp 405-7
84 Farmer (1957) p27
85 Culler (1956) p464

Similarly, Fletcher from Harwell in the UK commented on the "well established but elaborate" nature of reprocessing. [86]

During the development of the second reprocessing plant, the experience gained from the design and operation of the first plant was used extensively in developing the process and design philosophy of the new plant. [87] At the commencement of the project, the Development Group had experience of both the existing plant and additional solvent extraction processes it had designed and the published information on solvent extraction processes in the United States and in Canada. [88] Considerable use was made of the working experience obtained from the use of the first plant [89] and the chemical process used in the second plant was essentially the same as was used in the first plant. [90]

3.3.1.2. The Need for the Second Plant

In November 1963, the first plant was run down [91] and reprocessing in the second plant began in 1964. [92] Before operation of the second plant had even begun, the need for reprocessing appeared doubtful. Supposedly, the plutonium that was separated was to be used in fast breeder reactors and the uranium was also to be reused. However, the economics of recovery and reuse were tenuous. By 1962, there was already a plutonium surplus. [93] The Chairman of the Windscale Local Liaison Committee commented:

---

86 Fletcher (1956) p459
87 Corns (1964) p233
88 Warner (1964) p224
89 Warner (1964) p225
90 Windscale LLC (1961) p4
91 Windscale LLC (1963) p3
92 Bailey (1990) p12
93 Windscale LLC (1962) p4

"everyone hoped that plutonium would eventually be used as a nuclear fuel" [94]

In 1963, it was reported to the Windscale Local Liaison Committee that work was being undertaken to produce fuel elements spiked with plutonium in order to "find an outlet" for plutonium. [95] Uranium also presented a stockpile problem. In the 1955 White Paper it was noted that:

"Recent evidence suggests that uranium is more plentiful than was once thought; considerable workable deposits of medium-grade ore are known while the widespread existence of low-grade ores implies that adequate quantities can be produced from them if necessary." [96]

Uranium contains the 'isotopes' U238 and U235. It is the U235 content of uranium which is important in uranium fuel as this is the isotope that can be used to release energy. The uranium recovered through the reprocessing of spent fuel, will have lost some of its initial uranium 235 as it will have been used in the reactor. Thus, despite the fact that solvent extraction had been developed as a gamble to allow uranium separation as well as plutonium separation, [97] the uranium that it produces is of low worth. By 1963, a spokesman from the Canadian nuclear industry, noted that the uranium separated from irradiated natural uranium had essentially no value. [98]

It was, therefore, clear from the outset that there was no compelling economic justification for the second reprocessing plant. One chemist from the Belgian nuclear industry commented:

---

94 Windscale LLC (1962) p4
95 Windscale LLC (1963) p4
96 Cmd. 9389 (1955) p8
97 Gowing (1974) vol II, p404
98 Aikin in Culler (1963) p442

"It appears to me ... that economic considerations are not the main factors in aqueous reprocessing. To some extent, even the necessity of reprocessing is somewhat questionable. Other considerations such as policy and programmes, have been advanced. When hearing this I cannot help feeling that it is, on a small scale, rather similar to what happens on a much larger scale in armament questions: everybody knows that it may not be necessary, nevertheless nobody dares not to do it." [*99*]

Despite these indications, the public UK position was that the fast breeder programme was imminent and that plutonium separation was required to fuel the programme. For example, Hughes of the UKAEA commented that:

"We have no doubt whatsoever that, as far as the new separation plant at Windscale is concerned, the processing of 5 tons/day fuel, producing approximately 3 tons of plutonium, is going to be economic. I wouldn't like to quote off the cuff the estimated cost of manufacture of plutonium at this stage, but I will say that our main worries in Britain are that we will not have enough plutonium to satisfy our needs. It is anticipated that we will build a plutonium-burning prototype fast reactor, which - again, we hope - will be the father of another series of reactors for electrical generation in Britain. The initial reactor, details of which are not yet finalized, should be commissioned by the early 1970's. I have no doubt that, as in the past with other reactor systems, it will be a success, and that by the mid-1970's electrical generation by the Central Electricity Generating Board will be undertaken, and then the plutonium that has been accumulated in the intervening period between mid-1965 and mid-1975 will indeed be barely adequate to meet our needs." [*100*]

Thus in 1964, Warner of the UK Atomic Energy Authority pronounced:

"In 1955, the United Kingdom initiated a major nuclear power programme ... The programme was to be the first phase of a balanced power system of thermal and fast reactors in which plutonium, from the first generation of Magnox reactors, would be used in the fast reactors."

"A new reprocessing plant was essential in this cycle because the projected arisings of irradiated fuel exceeded the capacity of the first separation plant at Windscale." [*101*]

---

99 D'Hont in Culler (1963) p454
100 Hughes in Culler (1963) pp 443-4
101 Warner (1964) p224

3.3.2. The Onset of Oxide Reprocessing

Within a year of the run down of the first separation plant, the UKAEA were planning to restart it for the reprocessing of "oxide" fuel. The fuel used in the military reactors and in nuclear power stations built in the first nuclear power programme used uranium metal. However, the nuclear power stations from the second programme and also many of the overseas nuclear reactors used uranium oxide rather than uranium metal as the fuel. This new fuel type introduces complications to reprocessing as the fuel rods require elaborate mechanical treatment and the fuel contains more radioactivity.

In November 1964, a paper was prepared for the Atomic Energy Executive, entitled "Reprocessing Plant for Oxide Fuel Elements". [*102*] It was proposed to use the first plant, which was fully depreciated, and it was anticipated that investment of £1.5M would yield a facility capable of handling 300 te/year oxide fuel. [*103*] Essentially it was proposed to provide equipment in which all known types of oxide fuel could be cut into small pieces and dissolved in nitric acid. [*104*] The acid solution of dissolved spent fuel was to be sent through one cycle of solvent extraction within the old plant before it was sent to the second solvent extraction plant which had just been built. [*105*] In December 1964, the Atomic Energy Authority approved initial expenditure on the conversion of the first separation plant for oxide reprocessing [*106*] and in August 1969 the commissioning of the converted plant, known as the 'Head End' plant was completed. [*107*]

---

102 Tuohy (1964)
103 Tuohy (1964) p1
104 Tuohy (1964) p2
105 Tuohy (1964) Appendix I p2
106 Hill (1965) p1
107 Hudson (1990) p19

3.3.2.1. The Need for Oxide Reprocessing

As for the second reprocessing plant, the need for the plant conversion to allow oxide reprocessing was clearly questionable at a very early stage. The White Paper produced in 1964, to announce the oxide nuclear power programme, acknowledged that the plutonium credit had been reduced. [*108*] This meant that the relative cost of nuclear power had risen since 1955. [*109*] Consequently, nuclear power was not competitive with conventional power as was previously thought. [*110*] This reduction in the plutonium credit had the further effect of diminishing the putative economic justification for reprocessing. However, reprocessing policy was already firmly inculcated [*111*] and it had long been assumed that fuel from the oxide programme would be reprocessed. [*112*] [*113*]

In 1964, it was reported that Windscale would be reprocessing all UK spent fuel from the nuclear power programme [*114*] and that addition of the converted oxide plant would allow the reprocessing of fuel from any kind of reactor. [*115*] In 1965, the Windscale Local Liaison Committee were told that:

> "Whatever types of reactors are built in this country, the spent fuel from them will be processed at Windscale." [*116*]

The economic case put forward for the reprocessing of oxide fuel was tenuous. For example, a paper prepared by the Atomic Energy Authority in 1964 commented that:

---

108 Cmnd. 2335 (1964) p2
109 Cmnd. 2335 (1964) p2
110 Cmnd. 2335 (1964) p2
111 CEGB (1965) p8
112 Warner (1964) p230
113 Windscale LLC (1960) p3
114 Windscale LLC (1964) p4
115 Windscale LLC (1964) p4
116 Windscale LLC (1965) p3

"In examining the provision of a Head-End Plant as a business proposition, the Reactor Group, although part of the Authority, should be looked upon as a potential customer, in that irradiated fuel will arise from the [Authority's oxide fuelled reactors, the] W.A.G.R. and [the] S.G.H.W. and there is a good case for reprocessing this fuel to recover U235 and plutonium, provided a price can be quoted which is less than the current market value of these materials. ... even if nil value is given to the plutonium, it is reasonable to consider the interest charges that would accrue on the U235 content of W.A.G.R. fuel, amounting to £280,000 in the period from 1968 to 1972, and to offset this charge against the cost of reprocessing." [*117*] [*118*]

3.3.2.2. The Storage Option

Storage offers a considerably cheaper option for spent fuel management than reprocessing. Moreover, storage is flexible as it allows the possibility of reprocessing at some later stage [*119*] if it should prove to become economic. In 1963, a strategy of storage rather than reprocessing was already being considered within the nuclear industry abroad. [*120*] If fuel is reprocessed before the separated plutonium and uranium are required, the capital cost of the reprocessing plant is incurred earlier than is necessary. The delay achieved by storage reduces the capital charge per tonne of fuel and thus the cost of the products if the stored fuel is eventually reprocessed. [*121*] This effect is increased if the reprocessing which is undertaken prematurely is on a small scale. [*122*] The amount of spent oxide fuel arising in the UK was not expected to be significant until 1972. [*123*] Prior to that, only modest arisings of oxide fuel (from the Windscale AGR and the Winfrith Steam Generating Heavy Water Reactor (SGHW)) were expected. [*124*] Thus, in 1964, it was noted that:

---

117 Tuohy (1964) p3
118 Square brackets '[...]' in the text of a quote denote text which is added for clarification and is not part of the original quote.
119 Health and Safety Commission (1993) p6
120 Aikin in Culler (1963) p445
121 Tuohy (1964) p3
122 Tuohy (1964) p3
123 Tuohy (1964) p1
124 Tuohy (1964) p1

"Unless there is a very pressing need for early recovery of 1.6% U235 in discharged W.A.G.R. fuel, or of the plutonium in discharged W.A.G.R. and S.G.H.W. fuel, there is no case based on the United Kingdom programme alone for providing an oxide fuel reprocessing plant before 1972. There is ample pond capacity at Windscale and Winfrith to store all discharged irradiated fuel in the interim period. Any delay in the implementation of the civil oxide fuelled reactor programme introduces a corresponding delay in the need for a fuel reprocessing plant." [*125*]

3.3.2.3. Commercial Considerations

Although it was already quite apparent as early as 1964 that there was no compelling economic argument for the immediate reprocessing of UK fuel, the prospect of obtaining foreign reprocessing contracts introduced an additional set of considerations. It was felt that it was important to establish the Authority in the oxide fuel reprocessing business [*126*] and that facilities for oxide reprocessing should be provided as early as was possible, ie by 1968. [*127*] It was concluded that:

"An oxide fuel reprocessing plant built to operate prior to 1972 can only be justified on the basis of obtaining sufficient overseas reprocessing business to make it a sound economic proposition." [*128*]

However, it was argued that oxide reprocessing capacity:

"should be provided as soon as possible to give the Authority early entry into the European market, which is of high potential profitability." [*129*]

Establishment of oxide reprocessing would improve the job prospects at the Windscale site. In 1961, the number of people employed at Windscale had peaked at 5000 and had steadily reduced in the following years. [*130*] In 1962, the Windscale Local Liaison Committee were warned that due to the reduction in

---

125 Tuohy (1964) p1
126 Tuohy (1964) p1
127 Tuohy (1964) p4
128 Tuohy (1964) p1
129 Tuohy (1964) p1
130 Windscale LLC (1972) p5

reprocessing requirements the amount of production work throughout the works would be on a reduced scale for a number of years. [*131*] It had already been necessary to redeploy staff and there were no prospects of new plants coming to the site. [*132*] The problem was magnified by the fact that the second plant had been specifically designed to reduce staffing requirements. A number of processes which had previously been carried out in separate buildings were grouped together in the second plant, and extensive use was made of automatic equipment and centralized control. [*133*] As a result, although the throughput of second plant was substantially increased, the requirements for operating and maintenance personnel were halved. [*134*]

Employment prospects were also a consideration for UKAEA professional staff. For example, Hughes commented at a 1963 Symposium:

> "it was said that the first question that would be debated was whether processing of nuclear fuel was an economic proposition or not - I was very much afraid that the Symposium might in fact recommend that we stopped processing, and this would put me ... an expert without a job." [*135*]

If the reprocessing of oxide fuel in the 'Head End' plant did go ahead, employment prospects would be improved. In 1963, the Windscale Local Liaison Committee was informed:

> "At the present time the Authority is offering to process fuels from European Reactors, and the development of the head-end plant for the dissolution of these advanced oxide fuels is proceeding. ... [however] it would be most unwise to generate a feeling of excessive optimism with regard to the future of Windscale". [*136*]

---

131 Windscale LLC (1962) p3
132 Windscale LLC (1962) p3
133 Corns (1964) p239
134 Corns (1964) p239
135 Hughes in Culler (1963) p443
136 Windscale LLC (1963) p4

In November 1964, a contract worth several million pounds for the reprocessing of Italian Magnox fuel was signed. [*137*] The Local Liaison Committee was told:

> "the unique capacity of this Works to extract plutonium from irradiated fuel elements offered the opportunity to make it a sound commercial unit in the future." [*138*]

3.3.2.4. Timing

In 1965, the commercial opportunities for oxide reprocessing did not look as strong as they had twelve months previously. An expected letter of intent was not yet forthcoming and the case for the conversion of the first plant to enable it to deal with oxide fuel required reconsideration. [*139*] The overseas commercial position was difficult to judge. [*140*] However, it was remarked that the reprocessing business had been one the Authority's most profitable overseas activities in recent years [*141*] and that the potential for overseas oxide reprocessing contracts was good if it was possible to offer the service at the same time as competitors. [*142*] It was felt that quite modest commercial success would be very profitable as a particularly high proportion of the costs were fixed. [*143*]

Interestingly, in the light of the reconsideration of the potential for overseas contracts for the converted plant, the arguments concerning the timing of the requirement for reprocessing of UK fuel were revised. Although the Head End plant was first conceived for overseas fuel [*144*] in 1965 it was argued that:

---

137 Windscale LLC (1964) p4
138 Windscale LLC (1964) p5
139 Hill (1965) p1
140 Hill (1965) p4
141 Hill (1965) p2
142 Hill (1965) p2
143 Hill (1965) p4
144 Warner (1966) p2

"The head end treatment plant will be an essential part of the fuel cycle for the Windscale A.G.R., the Winfrith S.G.H.W. and, most important, the second civil nuclear power programme, of which Dungeness B is the first station. The necessity for the plant cannot be in doubt, the only question is one of timing." [*145*]

"Twelve months ago it was thought that leaving the fuel from the Windscale A.G.R. and the Winfrith S.G.H.W. unprocessed until 1972 would have negligible effect on the supply and demand position for plutonium and U.235. Changes that have taken place in the last twelve months indicate that this is no longer true. ... it is important that all enriched uranium fuel be reprocessed as rapidly as possible for the recovery and re-use of unburnt U.235." [*146*]

The early start of oxide reprocessing, before it was definitely needed, which was advocated in 1964, would cost an additional £400 000 due to the interest charges and depreciation allowance. [*147*] However, in January 1966 the AEA supported the commercial judgement of the Production Group that the construction of facilities for oxide reprocessing should proceed forthwith. [*148*] The minutes recorded that:

"It might not be easy to establish the case with the Treasury, but he [Sir Alan Hitchman] did not think they could in the last resort ignore the considered commercial judgement of the Authority." [*149*]

3.3.3. The THORP Proposal

Following this endorsement of the Authority's first foray into oxide reprocessing, consideration of the longer term prospects were immediately undertaken. In 1966 a paper entitled: "The Future Pattern of Reprocessing at Windscale" [*150*] was presented to the Production Group Technical Committee. [*151*] It was considered that:

---

145 Hill (1965) p2
146 Hill (1965) p3
147 Hill (1965) p4
148 Atomic Energy Authority (1966) p3
149 Atomic Energy Authority (1966) p3
150 Warner (1966)
151 Production Group Technical Committee (1966) p2

"The Dungeness 'B' reactor tenders indicate the competitiveness of nuclear power over conventional electrical generation and have led to the certainty that nuclear power will increase rapidly in the near future." [*152*]

"There would seem no doubt that C.F.R. [the Commercial-scale Fast Reactor] is likely to be competitive with thermal reactor systems and it is probable that from 1980 onwards nuclear power investment will largely be in the C.F.R. field" [*153*]

"Against this fluid background it is difficult to make a long term prediction of the reprocessing requirements at Windscale, but, on the other hand, it should be borne in mind that, from the initiation of development to the commissioning of a major separation complex, a period of some eight years is usual" [*154*]

It was anticipated that investment in fast breeder reactors could be limited due to the availability of plutonium. [*155*] The Production Group Technical Committee concluded that:

"the rapid rise in plutonium throughput in the early 1980's implied an increasing dependence of the national power programme on reprocessed fuel. Under such circumstances the U.K.A.E.A. would be seriously criticised if deliveries of fuel to a reactor were delayed during the commissioning of a new plant." [*156*]

It was considered that the oxide processing capacity of the newly converted first separation plant would be exceeded between 1973 and 1974 [*157*] and that even with expansion of this plant [*158*]:

"it would appear pretty certain that we are facing a new Separation complex in the late seventies." [*159*]

---

152 Warner (1966) p1
153 Warner (1966) p1
154 Warner (1966) p1
155 Warner (1966) p6
156 Production Group Technical Committee (1966) p4
157 Warner (1966) p2
158 Warner (1966) p3
159 Warner (1966) p3

3.3.3.1. Choice of Technology

Given the magnitude of the investment that would be required if a third reprocessing plant were built, in 1966 a design study was initiated in order to identify the optimum technology for the new plant. It was commented that:

> "As the types of process chosen for the next reprocessing complex will commit a large sum of money to a plant designed to last for at least 20 years, we cannot afford to take a superficial view in our choice of process, nor can we afford the liberal approach of the Americans in covering all possible technological approaches in the laboratory. We therefore propose that the design study will be done thoroughly to enable us confidently to make the decision for the new plant". [*160*]

A two to three year study was proposed [*161*] to consider alternative processes for the reprocessing of fuel, ranging from the conversion of the uranium and plutonium into volatile fluorides, [*162*] to the extraction of the fuel by molten salts or molten metals. [*163*] It was noted that:

> "Enough has been said ... to indicate the complexity of the problem ... There can be no hope at this time of providing a firm policy line." [*164*]

However, given the previous experience in solvent extraction technology it was unlikely that the study would recommend adoption of a new technology for THORP. In 1968, it was decided to continue with established technology for the new plant. A completely novel process would have to bear either development charges or the cost of purchasing new technology. [*165*] Moreover the UKAEA had considerable knowledge and experience of solvent extraction and an alternative process would have had to show very substantial technical and economic advantages to justify adoption. [*166*] In September 1968, the committee concluded that there was no evidence to indicate that a different

---

160 Warner (1966) p8
161 Warner (1966) pp 3,6
162 Warner (1966) p7
163 Warner (1966) p8
164 Warner (1966) p3
165 Production Group Technical Committee (1966) p4
166 Production Group Technical Committee (1966) p4

technology would be required for the THORP plant [*167*] and by this time a solvent extraction flowsheet for the conceptual plant had already been drawn up. [*168*]

3.3.3.2. Commercial Considerations

During the late 1960s work continued to build up the order book for reprocessing of overseas fuel. The reprocessing of Italian Magnox fuel was begun during 1966. [*169*] By 1967, a bid had been made for the reprocessing of Japanese Magnox fuel, [*170*] and the contract was obtained by 1968. [*171*] In 1966, it was considered that contracts could also be obtained for the reprocessing of oxide fuel from overseas reactors as a result of the commercial initiatives which were being undertaken in Europe. [*172*] It was estimated that by 1973 the amount of foreign oxide fuel to be reprocessed would be about 50 te/y. [*173*] By 1980, an even larger throughput was anticipated. [*174*] In September 1968, it was reported that the overseas order book for overseas oxide fuel reprocessing had begun to fill and that there was the prospect for a substantial order for fuel reprocessing in the period 1972/77. [*175*] It was considered that if this order was obtained THORP might be required for 1976. [*176*]

In October 1968, orders had been received for the reprocessing of oxide fuel from Italy, Canada and Switzerland [*177*] and in 1970 it was reported that contracts for

---

167 Production Group Technical Committee (1968) p6
168 Tatlock (1968) p2
169 Windscale LLC (1966) p3
170 Windscale LLC (1967) p2
171 Windscale LLC (1968) p2
172 Warner (1966) p1
173 Warner (1966) p1
174 Warner (1966) p1
175 Tatlock (1968) p2
176 Tatlock (1968) p4
177 Windscale LLC (1968) p2

oxide reprocessing had been obtained from Italy, Sweden, Spain, Switzerland and other countries. [*178*] In 1971, BNFL was established. The Windscale Local Liaison Committee was informed that:

> "The industry is developing to meet the fuel requirements for reactors anywhere in the world. There is a potentially large market to be tapped and won. In order to meet the new situation the former Production Group of the UKAEA is now established as British Nuclear Fuels Limited, the changeover having occurred on 1 April 1971. ... The establishment of the new Company would enable the Works to compete on improved terms in competition with organisations overseas, in the export market." [*179*]

3.3.4. Head End Expansion

In December 1966, the Production Group Technical Committee concluded that the requirement for THORP could be postponed to 1978 by expanding the capacity of the Head End plant. [*180*] In September 1968, it was noted that delaying the construction of THORP would save £1M/year for each year of delay as well as allowing further time for THORP design and development. [*181*] The actual timing of the requirement for the Head End Expansion and for THORP construction depended markedly on the extent of the reprocessing business secured. [*182*] In 1968, it was predicted that, if an expected order was forthcoming, Head End expansion could be required by 1973. [*183*] It was also calculated that the THORP would be needed in 1979, when plutonium demand would exceed supply. [*184*]

In 1969, the position was more cautious, and it was stated that:

---

178 Windscale LLC (1970) 19 November 1970, p2
179 Windscale LLC (1971) p3
180 Production Group Technical Committee (1966) p3
181 Production Group Technical Committee (1968) p4
182 Production Group Technical Committee (1968) p4
183 Tatlock (1968) p4
184 Tatlock (1968) p2

"With the uncertain position on commercial business, and with the lack of knowledge of the next stage of the domestic nuclear programme, it would be very difficult to justify such a C.E.P. [Capital Expenditure Programme for Head End extension] on present information. ... The Working Party is strongly of the opinion that before a decision to prepare a C.E.P. for a second head end plant is made, an economic evaluation should be carried out by the Commercial Branch, to examine the expected return on invested capital arising from anticipated future business. Since the cost of a new head end plant is likely to be about £2M, it is important to decide whether future business expectations will support such investment." [*185*]

However, in 1972, the attitude to the potential for further contracts had significantly changed. [*186*] A capital expenditure proposal for Head End Expansion was submitted to the BNFL Board of Directors [*187*] and on 23 February 1972 the proposal was endorsed. [*188*] The alterations were due to be completed by January 1975 [*189*] and the total cost of the planned work was estimated to be £3.7M. [*190*]

Two main limitations to the potential for the expansion of current facilities were recognised. Firstly the logistical problems attached to refurbishment [*191*] [*192*] [*193*], and secondly the plutonium clearance for the Magnox plant. After treatment in the Head End plant, oxide fuel was sent through the Magnox reprocessing building. When the Magnox plant was originally designed, it was recognised that safeguards had to be introduced in order to prevent a critical accumulation of plutonium [*194*] which would give rise to very high gamma and neutron radiation fields. [*195*] Due to the large volumes going through the plant it was impossible to use all geometrically safe equipment (equipment which is of such a shape and size that criticality could never occur). [*196*] Instead, the object

185 Buck (1969) pp 5-6
186 Franklin (1972) p4
187 Franklin (1972) p1
188 BNFL Board of Directors (1972) p6
189 Franklin (1972) p2
190 Franklin (1972) p3
191 Warner (1966) p3
192 Production Group Technical Committee (1968) p4
193 Buck (1969) p5
194 Windscale LLC (1962) p6
195 Windscale LLC (1962) p6
196 Windscale LLC (1962) p6

was to ensure by sophisticated instrumentation, that plutonium concentrations would never reach a dangerous level. [*197*] The design throughput of the second plant was 10 kg Pu/day. [*198*] In 1966, after pilot plant trials, clearance for 25 kg Pu/day was given [*199*] and it was proposed that clearance could be increased to 35 kg Pu/day after modification. [*200*] Without modification, it was predicted that, in 1978, plutonium clearance would become the limiting factor on plant throughput. [*201*] However, in 1968 the clearance had reduced to 12.5 kg Pu/day [*202*] and in 1970 major modifications requiring prolonged shut-down became necessary due to the increasing plutonium throughput. [*203*]

When it was decided in 1972, to go ahead with Head End expansion, it was noted that:

> "The proposal is mainly concerned with the provision of plant similar in design and construction to that already installed ... It should therefore have little associated technical risk." [*204*]

3.3.5. The Abandonment of Oxide Reprocessing

On 26 September 1973, oxide reprocessing was abandoned when radioactive gas escaped into the working area of the Head End plant and contaminated the workers. Clean-out of the plant during shut-down had failed to remove intensely radioactive solids [*205*] from the process vessels. [*206*] The heat generated from these solids produced temperatures of up to hundreds of degrees centigrade. [*207*]

---

197 Windscale LLC (1962) p6
198 Tatlock (1968) p3
199 Warner (1966) p2
200 Warner (1966) p2
201 Warner (1966) p3
202 Tatlock (1968) p3
203 Windscale LLC (1970) 19 November 1970, p2
204 Franklin (1972) p1
205 Cmnd. 5703 (1974) p6
206 Windscale LLC (1974) p2
207 Cmnd. 5703 (1974) p8

During recharge of the plant acidified solvent came into contact with the radioactive solids and reacted to produce a chemically explosive mixture. [*208*] [*209*] [*210*] Radioactive gas was released into the working area and all 35 men working in the building became contaminated. [*211*] BNFL has reprocessed no oxide fuel since this accident. [*212*] [*213*]

3.3.6. Plans for THORP

Just nine days after the shut down of the Head End plant, BNFL's Oxide Fuel Reprocessing Working party met to discuss the provision of new oxide facilities into the 1980s. [*214*] It was proposed that the failed Head End plant, [*215*] which had processed a total of 90t [*216*] of fuel in its four year life, [*217*] should be expanded to allow a reprocessing capacity of 400 te/year. [*218*] This represented an eighteen-fold increase in capacity. In 1974, expansion plans for the abandoned plant were still underway [*219*] and it was proposed to spend £13M to achieve the 400te/y capacity. [*220*] It was feared that even with these modifications BNFL would not be able to meet the expected demand for oxide reprocessing and plans were in hand for three 800-1000 te/y plants to be in operation in the 1980s. [*221*] Dr Franklin commented to the BNFL Board:

> "planning and preparations should go ahead on the assumption that BNFL will be a world-scale fuel reprocessor in the 1980's." [222]

---

208 Cmnd. 5703 (1974) p8
209 Windscale LLC (1974) p2
210 Cmnd. 6618 (1976) p59
211 Cmnd. 5703 (1974) pp 2,8,10
212 Hudson (1990) p19
213 Albright (1993) p95
214 OFRWP (1973) p2
215 OFRWP (1973) p5
216 Hudson (1990) p19
217 Cmnd. 5703 (1974) pp 1,2
218 OFRWP (1973) p5
219 Franklin (1974) pp 3,4
220 Franklin (1974) App IV pp 1,2
221 Franklin (1974) p5
222 Franklin (1974) p7

BNFL's expansion plans were made public in the winter of 1974/5. [*223*] Following public discussion [*224*] the planning application was called in by Peter Shore, the Secretary of State for the Environment [*225*] [*226*] and became the subject of the Windscale Public Inquiry held from June to November 1977. [*227*] After 100 days of hearings, and consideration of 1,500 documents [*228*] the Inquiry Inspector recommended that BNFL should be granted permission to construct THORP. [*229*]

3.4. SUMMARY

It may be seen that the 'decision' to build THORP emerged over time. [*230*] Reprocessing was established in the UK, following the development of plutonium separation during the Second World War in the United States. The onset of British military reprocessing in the 1950s, was followed by the construction of a very similar plant to reprocess fuel from nuclear power stations. When the second phase of the UK nuclear power programme was announced in 1964, it was decided to convert the military reprocessing plant to handle the new 'oxide' fuel that would be produced. It was already clear by this time that there was no pressing economic requirement for the uranium and plutonium produced from reprocessing. Despite this, due to the possibility of obtaining foreign reprocessing

---

223 BNFL (1977) p2
224 BNFL (1977) p2
225 BNFL (1977) p3
226 Pearce (1979) p227
227 Parker (1978) vol I, p1
228 Parker (1978) vol I, p1
229 Parker (1978) vol I, p83
230 Parallels may be drawn between the stepwise emergence of the THORP decision and incrementalism. This supports Lindblom's hypothesis that decision makers do not actually use the synoptic approach. [Braybrooke (1970) p23] However, due to the lack of genuine partisan involvement in the Windscale decision [see for example Williams (1980) pp 315-327] and the lack of flexibility in the THORP proposal, the decision to build THORP was not incremental in the Lindblom sense.

contracts, ambitious expansion plans were drawn up. Oxide reprocessing was abandoned in 1973, following an accident. However, by this time considerable work had been undertaken to obtain foreign reprocessing contracts, and to develop plans for the large new oxide plant that became known as THORP: which was the subject of the Windscale Public Inquiry in 1977.

The historical development of the decision to build THORP, which has been traced in this chapter, supports the conclusion of Wynne (1980) that the Windscale Inquiry was a legitimation exercise to:

> "sanctify a decision already determined by well-buttressed assumptions and commitments". [*231*]

Given that the decision to build THORP was effectively determined prior to the Windscale Public Inquiry, the use of the Windscale Inquiry as a test of the synoptic method is not robust. However, lessons from this case study may be used in order to ensure that the conclusions drawn from the second case study are robust. In order to allow robust conclusions to be drawn concerning the viability of the synoptic method, an approach must be developed such that the conclusions drawn are valid, whether or not the synoptic method was actually applied to the decision taken. In the following chapter the methodology developed in order to achieve this objective is outlined, and the second case study is introduced.

---

231 Wynne (1980) p166

4. SAFETY ASSESSMENT OF NUCLEAR WASTE DISPOSAL

4.1. INTRODUCTION

In the previous chapter, it was concluded that in order to provide a robust test of Lindblom's hypothesis that the synoptic approach decision making is not achievable, a methodology must be developed such that the conclusions drawn are valid, whether or not the synoptic method is actually applied to the decision examined in the case study. In this chapter the methodology developed, using lessons drawn from the first case study, is outlined, and the second case study is introduced.

4.2. THE METHODOLOGY APPLIED TO THE SECOND CASE STUDY

In the previous case study it was concluded that a methodology was required that allowed robust conclusions to be drawn, despite the ambiguity introduced by the political constraints faced by decision makers. The evaluation of the synoptic method, through the evaluation of a decision that was ostensibly made using the synoptic method, is open to the criticism that the synoptic method was actually peripheral to the decision making process, and was not actually ***applied*** to the decision taken. Therefore, the critical importance of developing a methodology that would allow robust conclusions to be drawn, despite the ambiguous role of the synoptic method, was highlighted.

In the second case study this objective is achieved through the direct evaluation of the viability of adopting the synoptic method. Evaluation of the viability of the method, rather than evaluation of the success or otherwise of a decision overtly taken using the method, allows Lindblom's hypothesis to be tested directly, and therefore is robust to the criticism outlined above. In this case study, the viability of the synoptic method is evaluated through the analysis of the Nirex safety assessment of the behaviour of nuclear waste in a repository.

4.2.1. The Nirex Case Study

Nirex, the Nuclear Industry Radioactive Waste Executive, propose to dispose of nuclear waste in an underground repository. In order to obtain regulatory approval to dispose of nuclear waste, Nirex are required to prepare a radiological safety assessment of the long term behaviour of the disposed waste. This requirement is equivalent to the third stage of the synoptic method which requires the exhaustive examination of the consequences of a proposed policy. In order for the synoptic method to offer the decision maker a viable approach to decision making, each one of the four stages must be achievable. Under Lindblom's hypothesis, it is predicted that, due to the overwhelming information demands of the synoptic method, the safety assessment work undertaken by Nirex will fail to provide a cogent analysis of the radiological safety of the proposed disposal facility. The analysis of the cogency of the safety assessment, independently of the decisions taken concerning nuclear waste disposal, overcomes the problem highlighted in the first case study. It is in Nirex's interest to prepare a safety assessment which is cogent, comprehensive and coherent and they are spending £6 million per year on a research programme involving 14 universities and 11 other research organisations. [*1*] In the following sections of this chapter the origin of the regulatory requirement for a quantitative assessment of the risks attached to disposal is traced and the techniques adopted in order to achieve the task are considered. The value of such an assessment is also discussed.

4.3. THE REQUIREMENT FOR A SAFETY ASSESSMENT

4.3.1. The International Development of Regulatory Criteria

The development of rigorous quantitative regulatory criteria in the UK for radioactive waste disposal has originated from international work undertaken within the last ten years. Publications from international organisations on radiological protection objectives specifically concerning the disposal of solid radioactive wastes did not appear until the early 1980s. [*2*] In 1983, the International Atomic Energy Agency (IAEA) published "Criteria for Underground Disposal of Solid Radioactive Wastes" (Safety Series No. 60). The purpose of the document was to provide a set of basic requirements and criteria for underground disposal of radioactive wastes. [*3*] This could be used by national regulatory authorities to develop their own specific national standards. [*4*]

The report noted that:

> "Recent efforts in this field have led to general agreement that underground disposal, with the wastes appropriately immobilized and isolated, can provide adequate protection for man and his environment." [*5*]

---

1 Nirex (1992) Safety Assessment
2 Hill (1990) p72
3 IAEA (1983) Criteria for Underground Disposal, pp 1-2
4 IAEA (1983) Criteria for Underground Disposal, pp 1-2
5 IAEA (1983) Criteria for Underground Disposal, Foreword

However, support for disposal was qualified by the requirement that the disposal option selected should be able to ensure that there would be no "unacceptable" [*6*] radiological impact. Thus, the report noted that:

> "It is essential, (therefore), in disposing of radioactive wastes, to ensure that radionuclides from the wastes will not reach the human environment in concentrations or quantities that could result in an unacceptable detriment at present or in the future." [*7*]

At that stage there was no agreement on the best method of expressing the consequence of migration of radionuclides from a repository. The use of the dose measurement alone was felt to be inadequate as it was felt that the probability of exposure should also be considered. [*8*] The issue was under active discussion when the report was published [*9*] and therefore the report did not contain any numerical radiological protection criteria. [*10*] However, the report introduced, at an international level, the idea that the probability that doses will be received needs to be considered when setting criteria. [*11*] It was suggested that:

> "One *straightforward* method by which this can be done is to incorporate the probabilities directly in the calculation of the performance of the disposal system and compare the result with a limit for the individual risk." (My emphasis) [*12*]

Other significant international publications produced at that time included reports by the World Health Organisation (WHO), [*13*] the Nuclear Energy Agency of the Organisation for Economic Cooperation and Development (OECD), [*14*] and the International Commission on Radiological Protection (ICRP). [*15*]

---

6 IAEA (1983) Criteria for Underground Disposal, p1
7 IAEA (1983) Criteria for Underground Disposal, p1
8 IAEA (1983) Criteria for Underground Disposal, p2
9 IAEA (1983) Criteria for Underground Disposal, p2
10 Hill (1990) p73
11 Hill (1990) p73
12 IAEA (1983) Criteria for Underground Disposal, p12
13 World Health Organisation (1982)
14 Nuclear Energy Agency (1984)
15 ICRP (1985)

The recommendations of the WHO report were largely in line with those of the IAEA report. [*16*] It recommended that the acceptability of waste disposal methods should be determined on the basis of the effect of predicted doses taking into account the probability that the dose will be incurred. [*17*] The main difference between the NEA report and those of the WHO and the IAEA were the scope and the level of detail. [*18*] The NEA report was considered to represent a "substantial international consensus" which formed the starting point for the ICRP work. [*19*] The group quantified individual risk limits and objectives that were to be "*applied over all time and space*". [*20*] (My emphasis)

The publication of the report: "Radiation Protection Principles for the Disposal of Solid Radioactive Waste" by the ICRP in 1985 was the first time that the Commission had provided explicit guidance on the resolution of the problems involved in assessing long-term radiological impacts of solid radioactive waste disposal and on the interpretation of the results of these assessments for decision making purposes. [*21*] The report considered that models developed from theoretical bases could be used to calculate a "reasonably predictable radiation exposure pattern in space and time." [*22*] In addition, probabilistic events such as flooding, geomorphological changes, human activities and meteorological effects should be taken into account using "best estimates" and "engineering judgements" to assess their probability of occurrence. [*23*] The report noted that:

> "Any assessment of radiation impact from radioactive waste disposal is subject to uncertainty. Within the overall uncertainty of the assessment, several different classes of uncertainty will be usually be present. These include not only the conventional uncertainties associated with an imperfect knowledge of the parameters used in the assessment and the appropriateness of the models, but also intrinsic uncertainties resulting

---

16 Hill (1990) p73
17 Hill (1990) p73
18 Hill (1990) p73
19 Hill (1990) p73
20 Hill (1990) p74
21 ICRP (1985) pp 1-2
22 ICRP (1985) p5
23 ICRP (1985) pp 5-6

from the statistical treatment of the variables, however certain they may be. Uncertainties due to things that are unknowable about the future and an imperfect knowledge of events affecting disposal site integrity and pathways are examples of conventional uncertainties. while the uncertainty in the expected outcome from low probability events is intrinsic. Whether the predicted impacts arise as a result of the normal release mechanisms or from disruptive events, there will always be uncertainty in the estimated radiation impact, because present knowledge of future conditions cannot be complete." [*24*]

Despite this caveat, on the extent of the uncertainties, the report provided quantitative guidance on limits that should be laid down for licensing of radioactive disposal sites. [*25*] The ICRP recommended that a dose limit of 1 mSv y^{-1} should apply for normal gradual processes which could be predicted, and an individual risk limit of 10^{-5} y^{-1} [*26*] should be applied for probabilistic events which were subject to greater uncertainty.

4.3.2. The Development of Regulatory Criteria in the UK

Early UK policy on disposal specified a numerical limit for the impact of disposal operations, but did not specify a rigorous requirement for calculations that would demonstrate that the limit would be adhered to. In 1959, the White Paper 'The Control of Radioactive Wastes' (Cmnd 884) [*27*] was published. The report noted that for radioactive wastes:

"the need to minimise the genetic damage to future generations, (which) calls for extra precautions as compared with those taken for other wastes and justifies a closer control over their production and disposal. There is a lively public interest and it is essential that this control should be *demonstrably adequate*." [*28*] (My emphasis)

24 ICRP (1985) p6
25 Hill (1990) p74
26 Hill (1990) p74
27 Cmnd. 884 (1959)
28 Cmnd. 884 (1959) p32

> "Having rejected the view that waste disposal should involve no irradiation of the public, we have to consider very carefully how much is permissible." [*29*]

The paper recommended that no individual should receive a dose greater than one-tenth of the ICRP level and that the whole population should not receive a dose greater than one rem per person in thirty years. [*30*] Specifically for land disposal the report recommended that:

> "the burial site should be carefully chosen so that there is no possibility of contamination of underground water supplies. Burial should be deep enough so that crops harvested nearby or on the land in future are not contaminated and so that excavation, e.g., for housing, will not disturb the active materials." [*31*]

The Radioactive Substances Act 1960 implemented the recommendations in Cmnd 884 and provided the first comprehensive and specific powers in relation to radioactive waste. [*32*] Twenty years later in 1979, a review of the 1959 White Paper was published. [*33*] This report strongly supported a policy of waste disposal [*34*] and endorsed the practice of basing the standards for radiological protection on the ICRP dose limitation standards. [*35*]

In 1984, the Department of the Environment (DoE) published the report: "Disposal Facilities on Land for Low and Intermediate-Level Radioactive Wastes: Principles for the Protection of the Human Environment". [*36*] This introduced the requirement for a rigorous assessment of the radiological impact of a disposal facility. The document contained the principles that the relevant Departments proposed to apply in considering whether authorisation should be given for a

---

29 Cmnd. 884 (1959) p33
30 Cmnd. 884 (1959) p34
31 Cmnd. 884 (1959) p37
32 Department of the Environment (1979) p28
33 Department of the Environment (1979)
34 Department of the Environment (1979) pp 109,116
35 Department of the Environment (1979) p113
36 Department of the Environment (1984)

proposed disposal facility for low and intermediate-level wastes under the Radioactive Substances Act 1960. [*37*] The report stated that:

> "Authorising Departments will require that proposals for a facility should include quantitative estimates of the activity likely to be released from the radioactive material and should describe how the various components of the facility act to limit its radiological impact." [*38*]

The report commented that:

> "there are uncertainties in predicting the exposures which could occur in the far future because population distributions and human habits may change in ways which cannot be foreseen. Recommendations to deal with the situation have been received from IAEA [*39*] and the Nuclear Energy Agency (NEA) [*40*] of the Organisation for Economic Co-operation and Development and have been taken into account." [*41*]

The report stipulated that the criteria used for assessment should not be based on dose, but on risk where the risk was defined as:

> "the probability that a given dose will be received multiplied by the probability that such a dose will result in a fatal cancer." [*42*]

The risk limit chosen was that associated with a dose of 1 mSv. However, in order to take account of health effects and exposure pathways not recognised at that time, and to avoid prejudicing future proposals that may expose the same population to radiation exposure, an additional margin of safety was included. The report concluded that:

> "The appropriate target applicable to a single repository at any time is, therefore, a risk to an individual in a year equivalent to that associated with a dose of 0.1 mSv: about 1 chance in a million." [*43*]

---

37 Department of the Environment (1984) p1
38 Department of the Environment (1984) p11
39 IAEA (1983) Criteria for Underground Disposal
40 Nuclear Energy Agency (1984)
41 Department of the Environment (1984) p12
42 Department of the Environment (1984) p14
43 Department of the Environment (1984) p14

In order to establish a case for a proposal to develop a waste disposal facility the developer must show: "that the radiological impact of disposal has been thoroughly assessed". [*44*] Information that the authorising departments will require from the developer will include:

> "results from the application of mathematical models used to predict radiological impacts using data on the wastes, the facility design and the site properties .. [and] .. comprehensive radiological assessments which should include:
>
> 55.1.1 an explanation of how the basic radiological requirements and general principles ... are met; [and]
>
> 55.1.2 an analysis of the probability that the facility might be disrupted by discrete external events." [*45*]

This change from the original numerical limit prescribed in 1959 with the simple proviso that the disposal option should be 'demonstrably adequate' to the explicit demand for a rigorous quantitative assessment of safety has imposed a significant demand on the nuclear industry.

4.4. SAFETY ASSESSMENTS

The provision of safety cases to meet regulatory requirements has three main stages. Firstly 'scenarios' which represent a computerised prediction of the behaviour of the facility are developed. Secondly, values are ascribed to the relevant parameters contained in the scenario, and finally the two are combined to allow the calculation of the radiological impact of the repository. These three stages are discussed below.

---

44 Department of the Environment (1984) p18
45 Department of the Environment (1984) p19

4.4.1. The Development of Scenarios

In order to assess the long-term, post closure, radiological safety of a repository a "scientific understanding of the behaviour of the facility, its environs and its radioactive contents over a timescale of many thousands of years" is required. [*46*]

In performance assessments predictions of repository behaviour are encoded into numerical algorithms, or 'mathematical models'. Different sets of models describe different possible global environments that could determine the future evolution of the repository. The boundary conditions are normally referred to as scenarios. [*47*] In order to generate a mathematical scenario which is suitable for the assessment programme, a conceptual model of the possible behaviour of the repository system is developed, which is then developed into a calculational model, and then into a computer code. [*48*] The basis of scenario development is the compilation of a list of phenomena that are potentially important for the safety of the repository. [*49*] Initially the list should be comprehensive and should include all imaginable phenomena that could affect repository safety. People with a wide range of interests and expertise should be used in the process in order to avoid:

> "unconscious screening due to the prejudices or lack of imagination of the participants in the identification exercise." [*50*]

The factors that need to be considered in order to ensure comprehensive scenario development are numerous and far-ranging. Natural phenomena that may be important include: extra terrestrial impacts, geological effects, climatological

---

46 Nirex (1989) Deep Repository Project, pH1
47 McCombie (1990) p96
48 McCombie (1990) p97
49 Hodgkinson (1990) p337
50 Hodgkinson (1990) p338

events, geomorphological and hydrological processes, and transport and geochemical and ecological changes. Human activities such as design and construction; operation and closure; and post closure sub-surface and surface activities should be considered. In addition, waste and repository effects including thermal, chemical mechanical and radiological impacts should be incorporated into the scenario development process. Within these broad headings more specific examples of the phenomena to be considered should be included. For example, under the heading of mechanical effects on the waste and the repository, the relevant possibilities would include:

i) Canister or container movement;
ii) Changes in in-situ stress field;
iii)Embrittlement and cracking;
iv) Subsidence/collapse;
v) Fracturing, and
vi) Gas effects (pressurisation, disruption, explosion, fire). [*51*]

Once this list has been produced, it is possible to screen out certain phenomena using criteria such as physical unreasonableness, low likelihood, negligible effect on repository or environment, outside timescale of interest, or outside regulatory interest. However, the possibility that one otherwise unimportant phenomena will become important through interaction with other factors must be borne in mind during the screening process. [*52*]

Once the significant features events and processes have been decided upon it is very difficult to proceed in a structured way from a large number of events and

---

51 Hodgkinson (1990) pp 348-350
52 Hodgkinson (1990) pp 338-339

processes to a small number of representative scenarios. [*53*] Given the "deadlock" [*54*] at this stage a more top-down procedure for scenario formation has been suggested which starts from the end-point and postulates sets of states that could result in this end point. Under this methodology scenario elements based on generic concepts are defined, such as:

Cause	eg. natural phenomena, human activities, repository effects) and
Field of Effect	eg. near-field, far-field, biosphere, or release, transport, exposure

From these, potential scenarios are developed by reference to the list of phenomena. [*55*]

Despite these attempts at systematising the approach to scenario development, the difficulties of making such wide-ranging predictions over all time and space presents significant difficulties. These may be illustrated by the specific example of the human intrusion scenario.

Assessments of human intrusion are seen as an integral part of the overall safety studies for repositories and may be the dominating factor contributing to the overall risk associated with the disposed waste. [*56*] However, Grimwood of BNFL has commented that:

> "Most of man's future does not even exist as a possible thought in the back of our heads. In other words, we are limited in our ability to even imagine

---

53 Hodgkinson (1990) p342
54 Hodgkinson (1990) p342
55 Hodgkinson (1990) pp 342-343
56 Grimwood (1990) pp 385-386

all that may happen in the future and there is a potential for scenarios that we cannot now identify and this has to be recognised." [*57*]

The Government Radioactive Waste Management Advisory Committee (RWMAC) consider that the sum of the contributions from the scenarios will only give a meaningful estimate of risk if the set of scenarios is comprehensive. [*58*] However, the DoE consider that no formal scientific proof can be provided that all possible futures have been considered in an assessment. [*59*] The DoE also consider that under the present *ad hoc* scenario selection methods it will be difficult to demonstrate that the set of scenarios analysed is complete. [*60*]

4.4.1.1. Verification and Validation

The mathematical models used to calculate the long term radiological impact of radioactive waste repositories under each scenario must be verified and validated to ensure that they may be used with confidence. Verification of the model involves checking that the computer model is performing the calculations correctly. [*61*] Validation involves checking that the model is a true representation of the real world. [*62*] Difficulties associated with the verification and validation of the models will be considered below.

i) Verification

RWMAC consider that it is essential that a model is verified if there is to be any confidence in the results. [*63*] The computer code used for the modelling solves a

---

57 Grimwood (1990) p387
58 RWMAC (1990) Safety Assessment Modelling, p17
59 RWMAC (1990) Safety Assessment Modelling, pp 62-63
60 RWMAC (1990) Safety Assessment Modelling, pp 62-63
61 RWMAC (1990) Safety Assessment Modelling, p28
62 RWMAC (1990) Safety Assessment Modelling, p29
63 RWMAC (1990) Safety Assessment Modelling, p28

given set of equations with given inputs by numerical manipulations. In order to properly verify and document the code, it should be established that the code is:

> "mathematically correct in the formulation and solution. and properly documented on its function, accuracy, required discretization and ranges of applicability." [*64*]

Work carried out for the Commission of the European Communities (CEC) to assess the reliability of predictions made using computer codes has indicated that:

> "'human error' is a significant issue affecting the reliability of predictions." [*65*]

Verification of a code is a necessary condition for obtaining an adequate model. but it only implies that the code is mathematically correct, not that it gives a good representation of the natural system. International projects such as INTRACOIN and HYDROCOIN have shown that many codes often miss subtleties. [*66*] Even well posed mathematical problems often give rise to widely different solutions from different teams due to slight variations in the solution methodology or misinterpretations in the formulation. [*67*] In order to establish that the code provides a genuine representation of the natural world the code must be validated.

ii) Validation

Validation remains a key issue facing performance assessment. [*68*] The validation of a model requires:

---

64 Tsang (1990) p709
65 Knowles (1990) pp 749,754
66 Carrera (1990) p483
67 Carrera (1990) p483
68 McCombie (1990) p98

a) Comparison of the model results with experimental results.

b) Evaluation of the procedures for constructing conceptual and calculational models.

c) Evaluation of the methods for studying data and parameter correlation. [*69*]

Part of the validation process involves calibration of the model, in which model results are compared with observed data which the model is designed to simulate. For safety assessment of nuclear waste repositories this inevitably involves the use of short-term data for predictions that span thousands of years into the future. [*70*] Thus, although it may be possible to develop models which are adequate in the short-term by backfitting them on to test data, the extrapolation of these models to long term behaviour (beyond the time scale of the experiment) is unvalidated. [*71*] Work carried out for the DoE has indicated the scale of this problem, thus:

> "timescales of interest are generally decades to millenia and spatial scales are typically metres to kilometres. In contrast, typical experimental timescales are weeks to months and spatial scales may be as little as a few millimetres." [*72*]

The conceptual model used in the assessment includes both structural and process aspects which must both be validated. The structural model refers to the geometric properties of the system such as fracture density, faults, heterogeneity etc; and the process model covers physical and chemical phenomena such as dissolution, precipitation, colloid transport and so on. Therefore, it is possible to describe a particular model as validated with respect to a particular process or to a site specific system. [*73*] There is no such thing as a model validated in the generic sense. [*74*] Moreover, given the uncertainties inherent in natural system

---

69 Tsang (1990) p707
70 Tsang (1990) p709
71 Knowles (1990) p755
72 Laurens (1988) pp 297,299
73 Tsang (1990) p709
74 Tsang (1990) p710

studies complete validation of computational models can rarely, if ever, be achieved. [*75*] One commentator has stated that:

> "Validation ... is an outstanding difficulty especially with regard to prediction rather than replication. It appears that the capacity to solve mathematical models of the physical situation exceeds the ability to characterise it in the first place." [*76*]

In response to questions put to them by RWMAC, Nirex stated that they considered any mathematical model an imperfect representation of reality. [*77*] RWMAC have concluded that:

> "No complete assessment system has been validated and indeed it seems impossible that one ever could be fully quantitatively validated". [*78*]

4.4.2. Provision of Data

In order to apply the computer model and obtain results, data must be used to allow the calculation of the safety of the repository under each of the scenarios.

The difficulties of obtaining the necessary data may be illustrated with the specific example of geochemistry. Understanding of the chemical transport mechanisms for radionuclides from the repository is recognized as vital to the development of the scientific basis of the safety case. [*79*] However, the chemistry of the most critical nuclides from the point of view of long term safety (Tc, I, Np, Pu, Am) is complex and Vovk of the IAEA has commented that:

> "our understanding of their geochemistry is at an infantile stage." [*80*]

---

75 Broyd (1990) p740
76 Knowles (1990) p754
77 RWMAC (1990) Safety Assessment Modelling, p81
78 RWMAC (1990) Safety Assessment Modelling, p29
79 Vovk (1990) p977
80 Vovk (1990) p974

Nirex have stated that they are confident that all the data requirements for providing a robust safety assessment can be met. [*81*] There are two different approaches that may be taken to the overcoming the problems that arise due to lack of data. Under the deterministic approach values are ascribed to the parameter and a straight forward calculation may be made. Under the probabilistic approach parameters are ascribed a range of values with a given probability distribution, and many thousands of calculations are performed until convergence is achieved. [*82*]

4.4.2.1. The Deterministic Approach

There are three different stages in the deterministic calculation.

i) Best estimates values are ascribed to all the input data.
ii) In order to identify the most important (or sensitive) parameters the risk calculation is repeated many times, varying each parameter in turn.
iii) The most sensitive parameters are ascribed best and worst credible values and a final risk calculation is made which results in a central risk value together with its upper and lower bounds. [*83*]

The advantage of the deterministic approach is that it does not make undue demands on computer time. [*84*] However, the DoE hold the view that given the uncertainties in the long term future the deterministic approach cannot be relied upon. [*85*] Thompson of the DoE has written:

---

81 RWMAC (1990) Safety Assessment Modelling, p75
82 RWMAC (1990) Safety Assessment Modelling, pp 24-25
83 RWMAC (1990) Safety Assessment Modelling, p24
84 RWMAC (1990) Safety Assessment Modelling, p24
85 RWMAC (1990) Safety Assessment Modelling, p57

> "approaches using "best estimates" have been rejected as they are difficult to justify scientifically." [*86*]

Neil Chapman of the British Geological Survey (BGS), whose work [*87*] has been used by Nirex as a focus in their site selection process, [*88*] has written:

> "The technique is suitable for the rapid **qualitative** appraisal of options at a generic level but, we suggest, the calculated doses and the times at which doses are received should not be used quantitatively, particularly in a regulatory sense." [*89*]

The "considerable oversimplification" [*90*] of the deterministic approach gives rise to a smooth curve in the risk/time calculation. However, Chapman argues that this representation is unrealistic. [*91*]

4.4.2.2. The Probabilistic Approach

The probabilistic approach attempts to provide a more accurate risk estimate when input data are either variable or "imperfectly known". [*92*] Each input parameter is ascribed a probability distribution of values. Under the Monte Carlo approach a computer is used to calculate the risk many thousands of times selecting a random set of input parameters each time. More probable values for the parameters will be selected most often, but there will also be a chance that low probability values are selected. [*93*] The arithmetic mean of the results, which is termed the 'expectation value' of the risk, is calculated at given intervals. When the expectation value has reached a constant value the calculation is said to have

86 Thompson (1987) p207
87 Chapman (1986)
88 Nirex (1989) Deep Repository Project, pp 14-15
89 Chapman (1990) p321
90 Chapman (1990) p321
91 Chapman (1990) p322
92 RWMAC (1990) Safety Assessment Modelling, p25
93 RWMAC (1990) Safety Assessment Modelling, p25

'converged'. The converged expectation value of the risk is the result used. [*94*] A significant disadvantage of the probabilistic approach is the amount of computer time required. In order to avoid prohibitive expense, simplified models must be used. [*95*] Nirex have commented that "lumping" together uncertainties into a probabilistic code, which necessarily uses simplified models, is not necessarily illuminating. [*96*]

Similarly, Chapman has commented that the probabilistic approach:

> "has a number of shortcomings for modelling processes in the Earth Sciences where data are frequently sparse, and likely to remain so, or where the technique masks the complexity of the natural environment." [*97*]

Chapman cites three main problems with the probabilistic approach:

i) The geological environment undergoes processes, not events, which "cannot be treated in a random probabilistic fashion"; [*98*]

ii) There is insufficient data available to obtain a statistically meaningful result, and [*99*]

iii) In certain cases deterministic methods must be used in order to avoid the selection of invalid parameters. [*100*]

Chapman concludes that:

> "The message from geologists to performance assessors is thus that deterministic analysis is considerably more appropriate in describing the natural environment than is probabilistic analysis." [*101*]

---

94 RWMAC (1990) Safety Assessment Modelling, p25
95 RWMAC (1990) Safety Assessment Modelling, p25
96 RWMAC (1990) Safety Assessment Modelling, p58
97 Chapman (1990) p323
98 Chapman (1990) p323
99 Chapman (1990) p324
100 Chapman (1990) p324
101 Chapman (1990) p324

It may be concluded that neither of the techniques available to overcome the problems that arise due to lack of data is wholly satisfactory.

4.4.3. The Value of Safety Assessments

Using the methodology described above whereby hypothetical futures are encoded into computer models and values are ascribed to the relevant parameters a figure may be calculated for the predicted risks due to radioactive waste disposal. These are generally presented in terms of predicted dose or risk as a function of time and may thus be used for the purposes of regulatory requirements to indicate that the risk will not exceed a specified limit at any time in the future. [*102*]

In March 1989, Nirex published the "PERA" Report - "Deep Repository Project, Preliminary Environmental and Radiological Assessment and Preliminary Safety Report" [*103*] The report was addressed primarily to the regulatory departments of Government as the first step in the process of seeking authorisation for a repository. [*104*] It described Nirex's use of radiological safety assessments to indicate that the radiological safety targets could be met by the proposed repository. [*105*]

Nirex commented that:

> "by gaining a fundamental understanding of the processes concerned, descriptive mathematical models can be formulated which, together with measured data, can be used to make confident predictions about the distant future." [*106*] [*107*] [*108*]

---

102 Chapman (1990) p320
103 Nirex (1989) Deep Repository Project
104 Nirex (1989) Deep Repository Project, p(iv)
105 Nirex (1989) Deep Repository Project, pp (vii), 34-38, H1
106 Nirex (1989) Deep Repository Project, pH1
107 see also Saunders (1987) NSS/G101 pp 1,3-4
108 'NSS' reports are part of the Nirex Safety Studies series of reports.

Similarly, RWMAC have commented:

> "A common feature of these assessments, and of other comprehensive assessments carried out in other countries, is that there is unlikely to be any release of radioactivity into man's accessible environment for several hundred to a few thousand years, and that the maximum risks to individuals are generally much less than one in a million-per year. [*109*]

This level of confidence in the safety assessment process is not shared uniformly within the nuclear industry. For example, Johansson, of the National Institute of Radiation Protection in Sweden has written:

> "A full safety assessment, whose result could be interpreted so as to predict the health effects must be quantitative. All the future events that will take place in the repository, the surrounding rock and the radionuclide recipient must be fully known. In fact, if we want to calculate the collective effective dose equivalent committed we have to include all changes on a global scale. However, it is obvious that this is not meaningful." [*110*]

Merz and Schifferstein, from the German nuclear industry, have commented that:

> "The claim for a safe insulation of radioactive wastes from the biosphere over periods of time long enough for their toxicity to decay to sufficient low values poses problems to human society which are unique as compared to the past. The call for an assessment of the consequences of human activities and the risks involved for periods of hundred thousands to millions of years has never been articulated so emphatically as in connection with radioactive wastes today. The claim to predict the consequences of human activity for periods surpassing all imagination is largely governed by wishful thinking on the part of the contractors." [*111*]

Chapman has specifically criticised the use of dose against time curves which are used to show that the risk does not exceed the regulatory limit, commenting that:

> "It is rarely stated explicitly that this type of presentation is extremely stylized. These curves are easily misconstrued as predictions of some real 'future' or set of futures, whereas the extent to which they will diverge from the real evolution of the natural environment is, we believe, very poorly comprehended." [*112*]

---

109 RWMAC (1990) Safety Assessment Modelling, pp 10-11
110 Johansson (1990) p313
111 Merz (1990) p300
112 Chapman (1990) p320

> "The utility of **quantitative** radiological calculations of doses or risks beyond some hundreds of years is difficult to defend". [*113*] (Author's emphasis)

Similarly, Hill of the NRPB has commented:

> "One school of thought holds that the best approach is, as ICRP have recommended, to apply dose and risk limits over all time, recognising that the calculations are stylised and that the results are not predictions of actual doses and risks, but only measures devised to demonstrate compliance with the underlying principle. At the other extreme, there are those who feel that any calculation of dose or risk in the far future is meaningless". [*114*]

In 1990, the US National Research Council (US-NRC) published a position statement on radioactive waste management [*115*] which stated that:

> "Engineers and scientists, no matter how experienced or well trained, are unable to anticipate all of the potential problems that might arise in trying to site, build, and operate a repository. Nor can science "prove" (in any absolute sense) that a repository will be "safe"". [*116*]

It may be concluded that although the use of computer modelling together with estimates of data does allow a calculation of radiological impact to be made, the value of this calculation is controversial. Many observers within the nuclear industry and the scientific community who are involved in the assessment programme argue that such calculations are not capable of providing the rigorous proof of safety which is required by the regulators.

---

113 Chapman (1990) p328
114 Hill (1990) pp 76-77
115 U.S. National Research Council (1990)
116 U.S. National Research Council (1990) p3

4.5. SUMMARY

In this case study, the viability of the synoptic method is evaluated through the analysis of the Nirex safety assessment of the behaviour of nuclear waste in a repository. In order to obtain regulatory approval to dispose of nuclear waste. Nirex are required to prepare a radiological safety assessment of the proposed disposal facility. This requirement is equivalent to the third stage of the synoptic method which requires the exhaustive examination of the consequences of a proposed policy.

The provision of a safety assessment may be achieved through the use of hypothetical scenarios encoded into computer programs, together with estimates for the data which are not available. However. the value of the results obtained by such techniques, is not uniformly accepted. The following five chapters of the thesis will consider the credibility of the Nirex safety assessment in order to test Lindblom's hypothesis that a synoptic approach to decision making is not achievable. The following chapter considers the impact of gas generation on repository design and the difficulties that this presents for the safety assessment. The subsequent chapters consider the methodology used by Nirex to quantify the long-term radiological impact of nuclear waste disposal.

5. REPOSITORY DESIGN AND THE IMPACT OF GAS GENERATION ON REPOSITORY SAFETY

5.1. INTRODUCTION

In order to obtain regulatory approval for nuclear waste disposal Nirex must prepare a synoptic analysis of the radiological impact of the proposed repository. This chapter considers the impact of gas generation on design of the proposed repository, and the difficulties that this presents for the safety assessment. Nirex propose to bury 2 million cubic metres of radioactive waste underground [*1*] and it is estimated that these wastes will produce their own volume of gas every ten years. [*2*] In total, Nirex predict that the volume of gas generated will be 400 times the volume of the repository [*3*] However, Nirex did not identify the significance of gas generation until an initial review was carried out in 1985/6 [*4*] and the design of the repository has not taken gas production into account. [*5*]

The gases produced are potentially explosive. They also present a risk due to their radioactivity and toxicity. However, the primary problem presented by gas production is that the requirement to allow the gases to escape from the repository must override the requirement for a repository design that prevents the escape of radioactivity.

---

1 Nirex (1989) Deep Repository Project, Table 2.2
2 Cooper (1987) NSS/R102, p42
3 Lever (1988) p124
4 Cooper (1987) NSS/R101, p113
5 Jeffries (1991) Executive Summary p(i)

5.2. THE VOLUME OF GAS PRODUCED

Nirex estimate that one billion cubic metres of hydrogen will be generated in the nuclear waste repository due to the corrosion of steel. [*6*] It is also estimated that 3 million cubic metres of methane and 3 million cubic metres of carbon dioxide will be generated from the breakdown of paper and wood in the waste. [*7*] Nirex have estimated that the gas will be produced at an initial rate of 10,000 cubic metres per year. [*8*] If these gases are not released it is feasible that pressures may develop which could present a considerable threat to the overall safety of the repository. [*9*]

5.3. THE REPOSITORY DESIGN

Nirex did not identify the significance of gas generation until an initial review was carried out in 1985/6. [*10*] The design of the Nirex repository has not taken gas production into account. [*11*] The design of the repository has been chosen in order to limit the quantity of radioactivity carried out of the repository by groundwater [*12*] through deep burial of the waste and extensive use of steel and concrete to seal the waste. [*13*] It is proposed that the waste will be buried in caverns half a mile underground. [*14*] Concrete will be used to grout the waste into steel containers which will be placed in the caverns and the spaces between the containers will be filled with additional concrete. [*15*] It is assumed that by entombing the waste in such a way the rate that radioactivity is carried out of the

6 Lever (1988) p118
7 Lever (1988) p118
8 Lever (1988) p119
9 Jeffries (1991) p124
10 Cooper (1987) NSS/R101, p113
11 Jeffries (1991) Executive Summary p(i)
12 Nirex (1989) Deep Repository Project, pp 13-14
13 Nirex (1989) Deep Repository Project, pp 13-14
14 Nirex (1991) Sellafield Repository Project, p4
15 Nirex (1989) Deep Repository Project, Fig 3.1

repository will be low enough to ensure that the radiological impact is "harmless". [*16*] [*17*]

However, due to the large volume of gas that will be generated in the repository. [*18*] the design objective of containing the radioactivity must be overridden by the requirement to release gas and avoid a pressure build-up. The IAEA have commented:

> "The main question is to find an acceptable compromise between the water impermeability of the repository and the quality of the sealing and, on the other hand, the need to release the gas overpressure." [*19*]

5.3.1. The Requirement for a Physical Barrier

The principle mechanism for the carriage of radionuclides out of the repository will be transport in water. [*20*] Nirex have calculated that water will enter the repository at a rate of $300m^3$/day [*21*] and within 10 years will saturate the repository. [*22*] Following saturation this water will flush radioactivity out of the repository. [*23*] The radionuclides of particular concern are those which are highly soluble. In particular, caesium, strontium, iodide, and tritiated water [*24*] show relatively high solubility. [*25*] The solubility of caesium, iodide and tritium has been described as "unlimited" [*26*] [*27*] and the carriage of these radionuclides out of the repository is of primary concern. [*28*] In the reference repository design

---

16 Nirex (1988) NSS/G108, p5
17 Nirex (1989) Deep Repository Project, p14
18 Lever (1988) p124
19 IAEA (1989) in George (1989) NSS/R199, p4
20 Harris (1988) NSS/R125, p2
21 Cox (1989) NSS/R141, p(iii)
22 Cox (1989) NSS/R141, p8
23 Windsor (1989) NSS/R158, p(iii)
24 Harris (1989) NSS/R189, p2
25 Ewart (1989) NSS/G111, Table II
26 Ewart (1989) NSS/G111, Table II
27 Windsor (1989) NSS/R158, p12
28 Harris (1988) NSS/R125, p4

used by Nirex it is assumed that physical containment of radionuclides for 300 years will be provided. [*29*] [*30*] For example, the safety assessment calculations used to select Dounreay and Sellafield for detailed site investigation [*31*] assumed "total containment" for 300 years. [*32*] However, it is not possible to design the repository to simultaneously prevent the escape of radionuclides, but allow the escape of gas. The dilemma presented by the simultaneous requirement for gas release and radionuclide containment has prompted Nirex to redefine the word "containment", ie:

> "no containment system is total (eg metal containers may require vents to allow gases to escape) and as a result it is difficult to define 'containment' in an absolute sense. One working definition which is currently being considered is that the barrier should aim to restrict the toxicity of water just outside the barrier to being no greater than that which would be reached in the long term when the barrier has deteriorated and the long-lived radionuclides are homogenised throughout the repository." [*33*]

This ambiguous definition does not resolve safety issues that arise as a result of gas generation in the repository. At all levels the conflicting requirements, to seal in the radionuclides while simultaneously allowing the release of gas, produces irreconcilable contradictions in the safety assessment.

5.3.2. Use of Steel and Concrete as a Physical Barrier

Nirex have stated that:

> "A large proportion of the radioactivity in the waste is relatively short-lived - that is its radioactivity falls to negligible levels within a few hundred years. Some of the short-lived radionuclides dissolve rather easily and water access should therefore be prevented for approximately this period. ... the first barrier is a physical one - steel and concrete. ... There is no doubt that a combination of steel and concrete can provide

29 Ewart (1988) NSS/R103, p3
30 Windsor (1989) NSS/R158, p12
31 Cooper (1989) NSS/R168, p2
32 Ewart (1989) NSS/G111, Table I, p5
33 Atkinson (1988) NSS/G102, p1

> virtually total containment of the shorter-lived components of the waste for the necessary period." [*34*]
>
> "each individual component is designed to maximise its effective contribution to the whole and provide 'strength in depth'" [*35*]

However, this concept of 'strength in depth' must be compromised due to the problems created by gas generation. The compromises made and their impact on the safety assessment are discussed below.

5.3.2.1. Steel

Nirex's stated requirement for the steel container is that:

> "stainless steel containers for LLW and ILW in a Nirex repository ... will be required to remain intact for up to a few hundred years." [*36*]

Nirex are confident that such a requirement can be met. For example, Nirex commented in 1987:

> "Stainless steels are inherently corrosion resistant and the programme aims to prove this under repository conditions. Carbon steels corrode at a known slow rate and the approach is to use a container thick enough to last for the required time." [*37*]

Two years later, in 1989, Nirex published a report announcing that it was likely that they would make large holes in the containers in order to allow gas to escape. [*38*] Without such holes it is possible that:

> "the pressure rise could ultimately lead to fracturing of the vault or the flow field environment, possibly providing pathways that could accelerate the movement of nuclides to the surface." [*39*]

---

34 Saunders (1987) NSS/G101, pp 10-11
35 Atkinson (1988) NSS/G102, p1
36 Marsh (1988) NSS/R126, p25
37 Saunders (1987) NSS/G101, p10
38 Nash (1989) NSS/R201, p1
39 Nash (1989) NSS/R201, p1

However, such holes will inevitably allow radioactivity as well as gas to escape from the containers. Nirex have calculated that even if holes as small as 1mm are made significant concentrations of activity will escape from the canisters. [*40*] The diameters of the holes that Nirex are considering range from 10mm to 100mm. [*41*] Moreover, the value of simply making holes in the containers to allow the gas to escape is questionable. A report prepared for the DoE in 1988, considered that in order to allow gas to escape freely to the atmosphere and so avoid accumulation it may be necessary to provide a vent pipe. [*42*] In 1991, a further DoE report concluded that:

> "little is known about the use of these methods in a deep repository over a very long period. In particular, the use of passive venting [is] ... thought to be appropriate only during the operational phase of the repository." [*43*]

5.3.2.2. Concrete

Concrete is a porous material and its performance as a physical barrier depends on the extent that dissolved species may be transported through intact concrete, or through potentially faster pathways such as cracks and joints. [*44*] Concrete is brittle and prone to cracking. [*45*] It is likely that some cracking of the concrete will occur either due to thermal or humidity gradients during curing in the short term or due to ground settlement in the longer term. [*46*] In addition, it is possible that the waste packages could provide interfaces or geometrical features that will enhance the generation of cracks. [*47*] The dimensions of the cracks could range from microcracks to relatively gross fractures depending on how the stresses

---

40 Tasker (1990) p463
41 Nash (1989) NSS/R201, p2
42 Cremer (1988) pp 8-3, 8-5
43 Jeffries (1991) p54
44 Atkinson (1988) NSS/G102, p13
45 Guppy (1988) NSS/R105, p1
46 Guppy (1988) NSS/R105, p(ii)
47 Rodwell (1989) NSS/R200, p4

causing the crack are relieved. [*48*] Any cracks in the concrete barrier have the potential to provide rapid transport pathways for radionuclides. [*49*] Therefore any cracks could adversely affect the performance of concrete as a barrier to radionuclide migration. [*50*] Although Nirex have calculated that:

> "Present indications are that good quality structural concrete 300mm in thickness will be an effective barrier to contain tritium for at least 10 years and cesium [sic] and strontium for over 100 years. *The major cause of uncertainty is the possible impact of defects in the concrete (cracks and joints) which could act as fast transport pathways.*" [*51*] (My emphasis)

The calculated containment times given above neglect the possible impact of cracks in the concrete which could act as fast transport pathways. [*52*] Nirex have concluded that:

> "long containment times will be realised only as long as short-circuit transport along cracks and interfaces is not significant." [*53*]

It is possible that the gas pressures which build up in the repository may be sufficient to crack the cement. [*54*] Such cracks would reduce the integrity of the concrete and could enhance the flow of contaminated water from the repository. [*55*] It is therefore necessary for Nirex to show that gases will be able to escape satisfactorily from the repository. [*56*] This introduces conflict into the properties which are sought for concrete. Concretes with low transport characteristics are required for physical containment, but in order to allow dissipation of gas relatively easy transport is desirable. [*57*] Similarly concrete without cracks is sought to contain radioactivity, but concrete with cracks is sought to release gas.

---

48 Guppy (1988) NSS/R105, p1
49 Guppy (1988) NSS/R105, p1
50 Guppy (1988) NSS/R105, p1
51 Atkinson (1988) NSS/G102, p(iv)
52 Atkinson (1989) NSS/G110, p(iv)
53 Atkinson (1989) NSS/G110, p17
54 Rees (1989) NSS/G112, p(i)
55 Rees (1989) NSS/G112 p1
56 Rodwell (1989) NSS/R200, p(ii)
57 Atkinson (1988) NSS/G102, pp 15-16

The potential for intact concrete, or cracked concrete to offer a physical barrier is considered below.

i) Intact Concrete

In order to prevent the escape of radionuclides, low permeability concrete is required. In 1988, in a Status Report on repository design Nirex stated that:

> "the aim is to restrict the mobility of radionuclides in aqueous solution by the use of impermeable (or relatively impermeable) materials." [*58*]

Similarly, in work prepared for Nirex in 1988, Harris commented:

> "The performance of cementitious material as a mainly physical barrier to the escape of dissolved radionuclide species from a repository depends on the mass-transfer characteristics of the chosen material. In particular ... the water permeability [is] important." [*59*]

Conversely, in a further Nirex report published in 1989, Harris reported that:

> "The requirement for a material to backfill a radioactive waste repository has led to a preliminary mix design based on a 2:1 mixture of lime (calcium hydroxide) and ordinary Portland cement. The material was designed to give a very high permeability." [*60*]

In an attempt to overcome this contradiction, Nirex have proposed that two different types of concrete are used - structural concrete and backfill material. [*61*] The structural material would provide the barrier properties and the backfill material would be designed to be permeable. [*62*] However, this does not provide a satisfactory resolution of the problem, as the structural concrete will not be able to simultaneously contain radionuclides and allow the escape of gases.

---

58 Atkinson (1988) NSS/G102, p1
59 Harris (1988) NSS/R125, Abstract
60 Harris (1989) NSS/R189, Abstract
61 Atkinson (1988) NSS/G102, p16, Fig 1
62 Atkinson (1988) NSS/G102, p16

The problem presented by structural concrete may be appreciated by considering the mechanism of gas transport through concrete. Under dry conditions it would be possible for the gas to escape from intact concrete simply by diffusion. [*63*] However, it is unlikely that the repository will be dry [*64*] and the effect of the presence of water could be crucial to the ease of gas migration through the concrete. [*65*] The effect of water on concrete permeability to gas is not entirely understood. This is largely due to difficulties found in permeability measurement, and due to the complex relationship between presence of water and the microscopic features of the concrete. [*66*]

Under wet conditions concrete pores will become blocked with water. [*67*] Gases have a low solubility and Nirex have concluded that diffusion of dissolved gas through water in the pores would not be adequate to contribute significantly to gas transport. [*68*] Therefore, gas will be unable to escape from the repository unless a sufficient pressure is built up in the pores to displace the water. [*69*] The pressure required to oust the water from the pores is proportional to the size of the pore and it has been concluded that for some cements the gas pressures required would be so large that it is unlikely that the gas would be able to displace the water. [*70*] The pressures that would be sustainable in the vault before fracturing occurred are uncertain. [*71*] However, it has been concluded that structural concretes present a particular problem, and Nirex have stated that:

> "For structural concretes the pressure differential required to overcome the capillary forces could represent a substantial increment to the hydrostatic pressure and would raise questions about possible fracture generation." [*72*]

---

63 Atkinson (1988) NSS/G102, pp 8,9
64 Atkinson (1988) NSS/G102, p9
65 Rodwell (1989) NSS/R200, p5
66 Rodwell (1989) NSS/R200, p6
67 Atkinson (1988) NSS/G102, p9
68 Rodwell (1989) NSS/R200, p5
69 Atkinson (1988) NSS/G102, p9
70 Atkinson (1988) NSS/G102, p9
71 Rodwell (1989) NSS/R200, p2
72 Rodwell (1989) NSS/R200, p6

ii) Cracked Concrete

Ironically, Nirex have suggested that fracture generation in concrete will be avoided by the migration of gas through cracks that already exist. [*73*]

> "The transport of gases through concrete should be sufficiently rapid to avoid pressurisation effects in the repository. ... Under fully saturated conditions ... it is likely that gas will be transported preferentially along defects, such as cracks and interfaces". [*74*]

It is even noted that if additional fractures are formed they will serve to: "ease gas transport". [*75*]

Little is known about the transport characteristics of typical defects or the way the defects are likely to be interlinked [*76*] and the impact of cracks and joints presents a major cause of uncertainty. [*77*] There is little experimental data available about gas migration through concrete in large structures under repository conditions. [*78*] In 1989, in work prepared for Nirex, Rodwell commented:

> "Whether or not such fissures would exist in the backfill of a repository and provide continuous connected pathways through a vault is at present a matter of conjecture." [*79*]

The conflicting attitude of Nirex to cracks in concrete is exemplified by their contradictory stance on the phenomena of autogenous healing of cracks in concrete. Cracks in concrete could provide a fast transport pathway for radionuclides and as such could impair the performance of the concrete as a

---

73 Atkinson (1988) NSS/G102, p9
74 Atkinson (1988) NSS/G102, p(iii)
75 Rees (1989) NSS/G112, p(i)
76 Atkinson (1988) NSS/G102, p10
77 Atkinson (1988) NSS/G102, p43
78 Rodwell (1989) NSS/R200, p1
79 Rodwell (1989) NSS/R200, p6

barrier to radionuclide migration. [*80*] However. Atkinson has commented that cracks and joints "could actually have a negligible effect because there is evidence to suggest that they are self-healing". [*81*] In contrast, Rodwell has expressed concern that if a fissure network did exist in the concrete that could allow the relief of gas pressure a self-healing mechanism may operate to seal the fissures. [*82*] Guppy has carried out a review for Nirex on the potential for crack healing and its relevance to a radioactive waste repository. [*83*] It was concluded that the mechanism of crack healing was not understood [*84*] and little work had been done on the subject. [*85*] No experiments were reported which were directly relevant to the conditions expected to be found in a repository [*86*] and there was doubt that the conditions in a repository would be suitable to allow such healing to take place. [*87*]

5.3.3. Rock as a Physical Barrier

Fractures in the rock surrounding the repository can provide pathways that could provide express routes for the escape of radioactivity back to the surface. [*88*] [*89*] Therefore gas that has escaped from the repository must be able to reach the surface without developing pressure build-ups that could damage the integrity of the host rock. The rock surrounding the repository provides an important barrier to the migration of radionuclides back to the human environment. [*90*] The most likely natural mechanism by which radionuclides might penetrate this barrier is by

---

80 Guppy (1988) NSS/R105, p(i)
81 Atkinson (1988) NSS/G102, p15
82 Rodwell (1989) NSS/R200, p6
83 Guppy (1988) NSS/R105, p(i)
84 Guppy (1988) NSS/R105, p(i)
85 Guppy (1988) NSS/R105, p(ii)
86 Guppy (1988) NSS/R105, p15
87 Guppy (1988) NSS/R105, p(i)
88 Nash (1989) NSS/R201, p1
89 Jeffries (1991) p124
90 Herbert (1990) NSS/R223,p(iii)

transport in groundwater which is carried back to the surface through fractures. [*91*] Gas overpressurisation presents concern as it is possible that gas build up in the rock may create fractures. [*92*] In 1990, Nirex commented that:

> "if the flow of gas were sufficiently impeded, the pressure in the repository would rise. Such a pressure rise could ultimately lead to fracturing of the repository environment, possibly providing pathways that could accelerate the movement of radionuclides to the surface." [*93*]

Similarly, in 1991, a DoE report has concluded that:

> "The effects of gas pressure on the surrounding rocks are potentially the most important aspects of gas migration, as dilation and ... fracturing could lead to enhanced groundwater flow rates and consequently enhanced radioactive nuclide transport." [*94*]

> "it is feasible that pressures may develop which could represent a considerable threat to the overall safety of the repository" [*95*]

Conversely, a Nirex reported prepared in 1989 stated that:

> "The latest work is indicating that gas will not present a major problem." [*96*]

In 1990, a report prepared for Nirex considered two possible effects of overpressurisation; the production of fractures and the dilation of existing fractures. [*97*] The potential for fracturing was considered using four different models. [*98*] It was concluded that the rock around a repository would be able to sustain pore fluid pressures up to 1.4 times the hydrostatic pressure before large scale fracturing could occur. [*99*] However, in 1991 a DoE report commented:

> "At the current time, there is little understanding of rock fracturing, and most fracture theory is 'borrowed' or developed from theories of metal fracture. It is well known that under rapid loading conditions, a metal will

---

91 Herbert (1990) NSS/R223, p1
92 Rodwell (1989) NSS/R200, p8
93 Nash (1990) NSS/R208, Executive Summary
94 Jeffries (1991) p47
95 Jeffries (1991) p124
96 George (1989) NSS/R199, p2
97 Nash (1990) NSS/R208
98 Nash (1990) NSS/R208. Executive Summary
99 Nash (1990) NSS/R208, Executive Summary

> be stronger than under slow loading conditions ... At present, there is no accepted methodology for modelling the effects of slow gas pressure build-up on the surrounding rock mass, and its feed-back effect on the flow properties." [*100*]

The dilation of existing fractures could occur at lower pressure rises than the pressures required to induce fracturing. [*101*] An increase in the pore fluid pressure by just 10% over the hydrostatic pressure (at 750m) was predicted to cause an increase by two orders of magnitude in the permeability of a crack 1 micrometer and 0.1m long. [*102*] However, if a continuous crack of 1m length existed within the rock then permeability changes of up to five orders of magnitude have been predicted. [*103*] The DoE report commented:

> "This is significant, as it indicates that where larger fractures are present in the rock, they would be expected to provide not only the dominant contribution to the initial permeability, but also to any increase in permeability caused by a rise in fluid pressure." [*104*]

Conversely, the Nirex report commented:

> "Such permeability enhancements would facilitate gas movement away from a vault and reduce the magnitude of the pressure rise caused by gas generation." [*105*]

This contrast highlights the dilemma posed by gas generation.

Building an understanding of the behaviour of gas within rock in order that it may be incorporated into the safety assessment has proved to be difficult. In 1991, the DoE carried out a review of the understanding and treatment of gas effects on nuclear waste disposal. They concluded that:

> "In the course of the study, considerable deficiencies in the current methods for dealing with gas effects have been identified. There is a lack

---

100 Jeffries (1991) p119
101 Nash (1990) NSS/R208, p11
102 Nash (1990) NSS/R208, Executive Summary
103 Nash (1990) NSS/R208, p10
104 Jeffries (1991) pp 116-117
105 Nash (1990) NSS/R208, p10

of relevant data, and at present there is only a limited ability to model rock fractures with achievable information" [*106*]

One of the major limitations to the incorporation of gas effects in the safety assessment is that much of the data required is either not available or is not sufficiently accurate to be used with any confidence. [*107*] The report commented:

> "In many cases, not only are the necessary data unavailable at present, but they may be impossible to obtain from a realistic and practical site study." [*108*]

Similarly, a further DoE report has commented:

> "some of the uncertainties inherent in geological and hydrogeological interpretations can sometimes never be resolved." [*109*]

A large proportion of the data required to calculate gas flow from a repository is dependent on the actual site chosen for the repository. [*110*] Other potential sources of information, which may be used in order to build up an understanding of gas transport in rock, are papers which are already available in the literature and field work which has been undertaken at other sites.

In 1988, Nirex carried out a literature review on the migration of gases through rock. [*111*] Very little data was found. [*112*] Direct approaches to organisations yielded a small amount of information - the principle response being requests for eventual access to the results. [*113*] Moreover, it was reported that:

---

106 Jeffries (1991) p124
107 Jeffries (1991) p113
108 Jeffries (1991) p127
109 McEwen (1990) Executive Summary p(iv)
110 Jeffries (1991) p126
111 Tomlinson (1988) NSS/R146,
112 Tomlinson (1988) NSS/R146, pp (ii)-(iii)
113 Tomlinson (1988) NSS/R146, pp (ii)-(iii)

> "consensus is lacking for an established protocol in laboratory and field-testing methods, even for similar objectives. Sometimes there is wide disparity between the approaches of individual researchers to quantitative modelling to attain the same goals. Definitions of parameters (e.g. 'diffusion coefficient', 'vertical diffusion', 'dispersion', 'conductivity') do not always agree from one source to another. Caution should be exercised, therefore, when comparing results and using listed data in numerical simulation exercises: every reference used must be examined carefully for discrepancies in definition and philosophy from the researcher's own convention." [*114*]

The general conclusion of the review was that there was little of direct relevance in the literature to the problem being tackled in the disposal area. [*115*]

Nirex have carried out field trials in order to validate gas migration calculations, however their value has been limited [*116*] and a consistent approach to matching the results to the models was not achieved. [*117*] Tests were carried out at a slate formation in Cornwall which was felt to provide a natural analogue to the low permeability, hard fractured rocks that are possible environments for the repository. [*118*] The experiments were a first attempt at quantifying gas dispersion in such systems through in-situ investigations in the Nirex programme. [*119*] Although the general trends of the field results were understood, the more detailed features were less tractable and it was not clear whether they represented real physical effects or experimental artefacts. [*120*] Moreover, it was difficult to replicate even order of magnitude flow rates during experiments. [*121*]

The impact of the lack of understanding of the behaviour of gas in rock on the safety assessment is increased by the fact that in addition to fracturing effects,

---

114 Tomlinson (1988) NSS/R146, p37
115 Rees (1989) NSS/G112, p9
116 Rees (1989) NSS/G112, p3
117 Rees (1989) NSS/G112, p9
118 Elliot (1989) NSS/R147 p18
119 Elliot (1989) NSS/R147 p19
120 Elliot (1989) NSS/R147 p19
121 Elliot (1989) NSS/R147 p19

other mechanisms may be identified by which gases could increase the rate that radionuclides are carried back to the surface. In 1989, Nirex [*122*] listed three possible mechanisms which could result in the early release of contaminated groundwater to the human environment due to the generation of gas. These were: (1) forcing of contaminated water from the repository by the build-up of gas pressure; (2) cyclic processes involving successive build-ups of gas pressure, ejection of water, gas pressure reduction and resaturation; and (3) entrainment of water by the gas flow.

The first mechanism, involving the forcing of water from the repository due to gas build-up [*123*] was studied by Nirex in 1989. [*124*] Gas will remove water from migration channels [*125*] by a piston-like displacement. [*126*] It was calculated that the generation of gas within the repository would lead to the expulsion of water over 100 years. [*127*] It is possible that the expelled water would be carrying contamination. [*128*] It was concluded that further consideration of this phenomenon was required. [*129*] However, there has been very little work undertaken on the direct effects of gas production on the carriage of radionuclides out of the repository. In 1991, a DoE report commented that:

> "it is clear that whilst there are a great number of reports from a wide range of research centres with some relevance to gas migration, there is relatively little published work directly related to the potential risk of the presence of gas and none on the effects of gas on radionuclide migration." [*130*]

---

122 Rees (1989) NSS/G112, p9
123 Rodwell (1989) NSS/R200, p8
124 Cox (1989) NSS/R141
125 Rodwell (1989) NSS/R200, p7
126 Cooper (1989) NSS/R168, p29
127 Cox (1989) NSS/R141, p9
128 Cox (1989) NSS/R141, p9
129 Cox (1989) NSS/R141, p9
130 Jeffries (1991) p125

5.4. THE RISK OF EXPLOSION

5.4.1. Underground Explosion

In addition to the impact that gas generation has on repository design, the explosive nature of the gases generated in the repository must also be considered in the safety assessment. [*131*] Hydrogen and methane form the bulk of the gases generated by the waste in the repository. Both of these gases are potentially explosive. In 1988, a report prepared for the DoE on flammable gas production in radioactive waste repositories concluded that:

> "The state of the art with respect to flammable gas in nuclear repositories can be described as primitive." [*132*]

The report used as an analogy the Abbeystead explosion that occurred in 1984. [*133*] In May 1984, an explosion occurred in a valve house set into the hillside at Abbeystead and sixteen people were killed. [*134*] A further DoE report has concluded that a similar explosion could occur in the Nirex repository. [*135*] The Abbeystead explosion was caused by ignition of a mixture of methane and air which had accumulated in the valve house. [*136*] The methane was of ancient geological origin and had percolated through the concrete walls of the tunnel. It had not been expected that gas would be found in the area. [*137*] In addition to the methane and hydrogen that will be generated within the repository, natural gas is found in the area of the Sellafield site where Nirex plan to construct the proposed repository. All the initial boreholes at Sellafield are to be drilled using

---

131 Stenhouse (1991) NSS/R262, p1
132 Cremer (1988) p1-1
133 Cremer (1988) p(i)
134 Health and Safety Executive (1985) p1
135 Jeffries (1991) p58
136 Health and Safety Executive (1985) p19
137 Jeffries (1991) p58

full hydrocarbon safety measures. Sellafield lies within a hydrocarbon licence block and up-dip from the gas fields in Morecambe Bay, where gas is trapped within the Ormskirk Sandstone beneath the Mercia Mudstone Group. Gas has also been found even closer to the Sellafield site near Walney Island, having migrated to be trapped under glacial till. Potential gas traps in the Sellafield area are likely to be associated with the St Bees Shales and the St Bees Evaporites. [*138*]

The cause of the ignition of the methane at Abbeystead was not positively identified. [*139*] In addition to obvious possible causes such as smoking and sparking from electrical equipment, a report by H M Electrical Inspector indicated that sufficient energy to initiate the explosion could have been generated from a spark of static electricity from clothing. [*140*] It is possible that the explosion may have been ignited simply by someone taking off a garment made of synthetic material. [*141*] In 1991, a DoE report commented that:

> "It is a matter of common observation that flammable vapours and gases are very easily ignited when mixed with air or oxygen. ... During construction and the operational phase of the repository, several potential sources of ignition would be present" [*142*]

A fire in the repository could present serious problems producing noxious and possibly toxic fumes and creating voids which could prevent work on the repository. [*143*] The theoretical maximum flame temperatures for methane/air fires is 1100^{o}C. A fire at up to 1000^{o}C could release volatile radionuclides such as caesium- 134, caesium- 137, silver-110m, and ruthenium-106 from the radioactive waste in the repository. [*144*] If there is an explosion the waste

---

138 McEwen (1990) p29
139 Health and Safety Executive (1985) p19
140 Health and Safety Executive (1985) p15A
141 Health and Safety Executive (1985) p15A
142 Jeffries (1991) pp 58-9
143 Jeffries (1991) p55
144 Jeffries (1991) p55

containment could be breached, the surrounding rock and concrete could be shattered and the waste displaced. [*145*] Given the proposed geometry of the disposal caverns it is possible that: "the flame may accelerate and undergo transition from deflagration to detonation." [*146*] The pressures generated by gas detonation are complex and can be as high as 20 bar. The detonation shock wave and flame front travel at a constant velocity of the order of 1800 m/s. Even if detonation does not occur, because of the obstacle effects, flame propagation could produce pressures of the order of 5 bar which could probably disrupt the structures of the repository. [*147*]

The experience of nuclear waste burial at Dounreay in Scotland demonstrates that the explosion risk may be significant. In 1977, an explosion in the waste disposal shaft destroyed the reinforced concrete cover and waste disposal ceased. [*148*] The explosion was so violent that pieces of the reinforced concrete slab covering the shaft were ejected beyond the boundary fence. [*149*] The cause of the explosion was probably a reaction between water and NaK (sodium-potassium), producing hydrogen which would have been ignited by the burning NaK. Although NaK-contaminated items were routinely disposed of they were generally cleaned before disposal and it was concluded that insufficiently cleaned items had been dumped. [*150*] An investigation into the incident concluded that the possibility of a further explosion could not be ruled out. Moreover, even if no unreacted NaK remained, the gases generated by the degradation of organic material, the corrosion of metals or radiolysis may be explosive. [*151*]

---

145 Jeffries (1991) p57
146 Jeffries (1991) p57
147 Jeffries (1991) p57
148 Nicholls (1990) vol I, p19
149 Nicholls (1990) vol II, pD2
150 Nicholls (1990) vol II, pD2
151 Nicholls (1990) vol II, pD3

5.4.2. Surface Explosion

In addition to the risk of underground explosion Nirex have also expressed concern that if a sufficient quantity of hydrogen or methane gas escaped from the repository and reached the surface, the potential for an explosion above ground would exist. [*152*] It is estimated that 2 million cubic metres of hydrogen will be produced per year. [*153*] The potential for surface explosion above a repository has been considered in a report prepared for the DoE. [*154*] It was concluded that the potential for a problem existed if the gas leaked into drains in public roads or cellars in houses. [*155*] Nirex have used a gas blow-out incident that occurred in Ohio to illustrate the possible effects of a sudden large release of large quantities of gas. [*156*] The sudden release of methane gas was sufficient to cause one explosion in a home in which the basement floor of the house was lifted several inches and the foundation was cracked. Structural damage was inflicted on several other houses and residents in an area of 11 km^2 were evacuated due to the explosive hazard. [*157*] [*158*]

Given the risk of surface explosion, an investigation was undertaken by Nirex [*159*] in order to establish the potential for the geological surroundings of the repository to attenuate the concentration of the hydrogen and methane gases before they reached the surface. A variety of potential attenuation mechanisms were considered. Solubility was expected to offer little reduction as the solubility of methane and hydrogen is low. [*160*] Similarly, the possibility of sorption trapping the gases is also low as both hydrogen and methane belong in the weak

---

152 Stenhouse (1991) NSS/R262, p1
153 Stenhouse (1991) NSS/R262, p34
154 Cremer (1988)
155 Cremer (1988) p9-1
156 Stenhouse (1991) NSS/R262, p31
157 Stenhouse (1991) NSS/R262, p31
158 Kelly (1985) p205
159 Stenhouse (1991) NSS/R262
160 Stenhouse (1991) NSS/R262, pp 6-7

sorption category. [*161*] The available literature on the potential for chemical processes to reduce the concentration of the leaking gases was described as "relatively sparse". [*162*] Although there is a "wealth of literature" on hydrogen and methane reactions, the extreme experimental conditions used in the experiments meant that "this body of information can largely be dismissed." [*163*] In the absence of direct evidence, geochemical models may be invoked. [*164*] However, the general drawback of these models is that they are based only on thermodynamic principles and assume that equilibrium conditions apply. [*165*] As many of the relevant processes and mechanisms occur slowly an instantaneous equilibrium approach is not strictly applicable. [*166*] The Nirex report concluded that:

> "it is impossible to predict, in the absence of supporting kinetic data, how much attenuation will actually occur." [*167*]

In addition to physical and chemical attenuation mechanisms it is possible that the action of microbes on the gases could reduce their concentration. However, such a mechanism could also affect the potential radiological hazard due to tritium and carbon-14. [*168*] The products of bacterial oxidation of hydrogen and methane will be more accessible to humans and such processes offer pathways for tritium (hydrogen-3) and carbon-14 intake. [*169*] Moreover, there is a sparsity of data on gas consumption rates by microbes in the soils which are representative of the proposed repository sites [*170*] and the presence of microbes in the correct environmental conditions for functioning cannot be guaranteed. [*171*]

---

161 Stenhouse (1991) NSS/R262, p5
162 Stenhouse (1991) NSS/R262, p8
163 Stenhouse (1991) NSS/R262, p32
164 Stenhouse (1991) NSS/R262, p9
165 Stenhouse (1991) NSS/R262, p9
166 Stenhouse (1991) NSS/R262, p10
167 Stenhouse (1991) NSS/R262, p32
168 Stenhouse (1991) NSS/R262, p34
169 Stenhouse (1991) NSS/R262, p33
170 Stenhouse (1991) NSS/R262, p34
171 Stenhouse (1991) NSS/R262, p33

The final conclusion of the Nirex investigation was that:

> "we have identified no convincing mechanisms in the geosphere which could result in significant attenuation of H_2 and CH_4 [hydrogen and methane]." [*172*]

5.5. THE RADIOACTIVITY AND TOXICITY OF THE GASES PRODUCED

A third hazard presented by gas generation, which must be included in the safety assessment of the repository, is the direct hazard arising from the gases due to their radioactivity and toxicity. Nirex have identified nearly thirty different radioactive and toxic gases that may form in the repository. [*173*] These include chlorine and ammonia, as well as radioactive gases such as radon and krypton. [*174*] Moreover, the substitution of radioactive isotopes such as tritium, a radioactive form of hydrogen, and carbon-14 for natural isotopes will further increase the production of radioactive gases. Nirex have concluded that essentially all the tritium associated with solid radioactive waste has the potential for being released as a gas. [*175*] They have also estimated that gases containing carbon-14 will be released at a rate of 0.6TBq/y for 500 years. [*176*]

It is possible that other factors that Nirex have not taken into account could significantly alter present understanding on the behaviour of toxic gases. For example, work prepared in 1990 considered the volatilisation of the radionuclides tin and iodine from soil and plants. It was considered that since detection of volatile products in the environment is difficult, the role of volatilisation in mobilising and cycling certain elements may have been previously

---

172 Stenhouse (1991) NSS/R262, p34
173 Lever (1988) p126
174 Lever (1988) p126
175 Jefferies (1990) NSS/R198, p(ii)
176 Jefferies (1990) NSS/R198, p18

underestimated. [*177*] Since volatile compounds can be dispersed rapidly and widely their rate of production is a vital step in the biological cycling or concentration of trace elements. [*178*] It was concluded that a great deal of further work was required to understand the processes involved in volatilisation and to quantify the fluxes that could occur over the timescales relevant to waste disposal assessment. [*179*]

5.6. SUMMARY

In the safety assessment of nuclear waste disposal, Nirex aim to demonstrate that through burial of nuclear waste in a concrete and steel structure underground, the migration of radioactivity back to the human environment will be prevented until it has become 'harmless'. [*180*] However, the barriers that are designed to retard the release of radionuclides will also serve to prevent the escape of gas. If a sufficient pressure is allowed to build up the resulting damage to the repository and the surrounding rock could increase the speed that contaminated water is carried back to the surface. In order to avoid overpressurisation, Nirex propose to deliberately breach the containment that the proposed repository is meant to ensure.

In addition, the gases generated are potentially explosive. It is possible that during the operation and construction of the repository an explosion could occur, similar to the explosion that occurred at Abbeystead which killed 16 people. Moreover, the release of the gases could result in an above ground explosion.

---

177 Arnold (1990) NSS/R219, p5
178 Arnold (1990) NSS/R219, p6
179 Arnold (1990) NSS/R219, p27
180 Nirex (1988) NSS/G108, p5

Additionally, the radioactivity and toxicity of the gases released could present difficulties at the surface.

The dilemmas and contradictions in the Nirex safety case that arise due to gas production do not appear to have been resolved. In particular, the compromise that must be reached between design for radionuclide containment or design for gas dissipation appears to present Nirex with an intractable problem.

6. ASSESSMENT OF THE QUANTITY OF RADIONUCLIDES THAT WILL DISSOLVE IN GROUNDWATER

6.1. INTRODUCTION

In the previous chapter it was established that it will not be possible to design the proposed repository such that the escape of radionuclides will be prevented. It will be necessary to breach the containment offered by the repository design in order to allow the release of gas. Therefore, groundwater will be able to enter the repository and dissolve radionuclides, which may then be carried out of the repository. In order to calculate the radiological impact of these radionuclides for the safety assessment, the quantity that dissolve must be determined. The following two chapters are concerned with the methodology adopted by Nirex in order to determine the quantity of radionuclides that will be dissolved when groundwater enters the repository.

The calculation of the quantity of radionuclides that will dissolve is problematic, as it is extraordinarily dependent on the specific details of the chemical environment of the radionuclide which is assumed for the safety assessment. Subtle adjustment of the assumptions made concerning the nature of the solid material holding the radionuclide, or the composition of the groundwater dissolving the radionuclide, may result in substantial variations in the results obtained. To by-pass these difficulties Nirex use a parameter described as the "solubility of the element" which aims to subsume these complexities within one piece of data. The authenticity of this approach will be examined. This chapter will consider the basic utility of the methodology. It will also consider the results of validation exercises carried out by Nirex and the DoE. The following chapter will consider in more detail the validity of the underlying concepts used.

6.2. NIREX METHODOLOGY

In order to determine the radiological impact of the repository, Nirex ascribe to each radionuclide a solubility parameter, such that the quantity of radionuclides that will dissolve in groundwater, and be carried from the repository may be calculated. To generate this data, Nirex first identify a solid that will be assumed to contain the radionuclide. Secondly, Nirex define the composition of the groundwater that will dissolve the radionuclide. Problems associated with this methodology are discussed below.

6.2.1. Choice of Solid

Different solids have widely different solubilities. [*1*] [*2*] The particular solid chosen by Nirex for a particular radionuclide, as the solid that will contain the radionuclide under repository conditions, is critical in determining the value to ascribe to the "elemental solubility". [*3*] This presents significant difficulties as it is often the case that the identity of the relevant solid is unknown. [*4*] For example, one commentator from the Canadian nuclear industry has commented:

> "it is very difficult to predict what solids will be present. You only have to get out a handbook on uranium to see how many minerals are present in the Earth's crust. There are literally hundreds of minerals for uranium and on that scale, our knowledge for plutonium and technetium is very small indeed." [*5*]

1 Pilkington (1988) NSS/R116, p6
2 Liezers (1988) NSS/R112, p(i)
3 Pilkington (1988) NSS/R116, p6
4 Pilkington (1988) NSS/R116, p3
5 Sargent (1991) pp 612-3

For there to be any confidence in the safety assessment, the choice of the solid used in the assessment is of paramount importance. However, in 1989 Nirex reported that the majority of the errors in the solubility database used in the selection of Sellafield as the chosen site for the proposed repository [*6*], were due to incorrect choice of solid. [*7*]

6.2.2. Definition of Groundwater Composition

Groundwater contains a wide variety of chemicals, some of which may react with radionuclides when they have dissolved. [*8*] Such reactions can have an extraordinary effect on the tendency of radionuclides to come into solution. Therefore, the calculated solubility of a particular radionuclide will depend critically on the groundwater composition that has been assumed in the assessment. [*9*] Experiments undertaken by Nirex to test the predicted solubility of radionuclides under repository conditions have been undermined by uncertainty over which reactions will take place. [*10*] The complexity of the situation is illustrated below using americium as an example.

In 1988 Nirex published the results of a laboratory experiment undertaken to test predictions made for "americium solubility". The water used in the experiment contained 'hydroxide ions', 'carbonate ions' and 'sulphate ions' in addition to molecules of water. Four different chemical species that could be produced if americium reacted with these chemicals were listed. The total concentration of dissolved americium is obtained from the combined contribution from each of the

---

6 Cooper (1989) NSS/R168, p2
7 Ewart (1989) NSS/G111, p12
8 Ewart (1989) NSS/G111, p2
9 Francis (1988) NSS/R140, p18
10 Cooper (1987) NSS/R101, pp 64-66

dissolved species that contain americium. However, the concentration of these species varies enormously with the experimental conditions. It was observed that total americium concentration varied one thousand fold within the experiment. It was reported that the value initially predicted for the 'americium solubility' showed no similarity to the experimental results and that the data used in the calculations had to be altered. [*11*]

In order to illustrate more generally the problems associated with the generation of "elemental solubility" data the example of uranium will be considered.

6.2.3. 'Uranium Solubility'

The solubility of uranium is very significant in making the safety case for a nuclear waste repository. [*12*] There is a large amount of uranium in nuclear waste. [*13*] Consequently, the radioactive decay products (the daughter elements) of uranium are likely to dominate the long-term radiological impact of the repository. [*14*] Nirex have assumed that low "uranium solubility" will ensure that the release of uranium from the repository is spread over time and consequently that a low peak dose of radioactivity will be achieved. [*15*] Therefore, the value ascribed to "uranium solubility" is extremely important. [*16*]

---

11 Atkinson (1988) NSS/R104, pp 6-7
12 Cooper (1989) NSS/R168, p22
13 Ewart (1988) NSS/G103, p11
14 Ewart (1988) NSS/G103, p11
15 Ewart (1988) NSS/G103, p11
16 Ewart (1988) NSS/G103, p11

6.2.3.1. Choice of Solid

The determination of the appropriate value to use for the solubility of uranium in the safety assessment is complicated by uncertainties over the nature of the solid that should be used in the calculation. [*17*] The values actually ascribed by Nirex to the "uranium solubility", for the purposes of safety assessments, have varied considerably and have increased from 10^{-8}M in 1987 [*18*] to 10^{-6}M in 1989. [*19*] These values may be compared to the reported values for "uranium solubility" which vary from 3 x 10^{-5} M to 0.03M. [*20*] The complexity of the situation may be appreciated by consideration of the diverse spectrum of "uranium solubility" values obtained by Nirex through experiments on uranium solids. Experiments reported by Nirex in 1988 gave a value of 10^{-5} M [*21*] for one uranium compound, but 10^{-10} M for another compound. [*22*] This is a one hundred thousand fold variation. Nirex concluded that it would be appropriate to use the intermediate value of 10^{-7}M for the safety assessment calculations. [*23*]

In 1989 Nirex reported further experimental results. The solubility reported for one of the compounds [*24*] was 7000 times higher than the result that had been reported in 1988. [*25*] It was also 7000 times higher than a calculated solubility quoted by Nirex. [*26*] For the assessment Nirex decided to use two different "uranium solubility" figures to allow for two different solid forms. [*27*] The values chosen were 10^{-6}M for a hydroxide and 3×10^{-10}M for a dioxide. The

17 Ewart (1988) NSS/G103, p11
18 Hodgkinson (1987) NSS/A100, p23
19 Ewart (1989) NSS/G111, p16
20 Cross (1989) NSS/R119, p6
21 Ewart (1988) NSS/G103, p11
22 Ewart (1988) NSS/G103, p12
23 Ewart (1988) NSS/G103, p12
24 Ewart (1989) NSS/G111, p16
25 Ewart (1988) NSS/G103. p12
26 Ewart (1989) NSS/G111. p16
27 Ewart (1989) NSS/G111. Table II

dioxide figure is 2000 times less than the experimentally observed dioxide solubility. [28]

6.2.3.2. Definition of Groundwater Composition

The water that enters the repository will contain other chemicals in addition to molecules of water. These additional chemicals may react with uranium compounds and affect the quantity of uranium that dissolves. Three types of reaction that may take place are considered below.

i) Reactions with Oxygen

Oxygen in the groundwater may 'oxidise', or capture electrons from, the radionuclides. The number of electrons captured from a chemical element is known as its 'oxidation state' and is usually written in Roman numerals. The uranium solubility experiments considered above assumed that the uranium would be present as uranium (IV). [29] [30] However, uranium may be present as uranium (IV), (V) or (VI) [31] and under oxidising conditions, uranium will mainly be present as uranium (VI), not uranium (IV). [32] Uranium (VI) is relatively mobile. [33] In the presence of dissolved oxygen uranium dioxide (where the uranium is present as U(IV)) is oxidised to U(VI) and dissolves. [34] This reaction which has important implications for "uranium solubility" was studied by Brown (1991). [35] It was concluded that a change in the oxygen concentration from 10^{-5}M to 10^{-6}M would result in the oxidation of the uranium

---

28 Ewart (1989) NSS/G111, p16
29 Ewart (1988) NSS/G103, p11
30 Ewart (1989) NSS/G111, p16
31 Cooper (1987) NSS/R101, p15
32 Bloodworth (1989) NSS/R175, p9
33 Bloodworth (1989) NSS/R175, p9
34 Brown (1991) NSS/R188, p16
35 Brown (1991) NSS/R188, p16

dioxide to uranium trioxide [*36*] and consequently a considerable increase in the "uranium solubility".

ii) Reactions with Sodium and Calcium

Water in the repository will contain sodium and calcium ions that have been released from the concrete. [*37*] These may precipitate out with uranium (VI) as solids known as 'uranates' [*38*] and it is possible that the precipitation of uranates will determine 'uranium solubility' under these conditions. [*39*] A wide variety of sodium, calcium and mixed uranium (VI) uranates are known, but there are only limited data available for these solids and none for the equivalent uranium (IV) solids. [*40*] Experiments reported in 1988 supported the assumption that the uranates were formed, but did not provide precise data on their composition. [*41*]

In 1988, Nirex attempted to duplicate 'uranium solubility' results obtained experimentally by calculating what the solubility of uranium would be if it were controlled by the precipitation of a uranate solid. [*42*] However, none of the results reproduced the experimental solubility data. [*43*] In fact the best match between experimental and calculated 'solubilities' was achieved if a different compound altogether (hydrated trioxide) was used in the calculations. [*44*] [*45*] From these results, Nirex concluded that the solubility limiting solid in the experiments was none of the uranate solids considered in the calculations. [*46*] Nevertheless, it was concluded that the precipitate was still most likely to be a

---

36 Brown (1991) NSS/R188, p16
37 Cooper (1988) NSS/R133, p29
38 Greenwood (1984) p1473
39 Cooper (1988) NSS/R133, p29
40 Cooper (1988) NSS/R133, p29
41 Cooper (1988) NSS/R133, p29
42 Cooper (1988) NSS/R133, p29
43 Cooper (1988) NSS/R133, p29
44 Cooper (1988) NSS/R133, p29
45 Greenwood (1984) p1471
46 Cooper (1988) NSS/R133, p30

uranate and it was decided that relevant uranate data could be obtained by working backwards from the experimental results. [*47*]

In order to determine the composition of the uranate an X ray study was undertaken. Firstly precipitates of uranium (VI) in contact with solutions of sodium and calcium hydroxide, rather than cement water, were studied. Even with these simpler conditions it was not possible to identify the precipitates from the two solutions. However, it was decided to call the two solids "sodium uranate" and "calcium uranate" and use the X ray data from these to decide whether or not "sodium uranate" or "calcium uranate" was precipitated from uranium (VI) in cement water. [*48*] Two different solid precipitates were obtained depending on how much cement was used. [*49*] From the similarities and resemblances that Nirex perceived in the X ray data for the cement water precipitates, and the hydroxide solution precipitates, Nirex felt able to identify the solid formed from the liquid with less cement as "sodium uranate" and the solid formed from the liquid with more cement as "calcium uranate". [*50*] It was concluded that if there were any uranium present as uranium (VI) in the water in and around the repository its concentration might be controlled by the precipitation of calcium uranate. However, without crystalline material available for study it was difficult to identify what the solid was that was precipitating. [*51*] Without such knowledge the value of predictions of the behaviour of the solid is dubious.

---

47 Cooper (1988) NSS/R133, p30
48 Cooper (1988) NSS/R133, p36
49 Cooper (1988) NSS/R133, p37
50 Cooper (1988) NSS/R133, p37
51 Cooper (1988) NSS/R133, p38

iii)Reactions with Carbonate and Hydroxide

Limestone contains carbonate. [*52*] The extensive use of limestone in the repository will mean that carbonate is available in the water in and around the repository. This has significant implications for the value assumed for the 'uranium solubility' as the tendency for U(VI) to form chemical compounds with species such as carbonate is responsible for its relative mobility, as the compounds formed are soluble. [*53*] However, the difficulties associated with the identification of the dissolved chemical species that will contain the uranium may be appreciated by consideration of earlier calculations carried out by Nirex on 'uranium solubility', which assumed that dissolved uranium would be attached to hydroxide ions. The data used for the hydroxide species was estimated and adjusted such that the calculations fitted the experimental results. [*54*] The only relevant data available for use as a starting point for the estimates, had been measured under conditions where hydroxide complexes are not formed. [*55*] Nirex adjusted the estimates until the calculations fitted the experimental results. [*56*] It may be concluded the potential for such reactions to occur introduces considerable difficulties and uncertainties into the safety assessment.

6.3. VALIDATION TESTS

The generation of 'elemental solubility' data is problematic. The chemical systems that would be found under repository conditions are extremely complicated. Therefore, the identification and measurement of pertinent data for use in 'elemental solubility' calculations presents exceptional difficulties. In order to test the validity of the methodology that has been used, both Nirex and the DoE

52 Greenwood (1984) p133
53 Bloodworth (1989) NSS/R175, p9
54 Cooper (1988) NSS/R133, p30
55 Cooper (1988) NSS/R133, p30
56 Cooper (1988) NSS/R133, p30

have undertaken validation work. Three validation exercises are discussed below; the 'LIPAS' test; the 'REDOX' test; and the 'Pocos de Caldas' test which was carried out at a uranium mine in Brazil.

6.3.1. The LIPAS Test

Calculations such as those described above are based on data concerning the way that chemical stabilities change when two important parameters, the "pH" and the "redox potential", are changed. The pH is a measure of the hydrogen ion (H^+) concentration and the redox potential is a measure of the ability of the chemical system to alter the oxidation state of an added element. Nirex use a geochemical computer code to calculate the impact of pH and redox potential on the chemical species present. The code is known as PHREEQE, which stands for "**pH R**edox **Eq**uilibrium **E**quations". [*57*] It is used in conjunction with the HATCHES database, where HATCHES stands for "**Ha**rwell/Nirex **T**hermodynamic Database for **Ch**emical **E**quilibrium **S**tudies". [*58*]

As discussed above, the exact nature of the species present will significantly affect the behaviour of the radionuclides within the repository. [*59*] Therefore, it is important to have confidence that the computer calculations correctly predict which species will be present. In order to test the computer predictions, Nirex developed a laboratory technique that allowed chemical species in solution to be measured directly. [*60*] [*61*] The technique, known as LIPAS (Laser Induced Photoacoustic Spectroscopy), [*62*] measured the laser energy absorbed by the

---

57 Cross (1989) NSS/R119, p(i)
58 Cross (1989) NSS/R119, p(i)
59 Cross (1989) NSS/R119, p1
60 Cross (1989) NSS/R119, p(i)
61 Cooper (1987) NSS/R102, p16
62 Cross (1989) NSS/R119, Abs

species of interest. [63] By comparing this to the energies absorbed by a standard it is possible to attribute a given absorption peak to a particular species. In addition the peak height may be calibrated in order to allow the concentration of the species to be calculated. [64] It was hoped that the direct identification of the species present using the LIPAS technique, would provide confidence in the use of the computer codes and databases employed by Nirex. [65] [66] [67]

To provide controlled chemical conditions that would avoid the introduction of chemical reactions that would complicate the test; the equipment was carefully constructed using inert materials and care was taken to exclude trace chemicals that might interfere with the reactions that were included in the calculation. Inert plastics, ceramics, gold, [68] ruby and sapphire [69] were used in the design of the equipment. In addition, oxygen was prevented from entering the system by the use of a high purity helium gas purge and by operating the system in a nitrogen-atmosphere glove box. [70] [71] In order to minimise the interference from the carbonate ion, low carbonate content reagents were specially prepared. [72]

6.3.1.1. Tests on Uranium

Two tests were carried out, one at pH 1 and another at pH 8. First of all, the computer was used to predict which species would be present as an applied electrical potential was varied, then the prediction was tested using the LIPAS technique. At pH 1, it was predicted that the uranium could be present as U(IV),

---

63 Cross (1989) NSS/R119, p1
64 Cross (1989) NSS/R119, p5
65 Cross (1989) NSS/R119, p(i)
66 Francis (1988) NSS/R140, p16
67 Cooper (1988) NSS/R133, p28
68 Cross (1989) NSS/R119, p(i)
69 Cross (1989) NSS/R119, p4
70 Cooper (1988) NSS/R133, p64
71 Cross (1989) NSS/R119, p2
72 Cross (1989) NSS/R119, p6

U(V) or U(VI). [*73*] However, the proportion of uranium represented by each of these three oxidation states was expected to change as the applied electrical potential was changed. At the two extremes of applied potential only one oxidation state was expected, and this was found. [*74*] At the highest applied potential (0.28V), the highest oxidation state, U(VI) was found; and at the lowest applied potential (0V), the lower oxidation state, U(IV) was found. [*75*]

The real test of the computer code's ability to identify the precise proportions of the U(IV), U(V) and U(VI) that would be found, was provided at the intermediate value of the applied potential (0.16V). However, at this potential the match obtained between predicted results and observed results was poor. [*76*] In order to improve the match, the values of the parameters used in the calculations was changed. [*77*] The validity of altering parameters in order to "predict" results which have already been measured is highly questionable.

At pH 8 it was predicted that U(IV) would dominate throughout the experiment. [*78*] In fact, a mixture of U(IV), U(V) and U(VI) was observed. [*79*] Again modification of the parameters used by the computer code was undertaken in order to better match the "prediction" and the experimental results. [*80*] Two different modifications were tried. Neither was successful. One method had the result of predicting that U(V) would be present, rather than the mixture; and the other method required unreasonably high parameter values. [*81*]

---

73 Cross (1989) NSS/R119, p9
74 Cross (1989) NSS/R119, Fig 13
75 Cross (1989) NSS/R119, Fig 13
76 Cross (1989) NSS/R119, Fig 13a
77 Cross (1989) NSS/R119, p9
78 Cross (1989) NSS/R119, p10
79 Cross (1989) NSS/R119, Fig 21
80 Cross (1989) NSS/R119, p10
81 Cross (1989) NSS/R119, p10

It was concluded that the uranium database was inadequate. [*82*] Given that much of the data included was estimated it was considered that such inadequacies were likely. [*83*] In addition, it was considered that the assumption made in the calculations, that the rate of chemical reaction was irrelevant, was unlikely to be correct. [*84*]

6.3.1.2. Tests on Neptunium

The neptunium tests were not successful. It was predicted that under the conditions used, Np(IV) species would dominate, except at the highest pH and applied potential, where Np(V) would be found. [*85*] In fact, Np(V) dominated throughout the experiments and Np(IV) was not found. [*86*] The exact nature of the Np(V) species formed was problematic and the results were not readily explicable. [*87*] In addition to LIPAS, a second technique known as voltammetry was used a means of obtaining information on the neptunium species present in solution. [*88*] However, its use was unsuccessful and was abandoned. [*89*]

6.3.2. The Redox Test

In order to be in any position to ascribe an "elemental solubility" for a given element its oxidation state must be known. This will depend on the other chemicals that are present, as they may change the initial oxidation state of the

---

82 Cross (1989) NSS/R119, p10
83 Cross (1989) NSS/R119, p10
84 Cross (1989) NSS/R119, p10
85 Cross (1989) NSS/R119, pp 15, 31
86 Cross (1989) NSS/R119, pp 15,16
87 Cross (1989) NSS/R119, pp 15,16
88 Cross (1989) NSS/R119, p17
89 Cross (1989) NSS/R119, p18

element. An increase in oxidation number is known as oxidation, and a decrease is known as reduction. The potential of chemicals in the groundwater to oxidise or to reduce radionuclides is a critical parameter for the safety assessment. [*90*] [*91*] Nirex have commented that:

> "This is one of the most important chemical parameters affecting the release of radionuclides from wasteforms, since the solubility of a nuclide can vary by many orders of magnitude depending on its oxidation state. Certain nuclides are less soluble in their reduced form, so conditions of low E_h [oxidation potential] are desirable in the backfill pore water." [*92*]

The solubility of a number of important radionuclides is strongly dependent on the oxidation potential. [*93*] Some important radionuclides are less soluble in their lower oxidation states. [*94*] [*95*] For example, selenium is about 20,000 times less soluble in the reduced form [*96*] and technetium is about one billion times less soluble in the reduced form. [*97*] It has been assumed by Nirex that the corrosion of steel in the repository will establish reducing conditions [*98*] [*99*] through the production of hydrogen and iron (II). Hydrogen and iron (II) are assumed to determine the oxidation potential that will be found in the repository. [*100*] [*101*] [*102*]

One of the first major applications by Nirex of the CHEQMATE (**CH**emical **EQ**uilibrium with **M**igration **A**nd **T**ransport **E**quations) [*103*] computer code was

---

90 Atkinson (1988) NSS/R104, p5
91 Ewart (1988) NSS/G103, p1
92 Cooper (1987) NSS/R101, p78
93 Ewart (1988) NSS/G103, p18
94 Atkinson (1988) NSS/G102, p2
95 Cooper (1987) NSS/R101, p13
96 Pilkington (1988) NSS/R116, p7
97 Pilkington (1988) NSS/R120, p2
98 Atkinson (1988) NSS/G102, p2
99 Atkinson (1988) NSS/R104, p5
100 Atkinson (1988) NSS/R104, p2
101 Cooper (1987) NSS/R101, p13
102 Cooper (1987) NSS/R102, p20
103 Cooper (1987) NSS/R101, p77

the prediction of the evolution of the oxidation potential in the repository. [*104*] This calculation was very important as the oxidation potential assumed to be generated by the corrosion products is used to define the chemistry of the repository environment for further calculations and experiments. [*105*] [*106*] In 1988, Nirex commented that the assumption, that reducing conditions would be established fairly quickly in the repository and would be maintained for a long period, had been justified by the computer calculations. [*107*] Although in 1989 it was noted that:

> "this may not be a valid assumption when the modelling extends beyond 10^6 years" [*108*]

It was assumed in the calculation that initially the repository would be saturated with oxygen which would produce oxidising conditions. [*109*] However, as the steel in the repository corroded the oxygen would be used up and hydrogen and iron (II) would be generated. [*110*] The computer code calculated oxygen depletion as a function of time, and as a function of distance from steel. [*111*] Hydrogen concentration as a function of time was also calculated [*112*] and used to calculate the predicted oxidation potential. [*113*] Given that the predicted hydrogen concentration was several orders of magnitude greater than the predicted iron (II) concentration, it was considered correct to assume that the oxidation potential would be controlled by the hydrogen concentration. [*114*] Nirex stated that:

> "the absence of significant influence from the aqueous hydrogen (which) seems unlikely" [*115*]

---

104 Cooper (1987) NSS/R101, p78
105 Ewart (1988) NSS/G103, p1
106 Guppy (1991) p3
107 Ewart (1988) NSS/G103, p26
108 Ewart (1989) NSS/G111, p6
109 Cooper (1987) NSS/R101, p78
110 Cooper (1987) NSS/R101, p79
111 Cooper (1987) NSS/R101, p80
112 Cooper (1987) NSS/R101, p80
113 Cooper (1987) NSS/R101, pp 81,85
114 Cooper (1987) NSS/R101, pp 80-81
115 Cooper (1987) NSS/R101, p85

Nirex commented that the sensitivity of their prediction to the most uncertain parameters had been tested. [*116*] Sensitivity studies were carried out on: the pressure at which gas bubbles form; [*117*] the choice of solid corrosion products used in the calculation; [*118*] the corrosion rate [*119*] and the diffusion rates. [*120*]

A validation test of the calculations was undertaken in work commissioned by the DoE. A central assumption of Nirex safety assessment work is that equilibrium between all oxidising and reducing species can be guaranteed. [*121*] In order for the arguments used in the safety assessment to be sustainable, it is necessary that this assumption is valid. [*122*] However, the results of the validation test indicated that it is not possible to demonstrate conclusively that equilibrium will be attained. [*123*] This problem is particularly important for dissolved hydrogen which is generally considered to be inert. [*124*] The DoE report concluded that:

> "an assumption that the hydrogen will control the E_h [oxidation potential] of the repository ... seems unreasonably optimistic." [*125*]

A further complication is introduced by the presence of radioactivity. Radioactivity in the repository may produce oxidising conditions [*126*] through the impact of the chemicals produced by the radiolytic dissociation of water. [*127*] It is possible that, not only will the radiolysis products oxidise the radionuclides that they come into contact with, but in addition, the iron (II) in the repository

---

116 Cooper (1987) NSS/R101, p79
117 Cooper (1987) NSS/R101, p82
118 Cooper (1987) NSS/R101, p82
119 Cooper (1987) NSS/R101, p83
120 Cooper (1987) NSS/R101, p84
121 Guppy (1991) Abs
122 Guppy (1991) p3
123 Guppy (1991) Abs, ES
124 Guppy (1991) ES, pp 3,4,24,26
125 Guppy (1991) p24
126 Guppy (1991) p3
127 Guppy (1991) p27

could be oxidised to iron (III). [*128*] This would shift the oxidation potential of the repository as a whole. [*129*] Given the low concentration of iron (II), it would require only very small concentrations of radiolysis products to shift repository potential and produce oxidising conditions. [*130*]

Overall the report concluded that:

> "it is conceivable that a situation will arise whereby higher concentrations of radioelements will exist in the aqueous phase of the repository than would be predicted from thermodynamic calculations or from laboratory experiments in which unrealistic concentrations of reducing species have been used to establish the redox potential." [*131*]

6.3.3. The Pocos de Caldas Test

In 1991, Nirex reported the results of a field test, carried out at the Pocos de Caldas uranium mine in Brazil, of uranium solubility calculations. [*132*] It was assumed for the solubility calculation that the uranium would be present as uranium dioxide. [*133*] On this basis, the predicted solubility of the uranium was calculated to be 1.4 x 10^{-11} mg/l (6 x 10^{-17} M). [*134*] The measured concentration at the site was 3 x 10^{-3} mg/l (1 x 10^{-8} M) - a 200 million fold error. [*135*]

Nirex did not establish the cause of the error. Strangely the report concluded that:

---

128 Guppy (1991) p27
129 Guppy (1991) p27
130 Guppy (1991) p4
131 Guppy (1991) p4
132 Cross (1991) NSS/R252, p (i)
133 Cross (1991) NSS/R252, pp 8,12
134 Cross (1991) NSS/R252, pp 9,10
135 Cross (1991) NSS/R252, p10

"The results of these calculations give further encouraging agreements with field data ... and generally continue(s) to give confidence in the validity of using such modelling techniques in other problems associated with the migration of radionuclides away from a nuclear waste repository." [*136*]

6.4. SUMMARY

The Nirex safety assessment computes the carriage of radionuclides in contaminated groundwater, using one parameter the "elemental solubility" for each radionuclide. This parameter is derived from secondary computations which purport to specify the appropriate 'elemental solubility' under the projected repository conditions. However, the chemical systems involved are extremely complex and present prohibitive computational difficulties. Analysis of the methodology used to generate the 'elemental solubility' data indicates that the approach confounds chemical authenticity. This conclusion is confirmed by the failure of the validation tests which have been undertaken in order to assess the authenticity of the approach. Due to the diversity of chemical behaviour, reliance on a single parameter for each element does not provide a robust approach to safety assessment.

---

136 Cross (1991) NSS/R252. p14

7. DIFFICULTIES IN THE ASSESSMENT OF THE QUANTITY OF RADIONUCLIDES THAT WILL DISSOLVE IN GROUNDWATER

7.1. INTRODUCTION

In the previous chapter, it was demonstrated that the methodology used by Nirex in order to calculate the quantity of radionuclides that will be carried from the repository in groundwater is not able to generate robust data for the safety assessment. In this chapter, it will be demonstrated that this problem will not be overcome simply by an extended period of data gathering as the underlying concepts used to generate the data are fundamentally flawed. In order to overcome these difficulties, it will be shown that a significant commitment of additional resources would be required to ensure that the underlying assumptions used, to calculate the quantity radionuclides expected to dissolve, are soundly based.

Three problems will be considered in this chapter. Firstly, the assumption that the chemical species carrying the radionuclide may be readily identified. Secondly the assumption that the quantity of a given species can be readily calculated and thirdly, the assumption that radionuclides will be exclusively carried in the groundwater as dissolved species.

7.2. IDENTIFICATION OF THE COMPOUNDS CARRYING RADIONUCLIDES

In order to calculate the quantity of radionuclides that will be carried by the groundwater, the identity of the chemical species that will be carrying the radionuclides must be known. This is problematic as the groundwater will contain a large number of chemicals that could react with the radionuclides and produce a large number of chemical compounds. These difficulties are increased by the presence of a diverse and complicated variety of organic chemicals, which are released when the organic material in the repository breaks down. Nuclear waste contains organic materials such as paper and plastic. In the repository these materials will break down to produce small organic chemicals which may react with radionuclides and produce soluble compounds. [*1*] This effect will increase the quantity of radionuclides that may be carried by groundwater migrating from the repository and, therefore, has important implications for the safety assessment. [*2*] In 1989, the IAEA concluded that the solubility increase caused by organic break down products could increase the radiological impact of the repository above the regulatory target dose. [*3*]

Given this problem, Nirex must demonstrate that the identity of the chemicals causing the solubility increase have been identified, and will not lead to doses above the regulatory limit. If this is not possible, organic material must be excluded from the repository.

---

1 Ewart (1989) NSS/G111, p42
2 Ewart (1988) NSS/G103, p19
3 IAEA (1989) in George (1989) NSS/R199, p3

7.2.1. Identification of Organics

Developing a full understanding of the behaviour of organic material in the repository, in order to identify the chemicals responsible for the solubility increase, is difficult. Nuclear waste contains a wide variety of organic materials and each of these may break down in many different ways. Therefore, the prediction of which organic chemicals will finally be produced and the effects that they will have on radionuclide solubility, is a formidable task. A large volume of the wastes to be placed in the repository will contain organic materials. Approximately 400,000 cubic metres of the waste will consist of cellulosic material (such as paper and wood); 200,000 cubic metres of the waste will consist of plastics; and approximately 150,000 cubic metres of the waste will be contaminated soil. [*4*] [*5*] The organic waste streams which are of particular relevance for the safety assessment are those which contain a number of major organic components (such as polyvinylchloride, polyethylene, neoprene rubber, Hypalon rubber, and cellulosic materials) as well as a host of other materials that will include at least traces of a wide variety of commercially available plastics and rubbers. [*6*]

There are several mechanisms by which the organic materials in the repository may decompose to produce smaller organic chemicals. The most important mechanisms are those caused by the alkalinity of the concrete pore water; the radiation from the waste; and the effects of microbes. [*7*] The identity of the chemicals produced will depend on the original composition of the material. Materials that contain cellulose are particularly vulnerable to decomposition under repository conditions and will form a complex series of products. [*8*] [*9*] Analysis

4 Hodgkinson (1987) NSS/A100, p14
5 Nirex (1989) Deep Repository Project, Table 2.2
6 Cross (1989) NSS/R151, p1
7 Berry (1989) NSS/R183, p1
8 Ewart (1988) NSS/G103, p19

of the chemicals formed during experiments on decomposition. has indicated that a wide range of chemicals are produced. [*10*] [*11*] Due to the diversity of organic materials found in nuclear waste, and the complexity of the reaction pathways that lead to the decomposition, it is difficult to predict in detail which break down products will be formed. [*12*] [*13*]

The impact of the decomposition products on radionuclide solubility has been tested by Nirex. The results have indicated increases in solubility for all of the organic materials tested [*14*] [*15*] and have demonstrated that very low concentrations of organics may significantly increase radionuclide solubility. [*16*] Trace concentrations of certain organics were observed to increase plutonium solubility over one thousand times. [*17*] However, these experiments do not provide information on the identity, or concentration, of the chemicals that are causing the effect. [*18*] It is this primary data, on the identity of the chemicals causing the effect, which is required in order to develop a fuller understanding of the behaviour of organic material, such that the long term predictions required for the safety assessment may be undertaken. [*19*]

As Nirex do not have the primary data needed for the safety assessment, a variety of alternative strategies have been adopted in order to attempt to develop an understanding of the behaviour of organic materials in the repository. For example, work has been done to attempt to correlate organic decomposition products from existing waste sites to radionuclide solubilities. [*20*] However,

---

9 Cooper (1987) NSS/R102, p21
10 Cross (1989) NSS/R151, p1
11 Berry (1989) NSS/R183, p1, Fig 1
12 Cross (1989) NSS/R151, p(ii)
13 Atkinson (1988) NSS/R104, pp9,10
14 Cross (1989) NSS/R151, p(ii)
15 Ewart (1989) NSS/G111, p28
16 Cooper (1989) NSS/R168, pp 10,12
17 Ewart (1988) NSS/G103, p19
18 Greenfield (1990) p71
19 Greenfield (1990) p71
20 Cooper (1988) NSS/R133, p74

despite the large amount of data published on leachates from waste sites, it was not possible to relate the degradation of individual waste fractions directly with the observed radionuclide solubilities. [*21*] A second area of work involved an attempt to duplicate the effect of waste decomposition products on radionuclide solubility, through the synthesis of a "laboratory leachate". [*22*] However, the project was unsuccessful. The artificial leachate did not increase solubility to the extent found for the real leachate. [*23*] This indicated that an unidentified chemical had been left out of the synthetic mixture. [*24*] A third set of experiments, specifically aimed at attempting to reproduce the effects of the cellulose decomposition products have been undertaken. Cellulose break products are believed to produce the largest increase in radionuclide solubility and increases of 10 000-fold have been observed. [*25*] [*26*] In order to attempt to reproduce this effect, chemicals believed to be implicated in the solubility increase were isolated and studied. [*27*] However, it was not possible to identify the chemical which was responsible for the solubility increase. [*28*]

Due to the lack of data, and the lack of understanding, the incorporation of the organics effect in safety assessment calculations is difficult. Early attempts by Nirex to calculate the effect of organic degradation products on radionuclide solubility were not successful and did not reproduce the experimental results. [*29*] In 1987 Nirex wrote that:

> "sufficient experimentally determined data were found to enable the prediction of [plutonium organic complexes] ... appropriate to the near-field." [*30*]

---

21 Cooper (1988) NSS/R133, p74
22 Cooper (1988) NSS/R133, p97
23 Cooper (1988) NSS/R133, p97
24 Cooper (1988) NSS/R133, p97
25 Cross (1989) NSS/R151, p(ii)
26 Ewart (1988) NSS/G103, p19
27 Cross (1989) NSS/R151, p1
28 Cross (1989) NSS/R151, p(i)
29 Cooper (1988) NSS/R133, p30
30 Cooper (1987) NSS/R101, p21

Subsequent work carried out by Nirex highlighted the inadequacies of the database. In 1989, Nirex attempted to use their database to predict plutonium solubilities measured during experiments. [*31*] However, it was found that the database was insufficient and had to be extended. [*32*] Only limited data was available from the literature to extend the database and it was necessary to estimate data, using data obtained from different organic chemicals [*33*] and different radionuclides. [*34*] The results of the preliminary calculations using the extended database indicated that none of the chemical species that had been included in the calculation were able to account for the relatively high plutonium solubilities observed in the experiments. [*35*]

7.2.2. Exclusion of Organics

The problem of solubility enhancement due to the presence of organics has introduced a great deal of uncertainty concerning the acceptable disposal criteria for organic material contaminated with long-lived radionuclides such as plutonium. [*36*] Nirex have not yet specified the conditions, if any, under which it will accept for disposal organic material contaminated with long-lived radionuclides. [*37*] A solution to the problem is still awaited. [*38*] Presently there are approximately 20,000 drums, 2,500 filters and 400 crates of plutonium contaminated material in storage in some 13 different buildings at Sellafield and Drigg and at open locations around the site. [*39*] Storage in this "raw" state is unsatisfactory [*40*] and the delays caused by the lack of a final decision from

---

31 Cross (1989) NSS/R151, p(ii)
32 Cross (1989) NSS/R151, p(iii)
33 Cross (1989) NSS/R151, p(iii)
34 Cross (1989) NSS/R151, pp (iii),3
35 Cross (1989) NSS/R151, p3
36 Health and Safety Commission (1992) p6
37 Health and Safety Commission (1992) p6
38 Health and Safety Commission (1992) p9
39 Health and Safety Commission (1992) p7
40 Health and Safety Commission (1992) p7

Nirex increase the operator doses arising from the wastes. [*41*] There is also the possibility of a fire in one of the stores. [*42*] The condition of some of the waste containers is a cause for concern and it is necessary, periodically, to repackage some of the wastes. [*43*] This results in operator exposure due to the inspections and the movement and shuffling required to gain access to the degraded waste packages. [*44*] The radioactivity of material contaminated with plutonium increases with time due to the growth of other nuclides such as americium produced from plutonium decay. [*45*] It is estimated that the doses arising from the plutonium stores will double in the twelve years from 1988 to 2000. [*46*]

BNFL propose to mix the wastes with cement. [*47*] However, formal agreement has not been sought or given to mix either plutonium contaminated material or raw intermediate level wastes containing organics with cement [*48*] as this would not serve to exclude organic material from the repository. Two other waste management options, incineration and separation, which would result in the exclusion of the organic material, have been rejected. Incineration is problematic due to the high levels of plutonium, which introduces the threat of a criticality accident. [*49*] BNFL have concluded that the disadvantages of incineration outweigh the advantages. [*50*] Separation of contaminated organic material has been considered, but is not thought to be practicable. [*51*] It may therefore be concluded that the difficulties associated with the presence of organic materials in nuclear waste, have not yet been resolved.

---

41 Health and Safety Commission (1992) p9
42 Health and Safety Commission (1992) p7
43 Health and Safety Commission (1992) p7
44 Health and Safety Commission (1992) p7
45 Health and Safety Commission (1992) p4
46 Health and Safety Commission (1992) p7
47 Health and Safety Commission (1992) pp 5,7
48 Health and Safety Commission (1992) p7
49 Health and Safety Commission (1992) p7
50 Health and Safety Commission (1992) p8
51 Health and Safety Commission (1992) p6

7.3. CALCULATION OF THE QUANTITY OF COMPOUNDS CARRYING RADIONUCLIDES

If it is assumed that it is possible to identify the chemical species that are carrying the radionuclides in the groundwater, the quantity of radionuclides carried in the groundwater is then calculated using data on the extent to which the dissolved species will be formed. In order to quantify the extent to which a particular species will be formed, the chemical equilibrium constant, 'K', must be known for that species. However, the K values for each species (and therefore the extent to which a given species will be formed) vary considerably as the chemical conditions change. In order to calculate the quantity of a particular species that will formed, it is important to use the correct value for K.

One particularly important variable that affects K values is the ion concentration. Ions carry an electrical charge and even if the ions present do not react with radionuclides directly, they will interact with them electrostatically and affect their reactions with other chemicals. [52] In order to attempt to quantify this effect, chemists specify a value for K under hypothetical conditions, which is known as K_0, and use an equation to predict how K will change as the concentration of dissolved ions is changed. [53] [54] These equations affect practically all the chemical data that Nirex use for the safety assessment, and errors in the extrapolation between K values could lead to major errors in the calculation of the quantity of radionuclides that will be carried by groundwater. [55] Nirex have reported extrapolation errors of the order of 10 million. [56]

52 Cooper (1988) NSS/R133, p32
53 Atkins (1982) pp 263-264,315-316
54 Cooper (1988) NSS/R133, p32
55 Cooper (1988) NSS/R133, p32
56 Colston (1990) NSS/R204, ES. [Calculated range of K_0 varied from 0.06 to 10^6]

This problem is exacerbated by the fact that the extrapolation has to be carried out twice, firstly a measured K value taken from chemical literature has to be recalculated to give a K_0 value, and secondly K must be recalculated under repository conditions. [*57*] The extrapolation difficulties are more acute at high ion concentrations, where the available equations are subject to more uncertainty. The only completely theoretical approach to the problem, Debye-Huckel theory, [*58*] is limited to such low ion concentrations that it is irrelevant to most practical situations. [*59*] [*60*] [*61*] However, for many reactions, K values cannot be measured accurately, or at all, at low ion concentration [*62*] and the great majority of experimental data reported in the chemical literature has been obtained at high ion concentrations. [*63*] This is invariably true for reactions involving ions of high charge which includes most actinide species. [*64*] The actinide series includes uranium, plutonium and neptunium. Nearly all of the equilibrium constants of the actinides have been measured at high ion concentration. [*65*]

An alternative to Debye-Huckel theory is the Davies equation, which is one of the most widely used methods for extrapolating K values. [*66*] The Davies equation is purely empirical. [*67*] [*68*] It extends the extrapolation range to some extent, and has been used by Nirex, as it is available as an option on the computer code that they use. [*69*] However, it is only strictly valid up to about 0.1 M. [*70*] [*71*] By comparison, most measurements in the chemical literature, are made at

---

57 Colston (1990) NSS/R204, ES
58 Atkins (1982) p316
59 Chandratillake (1988) NSS/R149, p3
60 Cooper (1988) NSS/R133, p32
61 Atkinson (1988) NSS/G102, p35, Fig 12
62 Chandratillake (1988) NSS/R149, p2
63 Colston (1990) NSS/R204, p7
64 Chandratillake (1988) NSS/R149, p2
65 Colston (1990) NSS/R204, p3
66 Colston (1990) NSS/R204, p4
67 Colston (1990) NSS/R204, p5
68 Cooper (1988) NSS/R133, p32
69 Chandratillake (1988) NSS/R149, p6
70 Cooper (1988) NSS/R133, p32
71 Chandratillake (1988) NSS/R149, p3

concentrations of about 4-5 M. [*72*] K_0 values obtained from these measurements through the use of the Davies equation, may be "completely meaningless". [*73*] In 1988, Chandratillake reported an urgent need for an alternative equation to use for the extrapolation. [*74*]

The extrapolation method generally agreed to be the best is called the "Pitzer method" [*75*] and results from this method can be impressive. [*76*] [*77*] However, the Pitzer method requires a large number of parameters, some of which have not been measured, and some may even be unmeasurable. [*78*] For most situations too many parameters are required to make application of the approach a practical proposition [*79*] [*80*] and the Pitzer method has been rejected by Nirex due to the lack of sufficient data. [*81*]

Given these problems, Nirex have returned to the Davies equation. However, in order to avoid the large errors found at high ion concentrations, Nirex have adopted a modified version of the equation known as the "Truncated Davies" equation, which is the same as the Davies equation up to 0.3 M. [*82*] [*83*] At concentrations higher than this the Truncated Davies equation simply assumes that the magnitude of the correction remains the same as the value obtained at 0.3 M. [*84*] [*85*] This rather ad hoc approach has been considered acceptable by

---

72 Cooper (1988) NSS/R133, p32
73 Brown (1991) NSS/R188, p5
74 Chandratillake (1988) NSS/R149, p6
75 Chandratillake (1988) NSS/R149, p3
76 Chandratillake (1988) NSS/R149, p4 see also Fig 1
77 Cooper (1988) NSS/R133, p32
78 Chandratillake (1988) NSS/R149, p5
79 Cooper (1988) NSS/R133, p32
80 Brown (1991) NSS/R188, p5
81 Chandratillake (1988) NSS/R149, p6
82 Brown (1991) NSS/R188, p5
83 Colston (1990) NSS/R204, ES, p5, Fig 6
84 Brown (1991) NSS/R188, p5
85 Colston (1990) NSS/R204, ES, p5, Fig 6

Nirex given the large uncertainties associated with the quality of the data. [*86*]

Nirex have commented that given the lack of data:

> "there must be a considerable element of speculation in any proposed procedures." [*87*]
>
> "for the great majority of experimental studies, ... there are insufficient data to define accurately ... the thermodynamic equilibrium constants." [*88*]

It may be concluded that the calculations undertaken by Nirex, in order to assess the quantity of radionuclides that will be carried by a particular chemical species, are of questionable validity as the procedures undertaken to elicit pertinent data from the available chemical literature are subject to a considerable degree of uncertainty.

7.4. INCLUSION OF ALL COMPOUNDS CARRYING RADIONUCLIDES

The simple picture of radionuclides existing in the repository either dissolved in water or precipitated as a solid, ignores the presence of colloids. Colloids are very fine suspended particles which have properties in between those of a solution and a fine suspension. The presence of colloids within the repository radically undermines the concept of solubility that is assumed in the safety assessment.

7.4.1. The Importance of Colloids

The presence of colloids in the repository and the surrounding rock can increase the capacity of water to carry radionuclides out of the repository [*89*] [*90*] and

86 Colston (1990) NSS/R204, pp 4,5,8
87 Colston (1990) NSS/R204, p7
88 Colston (1990) NSS/R204, p8
89 Cooper (1988) NSS/R133, p139

increase the speed that contaminated water will reach the surface. [*91*] [*92*] [*93*] The fact that radionuclides may be bonded to colloids that are dispersed in water migrating from the repository provides a mechanism for the transport of radionuclides that is faster than would be predicted by other mechanisms. [*94*] In 1989, Nirex commented:

> "There is increasing evidence that many radionuclides associate with organic or inorganic colloids and that such association may affect the expected mobilities of the radionuclides in the geosphere." [*95*]

Radionuclides may form colloids themselves, [*96*] or may become attached to colloidal particles already present in the groundwater. [*97*] In addition, colloids containing radionuclides may be generated from repository construction materials. [*98*] [*99*] [*100*] [*101*] Each of these processes can increase the radionuclide burden that may be carried by groundwater migrating from the repository. [*102*]

7.4.2. Colloid Mobility

If the colloid is small enough to be carried through the pores in the rock surrounding the repository it may have a significant impact on the quantity of radionuclides that may be carried from the repository to the surface. [*103*] In addition to size, colloid mobility will also be related to the density, chemical

---

90 Ewart (1989) NSS/G111, p40
91 Lever (1990) NSS/G113, p(iv)
92 Cooper (1988) NSS/R133, p139
93 Ivanovich (1989) NSS/R206, p22
94 Cooper (1987) NSS/R102, p31
95 Longworth (1989) NSS/R165, p(i)
96 See for example Greenwood (1984) pp 451,458,1478
97 Longworth (1989) NSS/R165, p1
98 Longworth (1989) NSS/R165, p1
99 Cooper (1987) NSS/R101, p151
100 Lever (1989) NSS/G105, p25
101 Lever (1990) NSS/G113, p36
102 Longworth (1989) NSS/R165, p1
103 Cooper (1987) NSS/R101, p149

characteristics and electrical charge of the colloid. [*104*] [*105*] It is possible that electrical forces between a charged colloid and the charged walls of rock pores may act to keep colloids away from the walls of the pore space and therefore lead to faster transport than would otherwise be expected. [*106*]

7.4.3. Colloid Sources

In addition to the colloids which are formed by the radionuclides themselves, there are numerous other colloids available that may capture radionuclides. Significant amounts of colloids may be released from cements [*107*] and many of the materials present in the repository may produce colloids. For example, waste material, buffer, backfill, cementitious grouts, [*108*] and corrosion products present in the repository [*109*] are all capable of forming colloids. It is also possible that colloids may form at the rock/repository interface [*110*] and additional colloids may be formed as radionuclides interact with chemicals in the rock. [*111*]

Colloids are ubiquitous in the environment. [*112*] They are found in most rock/water systems and naturally occurring radionuclides are often associated with them. [*113*] These colloids may be based on materials as diverse as iron oxides, clay minerals, detrital silica, calcite, and organic molecules such as humic and fulvic acids [*114*] [*115*] and materials such as iron/manganese oxyhydroxides are

---

104 Lever (1989) NSS/G105, p25
105 Lever (1990) NSS/G113, p35
106 Lever (1990) NSS/G113, p35
107 Cooper (1987) NSS/R101, p151
108 Lever (1989) NSS/G105, p25
109 Lever (1990) NSS/G113, p36
110 IAEA (1989) in George (1989) NSS/R199, p6
111 Longworth (1989) NSS/R165, p17
112 Cooper (1988) NSS/R133, p132
113 Lever (1990) NSS/G113, p36
114 Ivanovich (1989) NSS/R206, p22
115 Longworth (1989) NSS/R165, p1

able to bind heavier metals such as the actinides into stable transportable colloidal complexes. [*116*]

7.4.4. Colloids and Solubility

It is clear that colloids are able to increase the concentration of radionuclides above the 'elemental solubility'. [*117*] However, the extent to which colloids are formed and their behaviour under repository conditions present very complex difficulties for the safety assessment. [*118*] Most actinide activity in water migrating from the repository will be present as colloids. [*119*] However, the experimental programmes undertaken by Nirex in order to obtain values for the "elemental solubilities" of radionuclides, remove any colloids formed. [*120*] [*121*] In response to this dilemma Nirex have proposed that the word 'solubility' should be redefined in terms of the pore size of the cement and the concrete:

> "The apparent solubility ... will depend strongly on the method of solid liquid phase separation used in the experiment. In order to apply the results of such experiments to the actual repository, a more rigorous definition of a solution derived from a knowledge of the pore size of the concrete and host geology is desirable." [*122*]

The importance of colloid formation as a determinant of solubility was highlighted by the 'equilibrium leach test' programme undertaken by Nirex, in order to simulate the chemical conditions that would be found in a repository. [*123*] It was found that radionuclides may be present in water largely as colloids or fine particles. [*124*] For example, a 1000 fold increase in the plutonium

---

116 Ivanovich (1989) NSS/R206, p25
117 Ewart (1988) NSS/G103, p26
118 Ewart (1988) NSS/G103, p25
119 Cooper (1989) NSS/R168, p9
120 Ewart (1989) NSS/G111, p40
121 Pilkington (1988) NSS/R116, p5
122 Ewart (1988) NSS/G103, p25
123 Biddle (1989) NSS/R130, p(i)
124 Biddle (1989) NSS/R130, p18

concentration over a twelve month period was observed [*125*] which was attributed to colloid formation. [*126*] It was observed that:

> "The evidence indicates that radionuclides may be present in leachates in largely colloidal or very fine particulate form. *This emphasises the need for the more comprehensive use of some form of membrane filtration in future tests*." [*127*] (My emphasis)

The rock surrounding the repository may not provide this level of filtration, [*128*] and therefore the use of such filtration techniques to generate data for the safety assessment must be treated with caution.

7.4.5. Nirex Research on Colloids

The Nirex colloid research programme was given formal authorisation in early 1987. [*129*] The objective of the research programme undertaken, was to establish whether colloids would have an important role in the transport of radionuclides from the repository. [*130*] In particular, it was hoped to establish whether colloid transport would result in higher radionuclide concentrations than would otherwise be expected. [*131*] It was noted that if colloid effects were found to be significant, the data obtained from the research programme would have:

> "direct application in models to predict colloid transport processes, which will be required in site assessments." [*132*]

It was noted that:

---

125 Biddle (1989) NSS/R130, pp 16,17, Fig 5
126 Biddle (1989) NSS/R130, pp 16,17
127 Biddle (1989) NSS/R130, p18
128 Pilkington (1988) NSS/R116, p7
129 Cooper (1987) NSS/R101, p151
130 Cooper (1987) NSS/R101, p152
131 Cooper (1987) NSS/R101, p152
132 Cooper (1987) NSS/R101, p152

> "This task is experimentally challenging, but will be an essential requirement to assess the potential role colloids may have in any migration process." [*133*]

Experimental work on colloids is extremely difficult, and variables such as time. temperature, initial concentration, presence or absence of cement, and cement type, may affect the results obtained. [*134*] For example, lead solubility values obtained experimentally varied 2 million-fold depending on the initial lead concentration. [*135*] It was considered that this variation could be due to colloid formation. [*136*]

Natural colloid systems are complex and ill-defined. [*137*] Attempts to characterise natural colloids by ascribing physical properties to them, gives different results depending on the technique used. [*138*] Moreover, a literature review on natural colloids carried out for Nirex, concluded that the nature of the colloids found would be specific to the particular site studied. [*139*] The colloid work undertaken by Nirex in 1987 was specifically aimed at the type of colloids likely to be found at the four disposal sites Nirex later abandoned. [*140*] [*141*]

7.4.6. The Inclusion of Colloids in the Safety Assessment

Despite the assurances given by Nirex in 1987, the potential for colloidal species to increase the concentration of the radionuclides in water carried from the repository is not adequately included in the safety assessment. [*142*] [*143*] The

133 Cooper (1987) NSS/R101, p151
134 Berry (1988) NSS/R122, p(ii)
135 Cooper (1988) NSS/R133, p43
136 Cooper (1988) NSS/R133, p43
137 Cooper (1988) NSS/R133, p133
138 Cooper (1988) NSS/R133, p133
139 Cooper (1987) NSS/R101, pp 46-47
140 Cooper (1987) NSS/R101, p151
141 RWMAC (1990) Waste Watchers, pp 4-5
142 Ewart (1988) NSS/G103, p25
143 Ewart (1989) NSS/G111, p39

impact of colloids has not been directly included in the assessment [*144*] as the behaviour of colloids is not sufficiently understood. [*145*] Although scoping calculations have been undertaken to assess the chemical behaviour of colloids, they are of necessity simple [*146*] and are based on crude approximations [*147*]. They may prove to be inadequate when improved data becomes available. [*148*] [*149*]

In 1989, Ivanovich, in a report commissioned for Nirex concluded that colloids appeared to be capable of transporting a significant proportion of mobile actinides. For example, natural organic colloids are able to carry more that 80% of the uranium isotopic load and can cause a hundredfold or more enhancement of thorium isotope transport. [*150*] Ivanovich concluded that the presence of colloids required a new approach to the calculation of the radionuclide content of groundwater migrating from a repository [*151*] which demanded a large amount of additional data. [*152*]

However, Lever reported in 1990 that:

> "The understanding of the importance of [mobile colloids] has not reached the stage for them to be included explicitly in assessment models" [*153*]

---

144 Ewart (1989) NSS/G111, p8
145 Ewart (1989) NSS/G111, p40
146 Lever (1989) NSS/G105, p26
147 Lever (1990) NSS/G113, p37
148 Lever (1989) NSS/G105, p26
149 Lever (1990) NSS/G113, p37
150 Ivanovich (1989) NSS/R206, p25
151 Ivanovich (1989) NSS/R206, p25
152 Ivanovich (1989) NSS/R206, p26
153 Lever (1990) NSS/G113, p14

7.5. SUMMARY

It was concluded in the previous chapter that, due to the diversity of chemical behaviour that will be found in the Nirex repository, reliance on a single parameter for each radionuclide, in order to compute the quantity of radioactivity that will be carried by the groundwater, does not provide a robust approach to safety assessment. In this chapter, it has been demonstrated that this problem will not be overcome simply by an extended period of data gathering as the underlying concepts used to generate the data are fundamentally flawed. Three examples were considered. Firstly, the assumption that the chemical species carrying the radionuclide may be readily identified, is undermined by the presence of a complex variety of organic chemicals which form highly soluble radionuclide compounds that Nirex have not be able to identify. Secondly, the assumption that the quantity of a given species can be readily calculated, is undermined by the inadequacies of the methodology used by Nirex to derive pertinent data from the chemical literature. Finally, the assumption that radionuclides will be exclusively carried in groundwater as dissolved species, is undermined by the presence of colloids. Colloids may carry a significant quantity of radionuclides, but due to lack of understanding they are not adequately included in the safety assessment.

In order to overcome the difficulties outlined in this chapter a significant commitment of additional resources would be required.

8. WATER FLOW FROM THE REPOSITORY

8.1. INTRODUCTION

The previous two chapters considered the methodology used by Nirex to calculate the quantity of radionuclides that will be carried by groundwater migrating from the repository. The following two chapters will consider (i) the methodology used by Nirex to calculate the rate that groundwater carrying radionuclides is carried back to the human environment; and (ii) the approach that has been taken by Nirex to hydrogeological considerations. This chapter will consider the methodology used by Nirex to predict the rate and direction of groundwater flow. The incorporation of groundwater flow considerations into the selection of the site for the proposed repository will also be considered. The following chapter will consider Nirex's proposal to begin excavation at the proposed repository site.

The repository Nirex propose to construct has the same volume as the Channel tunnel [*1*] and is designed to hold over three million tonnes [*2*] of radioactive waste. Nirex have calculated that groundwater will enter the repository at a rate of 300 cubic metres per day [*3*] and that within 10 years the repository will become saturated [*4*] and groundwater will begin to flush the radioactivity out of the repository. [*5*] Groundwater is an important resource [*6*] [*7*] and provides 35% of the water used by the public in the UK. [*8*] The risk of contaminated

---

1 Barker (1992) p40
2 Nirex (1989) Deep Repository Project, Table 2.2
3 Cox (1989) NSS/R141, p(iii)
4 Cox (1989) NSS/R141, p8
5 Windsor (1989) NSS/R158, p(iii)
6 Mather (1988) Groundwater Pollution, p39
7 Price (1985) p1
8 Mather (1988) Groundwater Pollution, p39

groundwater from the repository reaching the human population at the surface depends fundamentally on the way that groundwater travels from the repository. [*9*] [*10*] This is known as the hydrogeology of the site. [*11*]

Nirex have commented:

> "We know ... how groundwater moves through geological strata" [*12*]
>
> "The safe disposal of radioactive waste is very straightforward." [*13*]

This view is not shared by the scientific community. Groundwater flow is very complicated and difficult to predict. There is a severe lack of information on the hydrogeology of possible repository sites. Moreover the methods available to assess the suitability of a proposed site are very limited and may even serve to make the site unsuitable. The geology of the Sellafield site which has been selected by Nirex for the proposed repository presents particular problems due to its complexity, and because the contaminated groundwater flowing out of the repository will travel upwards to the surface.

8.2. PREDICTION OF WATER FLOW

Groundwater can travel through pores or fractures in rock [*14*] and fractures in particular could provide express routes for the transport of radioactivity from the repository to the surface. [*15*] [*16*] In order to assess the radiological impact of contaminated groundwater, the rate and direction of groundwater flow must be

---

9 Fyfe (1984) p538
10 Price (1985) p10
11 Price (1985) p2
12 Nirex (1990) Why do We Need to do Research, p1
13 Nirex (1990) How Engineered Barriers Work, p1
14 Price (1985) p10
15 Nash (1989) NSS/R201, p1
16 Jeffries (1991) p124

known. However, the prediction of groundwater flow is difficult due to the lack of available data, and more importantly, due to the lack of understanding of the way that groundwater travels. These problems are enormously increased by the timescales over which the hydrogeological predictions for the safety assessment must be made.

8.2.1. Difficulties Arising Due to Lack of Data

Historically, the study of rocks which have a low permeability, and therefore would allow little contaminated water to return to the surface, has been neglected because previously there was limited use for the information. [*17*] In 1982, Mather of the Institute of Geological Sciences, who were responsible for geological research on nuclear waste disposal, [*18*] commented:

> "Although a considerable amount is known about the geology of the UK, the type of information required to assess the geological barrier provided by various formations is largely unavailable." [*19*]

Similarly, in 1989 RWMAC stated:

> "although several simplified assessments of conceptual sites, for which there are no specific data, have been performed, the number of comprehensive site-specific assessments carried out in the UK can be counted on one hand." [*20*]

Obtaining rock permeability data is not straightforward. Many of the techniques used to determine rock permeability will change the way that groundwater flows and this presents significant problems. The measurement of permeability in rocks thought to possess low permeability is particularly problematic, as it is possible that the measurement techniques used may serve to increase permeability. The

---

17 Mather (1982) p168
18 Mather (1982) p167
19 Mather (1982) p168
20 RWMAC (1989) p29

most important measurements are made using boreholes. [*21*] However, drilling boreholes may substantially alter rock permeability. For example work prepared for the DoE has stated that boreholes:

> "can provide the most open pathways for the transport of radionuclides." [*22*]
>
> "if too many boreholes are drilled this might compromise the integrity of the host rock". [*23*]

In addition, to the permeability implications of the use of boreholes to determine rock permeability, their utility is further limited by logistical difficulties. Although boreholes will provide some of the most important data for the groundwater flow calculations, the derivation of data from boreholes is often difficult, expensive and time consuming. [*24*] Furthermore, very little data obtained from boreholes can be directly used. [*25*] Consequently, in order to determine permeability from borehole measurements certain assumptions must be made [*26*] which may or may not be valid. [*27*] The investigation of low permeability rocks is very specialised work and very few people in the UK have any relevant experience of the very detailed work that will be necessary. [*28*] It is likely to be difficult to obtain sufficient high quality personnel with field experience, as similar work is being planned in Europe and the US at the same time. [*29*]

The difficulties of obtaining and correctly interpreting hydrogeological data may be illustrated by problems posed by fractures. Fracture data is critically important because if fractures are present, most of the water movement will take place

---

21 McEwen (1990) pp 17,18
22 McEwen (1990) p17
23 McEwen (1990) p33
24 McEwen (1990) p17
25 McEwen (1990) p15
26 McEwen (1990) p15
27 McEwen (1990) p55
28 McEwen (1990) pp 131,145,147,151
29 McEwen (1990) p152

through the fractures, [30] and the fractures will dominate and control water flow. [31] One geologist has commented:

> "it can be assumed that faults [major fractures [32]] in crystalline rocks will be regions of increased transmissivity and that they will act as "express routes" between the repository and the biosphere. Hence their properties and disposition become of crucial importance to the viability of a proposed repository." [33]

The measurement techniques used to obtain data on fractures are problematic. For example fractures may become sealed by drilling mud used in boreholes, or deformed by stress changes associated with the drilling. [34] Moreover, some tests:

> "can lead to the opening of existing fractures and even the creation of new ones". [35]

Quite apart from these problems, there is information that may be required that is simply not feasible to obtain. [36] For example, the complete area that a fracture covers can only be measured "by completely dismantling a given rock mass". [37] Similarly, the geometry of flow within channels in a system of irregular fractures: "is probably undeterminable in detail." [38] Work prepared for the DoE has concluded:

> "all features (fracture zones in particular) in which significant flow occurs must be described; preferably on both the microscopic and macroscopic scales. This can be difficult, as transport is often localised in channels, and the steep dips of many fracture zones can introduce unquantifiable biases into any interpretation of data from what are often vertical boreholes. ... statistically valid data on fracture trace lengths, fracture contact areas etc. are very difficult to obtain from the small surface area of the fracture that is intersected by the borehole" [39]

---

30 Lever (1990) NSS/G113 p15
31 Chapman (1987) The Geological Disposal of Nuclear Waste, p100
32 Chapman (1987) The Geological Disposal of Nuclear Waste, p100
33 Black (1991) p9
34 Priest (1986) p85
35 Priest (1986) p85
36 McEwen (1990) p(iv)
37 Priest (1986) p49
38 Chapman (1987) Site Selection and Characterization, p186
39 McEwen (1990) p26

Some of the uncertainties inherent in geological interpretation may never be resolved. [*40*] Research prepared for the DoE in 1990 concluded that:

> "Some of the data that are required by the models cannot be obtained satisfactorily from site investigations." [*41*]

For example, Cooling of the DoE has commented:

> "site investigation is really a snapshot in time - the ground properties may be completely different in one year, ten years or one hundred years." [*42*]

Similarly, Michael Price of the British Geological Survey (BGS) has written:

> "field methods provide rather inaccurate measurements on what was representative material only before the test boreholes were drilled through it. Even to the least cynical, it may appear by now that aquifers are so variable, and the methods for studying them so imprecise and beset with problems, that the prediction of groundwater behaviour requires a crystal ball" [*43*]

8.2.2. Difficulties Arising Due to Lack of Understanding

A more fundamental problem for the safety assessment than the lack of data on rock permeability, is posed by the lack of understanding of the factors that determine groundwater flow. In 1990, the US National Research Council (US-NRC) wrote:

> "it is impossible to stretch the almost always incomplete understanding of a site into an accurate quantitative projection of whether a repository will be safe if constructed and operated there. Even after a detailed and costly examination of the site itself, only an informed judgement can be reached, and even then there will be uncertainties." [*44*]

---

40 McEwen (1990) p138
41 McEwen (1990) p(iv)
42 Cooling (1987) p142
43 Price (1985) p144
44 U.S. National Research Council (1990) p24

This problem will be illustrated using the example of groundwater flow through fractures. In 1984, the International Council of Scientific Unions committee on geological disposal of high level wastes commented that:

> "fracture systematics are not well studied and are even less well understood. Of all waste disposal problems, understanding the hydrological characteristics of fracture systems is one of the most urgent areas for study." [*45*]

Water flow through fractures is complicated, as there are many different routes that migrating groundwater can take through fractures, and many different ways that it can travel. In order to be able to compute the long term radiological impact of a repository in fractured rock, Nirex must subsume the complexities of groundwater flow through fractures into a mathematical representation or 'model' of the flow of groundwater from the repository. Different levels of approximation may be used in the mathematical representation of groundwater flow. For example, at one extreme fractured rock could be viewed simply as homogeneous porous material. At the other extreme it could be attempted to identify and incorporate each fracture into the mathematical representation of the rock and from this to attempt to trace the route that migrating groundwater will take as it travels from the repository. Although more approximate models will ease difficulties associated with data gathering and computation, the results of the safety assessments produced using approximate models will be less robust. Therefore, in 1987 Cooling of the DoE stated that "the 3-D connectivity of the fracture network must be modelled." [*46*] However, modelling to this level of detail is difficult, and work carried out for the DoE concluded that:

> "None of the models provides an adequate representation of fluid flow and contaminant transport in a three-dimensional fracture network." [*47*]

---

45 Fyfe (1984) p539
46 Cooling (1987) p135
47 Priest (1986) p235

Cooling commented this: "really rules them all out for realistic modelling of radionuclide migration from a repository". [*48*]

Given the difficulties of accurately modelling fractured rock, conventional approaches are based on averaging procedures that treat rock as a continuum. [*49*] However, the concept of an equivalent continuum permeability for a fracture network is of limited value since individual, highly conductive fractures continue to have an influence on fluid flow even when large volumes of rock are considered. [*50*] One anomalous highly conductive fracture could completely invalidate the equivalent continuum approach [*51*] and fluid flow in fractured rock can only be analysed using a model of the discrete fracture network. [*52*] In work carried out for the DoE in 1986, Priest concluded that:

> "it is not possible to guarantee the safety of a repository in any rock mass until comprehensive three-dimensional discontinuity [fracture [*53*]] data have been analysed by a three-dimensional fluid flow model." [*54*]

The difficulties associated with attempting to incorporate the radiological implications of fractures at the repository site into the safety assessment, when groundwater flow through fractures is not thoroughly understood, have not yet been resolved. In 1990, the US-NRC stated that:

> "the modelling of groundwater flow through fractured rock lies at the heart of understanding whether and how a repository in hard rock will perform its essential task of isolating radioactive materials. The studies done over the past two decades have led to the realization that the phenomena are more complicated than had been thought. Rather than decreasing our uncertainty, this line of research has increased the number of ways in which we know that we are uncertain." [*55*]

---

48 Cooling (1987) p137
49 Lever (1990) NSS/G113, pp 3,15
50 Priest (1986) pp 236-7
51 Cooling (1987) p137
52 Priest (1986) p237
53 Priest (1986) p4
54 Priest (1986) p241
55 U.S. National Research Council (1990) p4

In 1990 Nirex stated that fracture flow could not be explicitly modelled. [*56*] They identified fracture flow as a key area where development of understanding was required [*57*] and conceded that current safety calculations "treat fractured rock in a very simple manner." [*58*] In March 1992, in their report on the geology and hydrogeology of Sellafield Nirex commented:

> "From a hydrogeological viewpoint, faults [major fractures [*59*]] are conceived as features with poorly known properties." [*60*]

Despite the fact that borehole studies at Sellafield clearly indicated that groundwater flow at Sellafield is dominated by fractures, [*61*] and that enhanced transmissivity faults could provide a route for radioactively contaminated groundwater to the surface, [*62*] Nirex did not use a three dimensional fracture flow model to interpret the borehole measurements. [*63*]

8.2.3. Difficulties Arising Due to Timescale

The difficulties that arise due to the lack of understanding of the way that water flows through rock are enormously increased by the massive timescale over which the hydrogeological predictions for the safety assessment have to be made. The wastes to be disposed of by Nirex present the same long term risk as high level wastes. [*64*] Over one million tonnes of the waste to be buried (ILW) [*65*] will be sufficiently radioactive to require handling using remotely controlled machines. [*66*] These wastes contain radioactive elements that will present a risk to future

---

56 Lever (1990) NSS/G113 p(v)
57 Lever (1990) NSS/G113 p46
58 Lever (1990) NSS/G113 p48
59 Chapman (1987) The Geological Disposal of Nuclear Waste, p100
60 Nirex (1992) The Geology and Hydrogeology of Sellafield, vol I, p115
61 Nirex (1992) The Geology and Hydrogeology of Sellafield, vol I, p105
62 Nirex (1992) The Geology and Hydrogeology of Sellafield, vol I, p117
63 Nirex (1992) The Geology and Hydrogeology of Sellafield, vol I, p119; vol II Fig. 50
64 Chapman (1986) p312
65 Nirex (1989) Deep Repository Project, Table 2.2
66 Nirex (1992) Sellafield Project Consultation, p7

generations for millions of years. [*67*] In 1976, the Royal Commission on Environmental Pollution commented:

> "In considering arrangements for dealing safely with such wastes man is faced with time scales that transcend his experience." [*68*]

Scientists have never before been asked to answer disposal problems on this timescale. [*69*] In 1985, the Institution of Geologists stated:

> "Geologists in Britain are being asked to predict geological conditions for hundreds of thousands and possibly millions of years hence. This requirement is unprecedented" [*70*]

The US-NRC have concluded that:

> "use of geological information and analytical tools - to pretend to be able to make very accurate predictions of long-term site behaviour - is scientifically unsound." [*71*]

Nirex's track record on geological predictions is not good. For example in 1987 Nirex published the results of calculations on the safety of clay disposal sites over the next one million years. [*72*] Doubt was cast on the accuracy of these calculations by the results of field tests carried out for Nirex by the BGS. These results indicated that for both the Elstow and Killingholme sites the wrong direction had been predicted for the groundwater flow. [*73*] [*74*] In 1990, work prepared for the DoE concluded that it is "difficult to envisage" whether safety calculations can be carried out for clay sites "as the fundamental processes that are operating are not understood". [*75*]

---

67 Nirex (1990) Deep Repository Project, Table 2.3
68 Cmnd. 6618 (1976) p80
69 Fyfe (1984) p537
70 Institution of Geologists in Environment Committee (1986) vol III, p665
71 U.S. National Research Council (1990) p5
72 Hodgkinson (1987) NSS/A100, pp 30,31
73 Ross (1989) NSS/R169, p(ii)
74 Ross (1989) NSS/R172, p(iii)
75 McEwen (1990) p140

Similarly Nirex have experienced difficulties in attempting to predict the hydrogeology at the proposed repository site at Sellafield. These problems are discussed below.

8.3. WATER FLOW AND REPOSITORY SITE SELECTION

It is important to select a repository site such the quantity of radionuclides carried by groundwater from the repository back to the human environment is minimal. Therefore groundwater flow is an important consideration in repository site selection. However, other criteria, such as local opposition, may also have a considerable influence on the site that is chosen for repository construction. When Nirex were first set up they initially opted for Billingham in Cleveland, and Elstow in Bedfordshire as potential sites for radioactive waste disposal. [*76*] However, in 1985 [*77*] in the face of vociferous local opposition Nirex abandoned work at Billingham. Subsequently in May 1987, work on sites at Elstow, Bradwell, Fulbeck and South Killingholme was also abandoned. [*78*] In November 1987, Nirex launched a public consultation document "The Way Forward". Fifty thousand copies were distributed and 2,500 responses were received. Only two areas of the country Caithness, home of the Dounreay nuclear plant, and Cumbria, home of Sellafield, showed a "measure" of support for the repository. [*79*] In March 1989 Nirex announced that they would limit further investigations to Dounreay and Sellafield. [*80*] However, a referendum carried out in Dounreay for Caithness District Council found that 74% of the voters were opposed to repository construction in their area. [*81*] In July 1991 Nirex

---

76 Nirex (1984) p6
77 Nirex (1989) Deep Repository Project, pA3
78 RWMAC (1990) Waste Watchers, pp 4-5
79 Nirex (1989) Deep Repository Project, pp 50,51
80 Nirex (1989) Deep Repository Project, p51
81 Anon (1990) January 1990, p6

announced that it had selected Sellafield as its favoured site for repository construction. [*82*]

The relative importance of the criteria applied during repository site selection could have significant implications for the safety assessment. In 1988 Nirex commented that:

> "Current nuclear facility sites have been chosen on grounds other than suitable geology and hydrogeology to contain radioactive materials." [*83*]

The critical importance of hydrogeological criteria in repository siting decisions, has been demonstrated by the US experience of siting radioactive waste disposal sites. Millions of cubic metres of nuclear wastes in the US were buried at the sites of existing nuclear facilities [*84*] with hydrogeological considerations only a secondary factor in the siting decision. [*85*] Radioactivity has migrated from the sites at faster rates and in different directions than expected [*86*] and the clean-up of the sites will cost tens of billions of dollars. [*87*]

8.3.1. Water Flow at Sellafield

In 1980, the Institute of Geological Sciences reported that Sellafield would be unsuitable on hydrogeological grounds as a site for a nuclear waste repository. [*88*] Similarly, in March 1991 Christopher Harding, Chairman of BNFL, admitted that Sellafield was "probably not the best geology" [*89*] for a repository

---

82 Nirex (1991) Sellafield Repository Project, p2
83 Nirex (1988)
84 U.S. Congress Office of Technology Assessment (1991) p4
85 Robertson (1984) p105
86 Robertson (1984) p107
87 U.S. Congress Office of Technology Assessment (1991) p4
88 Robins (1980) p7-9
89 Highfield (1991)

site. The geology at Sellafield is not simple. [*90*] Rapid changes in rock type, accompanied by extensive major faulting are found at the site. [*91*] There are numerous additional factors which contribute to the enormous complexity of groundwater flow at Sellafield. The geology of the Sellafield region is characterised by areas with extensive and thick glacial and recent deposits which influence the groundwater flow regime and make site investigation more difficult by obscuring even major structures. [*92*] Many of the most significant structural elements in the Sellafield area are covered by such deposits and this is one of the main reasons why so little is known of the detail of the fault structures in the area. [*93*] Moreover, the presence and properties of these glacial sediments could have a major influence on the pattern of groundwater flow [*94*], but attempts at modelling the groundwater flow and radionuclide transport within such deposits by BNFL has proved far from easy. [*95*] Work prepared for the DoE has concluded that:

> "there are likely to be large uncertainties in understanding the structure of glacial deposits however much work is carried out. It may have to be accepted that their presence ... can only be treated as an additional uncertainty in the analysis." [*96*]

Despite the large degree of uncertainty found in the glacial sediments Nirex have concluded that the most uncertain region is that of the basement rock. [*97*] All rocks contain fractures which can provide major conducting pathways for the carriage of contaminated water. [*98*] Cracks were formed in the Borrowdale Volcanics at Sellafield when the lavas cooled. [*99*] Fracture patterns can be highly complex and almost random [*100*] and in 1990 Nirex stated that water flow

90 McEwen (1990) p32
91 McEwen (1990) p97
92 McEwen (1990) p113
93 McEwen (1990) p112
94 McEwen (1990) p113
95 McEwen (1990) p113
96 McEwen (1990) p114
97 Nirex (1992) The Geology and Hydrogeology of Sellafield, p119
98 Priest (1986) p84
99 Robins (1980) p7-8
100 Priest (1986) pp 4,6

through fractures cannot be explicitly modelled. [*101*] The difficulties associated with fracture modelling were discussed above.

The site investigation programme at a potential repository site, is designed to increase the confidence in the safety assessment to a level at which a choice can be made on the general suitability of a site. [*102*] However, in a complex geological environment it will probably be impossible to adequately reduce some of the inherent uncertainties in hydrogeological modelling, and a site may be abandoned for this reason alone. [*103*] In 1990, work prepared for the DoE pointed out that for a complex site even if a large amount of site investigation work were carried out the data obtained may actually have a larger uncertainty than the values obtained by estimation. [*104*] It was concluded that given the inherent problems of attempting to model complex geological environments:

> "some form of decision process needs to be set up to determine how a site might be discarded." [*105*]

In March 1989, when Nirex announced that future site investigation work would be limited to Sellafield and Dounreay, Nirex predicted that radioactively contaminated water that migrated from a repository at Sellafield would be carried directly towards the sea. [*106*] On this basis they calculated the safety of a repository at Sellafield for the next one hundred million years. [*107*] These initial calculations were carried out using estimates rather than real data [*108*] as there was little direct geological information available about the Sellafield site. [*109*] However, when real data became available, an additional feature of the

---

101 Lever (1990) NSS/G113 p(v)
102 McEwen (1990) p116
103 McEwen (1990) p152
104 McEwen (1990) pp 140-1
105 McEwen (1990) p140
106 Nirex (1989) Deep Repository Project, p71
107 Nirex (1989) Deep Repository Project, pp 78-9
108 McEwen (1990) p34
109 McEwen (1990) p34

hydrogeology at Sellafield was discovered that Nirex had failed to take into account.

It was discovered that the water at the Sellafield site was up to six times more saline than sea-water. [*110*] The effect of salt water is to drive contaminated water back upwards to the surface. [*111*] [*112*] [*113*] [*114*] In April 1992, John Mather professor of geology at London University commented:

> "Any sort of upward migration is what they do not want in that area and they have got it". [*115*]

Similarly, in May 1993, [*116*] RWMAC stated that:

> "The recognition of upward head gradients requires careful investigation and explanation, since it could indicate the potential for relatively short groundwater flow paths a few hundred metres in length upwards from a repository site into the Sherwood Sandstone Aquifer above. As a consequence relatively short return times of groundwater flow from the vicinity of the repository into the biosphere could result. ... it is an open question as to whether the observed variability in the hydrogeological conditions at Sellafield will provide unequivocal evidence that the stringent hydrogeological conditions required for a deep radioactive waste repository can be met at this site." [*117*]

8.4. SUMMARY

In order to calculate the quantity of radionuclides that will be carried from the repository to the surface, the rate and direction of water flow through the rock surrounding the repository must be known. This presents severe difficulties for

110 Nirex (1992) The Geology and Hydrogeology of Sellafield, p106
111 Lever (1990) NSS/G113, p41, Fig. 6
112 Nirex (1992) The Geology and Hydrogeology of Sellafield, vol I, pp 106,114,118,120; vol II, Fig. 46, Fig. 49
113 Environmental Resources Ltd (1992) Executive Summary
114 RWMAC (1993) Thirteenth Annual Report, p15
115 Wilkie (1992)
116 RWMAC (1993) 11 May 1993
117 RWMAC (1993) Thirteenth Annual Report, p17

the safety assessment due to the lack of understanding of groundwater flow, and the lack of available data. Moreover, the techniques which are available to measure water flow through rock cause considerable damage and may serve to make a proposed site unsuitable for repository development.

It is important that the site which is finally selected for repository development would allow a minimal quantity of radionuclides to migrate to the human environment. Therefore, a site should be selected where groundwater flow is slow and not towards the surface. However, other criteria such as local opposition to repository development, may also have a considerable influence on the site that is chosen for repository construction. Currently, Nirex propose to develop a repository at Sellafield in Cumbria, the site of BNFL's reprocessing facility. The selection of this site presents serious difficulties for the safety assessment due to the complexity of groundwater flow at the site, and due to the presence of upward moving groundwater. In the following chapter, Nirex's proposal to begin excavation at the proposed repository site will be considered.

9. ROCK EXCAVATION AND SAFETY ASSESSMENT

9.1. INTRODUCTION

In order to assess the radiological impact of a proposed repository, the rate and direction of contaminated water flow from the repository must be known. This requires a detailed knowledge of the hydrogeology of the site. In the previous chapter the difficulties associated hydrogeological site investigations were discussed. In this chapter Nirex's proposal to begin excavation work at the proposed repository site will be examined. Three aspects of the policy proposal will be considered:

i) The damage to the site hydrogeology that will be caused by the disruption.
ii) The need for further research.
iii) The role of the excavation as a source of information for the safety assessment.

9.2. EXCAVATION DAMAGE

In October 1992, Nirex announced that they proposed to concentrate further safety assessment work in a cavern to be excavated [*1*] [*2*] at Sellafield. The proposed excavation will severely disrupt the surrounding rock [*3*] and may create

1 Curd (1992) p50
2 Nirex (1992) A Rock Characterisation Facility
3 Jeffries (1991) p33

flowpaths for contaminated water. Research carried out for the DoE in March 1991, stated that:

> "Any changes in the rock mass properties can lead to the formation of preferential flow paths in the near vicinity of the excavation" [*4*]

The creation of such flow paths has considerable implications for the safety assessment as escape of contaminated water is believed to be the primary risk presented by a nuclear waste repository. The DoE report commented that:

> "considerable migration pathways may be created or reactivated, [by excavation] thus increasing the risk of fluid flow from the repository site." [*5*]

Given this risk, understanding the effects of excavation on the permeability of the surrounding rock is critical. The current understanding of excavation effects will be discussed below.

9.2.1. Factors Contributing to Excavation Damage

The damage to rock caused by excavation, arises both from the disruption of the force equilibrium in the rock, and the damage caused by the excavation technique used. [*6*] Both of these factors may alter the permeability of the surrounding rock through the opening of existing fractures or the creation of additional fractures. [*7*] It has been observed experimentally that excavation may completely change the direction and magnitude of the permeability axes in the rock. [*8*] For excavations in deep rock it is expected that the permeability of all fractures in the damaged zone will be increased. [*9*] In addition to these overt effects, excavation may

---

4 Jeffries (1991) p37
5 Jeffries (1991) p33
6 Jeffries (1991) p36
7 Jeffries (1991) p93
8 Jeffries (1991) p93
9 Jeffries (1991) p94

introduce other, more subtle factors, which may also have a considerable impact on the permeability of the rock surrounding an excavation. The complexity of the interaction of these factors, and the resultant difficulties in building an understanding of the impact of excavation on rock permeability, is discussed below.

9.2.1.1. Disruption of Force Equilibrium

Rock in the Earth's crust is subjected to many forces [*10*] including: gravitational forces, which are determined by the weight of the overlying rock; [*11*] tectonic forces, which result from the differential movements of parts of the Earth's surface; [*12*] structural forces, which are caused by geological discontinuities and heterogeneities; [*13*] and residual forces, which are associated with the previous climatic history of the rock site. [*14*] Over geological time these contributing forces achieve equilibrium. [*15*] This equilibrium will be disrupted by excavation and the forces will be redistributed. [*16*] The disruption of the force equilibrium may have a significant effect on the excavated rock. Possible impacts include: alteration of the hydrogeological regime around the excavation; movement or loosening along existing fractures; or even failure of intact rock. [*17*] Thus the permeability of the rock mass can be affected due to rock fracturing, [*18*] fracture movement, [*19*] or loosening of rock structure. [*20*]

---

10 Jeffries (1991) p34
11 Jeffries (1991) p34
12 Jeffries (1991) p35
13 Jeffries (1991) p36
14 Jeffries (1991) p36
15 Jeffries (1991) p36
16 Jeffries (1991) p36
17 Jeffries (1991) p36
18 Jeffries (1991) p37
19 Jeffries (1991) p37
20 Jeffries (1991) p37

The impact on rock permeability of fracture creation may readily be appreciated. However, force redistribution may also have a profound impact on the permeability of existing fractures and the permeability of rock is fundamentally related to the forces to which the rock is subjected. [21] Force redistribution will affect existing fractures through two primary mechanisms. Firstly, the aperture of a fracture will be affected by the extent of compression and this will affect the resistance to flow - resistance decreasing as aperture increases. [22] Secondly, as compression is reduced the points of contact between the two fracture surfaces will be reduced and so the flow path will become shorter and less tortuous. [23] The extent of the zone affected by redistribution of forces caused by the excavation is difficult to predict. [24] Effects have been observed at a distance sixty times greater than the diameter of tunnel excavated, moreover such effects may be observed long after apparent stability has been re-established. [25] This will exacerbate the difficulties of predicting the range of the disruption zone caused by force redistribution.

9.2.1.2. Excavation Technique

The energy imparted to a rock by the act of excavation will damage the rock. [26] The extent of this damage will depend on the total amount of energy that is used by the excavation technique; and the extent to which it is focussed. [27] There are two main methods of excavation: the drill and blast technique, which uses explosives; [28] and continuous techniques, which normally involve boring. [29]

---

21 Jeffries (1991) p45
22 Jeffries (1991) p45
23 Jeffries (1991) p45
24 Jeffries (1991) p92
25 Jeffries (1991) p92
26 Jeffries (1991) p40
27 Jeffries (1991) p40
28 Jeffries (1991) p40
29 Jeffries (1991) p41

The drill and blast excavation technique uses explosives in order to release large amounts of energy rapidly to the rock mass. [*30*] This process causes the rock to fail and fragment and produces rock which is shattered, crushed and cracked. [*31*] Work undertaken for the DoE concluded that drill and blast excavation:

> "may result in a wide ranging zone of increased fracture density and therefore a possible preferential flow path" [*32*]

Continuous techniques of excavation, break the rock by applying high and very localised compressive forces to the rock in order to cause a localised shear failure. [*33*] The localised nature of the force is believed to minimise the damage to the rock caused by the excavation technique. [*34*] Comparisons of continuous excavation methods with drill and blast techniques have found that the disturbed zone around a drill and blast tunnel is considerably greater than around a machine excavated tunnel. [*35*] This reduction in the depth of the disturbed zone found with the continuous method would enable better sealing. [*36*] Sir William Halcrow, consultants to Nirex, have recommended that "the most appropriate method of construction" of the proposed excavation would "utilise blind boring techniques". [*37*] Halcrow rejected the use of the drill and blast technique as it could disrupt the surrounding geology and shaft sealing and therefore increase the flow of groundwater into the excavated shaft. [*38*] Despite this recommendation, Nirex intend to use conventional drill and blast techniques [*39*] which are expected to be faster than the blind boring méthod. [*40*]

---

30 Jeffries (1991) p40
31 Jeffries (1991) p40
32 Jeffries (1991) p42
33 Jeffries (1991) p41
34 Jeffries (1991) p41
35 Jeffries (1991) p42
36 Jeffries (1991) p42
37 Anon (1992) p1
38 Anon (1992) p1
39 Nirex (1992) A Rock Characterisation Facility, pp 8,9,12,13
40 Anon (1992) p1

9.2.1.3. Other Factors

In addition to the permeability changes described above, caused by the creation and dilation of fractures, the excavation of a shaft will have many other effects which may also affect rock permeability. Examples of such effects are listed below:

- i) gases generated during blasting (such as carbon dioxide, water vapour and nitrogen) will be forced into the fractures [*41*];
- ii) drilling debris may be transported into the fractures [*42*];
- iii) blasting may shake loose fine grained particles from the rock which may be carried into the fractures [*43*];
- iv) pressure reduction may allow degassing of the groundwater which would create bubbles and therefore two-phase flow [*44*];
- v) chemical precipitation may occur. [*45*]

These effects considerably increase the complexity of the situation, and therefore increase the difficulties of predicting the effects of excavation on rock permeability.

9.2.2. Current Understanding of Excavation Damage

In 1977, the Stripa mine in Sweden was turned into a research facility in order to study the potential for rock to prevent radioactivity migrating from a repository

41 Olsson (1992) p290
42 Olsson (1992) p291
43 Olsson (1992) p291
44 Olsson (1992) pp 292-3
45 Olsson (1992) p294

back to the surface. [46] During the course of the investigations carried out at the site it became clear that models used to describe groundwater flow needed to be demonstrated to be correct and appropriate. [47] This was to be achieved through a validation project where blind predictions were compared to measurements. [48] This was the rationale for the five year Site Characterisation and Validation (SCV) project carried out at the site from 1986 to 1991. [49] The basic experiment was to predict the distribution of water flow and tracer transport through a volume of rock, before and after excavation of a sub-horizontal drift and compare these predictions to actual field measurements. [50] In April 1992 the Final Report of the Site Characterisation and Validation Project was published. [51] It stated that:

> "The attempts to model the inflow to the drift were not successful due to inadequate understanding of the hydrology of the disturbed zone around drifts." [52]

A similar conclusion was reached by Black who stated that: "the precise mechanisms which are controlling the changes" are "unknown". [53] Thus it may be concluded that the physical processes which are important to flow in the disturbed zone around an excavation are not well understood. [54] [55] However, Jeffries (1991) concluded that: "one may not yet safely ignore them." [56]

---

46 Olsson (1992) p1
47 Olsson (1992) pp 1-2
48 Olsson (1992) p2
49 Olsson (1992) p2
50 Olsson (1992) p2
51 Olsson (1992)
52 Olsson (1992) p317
53 Black (1991) p7
54 Olsson (1992) pp 312,317
55 Jeffries (1991) pp 33,129
56 Jeffries (1991) p130

9.3. THE NEED FOR FURTHER RESEARCH

The lack of understanding of the way that water flows through rock, discussed above in the context of the impact of excavation effects, encroaches on virtually all aspects of the hydrogeology of repository site investigation. This problem, which has important ramifications for disposal policy, was discussed in more detail in the previous chapter. However, the extent of the problem may be appreciated by the fact that the Stripa project concluded that: "one of the major outstanding questions", namely the relationship between the hydraulic transmissivity of a fracture and its flow aperture [*57*] was still unresolved. In addition, it was observed that there is as yet no proven method to estimate the "flow wetted surface" of a fracture or channel network even though this has "a fundamental impact" on transport. [*58*]

Given this general lack of understanding it has been proposed that a site dedicated to research should be developed. The Stripa project concluded that:

> "Dedicated studies of the hydraulic and mechanical properties of the disturbed zone definitely have to be initiated in the future." [*59*]

Similarly, work prepared for the DoE in 1990 concluded that:

> "Prior to planning and carrying out a site investigation it is essential that the correct concepts, tools and techniques are available for use on a routine basis. To achieve this in the UK, ... almost certainly requires an experimental site in order to test the concepts of groundwater flow and to allow the tools and techniques to be developed." [60]
>
> "Such a site could provide, as similar sites do in other countries, a test bed for testing inter-borehole hydraulic and geophysical techniques, fracture network analysis, hydrochemical sampling and hydraulic testing equipment in single boreholes etc, *before any of these techniques are required in a shaft* " [*61*] (My emphasis)

---

57 Olsson (1992) p314
58 Olsson (1992) p314
59 Olsson (1992) p316
60 McEwen (1990) p132, see also p151
61 McEwen (1990) p132

The need for an experimental site "explicitly excluded from being a potential operational facility" was also indicated by the Environment Committee in 1986. [*62*]

9.3.1. The Sellafield Excavation as a Research Facility

Despite the clear requirement for a site specifically dedicated to research, DoE research has concluded that:

> "The URL [Underground Research Laboratory [*63*]] that Nirex is likely to construct is not planned to be research orientated" [*64*]

Due to the depths required for investigation work at Sellafield; Sellafield is in fact unsuitable for research orientated work. In 1980, the Institute of Geological Sciences commented that:

> "the cost of investigating [the Borrowdale Volcanic Series at Sellafield] ... at depth is likely to be prohibitive." [*65*]

Similarly, research prepared for the DoE in 1990 concluded that:

> "The methodology which needs to be worked out for assessing the rock mass is best done ... at depths considerably less than the current deep boreholes planned for Sellafield ... Obtaining the same insight into the site investigation methodology will be much more costly if it is carried out as part of the main investigations, because the time and cost implications of this learning process increase very markedly with depth." [*66*]

The fact that the Sellafield excavation will not be research orientated is further confirmed by the timetable constraints, [*67*] which are discussed below.

---

62 Environment Committee (1986) vol I, p(lvii)
63 McEwen (1990) p16
64 McEwen (1990) p116, see also pp (iii), 17
65 Robins (1980) p7-9
66 McEwen (1990) p132
67 Nirex (1992) Target Programme

9.3.2. The Timescale Required for Research

9.3.2.1. Experience at the Stripa Site

The Stripa project highlighted the critical importance of allowing sufficient time for safety assessment work carried out underground. Despite the fact that the Stripa project lasted for fifteen years [*68*] the final report on the project commented that the time allocated for tests was insufficient and the interpretation of the results was adversely affected. [*69*] It was concluded that:

> "due to time and funding constraints, it was not possible to perform specific experiments within the framework of the SCV [Site Characterization and Validation] Project to resolve the issues." [*70*]
>
> "the very tight schedule required tests to be performed as pressure fields were still responding to previous tests. This generated inaccuracies in the qualitative results which could have been eliminated by allowing longer periods of pressure stabilization between tests." [*71*]

These timetable problems are exacerbated by the fact that the hydrogeology of the site will change over time. For example at the Stripa lab a 20% increase in the total flow to the Validation Drift was observed after 9000 hours (375 days). [*72*] Moreover the excavation response of rock will change with time due to factors such as creep and stress relaxation [*73*] and in situ studies of the extent of fracture zones around a deep mine have shown that the radius of the fracture zone may increase ten-fold over time. [*74*] The Stripa project recommended that for future investigations ample time should be allowed for the tests to be carried out. [*75*]

---

68 Olsson (1992) pp 1,2
69 Olsson (1992) p299
70 Olsson (1992) p278
71 Olsson (1992) p304
72 Olsson (1992) p282
73 Jeffries (1991) pp 92,112
74 Jeffries (1991) p94
75 Olsson (1992) p299

9.3.2.2. The Sellafield Excavation Timetable

In 1991, research prepared for the DoE concluded that the safety assessment work carried out prior to the disposal of nuclear waste would be limited due to:

> "non-technical constraints, such as the calender time allotted for the assessment" [*76*]

Undue haste has already affected the quality of the safety assessment results obtained by Nirex; for example the short duration of the tests carried out in the borehole programme at Sellafield has produced uncertainty in the results obtained; [*77*] and the concern expressed by the DoE report was confirmed by the 1992 timetable for the Sellafield excavation prepared by Nirex. The timetable is given below:

Launch of Consultation	October 1992
Planning Application	1st half of 1993
Approval Date	31 December 1993
Access to 650m BoD Horizon	1st half of 1996
Go/No Go Decision on Sellafield	From 2nd half of 1996
Repository Planning Application	From late 1996
Planning Approval following Public Inquiry	From late 1999
Repository Commissioning	2007 [*78*][*79*]

---

76 Jeffries (1991) p128
77 Nirex (1992) The Geology and Hydrogeology of Sellafield, p95
78 Nirex (1992) Target Programme
79 Nirex (1992) A Rock Characterisation Facility, p4

It may be seen that Nirex propose that just 6 months of investigation work within the excavation will be sufficient to determine whether it is appropriate to construct a repository at the site. In February 1993, RWMAC commented:

> "This timing would provide inadequate time for the establishment of the RCF [Rock Characterisation Facility] and the associated ... investigations" [*80*]

9.4. THE EXCAVATION AS A SOURCE OF INFORMATION

In November 1992, Sir Richard Morris, the chairman of Nirex, commented that:

> "This [excavation] approach enables ... us to put men and equipment down to the depths planned for the eventual disposal chambers, and study the integrity of the rock at depth, its fractures, how water moves through it. ... Results from this facility will help us form greater confidence in our safety assessment". [*81*]

However, the value of the excavation as a means of gathering information is severely limited. There are many diverse factors which will seriously reduce the quantity and quality of the information that may be obtained from the excavation. In this section difficulties arising due to siting constraints, shaft sealing effects and excavation damage will be considered. Finally the role of the excavation as a source of information for the safety assessment will be examined.

9.4.1. Limitations Due to Siting Constraints

A shaft could act as a significant by-pass for contaminated water through an otherwise impermeable layer [*82*] [*83*] and it is possible that the excavation of

80 RWMAC (1993) Rock Characterisation, p10
81 Morris (1992) p8
82 Jeffries (1991) p64
83 McEwen (1990) p39

shafts could provide a "short circuit" to the biosphere. [*84*] There are inherent difficulties associated with performing an in depth site investigation while keeping the local structure as intact as possible. [*85*] In 1991 Black, a consultant to Nirex, [*86*] commented that the creation of a zone of disturbance around an excavation was unavoidable. [*87*] He concluded that:

> "The effect of this "zone of disturbance" could be to provide an "express route" to the biosphere." [*88*]

It is therefore important to position any shaft with consideration to the direction of any regional groundwater flow. [*89*] However, this introduces a direct contradiction into the siting consideration for the shaft as more data will be required in the direction of radionuclide transport from a repository, and it is in this direction that, by definition, areas of upflowing groundwater must exist. [*90*]

9.4.2. Limitations Due to Shaft Sealing Constraints

The amount of data that can be obtained from a shaft depends on the type of rock excavated. [*91*] In softer formations, and particularly in those with higher hydraulic conductivities, a shaft cannot be constructed without some form of temporary support in order to prevent groundwater ingress and shaft wall failure. [*92*] This will affect the amount of information that can be obtained. This is a particular problem at Sellafield, where Nirex propose to site the repository excavation, as the basement rock is to be accessed by a shaft through the St Bees

---

84 Jeffries (1991) p65
85 Jeffries (1991) Executive Summary p2
86 Nirex (1992) The Geology and Hydrogeology of Sellafield
87 Black (1991) p7
88 Black (1991) p7
89 McEwen (1990) p39
90 McEwen (1990) p39
91 McEwen (1990) pp 116-117
92 McEwen (1990) p117

Sandstone. [93] In 1980, a report prepared by the Institute of Geological Sciences commented that shaft sinking within this formation would be extremely difficult due to the ingress of groundwater. [94] Sir William Halcrow calculated, that the rate of water inflow during excavation through sandstone, could be as much as 375 litres/second. [95] Halcrow recommended the prior injection of a grout curtain around the planned shafts; however this advice was rejected by Nirex. [96] Nirex propose to freeze the ground surrounding the shaft to prevent water ingress [97] and to line the shafts through the sandstone and Brockram sequence with concrete. [98] Inevitably, measures deliberately taken to prevent water flow will distort the flow information that is obtained.

9.4.3. Limitations Due to Excavation Damage

Rock excavation alters the permeability of the rock excavated. Rock permeability is a critical aspect of disposal safety assessment, as enhanced permeability will allow enhanced migration of radionuclides from a repository. However, the impact of excavation on permeability is poorly understood. The Stripa Project concluded that:

> "Considering the large, and currently poorly understood, effects of drift excavation on hydraulic properties, the use of observations in drifts and tunnels for characterisation of flow and transport in the rock mass must be treated with caution". [99]

It may be seen that the usefulness of the permeability information that may be gained from the proposed excavation is highly questionable.

---

93 McEwen (1990) p117
94 Robins (1980) p7-9
95 Anon (1992) p1
96 Anon (1992) p1
97 Nirex (1992) A Rock Characterisation Facility p12
98 Nirex (1992) A Rock Characterisation Facility p13
99 Olsson (1992) p316

9.4.4. The Role of the Sellafield Excavation in the Safety Assessment

The publication of Nirex Report Number 263 "The Geology and Hydrogeology of Sellafield" [*100*] in March 1992 demonstrated that Nirex's current understanding of the hydrogeology of the Sellafield site is inadequate for the safety assessment. Groundwater travel times were not comprehensively investigated [*101*]: too few measurements were taken to determine the appropriate values for the hydrogeological parameters [*102*] and the assumption that water flow was driven by topography proved to be incorrect. [*103*] Moreover, it was not possible to quantitatively simulate all of the borehole results [*104*] and no realistic conceptual model could be produced to explain the data obtained. [*105*] Similarly, in October 1992, RWMAC commented that the most likely direction of groundwater flow at the site remained to be established. [*106*]

It is important that these inadequacies are addressed, and the information necessary for the long term safety case for the repository is obtained before the site is excavated. Once shaft sinking has begun the base hydrogeology will be destroyed. RWMAC have commented:

> "Once the shafts are underway, the groundwater regime will be disturbed and so the "base hydrogeological regime", upon which the long-term safety case will be dependent will be destroyed." [*107*]

---

100 Nirex (1992) The Geology and Hydrogeology of Sellafield
101 Nirex (1992) The Geology and Hydrogeology of Sellafield, p119
102 Nirex (1992) The Geology and Hydrogeology of Sellafield, p93
103 Nirex (1992) The Geology and Hydrogeology of Sellafield, p97
104 Nirex (1992) The Geology and Hydrogeology of Sellafield, p120
105 Nirex (1992) The Geology and Hydrogeology of Sellafield, p121
106 RWMAC (1992) p1
107 RWMAC (1992) p1

The destruction of the base hydrogeological regime by the shaft means that the data necessary for the long term evaluation of the repository safety at a site must be obtained before the site is excavated. In 1990 research prepared for the DoE concluded that:

> "the construction of the shaft will perturb the groundwater flow regime" [therefore] ... "By drilling, testing and monitoring boreholes in the area of the proposed shaft *for a sufficiently extensive period before any construction commences*, the changes due to the shaft construction should be adequately quantified." [*108*] (My emphasis)

The report outlined a programme for work leading up to the construction of an underground shaft. The timetable included the requirement:

> "for boreholes to be drilled, tested and then monitored for a considerable period, probably two years, before shaft construction commences." [*109*]

Nirex plan to obtain permission to begin shaft excavation by the end of 1993 and to begin excavation immediately. [*110*] [*111*] Nirex do not plan to undertake the necessary prior monitoring [*112*] and therefore the results obtained from the investigations in the excavation will be meaningless for the long-term safety case.

9.5. SUMMARY

Despite the failings of the synoptic safety assessment, outlined in previous chapters, Nirex propose to begin excavation of the proposed repository site in 1994. After only six months of underground investigation at the site, Nirex expect to be in a position to decide whether Sellafield will provide a suitable site for a repository for nuclear waste disposal. In addition, to the fact that the underground

---

108 McEwen (1990) p116
109 McEwen (1990) p118
110 Nirex (1992) Target Programme
111 Nirex (1992) A Rock Characterisation Facility, p4
112 RWMAC (1993) Rock Characterisation, p8

investigation does not address the uncertainties associated with the safety of radioactive waste disposal. this approach to safety assessment is intrinsically flawed due to the severe constraints on the information available from underground investigations. More fundamentally, Nirex's excavation will destroy the hydrogeology it seeks to examine.

10. DISCUSSION AND CONCLUSIONS

10.1. INTRODUCTION

There are many approaches to the normative analysis of decision making, of which two extremes are the 'synoptic' and the 'incremental' approach. This thesis is concerned with the use of the synoptic approach within decision making concerning the management of nuclear waste. The synoptic approach to decision making refers to an approach to rational decision making that assumes as an ideal, comprehensiveness of information and analysis concerning a given problem [*1*] in order that the 'correct' option may be identified. Such an approach has been termed 'synoptic' by Lindblom, due to the high degree of synopsis, or comprehensiveness of view the decision maker attempts to achieve. [*2*] This approach may be compared to the incremental approach, under which policy is developed through incremental changes to existing policy.

Two examples of decision making concerning nuclear waste management are considered in the thesis which, overtly, display an overwhelming reliance on synoptic techniques. The two case studies considered are the Windscale Public Inquiry into the decision to build the THORP reprocessing plant, and Nirex's safety assessment of nuclear waste disposal. The synoptic approach has been widely criticised and Lindblom has argued that such an approach to decision making is not achievable. [*3*] In this thesis, the performance of the synoptic analyses undertaken in each of the case studies is used to test Lindblom's

1 Braybrooke (1970) pp 40,41
2 Lindblom (1965) p138
3 Lindblom (1965) p138

hypothesis that the synoptic approach does not provide a viable decision making tool.

10.2. THE SYNOPTIC METHOD

The synoptic approach to decision making aims to generate the 'correct' option through comprehensive analysis. In order that the analysis is comprehensive, it must consist of the following four steps: (1) prioritisation of objectives, (2) identification of possible solutions, (3) identification of consequences, and (4) final choice. These four steps are outlined below.

1. Prioritisation of Objectives.

    The objectives to be met must be identified and prioritised.

2. Identification of Possible Solutions.

    All possible means of achieving the objectives must be identified.

3. Identification of Consequences.

    Each of the policy options identified in (2) must be exhaustively examined in order to identify all of the probable consequences of adopting each of the available options.

4. Final Choice.

    The final choice must be made between each of the possible policy options in order to enable the decision maker to achieve the optimal result, given the objectives identified in (1) above.

The role of the synoptic approach in the case studies is considered below.

10.2.1. The THORP Case Study

In 1992, BNFL completed construction of the £1.8 billion reprocessing plant, THORP. The decision to build the plant was the subject of a Public Inquiry that was held in 1977. Ostensibly, the Inquiry was held in order to provide the Secretary of State for the Environment with the "fullest information possible", [*4*] in order to allow him to make the "right" [*5*] decision concerning the construction of the plant. The Inquiry lasted 100 days and considered 1,500 documents. Following the Inquiry, the Inquiry Inspector recommended that THORP should be built. The case for reprocessing was examined in this thesis, and it was concluded that the case for reprocessing has collapsed. The possibility of abandoning THORP, post-construction, is currently under consideration.

The collapse of the case for reprocessing, after it had been accepted by the Inspector at the Inquiry, supports Lindblom's hypothesis that the synoptic approach to decision making is not viable. However, this conclusion assumes that it is valid to view the outcome of the Windscale Inquiry as the result of synoptic analysis. This assumption is open to criticism. It has been argued that Windscale Inquiry should be viewed as a political exercise to legitimate a decision that was effectively predetermined and that the outcome of the Inquiry was prejudged. The historical context of the Windscale Inquiry was considered in this thesis, and it was concluded that the 'decision' to build THORP emerged over time, and was effectively determined prior to the Inquiry. Parallels may be drawn between the

4 Pearce (1979) p92
5 Shore (1979) p232

stepwise emergence of the THORP decision that was identified in the case study and incrementalism. For example:

i) the policy options chosen for analysis by the decision makers were only marginally different from the status quo;
ii) the number of alternatives considered was limited;
iii) the consequences of the alternatives considered was limited;
iv) the objectives were related to the available policies;
v) the conception of the objectives was reconstructed over time; and
vi) policy making proceeded through a chain of policy steps.

However, due to the lack of widespread political involvement and the lack of flexibility in the THORP proposal, the decision to build THORP was not incremental in the Lindblom sense. [*6*]

Given the ambiguity of the role of the Windscale Inquiry, it is not possible to draw robust conclusions concerning the viability of the synoptic method using the methodology applied in this case study. Lessons from this case study may be used to ensure that the conclusions drawn from the second case study are robust.

10.2.1.1. Lessons from the THORP Case Study

In order to test Lindblom's hypothesis that the synoptic approach to decision making is not viable, a methodology must be adopted such that the conclusions drawn are independent of the ambiguity introduced by the political constraints faced by decision makers. In order to achieve this objective, it is important to

---

6 The importance of incremental development in nuclear waste disposal policy has been examined by others [see for example Kemp (1988) pp 37-44; Blowers (1991) pp 24,26,315; Kemp (1992) p47; Berkhout (1991) p133].

distinguish between the ***utilisation*** and the ***application*** of a particular approach to decision making. Thus, although a particular approach to decision making may be *utilised* in the decision making process, it may not be *applied* to the decision actually taken and it may be peripheral to the decision making process. The need to distinguish between the *utilisation* and the actual *application* of the synoptic approach, supports Lindblom's hypothesis that the synoptic approach is not actually used by decision makers.

To enable robust conclusions to be drawn concerning the viability of the synoptic method, the conclusions drawn must be valid whether or not the synoptic method was actually *applied* to the decision taken. Conclusions concerning the success of the synoptic method, which are drawn on the basis of the success or otherwise of a particular decision ostensibly made using the synoptic method, are open to the criticism that the synoptic method was actually peripheral to the decision making process, and was not actually *applied* to the decision taken. These difficulties may be avoided if the criticisms of the synoptic method are addressed directly through the evaluation of the viability of adopting the method. Consideration of the viability of the method, rather that the success of a decision overtly taken using the method, allows Lindblom's hypothesis to be tested directly, and therefore is robust to the criticism outlined above.

10.2.2. The Nirex Case Study

In this case study, the viability of the synoptic method is evaluated through the analysis of the Nirex safety assessment of the behaviour of nuclear waste in a repository. In order to obtain regulatory approval to dispose of nuclear waste, Nirex are required to prepare a radiological safety assessment of the proposed disposal facility. It is in Nirex's interest to prepare a safety case which is cogent, comprehensive and coherent, and they are spending £6 million per year on a research programme involving 25 research institutions.

The requirement to prepare a safety case is equivalent to the third stage of the synoptic method which requires the exhaustive examination of the consequences of a proposed policy. In order for the synoptic method to offer the decision maker a viable approach to decision making, each one of the four stages must be achievable. Under Lindblom's hypothesis, it is predicted that, due to the overwhelming information demands of the synoptic method, the safety assessment work undertaken by Nirex will fail to provide a cogent analysis of the radiological safety of the proposed disposal facility. Moreover, Lindblom predicts the way that the method is expected to fail and this may be compared to the observed results of the case study.

10.2.2.1. Results of the Case Study

In order to assess the radiological safety of a repository for nuclear waste disposal, the quantity of radionuclides that may be expected to leave the repository and return to the surface must be computed. Nirex anticipate that the most likely process by which radionuclides may migrate from a repository, will be through dissolution and carriage in the surrounding groundwater. Therefore, in order to quantify the radiological impact of a repository, the quantity of radionuclides that dissolve must be computed and the rate and direction of groundwater flow must be known. In the case study, the methodology used by Nirex in order assess the quantity of radionuclides that will dissolve and the methodology used to predict the behaviour of groundwater was evaluated.

It was found that the inconsistencies, inadequacies, and absurdities within the methodology used by Nirex, demonstrate that Nirex are not able to provide a synoptic analysis of the consequences of nuclear waste disposal. Moreover, it was found that the synoptic method failed in the way predicted by Lindblom. Thus the problems found in the safety assessment are seen to arise due to lack of understanding, lack of data, lack of resources, and the open-endedness of the analysis required. This poses a particular problem for Nirex as it is found that work in one area of investigation often has repercussions in another area, but the synoptic approach does not provide Nirex with a strategy to contend with this constant feedback. In the following section, the pattern of the failure of the synoptic method predicted by Lindblom is compared to results obtained from the case study.

10.2.2.2. The Pattern of the Results

In this section, the pattern of failure observed in the synoptic assessment attempted by Nirex, will be outlined under the headings predicted by Lindblom. In order to avoid repetition, just one or two examples are listed under each heading, and examples are drawn primarily in the sequence in which they occur in the text. For most of the headings it would be possible to draw examples from a variety of chapters.

1. Limitations of Intellectual Capacity.

The synoptic method insists on comprehensiveness of analysis. All of the relevant facts concerning a given problem must be understood in great detail - this is not a credible requirement.

The safety assessment of nuclear waste disposal requires a comprehensive analysis of the future behaviour of a proposed repository. The safety assessment will only achieve a meaningful estimate of risk if all sequences of possible future events that will make a significant contribution to risk is included. The factors that need to be considered in order to ensure a comprehensive analysis are numerous and far-ranging. Natural phenomena that may be important include: extra terrestrial impacts, geological effects, climatological events, geomorphological and hydrological processes, and transport and geochemical and ecological changes. Human activities such as design and construction; operation and closure; and post closure sub-surface and surface activities should be considered. In addition, waste and repository effects including thermal, chemical mechanical and radiological impacts should be incorporated into the assessment. It is not possible to guarantee that all of the relevant possible futures have been included, and commentators from within the nuclear industry, have commented that the claim to be able to predict the long term radiological impact of a repository "is largely governed by wishful thinking". [7]

The difficulties that arise due to the requirement for comprehensive analysis are not esoteric, but raise fundamental problems for the safety assessment. For example, in order to prevent radionuclides migrating from the repository, the repository has been designed to attempt to ensure that the materials used in its

---

7 Merz (1990) p300

construction provide a physical barrier. The safety assessment has been computed on the basis that absolute physical containment may be guaranteed for the first 300 years. However, the assumption of absolute containment neglects the generation of gas in the repository. Nirex have estimated that 1 billion cubic metres of gas will be generated. In order to avoid overpressurisation effects, this gas must be allowed to escape. However, providing pathways for gas release will inevitably require the breaching of the physical containment that has been assumed in the safety assessment. This introduces intractable contradictions that have not been resolved. The failure to identify the significance of gas generation in the safety assessment, may be viewed as a failure of the synoptic method due to limitations of human intellectual capacity.

2. Limitations on Information Available.

The raw data available to achieve comprehensive policy analysis is not available.

In addition to the overpressurisation risks that arise due to gas generation, gas generation also affects the safety assessment due to the possibility of explosion, and due to the radioactivity and toxicity of the gases produced. Nirex have undertaken work in order to attempt to quantify these risks. However, the studies have been limited due to the lack of available data.

The limitations on the information available severely affects the computation of the quantity of radionuclides that will dissolve in the groundwater surrounding the repository. In order to calculate the quantity of radionuclides that will be carried from the repository in migrating groundwater, the quantity of radionuclides that dissolve in groundwater must be calculated. This requires information concerning the nature of the dissolving radionuclide compound, and the nature of the chemical environment offered by the groundwater. Subtle adjustment in either of these components of the safety assessment may result in substantial variations in the results obtained. Validation exercises undertaken by Nirex and the DoE. in order to test the veracity the safety assessment, indicated formidable shortcomings in the data used.

3. Limitations on Resources Available.

A problem requires a solution within a finite amount of time. The indefinite commitment of time and resources in order to identify the optimum solution is not viable.

Despite the investment of £6M per year and the involvement of 25 research institutions, the Nirex safety assessment research programme is not able to meet the resource demands of synoptic analysis. For example, in order to attempt to overcome unmanageable information requirements, Nirex have adopted a simplified approach to the calculation of the quantity of radionuclides that will dissolve in migrating groundwater. To by-pass the difficulties associated with the complexity of the chemical systems governing the quantity of radionuclides that will dissolve, Nirex use a parameter described as the "solubility of the element" which aims to subsume the complexities into one piece of data. The use of such a parameter assumes that the dissolved compounds carrying each radionuclide may be readily quantified, and that all relevant compounds will be included. These assumptions are invalidated due to difficulties that arise through the usage of data taken from chemical literature. The presence of colloids also presents severe difficulties.

Nirex use an extrapolation technique to derive data concerning the quantity of radionuclides that will dissolve under repository conditions, from data that is available in the literature. Data taken from chemical literature has generally been measured under conditions that will not pertain to the safety assessment. There are many alternative extrapolation techniques available that may be used to derive data pertinent to the safety assessment. However, the technique generally agreed to be the best requires the measurement of a large number of parameters and has been rejected as impractical. Instead, Nirex have adopted a "truncated" version of a more straightforward approach. The ad hoc nature of this approach introduces an element of speculation into the results obtained.

These uncertainties in the safety assessment are increased by the presence of a group of chemicals known as 'colloids', whose behaviour is very difficult to quantify. Colloids are very fine suspended particles which have properties in between those of a solution and a fine suspension. Their presence can increase the capacity of water to carry radionuclides. Colloids do not behave in the same way as dissolved compounds, and their presence introduces very complex difficulties for the safety assessment. Experimental work on colloids is extremely difficult, and the results obtained may vary with the technique used. Due to these difficulties it has not proved possible to include colloids explicitly in the safety assessment.

4. Prioritisation Difficulties.

The identification of the objectives to be met through a given solution, and the prioritisation of potential solutions is not feasible. In particular, values will change over time and there will be disagreement over the importance of different values.

There is a trade-off between the radiological impact of the repository and the current operational dose. The radioactive waste that Nirex propose to dispose of in the repository contains organic materials such as paper and plastics. These are expected to break down in the repository and produce small organic chemicals, which may react with radionuclides to produce compounds which are highly soluble. Solubility increases of up to 10,000 fold have been observed in the presence of such break down products, thus increasing the quantity of radionuclides that may be carried by the migrating groundwater. In order to overcome this problem, the possibility of excluding organic material from the repository is under consideration. However, the objective of excluding organics in order to reduce the radiological impact of the repository, conflicts with the operational requirements of BNFL. Presently there are over 20,000 containers of radioactive waste containing organic material in a "raw" state in storage at Sellafield. BNFL propose to encapsulate these wastes in concrete in order to reduce operator doses arising from the wastes. Encapsulation would not serve to remove organic material from the waste, and the issue of the relative priority of current operator dose, compared to future repository safety remains to be resolved.

5. Relationship of Fact and Value.

In the actual process of decision making fact and value are closely intertwined. Decision makers do not know which values are relevant to the prioritisation process until the consequences of possible options have been identified.

In 1980, Sellafield was rejected as a site for repository development due to poor hydrogeology. Following the rejection of Sellafield on technical grounds, Nirex attempted to site disposal facilities at various locations around the country, but were forced to abandon these sites due to the strength of local opposition. Following the rejection of these sites on political grounds, Nirex returned to Sellafield. In 1991 Nirex announced that they intended to concentrate further site investigation work at Sellafield. The site investigation programme carried out at Sellafield has indicated that the hydrogeology of the site is extremely complex; and that groundwater migrating from a repository at the site may travel straight upwards to the surface. Thus, it may be seen that the 'facts' concerning the suitability of the Sellafield site for repository development, are closely intertwined with the relative importance of the value Nirex place on public reaction to repository development, and the value placed on hydrogeological considerations.

6. Openness of the System of Variables.

In actual policy making situations it will not always be possible to identify a closed system of variables that is of sufficient size to encompass all of the information required for the problem.

In order to attempt to overcome the difficulties that arise due to the openness of the system of variables, Nirex have attempted to derive systems that are superficially closed. This is achieved through the artificial derivation of concepts which have little or no physical meaning. For example, the concept of 'elemental solubility', discussed above, encompasses a range of values that may vary up to one billion-fold. Similarly, the concept of rock 'permeability' [8] incorporates a wide variety of complex physical phenomena which are not understood and present severe difficulties for the safety assessment. For example, the most important measurements for obtaining rock 'permeability' data are made using boreholes, but the drilling of the boreholes may itself make rock 'permeable'. Thus, it may not be possible to obtain robust information on the permeability of rock at the proposed repository site, as the measurement technique used may alter the permeability of the rock.

7. Lack of Strategic Sequence for Analysis.

The synoptic method demands that the decision maker achieves a comprehensiveness of information and understanding, but does not provide guidance on how to achieve this ideal.

It may be seen that the information gathering difficulties predicted by Lindblom may be found throughout this case study and that the lack of a strategic sequence for analysis presents Nirex with severe difficulties. For example, the attempt by Nirex to obtain comprehensive information on gas flow through rock, by undertaking a literature search revealed that very little information was available. Moreover, the information that was available was of limited value due to

---

8 Lever (1990) NSS/G113, p5

"discrepancies in definition and philosophy" [9] between researchers. Similarly, the relevance of much of the research undertaken by Nirex on solubility is brought into question by the different experimental protocols used to obtain the data. The use of filtration techniques to exclude colloids may lead to underestimation of the quantity of radionuclides that will be carried by migrating groundwater. However, the inclusion of colloids presents difficulties as their behaviour is poorly understood and difficult to quantify.

Difficulties associated with the lack of a strategic system for analysis are also found within the work undertaken to attempt to quantify the rate of groundwater flow from the proposed repository. For example, the lack of understanding of water flow through fractures has led to an extensive research programme. However, it has been concluded that:

> "Rather than decreasing our uncertainty, this line of research has increased the number of ways in which we know that we are uncertain." [10]

The lack of a strategic sequence for analysis also has direct logistical implications. For example, Nirex propose to excavate a shaft at Sellafield in order to obtain further hydrogeological information. It is important that data is obtained from the rock which is expected to provide the pathway for radionuclides migrating to the surface. However, excavation of this rock will increase the potential for water to flow along this pathway, and may provide an "express route" [11] for transport of radionuclides to the surface. Therefore, the shaft should be sited away from areas of upward moving groundwater. This introduces a direct contradiction into the shaft siting criteria. The problems associated with shaft excavation are considerably increased by the lack of understanding of rock excavation effects. Rock excavation will alter the permeability of the surrounding rock. There are

---

9 Tomlinson (1988) NSS/R146, p37
10 U.S. National Research Council (1990) p4
11 Black (1991) p7

many factors which may contribute to the observed permeability change, and the effect is not understood. Given these problems, it has been proposed that a generic research project should be established, similar to the 15 year project undertaken at Stripa in Sweden. Nirex do not propose to undertake generic research of this nature.

8. Policy Constraints.

The concept of a policy problem as a detached conundrum requiring a solution algorithm does not adequately adhere to the variety of evolving situations that require policy adoption and modification in the real world.

It is Nirex policy to begin excavation work at Sellafield in 1994. This policy conflicts with the requirements of the synoptic safety assessment. In order, to establish a long term safety case for the repository, Nirex must use data obtained before excavation is underway. Excavation work will destroy the base hydrogeology on which the long term safety case is dependent. Currently, it is not Nirex policy to carry out the necessary data gathering work prior to rock excavation.

10.3. INCREMENTALISM

The results of these case studies tend to support the position of the incrementalist. The incremental approach to decision making insists that decision makers do not actually use the synoptic approach, but have developed a more sophisticated system that is able to by-pass the problems associated with the synoptic method.

Under the incremental approach to decision making policy is developed through incremental changes to existing policy not requiring synoptic analysis. Lindblom argues that decision making should be seen as a process, involving extensive political interaction, rather than a one-off event involving extensive analysis. Under this approach the fundamental importance of flexibility and widespread political involvement is stressed. [*12*]

Given the difficulties associated with the synoptic appraisal of the safety of nuclear waste disposal, some commentators have argued for a more flexible approach to waste management which incorporates the option of waste retrievability. [13] [14] [15] It is argued that the possibility of the omission of unforeseen eventualities in the safety assessment, may lead to the underestimation of the risks arising from waste disposal. Therefore, it is argued that the opportunity for ameliorative action through the recovery of the waste should be maintained.

10.4. CONCLUSION

In this thesis, the performance of the synoptic method has been evaluated in order to test Lindblom's hypothesis that the synoptic approach to decision making is not achievable. The outcome of the first case study led to the modification of the methodology used in the second case study in order that robust conclusions could be drawn. Thus, the success of the synoptic method, was addressed rather than the success of a decision ostensibly made using the method, as the role of the

---

12 The importance of widespread political involvement in decision making concerning nuclear waste management has been discussed elsewhere [see for example Kemp (1992) pp 50-51,77-81; Williams (1980) pp 315-327; Blowers (1991) pp 24,324; Pearce (1979); Berkhout (1991) pp 205-224; Wynne (1982)].

13 Fyfe (1984) p538

14 Institution of Geologists in Environment Committee (1986) vol III, p666

15 Swedish National Board for Spent Nuclear Fuel (1988) p14

synoptic method in decision making is ambiguous. It has been argued that the synoptic method is used as a political legitimisation tool to legitimate a decision that has already been taken. Consideration of the viability of the synoptic method, rather than the success of a decision overtly taken using the synoptic method, allows Lindblom's hypothesis to be tested directly, and therefore is robust to criticisms arising from the ambiguity surrounding the role of the synoptic method in decision making. The direct evaluation of the synoptic method in the second case study vindicated Lindblom's hypothesis that the synoptic approach to decision making is not achievable. Moreover, it was found that the synoptic method failed in the way that Lindblom predicted that it would. Furthermore, the synoptic analysis considered in this case study comprises technical data concerning the chemistry and geology of the proposed repository. Such data is not subject to the intangibles that pervade data concerning social and economic policy options. Thus, the use of this case study provides a strong test of the synoptic method. It may therefore be concluded that this case study provides a powerful indictment of the synoptic method, that has broad application outside of the sphere of decision making in nuclear waste management.

11. BIBLIOGRAPHY

Albright (1993)
D. Albright, F Berkhout and W. Walker.
World Inventory of Plutonium and Highly Enriched Uranium, 1992.
Stockholm International Peace Research Institute.
ISBN 0 19 829153 1.
Oxford: Oxford University Press, 1993.

Allen (1987) NSS/R106
A.J. Allen, M.A. Bourke, P.J. Bourke, and N.L. Jefferies.
Preliminary Neutron Scattering Studies of Porosity of Clay.
NSS/R106.
Nirex, 1987.

Allen (1988) NSS/R160
A.J. Allen, A.H. Baston, P.J. Bourke and N.L. Jefferies.
Small Angle Neutron Scattering Studies of Diffusion and Permeation through Pores in Clays
NSS/R160.
Nirex, 1988.

Allen (1989) NSS/R192
A.J. Allen, A.H. Baston, P.J. Bourke and N.L Jefferies.
The Application of Small-Angle Neutron Scattering to the Study of Mass Transfer in Clays.
NSS/R192.
Nirex, 1989.

Angell (1989)
M.G. Angell, J. McPhillimy, A.W. Phillips, C. O'Tallamhain, E. Wood, M. Blackbourn, C.C. Carter and D.J. Wheeler.
Packaging, Storage and Direct Disposal of Spent AGR Fuel.
DOE/RW/89-098.
Department of the Environment, November 1989.

Anon (1989)
Exploring the Offshore Options.
Nuclear Engineering International.
February 1989, **34**(414), 33-35.

Anon (1990) January 1990
Caithness 'No!' to Nirex Waste Dump.
SCRAM: The Safe Energy Journal.
ISSN 0140 7340.
December 1989/January 1990, (74), 6.

Anon (1990) March 1990
Assessing Sellafield's Vitrification Technology.
Nuclear Engineering International.
March 1990. **35**(428), 43-46.

Anon (1992)
Nirex 'Rejected' Halcrow Advice.
Construction Weekly: The News Magazine for the Industry.
4 November 1992, 1.

Arnold (1990) NSS/R219
L. Arnold
Volatilisation of Radionuclides from Soil and Plants: Sn and I.
NSS/R219.
Nirex, 1990.

Atkins (1982)
P.W. Atkins.
Physical Chemistry.
ISBN 0-19-855151-7.
Oxford: Oxford University Press, 1982.

Atkinson (1988)
A. Atkinson, F.T. Ewart, S.Y.R. Pugh, J.H. Rees, S.M. Sharland, P.W. Tasker and J.D.Wilkins.
Experimental and Modelling Studies of the Near-Field Chemistry for Nirex Repository Concepts.
In OECD Nuclear Energy Agency, *Proceedings of an NEA Workshop on Near-Field Assessment of Repositories for Low and Medium Level Radioactive Waste, Baden, 23-25 November 1987.*
Paris: OECD, 1988, pp.143-157.

Atkinson (1988) NSS/G102
A. Atkinson and G.P. Marsh.
Engineered Barriers: Current Status.
NSS/G102.
Nirex, 1988.

Atkinson (1988) NSS/R104
A. Atkinson, F.T. Ewart, S.Y.R. Pugh, J.H. Rees, S. M. Sharland, P.W. Tasker and J.D. Wilkins.
Experimental and Modelling Studies of the Near-Field Chemistry for Nirex Repository Concepts.
NSS/R104.
Nirex, 1988.

Atkinson (1988) NSS/R127
A Atkinson, A. Haxby and J.A. Hearne.
The Chemistry and Expansion of Limestone -- Portland Cement Mortars Exposed to Sulphate Containing Solutions.
NSS/R127.
Nirex, 1988.

Atkinson (1989) NSS/G110
A. Atkinson and G.P. Marsh
Engineered Barriers: Current Status 1989.
Nirex. Report NSS/G110, 1989.

Atkinson (1989) NSS/R187
A Atkinson and J.A. Hearne.
The Hydrothermal Chemistry of Portland Cement and its Relevance to Radioactive Waste Disposal.
NSS/R187.
Nirex, 1989.

Atkinson (1989) NSS/R196
A Atkinson and J.A. Hearne.
Mechanistic Model for the Durability of Concrete Barriers Exposed to Sulphate-Bearing Groundwaters.
NSS/R196.
Nirex, 1989.

Atomic Energy Authority (1966)
Internal Document.
Extract from Minutes of Atomic Energy Authority Meeting.
6 January 1966.

Bailey (1990)
B. Bailey.
The Long History of Magnox Reprocessing.
In *British Reprocessing, Special Nuclear Engineering International Publication.*
October 1990, 11-14.

Bairiot (1989)
H. Bairiot and C. Vandenberg.
Use of Mox Fuels; The Reasons to Start.
In IAEA (ed.), *Nuclear Fuel Cycle in the 1990s and Beyond the Century: Some Trends and Foreseeable Problems.*
Vienna: IAEA, 1989, pp. 65-95.

Barker (1992)
K. Barker
Drift Access Waste Repository for UK.
Nuclear Engineering International.
February 1992, **37**(451), 39-40.

Barraclough (1992)
I.M. Barraclough, S.F. Mobbs and J.R. Cooper.
Radiological Protection Objectives for the Land-Based Disposal of Radioactive Solid Wastes.
Documents of the NRPB
ISBN 0 85951 353 X
1992, **3**(3), 5-25

Baston (1990) NSS/R224
G.M.N. Baston, J.A. Berry and N.J Pilkington.
Studies of the Effects of Organic Materials on the Sorption of Tin and Radium.
NSS/R224.
Nirex, 1990.

Bath (1989) NSS/R170
A.H. Bath, C.A.M. Ross, D.C. Entwisle, M.R. Cave, K.A. Green, S. Reeder and M.B. Fry.
Hydrochemistry of Porewaters from London Clay, Lower London Tertiaries and Chalk at the Bradwell Site.
NSS/R170.
Nirex, 1989.

Beale (1988)
H. Beale and S.J. Taylor.
Deep Repository Design -- Offshore Concepts.
In *Disposal of Radioactive Waste in Seabed Sediments: International Conference.*
St. Catherine's College, Oxford, 20-21 September 1988

Bebbington (1976)
W.P. Bebbington.
The Reprocessing of Nuclear fuels.
Scientific American.
1976, **235**, 30-41.

Bell (1989) 24 May 1989
A. Bell.
Edge of Darkness.
Time Out.
24 May 1989, 11-15.

Bell (1989) 31 May 1989
A. Bell.
Edge of Darkness II.
Time Out.
31 May 1989, 9-11.

Berkhout (1990)
F. Berkhout, T. Suzuki and W. Walker.
The Approaching Plutonium Surplus: a Japanese/European Predicament.
International Affairs.
1990, **66**(3), 523-543.

Berkhout (1990) November 1990
F. Berkhout and W. Walker.
THORP and the Economics of Reprocessing.
ISBN 0 903622 42 4.
Sussex: University of Sussex Science Policy Research Unit, November 1990.

Berkhout (1991)
F. Berkhout.
Radioactive Waste, Politics and Technology.
ISBN 0 415 05492 3.
London: Routledge, 1991.

Berry (1988) NSS/R121
J.A. Berry, H.A. Coates, A. Green and A.K. Littleboy.
Sorption of Radionuclides on Geological Samples from the Bradwell, Elstow, Fulbeck and Killingholme Site Investigations.
NSS/R121.
Nirex, 1988.

Berry (1988) NSS/R122
J.A. Berry, J. Hobley, S.A. Lane, A.K.Littleboy, M.J. Nash, P. Oliver. J.L. Smith-Briggs and S.J. Williams.
The Solubility and Sorption of Protactinium in the Near-Field and Far-Field Environments of a Radioactive Waste Repository.
NSS/R122.
Nirex, 1988.

Berry (1989) NSS/R183
J.A. Berry, K.A. Bond, D.R. Ferguson and N.J. Pilkington.
Studies of the Effects of Organic Materials on the Sorption of Uranium and Plutonium.
NSS/R183.
Nirex, 1989.

Berry (1990) NSS/R182
J.A. Berry, K.A. Bond, M. Brownsword, D.R. Ferguson, A. Green and A.K. Littleboy.
Radionuclide Sorption on Generic Rock Types.
NSS/R182.
Nirex, 1990.

Betts (1989) NSS/R164
A.J. Betts and R.C. Newman.
The Resistance of Austenitic Stainless Steels to Pitting Corrosion in Simulated BFS/OPC Pore Waters Containing Thiosulphate Ions.
NSS/R164.
Nirex, 1989.

Biddle (1988) NSS/R118
P. Biddle, A.A. Davies, D.J. McGahan, J.H. Rees and P.E. Rushbrook.
The Evolution of Minor Active and Toxic Gases in Repositories.
NSS/R118.
Nirex, 1988.

Biddle (1989) NSS/R130
P. Biddle, M.D. Gale, J.G. Godfrey and D.R. Woodwark.
Equilibrium Leach Testing of Low Level Waste, Part 1 -- Effect of Backfill.
NSS/R130.
Nirex, 1989.

Biddle (1989) NSS/R205
P. Biddle
The Interaction of Volatile, Toxic Organic Species with Mineral Phases -- A Literature Review.
NSS/R205.
Nirex, 1989.

Billington (1990)
D.E. Billington, D.A. Lever and S.J. Wisbey.

Radiological Assessment of Deep Geological Disposal: Work for UK Nirex Ltd.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp. 271-281.

Bishop (1989) NSS/R193
G.P Bishop, C.J. Beetham and Y.S. Cuff.
Review of Literature for Chlorine, Technetium, Iodine and Neptunium.
NSS/R193.
Nirex, 1989.

Bishop (1989) NSS/R194
G.P. Bishop
Review of Biosphere Information, Biotic Transport of Radionuclides as a Result of Mass Movement of Soil By Burrowing Animals.
NSS/R194.
Nirex, 1989.

Bishop (1989) NSS/R195
G.P Bishop and C.J Beetham.
Biotic Transport of Radionuclides in Soils as a Result of the Action of Deep-Rooted Plant Species.
NSS/R195.
Nirex, 1989.

Black (1984)
D. Black.
Investigation of the Possible Increased Incidence of Cancer in West Cumbria; Report of the Independent Advisory Group.
ISBN 0 11 321006 X.
London: HMSO, 1984.

Black (1991)
J.H. Black and D.A. Gray.
The Disposal of Decommissioning and Other Wastes.
1991 Summer School on Radioactive Waste Management, Decommissioning and Clean Up.
Organized by IBC.
Jesus College, Cambridge, 8-11 July 1991.

Bloodworth (1989) NSS/R177
A.J. Bloodworth, S.J. Kemp, S.D.J. Inglethorpe and D.J. Morgan.
Mineralogy and Petrography of Caithness Flagstones Used in Sorption Experiments By Harwell Laboratory.
NSS/R177.
Nirex, 1989.

Bloodworth (1989) NSS/R175
A.J. Bloodworth and D.J. Morgan.
Mineralogy of Mudrocks: Analytical Requirements and Significance of Data to Site Assessment.
NSS/R175.
Nirex, 1989.

Blowers (1991)
A. Blowers, D. Lowry and B. Solomon.
The International Politics of Nuclear Waste
ISBN 0 333 49364 8
London: Macmillan Academic and Professional Ltd, 1991.

BNFL (1977)
British Nuclear Fuels Limited.
Statement of Submissions by British Nuclear Fuels Limited Pursuant to Rule 6 (6) of the Town and Country Planning (Inquiries Procedure) Rules 1974: Re. Windscale Planning Application
9 May 1977.

BNFL (1985)
Nuclear Fuel Reprocessing Technology.
BNFL, 1985.

BNFL (1988)
Health and Safety: Annual Report 1987.
BNFL, 1988.

BNFL (1989)
Nuclear Waste, What's to be Done about it?.
BNFL, 1989.

BNFL (1991) Annual Report
British Nuclear Fuels PLC.
Annual Report & Accounts 1989/1990.
BNFL, 1991.

BNFL (1991) Health and Safety Report
Health, Safety and the Environment: Annual Report 1990.
BNFL, 1991.

BNFL (1992)
British Nuclear Fuels PLC.
Annual Report & Accounts 1991/1992.
August 1992.

BNFL Board of Directors (1972)
Internal Document.
British Nuclear Fuels Limited Board of Directors.
Minutes of the Eleventh Meeting.
BNFL/B/11th Meeting.
23 February 1972.

BNFL Board of Directors (1974)
Internal Document.
Minutes of Thirty-sixth Meeting of the Board.
BNFL/B/36th Meeting.
3 July 1974.

BNFL Reprocessing Division Executive (1976)
Internal Document.
Minutes of Meeting.
RDE(76) 10th Meeting.
5 October 1976.

Bond (1990) NSS/R207

K.A. Bond, J.E. Cross and F.T. Ewart.
Thermodynamic Modelling of Uranium(VI) Sorption onto London Clay.
NSS/R207.
Nirex, 1990.

Bourke (1988) NSS/R135

P.J. Bourke, D. Gilling, N.L. Jefferies, D.A. Lever and T.R. Lineham.
Laboratory Experiments of Mass Transfer in the London Clay.
NSS/R135.
Nirex, 1988.

Bourke (1990) NSS/R159

P.J. Bourke, D. Gilling, N.L. Jefferies, D.A. Lever, and T.R Lineham.
Mass Transfer Through Clay By Diffusion and Advection: Description of Intraval Test Case 1a
NSS/R159.
Nirex, 1990.

Bourke (1990) NSS/R214

P.J. Bourke, N.L. Jefferies, T.R. Lineham and P. Nesirky.
Laboratory and Field Tests for Radionuclide Migration and High Flow Paths in Clay, Final Report.
NSS/R214.
Nirex, 1990.

Braybrooke (1970)

D. Braybrooke and C. Lindblom.
A Strategy of Decision: Policy Evaluation as a Social Process.
London: Collier Macmillan Publishers: 1970.

Breach (1978)

I. Breach.
Windscale Fallout; A Primer for the Age of Nuclear Controversy.
Middlesex: Penguin Books Ltd, 1978.

Brown (1991) NSS/R188

P.L. Brown, A. Haworth, S.M. Sharland and C.J. Tweed.
HARPHRQ: A Geochemical Speciation Program Based on PHREEQE.
NSS/R188.
Nirex, 1991.

Broyd (1990)

T.W. Broyd, D. Read, N. Harrison and B. Come.
Chemval -- An International Research Initiative for the Verification and Validation Testing of Chemical Speciation and Chemical Transport Computer Programs.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp. 737-748.

Buck (1969)

Internal Document.
C. Buck.
Interim Report of the Working Party to Consider a Second Head End

Plant.
Presented to the Production Group Technical Committee.
PGTC(69)P6.
11 March 1969, pp.6.

Butler (1990) NSS/R253
A.P. Butler and H.S. Wheater.
Model Sensitivity Studies of Radionuclide Uptake in Cropped Lysimeters.
NSS/R253.
Nirex, 1990.

Butterworth (1990) June 1990, p 16
D. Butterworth.
Slow but Sure.
BNFL News.
June 1990, 16.

Butterworth (1990) October 1990, p 12
D. Butterworth.
Capping it All!
BNFL News.
October 1990, 12.

Butterworth (1991) March 1991, p 1
D. Butterworth
Heseltine Praise for VIT Plant.
BNFL News.
March 1991, 1.

Butterworth (1991) March 1991, pp 6-7
D. Butterworth.
Best of British.
BNFL News.
March 1991, 6-7.

Carrera (1990)
J. Carrera and F.J. Samper.
Hydrological Modelling for the Safety Assessment of Radioactive Waste Disposal.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp. 481-500.

CEGB (1965)
Central Electricity Generating Board.
An Appraisal of the Technical and Economic Aspects of Dungeness B Nuclear Power Station.
London, July 1965.

CEGB/SSEB (1986)
The CEGB/SSEB Response to Recommendation 17 in the Environment Committee's Report on Radioactive Waste
CEGB/SSEB, November 1986.

Chandratillake (1988) NSS/R149
M.R. Chandratillake. V.J. Robinson and G.W.A. Newton.

Critically Selected Formation Constants for Some Actinide-Chloro Complexes.
NSS/R149.
Nirex, 1988.

Chandratillake (1990)
M.R. Chandratillake, G.W.A. Newton and V.J. Robinson.
Summary Report of University of Manchester Involvement in the CHEMVAL Project.
DOE/RW/90/075.
Department of the Environment, August 1990.

Chapman (1986)
N.A. Chapman, T.J. McEwen and H. Beale.
Geological Environments for Deep Disposal of Intermediate Level Wastes in the United Kingdom.
(IAEA-SM-289/37)
International Atomic Energy Agency Symposium, Hanover, 3-7 March 1986.
IAEA, 1986.

Chapman (1987) Site Selection and Characterization
N.A. Chapman, J.H. Black, A.H. Bath, P.J. Hooker and T.J. McEwen.
Site Selection and Characterisation for Deep Radioactive Waste Repositories in Britain: Issues and Research Trends into the 1990's.
Radioactive Waste Management and the Nuclear Fuel Cycle.
1987, **9**(1-3), 183-213.

Chapman (1987) The Geological Disposal of Nuclear Waste
N.A. Chapman, I.G. McKinley, and M.D. Hill.
The Geological Disposal of Nuclear Waste.
ISBN 0 471 91249 2.
Chichester: John Wiley & Sons, 1987.

Chapman (1990)
N.A Chapman and B. Come.
Long-Term Predictions -- Making Proper Use of Geological Evidence.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp. 318-329.

Charlesworth (1981)
F.R. Charlesworth, W.S. Gronow and A.W. Kenny.
Windscale: The Management of Safety.
ISBN 0 7176 00769.
London: Health and Safety Executive, 1981

Cmd. 9389 (1955)
A Programme of Nuclear Power.
Cmd. 9389.
London: HMSO, February 1955.

Cmnd. 2335 (1964)
The Second Nuclear Power Programme.
Cmnd. 2335.
London: HMSO, April 1964.

Cmnd. 5703 (1974)
Nuclear Installations Inspectorate.
Report by the Chief Inspector of Nuclear Installations on the Incident in Building B204 at the Windscale Works of British Nuclear Fuels Limited on 26 September 1973.
ISBN 0 10 157030 9.
London: HMSO, 1974.

Cmnd. 6618 (1976)
Royal Commission on Environmental Pollution, Sixth Report.
Nuclear Power and the Environment.
Cmnd. 6618.
London: HMSO, September 1976.

Cmnd. 884 (1959)
Cmnd. 884.
The Control of Radioactive Wastes.
ISBN 0 10 850041 1.
London: HMSO, November 1959

Colasanti (1990) NSS/R131
R. Colasanti, D.Coutts, S.Y.R. Pugh and A. Rosevear.
Microbiology and Radioactive Waste Disposal; Review of the Nirex Research Programme -- January 1989.
NSS/R131.
Nirex, 1990

Collier (1991) Fast Reactors
J. Collier.
Fast Reactors -- Investing in the Future.
Power in Europe.
12 September 1991, 2-3.

Collier (1991) Straight Talking
J. Collier.
Straight Talking from Chairman John Collier.
Nuclear Times.
January 1991, 6-7.

Collingridge (1980)
D. Collingridge.
The Social Control of Technology.
ISBN 0-335-10031-7.
Milton Keynes: The Open University Press, 1980.

Collingridge (1982)
D. Collingridge.
Critical Decision Making: A New Theory of Social Choice.
ISBN 0 86187 238 X.
London: Frances Pinter Publishers, 1982.

Collingridge (1983)
D. Collingridge.
Technology in the Policy Process: Controlling Nuclear Power.
ISBN O-86187-319-X.
London: Frances Pinter Publishers, 1983.

Collingridge (1984)
D. Collingridge and J. Douglas.
Three Models of Policymaking: Expert Advice in the Control of Environmental Lead.
Social Studies of Science.
1984 **14,** 343-70

Collingridge (1986)
D. Collingridge and C. Reeve.
Science and Policy -- Why the Marriage is so Unhappy?
Bulletin of Science, Technology and Society.
1986, **6**, 356-372.

Collingridge (1989)
D. Collingridge and P. James.
Technology, Organizations and Incrementalism: High Rise System Building in the UK.
Technology Analysis & Strategic Management.
1989, **1**(1), 79-97.

Collingridge (1990)
D. Collingridge.
Technology, Organizations and Incrementalism: the Space Shuttle.
Technology Analysis & Strategic Management.
1989, 2(2), 181-200.

Collingridge (1992)
D. Collingridge.
The Management of Scale
London: Routledge, 1992.

Collingridge (1994)
Forthcoming
D. Collingridge, A. Genus and P. James.
Inflexibility in the Development of North Sea Oil.
Technological Change and Social Forecasting.
1994.

Colston (1990) NSS/R204
B.J. Colston, M.R. Chandratillake, V.J. Robinson and J.E. Cross.
Correction for Ionic Strength Effects in Modelling Aqueous Systems.
NSS/R204.
Nirex, 1990.

Conroy (1978)
C. Conroy.
What Choice Windscale?.
London: Conservation Society Ltd and Friends of the Earth Ltd, 1978.

Cooling (1987)
C.M. Cooling and J.A. Hudson.
Geotechnical Aspects of the UK DOE-Sponsored Radioactive Waste Disposal Research Programme.
Radioactive Waste Management and the Nuclear Fuel Cycle.
1987, **9**(1-3), 123-149.

Cooper (1987) NSS/R101
M.J. Cooper and D.P Hodgkinson (ed).
The Nirex Safety Assessment Research Programme: Annual Report for 1986/87.
NSS/R101.
Nirex, 1987.

Cooper (1987) NSS/R102
M.J. Cooper and P.W. Tasker.
The Nirex Safety Assessment Research Programme for 1987/88.
NSS/R102.
Nirex, 1987.

Cooper (1988) NSS/R133
M.J. Cooper (ed).
The Nirex Safety Assessment Research Programme; Annual Report for 1987/88.
NSS/R133.
Nirex, 1988.

Cooper (1989) NSS/R168
M.J. Cooper (ed).
The Nirex Safety Assessment Research Programme; Annual Report for 1988/89.
NSS/R168.
Nirex, 1989.

Corns (1964)
H. Corns, D.W. Clelland, T.G. Hughes and J.W. de Lisle Nichols.
The New Separation Plant Windscale: Design of Plant and Plant Control Methods.
In *Proceedings of the Third United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1964.*
Volume 10.
New York: United Nations 1964. pp.233-241.

Cox (1989) NSS/R141
I.C.S. Cox and W.R. Rodwell.
Post-Closure Resaturation of a Deep Radioactive Waste Repository.
NSS/R141.
Nirex, 1989.

Cremer (1988)
Cremer and Warner.
Flammable Gas Production in Land 2 and Land 3/4 Radioactive Waste Repositories.
DOE/RW/88.023.
Department of Environment, February 1988.

Cross (1989) NSS/R119
J.E. Cross, D. Crossley, J.W. Edwards, F.T. Ewart, M. Liezers, J.W. McMillan, P.M. Pollard and S. Turner.
Actinide Speciation Further Development and Application of Laser Induced Photoacoustic Spectroscopy and Voltammetry.
NSS/R119.
Nirex. 1989

Cross (1989) NSS/R151
J.E. Cross, F.T. Ewart and B.F. Greenfield.
Modelling the Behaviour of Organic Degradation Products.
NSS/R151.
Nirex, 1989.

Cross (1990) NSS/R212
J.E. Cross and F.T. Ewart
HATCHES -- A Thermodynamic Database and Management System.
NSS/R212.
Nirex, 1990.

Cross (1991) NSS/R252
J.E. Cross, D.S. Gabriel, A. Haworth, I. Neretnieks, S.M. Sharland and C.J. Tweed.
Modelling of Redox Front and Uranium Movement in a Uranium Mine at Pocos de Caldas, Brazil.
NSS/R252.
Nirex, 1991.

Culler (1956)
F.L. Culler.
Reprocessing of Reactor Fuel and Blanket Materials by Solvent Extraction.
In United Nations, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 8-20 August 1955.*
Volume 9: Reactor Technology and Chemical Processing.
New York: United Nations, 1956, pp.464-483.

Culler (1963)
F.L. Culler.
Present and Future Role of Reprocessing in the Fuel Cycle.
In OECD European Nuclear Energy Agency, *Aqueous Reprocessing Chemistry for Irradiated Fuels Symposium, Brussels, 1963.*
OECD European Nuclear Energy Agency, 1963. pp 427-464

Curd (1992)
P. Curd.
Rock Laboratory.
New Scientist.
24 October 1992, 50.

Department of Energy (1991)
Department of Energy.
The Deparment of Energy's Nuclear R&D Programmes.
Department of Energy, August 1991.

Department of the Environment (1979)
Department of the Environment, Scottish and Welsh Office.
A Review of Cmnd 884: "The Control of Radioactive Wastes".
London: Department of the Environment, 1979.

Department of the Environment (1984)
Department of the Environment, Scottish Office. Welsh Office, and Department of the Environment for Northern Ireland; Ministry of Agriculture. Fisheries and Food.
Disposal Facilities on Land for Low and Intermediate-Level Radioactive

Wastes: Principles for the Protection of the Human Environment.
ISBN 0 11 751775.
HMSO, December 1984.

Dircks (1992)
W. Dircks.
Dircks Revives IAEA Plutonium Store Plan.
Power in Europe.
25 September 1992, 3-5.

Doran (1976)
Internal Document.
J. Doran.
Review of Reprocessing Strategies for Oxide Fuel Using the Existing Plants.
Note by J. Doran for British Nuclear Fuels Limited Reprocessing Division Executive.
RDE(76)79.
3 August 1976

Dunster (1992)
H.J. Dunster.
Effects of Radiation on Man and the Environment.
1992 Summer School on Radioactive Waste Management and Decommissioning.
Organized by IBC.
Jesus College, Cambridge, 29 June - 2 July 1992.

Electrowatt (1990)
The 1989 United Kingdom Radioactive Waste Inventory.
Report prepared for UK Nirex Ltd. and the Department of the Environment.
DOE/RW/89-110.
West Sussex: Electrowatt, October 1990.

Electrowatt (1992)
The 1991 United Kingdom Radioactive Waste Inventory.
Report prepared for UK Nirex Ltd. and the Department of the Environment.
DOE/RAS/92.010.
West Sussex: Electrowatt, November 1992.

Elliot (1989) NSS/R147
T. Elliot, M.J. Tomlinson, K.A. Foxford, D.J. Holbrough and D.M. Searle.
Migration of Gases Through Fractured Argillaceous Rocks: Experimental Work at the Reskajeage Farm Quarry Site, Cornwall.
NSS/R147.
Nirex, 1989.

Emmings (1989)
A. Emmings.
The Next Step for Radioactive Waste Management.
Atom.
May 1989, 6-8.

Energy Committee (1989)
House of Commons Energy Committee, First Special Report, Session

1989-1990.
Government Observations on the Third Report From the Committee (Session 1988-89) on British Nuclear Fuels PLC: Report and Accounts 1987-88.
London: HMSO, 6 December 1989.

Energy Committee (1990) 7 June 1990
House of Commons Energy Committee, Fourth Report, Session 1989-1990.
The Cost of Nuclear Power.
London: HMSO, 7 June 1990.

Energy Committee (1990) 4 July 1990
House of Commons Energy Committee, Fifth Report, Session 1989-1990.
The Fast Breeder Reactor.
London: HMSO, 4 July 1990.

Energy Committee (1990) 5 December 1990
House of Commons Energy Committee, Third Special Report, Session 1990-1991.
Government Observations on the Fourth Report from the Committee (Session 1989-90) on the Cost of Nuclear Power.
London: HMSO, 5 December 1990.

Environment Committee (1986)
House of Commons Environment Committee, First Report, Session 1985-1986.
Radioactive Waste.
London: HMSO, 28 January 1986.

Environmental Resources Limited (1992)
A Review of the Geology and Hydrogeology of Sellafield.
Interim Technical Appraisal, Final Report.
ITA/4.
Oxford: Environmental Resources Limited, June 1992.

Ewart (1988) NSS/G103
F.T. Ewart, S.Y.R. Pugh, S.J. Wisbey and D.R. Woodwark.
Chemical and Microbiological Effects in the Near Field: Current Status.
NSS/G103.
Nirex, 1988.

Ewart (1989) NSS/G111
F.T. Ewart, S.Y.R. Pugh, S.J. Wisbey and D.R. Woodwark.
Chemical and Microbiological Effects in the Near Field: Current Status 1989.
NSS/G111.
Nirex, 1989.

Ewen (1990) NSS/R229
J. Ewen
Basis for the Subsurface Contaminant Migration Components of the Catchment Water Flow, Sediment Transport, and Contaminant Migration Modelling System Shetran-UK.
NSS/R229.
Nirex, 1990.

Falck (1989) NSS/R174
W.E. Falck and A.H. Bath.
Vertical Changes in Chloride and Stable Isotope Compositions of Porewaters in Coastal London Clay: Numerical Modelling and Data Evaluation.
NSS/R174.
Nirex, 1989.

Farmelo (1992)
G. Farmelo.
Foreword.
In *An International Meeting at the Science Museum: Nuclear Chain Reaction 50th Anniversary.*
Supported by British Nuclear Forum.
London: 2 December 1992.

Farmer (1957)
F.R. Farmer.
The Problem of Liquid and Gaseous Effluent Disposal at Windscale.
Journal of British Nuclear Energy Conference.
January 1957, 26-39.

Fletcher (1956)
J.M. Fletcher.
Chemical Principles in the Separation of Fission Products from Uranium and Plutonium by Solvent Extraction.
In United Nations, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 8-20 August 1955.*
Volume 9: Reactor Technology and Chemical Processing.
New York: United Nations, 1956, pp.459-463.

Francis (1988) NSS/R140
A.J. Francis
The Nirex Safety Assessment Research Programme for 1988/89.
NSS/R140.
Nirex, 1988.

Franklin (1972)
Internal Document.
N.L. Franklin.
Capital Expenditure Proposal.
Submitted by N.L. Franklin to British Nuclear Fuels Limited Board of Directors.
BNFL/B/10/72.
15 February 1972.

Franklin (1974)
Internal Document.
N.L. Franklin.
Extension of Windscale Oxide Reprocessing Facilities.
Presented by N.L. Franklin to the British Nuclear Fuels Limited Board of Directors.
BNFL/B/74/38.
26 June 1974.

Fyfe (1984)
W.F. Fyfe. V. Babuska, N.J. Price. E. Schmid. C. F. Tsang, S. Uyeda and

B.Velde.
The Geology of Nuclear Waste Disposal.
Nature.
16 August 1984, **310**, 537-540.

Gardner (1990)
M.J. Gardner, M.P. Snee. A.J. Hall, C.A. Powell, S. Downes and J.D. Terrell.
Results of Case-Control Study of Leukaemia and Lymphoma among Young People Near Sellafield Nuclear Plant in West Cumbria.
BMJ.
17 February 1990, **300**, 423-429.

Garratt (1987) NSS/R153
T.J. Garratt
Talbot's Method for the Numerical Inversion of Laplace Transforms: An Implementation for Personal Computers.
NSS/R153.
Nirex, 1987.

Garratt (1987) NSS/R154
T.J. Garratt
Solution Methods for Compartment Models of Transport Through the Environment Using Numerical Inversions of Laplace Transforms.
NSS/R154.
Nirex, 1987.

George (1989) NSS/R199
D. George.
The Response to an IAEA Review of the Deep Repository Post-Closure Safety R & D and Site Assessment Programmes of UK Nirex Limited.
NSS/R199.
Nirex, 1989.

Gibb (1992)
F. Gibb.
Sellafield Cancer Case May Cost £10M.
Times.
15 October 1992.

Gilling (1987) NSS/R110
D. Gilling, N.L. Jefferies and T.R. Lineham.
Laboratory Measurements of the Solute Transport Properties of Samples from the Bradwell, Elstow, Fulbeck and Killingholme Site Investigations.
NSS/R110.
Nirex, 1987.

Goldschmidt (1956)
B. Goldschmidt, P. Regnaut and I. Prevot.
Solvent Extraction of Plutonium from Uranium Irradiated in Atomic Piles.
In United Nations, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 8-20 August 1955.*
Volume 9: Reactor Technology and Chemical Processing.
New York: United Nations, 1956, pp.492-497.

Goldschmidt (1982)
B. Goldschmidt.

The Atomic Complex; A Worldwide Political History of Nuclear Energy.
ISBN 0-89448-550-4.
Illinois: American Nuclear Society, 1982.

Goodess (1988) NSS/R137
C.M. Goodess, J.P. Palutikof and T.D. Davies.
Studies of Climatic Effects Relevant to Site Selection and to Assessments of the Radiological Impact of Disposal at Selected Sites.
NSS/R137.
Nirex, 1988.

Goodess (1990)
C.M. Goodess, J.P. Palutikof, and T.D. Davies.
A First Approach to Assessing Future Climate States in the UK Over Very Long Timescales: Input to Studies of the Integrity of Radioactive Waste Repositories.
Climatic Change.
1990, **16**, 115-140.

Goodess (1991) NSS/R257
C.M. Goodess and J.P. Palutikof (ed).
Proceedings of the International Workshop on Future Climate Change and Radioactive Waste Disposal.
NSS/R257.
Nirex, 1991.

Gowing (1974) vol I
M. Gowing, assisted by L. Arnold.
Independence and Deterrence: Britain and Atomic Energy, 1945-1952, Volume 1: Policy Making.
SBN 333 15781 8.
London: The Macmillan Press Ltd, 1974.

Gowing (1974) vol II
M. Gowing, assisted by L. Arnold.
Independence and Deterrence: Britain and Atomic Energy, 1945-1952, Volume 2: Policy Execution.
SBN 333 16695 7.
London: The Macmillan Press Ltd, 1974.

Greenfield (1991)
B.F. Greenfield, A. Rosevear and S.J. Williams.
Review of the Microbiological, Chemical and Radiolytic Degradation of Organic Material Likely to be Present in Intermediate Level and Low Level Radioactive Wastes.
DOE/HMIP/RR/91/002.
Department of the Environment, 1991.

Greenwood (1984)
N.N. Greenwood and A. Earnshaw.
Chemistry of the Elements.
ISBN 0-08-022057-6.
Oxford: Pergamon Press, 1984.

Gresley (1989)
J.A.B. Gresley.
Enriching Recycled Uranium.

Atom.
March 1989, 13-16.

Grimwood (1990)
P. Grimwood and C. Thegerstrom.
Assessment of the Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites -- Some Observations from an NEA Workshop.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp. 385-396.

Guardian (1977)
Windscale: A Summary of the Evidence and the Argument.
ISBN 0 85265 025 6.
London: Guardian Newspapers Ltd., 1977.

Guppy (1988) NSS/R105
R. Guppy
Autogenius (sic) Healing of Cracks in Concrete and its Relevance to Radwaste Repositores.
NSS/R105.
Nirex, 1988.

Guppy (1991)
R.M. Guppy and A. Atkinson.
"Experimental Investigation of Factors Affecting the Control of Redox Conditions Within a Radwaste Repository".
DOE/HMIP/RR/91/043.
Department of the Environment, April 1991.

Hancock (1989) NSS/R184
P.L. Hancock and C.P. North.
Geology of Reskajeage Farm Quarry (Nirex Research Site on Cornish Slate)
NSS/R184.
Nirex, 1989.

Harris (1988) NSS/R125
A.W. Harris, A. Atkinson, A.K. Nickerson and N.M.Everitt.
Mass Transfer in Water-Saturated Concretes
NSS/R125.
Nirex, 1988.

Harris (1989) NSS/R189
A.W. Harris and A.K. Nickerson.
Diffusion Under Water-Saturated Conditions in Preliminary Design Backfilling Grout (Lime Grout).
NSS/R189.
Nirex, 1989.

Harris (1989) NSS/R190
A.W. Harris and A.K. Nickerson.
Measurement of Radionuclide Diffusion in SRPC- and BFS/OPC-Based Concretes Using a Sectioning Technique.
NSS/R190.
Nirex, 1989.

Harris (1990) NSS/R216
A.W. Harris and A.K. Nickerson.
Diffusion Under Water-Saturated Conditions in PFA/OPC-Based Structural Concrete.
NSS/R216.
Nirex, 1990.

Hawarth (1987) NSS/R111
A. Howarth, S.M. Sharland, P.W. Tasker and C.J.Tweed.
Evolution of the Groundwater Chemistry Around a Nuclear Waste Repository.
NSS/R111.
Nirex, 1987.

Haworth (1988) NSS/R113
A. Haworth, S.M. Sharland, P.W. Tasker and C.J. Tweed.
A Guide to the Coupled Chemical Equilibria and Migration Code CHEQMATE.
NSS/R113.
Nirex, 1988.

Haworth (1988) NSS/R115
A. Haworth, S.M. Sharland, P.W. Tasker and C.J. Tweed.
Extensions to the Coupled Chemical Equilibria and Migration Code CHEQMATE.
NSS/R115.
Nirex, 1988.

Health and Safety Commission (1992)
Health and Safety Commission.
ACSNI Study Group on the Accumulation of Radioactive Waste.
ISBN 0 11 886342 8.
London: HMSO, 1992.

Health and Safety Commission (1993)
Health and Safety Commission.
Advisory Committee on the Safety of Nuclear Installations, Report 1991-92.
ISBN 0 11 882165 2
London: HMSO, 1993.

Health and Safety Executive (1985)
Health and Safety Executive, HM Factory Inspectorate.
The Abbeystead Explosion, A Report of the Investigation by the Health and Safety Executive into the Explosion on 23 May 1984 at the Valve House of the Lune/Wyre Transfer Scheme at Abbeystead.
ISBN 0 11 883795 8.
London: HMSO, 1985.

Health and Safety Executive (1986)
Health and Safety Executive.
Safety Audit of BNFL Sellafield 1986.
ISBN 0 11 883894 6
London: HMSO, 1986.

Health and Safety Executive (1992)
Health and Safety Executive.
News Release. *Sellafield Vitrification Plant -- NII Investigation into Shield Doors Incident.*
London: Health and Safety Executive, 13 February 1992.

Herbert (1990) NSS/R223
A.W. Herbert
Development of a Tracer Transport Option for the NAPSAC Fracture Network Computer Code.
NSS/R223.
Nirex, 1990.

Hibbs (1992) 6 July 1992
M. Hibbs.
Industry Seeks Accord with Bonn Over German Fuel Cycle Future.
Nuclear Fuel.
6 July 1992, **17**(14), 4-5,10-11.

Hibbs (1992) 20 July 1992
M. Hibbs.
German Government Looks to Privatize High-Level Waste Repository Operation.
Nuclear Fuel.
20 July 1992, **117**(15), 6-7.

Hibbs (1992) 13 August 1992
M. Hibbs.
German Route to Nuclear Consensus will be Long and Hard, Experts Say.
Nucleonics Week.
13 August 1992, **33**(33), 12-13.

Hibbs (1993) 4 January 1993
M. Hibbs.
German Utilities Ready to Sacrifice Hanau Mox Fabrication Plant.
Nuclear Fuel.
4 January 1993, **18**(1), 7-9.

Hibbs (1993) 14 January 1993
M. Hibbs.
Kohl Wants Nuclear Policy Issues Resolved by June 1993.
Nucleonics Week.
14 January 1993, **34**(2), 11-12.

Higgo (1987) NSS/R142
J.J.W. Higgo
Radionuclide Interactions with Marine Sediments.
NSS/R142.
Nirex, 1987.

Higgo (1988) NSS/R162
J.J.W. Higgo
Review of Sorption Data Applicable to the Geological Environments of Interest for the Deep Disposal of ILW and LLW in the UK.
NSS/R162.
Nirex, 1988.

Highfield (1991)
R. Highfield.
Nuclear Chief Attacks Lack of Information on Dump's Safety.
Daily Telegraph.
11 March 1991.

Hill (1965)
Internal Document.
J.M. Hill.
Oxide Fuel Reprocessing Plant at Windscale.
Note by J.M. Hill for the Atomic Energy Authority.
AEA(66) 1.
31 December 1965.

Hill (1990)
M.D. Hill.
Safety Objectives and Criteria for Waste Disposal.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9 -13 October 1989.*
Paris: OECD, 1990, pp. 71-80.

Hodgkinson (1987) NSS/A100
D.P. Hodgkinson and P.C. Robinson.
Nirex Near-Surface Repository Project Preliminary Radiological Assessment, Summary.
NSS/A100.
Nirex, 1987.

Hodgkinson (1990)
D.P. Hodgkinson and T.J. Sumerling
A Review of Approaches to Scenario Analysis for Repository Safety Assessment.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp. 333-350.

Howles (1990)
L. Howles.
Annual Review of Load Factor Trends.
Nuclear Engineering International.
April 1990, **35**(429), 12-18.

Hudson (1990)
P. Hudson.
Developing Technology to Reprocess Oxide Fuel.
In *British Reprocessing, Special Nuclear Engineering International Publication.*
October 1990, 17-20.

Hughes (1972)
T.G. Hughes, B.F. Warner, J.R. Catlin, A.S. Davidson and H. Corns.
Development. Design and Operation of the Oxide Fuel Reprocessing Plant at the Windscale Works of British Nuclear Fuels Ltd.
Peaceful Uses of Atomic Energy: Proceedings of the Fourth International Conference, Geneva, 6-16 September 1971, Volume 8, Uranium and

Thorium Ore Resources, Fuel Fabrication and Reprocessing.
Jointly sponsored by the United Nations and the International Atomic Energy Agency.
Vienna: International Atomic Energy Agency, 1972. pp. 367-373.

Hughes (1988) NSS/R144
M.A. Hughes and F.J.C. Rossotti.
Voltammetric Studies of the Solution Chemistry of Technetium.
NSS/R144.
Nirex, 1988.

IAEA (1983) Criteria for Underground Disposal
International Atomic Energy Agency.
Criteria for Underground Disposal of Solid Radioactive Wastes.
Safety Series No. 60
ISBN 92-0-123583-6.
Vienna: IAEA, 1983.

IAEA (1983) Handling and Storage
International Atomic Energy Agency.
Handling and Storage of Conditioned High-Level Wastes.
Technical Reports Series No. 229.
Vienna: IAEA, 1983.

IAEA (1990)
International Atomic Energy Agency.
IAEA Yearbook 1990.
Vienna: IAEA, 1990.

ICRP (1985)
Committee 4 of the International Commission on Radiological Protection.
Annals of the ICRP: Radiation Protection Principles for the Disposal of Solid Radioactive Waste.
Adopted by the Commission in July 1985.
Oxford: Pergamon Press, 1985.

Ivanovich (1988) NSS/R117
M. Ivanovich, G. Longworth, M.A. Wilkins, S.E.Hasler and M.J Lloyd.
Measurment of Effective K_D Factors for the Long-Lived Uranium and Thorium Isotopes in Samples of London Clay (Bradwell) and Mudrock (Fulbeck)
NSS/R117.
Nirex, 1988.

Ivanovich (1989) NSS/R206
M. Ivanovich
Aspects of Uranium/Thorium Series Disequilibrium Applications to Radionuclide Migration Studies.
NSS/R206.
Nirex, 1989.

Jackson (1989) NSS/R166
C.P. Jackson and C.L. Farmer.
Modelling Saline Intrusion for Repository Performance Assessment.
NSS/R166.
Nirex, 1989.

Jackson (1991) NSS/R259
C.P. Jackson, D.A. Lever and P.J.Sumner.
Validation of Transport Models for Use in Repository Performance Assessments: A View Illustrated for Intraval Test Case 1b.
NSS/R259.
Nirex, 1991.

James (1989)
N.J James and G.T. Sheppard.
Zircaloy Hazards in Nuclear Fuel Reprocessing.
In *The Role of R & D in the Nuclear Industry.*
Organized by the Nuclear Energy Committee of the Power Industries Division, IMeche.
London: 7-8 December 1989.

Jefferies (1990) NSS/R198
N.L. Jefferies
The Evolution of Carbon-14 and Tritium Containing Gases in a Radioactive Waste Repository.
NSS/R198.
Nirex, 1990.

Jeffries (1991)
R.M. Jeffries, S.K. Liew and J.B. Thomas.
Gas Migration in Deep Radioactive Waste Repositories; A Review of Processes, Data and Models.
DOE/HMIP/RR/91/029.
Department of the Environment, March 1991.

Johansson (1990)
G. Johansson and C. Haegg.
The Disposal of High Level Radioactive Waste and the Need for Assessing the Future Radiological Impact.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp. 309-317.

Johnson (1989)
A. Johnson, Chairman Reprocessing and Reactor Group BNFL.
Inside Sellafield.
Channel Four TV.
9 November 1989, 10-11.30 pm.

Johnson (1990)
L.F. Johnson
The Cost of Radioactive Waste Management: Is it Supportable?
In *Radioactive Waste Management, London, 5-6 February 1990.*
Organized by IBC.
London: 5-6 February 1990.

Johnson (1991) NSS/R254
R.H. Johnson, J.E. Morgan and C.J. Beetham.
The Behaviour of Tin in Coastal Marine Environments.
NSS/R254.
Nirex, 1991.

Kelly (1985)
W.R. Kelly, G. Matisoff and J.B. Fisher.
The Effects of a Gas Well Blow Out on Groundwater Chemistry.
Environmental Geology and Water Sciences.
1985, **7**(4), 205-213.

Kemp (1989) NSS/R176
S.J. Kemp, A.E. Milodowski and A.J. Bloodworth.
Mineralogy and Petrography of Samples of Permo-Triassic Sedimentary Strata from Cumbria.
NSS/R176.
Nirex, 1989.

Kemp (1988)
R. Kemp and T O'Riordan.
Planning for Radioactive Waste Disposal, Some Central Considerations.
Land Use Policy.
January 1988, 37-44.

Kemp (1992)
R. Kemp.
The Politics of Radioactive Waste Disposal.
ISBN 0 7190 3184 2
Manchester: Manchester University Press, 1992.

Kempe (1980)
T.F. Kempe, A. Martin and M.C. Thorne.
Long-Term Storage of Spent Nuclear Fuel.
Work carried out for the Nuclear Waste Management Division, Department of the Environment.
ANS Report No. 206.
Surrey: Associated Nuclear Services, June 1980.

Knight (1990) NSS/R218
Knight, D.
The Decomposition of Organic Matter in Soils as a Function of Climate and Land Use Management.
NSS/R218.
Nirex, 1990.

Knowles (1990)
N.C. Knowles, M.J.S. Lowe and B. Come.
On the Reliability of Predictions of Geomechanical Response -- Project COSA in Perspective.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp. 749-760.

Laurens (1987)
J.M. Laurens and M.C. Thorne.
The Demonstration of a Proposed Methodology for the Verification and Validation of Near Field Models.
In OECD Nuclear Energy Agency, *Proceedings of an NEA Workshop on Near-Field Assessment of Repositories for Low and Medium Level Radioactive Waste, Baden, 23-25 November 1987.*
Paris: OECD. 1988, pp. 297-307.

Lever (1988)
D.A. Lever and J.H. Rees.
Gas Generation and Migration in Waste Repositories.
In OECD Nuclear Energy Agency, *Proceedings of an NEA Workshop on Near-Field Assessment of Repositories for Low and Medium Level Radioactive Wast, Baden, 23-25 November 1987.*
Paris: OECD, 1988, pp. 115-127.

Lever (1989) NSS/G105
D.A. Lever
Radionuclide Transport by Groundwater Flow Through the Geosphere: Current Status.
NSS/G105.
Nirex, 1989.

Lever (1990) NSS/G113
D.A. Lever and D.R. Woodwark.
Radionuclide Transport by Groundwater Flow Through the Geosphere: Current Status 1989.
NSS/G113.
Nirex, 1990.

Liezers (1988) NSS/R112
M. Liezers, J.W. McMillan and P.M. Pollard.
A Review of the Potential of Photoacoustic and Photothermal Spectroscopy for the Characterisation of Actinide Solid Phases.
NSS/R112.
Nirex, 1988.

Lindblom (1958)
C. Lindblom.
Policy Analysis.
The American Economic Review.
1958, **48**, 298-312.

Lindblom (1959)
C. Lindblom.
The Science of "Muddling Through".
Public Administration Review.
1959, **19**, 79-88.

Lindblom (1965)
C. Lindblom.
The Intelligence of Democracy: Decision Making Through Mutual Adjustment.
London: Collier-Macmillan Limited, 1965.

Lineham (1989) NSS/R155
T.R. Lineham
A Laboratory Study of Gas Transport Through Intact Clay Samples.
NSS/R155.
Nirex, 1989.

Longworth (1989) NSS/R165
G. Longworth and M. Ivanovich.
The Sampling and Characterisation of Natural Groundwater Colloids:

Studies in Aquifers in Slate, Granite and Glacial Sand.
NSS/R165.
Nirex, 1989.

Marsh (1988) NSS/R126
G.P. Marsh
Progress in the Assessment of the Corrosion of Low and Intermediate Level Waste Containers Under Repository Conditions.
NSS/R126.
Nirex, 1988.

Marshall (1991)
P. Marshall.
Fuel Degradation During Dry Storage Creates Need for Engineered Solutions.
Nuclear Fuel.
25 November 1991, **16**(24), 15.

Marshall (1992) 23 July 1992
P. Marshall.
SNL Reports Profit for FY-91/92 Operating Hunterston, Torness.
Nucleonics Week.
23 July 1992, **33**(30), 5-6.

Marshall (1993) 21 January 1993
P. Marshall.
Leukemia Cluster Near Sellafield Continues to Show Excess Cases.
Nucleonics Week.
21 January 1993, **34**(3), 1-2.

Marshall (1993) 18 February 1993
P. Marshall and A. MacLachlan.
SNL Pursures Privatization to Ease Planning for Its Next Nuclear Unit.
Nucleonics Week.
18 February 1993, **34**(7), 1,15-16.

Marshall (1993) 4 March 1993
P. Marshall.
BNFL Fined for Second Failure of Sellafield Safety Interlocks.
Nucleonics Week.
4 March 1993, **34**(9) 8-9.

Marshall (1993) 15 March 1993
P. Marshall.
THORP Startup May Again be Delayed; Waste Return, Leaks, Cancer are Issues.
Nuclear Fuel.
15 March 1993, **18**(6) 8-9.

Martin (1983)
A. Martin, T.M. Fry and J. Edmunds.
Management of Spent Oxide Fuel from Thermal Reactors: the Environmental and Radiological Effects of Alternative Approaches.
DOE/RW/83.086.
Department of the Environment, July 1983.

Mather (1982)
J.D. Mather, N.A. Chapman, J.H. Black, and B.C. Lintern.
The Geological Disposal of High-Level Radioactive Waste -- A Review of the Institute of Geological Sciences' Research Programme.
Nuclear Energy.
June 1982, **21**(3), 167-173.

Mather (1988) Groundwater Pollution
J.D. Mather.
Groundwater Pollution and the Disposal of Hazardous and Radioactive Wastes.
In Institution of Water and Environmental Management, *Annual Symposium 1988: "Risk Management in Water and Environmental Services", London, 23-24 March 1988.*
London: 1988.

Mather (1988) Report of Discussion
J.D. Mather.
Introductions, Discussion, and Author's Replies.
In Institution and Water Management, *Proceedings of Annual Symposium 1988: "Risk Management in Water and Environmental Service, London, 23-24 March 1988.*
Suffolk: The Lavenham Press Ltd., pp.37-46.

McCombie (1990)
C. McCombie, T. Papp and S. Coplan.
The Development and Status of Performance Assessment in Radioactive Waste Disposal.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp. 92-114.

McEwen (1990)
T.J. McEwen, N.A. Chapman and P.C. Robinson.
Review of Data Requirements for Groundwater Flow and Solute Transport Modelling and the Ability of Site Investigation Methods to Meet these Requirements.
DOE/HMIP/RR/90/095.
Department of the Environment, August 1990.

Merz (1990)
E. Merz and K. Schifferstein.
Time Period of Concern for Longterm Safety Assessment of a Geological Radioactive Waste Repository.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp.299-308.

Milodowski (1989) NSS/R240
A.E. Milodowski, P.H.A. Nancarrow and B. Spiro.
A Mineralogical and Stable Isotope Study of Natural Analogues of Ordinary Portland Cement (OPC) and CaO-Si_{O2}-H_2O (CSH) Compounds.

NSS/R240.
Nirex, 1989.

Morgan (1990) NSS/R217
J.E. Morgan
Retention and Mobility of Artificial Radionuclides in Soil.
NSS/R217.
Nirex, 1990.

Morgan (1990) NSS/R220
J.E. Morgan and C.J. Beetham.
Review of Literature for Radium, Protactinium, Tin and Carbon.
NSS/R220.
Nirex, 1990.

Morone (1989)
J.G. Morone and E.J. Woodhouse.
The Demise of Nuclear Energy? Lessons for Democratic Control of Technology.
ISBN 0-300-04448-8.
London: Yale University Press, 1989.

Murray (1986)
N. Murray, D. Vande Putte and R.J. Ware
Implications of Long-Term Surface or Near-Surface Storage of Intermediate and Low Level Wastes in the United Kingdom.
DOE/RW/86/053.
Department of the Environment, February 1986.

Morris (1992)
R. Morris.
Text of TUSNE Annual Lecture 1992, Given by Sir Richard Morris, CBE, Chairman of United Kingdom Nirex Limited on 26th November 1992.
Nirex, 26 November 1992.

Nash (1989) NSS/R201
P.J. Nash, G. Nash and W.R. Rodwell.
Gas Escape from Vented Waste Canisters Grouted into a Repository Vault.
NSS/R201.
Nirex, 1989.

Nash (1990) NSS/R208
P.J. Nash and W.R. Rodwell.
Effects of Gas Overpressurisation on the Geological Environment of a Deep Repository.
NSS/R208.
Nirex, 1990.

Nicholls (1990)
D.B. Nicholls.
A Preliminary Radiological Risk Assessment of Management Options for the Dounreay Waste Shaft.
DOE/RW/90.082.
Department of the Environment, November 1990.

Nirex (1984)
Second Report.
To the Secretary of State for the Environment, Secretary of State for Scotland and Secretary of State for Wales.
Nirex, September 1984.

Nirex (1988)
Indefinite Storage -- The Unacceptable Option.
Nirex, January 1988.

Nirex (1988) NSS/G108
Presentation of the Nirex Disposal Safety Research Programme.
NSS/G108.
Nirex, 1988.

Nirex (1989) Deep Repository Project
Deep Repository Project: Preliminary Environmental & Radiological Assessment and Preliminary Safety Report.
Report No.71.
Nirex, March 1989.

Nirex (1989) Going Forward
Going Forward; The Development of a National Disposal Centre for Low and Intermediate-Level Radioactive Waste.
Nirex, 1989.

Nirex (1989) Review of Nirex Safety
Review of Nirex Safety Assessment Research Programme.
Nirex Report No. 101.
Nirex, 28 March 1989.

Nirex (1990) How Engineered Barriers Work
Nirex Fact Sheet: How Engineered Barriers Work.
2/90/6
Nirex, 1990.

Nirex (1990) Why do We Need to do Research
Nirex Fact Sheet: Why do We Need to do Research?.
2/90/11
Nirex, 1990.

Nirex (1991) Safe for All Time
UK Nirex Ltd.
Safe for All Time.
Nirex, October 1991.

Nirex (1991) Sellafield Repository Project
Sellafield Repository Project.
Nirex, December 1991.

Nirex (1992) A Rock Characterisation Facility
Sellafield Repository Project: A Rock Characterisation Facility Consultative Document.
Nirex Report No. 327.
Nirex, 21 October 1992.

Nirex (1992) Indefinite Surface Storage
Indefinite Surface Storage -- The Unacceptable Option.
Radioactive Waste -- Topical Briefs.
Nirex, January 1992.

Nirex (1992) Safety Assessment
Safety Assessment and Research
Radioactive Waste -- Topical Briefs.
Nirex, October 1992.

Nirex (1992) Sellafield Project Consultation
Sellafield, Project Consultation and Scoping Report.
Report No. 295.
Nirex, January 1992.

Nirex (1992) Target Programme
Internal Document.
Sellafield Repository: Target Programme for Rock Laboratory.
October 1992.

Nirex (1992) The Geology and Hydrogeology of Sellafield
The Geology and Hydrogeology of Sellafield.
Report No. 263.
Nirex, March 1992.

Noy (1990) NSS/R275
D.J. Noy
PRECIP: A Program for Coupled Groundwater Flow and Precipitation/Dissolution Reactions.
NSS/R275.
Nirex, 1990.

Nuclear Electric (1992)
Report and Accounts, 1991-92.
Nuclear Electric, 1992.

Nuclear Energy Agency (1984)
Nuclear Energy Agency.
Long-Term Radiation Protection Objectives for Radioactive Waste Disposal.
NEA Experts Report
Paris: OECD, 1984.

Nuclear Energy Agency (1985)
Nuclear Energy Agency.
The Economics of the Nuclear Fuel Cycle.
Paris: OECD, 1985.

Nuclear Energy Agency (1989)
Nuclear Energy Agency.
Plutonium Fuel, An Assessment.
Paris: OECD, 1989.

O'Riordan (1988)
T. O'Riordan, R. Kemp and M. Purdue.
Sizewell B: An Anatomy of the Inquiry.
London: The Macmillan Press Ltd., 1988.

O'Tallamhain (1986)
C. O'Tallamhain and C.J. Ealing.
Dry Storage of Magnox Fuel; Report of Joint NNC/GEC-ESL Studies Commissioned by Central Electricity Generating Board -- Contract F5088.
Cheshire: National Nuclear Corporation Limited, September 1986.

OFRWP (1973)
Internal Document.
Minutes of the Fifth Oxide Fuel Reprocessing Working Party.
OFRWP/M5.
5 October 1973.

Olsson (1992)
O. Olsson (ed.), J. Black, J. Gale, N. Barton, L. Birgersson, C. Cosma, B. Dershowitz, T. Doe, A. Herbert, D. Holmes, M. Laaksoharju, J. Long and I. Neretnieks.
Stripa Project 92-22: Site Characterization and Validation -- Final Report.
Technical Report.
ISSN 0349-5698.
Stockholm: SKB, April 1992.

Paleit (1987)
J.A. Paleit and J.A.B. Gresley.
Recycled Uranium -- A Valuable Commodity.
In IAEA (ed.), *Back End of the Nuclear Fuel Cycle: Strategies and Options.*
Vienna: IAEA, 1987, pp. 519-527.

Parker (1978)
Parker.
The Windscale Inquiry, Report Presented to the Secretary of State for the Environment on 26 January 1978.
ISBN 0 11 751314 8.
London: HMSO, 1978.

Passant (1990)
F.H. Passant.
Nuclear Power Station Wastes.
In *Radioactive Waste Management, London, 5-6 February 1990.*
Organized by IBC.
London: 5-6 February 1990.

Pearce (1979)
D. Pearce, L. Edwards and G. Beuret.
Decision Making for Energy Futures; A Case Study of the Windscale Inquiry.
ISBN 0-333-27438-5.
London: The Macmillan Press Ltd, 1979.

Pigford (1992)
T.H. Pigford, P.L. Chambre, and W.W.-L. Lee.
A Review of Near-Field Mass Transfer in Geologic Disposal Systems.
Radioactive Waste Management and the Nuclear Fuel Cycle.
1992, **16**(3-4), 175-276.

Pilkington (1988) NSS/R116
N.J. Pilkington, P.J. Shadbolt and J.D. Wilkins.
Experimental Measurements of the Solubilities of Selected Long-Lived Fission Products, Activation Products and Actinide Daughters Under High pH Conditions.
NSS/R116.
Nirex, 1988.

Pilkington (1988) NSS/R120
N.J. Pilkington and J.D. Wilkins.
Experimental Measurements of the Solubility of Technetium Under Near-Field Conditions.
NSS/R120.
Nirex, 1988.

Pilkington (1990) NSS/R186
N.J. Pilkington and N.S. Stone.
The Solubility and Sorption of Nickel and Niobium Under High pH Conditions.
NSS/R186.
Nirex, 1990.

Pitty (1988) NSS/R134
A.F. Pitty
Geomorphological Processes in Britain in a Periglacial Age.
NSS/R134.
Nirex, 1988.

Porter (1990)
J.D. Porter, D.S. Clarke, P. Roe, D. Vassilic-Melling, B. Einfeldt, R. Mackay and R. Glendinning.
Far Field Modelling of Radionuclide Migration.
DOE/RW/90/027.
Department of the Environment, March 1990.

Price (1985)
M. Price.
Introducing Groundwater.
ISBN 0-04-553006-8.
London: George Allen & Unwin, 1985.

Priest (1986)
S.D. Priest.
A Critical Review of the Data Requirements for Fluid Flow Models Through Fractured Rock.
DOE/RW/86/054.
Department of the Environment, January 1986.

Production Group Technical Committee (1966)
Internal Document.
Windscale Matters: Minutes of the First Meeting of the Production Group Technical Committee.
PGTC(66)M. 1.
12 December 1966.

Production Group Technical Committee (1968)
Internal Document.
Windscale Matters: Minutes of a Meeting held in the Production Group Board Room.
PGTC(68)5th Meeting.
25 September 1968.

Production Group Technical Committee (1969)
Internal Document.
Minutes of a Meeting held in the Production Group Board Room.
PGTC(69)2nd Meeting.
31 March 1969.

Quinn (1980)
J. B. Quinn.
Strategies for Change: Logical Incrementalism.
ISBN 0-256-02543-6.
Illinois: Richard D. Irwin, Inc., 1980.

Ragab (1990) NSS/R226
R. Ragab and J.D. Cooper.
Obtaining Soil Hydraulic Properties from Field, Laboratory and Predictive Methods.
NSS/R226.
Nirex, Report NSS/R226, 1990.

Rees (1988) NSS/G104
J.H. Rees and W.R. Rodwell.
Gas Evolution and Migration in Repositories: Current Status.
NSS/G104.
Nirex, 1988.

Rees (1989) NSS/G112
J.H. Rees
Gas Evolution and Migration in Repositories: Current Status, May 1989.
NSS/G112.
Nirex, 1989.

Reeves (1990) NSS/R213
A.D. Reeves and K.J. Beven
The Use of Tracer Techniques in the Study of Soil Water Flows and Contaminant Transport.
NSS/R213.
Nirex, 1990.

Reprocessing Division Executive (1974)
Internal Document.
Minutes of Second Meeting of Reprocessing Division Exective.
RDE(74)2nd Meeting.
December 1974.

Robertson (1984)
J.B. Robertson.
Geologic Problems at Low-Level Radioactive Waste-Disposal Sites.
Studies in Geophysics: Groundwater Contamination.
Geophysics Study Committee, Geophysics Research Forum, Commission on Physical Sciences, Mathematics, and Resources: National Research

Council.
Washington, D.C.: National Academy Press, 1984, pp. 104-108.

Robins (1980)
N.S. Robins.
The Geology of Some United Kingdom Nuclear Sites Related to the Disposal of Low and Medium-Level Radioactive Wastes, Part 1: UKAEA and BFNL Sites.
Institute of Geological Sciences, Natural Environment Research Council.
Report No. ENPU 80-5.
NERC, April 1980.

Rodwell (1989) NSS/R197
W.R. Rodwell
Modelling Studies of Gas Injection into Fractured Rock: The Interpretation of Field Results.
NSS/R197.
Nirex, Report NSS/R197, 1989.

Rodwell (1989) NSS/R200
W.R. Rodwell
Nearfield Gas Migration, A Preliminary Review.
NSS/R200.
Nirex, 1989.

Rosevear (1991) NSS/R263
A. Rosevear
Review of National Research Programmes on the Microbiology of Radioactive Waste Disposal.
NSS/R263.
Nirex, 1991.

Ross (1989) NSS/R169
C.A.M. Ross, A.H. Bath, D.C. Entwisle, M.R. Cave, M.B. Fry, K.A. Green and S. Reeder.
Hydrochemistry of Porewaters from Glacial Till and Chalk at the Killingholme Site, South Humberside.
NSS/R169.
Nirex, 1989.

Ross (1989) NSS/R172
C.A.M. Ross, A.H. Bath, D.C. Entwisle, M.R. Cave, M.B. Fry, K.A. Green, and S. Reeder.
Hydrochemistry of Porewaters from Jurassic Oxford Clay, Kellaways Beds, Upper Estuarine and Upper Lias Formations at the Elstow Site, Bedfordshire.
NSS/R172.
Nirex, 1989.

Rowan (1988) NSS/R108
S.M. Rowan, L. Donaldson and S. White.
A Comparative Study of the Pore Structures and Surfaces of Hardened Cement Pastes of Potential Use in Radioactive Waste Repositories.
NSS/R108.
Nirex, 1988.

RWMAC (1985)
Radioactive Waste Management Advisory Committee.
Sixth Annual Report.
ISBN 0 11 751795 X.
London: HMSO, June 1985.

RWMAC (1989)
Radioactive Waste Management Advisory Committee.
Tenth Annual Report.
ISBN 0 11 752265 1.
London: HMSO, November 1989.

RWMAC (1990) Eleventh Annual Report
Radioactive Waste Management Advisory Committee.
Eleventh Annual Report.
ISBN 0 11 752355 0.
London: HMSO, 1990.

RWMAC (1990) Safety Assessment Modelling
Radioactive Waste Management Advisory Committee.
Report of the Radioactive Waste Management Advisory Committee Subgroup on Safety Assessment Modelling for Deep Disposal Sites For Low- and Intermediate-Level Radioactive Waste.
ISBN 0 11 752308 9.
London: HMSO, 1990.

RWMAC (1990) Waste Watchers
Waste Watchers; The First Decade of the Radioactive Waste Management Advisory Committee.
August 1990.

RWMAC (1992)
Radioactive Waste Management Advisory Committee.
News Release.
21 October 1992.

RWMAC (1993) Rock Characterisation
Radioactive Waste Management Advisory Committee.
Radioactive Waste Management Advisory Committee: UK Nirex Limited's Consultative Document on A Rock Characterisation Facility.
February 1993.

RWMAC (1993) 11 May 1993
Radioactive Waste Management Advisory Committee.
Press Notice.
11 May 1993.

RWMAC (1993) Thirteenth Annual Report
Radioactive Waste Management Advisory Committee.
Thirteenth Annual Report.
ISBN 0 11 752805 6.
London: HMSO, 1993.

Sargent (1991)
F.P. Sargent.
Panel Session: Long-Term Predictions in the Field of Earth Sciences.
In L. Cecille (ed.), *Radioactive Waste Management and Disposal.*

Proceedings of the Third European Community Conference on
Radioactive Waste Management and Disposal, Luxembourg, 17-21 1990,
organized by the Commission of the European Communities.
Report No. EUR 13389.
ISBN 1-85166-657-5.
London: Elsevier Applied Science, 1991, pp. 612-613.

Saunders (1987) NSS/G101
P.A.H. Saunders
An Outline of Nirex's Research and Safety Assessment Programmes.
NSS/G101.
Nirex, 1987.

Seaborg (1992)
G. Seaborg.
Seaborg's Diary Recalls the Birth of Plutonium in Chicago in 1942.
Nucleonics Week.
19 November 1992, **33**(47) 9-10.

Select Committee on the European Communities (1988)
House of Lords Select Committee on the European Communities, 19th
Report, Session 1987-1988.
Radioactive Waste Management.
London: HMSO, 26 July 1988.

Sharland (1989) NSS/R136
S.M. Sharland and C.J. Newton.
The Long-Term Prediction of Corrosion of Stainless Steel Nuclear Waste Canisters.
NSS/R136.
Nirex, 1989.

Shaw (1990)
J. Shaw.
This is it -- and What a Lot We've Got!
Nuclear Times.
January 1990, 6-7.

Shore (1979)
P. Shore.
Speech Delivered in Manchester, 13 September 1978.
In D. Pearce, L. Edwards and G. Beuret (eds.), *Decision Making for Energy Futures; A Case Study of the Windscale Inquiry.*
ISBN 0-333-27438-5.
London: The Macmillan Press Ltd, 1979. pp 227-235.

Simon (1965)
H.A. Simon.
The Shape of Automation for Men and Management.
London: Harper & Row, 1965.

Simon (1976)
H.A. Simon
Administrative Behaviour
ISBN 0 02 929000-7
New York: The Free Press, Macmillan, 1976.

Simon (1982)
H.A. Simon.
Models of Bounded Rationality: Economic Analysis and Public Policy, Volume 1.
ISBN 0-262-19205-5.
London: The MIT Press, 1982.

SSEB (1989)
Hunterston 'A' Power Station Faces Closure.
PR 21/89.
SSEB, 20 March 1989.

Stenhouse (1991) NSS/R262
M.J. Stenhouse and H. Grogan.
Review of Reactions of Hydrogen and Methane in the Geosphere and Biosphere.
NSS/R262.
Nirex, 1991.

Swedish National Board for Spent Nuclear Fuel (1988)
National Board for Spent Nuclear Fuel.
Ethical Aspects on Nuclear Waste: A Seminar on Ethical Action in the Face of Uncertainty, Stockholm, Sweden, 8-9 September 1987
SKN Report 29.
Stockholm, April 1988.

Tasker (1990)
P.W. Tasker and S.J. Wisbey.
Source-Term Modelling for the Disposal of Low- and Intermediate-Level Radioactive Waste.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp. 459-469.

Tatlock (1968)
Internal Document.
J. Tatlock.
The Assessment of Future Reprocessing Requirements; A Re-Consideration of the Programme of Study.
Presented to the Production Group Technical Committee.
PGTC(68)P.13.
9 September 1968.

TCPA (1978)
Town and Country Planning Association.
Planning and Plutonium: Evidence of the Town and Country Planning Association to the Public Inquiry into and Oxide Reprocessing Plant at Windscale.
ISBN 902797 03 4.
London: TCPA, 1978.

Thompson (1987)
B.G.J. Thompson.
Uncertainty Analysis in Assessing the Risk Associated With the Disposal of Low and Intermediate Level Radioactive Wastes.

In OECD, *Uncertainty Analysis for Performance Assessments of Radioactive Disposal Systems, Proceedings of the NEA Seattle Workshop, 24-26 February 1987.*
Paris: OECD, 1987, pp. 206-220.

Thorne (1988) NSS/G106
M.C. Thorne
The Biosphere: Current Status.
NSS/G106.
Nirex, 1988.

Thorne (1989) NSS/G114
M.C. Thorne
The Biosphere: Current Status, December 1989.
NSS/G114.
Nirex, 1989.

Tomlinson (1988) NSS/R146
M.J. Tomlinson
Migration of Gases Through Argillaceous Rocks, A Literature Review.
NSS/R146.
Nirex, 1988.

Tsang (1990)
C.F. Tsang.
A Broad View of Model Validation.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp. 707-716.

Tuohy (1964)
Internal Document.
T. Tuohy.
Reprocessing Plant for Oxide Fuel Elements.
Note by T. Tuohy for the Atomic Energy Executive.
AEX(64) 101.
9 November 1964.

Tweed (1988) NSS/R132
C.J. Tweed
A Guide to PICKER -- A Data Selection Program for the Geochemical Code PHREEQE.
NSS/R132.
Nirex, 1988.

U.S. Congress, Office of Technology Assessment (1991)
U.S. Congress, Office of Technology Assessment.
Complex Clean-up: The Environmental Legacy of Nuclear Weapons Production.
OTA-0-484.
Washington, D.C.: U.S. Government Printing Office, February 1991.

U.S. Department of Energy (1989)
U.S. Department of Energy.
Final Version Dry Cask Storage Study.

DOE/RW-0220.
U.S. Department of Energy, February 1989.

U.S. National Research Council (1990)
U.S. National Research Council, Commission on Geosciences.
Environment, and Resources.
Rethinking High-Level Radioactive Waste Disposal; A Position Statement of the Board on Radioactive Waste Management.
Washington, D.C: National Academy Press, 1990.

Vovk (1990)
I.F. Vovk, J.J. Cramer and D.B. Curtis.
New Co-ordinated Research in Geochemistry of Long-Lived Transuranic Actinides and Fission Products.
In OECD Nuclear Energy Agency, *Proceedings of the Paris Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989.*
Paris: OECD, 1990, pp. 972-978.

Wakerley (1986)
M.W. Wakerley and J. Edmunds.
Long-Term Storage of Radioactive Solid Waste Within Disposal Facilities.
DOE/RW/86-080.
Department of the Environment, May 1986.

Wakerley (1989)
M.W. Wakerley, G.D. Burholt and A. Palit.
Waste Management and Radiological Safety Implications of Using Plutonium as a Fuel in UK Thermal Reactors.
DOE/RW/89.089.
Department of the Environment, August 1989.

Warner (1964)
B.F. Warner, W.W. Marshall, A. Naylor and G.D.C. Short.
The Development of the New Separation Plant, Windscale.
In *Proceedings of the Third United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1964.*
Volume 10.
New York: United Nations 1964. pp. 224-230.

Warner (1966)
Internal Document.
B.F. Warner, E.F. Kemp and H. Corns.
The Future Pattern of Reprocessing at Windscale.
Presented by J. Tatlock to the Production Group Technical Committee.
PGTC(66)3.
1966.

Watkins (1990) NSS/R221
B.M. Watkins
Interception, Retention, Absorption, and Translocation of Radionuclides by Vegetation following Application in Irrigation Waters.
NSS/R221.
Nirex. 1990.

Watkins (1991) NSS/R256
B.M. Watkins

Ecosystem Development and Biosphere Factors for Future Climate States.
NSS/R256.
Nirex, 1991.

Wildavsky (1979)
A. Wildavsky
The Art and Craft of Policy Analysis
ISBN 0 333 27347 8
London: Macmillan, 1979.

Wildavsky (1984)
A.B. Wildavsky.
The Politics of the Budgetary Process.
ISBN 0-316-94041-0.
Boston: Little, Brown and Company, 1984.

Wilkie (1992)
T. Wilkie.
Nuclear Waste Options Narrow.
Sunday Independent.
19 April 1992.

Williams (1980)
R. Williams.
The Nuclear Power Decisions: British Policies, 1953-78.
ISBN 0-7099-0265-4.
London: Croom Helm Ltd, 1980.

Williams (1990)
T. Williams.
A UK Perspective on Recycling.
In *The Uranium Institute, Annual Symposium, London, 5-7 September 1990.*
London: 5-7 September1990.

Williams (1993)
T. Williams.
Recovery Work gets Under Way.
Nuclear Times.
March 1993, 7.

Windscale ELC (1957)
Internal Document.
Minutes of the First Meeting of the Windscale Emergency Liaison Committee held at Windscale.
2 December 1957.

Windscale LC (1958) 14 January 1958
Internal Document.
United Kingdom Atomic Energy Authority, Industrial Group.
Minutes of the Second Meeting of the Windscale Liaison Committee held at Windscale.
14 January 1958.

Windscale LC (1958) 12 March 1958
Internal Document.
United Kingdom Atomic Energy Authority, Industrial Group.

Minutes of the Third Meeting of the Windscale Liaison Committee held at Windscale.
12 March 1958.

Windscale LC (1958) 15 April 1958
Internal Document.
United Kingdom Atomic Energy Authority, Industrial Group.
Minutes of the Fourth Meeting of the Windscale Liaison Committee held at Windscale.
15 April 1958.

Windscale LC (1958) 7 October 1958
Internal Document.
United Kingdom Atomic Energy Authority, Industrial Group.
Minutes of the Fifth Meeting of the Winscale Liaison committee held at Windscale.
7 October 1958.

Windscale LC (1959) 22 April 1959
Internal Document.
United Kingdom Atomic Energy Authority, Industrial Group.
Minutes of the Sixth Meeting of the Windscale Liaison Committee held at Windscale.
22 April 1959.

Windscale LLC (1959) 3 July 1959
Internal Document.
United Kingdom Atomic Energy Authority, Production Group.
Minutes of the Seventh Meeting of the Windscale Local Liaison Committee held at Windscale.
3 July 1959.

Windscale LLC (1960)
Internal Document.
United Kingdom Atomic Energy Authority, Production Group.
Minutes of the Eighth meeting of the Windscale Local Liaison Committee held at Windscale.
3 November 1960.

Windscale LLC (1961)
Internal Document.
United Kingdom Atomic Energy Authority, Production Group.
Minutes of the Ninth Meeting of the Windscale Local Liaison Committee held at Windscale.
9 November 1961.

Windscale LLC (1962)
Internal Document.
United Kingdom Atomic Energy Authority, Production Group.
Minutes of the Tenth Meeting of the Windscale Local Liaison committee held at Windscale.
8 November 1962.

Windscale LLC (1963)
Internal Document.
United Kingdom Atomic Energy Authority, Production Group.
Minutes of the Eleventh Meeting of the Windscale Local Liaison

Committee held at Windscale Works.
7 November 1963.

Windscale LLC (1964)
Internal Document.
United Kingdom Atomic Energy Authority. Production Group.
Minutes of the Twelfth Meeting of the Windscale Local Liaison Committee held at Windscale Works.
12 November 1964.

Windscale LLC (1965)
Internal Document.
United Kingdom Atomic Energy Authority, Production Group.
Minutes of the Thirteenth Meeting of the Windscale Local Liaison Committee held at Windscale Works.
30 November 1965.

Windscale LLC (1966)
Internal Document.
United Kingdom Atomic Energy Authority, Production Group.
Minutes of the Fourteenth Meeting of the Windscale Local Liaison Committee held at Windscale Works.
13 October 1966.

Windscale LLC (1967)
Internal Document.
Minutes of the Fifteenth Meeting of the Windscale Local Liaison Committee held at Windscale Works.
1 November 1967.

Windscale LLC (1968)
Internal Document.
United Kingdom Atomic Energy Authority, Production Group.
Minutes of the Sixteenth Meeting of the Windscale Local Liaison Committee held at Windscale Works.
24 October 1968.

Windscale LLC (1969)
Internal Document.
United Kingdom Atomic Energy Authority, Production Group.
Minutes of the Seventeenth Meeting of the Windscale Local Liaison Committee held at Windscale Works.
16 October 1969.

Windscale LLC (1970) 21 May 1970
Internal Document.
United Kingdom Atomic Energy Authority, Production Group.
Minutes of the Eighteenth Meeting of the Windscale Local Liaison Committee held at Windscale Works.
21 May 1970.

Windscale LLC (1970) 19 November 1970
Internal Document.
United Kingdom Atomic Energy Authority, Production Group.
Minutes of the Nineteenth Meeting of the Windscale Local Liaison Committee held at Windscale Works.
19 November 1970.

Windscale LLC (1971)
Internal Document.
British Nuclear Fuels Limited.
Minutes of the Twentieth Meeting of the Windscale Local Liaison Committee held at Windscale and Calder Works.
18 November 1971.

Windscale LLC (1972)
Internal Document.
British Nuclear Fuels Limited.
Minutes of the Twenty-First Meeting of the Windscale Local Liaison Committee held at Windscale and Calder Works.
23 November 1972.

Windscale LLC (1973)
Internal Document.
British Nuclear Fuels Limited.
Minutes of the Twenty-Second Meeting of the Windscale Local Liaison Committee held at Windscale and Calder Works.
21 November 1973.

Windscale LLC (1974)
Internal Document.
British Nuclear Fuels Limited.
Minutes of the Twenty-Third Meeting of the Windscale Local Liaison Committee held at Windscale and Calder Works.
22 November 1974.

Windscale LLC (1975) 14 March 1975
Internal Document.
British Nuclear Fuels Limited and Windscale and Calder Works.
Minutes of the Twenty-Fourth Meeting of the Windscale Local Liaison Committee held at Windscale and Calder Works.
14 March 1975.

Windscale LLC (1975) 2 July 1975
Internal Document.
British Nuclear Fuels Limited and Windscale and Calder Works.
Minutes of the Twenty-Fifth Meeting of the Windscale Local Liaison Committee held at Windscale and Calder Works.
2 July 1975.

Windscale LLC (1975) 14 November 1975
Internal Document.
British Nuclear Fuels Limited and Windscale and Calder Works.
Minutes of the Twenty-Sixth Meeting of the Windscale Local Liaison Committee held at Windscale and Calder Works.
14 November 1975.

Windscale LLC (1976) 5 April 1976
Internal Document.
British Nuclear Fuels Limited and Windscale and Calder Works.
Minutes of the Twenty-Seventh Meeting of the Windscale Local Liaison Committee held at Windscale and Calder Works.
5 April 1976.

Windscale LLC (1976) 20 September 1976
Internal Document.
British Nuclear Fuels Limited and Windscale and Calder Works.
Minutes of the Twenty-Eighth Meeting of the Windscale Local Liaison Committee held at Windscale and Calder Works.
20 September 1976.

Windscale LLC (1977) 12 January 1977
Internal Document.
British Nuclear Fuels Limited and Windscale and Calder Works.
Minutes of the Twenty-Ninth Meeting of the Windscale Local Liaison Committee held at Windscale and Calder Works.
WLLC/M(77)1.
12 January 1977.

Windscale LLC (1977) 13 May 1977
Internal Document.
British Nuclear Fuels Limited and Windscale and Calder Works.
Minutes of the Thirtieth Meeting of the Windscale Local Liaison Committee held at Windscale and Calder Works.
13 May 1977.

Windscale Transcript (1977)
Public Local Inquiry into an application by British Nuclear Fuels, Limited, referred to the Secretary of State under Section 35 of the Town and Country Planning Act 1971, for planning permission to establish a plant for reprocessing irradiated oxide nuclear fuels and support site services at Windscale and Calder Works, Sellafield, Cumbria.
Transcript of the Windscale Public Inquiry, Held on Tuesday 14th June 1977 and Succeeding Days, before The Hon. Mr Justice Parker, at the Civic Hall, Whitehaven, Cumbria, under the Town and Country Planning Act 1971.
1977.

Windsor (1989) NSS/R158
M.E. Windsor
STRAW: A Source-Term Code for Buried Radioactive Waste.
NSS/R158.
Nirex, 1989.

World Health Organization (1982)
World Health Organization.
Nuclear Power: Management of High-Level Radioactive Waste, Report on a Working Group, Bruges, 2-6 June 1980.
WHO Regional Publications, European Series No. 13.
ISBN 92 890 1104 1
Copenhagen: World Health Organization, 1982.

Wynne (1980)
B. Wynne.
Windscale: A Case History in the Political Art of Muddling Through.
In T. O'Riordan and K. Turner (eds.), *Progress in Resource Management and Environmental Planning.*
John Wiley & Sons Ltd, 1980, pp. 165-204.

Wynne (1982)
B. Wynne.

Rationality and Ritual; The Windscale Inquiry and Nuclear Decisions in Britain.
ISBN 0 906450 02 0.
Buckinghamshire: The British Society for the History of Science, 1982.

Young (1989)
A. Young.
Teamwork Triumph.
BNFL News.
May 1989, 6.