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LUCAS HEIGHTS RESEARCH LABORATORIES

THE SEISMIC SAFETY OF HIFAR

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ABSTRACT

The 10 MW research reactor HIFAR is located on the edge of the Sydney conurbation. The possibility of a seismic event in this region which might damage HIFAR and lead to a release of fission products is very small but cannot be dismissed. The nature of seismic events is discussed and the local seismology has been studied, leading to estimates of the size of an event with a 10,000 y return period and of the likelihood of other sized events. The safety significant features of HIFAR are described, and the effects that seismic events of varying size might have on these features are considered. It is judged that the primary coolant circuit will withstand the 10,000 y event without failure.

For very large events, a loss of coolant accident could occur, leading to fission product release. The likelihood and consequences of such events, in terms of radiation doses to the surrounding population, have been estimated. The best estimate of the likelihood that fission products might escape from the building is once in 45,000 years. The best estimate of the effective dose to the worst affected individual is 1.3 mSv, less than the annual background dose in the Sydney region. The seismic safety of HIFAR has been assessed in the context of the proposed regulatory objectives of the Nuclear Safety Bureau. HIFAR is judged to meet these objectives.

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CONTENTS

List of abbreviations used in the text

ANSTO	Australian Nuclear Science and Technology Organisation
BMR	Bureau of Mineral Resources (Commonwealth government)
CCA	Coarse Control Arm
CIS	Containment Isolation System
DTC	Department of Transport and Construction (Commonwealth government)
ECCS	Emergency Core Cooling Circuit
ECR	Emergency Control Room
EPSS	Electrical Power Supply Systme
HIFAR	High Flux Australian Reactor (the 10 MW reactor at Lucas Heights)
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiation Protection
LHRL	Lucas Heights Research Laboratories
LOCA	Loss of Coolant Accident
No 1 SB	The internal Storage Block
NSB	Nuclear Safety Bureau
PAL	Personnel Air Lock
PCC	Primary Coolant Circuit
PHGA	Peak Horizontal Ground Acceleration
RAT	Reactor Aluminium Tank
RCB	Reactor Containment Building
RPS	Reactor Protection System
SCC	Secondary Cooling System
SCS	Space Conditioning System
SL-1, SL-2	Seismic Level 1, Seismic Level 2
SM&D	Structural Mechanics and Dynamics
SR	Safety Rod
US AEC	United States Atomic Energy Commission
US NRC	United States Nuclear Regulatory Commission
VAL	Vehicle Air Lock
NSW	New South Wales

1 INTRODUCTION

HIFAR is a 10 MW research reactor located at Lucas Heights in the southern outskirts of Sydney. In common with all nuclear reactors, it accumulates an inventory of radioactive fission products, normally contained within the fuel elements. It is the responsibility of HIFAR's operators to ensure that these fission products are contained safely under all credible circumstances.

One such circumstance could be the advent of an earthquake in the region around HIFAR. Whilst large earthquakes are very unlikely in NSW, moderate sized ones occur occasionally. This report describes an assessment of the nature and effects on HIFAR of credible earthquakes.

The structure of the report is as follows. In section 2 the area around Lucas Heights is described and the nature of the seismic events that might occur in that region is discussed. In section 3 the HIFAR reactor, particularly its safety significant aspects, is described, and the effects that seismic events of varying size might have upon it are discussed. In section 4 the very unlikely large events that might have some significant effect on HIFAR are described: the dispersion of the fission products that might escape from the reactor in these circumstances, and the radioactive doses that people in the region might receive are discussed. In section 5 the overall risk is assessed, putting it into the context of regulatory requirements. Finally in section 6 the findings from the preceding sections are brought together and the conclusions presented.

2 SEISMIC EVENTS IN THE REGION AROUND LUCAS HEIGHTS

2.1 EARTHQUAKE CHARACTERISTICS

Modern earthquake theory is based on the concept of large sections of the earth's surface, "tectonic plates", slowly moving with respect to each other. Stresses build up in these plates, and earthquakes occur when the stresses are relieved by breakage of the crust at geological faults. Shock waves emanate from the faults causing vibratory ground motions at the earth's surface. A fault which is considered capable of generating further earthquakes is called "active". There are two types of seismic activity distinguished: interplate earthquakes, caused by one tectonic plate moving relative to an adjacent one; and intraplate earthquakes, which generally occur away from the boundaries of the tectonic plates. In the Sydney region, far from tectonic boundaries, it is the intraplate earthquakes which are of concern. These tend to be shallow, *ie* not more than 60 km below the surface.

When studying the effects of seismic events, it is important to distinguish between the magnitude of the event (usually expressed on the Richter scale, a measure of the total energy released by the event), and the effects at a specific site, commonly characterised by its intensity, a subjective measure based on observed effects at the site such as movement of trees, damage to houses, etc. The intensity is governed by the magnitude of the earthquake, its distance from the site, the nature of the medium through which it is transmitted, and the substratum below the site. For seismic damage calculations, more objective measures of local effects than intensity are needed. For this study the principal measure used is Peak Horizontal Ground Acceleration (PHGA). Other important measures were the duration and frequency content of the motions at the site. These were characterised in terms of a suite of earthquake motions with similar PHGA to that of principal concern.

Seismic hazard is a probabilistic phenomenon (Gutenberg and Richter 1941, Cornell 1968), and the intensity at any site can vary from negligible to very large. However, the traditional method of estimating and presenting the seismic hazard of nuclear sites has been deterministic. Two earthquake intensities are usually specified. These are termed the "SL-1 level" and the "SL-2 level" by the IAEA (1979, 1991)[†]. The SL-1 level is considered to be the maximum ground motion which reasonably can be expected to be experienced once during the operating life of the reactor. It is used as the design basis for plant whose failure would not cause

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[†] The US NRC use the terms "Operating Base Earthquake" (OBE) and "Safe Shutdown Earthquake" (SSE), which predate the IAEA terms SL-1 level and SL-2 level.

accident conditions. The SL-2 level corresponds directly to ultimate safety requirements. It has a very low probability of being exceeded, and represents the maximum level of ground motion to be used for design purposes.

More recently, presentation of seismic hazard in probabilistic terms has become more common. The chance that a particular location might experience a ground motion greater than a given intensity is expressed in terms of its return period or likelihood. The return period is the average time expected between events which equal or exceed the specified level. The likelihood, or average expected frequency, is the inverse of return period. The IAEA (1991) has commented that in some member states the SL-2 event corresponds to an event of 10^{-4} per year likelihood (10,000 year return period), and this practice has been adopted for HIFAR seismic assessment both by ANSTO and by the Nuclear Safety Bureau (NSB).

2.2 THE SEISMICITY OF LUCAS HEIGHTS

The Lucas Heights Research Laboratories (LHRL) are located on a sandstone plateau in the Sydney Basin. Figure 1, the current earthquake hazard map of South-eastern Australia (SAA 1993), shows the Sydney Basin to lie in a low intensity seismic zone: according to this map, the chance of an event with PHGA greater than 0.085 g in the next 50 years is less than 10%. In fact, local geological structures exhibiting recent seismic activity have not been identified, and records suggest that in the past 100 years the PHGA experienced at Lucas Heights has not exceeded 0.03 g, rather less than that predicted by Figure 1. At this level modern engineering structures should not suffer damage. Nevertheless, the potential for a damaging event cannot be ruled out entirely.

Studies of the seismicity of the LHRL up to mid-1994 are discussed by Higson (1995). His most important source references are the Department of Transport and Construction (DTC 1982), Corran (1988), Michael-Leiba (1989), Corran and Harries (1990), Somerville (1992), and Corran (1992). More recently, there has been a further study by Somerville (1994).

2.2.1 Estimation of ground acceleration

Both deterministic and probabilistic studies have been undertaken. The major deterministic study was undertaken by DTC (1982), who conducted a survey of the events and lineaments in the area surrounding LHRL (see Figure 2). It postulated the Nepean fault (at its closest approximately 33 km from HIFAR) to be an active fault for deterministic estimation, making clear that this was done only in the absence of any nearer active fault, and that the Nepean fault was not considered to be active. On this basis, DTC estimated the PHGA at Lucas Heights to be 0.13 g to 0.18 g for an SL-2 event. Corran (1988) made a deterministic evaluation similar to DTC's and proposed seismic criteria including an SL-2 ground acceleration of 0.16 g. This deterministic value was recommended to ANSTO for adoption as the SL-2 event by the Seismic Risk Coordinating Committee (Ebeling 1988). However, the NSB (1989) advised against this recommendation in favour of a conservative probabilistic value of 0.23 g, recommended by Higson.

Early probabilistic estimates of the earthquake hazard at Lucas Heights were made by Mumme (1976), DTC and Corran. The Bureau of Mineral Resources (BMR) was commissioned to undertake a further study, to estimate the intensity of an earthquake with a 10,000 year return period and related uncertainties. This study was undertaken by Michael-Leiba (1989), who estimated the 10,000 year return period PHGA to be between 0.15 g and 0.19 g, depending on the mean depth of earthquakes assumed. Corran and Harries (1990) reviewed this work and noted that for the earthquakes most likely to cause an SL-2 event, the most likely focal depth was 14 km, for which they estimated the 10,000 year return period PHGA to be 0.17 g on a best estimate basis.

With Higson (1990a) and the NSB in agreement, the value of 0.17 g has been adopted as the best estimate of the 10,000 year event for current seismic safety studies, and is plotted in Figure 3, Corran and Harries' interpretations of Michael-Leiba's data being used for other seismic events. On this basis, the return period for seismic events in excess of a specified peak horizontal ground acceleration may be expressed as

$$\{\text{Return period (years)}\} = 1.51\text{x}10^{6} \text{ x } \{\text{PHGA (g)}\}^{2.80}.$$

Records have been collected for the region for about 100 years, and it is estimated that the PHGA has not exceeded 0.03 g in that time (quoted in Corran 1983). From Figure 3 one would expect an event with PHGA in excess of 0.03 g about once in 85 years. This is a very satisfactory agreement.

The uncertainty associated with the SL-2 estimate is an important issue, as assessment calls for conservatism as well as best estimation of its value. Michael-Leiba estimated the uncertainty associated with her 10,000 year return period estimate to be ±0.09 g. This was derived by adding the following contributions

1. Uncertainty (1 standard deviation) in attenuation relationship ±0.04 g.
2. Uncertainty in source zone configuration, not significant.
3. Uncertainty in magnitude recurrence relationship ±0.02 g.
4. Uncertainty in graphical representation of source areas ±0.03 g.
5. Uncertainty in intensity/acceleration relationship. This could be significant because of the lack of local data on strong motion attenuation.

During their review, Corran and Harries discussed the issue of uncertainty with Michael-Leiba. It was agreed that uncertainties 1 to 4 could be considered to be largely independent, so that the combined uncertainty from these contributions would be the quadratic sum of the individual components, *ie* ±0.054 g. However, Corran and Harries had developed a digital method of performing the convolution carried out graphically by Michael-Leiba, thus allowing the uncertainty 4 to be eliminated. Uncertainties 1-3 amounted to ±0.045 g.

Taking into account the uncertainty regarding focal depth and the additional but unquantified source of uncertainty in the relationship between intensity and PHGA, Higson (1990a) recommended that the uncertainty at 0.17 g should be at least ±0.06 g. This was consistent with the NSB's earlier position that 0.23 g was a conservative estimate for the SL-2 event. However, the NSB (1993) later advised that they considered an event of 0.2 g PHGA would be appropriate for the SL-2 event.

Higson noted that Michael-Leiba considered the uncertainty estimated for a 10,000 year return period, expressed as a percentage of the best estimate PHGA (*ie* ±35%), to be applicable as a first approximation at other return periods of interest. These uncertainty bounds are shown in Figure 3, but no confidence levels can be associated with them: the uncertainty could be expected to increase with longer return periods, when the extrapolation is greater. However, the issue is not of great importance, as for events greater than the SL-2 event it is usual to consider only the best estimate.

2.2.2 Frequency content and duration

The frequency content and duration of relevant earthquake ground motions have been estimated. These depend on the magnitude of the earthquake and its distance from the site. Earthquakes most likely to cause the SL-2 event at LHRL have been estimated by Corran to be in the range of magnitude 5.75 to 6.25 on the Richter scale, with an epicentre about 15-20 km distant. In view of the lack of strong motion data for the region, Somerville (1992) carried out a study of the catalogue of seismic waveform recordings held by the US National Geophysical Data Center. Three earthquakes in this range were identified which were considered to have occurred in geological structures similar to that in the vicinity of Lucas Heights. Figure 4 shows an accelerogram of the waveform recorded at Carbon Canyon, CA, for an earthquake of Richter magnitude of 6.0, with duration of about 6 seconds. More recently Somerville (1994) has identified further records with similar PHGA but caused by earthquakes of magnitude between 5.4 and 6.9. The durations of these events lie between 3 and 20 seconds

In assessing the seismicity of LHRL, two important issues arose, whether to use a deterministic or probabilistic estimate of the SL-2 PHGA, and whether to use time series accelerograms or a frequency response spectrum to characterise the frequency content of the motions. Amongst Australian authorities DTC (1982) and Gaull, Michael-Leiba and Rynn (1990) advocate emphasis on probabilistic methods because deterministic methods require a thorough understanding of regional seismicity which is not available in Australia. However, although the IAEA has recognised probabilistic estimation of ground motions for some time, and although the UK Nuclear Installations Inspectorate in their Safety Assessment Principles for Nuclear Plants (NII 1993) recommend probabilistic methods, until recently the US NRC (1993) has accepted only deterministic methods. There has been considerable discussion in the US that deterministic methods do not reflect the state of the art in seismic analysis, and the US NRC has published a lengthy article in the US Federal Register (1992) indicating their future intention to accept probabilistic methods. The US Federal Register (1994) has announced that a Draft Regulatory Guide DG-1032 "Identification and characterisation of seismic sources and determination of safe shutdown earthquake ground motions", covering use of probabilistic methods, is to be issued for public comment.

Until recently frequency response spectra have been the standard way of characterising the nature of earthquake ground motions. The US Atomic Energy Commission issued their Regulatory Guide 1.60 specifying the design response spectra to be used in the US for seismic design of nuclear power plants (US AEC 1973). These spectra have conservative envelopes based on US conditions. Somerville (1994) showed that the response spectra derived from the suite of time series accelerograms he provided were site-specific and magnitude-specific to LHRL.

In the studies reported here, time series methods have been use for analysis of the major plant behaviour and frequency response spectra methods for analysis of minor components.

3 THE EFFECT OF SEISMIC EVENTS ON HIFAR

3.1 DESCRIPTION OF HIFAR

HIFAR is comprehensively described in the HIFAR Descriptive Manual (HDM 1995). The parts which are of concern in connection with earthquakes are the following.

- The fuel. This contains the radioactive fission products, and is canned in aluminium. Provided it is kept cool, the fission products cannot escape to impact on the community.
- The Reactor Protection System (RPS). This shuts the reactor down in emergency conditions by dropping six Coarse Control Arms (CCAs) and two Safety Rods (SRs) which absorb neutrons and prevent fission. Shutdown minimises the heat generated by the fuel in the reactor .
- The Primary Coolant Circuit (PCC). This includes the Reactor Aluminium Tank (RAT) which contains the radioactive fuel, the primary circuit piping, the heat exchangers, and the main and shutdown D_2O pumps. Provided the PCC stays intact, radioactive fission products cannot escape into the environment.
- The Reactor Block. This is the structure surrounding the RAT. Working outwards from the centre it includes a graphite reflector, a steel tank, and a massive concrete biological shield. It is supported on four cruciform columns
- The Emergency Core Cooling System (ECCS). If the PCC were damaged, this would collect any D_2O escaping from the PCC and pump it back into the RAT. Provided it worked the fuel would not overheat, even though there might be a massive leak in the PCC.
- The Reactor Containment Building (RCB). This is the structure surrounding the reactor block and providing it with lateral stability. It has a steel and concrete base, curved steel walls with 10 vertical steel H-section stiffeners, and a domed roof. It was designed to minimise leakage and the release to the environment of fission products should they escape from the PCC.
- The Containment Isolation System (CIS). Normally the RCB is ventilated with fresh air. However, if fission products were to be detected in the RCB, all the ventilation penetrations, and most of the other penetrations carrying fluids, would automatically seal (two seals per penetration).

- The airlocks. There is a Vehicle Air Lock (VAL) and three Personnel Air Locks (PALs), through which equipment and people can enter and exit the RCB. They must provide a seal at all times if the RCB is to remain airtight. Each has two sealed doors, one at each end, mechanically and electrically interlocked so that only one can be open at any time.
- The passive penetration seals. Each item (such as a cable) penetrating the RCB has two seals to ensure that it will not leak.
- The Space Conditioning System (SCS). If the CIS were to operate and seal the RCB it would be necessary to remove the heat generated inside the RCB to prevent it being pressurised above its safe limit. In practice, unavoidable small leaks in the RCB would probably prevent it reaching its design pressure even without the SCS, although as a general principle it is desirable to have a working SCS.
- The Secondary Cooling Circuit (SCC). This light water circuit transports the heat from the heat exchangers through the wall of the RCB to the cooling towers. It has an essential role when the reactor is operated at power, but is not essential once the reactor has shutdown and cooled down. The sealing of the RCB could be affected if the SCC were to rupture within the RCB.
- The Emergency Power Supply System (EPSS). This provides electrical power to the ECCS, shutdown pumps, SCS and other emergency facilities.
- The Internal Storage Block (No 1 SB). This contains spent fuel elements which must be kept cool for several days after removal from the reactor to prevent melting and releasing fission products.
- The RCB polar crane. This is the means of moving the large flasks used for fuel transport, etc. While it has no safety role, its failure could allow a heavy vessel to fall and damage other equipment.
- The adjacent buildings. Buildings B40 and B42 are linked to HIFAR by two of the PALs. B41 surrounds the VAL. While these buildings have no safety role their failure could conceivably damage the RCB either by falling onto it, or by acting through the PALs to overstrain it.
- The Emergency Control Room (ECR). This is the shielded room outside the reactor to which selected staff would go to monitor developments if the normal control room within the RCB were untenable.

If a severe earthquake were to occur, damage could conceivably occur to the reactor because of its own vibration or because of a heavy object (such as a fuel transport flask) falling onto it. Even so, fission products would only escape from the reactor core into the RCB if both the PCC leaked and the ECCS failed. Similarly, spent fuel could overheat and allow fission products to pass into the RCB if the No 1 SB were to leak because of intrinsic damage or because of damage by a heavy object falling on it. Nevertheless, even if one or other of these failure mechanisms allowed fission products to accumulate in the RCB, the leakage of fission products into the environment would be controlled provided that the RCB sealed and the CIS, SCS, airlocks, SCC and passive seals remained effective. The reactor would shut down and prevent further fission taking place either through the actions of the RPS or through its own intrinsic mechanisms.

The purpose of this section of the report is to discuss the ability of the various reactor components listed above to sustain events such as those discussed in Section 2.

3.2. STRUCTURAL ANALYSIS

When HIFAR was designed and constructed, no formal consideration was given to seismic issues, but since that time there has been considerable analysis of its seismic integrity. Many of its key components have been seismically qualified, and a number of modifications have been performed to strengthen other key components. Current practice is to seismically qualify any new or modified safety related components, and to review all items of plant in areas which could affect safety.

3.2.1 Initial seismic studies of HIFAR components by Peters and Ledwon

The first major study of HIFAR's seismic integrity was conducted by Peters and Ledwon (1984a,b, 1985). They examined the main structure, including the RCB and buildings B40, B41 and B42; the RAT; the PCC including main and shutdown pumps and heat exchangers; the SCC including the shield and experimental cooling circuits, the pipework inside and outside the RCB, and the pumps and pipes within the pumphouse (the cooling pond and towers were excluded as these were scheduled for refurbishment); the CCAs; the ECCS; and the electrical equipment in the RCB and pumphouse. Both direct and secondary damage were considered.

Most of this equipment was found to be capable of withstanding an event with PHGA of 0.2 g. Modifications were suggested for the deficient items. See Table 1 for details.

Peters and Ledwon found the strength of the clusters of holding-down bolts of the RCB stiffeners to be a limiting feature of the structure, and estimated that these might yield at PHGA of approximately 0.06 g. They recommended that these bolts be strengthened. However, it was subsequently found that their finite element model used floor loadings in the RCB which were considerably greater than could ever occur, leading to excessively conservative estimates of the stresses in the structure (Whatham 1989,1990).

3.2.2 Studies of the structure by Structural Mechanics and Dynamics

The consulting firm Structural Mechanics and Dynamics (SM&D) made two studies of the structure of the HIFAR building, a preliminary one (SM&D 1992), and an extended one (SM&D 1995). They mainly used finite element analysis. Their analyses modelled the reactor block with its cruciform columns, the operating floor, the No. 1 Storage Block (No 1 SB), the biological shield around the D_2O Plant Room, the polar crane, and the Reactor Containment Building stiffener columns, holding down bolts, curved wall plates, composite steel seal plate/reinforced concrete floor and vehicle airlock. The finite element analyses undertaken are discussed below and summarised in Table 2.

The model was excited through its support points by a three-axis set of acceleration waveforms scaled from those recommended by the Bureau of Mineral Resources (Somerville,1992, see Section 2). This approach differs from the response spectrum approach advocated by the Nuclear Safety Bureau (NSB), using US Reg Guide 1.60 (US AEC 1973). It has two advantages: it uses waveforms which take account of the fact that the generally smaller, shallower earthquakes occurring in the local intraplate region are of shorter duration and higher spectral frequency than those used to derive US Reg Guide 1.60; and it allows the build-up and decay of the structural vibrations to be followed. Somerville (1994) advised that use of US Reg Guide 1.60 was neither necessary nor appropriate in an Australian context.

In their first finite element analysis SM&D found that of the sets of waveforms supplied, the one taken at Carbon Canyon dam caused the most severe effects; this set was used for all their subsequent calculations.

Prior to SM&D's extended study Somerville (1994) reviewed the catalogue of seismic waveforms and identified others which were typical of what might be experienced at Lucas Heights in an event with PHGA of 0.2 g: he provided further waveforms, giving a total of eight sets. Whatham (1995) used these to excite a finite element model similar to those used by SM&D and confirmed that the Carbon Canyon set produced the most severe effects on the structure. He also constructed artificial waveforms by copying the part of the Carbon Canyon waveforms with the highest PHGA one or more times. He showed that exciting the model with these extended duration waveforms did not increase significantly the stresses calculated in the members (Whatham 1994).

SM&D scaled the waveforms so that the maximum acceleration in either of the two horizontal directions was 0.2 g, with 0.133 g in the vertical direction. Having performed a run, the estimated stress in each structural member was compared to its yield stress. By identifying the member which had the highest ratio of estimated stress to yield stress, the acceleration at which the first component would reach yield stress was estimated.

The attached model

For their first analysis SM&D assumed the No 1 SB to be attached to the operating floor, and the biological shield to be attached to the reactor block (the "attached" model). For this model, the limiting member was found to be the set of bolts attaching the No 1 SB to the operating floor approximately opposite the VAL:

they estimated that these bolts would start to yield at a PHGA of approximately 0.13 g[†]. For this model the ratios of estimated stress to yield stress of the stiffener holding-down bolts were well below unity.

SM&D estimated the dominant oscillatory mode to have a frequency of 6.93 Hz. This estimate is supported by Somerville, who analysed seismic waveforms recorded in free field and at the operating floor level of HIFAR at the time of the Cessnock earthquake in 1994. He found that HIFAR exhibited a prominent structural resonance in the region of 6 Hz (Corran 1995).

The detached model

In order to examine the performance of the structure for accelerations beyond the yield level of the "attached" model, a "detached" model was devised, which assumed that the operating floor was detached from the No 1 SB, and the biological shield around the D_2O Plant Room was detached from the reactor block.

For the "detached" model, it was found that the first bolt to reach its yield stress would be in one of the clusters of stiffener holding-down bolts opposite the No 1 SB, at a PHGA of 0.164 g. The vertical forces of the cruciform columns carrying the reactor and the bending moments of the operating floor beams were examined and shown to be non-critical at this level of excitation.

Other studies

SM&D used an elasto-plastic response analysis to estimate on a conservative basis that the ultimate capacity of the complete ring of clusters of stiffener holding-down bolts (*ie* the stage at which the last of these clusters of bolts would reach yield stress) would be 0.26 g, a factor of approximately 1.6 above the acceleration which first caused yielding. They noted that at this level the relative movements of the various members were at most 5 mm (on bolts with diameter 32 mm) and that the bolts were of mild steel which would be ductile and which would perform well in extension and shear exceeding the elastic limit: they therefore judged there would be no major damage to the plant.

SM&D also performed a simple ductility calculation of the outer ring of stiffener holding-down bolts when excited by a waveform with PHGA of 0.38 g, which had been estimated to have a return period of about 10^5 y (see Figure 3). From this analysis they concluded that the containment structure would survive such an event without serious damage.

Conclusions to preliminary study

In concluding their preliminary analysis, SM&D emphasised the importance of the connection between the operating beams and the No 1 SB in determining the behaviour of the structure. They noted that with the "attached" model, even if the complete set of stiffener holding-down bolts were all to yield at about 0.26 g, the lateral movement of the bolts would not exceed 5 mm, the bottom seal plate would still control movement of the building, and the mild steel bolts would yield without fracture in both extension and shear, hence major structural damage would not be expected.

Study extension

Following a review of SM&D's study, the NSB (1993) requested additional information to clarify some of the conclusions reached in the preliminary report. As a consequence, SM&D examined in more detail the structure and integrity of the wall surrounding the D_2O Plant Room and the importance of its connection to the bottom of the reactor block; the importance of the bridging structure connecting the top of the reactor

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[†] In their first report, SM&D scaled the PHGA corresponding to certain conditions by calculating the root mean square (RMS) of the two horizontal ground motions and finding the instantaneous peak value of the RMS motion. However, as reported by Corran (1995), Somerville advised that when estimating the PHGA for yield, it would be more conventional practice to scale from the larger of the two horizontal seismic motions rather than the RMS peak, as this gave a more conservative result, although use of the RMS peak was not unknown. This practice has been followed in SM&D's second report and in this report. The results in SM&D's first report are accordingly scaled *pro rata* in this section.

block to the roof of the control room; the effect of the equipment associated with the silicon rig; and the structure and integrity of the emergency airlock (SM&D 1995).

The preliminary model of 1992 was refined in a number of ways. The walls of the D_2O Plant Room were modelled as a series of plate elements with material properties which SM&D regarded as appropriate for the steel shot concrete with which it is constructed (Stephenson and Turner 1957). The effect of exciting the system with the same Carbon Canyon waveforms used in the preliminary analysis was investigated for four different models.

1. A first "disconnected" model: this was similar to the earlier "detached" model but incorporated all the structural changes to the preliminary model except that the emergency airlock was not modelled; there was no connection between the No 1 SB and the operating floor; and there was no connection between the base of the reactor block and the top of the D_2O Plant Room.
2. A second "disconnected" model: this was identical to the first except that the two horizontal waveforms exciting the system were rotated by 90°.
3. A third "disconnected" model: this was identical to (2) above but also incorporated the emergency airlock.
4. A "connected" model: this used the same earthquake waveforms as the second "disconnected" analysis, but the D_2O Plant Room roof was rigidly linked to the base of the reactor block along the edge of the Experimental Plant Room extension roof. In this model the plant was therefore not so stiff as in the earlier "attached" model but was more stiff than in the "disconnected" models.

The disconnected model

The findings of the "disconnected" runs were as follows.

a. When the "disconnected" model applies, the base of the reactor block can move slightly relative to the top of the D_2O Plant Room: the movement is of the order of 2-3 mm, which would not lead to significant load transfer between the two structures.
b. The bolt forces around the perimeter of the RCB are very similar for "disconnected" cases 1 and 2, the PHGA for onset of yield being 0.154 g in one case and 0.156 g in the other case, showing that the peak loads are substantially independent of the horizontal direction in which the waveforms are applied.
c. The bolt forces around the perimeter of the RCB are slightly more than those estimated by the preliminary "detached" model, initial yield in the later analysis occurring at a PHGA of 0.154 g compared to 0.164 g in the original, both occurring at the same bolt cluster.
d. The principal compressive and tensile stresses in the D_2O Plant Room, and their locations, remain virtually the same as those associated with their static condition.
e. The stresses in the RCB wall near the inner door of the emergency airlock are well below yield and it is judged that the inner door of the airlock could be closed after a large seismic event;
f. The stress at the outer end of the airlock changed little during the test earthquake, being dominated by the static stresses.

The connected model

The findings of the "connected" analysis were as follows.

a. The stiffener holding-down bolts carry less load when the structure is connected, the PHGA required to yield the most critical bolt cluster being about double that for the disconnected case at 0.306 g.
b. The stresses in the concrete walls of the D_2O Plant Room have increased significantly in these cases, the critical point being the corner of the roof, where the stresses are in the region of 10 MPa, at which the concrete might crack or crumble.

Conclusions to the extended study

SM&D stated the following conclusions to their extended study.

- The yielding of the first bolt cluster occurs at slightly lower PHGA in the later refined model than in the preliminary detached analysis.

- The horizontal direction of application of the ground motion waveforms has insignificant effect on the level of PHGA at first yield.
- Whilst the level of PHGA at onset of yield could be increased by increasing the stiffness of the connection between the base of the reactor block and the top of the D_2O Plant Room, it appears that this connection would yield at a PHGA below the SL-2 level.
- Equipment in the D_2O Plant Room connected to both the reactor block and the walls experiences relatively small relative displacements and therefore relatively small loads.
- The inner end of the EAL has very low stresses, so that the inner door would still be operational after the event.
- The outer end of the EAL has small changes of stress compared to the static stresses, so that the outer door would remain operable.

3.2.3 Seismic studies of penetrations and ventilation components

Some RCB penetrations, in particular those for the ventilation system, have been seismically qualified for seismic events with PHGA up to 0.2 g (see Table 1). The inner Keystone sealing valves, the outer water seals, and the ducts connecting them to the RCB wall have also been examined since they could affect the largest penetration. These components are robustly constructed, and the distances between the seals and the RCB wall are relatively small. There are no significant loads associated with any of this equipment and it is judged that the equipment is able to withstand well above 0.2 g. The remaining penetrations have not been specifically examined for seismic integrity, but it is judged that should they fail, following events up to and including those with PHGA equivalent to the SL-2 event, the damage would be restricted to minor cracking around welds, etc.

3.2.4 Summary - the impact of earthquakes on HIFAR

There are four major issues associated with the impact of any seismic event on HIFAR.

1. Would the reactor shut-down, remain at power or suffer a power excursion?
2. Would the PCC be damaged?
3. Would the ECCS prevent fuel element damage even if the PCC failed?
4. Would the RCB and associated components provide adequate containment?

Reactor behaviour

Seismic events would impart some motion to the reactor block. However, the fuel elements are located securely at top and bottom, and are unlikely to vibrate sufficiently to cause significant reactivity fluctuations. The top of the D_2O reflector might slosh, but the primary modes would oscillate about the centre, with only small variations in the reflector heights. Changes in the top level of the reflector have only minor effect on the reactivity (Connolly and Clancy 1993), so that such sloshing would have only a minor temporary effect on reactor power.

Minor movement of the core with respect to the outer boundary and movement of the graphite reflector would be small and unlikely to have significant effect. The SRs are raised above the core during operation, to ensure that they do not undergo nuclear overheating, and minor vibration would be of no concern. Significant vibration could only cause the rods to drop and absorb reactivity. The CCAs are well restrained in the vertical direction, and any motion relative to their mountings would cause them to come off their electromagnets, initiating shutdown. Sideways motion of the CCAs has been studied by Robinson (1992). He found that lateral movement of the CCAs caused reactivity fluctuations of about 0.014% dk/k per cm of blade tip lateral movement. Furthermore, such lateral movements would in general produce reactivity reductions for all except the outer blades, which have smaller effect, so it is judged that lateral CCA movement would not produce significant power excursions.

The RPS was examined by Peters and Ledwon (1985), who judged that it would withstand events with PHGA up to at least 0.2 g. Any significant power transients initiated by seismic events up to 0.2 g would therefore cause a reactor trip. It is judged highly unlikely that any RPS instrumentation or logic failures at higher accelerations would be of such a nature that the electromagnet relays would remain energised, preventing release of the CCAs. Indeed, it is likely that in an event with acceleration eventually exceeding 0.2 g the power supplies to the site would be broken, at least temporarily. This would be sufficient to initiate CCA release. Nelmes (1986) has made the point that the forces which the CCAs withstood when tested in air were much greater than those in D_2O, so it is very unlikely that any credible seismic event would damage the CCAs to the point where at least the majority could not fall into the core. Provided CCA release was initiated, the reactor would shut down and remain shut down.

It is therefore judged that seismically induced movements of the reactor block are unlikely to cause significant power transients. Any significant transient would be detected by the RPS, which would initiate reactor shutdown, and major events would be likely to impair the site power supplies, which would also cause shutdown either via the RPS or through fail-safe mechanisms. The CCAs are strong enough to withstand much greater forces than any caused by credible seismic events. It seems most likely that for small seismic events the reactor power will remain close to its operating level, and for larger events it will shut down either because of RPS action or because of power supply interruption. No mechanism can be identified which would inject so much positive reactivity that operation of the RPS would be needed to prevent fuel damage being caused by an induced power transient. The reactor response to transients induced by reactivity injection was discussed by Connolly and Clancy (1993). They noted that the reactor would withstand transients which injected positive reactivity of $dk/k = 0.6\%$ without assistance from the RPS. Such an injection would require lateral movement of the outer CCAs by more than 20 cm each, which is incredible.

Performance of the RCB and associated components

The RCB functions as part of the containment barrier. Moreover, it is structurally linked to the reactor block and thence the PCC. The studies undertaken by Peters and Ledwon and SM&D lead to the following conclusions about the performance of the RCB and its associated components.

- Below PHGA of 0.13 g the bolts attaching the No 1 SB to the operating floor would not yield, and the stresses in the stiffener hold-down bolt clusters would generally be a small fraction of their yield stress. There would be no yielding of any RCB structural member.
- Above PHGA of 0.13 g but below PHGA of 0.15 g the No 1 SB might cease to be attached to the operating floor, but there would be a low probability of yielding of any stiffener hold-down bolt group.
- At PHGA in excess of 0.15 g (the exact value depending on whether the connected or disconnected model were more applicable) the first stiffener holding-down bolt cluster would start to yield, but yielding of all bolt groups would not occur unless the event had PHGA in excess of 0.25 g (0.154 g x 1.6).
- Below PHGA of 0.38 g, the RCB structure would not suffer serious damage, and although all the stiffener holding-down bolt clusters would probably exceed their yield values they should not rupture. Parts of the bottom seal plate, walls and roof of the RCB would probably suffer local yielding but should not suffer ruptures that would aggravate leakage. The two Personnel Air Locks, the Vehicle Air Lock, and the Emergency Air Lock would continue to provide passive sealing with possibly some separation of their sealing faces.
- The Emergency Air Lock would continue to provide an exit route to staff in the RCB for events with PHGA up to and well beyond 0.2 g.

Damage to the PCC

The PCC comprises those components whose position is largely determined by the position of the D_2O plant room floor, those whose position is largely determined by the position of the reactor block, and a small number of pipes which interconnect these two sets. Rupture of the PCC might arise in three ways: excessive movement of one or more components in relation to its nominal mounting position; excessive differential movement between the two sets of PCC components because of movement of the reactor block in relation to the D_2O plant room floor; and movement of some extraneous object causing it to impinge on a PCC component.

Peters and Ledwon (1985) undertook analyses of the RAT and the other parts of the PCC for events with PHGA up to 0.2 g. They judged that these components would be structurally stable once certain modifications were introduced. With the exception of strengthening to the 1V4 anchorages, all these modifications have been implemented, and the 1V4 anchorages are being strengthened in the major shut down starting in September 1995. Simple linear extension of Peters and Ledwon's analyses show that the RAT and PCC will remain satisfactory to 0.25 g.

The work of SM&D showed that differential movement between the reactor block and the D_2O plant room floor would not exceed a few millimetres unless all the RCB bolt groups yielded. They estimated that this would not occur unless a seismic event had PHGA in excess of 0.25 g. Relative movement of the various PCC members would still be small, and it would remain unlikely that the PCC would fail[†].

SM&D have examined the seismic resistance of the D_2O plant room wall and judge that it will not be significantly damaged due to events with PHGA less than 0.25 g. Other investigators have made similar findings about the other components inside the D_2O plant room.

The PCC will therefore withstand events with PHGA up to 0.25 g. Above this level, the probability of PCC failure increases, and in the absence of analysis it is assumed to fail. However, should it fail, fission product release would be determined by the performance of the ECCS.

Performance of the ECCS given PCC failure

There seems to be no question that the ECCS could prevent fuel melting provided that the leak rate from the PCC were less than the return rate from the ECCS scavenge pumps. Hence provided that one pump worked, the ECCS would certainly prevent fuel melting for leak rates up to about 12 L s^{-1}, and if two pumps worked, leak rates up to 24 L s^{-1} could be tolerated. Connolly and Clancy (1993) have discussed the performance of the ECCS should the leak rate exceed these values, and the D_2O level drop to just above the downcomers. They judged that for credible flows there would still be enough head to ensure that Wolters' cooling would prevent melting.

Bolling (1975) calculated the stresses in the pipework associated with the ECCS. He showed that assuming zero damping of the longest unsupported pipe the tensile stress would be well below the maximum allowable at 0.23 g. Malone and Lloyd (1995) have examined the scavenge pump area and concluded it is qualified to 0.23 g. Lloyd (1985) assessed the seismic resistance of the power supplies and control systems for the shutdown and ECCS pumps and concluded that except for the anchoring of one cabinet, housing control equipment for the shutdown pumps, the equipment was qualified to 0.2 g. This cabinet has since been securely anchored. The ECCS depends on supply from the EPSS, which has been qualified to 0.23 g. It may therefore be concluded that the ECCS would not fail because of seismic events below PHGA of 0.2 g. Since the PCC is not expected to fail for events with PHGA below 0.25 g, fission product release into the RCB should only occur above 0.25 g.

Summary of seismic damage to HIFAR

The above analyses leads to the following answers to the four issues listed at the start of this section.

Would the reactor shut down, remain at power or suffer a power excursion? It appears incredible that a power excursion would occur under any circumstances. In all probability the CCAs would fall causing the reactor to shut down.

[†] In some earlier studies (*eg* Corran 1992) it was assumed that the PCC would fail once the first RCB stiffener holding-down bolt cluster reached yield stress. This assumption is now discounted following clearer recognition of the materials' properties and mechanical behaviour of the RCB.

Would the PCC be damaged? For events with PHGA below 0.25 g it is very unlikely that the PCC would fail. For greater events no analysis is available, and it is assumed that the PCC will fail.

Would the ECCS prevent fuel damage even if the PCC failed? The ECCS pipework and pumps are estimated to withstand events with PHGA up to 0.23 g, and the associated electrical equipment to 0.2 g. The ECCS as a whole should therefore remain functional for events with PHGA up to 0.2 g. Since the PCC is estimated to remain functional for events up to 0.25 g, the ECCS appears to perform no useful role. In fact, it provides a very useful redundant back-up. There is always some possibility that the PCC could fail below 0.25 g because of some unforeseen fault, and the ECCS would then most probably prevent fuel melting. Equally, there is a significant probability that the ECCS would continue to work following events above 0.25 g, and could prevent fuel melting if the PCC were to fail. In this study these scenarios have been excluded for simplicity.

Would the RCB and associated components provide adequate containment? Yielding of all the bolts holding down the RCB would not occur unless an event were to exceed a PHGA of 0.25 g, and below this level no significant degradation of the containment system would be expected. Above this level, but below a PHGA of 0.38 g, the holding down bolts would probably yield, but although the RCB might sustain some localised yielding it should not rupture. The RCB would therefore continue to provide some containment (This is discussed further in Section 4.1). The effects of earthquakes with PHGA greater than 0.38 g have not been modelled. The likelihood of such events is less than $1 \times 10^{-5} y^{-1}$. The Emergency Airlock would provide egress for staff for events with PHGA up to and beyond 0.2 g.

4 ESTIMATION OF THE CONSEQUENCES AND LIKELIHOODS OF MAJOR SEISMIC EVENTS

4.1 ESCAPE OF FISSION PRODUCTS

Section 3 concluded that for seismic events with PHGA less than 0.25 g the PCC would be unlikely to fail, the fuel would not be damaged, and there would be no escape of fission products. Events with PHGA greater than 0.25 g might cause fission products to escape into the RCB. However, for events with PHGA less than 0.38 g, the containment structure would remain standing with some degradation in leak-tightness: the situation would resemble the Loss of Coolant Accident (LOCA) scenarios extensively studied by McCulloch *et al* (1986). Events with PHGA greater than 0.38 g have been shown to have a likelihood less than once in 100,000 y, which in this study is considered to be the limit of credibility: their consequences are not discussed in this study.

4.2 LEAKAGE FROM THE RCB

For such LOCA scenarios, the consequences would be controlled by the rate at which air and fission products escaped from the RCB. In an earlier study Corran (1992) assumed conservatively that following an event that caused all the stiffener holding-down bolt clusters to yield, the RCB leak-rate might be as much as one change per hour. With the information from SM&D's studies it is now judged incredible that such a high leak rate could be caused by any seismic event of PHGA up to 0.38 g. The building ventilation system can only achieve such an air change rate when the ventilation fans are operating. Following a significant seismic event it is possible that the ventilation fan supply, which is not guaranteed, would fail. Even if it did not, if there was an escape of fission products into the shell the CIS detection system would normally shut the fans down and close the penetrations. Loss of power to the CIS system would achieve the same end. Finally, an administrative procedure is in place for manual de-energisation of the fans from the ECR should they not be otherwise de-energised (HIFAR incident instruction 1995). Without an active mechanism expelling the air, it could only leak from the RCB because wind blowing across the outside of the building caused some air to pass through it, or because the pressure inside the building was greater than outside.

4.2.1 Wind driven leakage through the RCB

Air could pass through the RCB if there were two or more leaks in the building. The air flow would be limited by the size of the smaller one. Beattie (1995) examined the question of wind-driven leakage through cracks and holes. He provided the data in Table 3.

The slower velocities through the cracks are due to the (wind) shear stresses adjacent to the wall, which according to Beattie must be taken into account for cracks less than 3 mm wide. He considered a crack of 1m length by 1 mm width, and an ambient wind velocity of 1 m s^{-1} (Pasquill G conditions) and showed that the air change would not exceed 2.5×10^{-5} m^3 s^{-1}. As the RCB air space is about 6800 m^3, the leak rate would be about 0.03% per day, much less than the authorised maximum leak rate of 10% per day at a differential pressure of 10 kPa.

No mechanism has been identified which would create cracks of the above size in the RCB structure. Major damage of ventilation penetrations is judged to be incredible. The other ductile RCB components might sustain localised yielding but this should not produce ruptures of the above size. Flow of air through the RCB due to wind driven leakage can therefore be neglected.

4.2.2 Leakage due to differential pressure

The LOCA study described by McCulloch *et al* considered passive leaks with maximum leak rates of 3% and 10% of RCB volume per day, based on measured leak rates. For a seismic scenario in which the containment boundary could have small cracks, no particular value of leak rate can be assigned. The pressure inside the RCB could increase because the heat introduced into the RCB warmed the air. This would cause leakage of air. However, Corran (1992) has suggested that the leak-rate would be limited to that of a "thermally controlled" model where sufficient heated air escaped to maintain the internal pressure substantially equal to that outside.

From the above discussion, it follows that the only scenarios which could credibly give rise to public consequences would be ones where the initiating event was a ground motion of PHGA in the range 0.25 g to 0.38 g, with conditional events being the size of the fission product source term and the atmospheric dispersion conditions once the fission products reached the environment. Such a set of scenarios is illustrated in Figure 5.

4.3 THE DOSE RECEIVED BY THE WORST PLACED MEMBER OF THE PUBLIC AT THE 1.6 km SITE BOUNDARY

The expression "fission product source term" describes the amount of fission product activity escaping from the RCB. This could take a range of values depending on the fuel history, the way in which the fission products pass into and behave within the RCB, and the way in which they escape. The present study follows the practice used by McCulloch *et al,* when considering internally induced LOCAs, of partitioning the range into two, divided at the median. The lower partition has been characterised by the median value, and the upper partition by the 90% upper bound. The amounts of fission products were estimated using the quantities of fission products in the air inside the RCB calculated by May (1987) and the thermally controlled model discussed above to determine how much of these escaped with time.

The dose received from a particular fission product source term is determined by the atmospheric dispersion conditions. These can vary widely depending on the wind speed, direction and inversion condition. Again, in this study the range was partitioned into two, the lower partition being characterised by a median set of conditions and the upper partition by a 90% upper bound condition, following the practice used by McCulloch *et al* and Petersen and Clark (1986)

Two programs, AIRBORNE and DISPDOSE, were developed by Miller (1987) to estimate doses at the 1.6 km site boundary. Particular fuel history, source term, and thermohydraulic model conditions are input to AIRBORNE and the cumulative activity released from the RCB is estimated. This is input to DISPDOSE with a set of atmospheric dispersion conditions, to estimate the doses to six tissues and organs, the child thyroid, uterus, whole body, lung, skin and bone marrow. The child thyroid dose was used in preference to the adult dose because Petersen (1985) showed the child thyroid dose to be 1.92 times the adult dose. The results for fault sequences initiated by within plant failures is reported in McCulloch *et al* (Cases 1-45).

Whatham (1992) derived an additional set of data to characterise the "thermally limited" model described in 4.2.2 above, and ran four cases using the source and atmospheric dispersion condition cases discussed above. The results of these cases, (denoted Cases 47-50, following the case numbers reported in McCulloch *et al*), are summarised in Table 4 and the graphs of Figures 6 to 10. For individuals who remained in the open for the first ten days of the event, after which most of the fission products would have passed. Case 48 shows the effective dose associated with the median conditions to be about 1.3 mSv, whilst Case 49 shows the doses associated with the two 90% upper bound conditions to be about 5.1 mSv. Since all individuals would in the normal course of events go inside to sleep, it is highly unlikely that any individual would receive 5 mSv even under the worst conditions.

Examination of the doses to an extended range of organs and tissues, both from cloud shine and inhalation, showed that the (child) thyroid dose was much the largest contributor to the effective dose.

4.4 ESTIMATION OF THE LIKELIHOOD OF INDIVIDUAL SCENARIOS

From the relationship given in Section 2.2.1 the best estimate likelihood of a seismic event with PHGA greater than 0.25 g is 3.2×10^{-5} per year, and the best estimate likelihood of a seismic event with PHGA greater than 0.38 g is 9.9×10^{-6} per year. Hence the best estimate likelihood of an event with PHGA within this range is 2.2×10^{-5} per year (return period about 45,000 y). The upper bound estimate for an event in this range is 5.1×10^{-5} per year (return period about 20,000 y).

To estimate the likelihood of the four scenarios characterised by partitioning at the median source term and atmospheric dispersion conditions, it is assumed that the probability of lying above or below the median source term value is independent of the weather conditions at the time of a seismic event. Since the probability of lying above or below a median is by definition 0.5, the probability of any particular scenario, given a seismic event causing fission product release, is 0.25. The likelihood of that scenario is the product of the probability of a seismic event causing fission product release and the probability of that scenario.

When estimating likelihood, it is important to distinguish between the likelihood of a LOCA, with consequent fission product release to the environment, and the likelihood of a particular worst placed individual being exposed to that radiation. A fission product plume emitted from HIFAR would affect only those in a fairly narrow arc down-wind - depending on the Pasquill category this could be 20-30° wide. The HIFAR Safety Document (HSD 1972) showed that for strong inversions (*ie* a Pasquill G category) the wind would favour the southern octant (45° arc) 46% of the time, the south-east octant 34% of the time and any other octant less than 11% of the time. The distribution would be less peaked for weaker inversions, going to any one octant less than 29% of the time. It follows that the probability of a particular individual being downwind would be no more than 0.46 (conservatively adjusted to 0.5).

The atmospheric conditions are independent of the seismic event, so that the likelihood of a particular combination of event, source magnitude, atmospheric condition and wind direction can be estimated by taking the product of event likelihood and conditional probabilities of source, dispersion condition and wind direction. The results are shown in Figure 5 and Table 4.

4.5 CALCULATION OF THE FATALITY RISK TO WORST PLACED INDIVIDUALS

For each of the four cases considered, the ICRP (1990) probability of fatality was estimated, using the ICRP 60 risk factor of 5×10^{-2} per Sievert effective dose. The fatality risk to the worst placed individual was then estimated from the product of the likelihood of such an individual receiving the estimated dose, and the probability of the dose causing a fatal cancer. The total risk to that individual was then estimated by summing the risk from all the cases. The results are again shown in Figure 5 and Table 4.

5 RISK ASSESSMENT

5.1 GENERAL APPROACH

Previous sections of this report have considered the conditions under which some fission products might be released from HIFAR, and the consequences and likelihoods of these conditions. In this section the acceptability of these consequences is considered. The requirements of the NSB are described, and the extent to which this study shows that HIFAR meets these requirements is discussed.

5.2 THE SAFETY REQUIREMENTS OF THE NUCLEAR SAFETY BUREAU

The safety requirements which HIFAR should meet have been defined by the NSB. They comprise REGBUR MEMO 1/82 (Regulatory Bureau 1982) and conditions specified by the NSB (1993).

5.2.1 REGBUR MEMO 1/82

REGBUR MEMO 1/82 comprises a set of safety assessment principles covering all aspects of nuclear design and operation. In particular it lays down two "probabilistic" concepts. The first relates to the number of "effective barriers" which are required to provide protection against anticipated events. Such barriers are to be capable of reducing the dose to individuals beyond the 1.6 km boundary to a level below the Emergency Reference Level (ERL), which is specified to be 0.3 Sv to the whole body, 0.15 Sv to the foetus, and 1 Sv to the child thyroid. The number of effective barriers needed is determined by estimating the likelihood and consequence of all events which could occur without the presence of any effective barrier: the minimum number which should be provided for any particular event is specified in paragraphs 13 to 15 of REGBUR MEMO 1/82. The second concept, laid down in Paragraphs 8 to 11 of REGBUR MEMO 1/82, relates to the maximum dose tolerable for each discrete fault sequence, based on its estimated likelihood.

Figure 11 illustrates both concepts. The hatched areas show the minimum number of effective barriers, based on the estimated consequences and likelihoods of each discrete fault sequence without considering the aid of effective barriers. To comply strictly with the criterion of paragraph 13, the consequences of discrete fault sequences falling anywhere in the single hatched area at the bottom right of the figure should be minimised by at least one barrier. However, paragraph 15 allows dispensation to be claimed for those very unlikely discrete fault sequences with likelihoods below the dotted line at 10^{-5} y^{1}, provided that it is shown that reasonable measures have been taken to minimise the likelihoods and consequences of such discrete fault sequences, and that for such very unlikely sequences, in which it is difficult to demonstrate compliance with paragraph 10, a case-by-case approach may be adopted. The unhatched areas indicate the range of discrete fault sequences deemed tolerable.

5.2.2 Other NSB requirements

The NSB (1993) repeated the requirement that ANSTO should comply with REGBUR MEMO 1/82, but also required ANSTO to carry out a traditional deterministic assessment, and referred to the S2 criterion, the IAEA's previous term for the present SL-2 criterion (IAEA 1991). In the absence of a precise guideline from the NSB, it is inferred that this requirement can be satisfied by demonstrating compliance with the IAEA's seismic safety principles. The NSB also suggested that the risk should be compared against the risk criteria of the NSW Department of Planning and that some consideration should be given to collective dose (societal risk) issues.

The NSW Department of Planning (1991) issued an advisory paper on the fatality risk criteria it considers appropriate for non-nuclear hazardous industry in the state. This includes criteria about the risk to individuals. These are summarised in Table 5.

5.3 ASSESSMENT OF SEISMIC ADEQUACY

5.3.1 Compliance with REGBUR MEMO 1/82

For the purpose of assessing the number of effective barriers required by REGBUR MEMO 1/82 paragraphs 13-15, consider the RCB to be a support and mitigation structure, not a purpose-built effective barrier. This approach is appropriate as the RCB, although serving as an effective barrier, cannot be considered to be entirely independent for large seismic movements - it must also provide essential support for the core and cooling circuits. Peters and Ledwon have concluded that the RAT will withstand 0.2 g, and the whole of the PCC will be qualified to 0.2 g once the modifications to 1V4, currently in hand, are complete. This conclusion is supported by SM&D's studies, which show that relative movements of the various parts of the plant would not exceed a few millimetres. It is therefore concluded that the PCC would be extremely unlikely to fail for events with PHGA up to at 0.15 g and most likely would withstand 0.25 g. This conclusion has been reached using the most conservative assumptions about application of exciting waveforms. Without failure of the PCC there would be no releases of radioactivity. In Figure 3, events with PHGA of 0.15 g are conservatively estimated to have a return period of more than 3000 years, so that for seismic events with return period up to 3000 years no radioactive consequences are anticipated. For such events no further barrier is required.

Whilst it is considered unlikely that the PCC would fail when subjected to events with PHGA below 0.25 g, at higher PHGA it could fail. At these levels, the ECCS could not be guaranteed, the fuel could melt, and fission products could escape into the RCB. However, as shown in Section 4.4, events with PHGA in the range 0.25 g to 0.38 g are estimated to have a return period in excess of 43,000 years, and for events with such likelihood REGBUR MEMO 1/82 paragraph 13 requires an effective barrier only if the doses exceed 1 Sv child thyroid or 0.3 Sv whole body. For events of PHGA up to 0.38 g the dose to individual members of the general public would not exceed 48 mSv child thyroid and 2.8 mSv whole body, assuming upper bound source term and atmospheric dispersion conditions (Case 49 of Table 4). These levels are at least an order of magnitude below those for which REGBUR MEMO 1/82 would require a further effective barrier.

Figure 3 shows that events with PHGA greater than 0.38 g have an estimated return period in excess of 100,000 years. Damage to the structure can be expected to increase progressively as the events increase in size, but on the basis of SM&D's ductility study it seems unlikely that the leak-rate would rise considerably until the events were much greater than 0.38 g. Since the upper bound estimates at 0.38 g do not exceed 48 mSv child thyroid and 2.8 mSv whole body, events causing doses to the general public approaching 1 Sv child thyroid or 0.3 Sv whole body can be expected to have a return period much greater than 100,000 years. Hence on the basis of Paragraph 15 of REGBUR MEMO 1/82 no effective barrier is required.

From the above arguments, for seismic purposes no additional effective barriers are necessary for HIFAR to comply with the requirements of paragraphs 13-15 of REGBUR MEMO 1/82, although the ECCS, supported by the EPSS, is likely to provide such a barrier for the great majority of the seismic events that can be anticipated.

Paragraphs 8-11 of REGBUR MEMO 1/82 prescribe the maximum tolerable radiological conditions for fault conditions. Paragraphs 8 and 9 cover events with expected return period less than 3000 years. For seismic events in this range the structure will remain within its elastic limits, the PCC will remain intact, and there will be no release of fission products. HIFAR therefore complies with the requirements of paragraphs 8-9 of REGBUR MEMO 1/82.

Paragraph 10 requires that events with expected return period greater than 3000 years should not cause doses to the general public in excess of 1 Sv child thyroid or 0.3 Sv whole body. As shown above, only seismic events with PHGA above 0.25 g might cause a release of fission products. These are estimated to have a likelihood (upper bound estimate) of $3.2 \times 10^{-5} y^{-1}$, equivalent to a return period in excess of 30,000 years. For events with PHGA between 0.25 g and 0.38 g the dose to individual members of the general public would not exceed 48 mSv child thyroid or 2.8 mSv whole body, assuming upper bound source term and atmospheric dispersion conditions.

For events with PHGA greater than 0.38 g, with return periods in excess of 100 000 years, the relationship between damage and event size cannot be predicted, although it seems unlikely that the RCB leak-rate would increase by as much as an order of magnitude until the event was very much larger. Paragraph 11 of REGBUR MEMO 1/82 recognises the problem of predicting the outcomes of very unlikely hypothetical events: following its approach it is judged that the unlikely incidence of such events, taken together with the general sound construction of the plant, do not justify further strengthening measures. On this basis it is claimed that HIFAR complies with all the radiological requirements of paragraphs 8-11 of REGBUR MEMO 1/82.

5.3.2 Compliance with IAEA seismic design guidelines

The NSB has required ANSTO to demonstrate that HIFAR be the subject of a traditional deterministic assessment. A suitable basis is the IAEA's guide for the seismic design and qualification of nuclear power plants (IAEA 1992). It categorises reactor structures, systems and components (termed items) in terms of their importance to safety in the event of an earthquake. Seismic category 1 items include those whose failure could directly or indirectly cause accident conditions; those required for shutting down the reactor, monitoring critical parameters, maintaining the reactor in a shutdown condition and removing residual heat over a long period; and those required to prevent radioactive releases or to maintain releases below limits established by the regulatory body for accident conditions.

This category clearly includes the PCC boundary, the ECCS, the EPSS, the SCS, and the containment boundary, including the RCB, the CIS, the airlocks and passive penetration seals. Such items are to be designed or demonstrated to withstand the consequences of SL-2 ground motions, taken to be a ground motion with PHGA of 0.2 g (NSB 1993).

Assurance that this is the case is provided by the work of SM&D and the other studies and modifications reported in Table 1. Specifically, there is a high degree of confidence that the prescribed SL-2 event would not cause the PCC to fail. Even if it were to fail, the RPS would shut the reactor down and the ECCS/EPSS system would provide core cooling, so preventing the fission products from escaping, and limiting the radioactive release into the RCB to tritium release. Even if the ECCS/EPSS system were to fail, it is judged that the building leak rate would be sufficiently low that the dose to individual members of the general public beyond the 1.6 km boundary would not exceed 48 mSv child thyroid or 2.8 mSv whole body. HIFAR therefore complies with the deterministic requirements of the NSB (1993).

5.3.3 Assessment of risk to individuals

The NSB has suggested that the risk should be compared against the risk criteria of the NSW Department of Planning (1991). The relevant ones are summarised in Table 5. From Table 4 the total fatality risk to the worst placed individual (located downwind on the 1.6 km site boundary) is estimated to be well below 5×10^{-9} y^{-1} on a conservative basis. This is at least two orders of magnitude below the most stringent criterion prescribed for non-nuclear hazardous industry by the NSW Department of Planning.

5.3.4 The societal risk issue

The NSB has suggested that consideration be given to societal risk issues. Societal risk is a measure of the likelihood that specific numbers of people sustain specific levels of harm as a result of operating a potentially hazardous facility. The societal risk for Cases 47-50 is currently being estimated. However, Murray (1990) has estimated the numbers of fatalities and non-fatal cancers arising from two of the cases discussed by McCulloch et al. Case 4 postulated a RCB leak-rate similar to those used in this study, so that the fission product release was about the same as for Case 49, the worst case considered in this report. Murray stated that he expected no fatalities and one to two non-fatal thyroid cancers for this case.

No commonly accepted criteria of levels of acceptability of societal risk are available either within the nuclear community or within NSW. Some criteria have been proposed, but they have no standing within Australia. Until the societal risks arising from the seismic events discussed in this report have been estimated, and a set of criteria have been agreed for assessing societal risk, no objective assessment is possible.

6 CONCLUSIONS

This report covers the range of issues affecting the seismic safety of HIFAR. Section 2 examines the issue of the nature of the seismic events that might impact on HIFAR. It shows that the event with a 10,000 year return period (the SL-2 event) has a peak horizontal ground acceleration of 0.17±0.06 g. This is consistent with Nuclear Safety Bureau (NSB) advice that HIFAR should be assessed to a SL-2 level of 0.2 g. Section 2 also addresses the question of the frequency content and duration of typical events with acceleration similar to the SL-2 event. Eight records of such events have been acquired: that for Carbon Canyon, CA, was found most conservative and used throughout the study

Section 3 considers the impact of seismic forces on HIFAR. Following are the principal findings.

- There is a high level of confidence that there will be no damage to the core, primary cooling circuit or safety related features for seismic events up to the SL-2 level.
- The space conditioning systems, and the ventilation system components concerned with sealing the reactor containment building (RCB), are qualified to withstand at least 0.2 g.
- Secondary damage through failure of the crane, D_2O Plant Room, or Silicon Rig platform will not occur for events with PHGA below 0.2 g.
- No 1 Storage Block is a double walled vessel qualified to 0.23 g.
- Adjacent buildings B40, 41 and 42 are qualified to at least 0.2 g. Differential seismic movements between B42 and the personnel airlock link will not damage the RCB.
- The primary cooling circuit (PCC) is expected to remain intact for events up to 0.25 g.
- The reactor protection system, emergency core cooling system and electrical power supply system will withstand events up to 0.23 g.
- Modifications to the secondary cooling circuit (SCC) pipelines are scheduled for the 1995 major shutdown. After these are complete, the SCC will withstand events up to 0.23 g.
- The RCB hold-down bolt clusters are manufactured from mild steel, a ductile structural material. The most stressed cluster is estimated to yield above 0.15 g. However, yielding of all the bolt clusters will not occur below about 0.25 g.
- For events above 0.25 g but below 0.38 g the bottom seal plate and the walls of the RCB might sustain some localised yielding but they are unlikely to be ruptured causing excessive leakage. The two Personnel AirLocks, the Vehicle AirLock, and the Emergency AirLock could have minor increases in their leak rates. The Emergency AirLock will continue to provide an exit route for staff in the RCB.

The most important finding is that no fission products are expected to be released from the core for seismic events less than 0.25 g. The return period for events greater than this level is estimated to be greater than 30,000 years.

Section 4 considers the release of fission products for events with PHGA in the grange 0.25 g to 0.38 g. Four scenarios are postulated and the consequences and likelihood of each are investigated. The cumulative activity released from the RCB is given for each scenario. The doses to several organs and tissues, and the effective dose, are estimated for the worst placed individual on the 1.6 km site boundary. The best estimate of the effective dose to such an individual is about 1.3 mSv. The risk of fatality of such an individual is conservatively estimated to be below 5×10^{-9} y^{-1}. The cumulative dose to the public out to a range of 56 km has been estimated, and hence estimates of the numbers of fatalities and non-fatal cancers have been estimated. On a best estimate basis there would be no fatalities and no non-fatal thyroid cancers for events with PHGA up to 0.38 g

Section 5 provides a seismic risk assessment for HIFAR. It covers the objectives arising from REGBUR MEMO 1/82. HIFAR is shown to have sufficient barriers and the likelihood of prescribed consequences is within tolerable limits. HIFAR satisfies the deterministic seismic guidelines of the IAEA. The estimated fatality risk to worst placed individuals is at least two orders of magnitude below the most stringent criterion of the NSW Department of Planning. Events beyond the design basis are very unlikely to cause either a fatality or a non-fatal thyroid cancer.

In summary therefore, ANSTO has complied in all respects with the seismic requirements of the NSB. HIFAR presents no significant risk to the surrounding community nor to the people of Sydney.

One way of putting the situation in perspective is to contrast the effects which members of the public might incur directly as a result of seismic events with those which might be experienced as a result of damage to HIFAR. In Australia, impact is customarily assessed in terms of the Modified Mercalli scale. Table 6 shows, for each increment on the Modified Mercalli scale, a summary of effects on the community, an equivalent range of Peak Horizontal Ground Acceleration, the likelihood of events in that range in the Lucas Heights region, and the expected effect on HIFAR. Unless the direct effects were very substantial, there would be no effect whatever on HIFAR, and even then the additional radiation dose to the worst affected members of the community would be no more than they could expect to receive every year in the natural course of events. However catastrophic the event, there would be no immediate fatalities of members of the public as a result of damage to HIFAR and it would be highly unlikely that any member of the public would eventually die from the effects of seismic damage to HIFAR..

7 ACKNOWLEDGMENTS

The question of the seismic safety of HIFAR has received considerable attention for more than ten years, and hopefully this report has resolved most of the outstanding issues. It seems appropriate therefore to acknowledge and thank those who have contributed significantly to the issue.

A lot of the ground breaking work in the 1970's and early 1980's was undertaken by Ivan Mumme. Don Higson pursued the question, initiating the study performed by the Department of Transport and Construction in 1982. The author became involved at that time, but could not have proceeded without advice from members of the BMR, notably Marion Michael-Leiba and Kevin McCue.

John Harries and Frank Nicholson provided useful comments throughout the period. John Whatham made many useful contributions in a number of areas, including finite element analysis, and consequence analysis. Don Higson throughout the period of study provided useful insights. Neil McDonald and Bob McAneny provided useful discussion and insights in recent discussions. Ken Lloyd and Geoff Malone have undertaken studies of various HIFAR components.

As well as those concerned with the purely seismic aspects of the study, there have been many contributors to the study of fission product releases. Major contributors were Geoff Clark, Joe Marshall, Fred May, Ross Miller, Allan Murray, Max Petersen, John Rodd and David Woods.

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Table 1 List of studies of modifications to HIFAR

Item	Study or modification	Comments	Status	Reference
Basic structure	Initial analysis of structure by Peters and Ledwon (P&L) Analysis of responses of basic structure to PHGA up to 0.38 g by SM&D	Yield of first set of stiffener hold down bolts at 0.154 g, of all stiffener bolts ~0.25 g. Sufficiently ductile to withstand 0.38 g without serious damage	Qualified	P&L (1984a,b) SM&D (1992) SM&D (1995)
Primary cooling circuit	RAT		Qualified	P&L(1985) CL 104450B
	Main pipes, heat exchangers and main pumps	1V4 anchorages to be strengthened	Qualified when complete	TN 105374
Secondary cooling circuit	Strengthening of pumphouse to 0.23 g	P&L recommendation. Based on GH&D work (0.23 g)	Qualified	P&L (1985) TN 104397
	Modification of pipe supports in pumphouse	Based on GH&D work (0.23 g)	Qualified	TN 104396
	Assessment of overhead travelling crane	NSB requirement	Qualified	TN 104799
	Control cubicles & switchboards in pumphouse	Anchored to floor and braced	Qualified	P&L (1985)
	Primary pipework, shield & experimental circuits	Assessed to withstand 0.2 g		
	Pipelines between RCB and pumphouse	Replacement scheduled for 1995 MSD	Qualified when complete	CL 105933
	Secondary pipework inside RCB	Will withstand 0.2 g (P&L)	Qualified	P&L(1985)
	Pipework supports in D_2O plantroom	To be assessed for corrosion at 1995 MSD To be strengthened at 1995 MSD	Qualified when complete	TN 105408
	Cooling towers	New tower installation qualified by VIPAC, calcs reviewed by DHC	Qualified	Harris (1984)
	Pipework header to cooling towers, and pipes from towers to pond	Seismic design by Smith, Bateman and Associates (SBA). Checked by DHC	Qualified	SBA (1986)
RPS	CCA motion	Up to 0.2 g seismic forces are much smaller than forces due to drops in air	Qualified	P&L(1985) Nelmes (1986)
ECCS	Analysis of ECCS pipes, D_2O shutdown and scavenge pumps Malone and Lloyd have made 2nd and 3rd stage submission re scavenge pumps	ECCS pipes and D_2O shutdown pumps qualified by Peters and Ledwon Scavenge pumps seismically resistant	Qualified	P&L (1985) Malone and Lloyd (1995)

Table 1 List of studies of modifications to HIFAR

Item	Study or modification	Comments	Status	Reference
EPSS	B70 structure designed to 0.2 g seismic specification		Qualified	Barton and Patterson (1983)
	B70 electrical equipment qualified to 0.23 g	All equipment concerned with ESPs and operator monitoring	Qualified	Lloyd (1986)
SCS	APR control cubicles	Qualified to 0.23 g	Qualified	TN 105400
	Motor compressor sets		Qualified	TN 105343
	Heat exchangers		Qualified	CL 104585
	Chilled water pump sets		Qualified	TN 104854
	APR pipe work	Currently being assessed		
RCB	Finite element study of RCB/reactor block/D_2O plant room/airlocks	No increase in leakage <0.154 g, leakage very unlikely to increase at 0.2 g, leakage limited to thermally limited value <0.38 g	Qualified	SM&D (1992) SM&D (1995)
Ventilation	Water seals on normal system	Qualified to 0.2 g	Qualified	CL 41632
	Water seals on active system	Qualified to 0.2 g	Qualified	CL 41743
	Interior ductwork and butterfly valves	Qualified to 0.2 g	Qualified	CL 41744
B42	Strengthened to withstand PHGA of 0.23 g in longitudinal direction	Work undertaken to GH&D design (1990)	Qualified	TN 104395
B40	Strengthened to withstand PHGA of 0.23 g in both horizontal directions	Work undertaken to GH&D design (1991-4)	Qualified	TN 104399 Addendum B
D_2O Plant Room	Analysis of responses of D_2O Plant Room to PHGA up to 0.31 g	Will not be significantly damaged <025 g	Qualified	SM&D (1995)
EAL	Analysis of responses of EAL up to 0.25 g	Closure of inner door and opening of outer door unaffected <0.2 g event	Qualified	SM&D (1995)
VAL	Assessed by P&L to 0.2 g	Collapse can be excluded	Qualified	P&L (1985)

Table 1 List of studies of modifications to HIFAR

Item	Study or modification	Comments	Status	Reference
B42 PAL	PAL/B42 link structure analysed	Isolated from movement of B42, will not damage RCB, minor modification due	Qualified	TN 104351 TN 105497
B40 PAL			Qualified	P&L (1985)
No 1 Storage Block	Storage block tank replaced by double walled vessel	Replacement vessel seismically qualified to 0.23 g	Qualified	Allen (1984)
Silicon rig platform	Designed and constructed to be seismically resistant to 0.23 g	Structure and seismic calculations done by GH&D and reviewed by ACS (90/5017/1 and 90/5028/1,2)	Qualified	SM&D (1995) GH&D (No date)

Note: References commencing CL or TN are to documents held by Engineering Records and Information System (ERIS), part of ANSTO Engineering Program's quality system. References commencing P&L denote Peters and Ledwon; SB&A denotes Smith Bateman and Associates; all other documents are as listed in the references.

Model	Particular features	Yield location	Onset of yield at PHGA (g)	SM&D reference
Attached	No 1 SB attached to operating floor, D_2O Plant Room top attached to reactor block	Bolts attaching No 1 SB to operating floor opposite VAL	0.13	1992
Detached	No 1 SB detached from operating floor, D_2O Plant Room roof detached from reactor block	Hold down bolt cluster opposite No 1 SB	0.164	1992
Disconnected No 1	As detached model, but improved modelling of D_2O Plant Room, and modelling of silicon rig equipment and bridging structure from reactor top to control room roof	Hold down bolt cluster opposite No 1 SB	0.154	1995
Disconnected No 2	As disconnected model No 1, but with the exciting signals rotated by 90°	Hold down bolt cluster opposite No 1 SB	0.156	1995
Disconnected No 3	As disconnected model No 2, but additionally incorporating the Emergency Air Lock	Not applicable	0.2	1995
Connected	As disconnected model No 2 except for rigid connection between D_2O Plant Room roof and base of reactor block	Hold down bolt cluster opposite No 1 SB	0.306	1995

Notes
a) Details of these studies are given, as specified, in either SM&D (1992) or SM&D (1995).
b) All studies used the same model except for the changes noted under Particular Features. The estimates for onset of yield were obtained using the Carbon Canyon abutment accelerograms provided by Somerville (1992).
c) The quoted values of Onset of Yield are based on the scaling used in SM&D (1995). See footnote on page 7 for a discussion.

Table 2 **Finite element studies undertaken by Structural Mechanics and Dynamics (SM&D)**

Pasquill stability class	Maximum wind speed m s^{-1}		
	In free air	Through small, shallow circular hole	Through crack 1 mm wide, 1 m long
F	2	0.61	0.126
G	1	0.27	0.025

Notes:

1. These data were provided by Beattie (1995)
2. The calculations assume that the depth of the crack to be 21 mm, the thickness of the HIFAR RCB wall

Table 3 Wind speed through cracks and holes

Case No.	Source term	Atmos -pheric dispersion	Estimated dose (mSv)					ICRP 60 risk	Likelihood that individual receives this dose (per year)		Individual risk (per year)	
			By inhalation			External whole body	Effective					
			Child thyroid	Lung	Marrow				Median	Upper bound	Median	Upper bound
47	M	U	15	0.48	0.0002	2.8	3.6	1.8E-4	2.7E-6	6.4E-6	4.9E-10	1.1E-9
48	M	M	3.4	.18	0.00005	1.07	1.3	6.3E-5	2.7E-6	6.4E-6	1.7E-10	4.0E-10
49	U	U	45.1	0.58	0.0006	2.8	5.1	2.6E-4	2.7E-6	6.4E-6	6.9E-10	1.7E-9
50	U	M	10.4	0.29	0.0002	1.1	1.6	8.0E-5	2.7E-6	6.4E-6	2.2E-10	5.1E-10
Total risk to worst placed individual (sum of above)											1.6E-9	3.7E-9

Notes:

1. The case numbers and source and atmospheric dispersion codes are as shown in Figure 5.
2. The child thyroid dose was estimated to be 1.92 times the adult thyroid dose (Petersen 1985).
3. The effective dose (E) has been calculated by summing the weighted doses(H_t) to a range of tissues and organs (i). The method follows ICRP (1990):

$$E = H_{ext} + H_{int} = H_{ext} + \sum_i W_i . H_i$$

where H_{ext} = body dose due to cloud shine. The weighting factors W_i are (child) thyroid - 0.05, lung - 0.12, marrow - 0.12.

4. The ICRP (1990) risk coefficient is 5 per 100 Sv effective dose
5. The estimated doses are what would be received by the worst placed individual on the 1.6 km site boundary, given that s/he remained in the open for a period of 10 days after the event

Table 4 **Doses and risks to worst placed individuals at the 1.6 km site boundary**

Individuals	Annual risk
Hospitals, schools, child care facilities, and old age housing	0.5×10^{-6}
Residential developments and places of continuous occupancy such as hotels and tourist resorts	1×10^{-6}
Commercial developments, including offices, warehouses, restaurants and entertainments centres	5×10^{-6}
Sporting complexes and active open space areas	10×10^{-6}
Industrial sites, within the boundary	50×10^{-6}

Table 5 **Tolerable fatality risk to individuals in NSW**

Modified Mercalli intensity	Direct effects on members of the public	PHGA range (g)	Expected return period (y)	Effect on HIFAR
5	Felt by most people. A few people frightened. Some breakage of crockery and glassware and toppling of unstable objects	0.01-0.02	5	None
6	Felt by all. People and animals alarmed. Some heavy objects including concrete roof tiles moved. Some instances of cracked plaster and slight damage to weak masonry	0.02-0.05	30	None
7	General alarm. Considerable damage to weak brittle construction, negligible damage to older and newer building of good design and construction	0.05-0.1	400	None
8	Alarm may approach panic. Heavy damage to weak brittle construction. Some damage to buildings of good design and construction but not specifically designed for earthquakes. Negligible damage to buildings designed for earthquake forces irrespective of age.	0.1-0.2	2,800	None
9	General panic. Conspicuous cracking of ground. Total collapse of weak brittle construction. Extensive damage to buildings not specifically designed for earthquakes. Some damage to older buildings designed for earthquakes. Negligible damage to modern earthquake resistant construction	0.2-0.25	17,000	Some damage to building structure but reactor core remains intact - no fission products released
		0.25-0.38	45,000	Primary circuit may fail. Effective dose at 1.6 km boundary <2 mSv, no more than the annual dose received from all other causes.

Table 6 Impact of seismic events on the community near Lucas Heights

Note: The relationship between Modified Mercalli Intensity and Peak Horizontal Ground Acceleration (PHGA) range has been taken from Walker (1995)

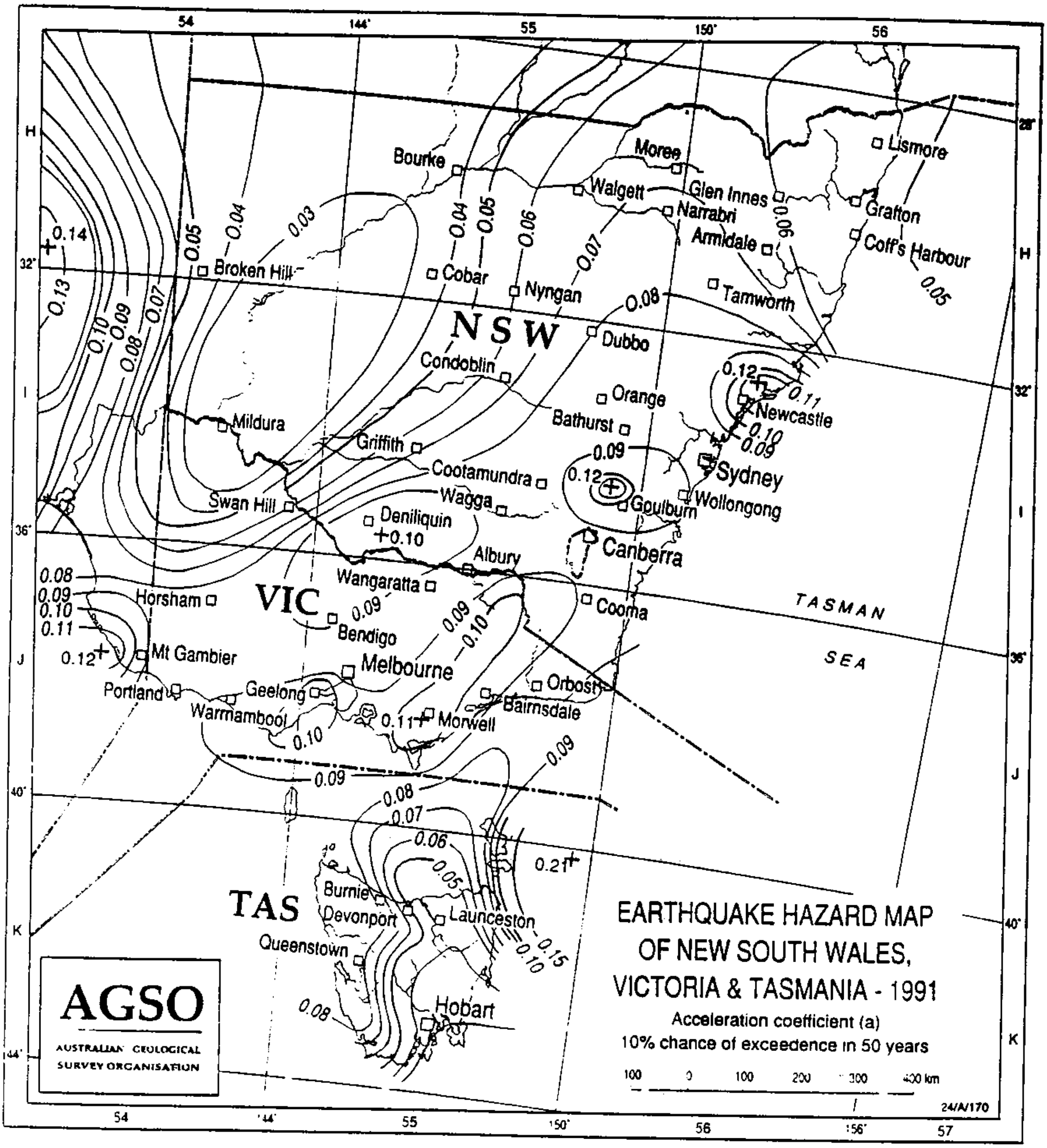


Figure 1 Acceleration coefficient map of New South Wales, Victoria and Tasmania. Source SAA (1993)

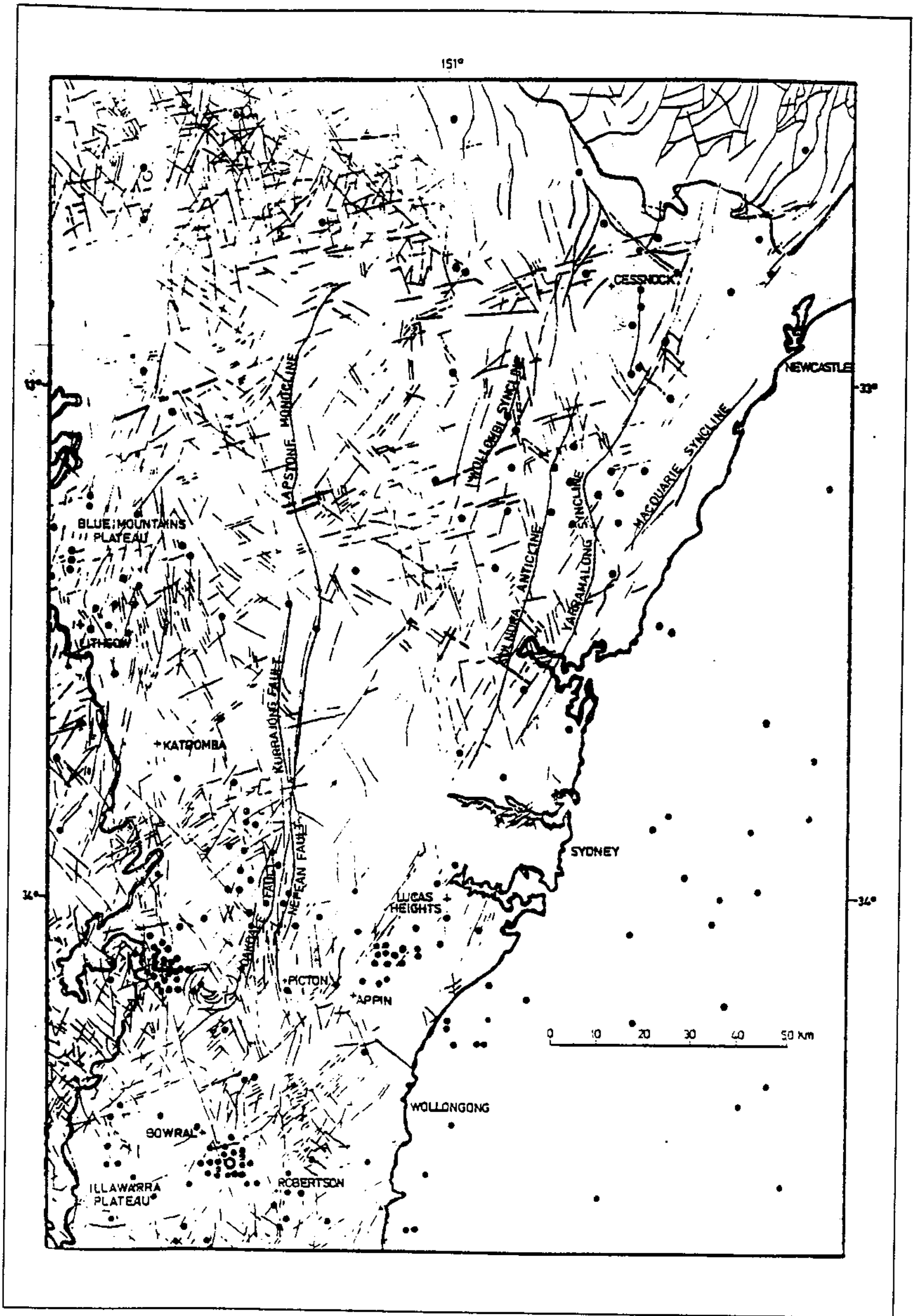


Figure 2 Lineaments and tremors related to structure in the Sydney Basin. Source DTC (1982)

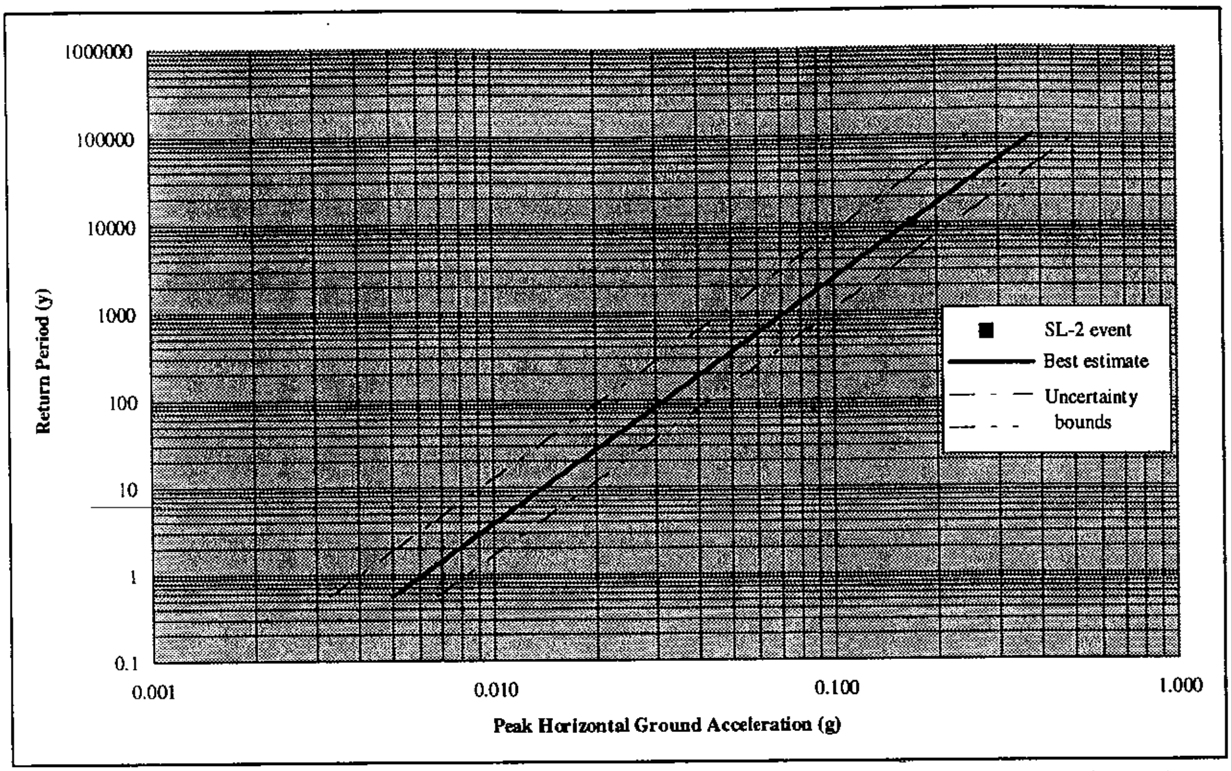


Figure 3 Return period of events in excess of specified Peak Horizontal Ground Acceleration at Lucas Heights

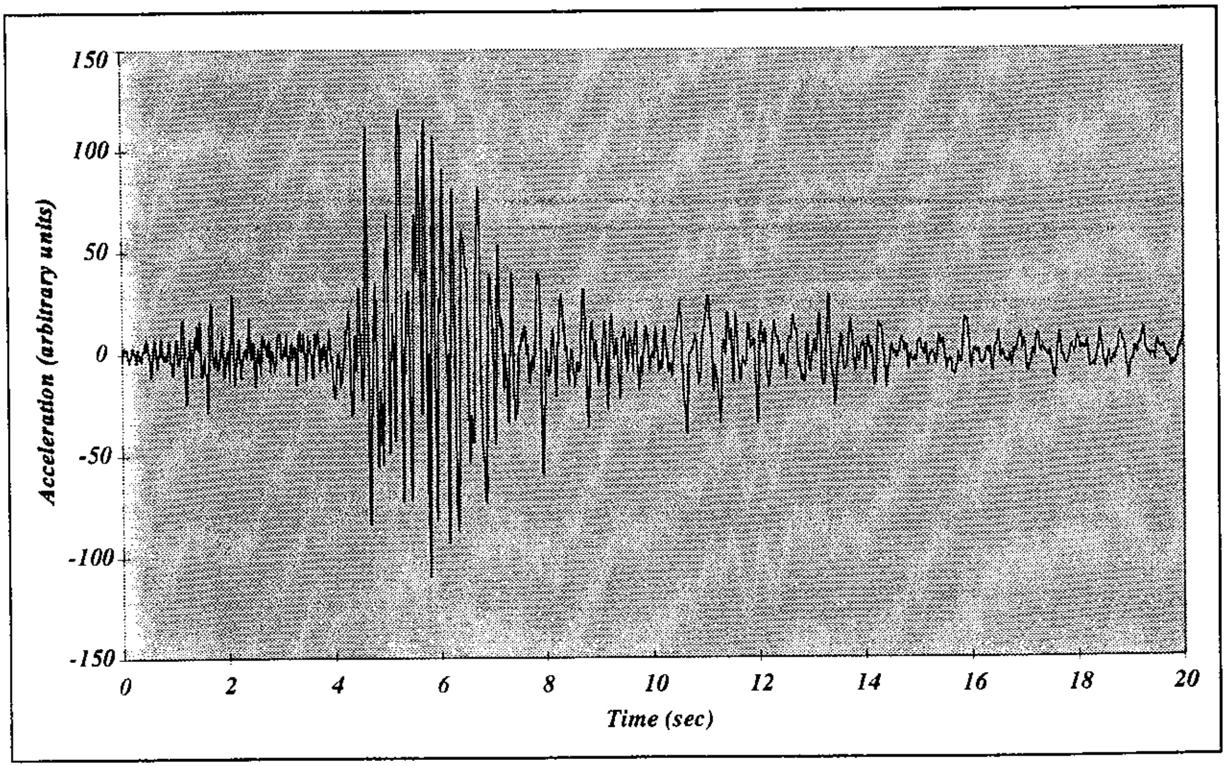
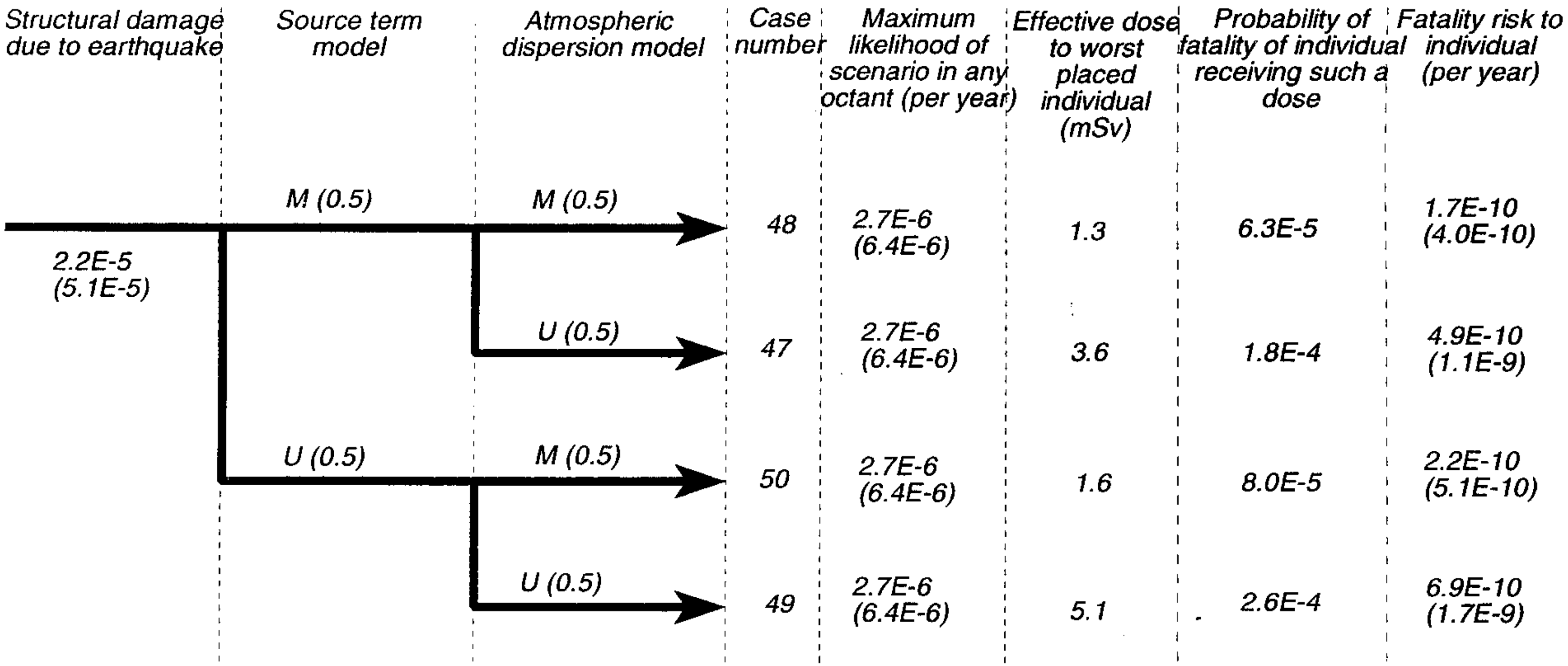


Figure 4 Example accelerogram (Carbon Canyon, 1 October 1987, Bearing 130°)



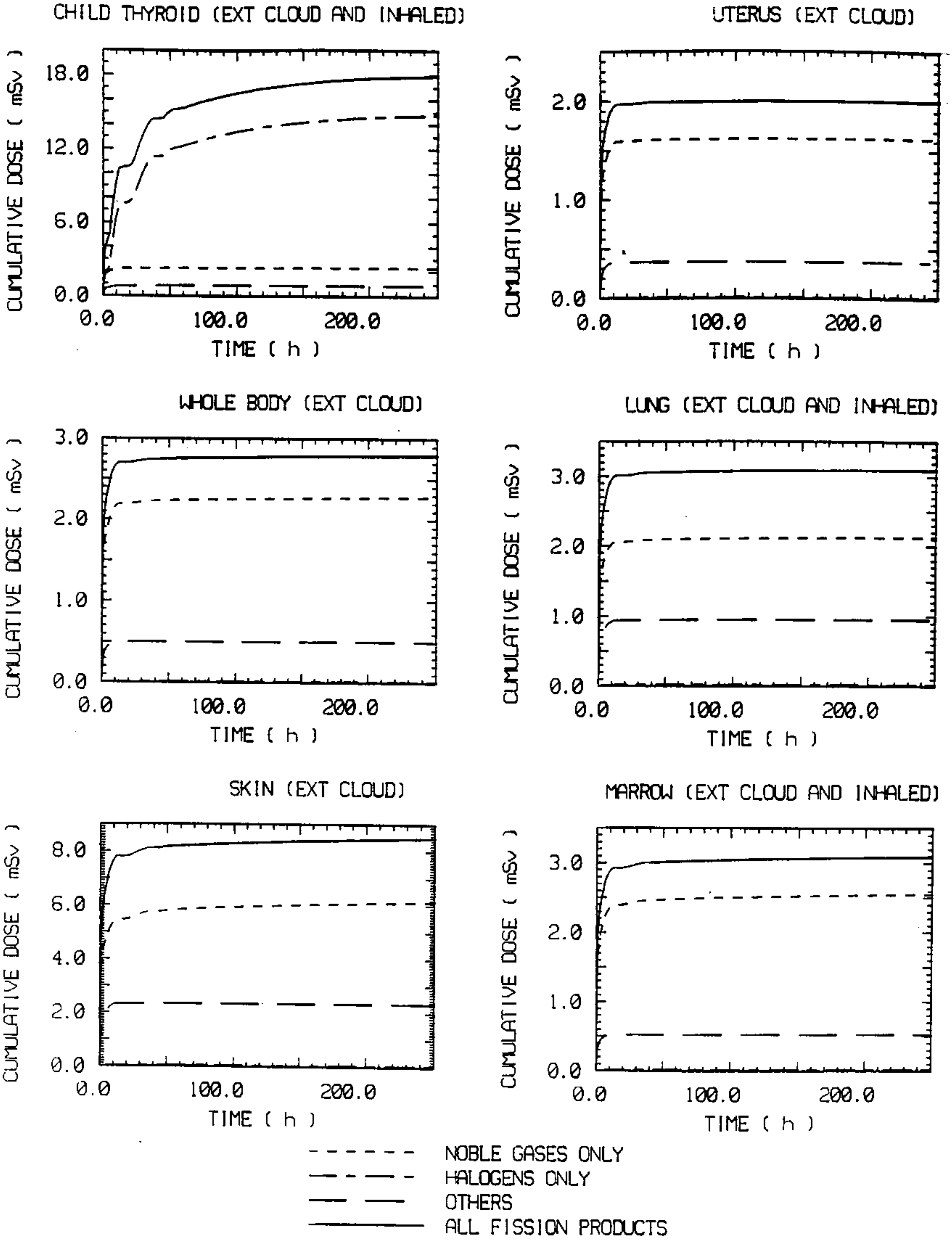
Notes:

1. *The likelihoods of events are shown as number pairs. The upper number is the best estimate and the lower (in brackets) the upper bound.*

2. *Events such as a particular source or atmospheric dispersion condition are characterised either by a median model (M) or an upper bound model (U). The conditional probabilities of these events are shown in brackets.*

3. *The probability of the plume lying in a particular octant is conservatively taken to be one half (0.5).*

Figure 5 Event tree showing estimated effects of significant seismic incidents on worst placed individual on 1.6 km site boundary


CHILD THYROID (EXT CLOUD AND INHALED)

UTERUS (EXT CLOUD)

WHOLE BODY (EXT CLOUD)

LUNG (EXT CLOUD AND INHALED)

SKIN (EXT CLOUD)

MARROW (EXT CLOUD AND INHALED)

Figure 6 Dose at 1.6 km, Case No 47

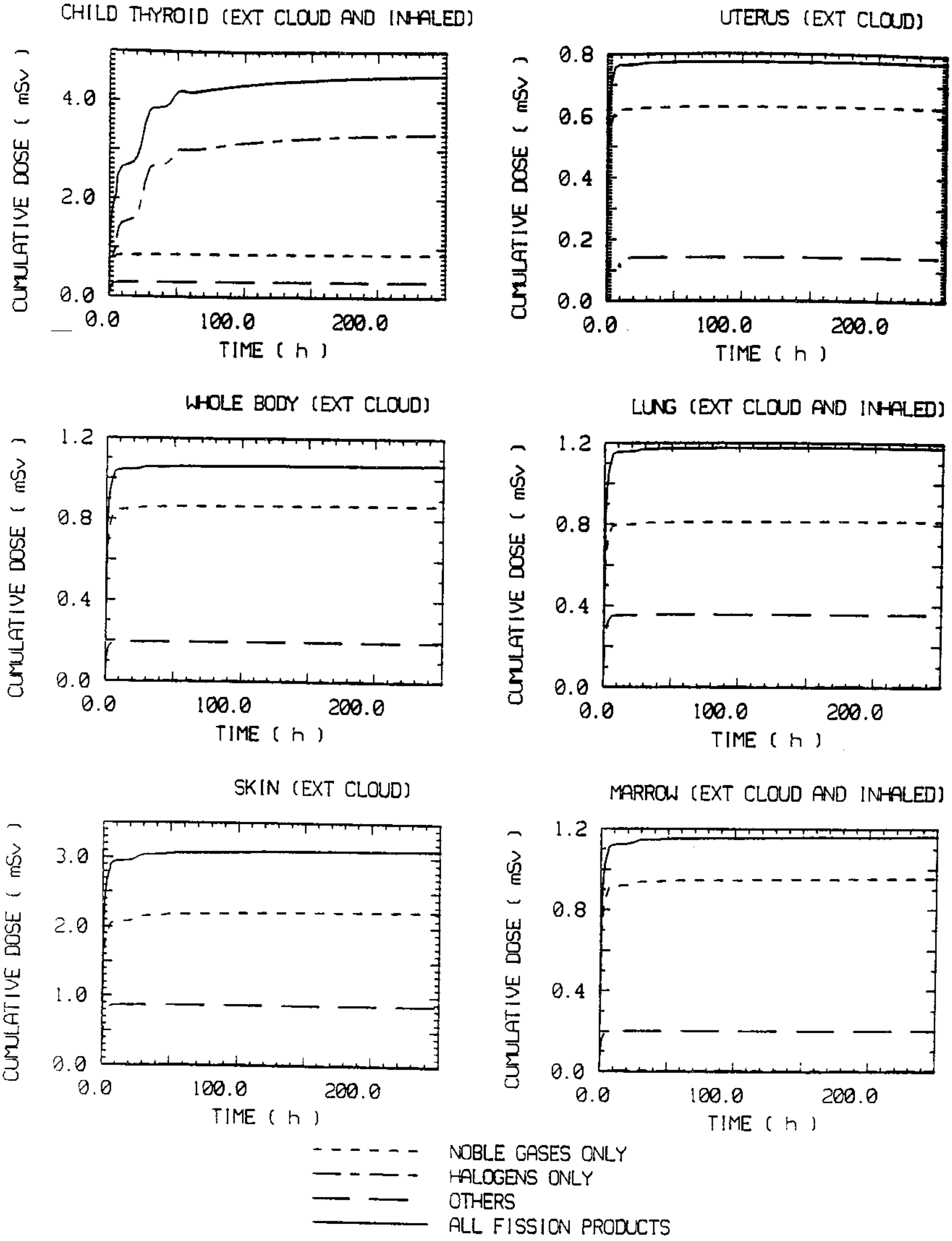


Figure 7 Dose at 1.6 km, Case No 48

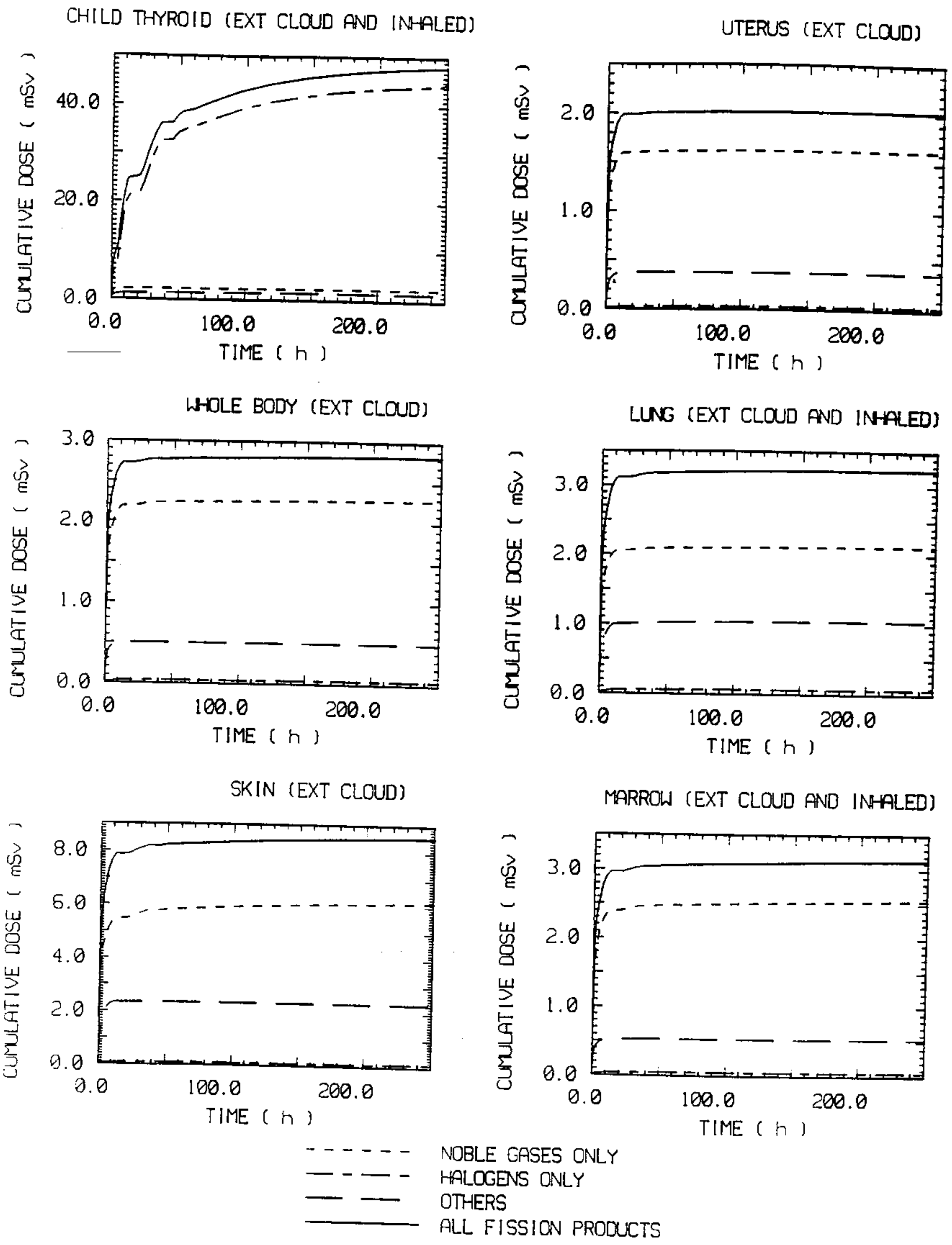


Figure 8 Dose at 1.6 km, Case No 49

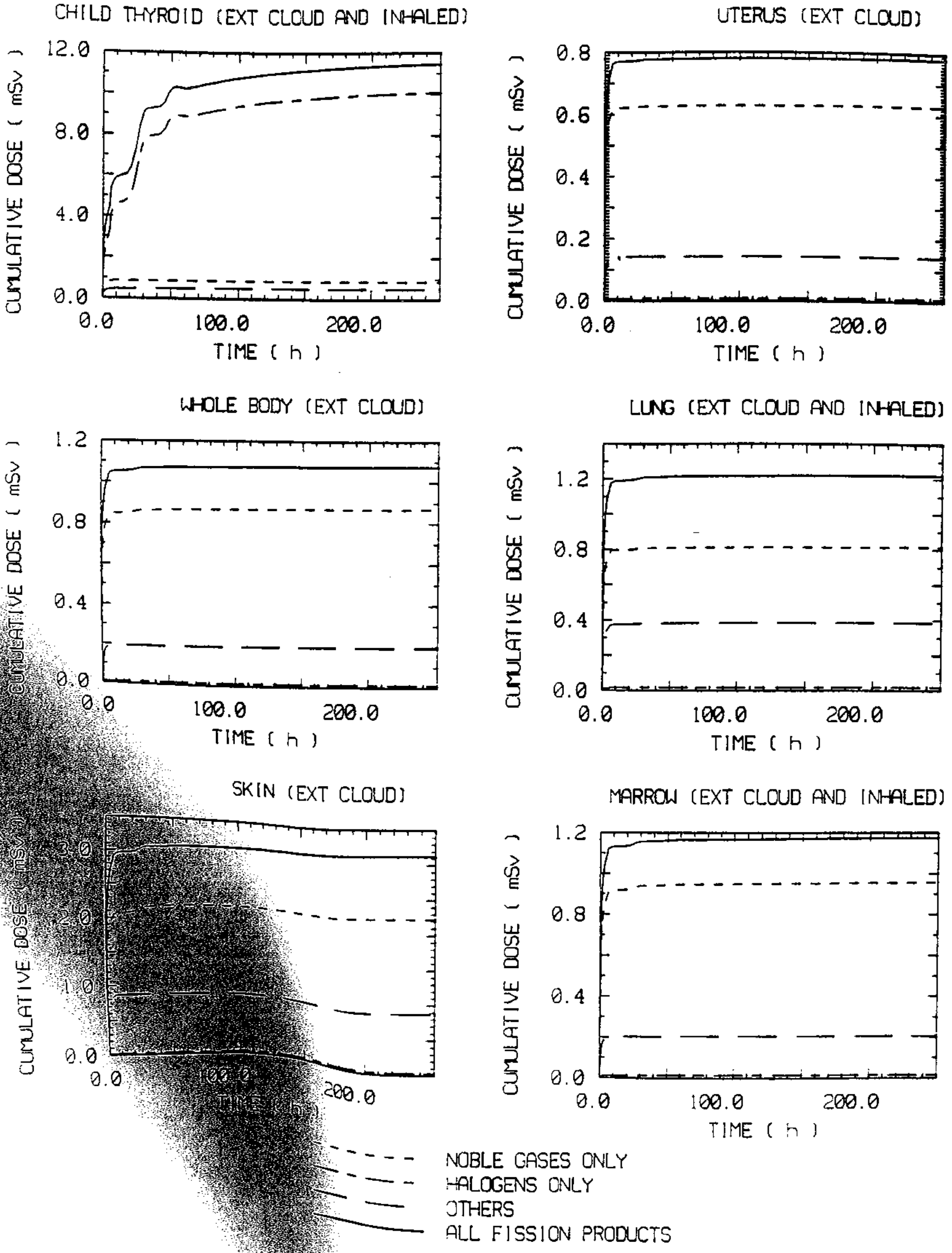
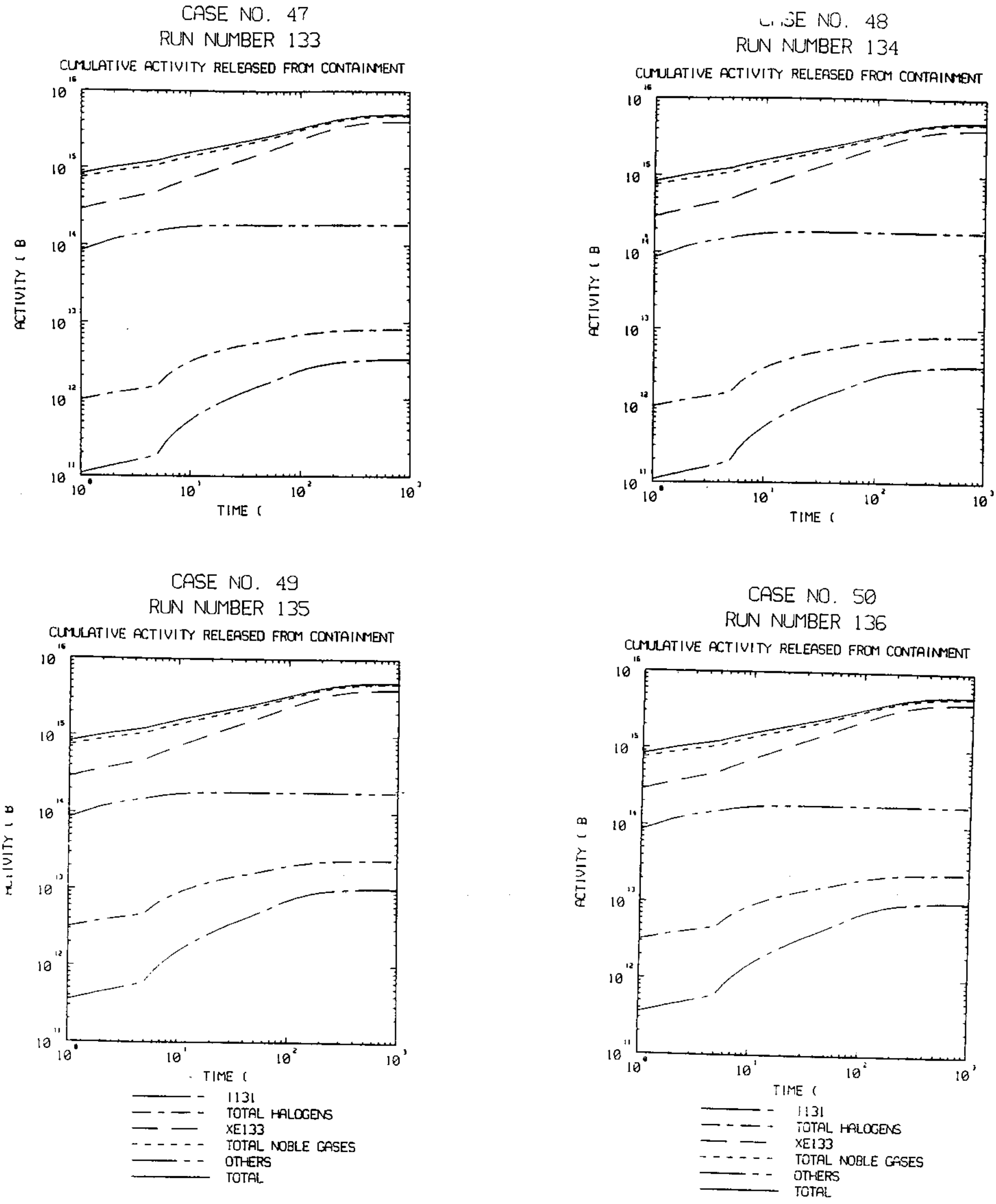


Figure 9 Dose at 1.6 km, Case No 50



CASE NO. 47
RUN NUMBER 133
CUMULATIVE ACTIVITY RELEASED FROM CONTAINMENT

CASE NO. 48
RUN NUMBER 134
CUMULATIVE ACTIVITY RELEASED FROM CONTAINMENT

CASE NO. 49
RUN NUMBER 135
CUMULATIVE ACTIVITY RELEASED FROM CONTAINMENT

CASE NO. 50
RUN NUMBER 136
CUMULATIVE ACTIVITY RELEASED FROM CONTAINMENT

Figure 10 Cumulative activity released from RCB. Cases 47-50

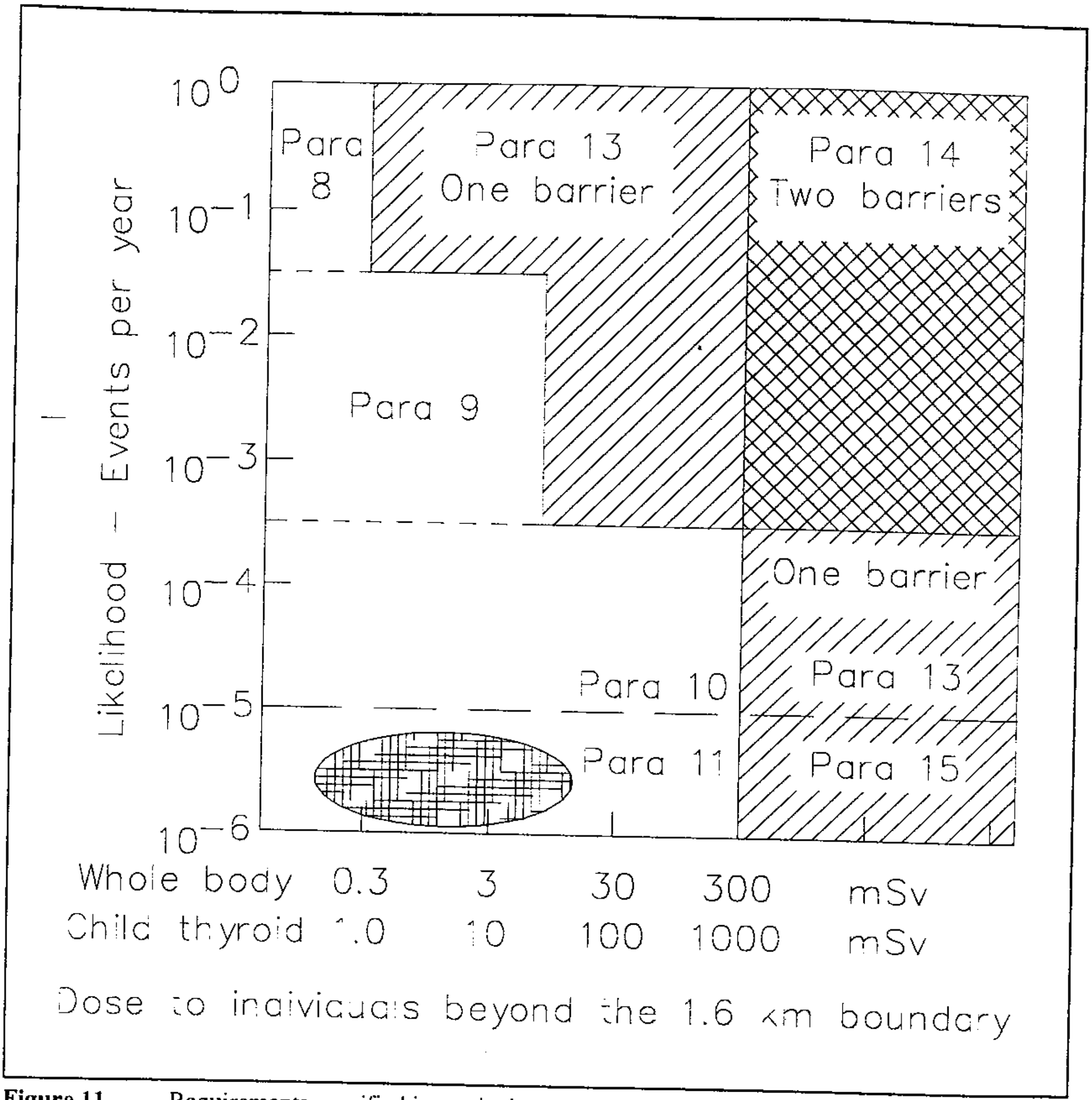


Figure 11 Requirements specified in particular paragraphs of REGBUR MEMO 1/82 relating to (i) minimum numbers of effective barriers given estimated likelihood and consequence of discrete fault sequences without benefit of barriers (the single and double hatched areas), (ii) maximum tolerable consequences given estimated likelihood of discrete fault sequences (the clear areas).

Note: The hatched ellipse shows estimates of the likelihood and consequences of the discrete fault sequence (scenario) studied, *ie* how a seismic event in the range 0.25 to 0.38 g would affect a particular individual located in the open at the 1.6 km boundary in a particular octant.. The best estimate is located at the centre of the ellipse, the upper bound estimates of consequence and likelihood are at the boundary. The consequence shown is the child thyroid dose of the worst placed individual, which is the dominant effect. The data are taken from Table 4 and Figure 5.