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**SOURCE TERM & BEHAVIOURAL PARAMETERS
FOR THE HIFAR LOSS OF COOLANT ACCIDENT**

by

F. G. MAY

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FOR A POSTULATED HIFAR LOSS-OF-COOLANT ACCIDENT

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ABSTRACT

The fraction of the fission product inventory which might be released into the atmosphere of the HIFAR reactor containment building (RCB) during a postulated loss-of-coolant accident (LOCA) has been evaluated as a function of time, for each classification of airborne radioactivity. This appraisal will be used as the source term for a computer program, which uses realistic attenuation of the fission product aerosol in a single compartment model with a defined leakrate to predict possible radioactive releases into the environment in a hypothetical bounding case reactor accident which is rather more severe in all major aspects than any single LOCA. Also given are the parameters governing the attenuation of the aerosol and vapours in the atmosphere of the RCB so that their behaviour may be accurately modelled. The source terms for several other types of accident involving the meltdown of fuel elements have also been considered but in less detail than the LOCA case. In some of the cases, the fission products are released directly to atmosphere, so there is no attenuation of the release by deposition within the RCB.

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GLOSSARY

CR-3	Accident at the Crystal River No. 3 reactor
DPR	D ₂ O plant room, located beneath the reactor and containing the external portions of the PCC
ECCS	Emergency core cooling system
HIFAR	High flux Australian reactor
L/U flask	Load/unload flask
ST flask	Shear and transport flask
LOCA	Loss-of-coolant-accident
MPE	Most probable estimate
PCC	Primary coolant circuit
PRTR	Plutonium recycle test reactor
<hr/>	
RAT	Reactor aluminium tank
RCB	Reactor containment building
ST flask	Shear and transport flask
TMI-2	The LOCA at Three Mile Island No. 2 reactor
UBE	Upper bounding estimate (usually 90 percentile)
90% CF	90% confidence factor, <u>i.e.</u> the factor by which the MPE must be multiplied to obtain the 90 percentile UBE.

1. INTRODUCTION

The consequences of a loss-of-coolant accident (LOCA) to the AAEC's 10 MW DIDO class reactor HIFAR have been assessed by using realistic fission product behaviour modelling to study a bounding case LOCA model, which is a composite of the least favourable features of several types of LOCA. By incorporating the worst features of each mode of failure, the modelling of the accident can be shown to be conservative.

In the past, when evaluating radiation exposure to individuals following a hypothetical reactor accident, it was usual to choose conservative values for all the source term and behavioural parameters, on the grounds that these values represented worst possible cases. Unfortunately, although it could be argued that ~~the values of individual parameters were reasonably chosen (say one chance in 2000~~ that the parameter would in practice be as bad as the one employed) the cumulative odds escalated astronomically when several of these worst possible cases were combined as, for example, the source term, the fission product behaviour in each compartment of the containment, and the meteorological conditions. Moreover, the problem was intensified by a tendency to choose crude and pessimistic accident models and ultra-conservative figures, whenever there was any doubt about the true range of the parameters.

The effect of this approach was to alarm the public with an unrealistic expectation of the hazards arising from nuclear reactors. By analogy, it was as if aviation safety were to be judged on the expectation that every flight emergency was likely to lead to the mid-air collision of two overcrowded jumbo jets, with the wreckage falling into a packed football stadium and a chemical factory, starting a release of toxic chemicals in a heavily populated area in adverse weather conditions.

A new approach was required to correct this situation. This would be done by employing more realistic accident scenarios combined with the most probable values of each parameter. The range of possible values for any parameter would be indicated by the use of a factor to multiply the most probable figure to give the 90 per cent upper bound, i.e. one chance in ten that the parameter would be worse than the one derived. This factor can be translated into an expected variance in the estimated parameter, assuming that the probability distribution is log-normal, so that when parameters are combined or modified, the variances may be summed. This permits a new factor to be calculated to keep the probabilities unchanged, or if required the variance may be used to calculate an entirely new factor for a different probability, say the 95 or 99 per cent upper bound.

1.1 Loss-of-Coolant Accident

Several LOCA sequences for HIFAR have been studied in detail by Connolly and Clancy [1985] with particular reference to the spatial distribution and time of melting of individual fuel tubes for different coolant leakrates. These analyses have been used in determining the probable maximum fission product releases for each accident sequence so that the bounding case model could be studied. Several out-of-core fuel-melting accidents were included in the study.

When modelling the fission product behaviour for the various accident scenarios, two values for each parameter would be employed. One set of parameters would be the most probable estimates and the other would be the 90 percentile upper or lower bounds, whichever was the most conservative. The final probability in this conservative case is difficult to predict, but it would be much less than one chance in ten. Using the 90 percentile estimates of four independent parameters of similar standard deviations, the resulting probability would be about one chance in 10 000. However, if the parameters are not truly independent, or not of equal weight, the probability is increased to some intermediate figure.

The predictions from this study on fission product releases and their subsequent behaviour are to be incorporated as the source terms and behaviour parameters in a computer program (AIRBORNE) to simulate the fission product behaviour in the reactor containment [Miller 1983]. A fission product inventory program (ICON) gives the total fission product inventory in HIFAR at any time before or after reactor shutdown for a typical irradiation history of a standard core [Fairclough and Hopper 1970]. The source term predicts the fraction of that inventory which would be released into the containment atmosphere at various times and the behaviour parameters permit AIRBORNE to predict how the fission product concentration in the containment atmosphere would vary with time. This allows the amount and type of radioactivity which may leak out of the reactor containment building (RCB) to be predicted for a variety of accident scenarios.

In addition, simplified versions of a number of other accident sequences involving the meltdown of irradiated fuel elements outside the reactor were considered and the source terms derived, so that the program AIRBORNE could be used to provide conservative estimates of the release to the environment. The accidents considered were the case of the dropped fuel element in the RCB, the case of drainage of coolant from the storage block in the RCB, and finally cases of damage to the shear and transport (ST) flask of varying degrees of severity on the roadway outside the RCB.

2. RELEASE FROM THE FUEL

Release of fission products from molten fuel depends, inter alia, on the vapour pressure and abundance of those chemical compounds which are able to form under the local conditions inside the metal fuel. Upon melting of highly-irradiated fuel, the considerable volume of both stable and radioactive fission gases, xenon and krypton, is almost completely released. This causes the liquid metal to foam, so increasing the surface area markedly and momentarily assisting the release of other volatile fission products, which approach saturation vapour pressure in the volume of liberated gas within the foam and are then sparged from the fuel as the foam collapses.

In the HIFAR LOCA, the flow of molten fuel down the fuel tube, under the influence of gravity, would collapse the foam immediately, expelling the fission gases and vapours while the molten fuel is still within the fuel element, so reducing the surface area of the liquid metal that further release of the volatile fission products would be inhibited. The drops of hot molten metal would slide rapidly around the wet surfaces of the primary coolant circuit (PCC) on a film of steam until they dropped into a pool of water, which in most accident sequences studied would still be inside the PCC. The metal drops would then solidify and the release of fission products would effectively cease.

An energetic metal-water reaction is considered to be extremely improbable in any HIFAR LOCA [Connolly 1983] and does not warrant consideration here.

Parker et al. [1967] measured the release of fission products from samples of irradiated uranium-aluminium alloy, similar to that of the HIFAR fuel element. The alloy was heated rapidly to temperatures between 700 and 1145°C and held at a constant temperature for either a two- or a sixty-minute period, in three different atmospheres - helium, air, or an 80:20 steam-air mixture. Heating was sufficiently brisk to reach the operating temperature before the foam began to collapse, and the two minute period appeared to be just long enough for most of the foam to disappear. The releases found in the sixty-minute period at high temperature were little larger than those observed in the two-minute period, indicating that the release occurred predominantly during the foaming of the metal.

Vapour pressure is normally a straight line on an Arrhenius plot, i.e. the vapour pressure is exponential when plotted against the reciprocal of the absolute temperature. Arrhenius plots of the fission product release fractions cannot be made directly owing to the cramping effect of the 100 per cent release boundary. However, by converting the release fraction into a release ratio ($f/(1-f)$), which compares the fraction (f) released to the fraction ($1-f$) remaining in the fuel after melting, the critical boundary disappears (since 100 per cent release

becomes an infinite release ratio) and an Arrhenius plot is then possible.

In this study, Arrhenius plots of Parker's data (listed in table 1) have been made by plotting the logarithm of the release ratio against the reciprocal of the absolute temperature for helium, steam-air and air atmospheres in figures 1, 2 and 3, respectively. The release ratios of the volatile fission products iodine, caesium, tellurium and ruthenium, at the melting point of the uranium-aluminium alloy (650°C) in each of the different atmospheres, were extrapolated from the lines of least squares fit, discarding the obvious points of error in figure 3. Linear regression analysis was also used to compute the variance in this extrapolation, in order to calculate the 90 per cent confidence factor (90% CF), i.e. the factor by which the most probable estimate (MPE) must be multiplied to obtain the 90 percentile upper bound estimate (UBE), which is greater than 90 per cent of all possible results (see appendix A). The dotted and dashed lines alongside each of the lines of least squares fit in figures 1, 2 and 3 show how the 90 percentile upper and lower bounds of the estimate vary for various interpolated and extrapolated values. The release ratios at 650°C and their 90% CFs for dry helium are listed in the first two columns of table 2.

The modifying effect of the moisture which would be present in the helium blanket in HIFAR (dew point 55°C \equiv 14.5% steam) was estimated, assuming an exponential response to changes in composition, by plotting the logarithm of the release ratios at 650°C against the atmospheric composition in figures 4a and 4b. An exponential model is considered to be the simplest one to describe the trend in the results but it is not the only possibility. Thus incorporation of this modifying effect slightly degrades the confidence in the result and thereby increases the 90% CF.

There would be a slight possibility, say one chance in 2000, that the modifying factor was unity, i.e. that no modification would be necessary to correct the trend in the experimental results. The curves corresponding to this 99.5 percentile upper bound are shown by the dashed lines in figures 4a and 4b. Assuming a log-normal probability distribution, the curves corresponding to the 90 percentile upper bound would be as shown by the dotted lines in these figures (see appendix A). The values for the modifying factor and its 90% CF are given in columns 3 and 4, respectively, of table 2. Note that this degradation in the confidence level is in addition to the statistical variance in the individual experimental points.

The modified release ratios for moist helium are given in column 5 of table 2, and column 6 gives the overall 90% CF, recalculated after summing the variances of the individual estimates (see appendix A).

The release ratios are then converted back into release fractions of the fission product inventory of the molten fuel. Column 7 gives the MPE of the fractional release and column 8 the UBE, i.e. the conversion of the product of the overall 90% CF and the MPE of the release ratio.

In addition to the fission products measured by Parker et al. [1967], table 2 includes the expected release fractions of several other fission products, estimated by comparison of their reported vapour pressures at 650°C with those of the more volatile fission products, which had been measured directly [Parker and Barton 1973]. A similar exercise was performed to calculate the fractional releases in an atmosphere of pure steam. The results are recorded in table 3. Table 4 gives the expected fractional releases at 650°C in air.

3. BEHAVIOUR IN THE PRIMARY COOLANT CIRCUIT

The noble gases would not deposit anywhere within the empty PCC although their daughters would. Under the reducing conditions inside the PCC during the LOCA, the volatile fission products would be released as CsI, CsOH and Te₂ compounds, which would only be volatile at the high temperatures adjacent to the overheated fuel. The more volatile elemental iodine, I₂, could not form within the PCC owing to lack of oxygen and the presence of a small amount of nascent hydrogen formed by reaction between the water vapour and the liquid metal.

The volume of fission product gas released from each molten fuel tube would be over a litre at 650°C; this is more than enough to fill the annular gaps separating each fuel tube from its neighbour (see figure 5).

The fission product gases and vapours, being much denser than either hot or cold helium, would flow down the fuel element, momentarily reversing the convective flow of helium rising up between the hot fuel tubes and returning down the cool outer jacket. This downward flow of fission gas would quickly transport the vapours into the cool region of the fuel element throat where almost all the condensable vapours would rapidly deposit on the cold outer casing.

The arrival of the noble gases in the larger volume of the throat could be expected to give rise to both diffusive and turbulent mixing. However, the resultant mixture would still be denser than the helium blanket and its downward progress would continue, but at a diminishing rate as mixing continued to reduce the density differences. Dilution of the noble gas with helium would rapidly reduce its density to below that of air, so that if any of the fission gases eventually sank to the level of the rupture, further progress would be halted until a flow of gas or steam provided the motive force to eject the fission products from the PCC.

Figures 6 and 7 are the results of experiments performed at the UK Atomic Energy Establishment, Winfrith [Clough 1983], which show, respectively, how caesium iodide vapour and tellurium vapour deposited when heated in a horizontal furnace tube in a stream of argon flowing at $200 \text{ cm}^3 \text{ min}^{-1}$. It can be seen that there was little if any escape from the furnace tube, even though the wall temperatures were higher than would be the case for the fuel assembly in the HIFAR LOCA. Convection currents within the horizontal furnace tube carried some of the vapour to the upstream side of the point of release in the caesium experiment, but this is not expected to occur in the HIFAR LOCA owing to the density difference of the gases involved and the vertical configuration of the assembly.

In the fuel assembly throat, the vapours would be supersaturated because the hot gases are cooled more rapidly by the adjacent cold surface than the vapours can be transported to the condensing surface. However, the degree of supersaturation appears unlikely to result, to any appreciable extent, in either homogeneous nucleation (*i.e.* bulk precipitation of the vapour) or heterogeneous nucleation on gas ions (*i.e.* cloud chamber effects). The critical supersaturation ratio for homogeneous nucleation of caesium iodide at the maximum concentrations in the LOCA conditions is estimated at about 9, by analogy with the work of Powell [1928] with water vapour at similar vapour pressures.

Heterogeneous nucleation on gas ions may occur at supersaturation ratios of about 4 [Wilson 1900]. Clough [1983] mentions no aerosol formation in the Winfrith experiments with either caesium iodide or tellurium in the furnace. Observations on the oxidation of sodium iodide heated in a stream of air were that no particulate aerosol was formed even though, at 700°C , 50 per cent of the sodium iodide evaporated from the furnace and condensed in the cooler regions of the tube, instead of being oxidised to elemental iodine. The composition of the vapours released in this manner was closely examined by a differential iodine sampler and any particulate aerosol would have been detected [May 1958].

However, the supersaturation of the vapour in the HIFAR fuel assembly would be such that some deposition of vapour could be expected on any condensation nuclei already present in the gas. Few nuclei are expected to be present in the helium blanket under normal conditions, but some may be created by the ruthenium that would be released in the LOCA [Parker *et al.* 1967]. It is considered that the release would be in the form of the only volatile oxide (RuO_4) which could provide a mechanism for the production of condensation nuclei, since the compound is considered to be unstable under the reducing conditions of a LOCA [USNRC 1981]. The decomposition products of ruthenium tetroxide would be far less volatile than the original compound, so their concentration in the gas phase may exceed the saturated vapour pressure by such a margin as to permit homogeneous nucleation to occur, even in the high temperature region adjacent to the overheated fuel. An aerosol could be expected to form spontaneously, by analogy with the formation of

a mixed chromium trioxide-sesquioxide aerosol from hot nichrome wire [Goldsmith and May 1966]. The other fission product vapours would condense on the ruthenium nuclei in the cooler regions of the fuel assembly, where they would compete with the walls as deposition sites.

The amount of volatile fission products remaining gasborne, due to the formation of this aerosol, is difficult to estimate. Fuchs and Sutugin [1966] reported that when their aerosol generator was operated under conditions optimised for the generation of the largest size of di-butyl phthalate droplets (i.e. relatively few condensation nuclei), only two per cent of the vapour was condensed on the nuclei, with 98 per cent on the walls of the generator. Consideration of the relative thermal conductivities of the carrier gas, the diffusivities of the vapours, ~~the physical dimensions of the diffusion paths and the differences~~ between condensation on solid particles and liquid droplets, suggests that a similar fraction of the vapour may remain gasborne in the HIFAR LOCA [Zettlemoyer 1969].

The fraction of the ruthenium tetroxide vapour dissociating to form the original condensation nuclei could be about 20 per cent with a 90% CF of 2.1, i.e. a maximum possible range of between four and 100 per cent. The fraction of all other fission product vapour becoming attached to this aerosol is estimated at two per cent, again with a 90% CF of 2.1, i.e. an order of magnitude down on the ruthenium (columns 1 and 2 of tables 5 and 6).

This is the most conservative model conceivable for the production of the fission product aerosol. However, if ruthenium tetroxide is not formed in helium, or is more stable than considered here, a lesser amount of aerosol would probably form due to homogeneous and heterogeneous nucleation.

Although gasborne for considerably longer than the fission product vapours, the aerosol would not persist in the gas phase indefinitely if it remains in the humid PCC. It would gradually be attenuated by droplet growth in the humid gas (the aerosol would be hygroscopic because of the caesium salts) and by thermophoresis and diffusiophoresis, i.e. movement of suspended particles down thermal and vapour gradients, respectively, by virtue of the imbalance in the transfer of energy and momentum (caused by the gradient) during collisions with the gas and vapour molecules.

The aerosol may be released into the D₂O plant room (DPR) without significant depletion, only if it is swept out of the PCC by the venting of the helium blanket through the break, but for this to happen the fuel must melt before the water level falls to the height of the break. This condition sets limits on the size and position of the leak; if the leakrate was greater than $\sim 50 \text{ L s}^{-1}$, the helium blanket would vent to atmosphere before any of the fuel had melted, no matter

where the break is located. At leakrates of about 15 to 20 L s⁻¹, depending upon position of the break, the helium blanket would vent in ~500 s, by which time ~20 per cent of the fuel would have melted. The maximum release of the aerosol would probably occur with a leakrate of about 10 L s⁻¹. According to the study by Connolly and Clancy [1985], conditions would have stabilised, with 26.7 per cent of the core having melted and flowed away, when the helium blanket vented at ~1000 s.

A large break in the PCC would give rise to rapid draining of the coolant and venting of the helium within ~30 s followed by ~90 s later by the start of fuel melting. About 50 per cent of the core would melt over the next ~400 s. If some of the noble gases and fission product aerosol sink to the level of the break, they may be expelled from the PCC when the helium expands as its average temperature rises. However, it seems unlikely that this fraction could be as high as 50 per cent of the release in view of the dilution with helium which must have taken place and the fact that pockets of noble gas must become trapped in unbroken parts of the lower pipework. Any particulate fission product aerosol remaining in the PCC would be severely depleted in the steadily increasing humidity, in the interval of about 100 minutes, before bulk boiling of the water trapped in the reactor aluminium tank (RAT), sweeps out the rest of the noble gases. Hence the initial release of fission product aerosol from a large break LOCA would probably be less than that from a small break LOCA, even though a greater fraction of the core would have melted.

When the heavy water trapped in the RAT had boiled away to a level below that of the fuel in the fuel assemblies, heat transfer would no longer be sufficient to prevent melting of the remaining fuel. Thus there would be a second release of fission gases and volatile fission products late in the LOCA in an atmosphere of flowing steam. Most of the condensable vapours would deposit in the cooler regions of the reactor pipework, the temperature of which would be about 100°C. However, an aerosol would probably again form and although there would be some attenuation of the aerosol by condensing steam [Goldsmith and Stinchcombe 1963], most of it could be swept into the DPR. The earliest that this second release could occur has been estimated to be five hours after a LOCA commenced, but the actual time is very dependent upon the rate of leakage of the trapped water past the fuel element nozzles and could be much later [Petersen 1985].

The water draining from the leak in the PCC into the DPR would become contaminated with deposited fission products, especially with the very soluble and hygroscopic caesium iodide. The time of arrival and subsequent increase in the specific activity of the contaminated water is difficult to predict and would be very dependent on the precise accident scenario under investigation. In many cases, much of the deposited activity would remain on dry surfaces within the PCC.

To provide the most pessimistic mechanism for transfer of deposited fission products from the PCC to the DPR, it is assumed that there could be a delayed start of the emergency core cooling system (ECCS). A failure or delayed start of the ECCS is a necessary feature of the accident scenarios under investigation, since if the ECCS starts up when required there will be no LOCA, or at least only a minor one involving slight damage to the core.

4. BOUNDING CASE SCENARIO AND SOURCE TERM FOR HIFAR LOCAs

Since it is not practicable to examine every possible LOCA scenario in detail, a bounding case LOCA model was provided by combining some least favourable features of several different scenarios, even when they were mutually exclusive; thus the consequences evaluated for the bounding case exceed those for the range of credible LOCA sequences.

The source term for the bounding case LOCA is based on an initial noble gas and particulate aerosol release 1000 s after the reactor trips because of low coolant level, with a similar release five hours later when second-stage melting is assumed to occur. There is also a gradual emanation of volatile iodine vapours from the contaminated water in the DPR, peaking after 3.5 days, as discussed in section 5.1 .

4.1 Initial Release

The noble gas is assumed to be almost completely released from 50 per cent of the fuel, corresponding to a large leakrate LOCA. Aerosol production is from the volatile fission products released into moist helium at 650°C from 27 per cent of the fuel, corresponding to a LOCA with an initial leakrate of 10 L s^{-1} , since this is the least favourable aerosol situation. Both noble gases and aerosol are assumed to be swept into the DPR at 1000 s, without further delay or attenuation, by the depressurisation of the helium blanket, which also corresponds to a leakrate of about 10 L s^{-1} (see table 5).

4.2 Second Release

The second fuel melt is assumed to occur five hours after the first, which corresponds to a LOCA with a high rate of leakage of trapped coolant from the RAT past the fuel element nozzles. Noble gas release at this time is from the remaining 50 per cent of the fuel, whereas the fission product aerosol is generated from the volatile fission products released into steam at 650°C, from 73 per cent of the fuel, namely the fraction remaining in a LOCA, with a leakrate of 10 L s^{-1} . Noble gases and aerosol are assumed to be swept into the DPR at this time without attenuation by the flow of steam from the RAT (see table 6).

4.3 Volatile Iodine Release from Contaminated Water

The bounding case scenario assumes a fault in the ECCS, so its start is delayed until after the initial fuel melt, which is assumed here to be 50 per cent of the core. All of the deposited activity is assumed to be washed from the surfaces of the PCC and become uniformly mixed with the total volume of coolant (9000 L) as it is re-circulated from the DPR sump to the PCC and back through the leak. Time zero for the start of the ECCS is assumed to be 1000 s after the reactor trips. This would appear to be the worst case in regard to both the specific activity of the contaminated water and its early arrival in the DPR of any of the possible LOCA scenarios, and hence fits the criteria of the bounding case.

5. BEHAVIOUR IN THE D₂O PLANT ROOM

Previous HIFAR LOCA studies [AAEC 1972] had pessimistically assumed that some of the volatile but non-gaseous fission products would be released as vapour from the PCC into the DPR. This is now considered to be impossible under the cool reducing conditions which would prevail within the PCC. The main transfer mechanism for non-gaseous fission products would be the flow of contaminated water; the subsidiary mechanisms being expansion of the helium, steam generation, and possible late venting of the helium circuit. All of these would carry some of the particulate fission product aerosol along with the main activity (the noble gases) into the DPR atmosphere.

Some accident sequences call for a major fracture of the pipework with sideways displacement of the broken ends. In this case, the molten fuel would drop into the water in the DPR sump which, at first sight, appears to provide a major alternative transport mechanism for fission products into the outer containment. However, the release of volatile fission product vapours directly into the DPR atmosphere from the drops of molten metal would be negligible, since the drops would be exposed at most for only a few seconds before they solidified, and all the noble gases would have already gone. Hardly any of the fuel would remain out of the water-filled sump since the molten fuel would slide around any wet horizontal surface, such as the tops of the heat exchangers, on a film of steam until it fell off the edge. The submerged fuel would solidify within a few seconds [Connolly and Clancy 1985], thus trapping the remaining fission products. Leaching of the fission products from the solidified granules of fuel by the water would be extremely slow. It is considered that any fuel remaining on dry horizontal surfaces would solidify even more rapidly since it would be in the form of small spattered drops and would be in good thermal contact with the cool metal surfaces [Connolly and Clancy 1985].

Bulk boiling of the water in the sump covering the reactor core would not occur because of the many paths by which heat can be lost from the sump. [Marshall and Rodd 1984]. Since no bubbles would be bursting at the water surface, there would be no aerosol production from the satellite drops to carry away contaminated water. With the exception of iodine, all of the fission products in the contaminated water would be involatile and so would be retained by the pool of water.

5.1 Iodine

Iodine initially would be in the form of the involatile iodide ion (because of the reducing conditions inside the PCC) but would be slowly oxidised to other chemical forms on coming into contact with the air [USNRC 1981]. One of the forms would be elemental iodine, I_2 , some of which would escape into the DPR atmosphere, even though the partition coefficient would favour retention of most of the elemental iodine in solution. Further slow oxidation of the dissolved iodine would convert it into the involatile iodate ion. Thus the concentration of iodine in the air over the contaminated water would slowly increase, peaking after about three to four days and then declining.

Figure 8 shows how the concentration of iodine-131 and xenon-133 in the Crystal River (CR-3) containment atmosphere varied after an incident in which 160 000 L of contaminated primary cooling water was accidentally discharged onto the floor of the isolated containment building [Morewitz 1981]. Ratios of the concentration of iodine in air to that in water varied from an initial value of about 10^{-6} : 1 to a peak value of 10^{-4} : 1 before declining.

An unknown volatile inorganic compound, traditionally known as Compound X, would be liberated along with the elemental iodine vapour. It is not certain whether Compound X is created in the gas, liquid or adsorbed phase, but it appears to be generated in about equal quantities with the elemental iodine vapour whenever the latter is released at low mass concentrations [May 1959]. For a time, Compound X was thought to be HOI vapour [Barry 1961; Kabat 1974] but there now appears to be considerable doubt about this identification, as the latest experimental evidence, although confirming the existence of the unknown vapour, suggests that HOI is involatile [Wilhelm 1983; Cox 1983]. Compound X can be differentiated from other volatile iodine species by its behaviour in a differential iodine sampler (the May pack). It is important that it be included in the modelling of the iodine behaviour in the reactor containment, since it has a significantly lower deposition rate than elemental iodine vapour.

The USNRC [1981] indicated that the final gaseous inorganic iodine concentration, in equilibrium with contaminated water at an iodine concentration of 10^{-6} mol L⁻¹ and a pH of 7, would be 10^{-12} mol L⁻¹ of air, i.e. a ratio of

10^{-6} : 1. In the present study, this is assumed to be equally divided between the two forms, elemental and Compound X.

The most volatile forms of radioiodine are the organic iodides, of which the most abundant is methyl iodide, CH_3I . The precise reaction by which this compound is formed is uncertain, as thermodynamic data suggest that methyl iodide is not a stable or favoured species and that if chemical equilibrium could be attained, the ratio of the concentrations of methyl iodide in air to total iodine in water would be of the order of 10^{-6} : 1. However, experimental studies almost invariably find much higher concentrations of methyl iodide than this value. To overcome this dilemma, it has been suggested that "the kinetics of non-equilibrium processes produce a quasi-equilibrium at a higher concentration" [USNRC 1981].

At Three Mile Island (TMI-2) a steady concentration of 10^{-11} moles of methyl iodide per litre of air was found in apparent equilibrium with water contaminated with iodine at 10^{-6} mol L^{-1} , i.e. a ratio of 10^{-5} : 1. Moreover, when the atmosphere in the containment was purged to remove the krypton-85, the concentration of methyl iodide, after an initial fall, recovered almost to its previous steady level, which suggests that some unidentified reaction was generating methyl iodide as rapidly as known reactions, such as hydrolysis, were destroying it [USNRC 1981]. The concentration of organic iodide observed at TMI-2 was much higher than the total airborne iodine concentration for the first thirty hours at CR-3.

Previous experimental work suggested that methyl iodide rapidly reached its equilibrium value, but these results had been obtained by releasing elemental iodine vapour directly into the containment. It would appear that less than 10 per cent of the organic iodide could have been formed by reaction in the aqueous phase at CR-3, the remainder being formed gradually by reaction with elemental iodine vapour, either in the gas or adsorbed phases, possibly being finally limited after two or three days by the availability of organic radicals.

The total mass of fission product iodine in the HIFAR reactor core after 100 days' irradiation is 9.4 g. The concentration of iodine in the contaminated water in the DPR during a HIFAR LOCA would be about 2×10^{-7} mol L^{-1} ; this is slightly less than the iodine concentration at TMI-2, but more than at CR-3.

Convection currents from the hot pipework cause both mixing of the air within the DPR and loss of air from the upper regions of the room to be replaced by cooler air drawn in around the doors. Measurement of the rate of influx by May and Petersen [1983] gave a value of 3.5 air-changes per hour of the 156 m^3 DPR during reactor shutdown. Under the hotter conditions occurring during a LOCA, this flow would be expected to increase to a maximum of five air-changes an hour,

or about 220 litres per second. An upper bound of 240 L s^{-1} has been selected as a conservative figure. However, the modelling of fission product behaviour in the LOCA is not very sensitive to the value selected for this parameter since it only controls the rate at which the iodine vapour concentration in the RCB approaches equilibrium rather than its absolute value. Moreover, the flow is bound to fall below the selected value in the later stages of the accident as the iodine approaches its peak volatility, so the value chosen is almost certainly very conservative.

6. D₂O PLANT ROOM MODELLING IN THE BOUNDING CASE

~~No credit for attenuation of aerosols or vapours in the DPR is given in the~~ modelling of the bounding case LOCA, and 'puff' releases of the noble gases and fission product aerosol directly into the RCB are assumed. The releases as fractions of the fission product inventory are given in tables 5 and 6.

This crude approach is conservative and implies an earlier contamination of the RCB than would actually occur. A partial correction for the delay that the presence of the DPR would cause would be to assume that the two releases were each emitted into the outer containment over a twelve-minute period instead of the instantaneous release adopted. More complete correction would call for the incorporation of an extra compartment in the mathematical modelling. This would permit the effects of variable airflow and the attenuation of the aerosol by the condensation of water vapour in the DPR to be studied.

Release of iodine vapours from the pool of contaminated water is modelled by the continuous injection of either 220 or 240 L s^{-1} of air at the appropriate iodine concentration, starting after a ten-minute delay. The concentration of iodine vapour in the outer containment approaches that of the DPR asymptotically, since the pool of contaminated water acts as a sink as well as a source of radioiodine vapour. Thus any iodine returning in the flow of well-mixed air from the outer containment to the DPR is removed from the modelling.

Release of the three forms of iodine vapour (I_2 , X and CH_3I) from the DPR into the outer containment is governed by the equation

$$R_{cit} = Q \left\{ \frac{F \cdot f}{V} \cdot A_{ct} \cdot B_{it} - \frac{1}{C} \cdot D_{cit} \right\} ,$$

where

R_{cit} is the rate of release into the containment of iodine compound c, isotope i, at time t, in atoms s^{-1} ;

- Q is the rate of airflow through the DPR, i.e. either 220 or 240 L s⁻¹;
- F is the maximum fraction of the core which is assumed to melt before the ECCS functions, i.e. 0.5;
- f is the fractional release of iodine from molten fuel in moist helium, taken from table 2, i.e. 0.0736 or 0.197;
- v is the volume of heavy water, i.e. 9000 L;
- C is the volume of the outer containment, i.e. 7 000 000 L;
- A_{ct} is the ratio of the iodine concentration of iodine compound c, at time t, to the aqueous concentration of total iodine, taken from figure 9;
- B_{it} is the number of atoms of iodine isotope i in the total fission product inventory at time t; and
- D_{cit} is the number of atoms of compound c, isotope i, still airborne in the outer containment at time t.

A 90% CF of 3 is considered the appropriate factor by which the most probable parameter A_{ct} is multiplied to obtain the 90 percentile conservative iodine release rate. This corresponds to one chance in 2000 that the iodine vapour releases from the contaminated water in the postulated HIFAR LOCA would differ from those observed at TMI-2 and CR-3 by more than a factor of ten.

7. FISSION PRODUCT BEHAVIOUR IN THE REACTOR CONTAINMENT BUILDING

The outer containment would provide the last barrier to the escape of the fission products in the LOCA. Since no containment is ever perfect, some of the radioactivity remaining airborne in the reactor containment building would leak into the atmosphere. However, the airborne activity would be attenuated in the containment by both radioactive decay and deposition of some of the vapours and the particulate aerosol. Leakage from the RCB would be caused initially by overpressurisation from the heat and steam liberated in the LOCA [Marshall and Rodd 1984] and later from changes in external atmospheric pressure [Miller 1984].

The noble gases, xenon and krypton, would not deposit in the RCB but their daughters would if they underwent decay within the containment. When the daughters are first formed, they are highly reactive chemically since they are single atoms of the alkali metals caesium or rubidium. They will deposit on the first solid or liquid surface they contact, whether it is a wall, a droplet or a condensation nucleus. It has been conservatively assumed that all of the noble gas daughters would become attached to the fission product aerosol.

The fission product aerosol would deposit slowly in the containment if the atmosphere was dry but more rapidly in humid conditions, especially if water was condensing in the space conditioners. In the LOCA, steam would be generated in the PCC and there would be significant condensation in the conditioners, even though much of the condensation early on would take place in the DPR.

Dry deposition of the aerosol is given in table 7. Column 2 gives the sedimentation velocity calculated by Schwendiman et al. [1963]. Linear regression analysis was used to calculate the turbulent diffusion deposition rate on vertical surfaces, given in column 4, from the work of Chamberlain [1962]. Column 3 gives the 90% CF calculated for each interpolated point of column 4 (see appendix A). Columns 5 and 6 give the estimated deposition rates on the floor (column 4 + column 2) and on the ceiling (column 4 - column 2), respectively. Column 7 gives the expected average deposition rate on all surfaces within the RCB assuming that the area of the walls is twice the area of the floor or ceiling. Column 9 gives the estimated overall 90% CF.

It can be seen that the minimum rate of deposition would occur with particles of diameter 0.4 μm , corresponding to an aerosol of considerable age. Initially, the fission product aerosol would be composed of smaller particles, but they would gradually grow to the equilibration size by agglomeration. It is conservatively assumed in the model that the aerosol would deposit at a constant rate of $9.0 \times 10^{-6} \text{ m s}^{-1}$, with a 90% CF of 1.3, even though it might take more than 24 hours for the deposition velocity to fall to this value. In an RCB with a total surface area of 3000 m^2 and a volume of 7000 m^3 , this would lead to an exponential decrease in the aerosol concentration with a deposition constant of 0.0139 h^{-1} , with a 90% CF of about 1.4.

In humid condensing conditions, the dry deposition rate would be enhanced by thermophoresis and diffusiphoresis plus, more importantly, droplet growth on the hygroscopic aerosol. These deposition mechanisms would be especially effective in the supersaturated region between the cooling coils of the space conditioners when condensation was occurring [Goldsmith and May 1966]. This was demonstrated in the PRTR accident [Perkins et al. 1965] where condensate from the conditioners had collected 100 times more particulate activity than the PRTR building surfaces. From the description given by Purcell [1966], the volume of the PRTR containment is estimated at 9300 m^3 with a surface area of 2420 m^2 , the wall area being about three times the floor and ceiling area. Column 8 of table 7 gives the estimated average deposition velocities in the PRTR containment. The minimum deposition velocity again occurs for a particle of 0.4 μm , which would give a conservative deposition constant of 0.00824 h^{-1} for dry conditions (90% CF = 1.4) and 0.824 h^{-1} for the condensing conditions of the PRTR accident (90% CF = 1.5).

For the HIFAR LOCA modelling, the deposition constant, α_t , for the particulate aerosol would have two components; one is for deposition in the condensate of the space conditioner and the other for deposition on the dry surfaces of the containment building:

$$\alpha_t = C_1 \cdot \Omega_t + C_2 \quad ,$$

where Ω_t is the rate of condensation of water vapour in the space conditioners at time t .

The constant, C_1 , was derived from the condensation rate in the PRTR accident of 680 kg h^{-1} and the estimate of α_t for the PRTR accident of 0.824 h^{-1} . The work of Goldsmith and Stinchcombe [1963] supports linking the two parameters together in this manner. A 90% CF of 1.6 is considered appropriate. The MPE of C_1 is 1.21×10^{-3} and C_2 is 0.0139. The conservative 90 percentile lower bound of C_1 is 7.56×10^{-4} and C_2 is 0.0099. Deposition of the aerosol in the DPR is ignored in the LOCA modelling, so these figures are considered to be very conservative.

Megaw and May [1962] released stable elemental iodine vapour, tagged with iodine-132, in amounts ranging from 0.1 to 100 mg, inside the RCBs of DIDO and PLUTO, reactors of the same class as HIFAR. They found that several volatile iodine compounds were rapidly formed, including Compound X and the compound known at that time as Compound Y and subsequently identified by Atkins and Eggleton [1963] as methyl iodide. The deposition behaviour in the dry containment was studied and deposition constants were measured for each recognisable iodine species.

Organic iodide remained airborne without significant deposition in the containment. Elemental iodine deposited from either a still or a stirred atmosphere with a half-life in the gas phase of about 20 minutes. There were no signs of saturation of the surfaces at the iodine concentrations employed. Compound X deposited with a half-life of 3.25 hours.

The maximum rate of release of iodine vapour from the pool of contaminated water in the HIFAR LOCA would be about 6 mg h^{-1} , which places it in the same range as the DIDO-PLUTO experiments. Total iodine contamination in the spilled coolant would be less than 700 mg which is only slightly higher than the experimental range.

Croft et al. [1963] performed tests with very high mass concentrations of elemental iodine vapour in a painted room of 30 m^3 volume, in both dry and fully saturated condensing conditions. They found little difference in deposition rates between wet and dry conditions. The surfaces of the room continued to adsorb iodine steadily, even though they had adsorbed the equivalent of 50 monolayers of

iodine. It would therefore appear reasonable to adopt the experimentally determined DIDO-PLUTO deposition constants for the HIFAR LOCA model. A 90% CF of 1.7 is considered appropriate for the iodine deposition constants.

8. BEHAVIOUR PARAMETERS FOR THE BOUNDING CASE MODEL

Table 8 gives the deposition constants used in the HIFAR bounding case model for each classification of fission product activity which is airborne in the RCB for both the MPE and the UBE cases.

Appendix B gives the MPE source term and appendix C gives the UBE source term for the HIFAR bounding case LOCA input to AIRBORNE [Miller 1983]. Figure 10 shows how AIRBORNE predicts that the concentration of the various species of airborne iodine-131 in the RCB would vary with time for the UBE case, both with and without the space conditioners, for a three per cent maximum daily leakrate from the RCB.

9. OUT-OF-CORE FUEL MELTING ACCIDENTS

Several accident sequences involving out-of-core fuel melting have been briefly analysed. These are described below.

9.1 The Dropped Fuel Element

A malfunction of the load/unload (L/U) flask is assumed to lead to the melting and refreezing of a single fuel element in the RCB. This would release the volatile and gaseous fission products directly into the dry RCB as a single 'puff' release in an oxidising atmosphere. Time zero would be at least 48 hours after reactor shutdown. A large proportion of the fission product vapours would deposit on cool surfaces, but some of the vapours would remain airborne by attachment to atmospheric condensation nuclei. This proportion is difficult to estimate precisely. It is conservatively estimated that it could vary from a low of two per cent for a fuel element melting inside the flask to a high of 50 per cent in the unlikely event that the fuel element was badly damaged, with the fuel tubes exposed and remote from the flask. Assuming a log-normal probability distribution, a median figure of 10 per cent has been selected for the analysis, with a 90% CF of 2.1.

About 75 per cent of the liberated iodine would be released as caesium iodide vapour owing to the abundance of caesium in the fuel element [USNRC 1981]. However, since the atmosphere is oxidising, the remainder would be released as either monatomic or elemental iodine vapour, which would be rapidly converted to a mixture of elemental iodine, organic iodide and Compound X vapours [May 1959].

Organic iodide would form rapidly by reaction of the elemental and monatomic iodine with trace organic vapours in the atmosphere. Consideration of the amounts of organic vapours likely to be present in the reactor containment atmosphere [Barnes *et al.* 1967] suggests that there would be sufficient to react with about 0.1 per cent of the total iodine in the fission product inventory of the complete core. This agrees with the amounts of organic iodide produced in the DIDO-PLUTO experiments [Megaw and May 1962]. The remaining iodine vapour is assumed to be equally divided between the elemental and the Compound X forms. A 90% CF of 2.1 is considered appropriate for all forms of iodine vapour.

It is conservatively assumed that out of the various forms of airborne iodine, only the caesium iodide vapour remaining unattached to condensation nuclei would be significantly depleted by deposition after escaping from the fuel element and the L/U flask. There would be a continuing slow oxidation of the deposited caesium iodide in air at ambient temperature, leading to a gradual emanation of both elemental iodine and Compound X. This has been simply modelled in the calculation by assuming that there would be minimum values, for both elemental iodine vapour and Compound X, below which the airborne concentration would not fall. From measurements of the oxidation of sodium iodide in air over the temperature range from 400 to 1200°C [May 1958] and the rates of deposition observed in the DIDO-PLUTO trials, conservative estimates of the fraction of elemental iodine which would be finally airborne at equilibrium are of the order of 10^{-10} of the total inventory of the core. Estimates of the minimum fraction of Compound X which remains airborne are an order of magnitude higher. A 90% CF of about 10 is considered appropriate.

Deposition constants in the outer containment would be similar to those adopted for the HIFAR bounding case LOCA, except for the dry atmosphere. Table 9 lists the estimated releases for a single element, expressed as fractions of the fission product inventory for the entire core. The deposition constants for each classification of the airborne fission products are given in table 8.

Appendix D gives the MPE source term and appendix E the UBE source term for the dropped fuel element case input to AIRBORNE [Miller 1983]. Figure 11 shows how AIRBORNE predicts that the concentration of the various species of airborne iodine-131 in the RCB would vary with time for the UBE case with a maximum leakrate of 1.4 per cent per day from the RCB owing to diurnal solar heating effects and barometric pressure variations.

9.2 Storage Block Coolant Drainage

During each monthly reactor shutdown, up to eight spent fuel elements are replaced by fresh ones. The transfer operations do not begin until 48 hours after the reactor has been shut down to allow the radioactive decay heating to fall to acceptable levels.

The fuel is transferred by the heavily shielded load/unload (L/U) flask to the water-cooled storage block where it remains within the reactor containment for a further cooling period of at least seven days. On some occasions, however, spent fuel may remain in the storage block for longer periods, say up to two months.

The fuel elements are transferred, using the L/U flask, to the shear and transport (ST) flask, where they are sheared to remove the shield plugs. They are then transferred in the ST flask, four elements at a time, to the cropping pond outside the reactor containment.

For loss of storage block cooling water to occur, the tank must be breached and allowed to drain. This is an unlikely state of affairs since the tank is protected within a concrete pit, there are alarms on the water level, and there are several methods, both automatic and manual, by which water could be added to overcome all but a very large leak.

The conservative assumption is made that one of the shield plugs has been removed at some time before the breach, so that convective currents generated by the overheated fuel elements would sweep the gaseous contents of the storage tank into the outer containment. The convective flow is conservatively estimated at six air-changes per hour, with a 90% CF of 1.9, i.e. a maximum possible range of 1.5 to 24 air-changes per hour.

Air cooling would probably prevent the spent fuel elements from melting provided that there were no restrictions on flow through the fuel elements. However, if the ends of the fuel element nozzles were still immersed in water so that free airflow was not possible, calculations (based on very conservative modelling) suggest that melting after about 30 minutes could not be ruled out.

It is assumed in case A that the contents of the storage block are eight newly discharged fuel elements, plus 12 older ones, and that melting occurs in an air atmosphere. In case B only the eight newly discharged fuel elements are present. Case A maximises the amount of long-lived noble gas and particulate activity, whereas case B maximises the specific activity of the organic iodide vapour, since the radioiodine is diluted with the minimum amount of long-lived iodine-129 and stable iodine-127.

About 75 per cent of the iodine release would be in the form of caesium iodide vapour, which would rapidly condense on either a cool surface or on one of the many condensation nuclei which would be present in the air-filled tank in a high radiation field [Megaw and Wiffen 1961]. It is estimated that about six per cent of the condensable fission product vapours would deposit upon condensation nuclei and thus remain airborne. The remainder of the iodine release would be in the form of monatomic or elemental iodine vapour, which would react with traces of organic vapour to form a mixture of organic iodide, elemental iodine and Compound X. Similar considerations to those used in the dropped fuel element case suggest that the organic iodide would be limited to an amount equal to 0.1 per cent of the total iodine inventory, with the remainder being equally divided between elemental and Compound X.

The molten fuel would drop into the water at the bottom of the tank and freeze. The total volume of noble gas released from each element would be less than 1.5 L which is an order of magnitude less than the internal volume of an element. Thus, unless the level of the water in the tank changed, either to displace the internal contents of the elements or to permit free flow of air through the fuel assembly, the noble gases and aerosol would remain trapped inside the elements. However, such an arrangement is unstable and sooner or later the fission products would be released. Since most of the short-lived fission products would have already decayed, the assumptions about the delay between melting and release into the outer containment are not critical and affect only the quantity of iodine vapours and aerosol still airborne.

It is conservatively assumed that there would be no delay between melting of the fuel elements and release of the airborne fission products from the fuel assemblies into the storage tank. For a flow of six air-changes per hour through the tank, the gases would spend an average of 10 minutes inside the tank before their release to the outer containment. During this period, there would be significant deposition of elemental iodine and Compound X on the surfaces of the tank.

The ratio of surface area to volume in the storage tank is a factor of ten higher than the ratio in the outer containment, so deposition constants would also be a factor of ten higher. Elemental iodine would deposit with a half-life of around two minutes, so only about three per cent would escape from the tank. Compound X would deposit with a 20 minute half-life, so about 71 per cent could be expected to be released into the outer containment. It is assumed that the fission product aerosol would not be significantly depleted before escaping from the storage tank.

Elemental iodine and Compound X would continue to be released into the storage tank by the slow oxidation of deposited caesium iodide by air at ambient temperature. The equilibrium fraction of elemental iodine remaining airborne in the RCB due to this slow release is conservatively estimated at 3×10^{-12} and the equilibrium fraction of Compound X at about 10^{-9} of the total iodine inventory of the complete core.

Using the UBE for the convective flow through the tank and the conservative 90 percentile lower values of the deposition constants, 33.7 per cent of the elemental iodine and 89.7 per cent of the Compound X would escape. The minimum fraction of elemental iodine remaining airborne in the RCB at equilibrium for the 90 percentile case would be 3×10^{-10} and the corresponding value for the Compound X would be 10^{-8} .

Table 10 lists the fission product releases into the outer containment for the storage block coolant drainage accident case A, as fractions of the fission product inventory of the entire reactor core, which is to be modelled as a single puff release using the deposition constants listed in table 8. Table 9 lists the releases in case B.

Appendix F gives the MPE source term and appendix G the UBE source term for the storage block coolant drainage case A input to AIRBORNE [Miller 1983]. Appendix H gives the MPE source term and appendix I the UBE source term for the storage block coolant drainage case B input. Figure 12 shows how AIRBORNE predicts that the concentration of the various species of airborne iodine-131 in the RCB would vary with time for the UBE scenario B case, with a maximum leakrate of 1.4 per cent per day from the RSB due to diurnal solar heating effects and barometric pressure variations.

9.3 Shear and Transport Flask Accident

Varying amounts of damage to the ST flask are considered possible owing to the failure of its trailer, to road accidents, crane failures, or maloperation during transfer from the RCB to the cooling pond in Building 23. Draining of the cooling water, followed by melting of the four spent fuel elements is assumed to follow. The likelihood of such accidents occurring outside the RCB is open to debate, but the possible consequences of fission products being released directly into the atmosphere make its inclusion in this study necessary.

- . In case A, the flask suffers damage to the cooling water pipework, but the flask is otherwise intact, although immovable.

- . In case B, the flask is assumed to have cracked open on falling from its trailer, but the fuel elements remain in the flask.
- . In case C, the flask is assumed to have broken open completely and the fuel elements fallen on the roadway.

In all cases, the four fuel elements are assumed to have decayed for nine days after reactor shutdown. In cases A and B, melting is assumed to take place within the flask in an air atmosphere after the cooling water has drained from the damaged flask. The surfaces within the flask would be quite cool, so most of the volatile fission products would deposit within the flask.

The intense radiation field in the flask would generate enormous numbers of condensation nuclei [Megaw and Wiffen 1961], which would keep some of the condensing fission products airborne within the flask. If all the fuel melted, the volume of long-lived and stable xenon and krypton fission product noble gases released would be less than 6 L at ambient temperature or about 18 L at 650°C. Upon mixing and cooling with the air in the flask, this volume of noble gas would displace about 12 L of the contaminated air from the flask. Internal capacity of the flask is greater than 80 L, which is the volume of the cooling water. Thus, in case A, less than 15 per cent of the radioactive gas and suspended aerosol would be released over a period of a few minutes in the initial pressurisation of the flask. The remainder of the radioactive noble gas would gradually escape from the flask over several hours by diffusion through the leak path, but this would not apply to the fission product aerosol of case A, which would be permanently trapped within the flask.

In case B, however, most of the fission product aerosol may gradually escape from the flask, depending on the size of the gap. It is conservatively assumed that there would be no deposition of the fission product aerosol within the flask in case B, and that for melting within the confines of the flask, six per cent of the condensing fission product vapour would remain airborne as an aerosol. Thus the release of fission products as an aerosol would be about 0.9 per cent, in case A, and six per cent, in case B, with a 90% CF of about 2.3.

In case C, the degree of exposure of the fuel elements bears some resemblance to the dropped fuel element case previously discussed. The fraction of the condensable fission product vapour release becoming attached to condensation nuclei in this case is estimated at 10 per cent, with a 90% CF of 2.3.

In case A, no elemental iodine vapour is expected to escape from the flask via the tortuous path through the damaged pipework, either in the initial puff or at the subsequent diffusion stage, as it is sufficiently reactive to be retained on any surface with which it comes into intimate contact.

In case B, some elemental iodine may be released from the flask if the gap is wide enough. The MPE for the fraction escaping from the flask is about three per cent, however, under the worst conditions this value might be exceeded by an order of magnitude. A 90% CF of 10 has therefore been chosen.

In case C, most of the elemental iodine may be released to the atmosphere. It has been conservatively assumed that all the elemental iodine formed is released to atmosphere, thus removing one factor in the calculation of the uncertainty in the estimate, and giving a 90% CF of 2.2.

All of the organic iodide formed in the flask would gradually diffuse out of the cracked flask in a few hours. The organic iodide fraction has been conservatively estimated, in all three cases, at 0.1 per cent of the total core iodine inventory, with a 90% CF of 2.2.

The iodine form known as compound X would diffuse out of the damaged flask very slowly as it adsorbed onto and desorbed from the surfaces lining the leak path. The compound X fraction has been conservatively estimated at 11 per cent of the iodine released from the fuel; it is estimated that in cases A and B, fraction escaping down the leak path in the 11-day mean lifetime for iodine-131, may be as high as 20 per cent, with a 90% CF of 3.3. In case C, it is assumed that all of Compound X would be released, thus the only area of uncertainty is the fractional release from the fuel, so the 90% CF falls to about 2.2.

Table 12 gives the source term for ST flask case A, table 13 for case B and table 14 for case C. Appendix J gives the MPE source term and appendix K the UBE source term for ST flask case A input to AIRBORNE. Appendices L and M give the MPE and UBE source terms, respectively, for ST flask case B, and N and O give the same terms for ST flask case C.

10. CONCLUSIONS

Previous modelling of the HIFAR LOCA [AAEC 1972] contained several extremely pessimistic assumptions, which could not be sustained in the more rigorous and realistic modelling adopted for this study:

- (a) That melting of the fuel would occur in an oxidising atmosphere. It was realised at the time that this assumption was wrong but it was adopted in the mathematical modelling (despite disclaimers in the text) because most of the experimental evidence had been obtained in oxidising atmospheres and it was thought that the fuel might still be molten when air diffused into the reactor late in the accident. This is now known to be impossible.

- (b) That the fuel would remain molten for a considerable period. More rigorous treatment of the accident modelling shows that the fuel is molten for only a few seconds as the drops of molten fuel follow the path of the water into the lowest parts of the pipework or plant room sump, where they quickly re-solidify as cooling is restored.
 - (c) That there would be a significant release of volatile fission product vapours, especially radioactive iodine, from the primary coolant circuit. This assumption was incorrect, since in a reducing atmosphere the release of iodine from the fuel would be in the form of caesium iodide, rather than the more volatile elemental iodine, and so would readily deposit on the cool wet surfaces of the primary coolant circuit in its passage to the break in the circuit.
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More realistic treatment of the LOCA has therefore reduced the estimates of radioiodine release by several orders of magnitude. This in turn has inflated the relative importance of several of the other types of accident involving fuel melting. However the modelling of these latter accidents has not been as realistic as that of the LOCA, and may contain simplistic (but conservative) assumptions which cannot be sustained when treated rigorously. The most obvious source of error is the omission of significant convective cooling of the fuel elements, which will overestimate the temperature reached by the elements, especially those that have been out of the reactor for many days.

Although the degree of conservatism has been reduced in the more realistic modelling adopted for the LOCA case, there are still a number of conservative assumptions in the modelling of the fission product behaviour. For example, the assumption that the initial dry deposition rate of the fission product aerosol would be no greater than that of the agglomerated aerosol at equilibrium, leads to significant underestimation of the collection rate in the space conditioners and of the initial deposition rate on surfaces in the RCB. These could lead to an overestimation of the amount of fission product aerosol leaking from the RCB in the HIFAR LOCA by a factor of about three compared with more rigorous treatment of the behaviour of the agglomerating aerosol. Deposition in the DPR is ignored. This is bound to lead to a pessimistic conclusion, especially in the case where the space conditioners are not functioning.

The cramping effect that the 100 per cent release boundary has on the 90 percentile figures for fission product release has also been ignored; this overestimates some of the 90 percentile values for iodine by about 15 per cent. Despite these shortcomings, the modelling goes a long way towards the ideal of predicting the most probable consequences of an accident involving melting of the fuel elements and, provided that the consequences predicted are tolerable, it should not be necessary to remodel the fission product behaviour more rigorously.

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TABLE 1
EFFECT OF MAXIMUM TEMPERATURE AND ATMOSPHERE
ON FISSION PRODUCT RELEASE FROM URANIUM-ALUMINIUM
ALLOY SPECIMENS ACCORDING TO PARKER *et al.* [1973]

Maximum Temp (°C)	Atmosphere	Percentage Release					Release Ratio			
		Xe, Kr	I	Te	Cs	Ru	I	Te	Cs	Ru
800	Helium	99.5	29.8	5.3	13.0	0.18	4.25E-1	5.60E-2	1.49E-1	1.80E-3
900	Helium	≈100	52.8	4.3	20.8	0.08	1.12E 0	4.49E-2	2.63E-1	8.01E-4
1000	Helium	≈100	82.1	2.9	47.7	0.19	4.59E 0	2.99E-2	9.12E-1	1.90E-3
1105	Helium	≈100	82.4	2.9	69.5	0.25	4.68E 0	2.99E-2	2.28E 0	2.51E-3
700	Air	97.9	37.8	0.3	3.1	0.02	6.08E-1	3.01E-3	3.20E-2	2.00E-4
800	Air	99.4	78.6	0.2	3.8	<0.1	3.67E 0	2.00E-3	3.95E-2	<1.00E-3
900	Air	100.0	91.9	2.1	6.2	0.1	1.13E 1	2.15E-2	6.61E-2	1.00E-3
1000	Air	99.8	97.3	<9.7	8.8	0.2	3.60E 1	<1.07E-1	9.65E-2	2.00E-3
1090	Air	100	98.4	44.8	12.4	0.6	6.15E 1	8.12E-1	1.42E-1	6.04E-3
1145	Air	100	94.2	62.0	18.6	0.4	1.62E 1	1.63E 0	2.29E-1	4.02E-3
700	Steam-Air	98.3	27.0	<0.03	0.6	<0.02	3.70E-1	<3.00E-4	6.04E-3	<2.00E-4
800	Steam-Air	99.5	76.8	0.3	1.1	0.1	3.31E 0	3.01E-3	1.11E-2	1.00E-3
900	Steam-Air	99.9	90.6	5.7	6.5	0.5	9.64E 0	6.04E-2	6.95E-2	5.03E-3
1000	Steam-Air	100	95.6	22.6	11.0	0.5	2.17E 1	2.92E-1	1.24E-1	5.03E-3
1085	Steam-Air	100	96.8	67.9	30.5	0.8	3.03E 1	2.12E 0	4.39E-1	8.06E-3

Note: Specimen held at the maximum temperature for two minutes.

TABLE 2
FISSION PRODUCT RELEASES FROM MOLTEN FUEL
AT 650°C IN A HELIUM ATMOSPHERE

Nuclide	Dry Helium Release Ratio	90% CF	Moist Helium Modifying Factor	90% CF	Moist Helium Release Ratio	Overall	
						90% CF	Fractional Release in Moist Helium MPE UBE
Xenon, krypton	-	-	-	-	-	1.01	9.90 E-1 1.00
Iodine, bromine	6.67 E-2	2.41	1.19	1.09	7.94 E-2	2.42	7.36 E-2 1.61 E-1
Tellurium	9.27 E-2	1.29	0.341	1.67	3.16 E-2	1.77	3.06 E-2 5.30 E-2
Caesium, rubidium	1.56 E-2	1.87	0.680	1.20	1.06 E-2	1.92	1.05 E-2 1.99 E-2
Ruthenium	8.57 E-4	3.38	0.771	1.13	6.61 E-4	3.40	6.61 E-4 2.24 E-3
Strontium	-	-	-	-	-	4	3 E-4 1 E-3
Barium, antimony	-	-	-	-	-	4	5 E-5 2 E-4
Molybdenum, technetium	-	-	-	-	-	6	2 E-11 1 E-10
All others	-	-	-	-	-	6	<4 E-12 2 E-12

MPE is the most probable estimate.

UBE is the 90 percentile upper bounding estimate.

TABLE 3
FISSION PRODUCT RELEASES FROM MOLTEN FUEL
AT 650°C IN A STEAM ATMOSPHERE

Nuclide	Steam-Air Release Ratio	90% CF	Steam Modifying Factor	90% CF	Steam Release Ratio	Overall	
						Fractional Release in Steam MPE	Fractional Release UBE
Xenon, krypton	-	-	-	-	-	1.01	9.90 E-1 1.00
Iodine, bromine	2.33 E-1	1.69	0.948	1.03	2.21 E-1	1.69	1.81 E-1 2.72 E-1
Tellurium	4.42 E-5	1.58	1.22	1.10	5.40 E-5	1.60	5.40 E-5 8.64 E-5
Caesium, rubidium	1.93 E-3	1.73	0.565	1.31	1.09 E-3	1.84	1.09 E-3 2.00 E-3
Ruthenium	1.34 E-4	1.90	1.05	1.02	1.41 E-4	1.90	1.40 E-4 2.68 E-4
Strontium	-	-	-	-	-	36	1 E-14 4 E-13
Barium, antimony	-	-	-	-	-	4	5 E-12 2 E-11
Molybdenum, technetium	-	-	-	-	-	6	2 E-11 1 E-10
All others	-	-	-	-	-	6	<1 E-12 1 E-12

TABLE 4
FISSION PRODUCT RELEASES FROM MOLTEN FUEL
AT 650°C IN AN AIR ATMOSPHERE

Nuclide	Air Release Ratio	90% CF	Fractional Release MPE	Overall	
				Fractional Release in Air UBE	UBE
Xenon, krypton	-	1.01	9.90 E-1	1.00	1.00
Iodine, bromine	2.88 E-1	1.24	2.24 E-1	2.63 E-1	2.63 E-1
Tellurium	2.14 E-5	1.55	2.14 E-5	3.32 E-5	3.32 E-5
Caesium, rubidium	1.88 E-2	1.29	1.85 E-2	2.37 E-2	2.37 E-2
Ruthenium	1.08 E-4	1.57	1.08 E-4	1.70 E-4	1.70 E-4
Strontium	-	36	1 E-24	4 E-23	4 E-23
Barium, antimony	-	4	1 E-12	4 E-12	4 E-12
Molybdenum, technetium	-	6	2 E-11	1 E-10	1 E-10
All others	-	6	1 E-12	6 E-12	6 E-12

TABLE 5
 INITIAL 'AEROSOL' RELEASE IN HIFAR 'BOUNDING CASE'
 LOCA MODEL. HELIUMBORNE RELEASE OF FISSION PRODUCTS
 FROM PRIMARY COOLANT CIRCUIT 1000 SECONDS AFTER REACTOR TRIP

Nuclide	Fraction of Release Remaining Gasborne	90% CF	Fraction of Fuel Melting	Overall		Fraction of Inventory Released into Plant Room	UBE
				90% CF	MPE		
<u>Gaseous</u>							
Xenon, krypton	1.00	1.0	0.50	1.01	4.95 E-1	5.00 E-1	
<u>Particulate</u>							
Iodide, bromide	0.02	2.1	0.27	3.17	3.97 E-4	1.26 E-3	
Tellurium	0.02	2.1	0.27	2.55	1.65 E-4	4.21 E-4	
Caesium, rubidium	0.02	2.1	0.27	2.69	5.67 E-5	1.53 E-4	
Ruthenium	0.20	2.1	0.27	4.18	3.57 E-5	1.49 E-4	
Strontium	0.02	2.1	0.27	5	1.6 E-6	8.0 E-6	
Barium, antimony	0.02	2.1	0.27	5	2.7 E-7	1.4 E-6	
Molybdenum, technetium	0.02	2.1	0.27	7	1 E-13	7 E-13	
All others	0.02	2.1	0.27	7	< 2 E-14	1 E-13	

Note: No fission product vapour is expected to escape from the cool PCC in the gas phase. Columns 1, 3 and 4 are the factors used convert table 2 to give columns 5 and 6.

TABLE 6

FINAL 'AEROSOL' RELEASE IN HIFAR 'BOUNDING CASE'
 LOCA MODEL. STEAMBORNE RELEASE OF FISSION PRODUCTS
 FROM PRIMARY COOLANT CIRCUIT FIVE HOURS AFTER REACTOR TRIP

Nuclide	Fraction of Release Remaining Gasborne	90% CF	Fraction of Fuel Melting	90% CF	Overall	
					Fraction of Inventory Released into Plant Room	MPE UBE
<u>Gaseous</u>						
Xenon, krypton	1.00	1.0	0.50	1.01	4.95 E-1	5.00 E-1
<u>Particulate</u>						
Iodide, bromide	0.02	2.1	0.73	2.48	2.64 E-3	6.55 E-3
Tellurium	0.02	2.1	0.73	2.41	7.88 E-7	1.90 E-6
Caesium, rubidium	0.02	2.1	0.73	2.61	1.59 E-5	4.15 E-5
Ruthenium	0.20	2.1	0.73	2.67	2.04 E-5	5.45 E-5
Strontium	0.02	2.1	0.73	39	2 E-16	8 E-15
Barium, antimony	0.02	2.1	0.73	5	7 E-14	4 E-13
Molybdenum, technetium	0.02	2.1	0.73	7	3 E-13	2 E-12
All others	0.02	2.1	0.73	7	<1 E-14	1 E-14

Note: No fission product vapour is expected to escape from the relatively cool PCC in the gas phase. Columns 1, 3 and 4 are the factors used to convert table 3 to give columns 5 and 6.

TABLE 7
 VARIATION OF THE DRY DEPOSITION VELOCITY OF AN AEROSOL
 WITH PARTICLE SIZE

Particle Diameter (μm)	Sedimentation* Velocity ($\mu\text{m s}^{-1}$)	90% CF**	Dry Deposition Velocity (μms^{-1})				Overall 90% CF	
			Walls**	Floor	Ceiling	Average		
2	320	1.21	0.77	320	0	80	64	1.1
1	89	1.15	1.86	91	0	24	19	1.2
0.5	26	1.21	4.50	30.5	0	10	8.8	1.3
0.4	18	1.25	5.99	24.0	0	9.0	8.4	1.3
0.3	12	1.30	8.65	20.7	0	9.5	9.3	1.4
0.2	6	1.39	14.5	20.5	8.5	14.5	14.5	1.5
0.1	2.2	1.56	35.2	37.4	33	35.2	35.2	1.7
0.05	1.2	1.76	85.3	86.5	84	85.3	85.3	2.0

*Schwendiman et al. (1963); ** Chamberlain (1962).

Note: See table 8 for the deposition constants used in the HIFAR 'Bounding Case' modelling.

TABLE 8
 DEPOSITION CONSTANTS FOR ALL FORMS OF AIRBORNE
 RADIOACTIVITY IN THE CONTAINMENT BUILDING

Classification	Deposition Constant α (h^{-1})	
	MPE	UBE
Noble Gases	0	0
Organic iodide	0	0
Elemental iodine	2.08	1.24
Compound X	0.213	0.127
Fission product particulate aerosol	$1.21 \times 10^{-3} \times \Omega_t + 0.0139$	$7.56 \times 10^{-4} \times \Omega_t + 0.0099$

Note: Ω_t is the condensation rate of water vapour in the space conditioners at time t.

TABLE 9
SOURCE TERM FOR THE 'DROPPED FUEL ELEMENT' ACCIDENT

Nuclide	Overall					Fraction of Inventory Released into Containment UBE
	Fraction of Release Remaining Airborne	90% CF	Fraction of Fuel Melting	90% CF	MPE	
<u>Gaseous</u>						
Xenon, krypton	1.00	1.0	0.04	1.01	3.96 E-2	4.00 E-2
<u>Vapour</u>						
Elemental iodine	6.88 E-2	2.1	0.04	2.2	6.16 E-4	1.36 E-3
Compound X	6.88 E-2	2.1	0.04	2.2	6.16 E-4	1.36 E-3
Organic iodide	1.13 E-1	2.1	0.04	2.2	1.01 E-3	2.22 E-3
<u>Particulate</u>						
Iodide, bromide	7.5 E-2	2.1	0.04	2.17	6.72 E-4	1.46 E-3
Tellurium	1.0 E-1	2.1	0.04	2.37	8.56 E-8	2.03 E-7
Caesium, rubidium	1.0 E-1	2.1	0.04	2.19	7.40 E-5	1.62 E-4
Ruthenium	1.0 E-1	2.1	0.04	2.38	4.32 E-7	1.03 E-6
Strontium	1.0 E-1	2.1	0.04	39	4 E-27	2 E-25
Barium, antimony	1.0 E-1	2.1	0.04	5	4 E-15	2 E-14
Molybdenum, technetium	1.0 E-1	2.1	0.04	7	8 E-14	6 E-13
All others	1.0 E-1	2.1	0.04	7	4 E-15	3 E-14

Note: Columns 1, 3 and 4 are the factors used to convert table 4 to give columns 5 and 6.

TABLE 10
SOURCE TERM FOR THE 'STORAGE BLOCK A' ACCIDENT

Nuclide	Fraction Formed	Fraction Escaping	90% CF	Fraction of Core Melting	90% CF	Overall		Fraction of Core Inventory Released into Containment	
						MPE	UBE	MPE	UBE
<u>Gaseous</u>									
Xenon, krypton	1.00	1.0	1.0	0.80	1.01	7.91 E-1	8.00 E-1		
<u>Vapour</u>									
Elemental iodine	1.22 E-1	3.0 E-2	12.5*	0.80	12.6	6.57 E-4	8.28 E-3		
Compound X	1.22 E-1	7.1 E-1	2.2*	0.80	2.2	1.55 E-2	3.41 E-2		
Organic iodide	5.58 E-3	1.0	2.1	0.80	2.2	1.00 E-3	2.19 E-3		
<u>Particulate</u>									
Iodide, bromide	4.50 E-2	1.0	2.1	0.80	2.17	8.06 E-3	1.75 E-2		
Tellurium	6.00 E-2	1.0	2.1	0.80	2.37	1.08 E-6	2.44 E-6		
Caesium, rubidium	6.00 E-2	1.0	2.1	0.80	2.19	8.86 E-4	1.94 E-3		
Ruthenium	6.00 E-2	1.0	2.1	0.80	2.38	5.18 E-6	1.23 E-5		
Strontium	6.00 E-2	1.0	2.1	0.80	39	4 E-26	2 E-24		
Barium, antimony	6.00 E-2	1.0	2.1	0.80	5	4 E-14	2 E-13		
Molybdenum, technetium	6.00 E-2	1.0	2.1	0.80	7	1 E-12	6 E-12		
All others	6.00 E-2	1.0	2.1	0.80	7	4 E-14	4 E-13		

Note:

Columns 1, 2, 4 and 5 are the factors used to convert table 4 to give columns 6 and 7.

*These values include a term to cover the uncertainty in the deposition within the storage tank.

TABLE 11
SOURCE TERM FOR THE 'STORAGE BLOCK B' ACCIDENT

Nuclide	Fraction Formed	Fraction Escaping	90% CF	Fraction of Core Melting	90% CF	Overall		MPE	UBE
						Fraction of Core Inventory Released into Containment	Fraction of Core Inventory Released into Containment		
<u>Gaseous</u>									
Xenon, krypton	1.00	1.0	1.0	0.32	1.01			3.17 E-1	3.20 E-1
<u>Vapour</u>									
Elemental iodine	1.18 E-1	3.0 E-2	12.5*	0.32	12.6			2.54 E-4	3.20 E-3
Compound X	1.18 E-1	7.1 E-1	2.2*	0.32	2.2			6.01 E-3	1.32 E-2
Organic iodide	1.40 E-2	1.0	2.1	0.32	2.2			1.00 E-3	2.19 E-3
<u>Particulate</u>									
Iodide, bromide	4.50 E-2	1.0	2.1	0.32	2.17			3.22 E-3	6.99 E-3
Tellurium	6.00 E-2	1.0	2.1	0.32	2.37			4.11 E-7	9.76 E-7
Caesium, rubidium	6.00 E-2	1.0	2.1	0.32	2.19			3.54 E-4	7.75 E-4
Ruthenium	6.00 E-2	1.0	2.1	0.32	2.38			2.07 E-6	4.94 E-6
Strontium	6.00 E-2	1.0	2.1	0.32	39			2 E-26	7 E-25
Barium, antimony	6.00 E-2	1.0	2.1	0.32	5			2 E-14	1 E-13
Molybdenum, technetium	6.00 E-2	1.0	2.1	0.32	7			5 E-13	2 E-12
All others	6.00 E-2	1.0	2.1	0.32	7			2 E-14	2 E-13

Note:

Columns 1, 2, 4 and 5 are the factors used to convert **table 4** to give columns 6 and 7.

*These values include a term to cover the uncertainty in the deposition within the storage tank.

TABLE 12
SOURCE TERM FOR THE 'SHEAR AND TRANSPORT FLASK' ACCIDENT CASE A

Nuclide	Fraction Formed	Fraction Escaping	90% CF	Fraction of Core Melting	90% CF	Overall	
						Fraction of Core Inventory Released to the Atmosphere MFE	UBE
<u>Gaseous</u>							
Xenon, krypton	1.0	1.0	1.0	0.16	1.01	1.58 E-1	1.60 E-1
<u>Vapour</u>							
Elemental iodine	1.1 E-1	0	-	0.16	-	0	0
Compound X	1.1 E-1	2.0 E-1	3.3*	0.16	3.4	7.96 E-4	2.72 E-3
Organic iodide	2.8 E-2	1.0	2.1	0.16	2.2	1.00 E-3	2.22 E-3
<u>Particulate</u>							
Iodide, bromide	4.5 E-2	1.5 E-1	2.3	0.16	2.4	2.42 E-4	5.84 E-4
Tellurium	6.0 E-2	1.5 E-1	2.3	0.16	2.6	3.08 E-8	8.12 E-8
Caesium, rubidium	6.0 E-2	1.5 E-1	2.3	0.16	2.4	2.66 E-5	6.48 E-5
Ruthenium	6.0 E-2	1.5 E-1	2.3	0.16	2.6	1.56 E-7	4.11 E-7
Strontium	6.0 E-2	1.5 E-1	2.3	0.16	40	2 E-27	8 E-26
Barium, antimony	6.0 E-2	1.5 E-1	2.3	0.16	5	2 E-15	8 E-15
Molybdenum, technetium	6.0 E-2	1.5 E-1	2.3	0.16	7	3 E-14	2 E-13
All others	6.0 E-2	1.5 E-1	2.3	0.16	7	2 E-15	1 E-14

Note:

Columns 1, 2, 4 and 5 are the factors used to convert table 4 to give columns 6 and 7.

*This value includes a term to cover the uncertainty in the deposition within the flask.

TABLE 13
SOURCE TERM FOR THE 'SHEAR AND TRANSPORT FLASK' ACCIDENT CASE B

Nuclide	Fraction Formed	Fraction Escaping	90% CF	Fraction of Core Melting	Overall			
					90% CF	Fraction of Core Inventory Released to the Atmosphere	UBE	
<u>Gaseous</u>								
Xenon, krypton	1.0	1.0	1.0	0.16	1.01	1.58 E-1	1.60 E-1	
<u>Vapour</u>								
Elemental iodine	1.1 E-1	3.0 E-2	10*	0.16	11.2	1.18 E-4	1.33 E-3	
Compound X	1.1 E-1	2.0 E-1	3.3*	0.16	3.4	7.96 E-4	2.72 E-3	
Organic iodide	2.8 E-2	1.0	2.1	0.16	2.2	1.00 E-3	2.22 E-3	
<u>Particulate</u>								
Iodide, bromide	4.5 E-2	1.0	2.3	0.16	2.4	1.61 E-3	3.87 E-3	
Tellurium	6.0 E-2	1.0	2.3	0.16	2.6	2.05 E-7	5.34 E-7	
Caesium, rubidium	6.0 E-2	1.0	2.3	0.16	2.4	1.78 E-4	4.26 E-4	
Ruthenium	6.0 E-2	1.0	2.3	0.16	2.6	1.04 E-6	2.70 E-6	
Strontium	6.0 E-2	1.0	2.3	0.16	40	1 E-26	4 E-25	
Barium, antimony	6.0 E-2	1.0	2.3	0.16	5	1 E-14	5 E-14	
Molybdenum, technetium	6.0 E-2	1.0	2.3	0.16	7	2 E-13	1 E-12	
All others	6.0 E-2	1.0	2.3	0.16	7	1 E-14	7 E-14	

Note:

Columns 1, 2 4 and 5 are the factors used to convert table 4 to give columns 6 and 7.

*These values include a term to cover the uncertainty in the deposition within the flask.

TABLE 14
SOURCE TERM FOR THE 'SHEAR AND TRANSPORT FLASK' ACCIDENT CASE C

Nuclide	Fraction Formed	Fraction Escaping	90% CF	Fraction of Core Melting	Overall			Fraction of Core Inventory Released to the Atmosphere
					90% CF	CF	MPE	
<u>Gaseous</u>								
Xenon, krypton	1.0	1.0	1.0	0.16	1.01	1.58 E-1	1.60 E-1	
<u>Vapour</u>								
Elemental iodine	1.1 E-1	1.0	2.2	0.16	2.3	3.94 E-3	9.07 E-3	
Compound X	1.1 E-1	1.0	2.2	0.16	2.3	3.94 E-3	9.07 E-3	
Organic iodide	2.8 E-2	1.0	2.1	0.16	2.2	1.00 E-3	2.22 E-3	
<u>Particulate</u>								
Iodide, bromide	7.5 E-2	1.0	2.3	0.16	2.4	2.69 E-3	6.45 E-3	
Tellurium	1.0 E-1	1.0	2.3	0.16	2.6	3.42 E-7	8.90 E-7	
Caesium, rubidium	1.0 E-1	1.0	2.3	0.16	2.4	2.96 E-4	7.10 E-4	
Ruthenium	1.0 E-1	1.0	2.3	0.16	2.6	1.73 E-6	4.49 E-6	
Strontium	1.0 E-1	1.0	2.3	0.16	40	2 E-26	6 E-25	
Barium, antimony	1.0 E-1	1.0	2.3	0.16	5	2 E-14	8 E-14	
Molybdenum, technetium	1.0 E-1	1.0	2.3	0.16	7	3 E-13	1 E-12	
All others	1.0 E-1	1.0	2.3	0.16	7	2 E-14	1 E-13	

Note: Columns 1, 2, 4 and 5 are the factors used to convert table 4 to give columns 6 and 7.

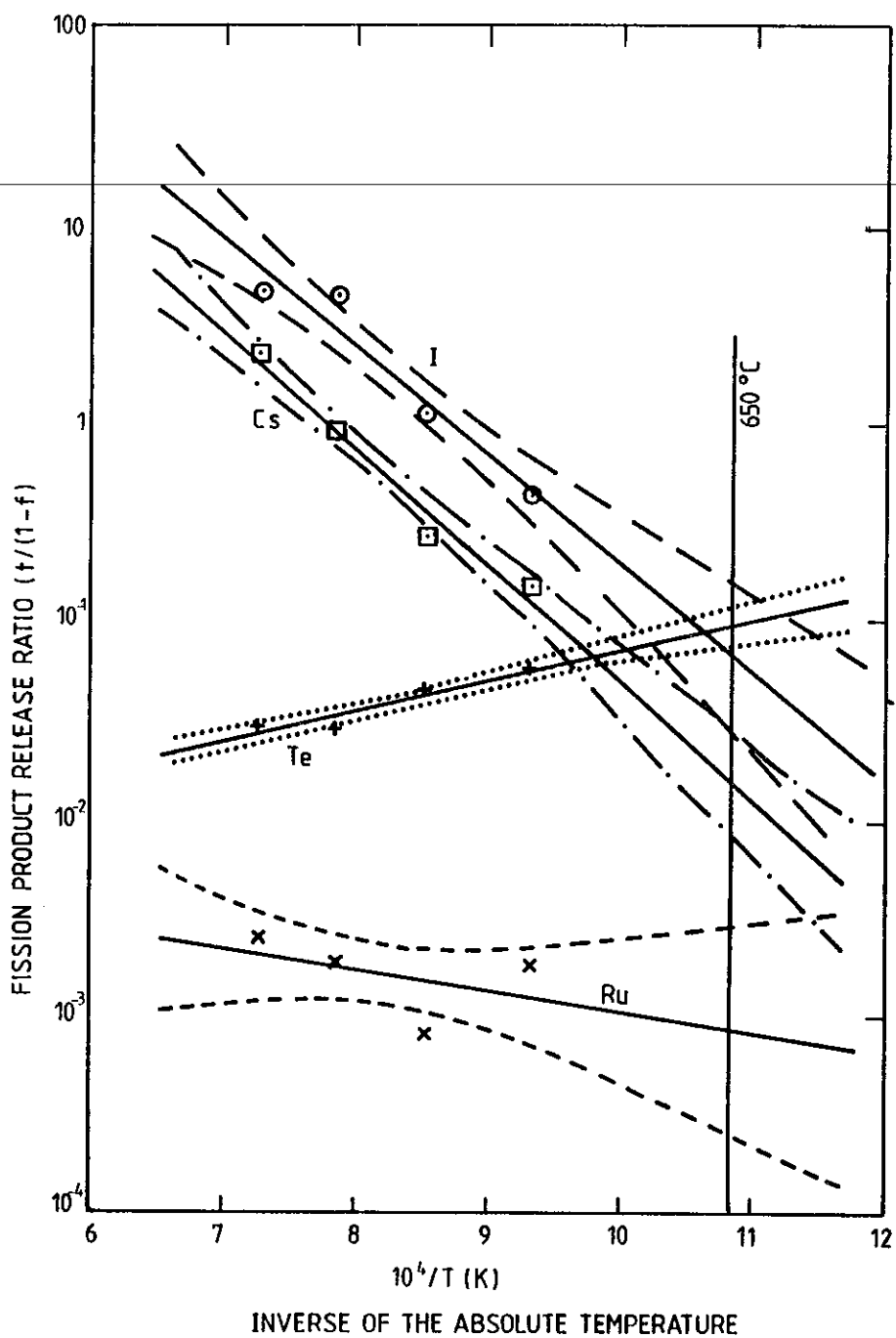


Figure 1 Arrhenius plot of fission product release ratio in helium

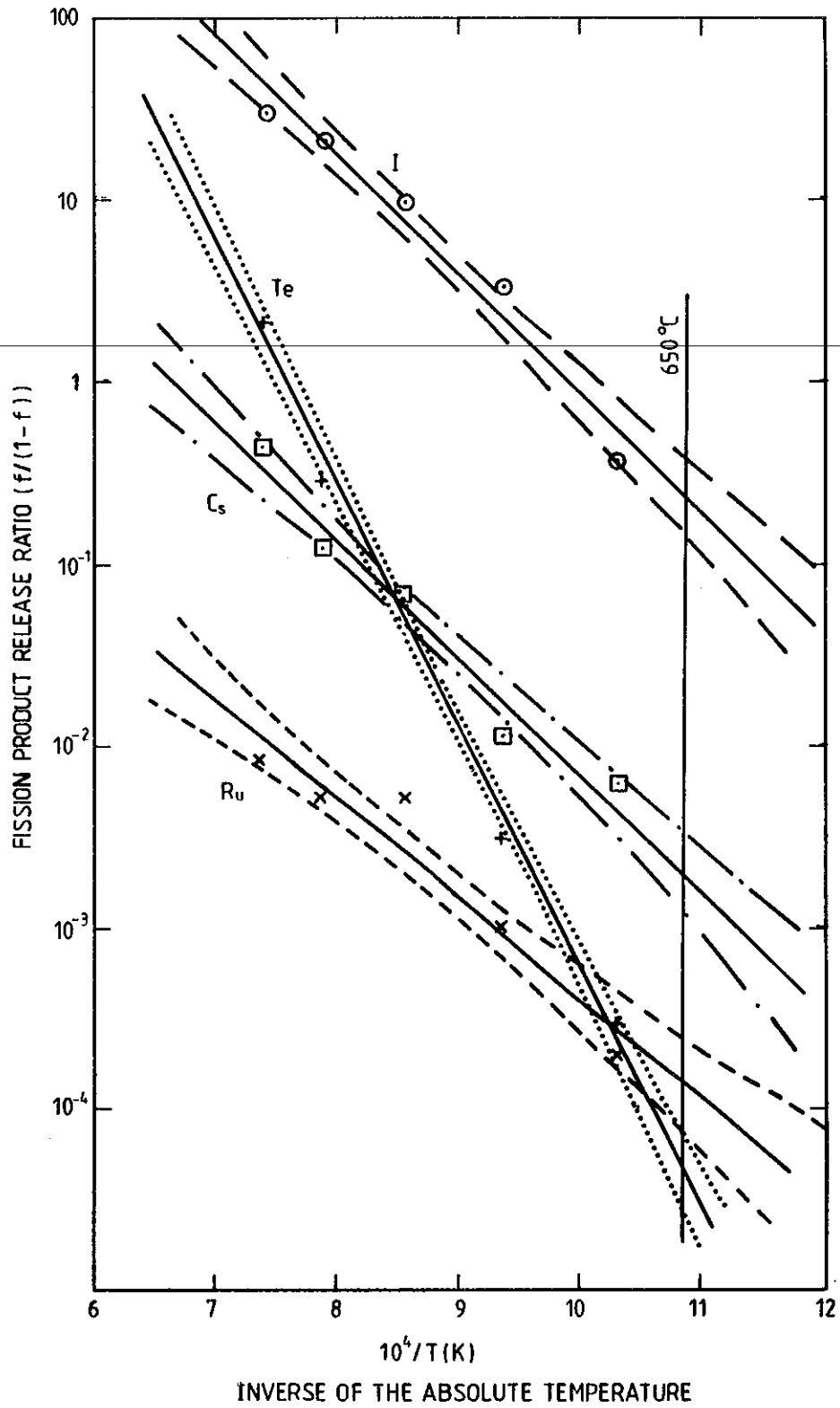


Figure 2 Arrhenius plot of fission product release ratio in an 80:20 steam:air mixture

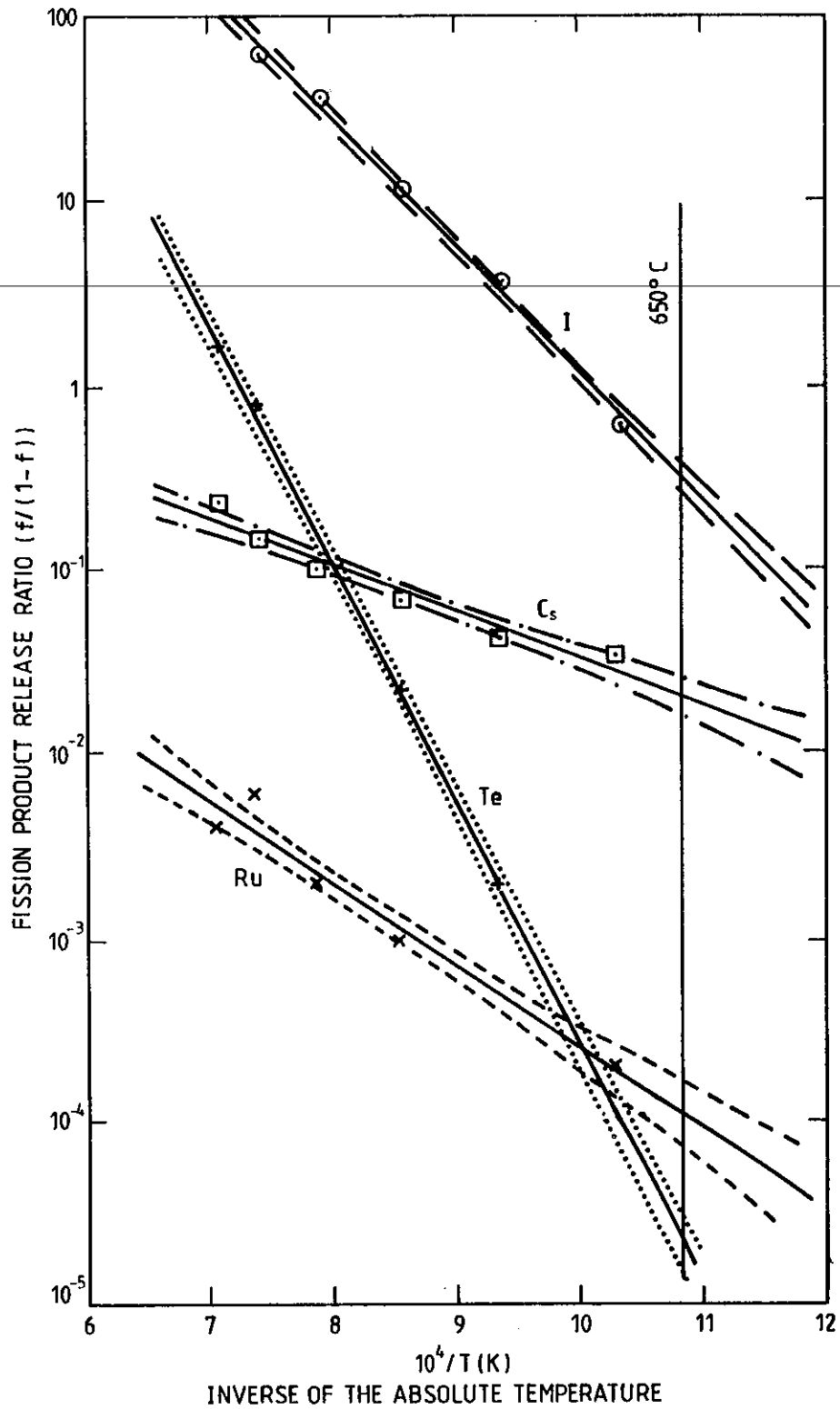


Figure 3 Arrhenius plot of fission product release ratio in air

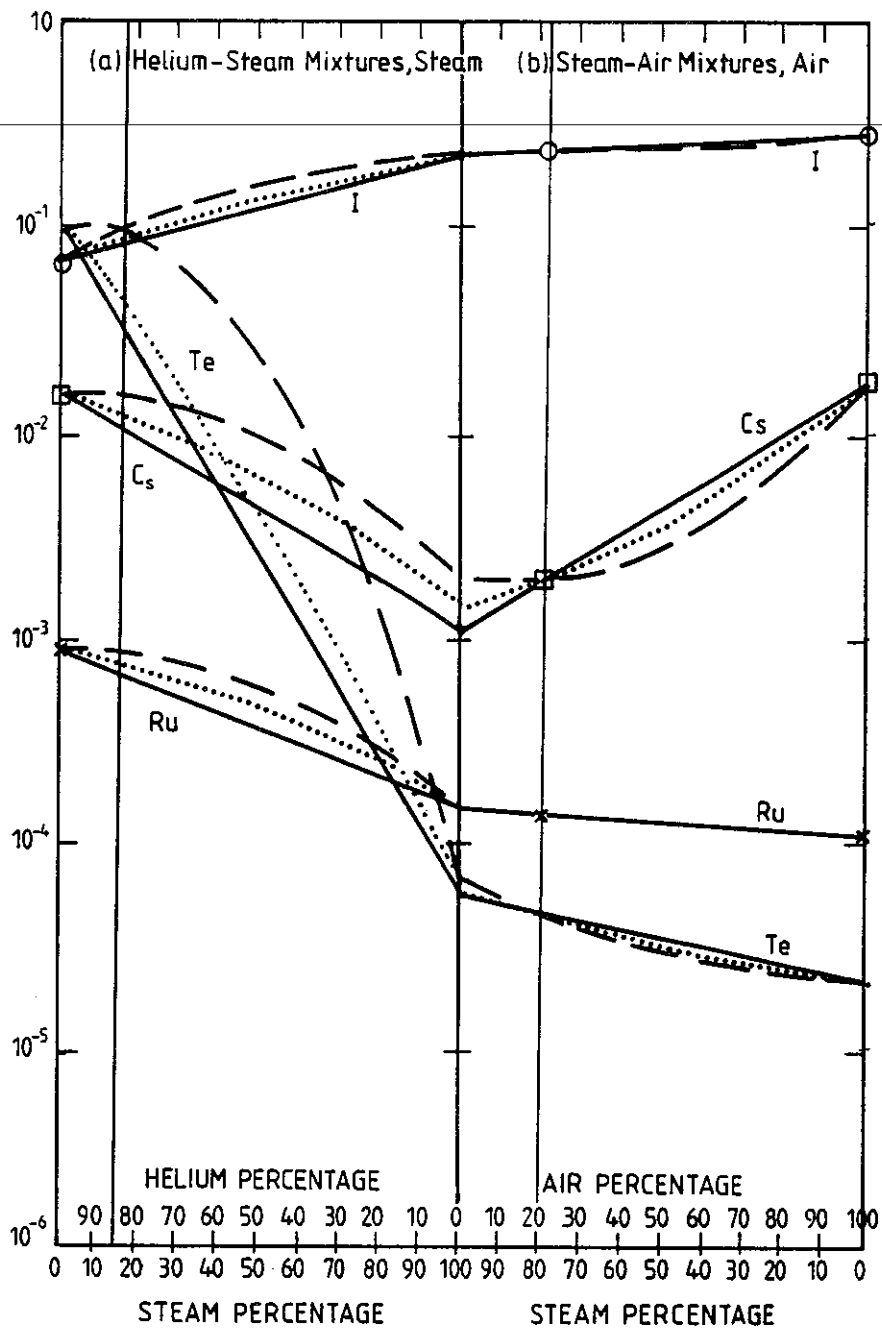


Figure 4 Effect of atmospheric composition on fission product release ratios

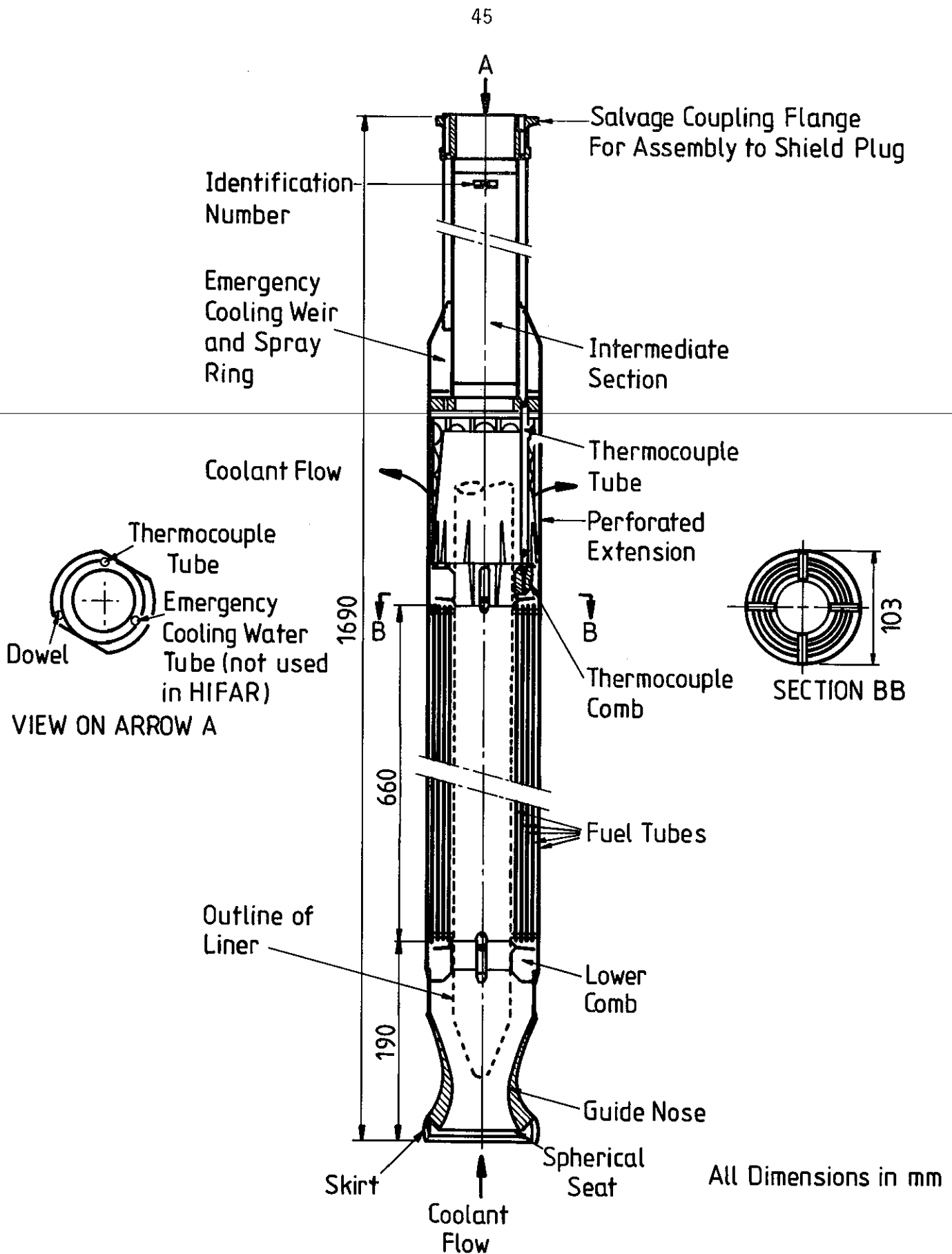


Figure 5 Fuel element Mark IV/5A

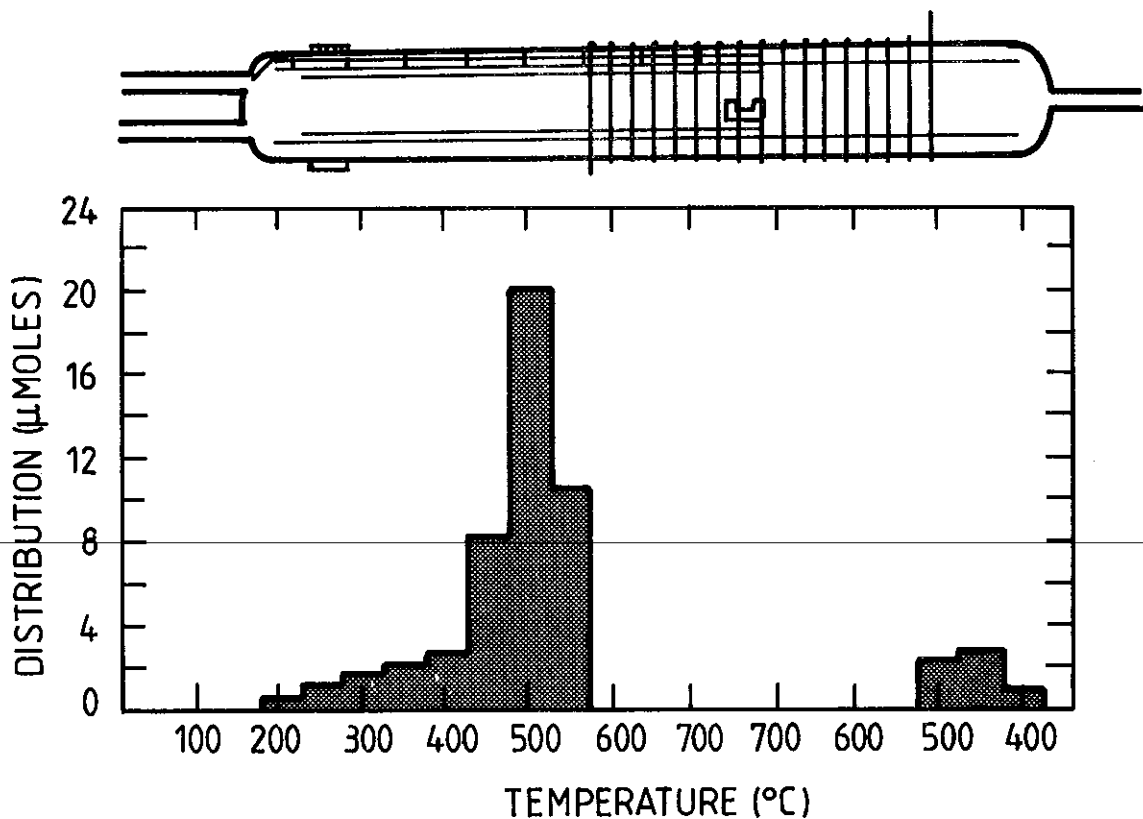


Figure 6 Caesium iodide deposition profile

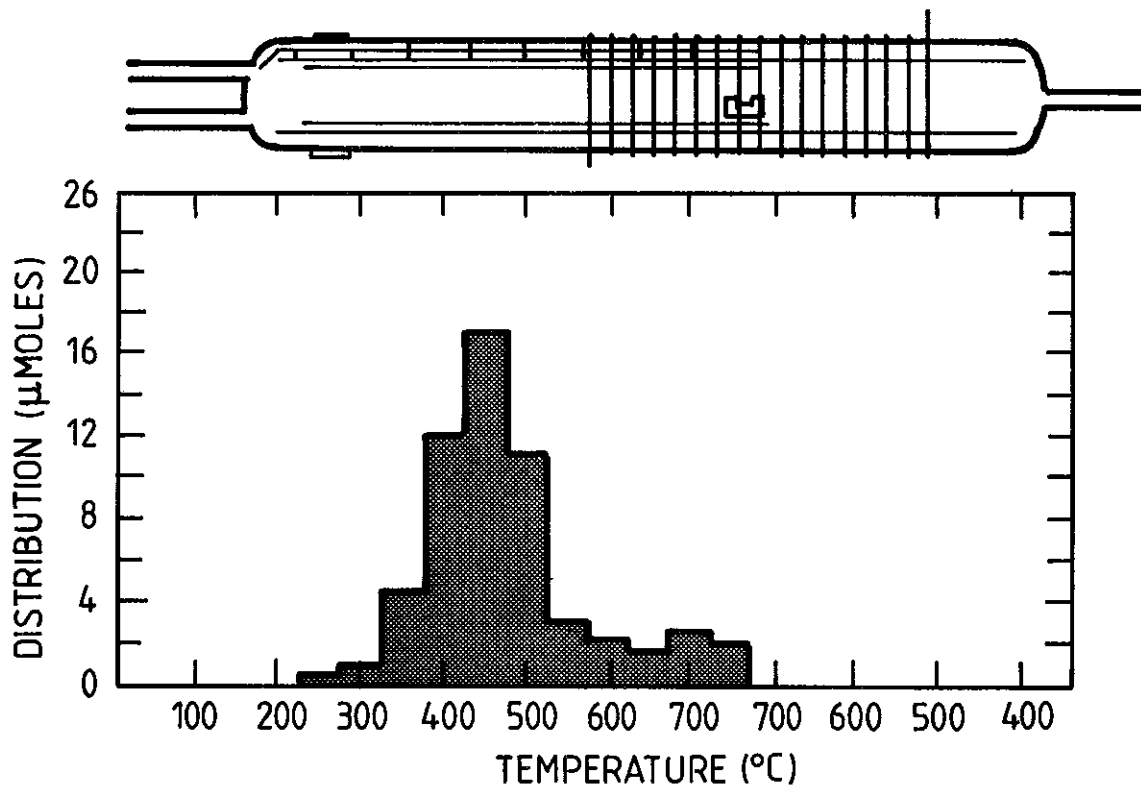


Figure 7 Tellurium deposition interaction profile

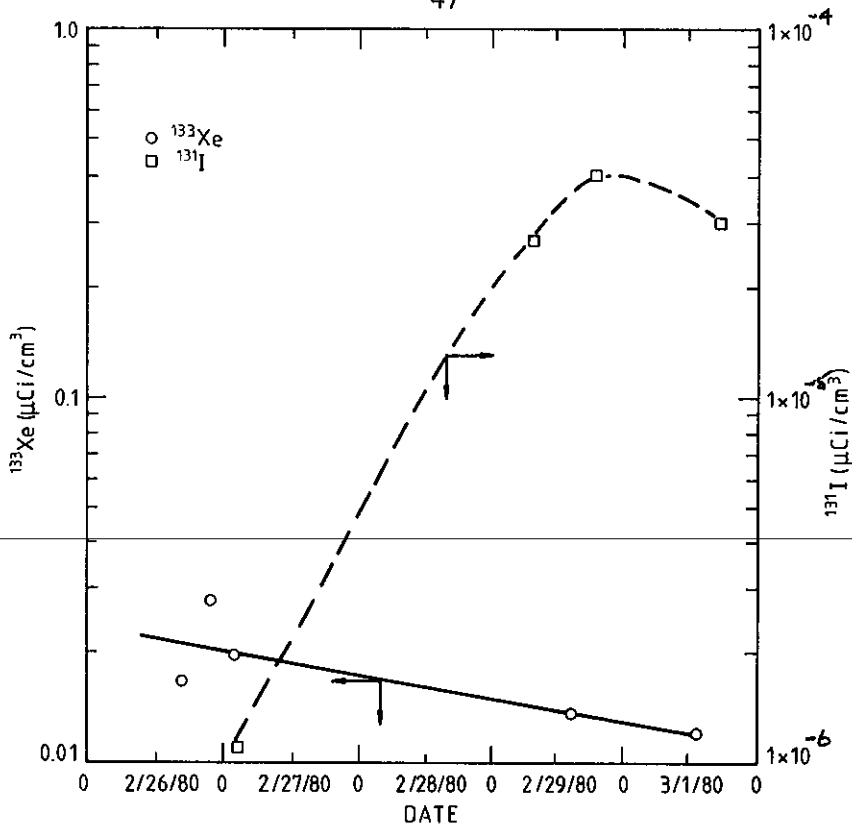


Figure 8 Concentration of ^{131}I and ^{133}Xe in the containment atmosphere following the Crystal River-3 incident

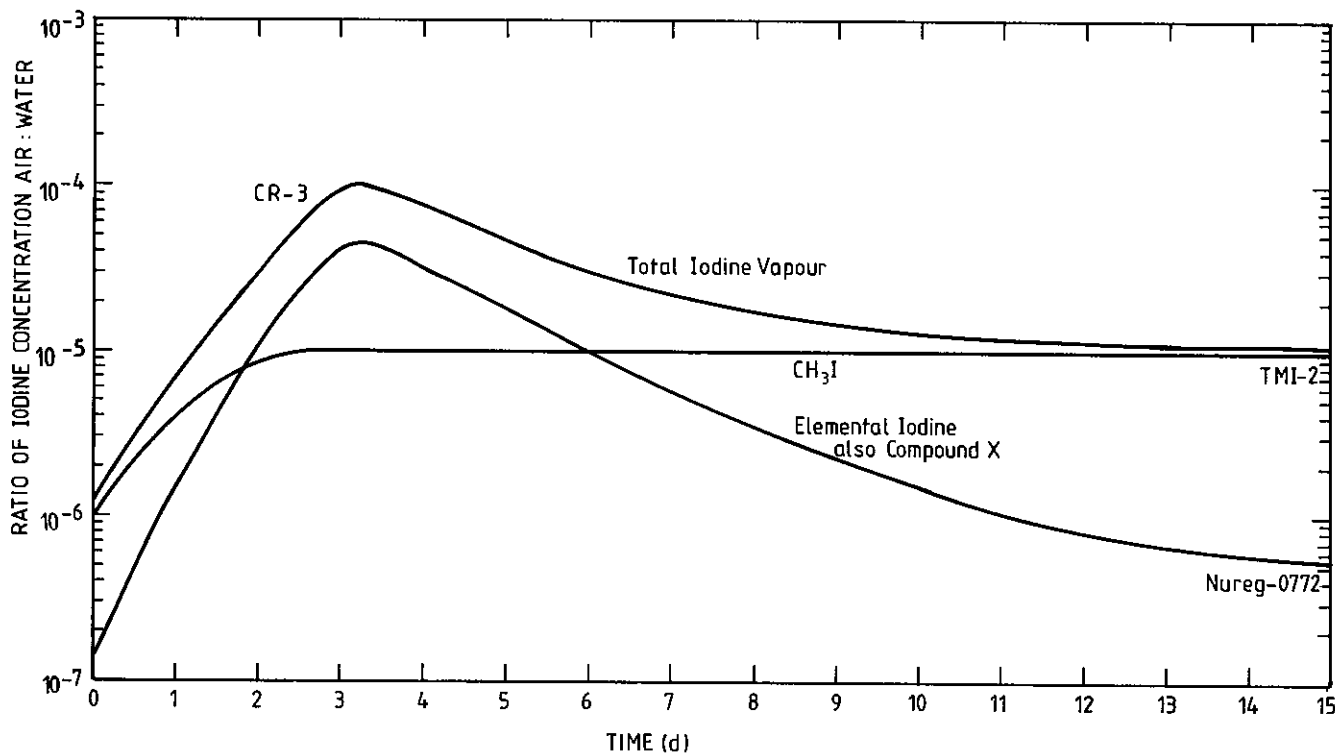


Figure 9 Variation of iodine volatility with time after LOCA

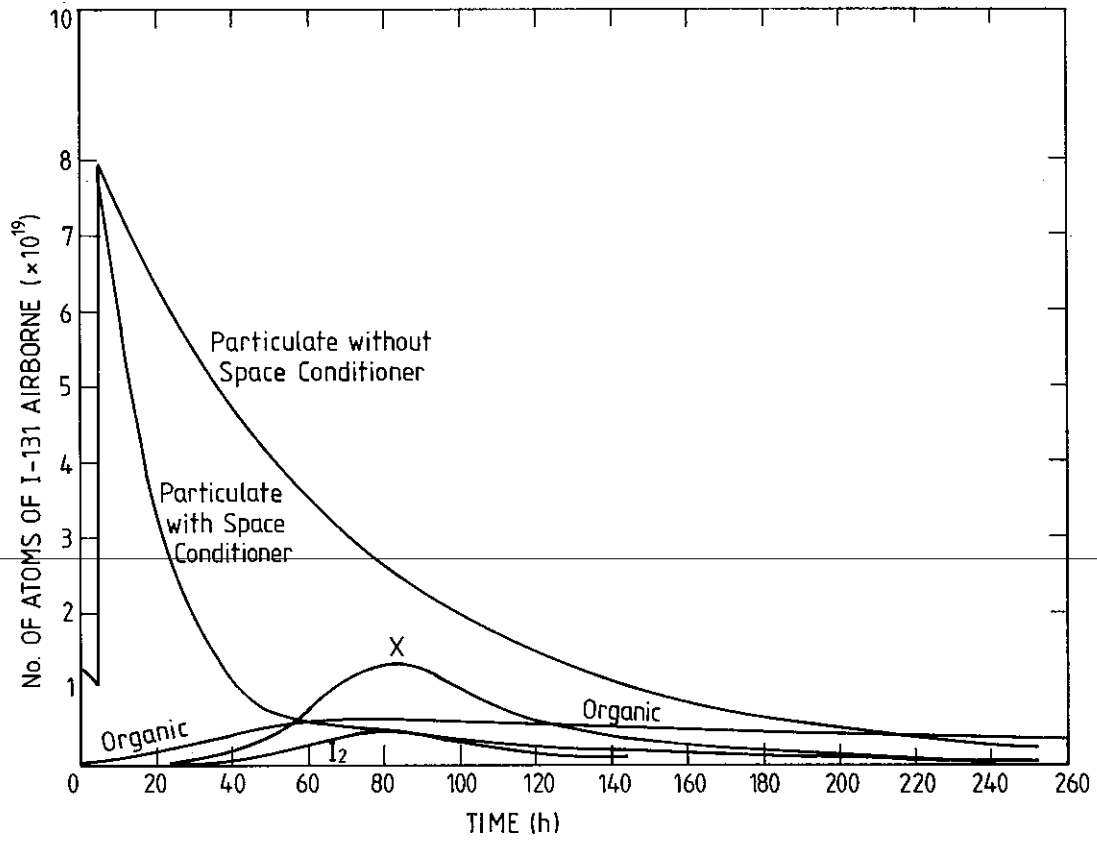


Figure 10 LOCA with space conditioners and without space conditioners

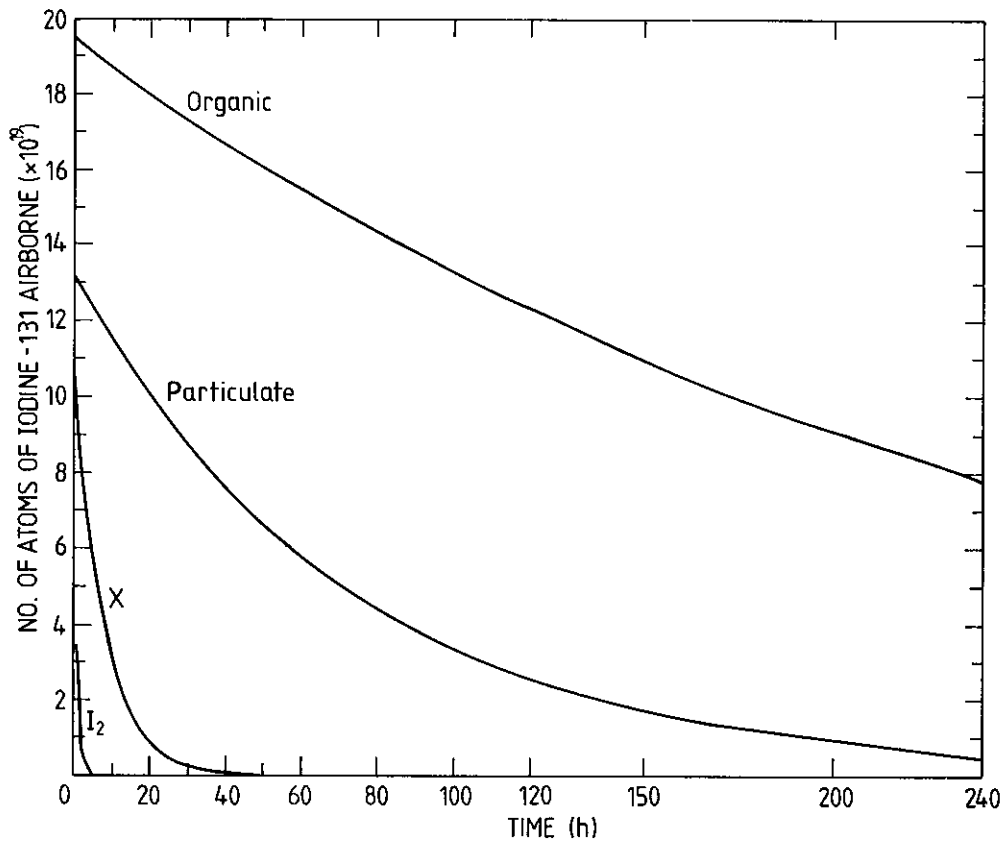


Figure 11 Dropped fuel element

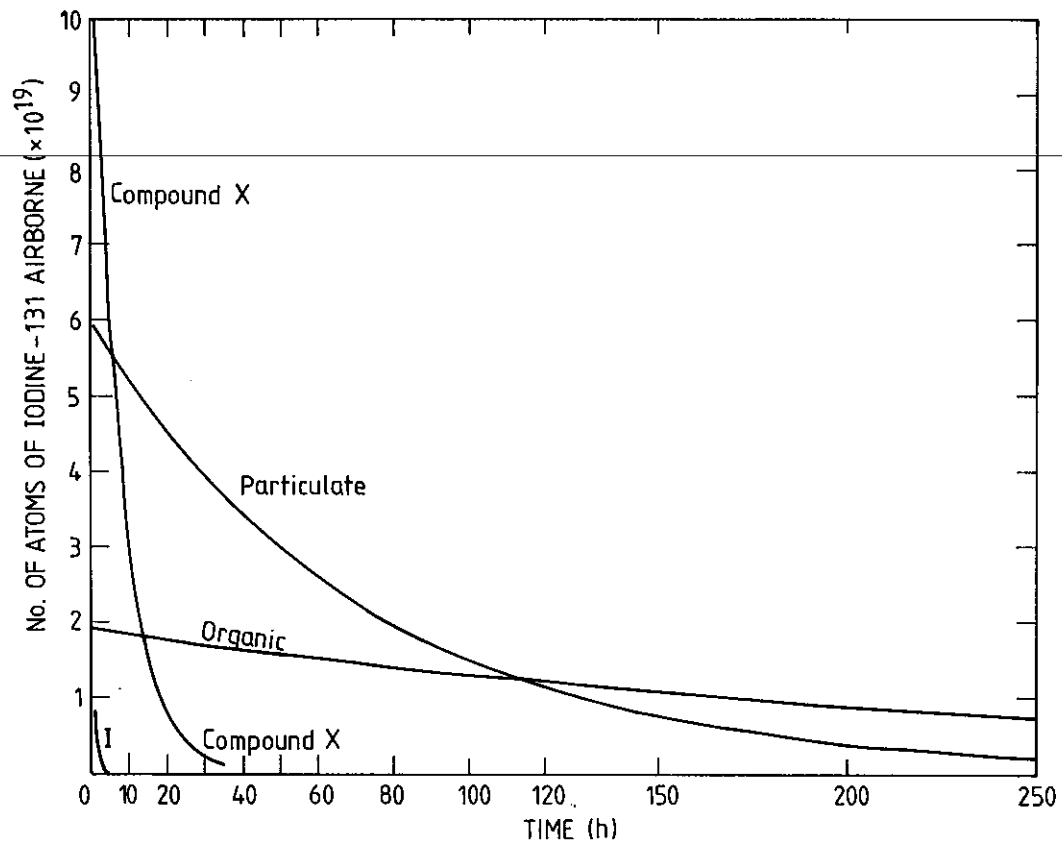


Figure 12 Storage block B

APPENDIX A
90% CONFIDENCE FACTOR

Arrhenius plots of the fission product release ratio, taken from the data of Parker et al. [1967], are given in figures 1, 2 and 3, for helium, steam-air and air, respectively. The release ratios at the melting point of the uranium-aluminium alloy, 650°C, were extrapolated from the lines of least squares fit for each element. The variance, $\sigma_{\hat{y}}^2$, in each extrapolated estimate was computed using the formula

$$\sigma_{\hat{y}}^2 = \left(\frac{\Sigma y^2 - \frac{(\Sigma y)^2}{n} - b \left\{ \Sigma xy - \frac{\Sigma x \Sigma y}{n} \right\}}{n - 2} \right) \cdot \left(\frac{1}{n} + \frac{\left\{ x_1 - \frac{\Sigma x}{n} \right\}^2}{\Sigma x^2 - \frac{(\Sigma x)^2}{n}} \right), \quad (A1)$$

where

$$y = \ln(\text{release ratio}) = \ln(f/(1-f))$$

$$x = 1/T, \text{ where } T \text{ is the absolute temperature,}$$

n is the number of experimental points,

b is the slope of the line of least mean squares fit,

x_1 = the reciprocal of the absolute temperature for which the prediction is being made (usually that corresponding to 650°C),

\hat{y} is the predicted value of y at x_1 , and

$\sigma_{\hat{y}}$ is the standard deviation in \hat{y} .

The 90% confidence limit in the extrapolated value is $1.283\sigma_{\hat{y}}$, and the 90 percentile upper and lower bounds to each estimate at various temperatures are shown by the dashed and dotted lines alongside the lines of least squares fit in figures 1, 2 and 3.

When \hat{y} is converted back into a release ratio, the 90% confidence limit becomes a 90% confidence factor (90% CF), i.e.

$$90\% \text{ CF} = e^{1.283\sigma_{\hat{y}}} \quad (A2)$$

and is the factor by which the most probable estimate must be multiplied (or divided) to obtain the 90 percentile upper (or lower) bounding estimate which is greater (or less) than 90% of all possible results. Note that for some parameters, the 90 percentile lower bounding estimate, for example deposition rates within the containment, is the value of interest since it is more conservative.

The standard deviation in \hat{y} is

$$\sigma_y^{\wedge} = \ln(90\% \text{ CF})/1.283 \quad (\text{A3})$$

Where additional parameters modify the estimated releases, an overall 90% CF must be computed. This is done by calculating the standard deviation in the estimate of each parameter from equation A3; squaring to obtain the variance; and summing the individual variances to obtain the overall variance, from which the overall 90% CF may be calculated from equation A2.

The velocity of deposition of the aerosol on walls within the containment was obtained from data of Chamberlain [1962] by performing a least squares fit on a log-log plot for particles under 2 micrometres depositing on smooth vertical surfaces. Equations A1 and A2 were used to determine the 90% CF values, y being the natural logarithm of the deposition velocity and x the natural logarithm of the particle diameter.

For those parameters in which the experimental data did not permit a statistical approach to the determination of the variance, an estimate was made of the possible spread in the results. The yardstick chosen was that there should not be more than one chance in 2000 that the parameter would be greater (or lower) than the estimated upper (or lower) bound. Assuming a log-normal probability distribution, the 99.5% confidence limit is 2.7 times the standard deviation. From this estimate the corresponding 90% CF can be calculated.

APPENDIX B
SOURCE TERM DESCRIPTION: LOCA, MOST PROBABLE VALUES

Time of second instantaneous release (hr)		5
Minimum fraction of elemental iodine airborne		0
Minimum fraction of inorganic iodine airborne (Compound X)		0
Return rate to plant room (per second)		3.10E-05
Deposition constants	elemental iodine (per hour)	2.08
	organic iodide (per hour)	0
	inorganic iodide (per hour)	.213
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	1.21E-03
	C2	1.39E-02

ELEMENT No.	RELEASE FRACTIONS	
	A	B
32	2.00E-14	1.00E-14
33	2.00E-14	1.00E-14
34	2.00E-14	1.00E-14
35	Br	3.97E-04 2.64E-03
36	Kr	4.95E-01 4.95E-01
37	Rb	5.67E-05 1.59E-05
38	Sr	1.60E-06 2.00E-16
39		2.00E-14 1.00E-14
40		2.00E-14 1.00E-14
41		2.00E-14 1.00E-14
42	Mo	1.00E-13 3.00E-13
43	Tc	1.00E-13 3.00E-13
44	Ru	3.57E-05 2.04E-05
45		2.00E-14 1.00E-14
46		2.00E-14 1.00E-14
47		2.00E-14 1.00E-14
48		2.00E-14 1.00E-14
49		2.00E-14 1.00E-14
50		2.00E-14 1.00E-14
51	Sb	2.70E-07 7.00E-14
52	Te	1.65E-04 7.88E-07
53	I	3.97E-04 2.64E-03
54	Xe	4.95E-01 4.95E-01
55	Cs	5.67E-05 1.59E-05
56	Ba	2.70E-07 7.00E-14
57		2.00E-14 1.00E-14
58		2.00E-14 1.00E-14
59		2.00E-14 1.00E-14
60		2.00E-14 1.00E-14
61		2.00E-14 1.00E-14
62		2.00E-14 1.00E-14
63		2.00E-14 1.00E-14
64		2.00E-14 1.00E-14
65		2.00E-14 1.00E-14
66		2.00E-14 1.00E-14

APPENDIX B (Continued)

VAPOUR RELEASE A : Elemental Iodine =	0
Organic Iodide =	0
Compound X =	0

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	1.24E-10
1.70E-01	1.26E-10
2.50E-01	1.27E-10
3.30E-01	1.29E-10
7.50E-01	1.33E-10
1.90E+00	1.51E-10
5.80E+00	2.31E-10
1.50E+01	5.77E-10
2.80E+01	1.77E-09
4.50E+01	7.27E-09
6.30E+01	2.39E-08
6.90E+01	3.19E-08
8.40E+01	3.81E-08
1.10E+02	2.04E-08
1.20E+02	1.63E-08
1.70E+02	4.97E-09
2.40E+02	1.35E-09
2.90E+02	7.10E-10
4.30E+02	4.61E-10
1.30E+03	4.44E-10
2.40E+03	4.44E-10

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	9.31E-10
1.70E-01	9.40E-10
2.50E-01	9.49E-10
3.30E-01	9.58E-10
7.50E-01	9.76E-10
1.90E+00	1.06E-09
5.80E+00	1.33E-09
1.50E+01	2.31E-09
2.80E+01	4.08E-09
4.50E+01	7.10E-09
6.30E+01	8.87E-09
2.40E+03	8.87E-09

APPENDIX C
SOURCE TERM DESCRIPTION: LOCA, 90% CONFIDENCE VALUES

Time of second instantaneous release (hr)		5
Minimum fraction of elemental iodine airborne		0
Minimum fraction of inorganic iodine airborne (Compound X)		0
Return rate to plant room (per second)		3.43E-05
Deposition constants	elemental iodine (per hour)	1.24
	organic iodide (per hour)	0
	inorganic iodide (per hour)	.127
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	7.56E-04
	C2	9.90E-03

ELEMENT No.	RELEASE FRACTIONS	
	A	B
32	1.00E-13	1.00E-14
33	1.00E-13	1.00E-14
34	1.00E-13	1.00E-14
35	Br	1.26E-03 6.55E-03
36	Kr	5.00E-01 5.00E-01
37	Rb	1.53E-04 4.15E-05
38	Sr	8.00E-06 8.00E-15
39		1.00E-13 1.00E-14
40		1.00E-13 1.00E-14
41		1.00E-13 1.00E-14
42	Mb	7.00E-13 2.00E-12
43	Tc	7.00E-13 2.00E-12
44	Ru	1.49E-04 5.45E-05
45		1.00E-13 1.00E-14
46		1.00E-13 1.00E-14
47		1.00E-13 1.00E-14
48		1.00E-13 1.00E-14
49		1.00E-13 1.00E-14
50		1.00E-13 1.00E-14
51	Sb	1.40E-06 4.00E-13
52	Te	4.21E-04 1.90E-06
53	I	1.26E-03 6.55E-03
54	Xe	5.00E-01 5.00E-01
55	Cs	1.53E-04 4.15E-05
56	Ba	1.40E-06 4.00E-13
57		1.00E-13 1.00E-14
58		1.00E-13 1.00E-14
59		1.00E-13 1.00E-14
60		1.00E-13 1.00E-14
61		1.00E-13 1.00E-14
62		1.00E-13 1.00E-14
63		1.00E-13 1.00E-14
64		1.00E-13 1.00E-14
65		1.00E-13 1.00E-14
66		1.00E-13 1.00E-14

APPENDIX C (Continued)

VAPOUR RELEASE A : Elemental Iodine = 0
 Organic Iodide = 0
 Compound X = 0

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	3.72E-10
1.70E-01	3.78E-10
2.50E-01	3.81E-10
3.30E-01	3.87E-10
7.50E-01	3.99E-10
1.90E+00	4.53E-10
5.80E+00	6.93E-10
1.50E+01	1.73E-09
2.80E+01	5.31E-09
4.50E+01	2.18E-08
6.30E+01	7.17E-08
6.90E+01	9.57E-08
8.40E+01	1.14E-07
1.10E+02	6.12E-08
1.20E+02	4.89E-08
1.70E+02	1.49E-08
2.40E+02	4.05E-09
2.90E+02	2.13E-09
4.30E+02	1.38E-09
1.30E+03	1.33E-09
2.40E+03	1.33E-09

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	2.79E-09
1.70E-01	2.82E-09
2.50E-01	2.85E-09
3.30E-01	2.87E-09
7.50E-01	2.93E-09
1.90E+00	3.18E-09
5.80E+00	3.99E-09
1.50E+01	6.93E-09
2.80E+01	1.22E-08
4.50E+01	2.13E-08
6.30E+01	2.66E-08
2.40E+03	2.66E-08

APPENDIX D

SOURCE TERM DESCRIPTION: DROPPED FUEL ELEMENT, MOST PROBABLE VALUES

Time of second instantaneous release (hr)		0
Minimum fraction of elemental iodine airborne		1.00E-10
Minimum fraction of inorganic iodine airborne (Compound X)		1.00E-09
Return rate to plant room (per second)		0
Deposition constants	elemental iodine (per hour)	2.08
	organic iodide (per hour)	0
	inorganic iodide (per hour)	.213
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	1.21E-03
	C2	1.39E-02

ELEMENT RELEASE FRACTIONS

No.		A	B
32		4.00E-15	0
33		4.00E-15	0
34		4.00E-15	0
35	Br	6.72E-04	0
36	Kr	3.96E-02	0
37	Rb	7.40E-05	0
38	Sr	4.00E-27	0
39		4.00E-15	0
40		4.00E-15	0
41		4.00E-15	0
42	Mo	8.00E-14	0
43	Tc	8.00E-14	0
44	Ru	4.32E-07	0
45		4.00E-15	0
46		4.00E-15	0
47		4.00E-15	0
48		4.00E-15	0
49		4.00E-15	0
50		4.00E-15	0
51	Sb	4.00E-15	0
52	Te	8.56E-08	0
53	I	6.72E-04	0
54	Xe	3.96E-02	0
55	Cs	7.40E-05	0
56	Ba	4.00E-15	0
57		4.00E-15	0
58		4.00E-15	0
59		4.00E-15	0
60		4.00E-15	0
61		4.00E-15	0
62		4.00E-15	0
63		4.00E-15	0
64		4.00E-15	0
65		4.00E-15	0
66		4.00E-15	0

APPENDIX D (Continued)

VAPOUR RELEASE A : Elemental Iodine = 6.16E-04
 Organic Iodide = 1.01E-03
 Compound X = 6.16E-04

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
6.90E+01	0
8.40E+01	0
1.10E+02	0
1.20E+02	0
1.70E+02	0
2.40E+02	0
2.90E+02	0
4.30E+02	0
1.30E+03	0
2.40E+03	0

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
2.40E+03	0

APPENDIX E
SOURCE TERM DESCRIPTION: DROPPED FUEL ELEMENT, 90% CONFIDENCE VALUES

Time of second instantaneous release (hr)		0
Minimum fraction of elemental iodine airborne		1.00E-09
Minimum fraction of inorganic iodine airborne (Compound X)		1.00E-08
Return rate to plant room (per second)		0
Deposition constants		
elemental iodine	(per hour)	1.24
organic iodide	(per hour)	0
inorganic iodide	(per hour)	.127
noble gases	(per hour)	0
Aerosol Deposition Coefficients :	C1	7.56E-04
	C2	9.90E-03

ELEMENT RELEASE FRACTIONS

No.		A	B
32		3.00E-14	0
33		3.00E-14	0
34		3.00E-14	0
35	Br	1.46E-03	0
36	Kr	4.00E-02	0
37	Rb	1.62E-04	0
38	Sr	2.00E-25	0
39		3.00E-14	0
40		3.00E-14	0
41		3.00E-14	0
42	Mo	6.00E-13	0
43	Tc	6.00E-13	0
44	Ru	1.03E-06	0
45		3.00E-14	0
46		3.00E-14	0
47		3.00E-14	0
48		3.00E-14	0
49		3.00E-14	0
50		3.00E-14	0
51	Sb	2.00E-14	0
52	Te	2.03E-07	0
53	I	1.46E-03	0
54	Xe	4.00E-02	0
55	Cs	1.62E-04	0
56	Ba	2.00E-14	0
57		3.00E-14	0
58		3.00E-14	0
59		3.00E-14	0
60		3.00E-14	0
61		3.00E-14	0
62		3.00E-14	0
63		3.00E-14	0
64		3.00E-14	0
65		3.00E-14	0
66		3.00E-14	0

APPENDIX E (Continued)

VAPOUR RELEASE A : Elemental Iodine =	1.36E-03
Organic Iodide =	2.22E-03
Compound X =	1.36E-03

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
6.90E+01	0
8.40E+01	0
1.10E+02	0
1.20E+02	0
1.70E+02	0
2.40E+02	0
2.90E+02	0
4.30E+02	0
1.30E+03	0
2.40E+03	0

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
2.40E+03	0

APPENDIX F
SOURCE TERM DESCRIPTION: STORAGE BLOCK FUEL MELT: A,
MOST PROBABLE VALUES

Time of second instantaneous release (hr)		0
Minimum fraction of elemental iodine airborne		3.00E-12
Minimum fraction of inorganic iodine airborne (Compound X)		1.00E-09
Return rate to plant room (per second)		0
Deposition constants	elemental iodine (per hour)	2.08
	organic iodide (per hour)	0
	inorganic iodide (per hour)	.213
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	1.21E-03
	C2	1.39E-02

ELEMENT No.	RELEASE FRACTIONS	
	A	B
32	4.00E-14	0
33	4.00E-14	0
34	4.00E-14	0
35	Br	8.06E-03
36	Kr	7.91E-01
37	Rb	8.86E-04
38	Sr	4.00E-26
39		4.00E-14
40		4.00E-14
41		4.00E-14
42	Mo	1.00E-12
43	Tc	1.00E-12
44	Ru	5.18E-06
45		4.00E-14
46		4.00E-14
47		4.00E-14
48		4.00E-14
49		4.00E-14
50		4.00E-14
51	Sb	4.00E-14
52	Te	1.08E-06
53	I	8.06E-03
54	Xe	7.91E-01
55	Cs	8.86E-04
56	Ba	4.00E-14
57		4.00E-14
58		4.00E-14
59		4.00E-14
60		4.00E-14
61		4.00E-14
62		4.00E-14
63		4.00E-14
64		4.00E-14
65		4.00E-14
66		4.00E-14

APPENDIX F (Continued)

VAPOUR RELEASE A : Elemental Iodine = 6.57E-04
 Organic Iodide = 1.00E-03
 Compound X = 1.55E-02

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
6.90E+01	0
8.40E+01	0
1.10E+02	0
1.20E+02	0
1.70E+02	0
2.40E+02	0
2.90E+02	0
4.30E+02	0
1.30E+03	0
2.40E+03	0

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
2.40E+03	0

APPENDIX G
SOURCE TERM DESCRIPTION: STORAGE BLOCK FUEL MELT: A,
90% CONFIDENCE VALUES

Time of second instantaneous release (hr)		0
Minimum fraction of elemental iodine airborne		3.00E-10
Minimum fraction of inorganic iodine airborne (Compound X)		1.00E-08
Return rate to plant room (per second)		0
Deposition constants	elemental iodine (per hour)	1.24
	organic iodide (per hour)	0
	inorganic iodide (per hour)	.127
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	7.56E-04
	C2	9.90E-03

ELEMENT **RELEASE FRACTIONS**

No.		A	B
32		4.00E-13	0
33		4.00E-13	0
34		4.00E-13	0
35	Br	1.75E-02	0
36	Kr	8.00E-01	0
37	Rb	1.94E-03	0
38	Sr	2.00E-24	0
39		4.00E-13	0
40		4.00E-13	0
41		4.00E-13	0
42	Mo	6.00E-12	0
43	Tc	6.00E-12	0
44	Ru	1.23E-05	0
45		4.00E-13	0
46		4.00E-13	0
47		4.00E-13	0
48		4.00E-13	0
49		4.00E-13	0
50		4.00E-13	0
51	Sb	2.00E-13	0
52	Te	2.44E-06	0
53	I	1.75E-02	0
54	Xe	8.00E-01	0
55	Cs	1.94E-03	0
56	Ba	2.00E-13	0
57		4.00E-13	0
58		4.00E-13	0
59		4.00E-13	0
60		4.00E-13	0
61		4.00E-13	0
62		4.00E-13	0
63		4.00E-13	0
64		4.00E-13	0
65		4.00E-13	0
66		4.00E-13	0

APPENDIX G (Continued)

VAPOUR RELEASE A : Elemental Iodine = 8.28E-03
 Organic Iodide = 2.19E-03
 Compound X = 3.41E-02

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
6.90E+01	0
8.40E+01	0
1.10E+02	0
1.20E+02	0
1.70E+02	0
2.40E+02	0
2.90E+02	0
4.30E+02	0
1.30E+03	0
2.40E+03	0

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
2.40E+03	0

APPENDIX H
SOURCE TERM DESCRIPTION: STORAGE BLOCK FUEL MELT: B,
MOST PROBABLE VALUES

Time of second instantaneous release (hr)		0
Minimum fraction of elemental iodine airborne		3.00E-12
Minimum fraction of inorganic iodine airborne (Compound X)		1.00E-09
Return rate to plant room (per second)		0
Deposition constants	elemental iodine (per hour)	2.08
	organic iodide (per hour)	0
	inorganic iodide (per hour)	.213
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	1.21E-03
	C2	1.39E-02

ELEMENT		RELEASE FRACTIONS	
No.		A	B
32		2.00E-14	0
33		2.00E-14	0
34		2.00E-14	0
35	Br	3.22E-03	0
36	Kr	3.17E-01	0
37	Rb	3.54E-04	0
38	Sr	2.00E-26	0
39		2.00E-14	0
40		2.00E-14	0
41		2.00E-14	0
42	Mo	5.00E-13	0
43	Tc	5.00E-13	0
44	Ru	2.07E-06	0
45		2.00E-14	0
46		2.00E-14	0
47		2.00E-14	0
48		2.00E-14	0
49		2.00E-14	0
50		2.00E-14	0
51	Sb	2.00E-14	0
52	Te	4.11E-07	0
53	I	3.22E-03	0
54	Xe	3.17E-01	0
55	Cs	3.54E-04	0
56	Ba	2.00E-14	0
57		2.00E-14	0
58		2.00E-14	0
59		2.00E-14	0
60		2.00E-14	0
61		2.00E-14	0
62		2.00E-14	0
63		2.00E-14	0
64		2.00E-14	0
65		2.00E-14	0
66		2.00E-14	0

APPENDIX H (Continued)

VAPOUR RELEASE A : Elemental Iodine = 2.54E-04
 Organic Iodide = 1.00E-03
 Compound X = 6.01E-03

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
6.90E+01	0
8.40E+01	0
1.10E+02	0
1.20E+02	0
1.70E+02	0
2.40E+02	0
2.90E+02	0
4.30E+02	0
1.30E+03	0
2.40E+03	0

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
2.40E+03	0

APPENDIX I
SOURCE TERM DESCRIPTION: STORAGE BLOCK FUEL MELT: B,
90% CONFIDENCE VALUES

Time of second instantaneous release (hr)		0
Minimum fraction of elemental iodine airborne		3.00E-10
Minimum fraction of inorganic iodine airborne (Compound X)		1.00E-08
Return rate to plant room (per second)		0
Deposition constants	elemental iodine (per hour)	1.24
	organic iodide (per hour)	0
	inorganic iodide (per hour)	.127
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	7.56E-04
	C2	9.90E-03

ELEMENT		RELEASE FRACTIONS	
No.		A	B
32		2.00E-13	0
33		2.00E-13	0
34		2.00E-13	0
35	Br	6.99E-03	0
36	Kr	3.20E-01	0
37	Rb	7.75E-04	0
38	Sr	7.00E-25	0
39		2.00E-13	0
40		2.00E-13	0
41		2.00E-13	0
42	Mo	2.00E-12	0
43	Tc	2.00E-12	0
44	Ru	4.94E-06	0
45		2.00E-13	0
46		2.00E-13	0
47		2.00E-13	0
48		2.00E-13	0
49		2.00E-13	0
50		2.00E-13	0
51	Sb	1.00E-13	0
52	Te	9.76E-07	0
53	I	6.99E-03	0
54	Xe	3.20E-01	0
55	Cs	7.75E-04	0
56	Ba	1.00E-13	0
57		2.00E-13	0
58		2.00E-13	0
59		2.00E-13	0
60		2.00E-13	0
61		2.00E-13	0
62		2.00E-13	0
63		2.00E-13	0
64		2.00E-13	0
65		2.00E-13	0
66		2.00E-13	0

APPENDIX I (Continued)

VAPOUR RELEASE A : Elemental Iodine =	3.20E-03
Organic Iodide =	2.19E-03
Compound X =	1.32E-02

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
6.90E+01	0
8.40E+01	0
1.10E+02	0
1.20E+02	0
1.70E+02	0
2.40E+02	0
2.90E+02	0
4.30E+02	0
1.30E+03	0
2.40E+03	0

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
2.40E+03	0

APPENDIX J
SOURCE TERM DESCRIPTION: SHEAR AND TRANSPORT FLASK: A,
MOST PROBABLE VALUES

Time of second instantaneous release (hr)		0
Minimum fraction of elemental iodine airborne		0
Minimum fraction of inorganic iodine airborne (Compound X)		0
Return rate to plant room (per second)		0
Deposition constants	elemental iodine (per hour)	0
	organic iodide (per hour)	0
	inorganic iodide (per hour)	0
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	0
	C2	0

ELEMENT No.	RELEASE FRACTIONS	
	A	B
32	2.00E-15	0
33	2.00E-15	0
34	2.00E-15	0
35	Br	2.42E-04
36	Kr	1.58E-01
37	Rb	2.66E-05
38	Sr	2.00E-27
39		2.00E-15
40		2.00E-15
41		2.00E-15
42	Mo	3.00E-14
43	Tc	3.00E-14
44	Ru	1.56E-07
45		2.00E-15
46		2.00E-15
47		2.00E-15
48		2.00E-15
49		2.00E-15
50		2.00E-15
51	Sb	2.00E-15
52	Te	3.08E-08
53	I	2.42E-04
54	Xe	1.58E-01
55	Cs	2.66E-05
56	Ba	2.00E-15
57		2.00E-15
58		2.00E-15
59		2.00E-15
60		2.00E-15
61		2.00E-15
62		2.00E-15
63		2.00E-15
64		2.00E-15
65		2.00E-15
66		2.00E-15

APPENDIX J (Continued)

VAPOUR RELEASE A : Elemental Iodine = 0
 Organic Iodide = 1.00E-03
 Compound X = 7.96E-04

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
6.90E+01	0
8.40E+01	0
1.10E+02	0
1.20E+02	0
1.70E+02	0
2.40E+02	0
2.90E+02	0
4.30E+02	0
1.30E+03	0
2.40E+03	0

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
2.40E+03	0

APPENDIX K
SOURCE TERM DESCRIPTION: SHEAR AND TRANSPORT FLASK: A,
90% CONFIDENCE VALUES

Time of second instantaneous release (hr)		0
Minimum fraction of elemental iodine airborne		0
Minimum fraction of inorganic iodine airborne (Compound X)		0
Return rate to plant room (per second)		0
Deposition constants	elemental iodine (per hour)	0
	organic iodide (per hour)	0
	inorganic iodide (per hour)	0
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	0
	C2	0

ELEMENT	RELEASE FRACTIONS		
	No.	A	B
	32	1.00E-14	0
	33	1.00E-14	0
	34	1.00E-14	0
	35 Br	5.84E-04	0
	36 Kr	1.60E-01	0
	37 Rb	6.48E-05	0
	38 Sr	8.00E-26	0
	39	1.00E-14	0
	40	1.00E-14	0
	41	1.00E-14	0
	42 Mo	2.00E-13	0
	43 Tc	2.00E-13	0
	44 Ru	4.11E-07	0
	45	1.00E-14	0
	46	1.00E-14	0
	47	1.00E-14	0
	48	1.00E-14	0
	49	1.00E-14	0
	50	1.00E-14	0
	51 Sb	8.00E-15	0
	52 Te	8.12E-08	0
	53 I	5.84E-04	0
	54 Xe	1.60E-01	0
	55 Cs	6.48E-05	0
	56 Ba	8.00E-15	0
	57	1.00E-14	0
	58	1.00E-14	0
	59	1.00E-14	0
	60	1.00E-14	0
	61	1.00E-14	0
	62	1.00E-14	0
	63	1.00E-14	0
	64	1.00E-14	0
	65	1.00E-14	0
	66	1.00E-14	0

APPENDIX K (Continued)

VAPOUR RELEASE A : Elemental Iodine = 0
 Organic Iodide = 2.22E-03
 Compound X = 2.72E-03

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
6.90E+01	0
8.40E+01	0
1.10E+02	0
1.20E+02	0
1.70E+02	0
2.40E+02	0
2.90E+02	0
4.30E+02	0
1.30E+03	0
2.40E+03	0

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
2.40E+03	0

APPENDIX L
SOURCE TERM DESCRIPTION: SHEAR AND TRANSPORT FLASK: B,
MOST PROBABLE VALUES

Time of second instantaneous release (hr)		0
Minimum fraction of elemental iodine airborne		0
Minimum fraction of inorganic iodine airborne (Compound X)		0
Return rate to plant room (per second)		0
Deposition constants	elemental iodine (per hour)	0
	organic iodide (per hour)	0
	inorganic iodide (per hour)	0
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	0
	C2	0

ELEMENT		RELEASE FRACTIONS	
No.		A	B
32		1.00E-14	0
33		1.00E-14	0
34		1.00E-14	0
35	Br	1.61E-03	0
36	Kr	1.58E-01	0
37	Rb	1.78E-04	0
38	Sr	1.00E-26	0
39		1.00E-14	0
40		1.00E-14	0
41		1.00E-14	0
42	Mo	2.00E-13	0
43	Tc	2.00E-13	0
44	Ru	1.04E-06	0
45		1.00E-14	0
46		1.00E-14	0
47		1.00E-14	0
48		1.00E-14	0
49		1.00E-14	0
50		1.00E-14	0
51	Sb	1.00E-14	0
52	Te	2.05E-07	0
53	I	1.61E-03	0
54	Xe	1.58E-01	0
55	Cs	1.78E-04	0
56	Ba	1.00E-14	0
57		1.00E-14	0
58		1.00E-14	0
59		1.00E-14	0
60		1.00E-14	0
61		1.00E-14	0
62		1.00E-14	0
63		1.00E-14	0
64		1.00E-14	0
65		1.00E-14	0
66		1.00E-14	0

APPENDIX L (Continued)

VAPOUR RELEASE A : Elemental Iodine =	1.18E-04
Organic Iodide =	1.00E-03
Compound X =	7.96E-04

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
6.90E+01	0
8.40E+01	0
1.10E+02	0
1.20E+02	0
1.70E+02	0
2.40E+02	0
2.90E+02	0
4.30E+02	0
1.30E+03	0
2.40E+03	0

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
2.40E+03	0

APPENDIX M
SOURCE TERM DESCRIPTION: SHEAR AND TRANSPORT FLASK: B,
90% CONFIDENCE VALUES

Time of second instantaneous release (hr)		0
Minimum fraction of elemental iodine airborne		0
Minimum fraction of inorganic iodine airborne (Compound X)		0
Return rate to plant room (per second)		0
Deposition constants	elemental iodine (per hour)	0
	organic iodide (per hour)	0
	inorganic iodide (per hour)	0
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	0
	C2	0

ELEMENT		RELEASE FRACTIONS	
No.		A	B
32		7.00E-14	0
33		7.00E-14	0
34		7.00E-14	0
35	Br	3.87E-03	0
36	Kr	1.60E-01	0
37	Rb	4.26E-04	0
38	Sr	4.00E-25	0
39		7.00E-14	0
40		7.00E-14	0
41		7.00E-14	0
42	Mb	1.00E-12	0
43	Tc	1.00E-12	0
44	Ru	2.70E-06	0
45		7.00E-14	0
46		7.00E-14	0
47		7.00E-14	0
48		7.00E-14	0
49		7.00E-14	0
50		7.00E-14	0
51	Sb	5.00E-14	0
52	Te	5.34E-07	0
53	I	3.87E-03	0
54	Xe	1.60E-01	0
55	Cs	4.26E-04	0
56	Ba	5.00E-14	0
57		7.00E-14	0
58		7.00E-14	0
59		7.00E-14	0
60		7.00E-14	0
61		7.00E-14	0
62		7.00E-14	0
63		7.00E-14	0
64		7.00E-14	0
65		7.00E-14	0
66		7.00E-14	0

APPENDIX M (Continued)

VAPOUR RELEASE A : Elemental Iodine = 1.33E-03
 Organic Iodide = 2.22E-03
 Compound X = 2.72E-03

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
6.90E+01	0
8.40E+01	0
1.10E+02	0
1.20E+02	0
1.70E+02	0
2.40E+02	0
2.90E+02	0
4.30E+02	0
1.30E+03	0
2.40E+03	0

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
2.40E+03	0

APPENDIX N
SOURCE TERM DESCRIPTION: SHEAR AND TRANSPORT FLASK: C,
MOST PROBABLE VALUES

Time of second instantaneous release (hr)		0
Minimum fraction of elemental iodine airborne		0
Minimum fraction of inorganic iodine airborne (Compound X)		0
Return rate to plant room (per second)		0
Deposition constants	elemental iodine (per hour)	0
	organic iodide (per hour)	0
	inorganic iodide (per hour)	0
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	0
	C2	0

ELEMENT **RELEASE FRACTIONS**

No.		A	B
32		2.00E-14	0
33		2.00E-14	0
34		2.00E-14	0
35	Br	2.69E-03	0
36	Kr	1.58E-01	0
37	Rb	2.96E-04	0
38	Sr	2.00E-26	0
39		2.00E-14	0
40		2.00E-14	0
41		2.00E-14	0
42	Mo	3.00E-13	0
43	Tc	3.00E-13	0
44	Ru	1.73E-06	0
45		2.00E-14	0
46		2.00E-14	0
47		2.00E-14	0
48		2.00E-14	0
49		2.00E-14	0
50		2.00E-14	0
51	Sb	2.00E-14	0
52	Te	3.42E-07	0
53	I	2.69E-03	0
54	Xe	1.58E-01	0
55	Cs	2.96E-04	0
56	Ba	2.00E-14	0
57		2.00E-14	0
58		2.00E-14	0
59		2.00E-14	0
60		2.00E-14	0
61		2.00E-14	0
62		2.00E-14	0
63		2.00E-14	0
64		2.00E-14	0
65		2.00E-14	0
66		2.00E-14	0

APPENDIX N (Continued)

VAPOUR RELEASE A : Elemental Iodine = 3.94E-03
 Organic Iodide = 1.00E-03
 Compound X = 3.94E-03

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
6.90E+01	0
8.40E+01	0
1.10E+02	0
1.20E+02	0
1.70E+02	0
2.40E+02	0
2.90E+02	0
4.30E+02	0
1.30E+03	0
2.40E+03	0

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
2.40E+03	0

APPENDIX O
SOURCE TERM DESCRIPTION: SHEAR AND TRANSPORT FLASK: C,
90% CONFIDENCE VALUES

Time of second instantaneous release (hr)		0
Minimum fraction of elemental iodine airborne		0
Minimum fraction of inorganic iodine airborne (Compound X)		0
Return rate to plant room (per second)		0
Deposition constants	elemental iodine (per hour)	0
	organic iodide (per hour)	0
	inorganic iodide (per hour)	0
	noble gases (per hour)	0
Aerosol Deposition Coefficients :	C1	0
	C2	0

ELEMENT		RELEASE FRACTIONS	
No.		A	B
32		1.00E-13	0
33		1.00E-13	0
34		1.00E-13	0
35	Br	6.45E-03	0
36	Kr	1.60E-01	0
37	Rb	7.10E-04	0
38	Sr	6.00E-25	0
39		1.00E-13	0
40		1.00E-13	0
41		1.00E-13	0
42	Mo	1.00E-12	0
43	Tc	1.00E-12	0
44	Ru	4.49E-06	0
45		1.00E-13	0
46		1.00E-13	0
47		1.00E-13	0
48		1.00E-13	0
49		1.00E-13	0
50		1.00E-13	0
51	Sb	8.00E-14	0
52	Te	8.90E-07	0
53	I	6.45E-03	0
54	Xe	1.60E-01	0
55	Cs	7.10E-04	0
56	Ba	8.00E-14	0
57		1.00E-13	0
58		1.00E-13	0
59		1.00E-13	0
60		1.00E-13	0
61		1.00E-13	0
62		1.00E-13	0
63		1.00E-13	0
64		1.00E-13	0
65		1.00E-13	0
66		1.00E-13	0

APPENDIX O (Continued)

VAPOUR RELEASE A : Elemental Iodine = 9.07E-03
 Organic Iodide = 2.22E-03
 Compound X = 9.07E-03

RELEASE RATES OF ELEMENTAL AND INORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
6.90E+01	0
8.40E+01	0
1.10E+02	0
1.20E+02	0
1.70E+02	0
2.40E+02	0
2.90E+02	0
4.30E+02	0
1.30E+03	0
2.40E+03	0

RELEASE RATES OF ORGANIC IODIDE

Time hours	Release Rate per second
0.0	0
1.70E-01	0
2.50E-01	0
3.30E-01	0
7.50E-01	0
1.90E+00	0
5.80E+00	0
1.50E+01	0
2.80E+01	0
4.50E+01	0
6.30E+01	0
2.40E+03	0