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THE TECHNICAL BASIS OF 'SPECTRAL SOURCE TERMS'
FOR ASSESSING UNCERTAINTIES IN FISSION PRODUCT
RELEASE DURING ACCIDENTS IN PWRs WITH SPECIAL
REFERENCE TO SIZEWELL-B.

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The Technical Basis of 'Spectral Source Terms'
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Reference to Sizewell-B

by

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SUMMARY

A probabilistic approach is described by which the conservatisms inherent in the traditional approach to determine FWR accident release source terms, exemplified by the Reactor Safety Study (WASH-1400), may be assessed, and 'spectral source terms' generated. The method is developed by analysing the mechanisms of fission product retention in the reactor primary circuit and the conservatisms built into the conventional treatment of transport through the containment and leak path to the release point. Detailed probability distributions are derived for the reduction factors applicable to the point value source term at successive transport stages in a number of accident sequences, and the general value and validity of the approach is discussed.

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1. Introduction

When Westinghouse were commissioned to carry out a probabilistic study of degraded core accidents for the Sizewell B reactor an important question was how best to estimate the fission product release fractions. Methods had been developed for the Reactor Safety Study (RSS)[1] and these had subsequently been used extensively in probabilistic risk analyses. However, in the intervening years, questions have arisen concerning the adequacy of the RSS release fractions. In the past few years, particularly, many authors have expressed the view that the RSS values are unduly conservative and that the release fractions should be re-evaluated in order to demonstrate that lower, and perhaps much lower values are justifiable. In particular, Levenson and Rahn[2] utilized evidence from previous accidental releases of radioactive materials to claim that 'natural processes' would serve to mitigate releases of activity to the environment. This focussed the attention of the technical community on the need to develop a more comprehensive understanding of these 'natural processes', and particularly of their effectiveness during a severe accident in a light water reactor.

The approach adopted by the authors of the RSS was determined by the information and time available to them. In its crudest form, this meant that where data or models were considered inadequate, an upper bound, or conservative approach was used. This is exemplified in their treatment of the primary circuit; calculations of the core heat up rate following loss of core cooling clearly show that most of the volatile fission products would be released into the reactor pressure vessel (RPV) and hence to the primary circuit before RPV failure. Even though the fission product transport pathway clearly led through the primary circuit, it was judged that the conditions of flow, temperature and internal structural arrangements were so complex and the processes so imperfectly understood that no reasonable calculations could be made. Consequently, application of the conservative approach meant that no retention of fission products in the

primary circuit was claimed. When compounded with other conservatisms, eg the amount of core material which would melt, the time of RPV failure and even such quantities as the time and mode of containment failure, this assumption has led to the widely held belief that the amounts of materials and hence the consequences of such an accident have been over-estimated. To be fair, the authors of the RSS recognised these issues and indeed presented a detailed discussion of, for example, primary circuit retention, before concluding that they must disregard it.

Three major reviews of fission product transport processes have been commissioned in the past two years, NDR610(S)[3] 'PWR degraded core analysis' (particularly chapters 2 and 7); NUREG 0772[4] 'Technical basis for estimating fission product behaviour during LWR accidents' and NUS 3808[5] 'Source Terms: an investigation of uncertainties, magnitudes and recommendations for research'. In addition, many papers referred to in these documents address particular technical areas. The general conclusion, agreed by the authors of all of these documents, is that whilst there is a considerable weight of evidence to give high confidence that the releases will be lower than suggested in the RSS, the 'state of the art' was such that quantitative justification was still some way off. There was however a consensus as to the requirements for future research needed to provide the necessary data, and many countries, including the UK, are now actively engaging in this work.

In an area as complex and diverse as fission product transport in a light water reactor system, a fully verified and accepted set of data may not become available for some time. The values obtained using RSS type methodology have been used as the baseline for evaluating the risk posed by the reactor from severe accidents. However, as there is such a weight of evidence supporting a change from the RSS values we have attempted, as an interim measure, to provide in this paper our current best judgement of the reductions which can be claimed using the information available to us. The values thus obtained have been

used in the calculations reported in NRPB R137[6] to provide an indication of the expected concomitant reductions in consequences.

We follow a procedure developed for the Zion and Indian Point Studies[7] for expressing uncertainties in the release fractions. This procedure is based on the concept of applying a set of discrete factors to the initial release fractions derived from the conservative methodology. The values derived in WCAP9991[9] are referred to as the 'first estimates' and they are in the form referred to as 'point values'. For a particular release category a set of discrete factors are chosen, typically 1, 1/2, 1/4, 1/10 and 1/20 of the point values. (Note that in some rare instances a class having a multiplying factor greater than 1 may be necessary if the specifics of the design of the plant or accident sequence evolution indicate that the nearest RSS value could be optimistic). To each of these factors we assign a probability that this release will be realized. A 'spectral distribution' of probabilities is thus generated, and we adopt the nomenclature 'spectral source term method' for this approach. The release fractions so obtained are called the second estimates. The principal issue addressed in this paper is the generation of the grounds for choosing the appropriate probabilities.

In the previous applications of this methodology, probabilities were assigned globally to the overall release fractions and the choice relied heavily upon expert judgement[7]. Here we extend and develop the method so that considerably more of the details of the accident sequence are directly addressed when assessing the uncertainties. Furthermore, judgement is replaced wherever possible by calculations, albeit in some instances rather crude calculations. This finer detail is achieved in the first instance by considering the three principal phases or 'sites' which influence fission product migration. Thus, retention

in the primary circuit, deposition within the containment due to natural processes and engineered safeguards and any mitigation due to the influence of the final leakage path to the environment are all treated separately.

It is clearly possible, in principle at least, to take the detailed investigations to a very fine level. The extent to which this is justifiable depends upon both the information and modelling capabilities available and the overall level of uncertainty in the whole probabilistic risk assessment process. At present, the level of detail described here is considered sufficient commensurate with all the other uncertainties inherent in the assessment of accident sequence progression.

There are three basic sources of uncertainty which need to be addressed. The methods described here permit each of them to be allowed for in the overall assessment. They are described below;

First the derived release categories may contain contributions from diverse sequences which reflect these phenomena to different extents, and we include here uncertainties associated with the combination of the various sequences into categories.

Second as we shall see later, the details of accident progression strongly affect the release and transport of fission products. Questions relating to the core heat-up rate, thermal-hydraulic conditions, fraction of core involved, occurrence of steam explosions, and timing and mode of debris dispersal following RPV failure, all influence the fission product behaviour, and generate uncertainties.

Third are what might be described as 'fundamental issues'. The detailed understanding of the physical and chemical processes (and, very importantly their inter-relationship) has uncertainties connected with it. This is at a level of both the mechanistic understanding and of the mathematical models

for realising this understanding. An example of this is the nucleation processes for the formation of aerosols. Presently there are reasonably comprehensive models available for aerosol behaviour, but this prejudices whether an aerosol could be formed in the first place. On the chemistry side, the chemical form of iodine is important, since it is now thought that CaI forms a particulate with quite different physical properties from the gaseous I_2 species previously assumed.

This paper considers both the generic problems associated with defining release fractions for a large, dry-containment, modern PWR of the Sizewell type and the specific application to this design. The results and discussion concerning the basic issues can readily be utilized for other reactor systems of this type and the results are deliberately presented in such a form as to make this as transparent as possible.

Because the second estimate release fractions were required early in the course of this study in order to permit the consequence calculations to be performed, some of the detailed separate effects calculations reported here could not be taken into account at that stage. This means that the distributions which can be derived from the calculations reported below have detailed differences from those used in the consequence analysis and repeated in Appendix M of the CECB's statement of case. Three specific examples should be noted. First, in section 4 we consider the effect of taking into account a realistic assessment of the internal surface area and available volume of the containment on the deposition of aerosols. For cases of delayed overpressure failure, where many hours are available for these processes to operate, these effects can be large, but the original results were in fact based on considerations appropriate to prompt containment failure. The text describes the situation applicable to the delayed failure but the final results quoted use only the more conservative prompt failure analysis. Second, during the course of this study parallel efforts were

underway to reassess the frequencies of the various accident sequences. This means that the final composition of the release categories was somewhat different from that assumed at the time this study began and used in the final values quoted here. Third, when the interfacing systems LOCA was first analysed, the dominant contribution was assessed to arise from failures in the valves separating the low pressure systems and the cold legs of the primary circuit. However, the most up-to-date analysis indicates that it is the hot leg connections which dominate. Thus, the analysis, presented in section 3 is for the hot leg situation. Table 3.4 gives the results of this analysis, whilst table 6.1 shows the results used in the consequence calculations. The differences are very small, and the analysis in section 3 contains all of the arguments pertinent to either the hot or cold leg situations.

The body of the paper is organised in the following way. Section 2 defines the spectral source term methodology and, in particular discusses in detail how the second estimate release fractions are derived from the information presented in the rest of the paper. In particular, it discusses the mathematical methods used to combine the discrete probabilities in a conservative way.

Section 3 covers the generally important area of primary circuit retention, firstly by detailing the general mechanisms by which fission products in either vapour or particle form can be deposited and trapped within the circuit and secondly by giving specific examples. The first example is the "interfacing systems LOCA" (the V sequence of the RSB). Here, we utilize calculations of the circuit conditions, temperatures, mass flow rates, etc to provide a detailed examination of the primary circuit retention. In addition, the influence of the residual heat removal circuits on fission product retention is examined. As with all of the examples given in the paper we give the calculated probability distributions at each stage of the transport pathway. Large break LOCA's, small break LOCA's and transient events are likewise each treated in detail. In all

of these examples we emphasise the additional information demanded from the plant engineers to satisfy the needs of a better estimate of fission product retention. The most obvious example arises when studying the large break LOCA. A hot leg break leads to little calculated retention as the flow path from the core to the break is short. However, a cold leg break requires that the volatile fission products pass through at least one steam generator before reaching the break. The differences in primary circuit retention in the two cases are large and it is necessary to obtain estimates of the relative frequency of hot to cold leg breaks to properly assess the primary circuit retention. A summary table of distributions for these four dominant accident types is given which can then be used appropriately in an overall estimate of the releases.

The next stages in the release pathway are the containment building and the leak path, which may include the auxiliary building. (This is excepting the interfacing LOCA V sequence which bypasses containment and only involves the auxiliary building). Section 4 addresses containment and auxiliary building fission product retention and Section 5 considers retention in leakage paths. Again, the general mechanisms available for retention are examined before detailed examples are given. The basic philosophy is the same as that for the primary circuit, but, of course, this part of the pathway was treated in the RSS. We are therefore concerned with estimating the conservatism in the original models used to calculate the 'point' estimates. In addition, the RSS 'point' values were calculated for only the early containment failure modes (except for basemat melt-through). The Zion and Indian Point PRA studies as well as the specific Sizewell B calculations indicate that there will be a delay of many hours in some cases before containment overpressure failure - thus even using exactly the same techniques as the RSS would lead to reductions in the 'point values'. This complicates the interpretation of the 'benefit' of the state-of-the-art methodology and we return to this point below.

In Section 6, the results obtained for the three stages of fission product migration are brought together to provide the second estimate release fractions for the Sizewell B reactor.

Finally, Section 7 includes a discussion and the conclusions of this study.

2. Spectral Source Term Methodology

This section defines in detail how the second estimate release fractions are calculated in the rest of the paper. The distinction between point value and spectral source terms is made, and the description of releases in terms of release categories and chemical classes[8] is reviewed. Then the discretisation of the distributions and the way in which they are obtained are presented. Finally the way in which these distributions are processed to make a final result is defined and illustrated using a particular example.

2.1 Point Value and Spectral Source Terms

As defined in [8], the source term consists of two different sorts of information about the release: the release fractions, the amounts of the various fission product species released, expressed as fractions of their core inventories at the start of the accidents, and the release characteristics, consisting of such information as the energy content, timing, duration and height of the release. In this work we are concerned with the release fractions only. In particular the term "spectral source term" (a short form of "spectral representation of source term release fractions") refers to a probability distribution over possible values of a release fraction.

The first-estimate release fractions are calculated using the methodology of the WASH-1400 study[1]. The application of these methods to the Sizewell-B design and various improvements in them is described in WCAP-9991[9]. The first-estimate release fraction $\phi^{(1)}$ is given by the formula

$$\phi^{(1)} = c \phi_c^{(1)} \quad \dots (2-1)$$

Here c is the fraction of the core inventory of the species in question which is released from the core in the accident being considered, and $\phi_c^{(1)}$ is the first-estimate fraction of the amount of the species entering the containment which is subsequently released to the environment. The core release fractions,

ϕ_i are those of WASH-1400, and the containment release fractions, $\phi_c^{(1)}$, are calculated using the CORRAL code, which uses first-order modelling to predict rates of plate-out of vapour, deposition of particulate, and spray washout. For some accident conditions the CORRAL results come directly from WASH-1400, while for others new CORRAL runs were specially commissioned.

The first-estimate calculation makes no allowance for retention in the primary circuit, in leak paths from the containment to the environment and, in cases where the release is to the auxiliary building instead of to the containment, in the auxiliary building. The second-estimate calculation attempts to take account of retention in these sites, as well as to improve the modelling of retention in the containment. But as well as attempting more detailed modelling of fission product transport, the second estimates differ from the first in the way they are used to present the results. For each accident the first estimate gives a single release fraction value for each species. This number is called a point value. By contrast the second estimate replaces this number by a probability distribution over a range of release fraction values, a so-called spectral source term. The use of the spectral methodology reflects the nature of the derivation of second-estimate release fractions. They are not calculated by a self-consistent and validated modelling of all the processes believed to be going on in the system. Rather they are based on expert judgement supplemented by separate effects calculations where possible. The spectral methodology allows the experts to express a judgement on how uncertain their results are. The arguments deployed in this paper for source term reductions are not intended as a substitute for the full modelling exercise. Instead they should be regarded as part of the initial scoping calculations, used here to provide interim estimates on likely conservatism in the first-estimate methodology, based on a general understanding of the relevant physics and chemistry.

2.2 Release Categories and Chemical Classes

For each of the many possible end conditions indicated by the Sizewell B severe accident event tree there will be a corresponding source term. To simplify the problem of dealing with large numbers of source terms in consequence calculations a decision was taken in WCAP-9991 to group those which are sufficiently similar into so-called release categories. The set of release fractions assigned to each release category is thereafter regarded as being conservatively representative of amounts released in all the accidents belonging to the category. In other words, the WCAP-9991 method of grouping events at pinch points was used to discretise further the wide spectrum of possible releases from the many accident sequences. This approach was also used in WASH-1400, but the discretisation for Sizewell B is finer than that in WASH-1400. Care is taken to ensure that the release fractions assigned to a particular release category constitute a reasonable upper bound to those for its constituent accident sequences.

Because the first estimates of the release fractions assume that no fission products are retained in the primary circuit, it is possible to define the categories on the basis of events in the containment. Thus the different release categories contain accidents that include the same key in containment events from amongst the following:

1. containment by-pass
2. early overpressure failure of the containment
3. an ex-vessel steam explosion leading to an enhancement of fission product release via oxidation mechanisms.
4. containment isolation failure or small containment by-pass.
5. late overpressure failure of the containment
6. vaporisation release
7. containment basement failure
8. containment spray system failure
9. successful maintenance of containment integrity and isolation.

Primary-circuit-related events play little part in this classification because primary circuit retention is not modelled in the first-estimate calculations. In all twelve release categories (UK1 - 12) were defined, and are briefly described in Table 2.1.

Of these twelve categories, five, namely UK1, 2, 5, 6 and 12 were selected for application of the spectral source term methodology to the derivation of second-estimate release fractions. The selection was made on the grounds that the chosen categories covered most of the source term phenomena of interest in a study of this kind, and also that they were the categories likely to dominate the risk.

Just as accidents are grouped into release categories, so all the chemical species which could possibly be released are grouped into eight chemical classes, according to the characteristics of their release from the core and transport through the system. The classes are based on those of WASH-1400, and are listed in Table 2.2. For this study only two classes are of interest: inorganic iodine-containing vapours (class 3) and alkali metal compounds (class 4). These are usually referred to as "iodine vapour" and "caesium particulate" respectively, following the principal contributors to the classes. Organic iodine has been omitted from consideration because its contribution to the consequences is small compared with other iodine forms for the higher release categories, even when the second estimate values for the other forms are employed. The analysis for caesium particulate also applies to any particulate material released predominately at the melt release phase (ie when the core is still in the reactor pressure vessel), but not to the more refractory materials released mainly when the core debris is on the floor of the containment. Clearly the primary circuit reductions are not applicable to releases from the core material which occur in the containment itself.

In this work the analysis is carried through for both iodine vapour and caesium particulate. However the balance of current evidence suggests that most of the iodine will be transported in the form of caesium iodide. Therefore the final results give spectral source terms for the caesium particulate only, a class

assumed applicable to the transport of iodine, caesium and probably tellurium as well. The switch of attribution of iodine transport from vapour to particulate also causes a change in the first-estimate release fractions as described in Section 6.

2.3 Discrete Probability Distributions

For each release category and for each chemical class of interest we start with a first-estimate release fraction, $\phi^{(1)}$. It is convenient to express the second-estimate release fractions, $\phi^{(2)}$, as ratios in terms of the factor (F) by which the first estimates are modified, namely

$$F = \phi^{(2)} / \phi^{(1)} \quad \dots (2-2)$$

Expressing results this way shows clearly how going beyond the WASH-1400 methodology changes the amounts released. Note that in this work there are many different fractions and fractions of fractions. Particular care is needed in keeping track of which is which. As explained above the second estimate is not a single value of F but rather a probability distribution over the possible values of F. To simplify the manipulation of these distributions and to avoid giving the results an aura of accuracy beyond their merit the continuous range of values of F is replaced by a discrete set of representative values, F_i , where $i = 1 \dots, N$. For the present study N is chosen to be 6, and the values chosen are

$$2, 1, 1/2, 1/4, 1/10, 1/20$$

The spectral source term is then a discrete probability distribution (DPD), a set of six numbers, $P(F)$, such that

$$0 \leq P(F_i) \leq 1 \quad \text{and} \quad \sum_{i=1}^6 P(F_i) = 1 \quad \dots (2-3)$$

Because F is after all a continuous variable, $P(F_i)$ is not the probability that F is exactly F_i , but rather the probability that it lies in some (unspecified)

interval around F_i . If a point value release fraction associated with the second estimates is required then the DPD mean,

$$\bar{F} = \sum_{i=1}^6 P(F_i) F_i \quad \dots (2-4)$$

can be used.

2.4 Deposition Stages

As the fission product moves from the degraded core to the environment there are distinct stages in its deposition. For release from the containment these are: primary circuit (P), containment building (C) and leak path (L). In UK1 the release is to the auxiliary building, so the stages are two: P and auxiliary building (A). For the second estimate each stage of the transport process is treated separately so that equation (2-1) is replaced by

$$\phi^{(2)} = \phi \phi_P^{(2)} \phi_C^{(2)} \phi_L^{(2)} \quad \dots (2-5)$$

except for UK1 where the form is

$$\phi^{(2)} = \phi \phi_P^{(2)} \phi_A^{(2)} \quad \dots (2-6)$$

(Note that to deal with the refractory oxides released at vaporisation phase directly into the containment (2-5) should be used with the $\phi_P^{(2)}$ factor removed). It is useful to define a second to first estimate ratio for each stage. The two equations above then become

$$F = F_P F_C F_L \quad \dots (2-7)$$

$$F = F_P F_A \quad (\text{for UK1}) \quad \dots (2-8)$$

Note that because the first estimate has deposition in C only, (ie $\phi_{P,L,A}^{(1)} = 1$)

$$F_{P,L,A} = \phi_{P,L,A}^{(2)} \quad \dots (2-9)$$

Although equations like (2-5) and (2-6) involving products of fractions are strictly true for any sequential processes, the use of fractions, ϕ , rather than the masses of the materials is strictly appropriate only when the fraction deposited is independent of the mass airborne. This is equivalent to the assumption that deposition is a first-order process, the rate of deposition of mass being directly proportional to mass airborne. With aerosols, agglomeration, a second-order process, can affect the rate of deposition. If this is a significant effect then one must work with masses of substances airborne and not just fractions of core inventory. Of course the final results can be expressed as a fraction, but this is no longer their natural representation. These caveats having been made, we continue to deal with the fractions in the present work, as we are interested in deviations from first estimates, estimates whose natural expression is in terms of fractions.

Expert judgement is applied to fission product transport and deposition to each sequential stage separately, and separate DPDs are arrived at for each of the fractions F_p , F_C , F_L and, for UKI, F_A , based on the six representative values F_i defined above. These separate-stage DPDs are the interface between the expert judgement and the statistical methodology defined in subsection 2.6 below, a process which converts them into an overall DPD for F . They themselves are not produced by some well-defined algorithm, but rather are a numerical expression of the uncertainties discovered in the review of first-estimate conservatisms. How these results are arrived at is described in Sections 3, 4 and 5.

2.5 Derivation of Separate-Stage DPDs

The first-estimate methodology uses various simplifications. At this stage of progress in modelling of fission product transport in PWR's going beyond these simplifications involves uncertainties; the purpose of the spectral methodology is to reflect these uncertainties and provide data upon which their importances can be judged. The original choice of how to make the simplifications was

intended to be conservative, so most of the statistical weight falls on the values $F_i \leq 1$. However the value $F_i = 2$ is allowed for to take account of cases where more sophisticated modelling could predict a release fraction greater than the first-estimate point value.

The uncertainties which go to make up the separate-stage DPDs are of three kinds:

1. Uncertainties in description of categories in terms of sequences
2. Uncertainties in knowledge of physical conditions in a sequence
3. Uncertainties in modelling consequences of physical conditions

As explained in 2.2, different accident sequences are grouped together into the same release categories, and the different sequences will have different first-estimate release fractions. Strictly speaking these differences are not uncertainties; the fractional contributions of each sequence to a category are known, and the release fractions could be added together weighted by these fractions to produce a category mean. However it is convenient to treat this question under the heading of uncertainties for the following reason. The point value for the category is taken to be one of point values of the contributing sequences. Allowances for the other sequences can be expressed by giving weight to non-unit values of F_i in the second-estimate spectral source term. On top of this there will in general be differences between the sequences in the way the uncertainties of the second and third kinds cause departures from the respective point values. In this case second-estimate release fractions should be divided by the category point value to calculate F , not that of the sequence under discussion.

Differences between first estimates for contributing sequences apply only to the containment building; first-estimate release fractions are all unity for other

stages. In fact differences between the sequences are small in the containment, and largest in the primary circuit. Containment building uncertainties of the second and third kinds are calculated without reference to sequence difference. By contrast the primary circuit modelling is carried out on a sequence-by-sequence basis.

In the present work the sequence results are not combined at the separate-stage DPD level. The categories UK5 and UK6 are split into subcategories A and B corresponding to large and small break LOCAs respectively, each with a different primary circuit DPD. An overall DPD is calculated for each subcategory, and only then were the results for the different sequences combined. For the final categorization used in the consequence calculations, the weighted average of these subcategories was used.

Once the choice of sequence has been fixed, or decided to be unimportant, there are still uncertainties as to the physical and chemical conditions which then obtain within the reactor system. For example, the amount of plate-out in the primary circuit following a LOCA depends strongly on the position of the break and on the subsequent flow pattern. Deposition in the containment depends on the surface area and free volume available. Uncertainties in these and similar factors are allotted to the second kind. Finally even when these conditions are well-defined there are still uncertainties in our basic knowledge of how to model the physical and chemical phenomena.

The separate-stage DPDs are derived from considerations of these diverse uncertainties. As explained earlier the procedure for doing this is based on judgement rather than on an algorithm. The uniform appearance of the DPDs conceals the fact that the sources and reliability of the input information vary considerably from case to case. In the reduction to a uniform format, a well-defined algorithm is applied. This is the subject of the next subsection.

2.6 Combining the Distributions

The probability of getting a particular sequence of reductions, (F_P, F_C, F_L) , is taken to be the product of the separate probabilities:

$$P(F_P, F_C, F_L) = P(F_P) P(F_C) P(F_L) \quad \dots (2-10)$$

Pre-empting the detailed rationalization in the rest of this paper we take for example, the case of particulate material in release category UK2. The separate-stage distributions are

F_i	2	1	1/2	1/4	1/10	1/20
$P(F_P)$	0	0.25	0	0.3	0.45	0
$P(F_C)$	0.1	0.4	0.4	0.1	0	0
$P(F_L)$	0	0.3	0.3	0.3	0.1	0

The probability of the sequence $(F_P = 1/4, F_C = 1/2, F_L = 1/2)$ is then

$$P(1/4, 1/2, 1/2) = 0.3 \times 0.4 \times 0.3 = 0.036$$

However it is not the sequence of reductions that are of interest, only the products. So we sum over all sequences of fractions with the same product. This can be expressed symbolically using Kronecker delta notation ($\delta_{A,B} = 1$ if $A = B$, $= 0$ if $A \neq B$):

$$P(F) = \sum_{F_P, F_C, F_L} \delta_{F, F_P F_C F_L} P(F_P) P(F_C) P(F_L) \quad \dots (2-11)$$

In our example the sequences of fractions with non-zero probability which lead to $F = 1/16$ are: $(1, 1/4, 1/4)$, $(1/4, 1, 1/4)$, $(1/4, 1/2, 1/2)$ and $(1/4, 1/4, 1)$. Therefore

$$P(1/16) = 0.0075 + 0.036 + 0.036 + 0.009 = 0.0885$$

This gives us an overall DPD, but one defined for a fraction not contained in the original set of six. To reduce the result to a DPD based on this original

set of F_i values we use a process called conservative condensation. This simply means that the probabilities of fractions not on the original list are added into the probabilities of the next largest fractions which are on the list. In our example $P(1/16)$ is added to $P(1/10)$ and the result is the new $P(1/10)$. Thus, the final results may be considerable overestimates of the release using this method. The effects of conservative condensation on the UK2 distribution are shown on Figure 2.1.

It is important to note that the use of the product rule in (2-10) requires an assumption of statistical independence, namely that the retention expected in the containment does not depend on retention in the primary circuit, and that leak path retention does not depend on what has gone on in the other two stages. This will be true for deposition mechanisms which are first order in the concentration, but not, for example, for aerosol agglomeration. Care has to be taken in claiming release reductions when this independence assumption might not be valid.

2.7 Concluding Remarks

In the present state of development of source term technology the spectral methodology may appear to conflict with the rationale of defining release categories. The spectral spread within a release category may overlap the point values of one or more adjacent categories. Therefore it might be that in principle the different release fractions in the distributions should be assigned to different release categories. However such an approach would be difficult and confusing to apply in practice, and there are countervailing arguments. The spectral methodology, as distinct from its specific application presented in the remainder of this work, is intended to be of continuing utility for the long-term future, when it is anticipated that data will be available to permit a more detailed breakdown of release categories. It is also anticipated that as the understanding of source term phenomena improves, the distributions

will tend to narrow. In other words, as uncertainties are resolved, the spectral source terms will tend to revert to point values. The conflict between release categories and the spectral methodology will then become unimportant.

3. Primary Circuit Retention

3.1 General mechanisms

We first review the general mechanisms which can act to retain fission products in the primary circuit, and limitations on these, before proceeding to discuss their effectiveness in individual accident sequences. For volatile inorganic iodine forms (I , I_2 , HI), the following processes will be considered:-

- a. Reaction with/plate-out on metal surfaces.
- b. Reaction with/plate-out on particulate, and deposition.
- c. Solution and partitioning into water.
- d. Reaction with other fission products and subsequent deposition.

For fission products which are classed as particulate in terms of their eventual release form (including CaI), possible retention mechanisms are:-

- a. Plate-out/condensation on structural surfaces whilst in the vapour form prior to transformation to particulate.
- b. Self-nucleation aerosol formation with subsequent deposition on surfaces.
- c. Plate-out on aerosol derived from structural/fuel materials, with subsequent surface deposition.
- d. Retention on wet surfaces and water scrubbing.

A more detailed consideration of these processes follows. The analysis shows that uncertainties in the specific description of an accident, principally in the thermal-hydraulic behaviour, contribute at least as much to overall uncertainty as those in the modelling parameters for physical processes. For this reason, a sensitivity analysis of the modelling parameters has not been attempted, and the values considered to be the best available have been employed. Geometric parameters such as surface areas are taken from the Sizewell B Reference Design. Fission product core inventories relate to the end of the third fuel cycle[10]. Volatile inorganic and caesium iodide forms of iodine are covered for the sake of completeness.

3.1.1 Volatile inorganic iodine

The thermodynamic analysis presented in NUREG-0772[4] shows that in a steam-iodine mixture at temperatures and pressures relevant to primary circuit (PC) accident conditions, I_2 will predominate at temperatures below 600°C, but atomic I will be dominant above 900°C. HI will be the dominant form at temperatures below 1200°C, when excess hydrogen is present. All three forms are highly reactive, and in processes where chemical reactivity is important, existing analyses usually do not distinguish amongst them.

a. Reaction with/plate-out on metal surfaces

It is well established that iodine is chemisorbed onto, and can react with, steel surfaces. The compound FeI_2 is stable below 500°C, although somewhat volatile, and NiI_2 is also stable in this temperature range. The topic has been reviewed in the context of gas reactor circuits by Hoinkis[11], and there is some evidence that the presence of steam enhances the retention of iodine at lower temperatures. Two factors may limit the effectiveness of the mechanism.

i. Surface saturation

The main areas of metal surface in the primary circuit are the RPV upper plenum (grid plate, support columns, control-rod guides, total area approximately 260 m²), and the steam generator heat exchangers (about 5100 m² per unit). Saturation loadings set a limit to the amount of iodine which can be retained on surfaces, and these are sensitive functions of temperature, but relatively insensitive to surface material. For a total iodine core inventory of about 12kg, a surface loading of 6×10^{-4} kg m⁻² uniformly over the four heat exchanger surfaces, or 2.4×10^{-3} kg m⁻² over one heat exchanger, would be required for total retention of iodine. Most of the available experimental data has been obtained for much lower gaseous iodine partial pressures than would apply in the accidents under consideration, and no data exist specifically for the tube material Inconel-600. However, the following generalisations can be made.

a. Little or no retention is to be expected on surfaces with temperatures 600°C or higher. Therefore using the current evaluations of upper plenum temperatures, retention by plate-out in the upper plenum can be eliminated in all cases. Iodine may, however, react with such high temperature surfaces to form volatile FeI_2 , which will condense in cooler parts of the circuit, or on particulate. FeI_2 has a vapour pressure of 10^{-5} atm at about 450°C.

b. For surface temperature 400°C, saturation loadings in the range $1-10 \times 10^{-5} \text{ kg m}^{-2}$ are expected, and for 250°C they rise to $5-20 \times 10^{-4} \text{ kg m}^{-2}$.

It is evident that provided the leakage path from the core gives sufficient exposure to the heat exchanger surfaces, and temperatures are below about 300°C, surface saturation effects should not set a limit to the retention of a significant fraction of the iodine core inventory. The possibility exists that interaction of different plated-out fission products (FP), for example iodine species and caesium compounds, might influence the saturation behaviour. In the absence of experimental evidence on this point, the deposition properties are treated here as independent.

ii. Deposition kinetics

Appendix 1 to Appendix VII of WASH-1400[1] presents a simplified calculational treatment of the surface deposition rates and retention factors for iodine in the upper plenum of the Reactor Pressure Vessel (RPV) and in the steam generator heat exchangers (HX). Surface reaction rate characterised by a deposition velocity, rather than mass transfer, is concluded in that work to limit the overall rate, for low pressure (~1 atm) conditions.

Considering only the steam generators, the fractional mass of iodine remaining gas-borne after transit time t sec through a tube is given by

$$M/M_0 = \exp(-v_d (A/V)t)$$

where v_d is the iodine surface deposition velocity (m s^{-1}), and A/V the surface area to volume ratio of the tube. Taking $A/V = 230 \text{ m}^{-1}$ as appropriate for the HX, this expression shows that for $> 50\%$ plate-out the product $v_d t$ must exceed $3.46 \times 10^{-3} \text{ m}$. Experimental values for v_d onto steel are sparse. Recent measurements [12] for elemental iodine suggest values of $10^{-5} - 10^{-6} \text{ m s}^{-1}$ from a steam carrier at atmospheric pressure onto Inconel-600 at 300°C . Other measurements [13] for elemental iodine onto stainless steel yield values around 10^{-5} m s^{-1} at 300°C and 10^{-4} m s^{-1} at 200°C . There is evidence that v_d is one to two orders of magnitude higher for HI than for I_2 in this temperature range (Genco et al [13]). Identification of the likely chemical form of inorganic iodine in specific accidents is, therefore, important. The analysis which follows suggests that HI will be the dominant volatile inorganic form in the cases considered, and a value of $v_d = 10^{-4} \text{ m s}^{-1}$ at 300°C appears a reasonable estimate for this species. A transit time in the steam generator tubes of 35s would then be required for 50% deposition of HI at 300°C .

b. Reaction with/plate out on structural particulate

Modelling of whole-core heat-up shows that a significant fraction of the central core region will be already hotter than steel and Zircaloy melt temperatures during the phase of major release of volatile FP, notably iodine and caesium. The volatile F.P will then be co-emitted with aerosol derived from molten structural materials, and the possibility of plate-out on the aerosol, with subsequent particulate deposition, exists. This topic has been considered in WASH-1400[1], Appendix H, and NUREG-0772[4], Chapter 6 and Appendix D. Both treatments concluded that the overall retention by the mechanism was likely to be small. Condensation of CsI on structural particulate was treated in NUREG-0772, and in all sequences considered, a large fraction of the released CsI, up to 90% in some cases, was found to become particulate associated (NUREG 0772-App D). The question of particulate retention in the primary circuit is then important and is discussed below.

An estimate of the extent of gaseous iodine plate-out on structural aerosol can be made along the lines of the treatment for structural surfaces. A mass release rate 0.2 kg s^{-1} for aerosol material from core (cf NUREG 0772, App D) yields a geometric surface of about $600 \text{ m}^2 \text{ s}^{-1}$ for spherical particles of radius $0.1 \mu\text{m}$ and density 104 kg m^{-3} . Assuming a uniform release rate of the iodine core inventory, 12 kg in 15 minutes, iodine is released at 0.013 kg s^{-1} . This gives a geometric area of $1.0 \times 10^{-20} \text{ m}^2$ per iodine atom available on the aerosol surface, somewhat smaller than the cross-section of an iodine atom ($\sim 10 \times 10^{-20} \text{ m}^2$). However, since the effective surface area of the aerosol could easily be 50-100 times the geometric area, surface saturation is unlikely to be limiting. The kinetics of deposition will follow the expression previously quoted

$$M/M_0 = \exp(-v_d \cdot (A/V) \cdot t)$$

where M = mass/unit volume of iodine remaining in the gas phase at time t

M_0 = initial mass/unit volume of gaseous iodine

v_d = deposition velocity of iodine onto aerosol surface

A/V = surface area of aerosol/unit volume of gas.

The effective value of A/V will be specific to each accident sequence. Values of v_d would be expected to be higher in this case than for oxidised solid steel surfaces, since the aerosol surface will be freshly-formed in a reducing atmosphere. There is the possibility that in high temperature regions of the circuit, such as the RPV upper plenum, significant reaction of iodine with Fe-based aerosol surface will form FeI_2 , which may condense in cooler regions. However, aerosol-steam reactions might inhibit this process. Silver-based aerosol derived from control rod materials might also act as a very effective iodine sink.

c. Solution and partitioning into water

In S and T initiated sequences where the P.C remains at high pressure during the iodine release stage, steam condensation may occur in cooler regions of the circuit, both onto structural surfaces and onto existing aerosol. Pockets of water, and in certain cases, water lutes, may exist along the path from core to escape point. Molecular I_2 and HI partition strongly into water. The behaviour of I_2 has been extensively investigated, and is reviewed in NUREG-0772, (Chapter 5 and Appendix C). It is clear that even at temperatures of 100-200°C, volume partition coefficients of 100 or more can be expected. Three possible retention mechanisms can be envisaged:-

- i. Scrubbing in water-lutes. This will be a highly effective retention mechanism, as evidenced by the iodine behaviour at TMI-2. It appears quite probable in T sequences, and may apply in some S sequences. Retention factors of at least 10, and possibly much more, are expected.

So long as the water remains in the primary circuit, or is released in bulk form to the containment, dissolved FP can be considered as effectively trapped. However, if the water is released from high temperature and pressure conditions in the primary circuit, flashing and droplet entrainment on entering the containment may lead to a significant fraction of the dissolved fission products becoming airborne in aerosol. Thus, the overall effectiveness of this mechanism needs to be considered in conjunction with the prevailing thermal-hydraulic conditions.

- ii. Partitioning into aqueous aerosol from steam condensation. This will be a rapid, mass-transfer limited process, and in any sequence where significant quantities of such aerosol exist in the P.C, iodine can be assumed to be almost entirely associated with it. Retention by surface deposition and settling is then possible.

iii. Deposition on wetted surfaces. The deposition velocities for iodine on to the surfaces of structures wetted by steam condensation would be expected to be mass transfer limited, and so be much higher than the surface reaction rate limited values for dry surfaces considered above. Thus in any accident sequence where the iodine-bearing gas is exposed to large areas of wetted surface as for example in the HX, substantial retention of iodine will result.

d. Reaction with other fission products, and subsequent deposition

Whole-core modelling of heat-up shows that iodine will be co-released with other volatile fission products, notably caesium. The possibility must be considered that even if iodine is released from fuel in elemental form, it will rapidly react in the primary circuit to form CsI, and that subsequent transport will be determined by this chemical form. Caesium released into steam will probably be converted into CsOH, but CsI is thermodynamically stable with respect to this in reducing steam atmospheres at temperatures below 1200°C, or even higher (NUREG 0772, Appendix C). The reaction



is probably the rate-determining process. The likelihood that this reaction goes nearly to completion in the hotter circuit regions, for example the upper RPV plenum, and the hot leg, can be estimated. Respective gas temperatures in these two regions derived from MARCH runs are typically 1100°C and 800°C. The partial pressure of I and Cs will be lowest in an A-type sequence, so that reaction will be slowest in this case. Taking mass release rates from the core of 0.013 kg s⁻¹ for I, 0.18 kg s⁻¹ for Cs, and total steam plus hydrogen flow 25 kg s⁻¹, appropriate to the major iodine release phase of an A-type LOCA, calculation shows that for 90% reaction of iodine with Cs in 1 second, a rate constant of 2.3 x 10⁴ dm³ mol⁻¹ s⁻¹ would be required. A bimolecular gas reaction of the type considered would be expected to have a much higher rate

constant than this at such elevated temperatures. It is reasonable to conclude that free iodine is unlikely to persist for more than a very short time within the primary circuit, and that the properties of CsI or other metal iodides will determine iodine transport. An additional vapour likely to be present in large quantities, with which iodine might react, is silver from the control rods. Silver iodide, AgI, is not so thermodynamically stable as CsI, but could be formed to a significant extent. Retention mechanisms for these iodides are considered in the following sections.

3.1.2 Aerosol and Particulate

Two sources of material which may ultimately be released from the primary circuit in aerosol form can be distinguished. One of these comprises volatile fission products (VFPs) such as caesium and tellurium which will be initially released from fuel as vapours, but may be transformed to particulate by condensation in the cooler regions of the primary circuit. A competing process for these will be condensation onto internal surfaces of the primary circuit, leading to retention. The second source consists of structural materials, steel and zircaloy, and to a lesser extent UO_2 , which will vaporise in the molten core regions, but condense rapidly after leaving the core. Current analyses (eg NUREG-0772[4]) indicate that most of this is expected to form aerosol in the upper plenum. Evidence on the nature of the structural aerosol is sparse, but initial particle sizes of around $0.1 \mu\text{m}$ appear probable (WASH-1400, App VII, App H). Control rod silver is fairly volatile, and would be expected to behave like the volatile F.Ps rather than other structural materials.

For the volatile materials, saturation vapour pressure (SVP) as a function of temperature is important in assessing the possibility of condensation. Some values of relevance (derived from NUREG 0772 and ND-R-610, Table VII/II) are:

T,K	800 (527°C)	1000 (727°C)	1200 (927°C)	1400 (1127°C)
	SVP (atm)			
Cs	0.157	1.19	4.36	10.65
CsI	1.07×10^{-5}	1.71×10^{-3}	3.68×10^{-2}	0.304
CsOH	2.33×10^{-4}	1.81×10^{-2}	0.329	2.61
Te	1.68×10^{-3}	5.88×10^{-2}	0.546	2.42
AgI	2.56×10^{-6}	2.81×10^{-4}	6.44×10^{-3}	6.03×10^{-2}
Ag	1.69×10^{-12}	7.41×10^{-9}	1.93×10^{-6}	7.24×10^{-5}
BaO	5.43×10^{-21}	1.62×10^{-15}	7.24×10^{-12}	2.93×10^{-9}

(Note: 1 atm = 0.1013 MPa)

Attention is confined to the volatile F.Ps in this analysis. Amongst these might be included Sr and Ba, but these are expected to rapidly be converted to refractory oxides in the presence of high temperature steam. Their primary circuit transport will then resemble that for structural aerosols.

a. Plate-out/condensation on structural surfaces whilst in the vapour form

When internal surface temperatures fall below the value at which the SVP of a given F.P species equals its partial pressure in the primary circuit gases, condensation onto the surface becomes possible. The effectiveness of the mechanism will depend on the available surface area at suitable temperature, and on the kinetics of condensation. Since large temperature differences will exist between the bulk gas and surface at each point along the flow path, condensation is likely to be closely coupled to heat and mass transport phenomena. An expression of the form

$$M/M_0 = \exp(-v_d (A/V) t)$$

analogous to that for surface plate-out of iodine will apply, where v_d is now the effective deposition velocity for surface condensation, and A/V the surface to volume ratio for the section of primary circuit pipework considered. The effectiveness of the mechanism will be very sequence dependent, since partial pressures of F.P species will be much higher when primary circuit pressure is maintained (small-break and transient sequences) than when it is low (large-break sequences)

b. Self-nucleation aerosol formation and deposition

If the degree of supersaturation of a given fission product vapour is high enough, self-nucleating aerosols may be formed in the circuit in lower temperature regions. If saturated steam is also present, co-condensation may occur, giving an aqueous aerosol loaded with the fission products. However, it appears that in most accident situations, and certainly during the phase of major volatile fission product release, sufficient structural aerosol will be present to act as nuclei for condensation, so that self-nucleation is probably unimportant in the full core-melt accidents considered here.

c. Plate-out/condensation on structural aerosol, with subsequent deposition

As outlined in considering volatile inorganic iodine, structural aerosols with large surface areas are expected to be generated throughout the stage of VFP release during core melt. When these aerosols cool below the saturation temperatures of VFP vapours in the gas, the fission products will condense onto them. There will be competition between condensation onto the aerosols and onto the primary circuit surfaces, the effectiveness of these sinks determined by the supersaturations relative to the respective surface temperatures, and by heat and mass transfer effects. We assume here that when a VFP vapour becomes supersaturated with respect to the temperature of an adjacent surface, condensation onto the surface is mass transfer limited. Mass transfer coefficients for condensation onto the aerosols are difficult to calculate, but because of the intimate mixing in the gas phase they can be assumed to be large, corresponding to relaxation times of at most a few seconds, or deposition velocities $> 10^{-2} \text{ m s}^{-1}$. Because of this, in any section of the primary circuit where the effective A/V ratio for aerosols is comparable with or greater than that of structures, condensation onto aerosols will predominate even though the aerosol surface temperature may be significantly higher than that of the walls. Surface saturation effects will set no limit to the extent of condensation, and when two or more vapours condense onto the same surface, the processes can be considered independent to a good approximation.

Once trapped on aerosols, volatile fission products will be retained in the primary circuit only if the particles are deposited onto surfaces. The effectiveness of retention is very sensitive to the aerosol characteristics of particle size, density and number density, which are ill-defined, as well as the nature of the flow path and residence time in the circuit. Modelling of these processes is extremely complex. The TRAP-MELT calculations quoted in NUREG-0772 include the deposition mechanisms of diffusion from turbulent or laminar flow, inertial impaction of large particles, and thermophoresis. However, they do not

include the process of agglomeration to form larger particles, or particle growth by steam condensation (with subsequent inertial or gravitational deposition). The effects of diffusiophoretic deposition with condensing steam are also excluded. These neglected processes will all contribute to increased primary circuit retention, so that the predictions of the TRAP-MELT code employed for NUREG-0772 must be viewed as significantly conservative. An assessment of the likely conservatism resulting from neglect of particle agglomeration is given in Figure 6-3 of NUREG-0772, where results of applying the QUICK code are presented. It is clear that in certain accident sequences, the TRAP-MELT calculations underestimate the effectiveness of primary circuit particulate retention by factors of 10 or more.

d. Retention on wet surfaces and water scrubbing

It seems likely that the sticking efficiency of aerosols generally, and especially aerosols composed largely of highly soluble materials such as CsI and CsOH, will be much greater on water-wetted surfaces than on dry surfaces. Also in any accident sequence where gas or steam-borne aerosols is transported through water lutes, there is the possibility of effective scrubbing, with concentration reductions by factors of ten or more. Such processes are difficult to quantify, and are not included in the TRAP-MELT code, but some allowance for them is needed where appropriate.

3.1.3 Resuspension from the primary circuit

A major reason advanced in WASH-1400[1] for neglecting primary circuit retention of fission products was the argument that material plated-out on the circuit surfaces during early stages of the accident development would be resuspended when surfaces heated up during later stages. More detailed knowledge of circuit temperatures gained subsequently from the MARCH code suggests that this argument is invalid.

The possibility exists, though, that at the stage of core-heat-up where the slumping of molten material into residual water in the lower plenum occurs, a burst of high-pressure, high-temperature steam will pass through the circuit which may give substantial resuspension of plated-out fission products. Such a process could be serious for a coherent core-slump, as envisaged in WASH-1400. However, current models of core melting (WCAP 9991, Ch 3[9]) suggest that this situation is very unlikely, and that molten core material will trickle into the lower plenum. This will drive steam at or somewhat above the saturation temperature through the circuit in a more steady fashion, which may actually reduce surface temperatures. The question of resuspension on depressurisation following RPV melt-through, which may be important in small break and transient sequences, is addressed in Section 3.2.4.

3.2 Application to Specific Accident Sequences

Norwithstanding the evidence that FP iodine will be transported in the primary circuit as CsI , it is also considered here as a volatile inorganic form. For estimates of retention of iodine and other VFP, processes in which they become dissolved in bulk water in the primary circuit, and are released in this form into the containment, are classed as primary circuit retention, since the probability of resuspension is small. For the interfacing LOCA, pool scrubbing processes in the auxiliary building are also included here, since Section 4 covers retention processes only for gas-borne FP.

Of the contributory factors to overall uncertainty, the precise description of the accident sequences of a given type plays at least as large a part as the uncertainties in physical and chemical modelling. This is particularly notable for large and small-break LOCAs, where very different primary circuit retention factors are expected between hot-leg and cold-leg breaks. Reliable data on the relative frequencies of these are not presently available, and the assumptions employed here, based on current judgement, may be subject to subsequent modification.

3.2.1 Interfacing LOCA (V- event*)

Accident description

The basic accident defined in WASH-1400 (Appendix I, Sec 4.1.6 and 4.1.7, Appendix V, Sec 4.6.1) envisages simultaneous failures of the two check valves installed in series in the low pressure injection (LPI) line to the reactor coolant system (RCS), with loss-of-coolant through this line by-passing containment. The design pressure of the LPI side (typically 6.2 MPa) is much lower than the RCS pressure (17.1 MPa) and rapid failure of the LPI circuit is anticipated, with flow of reactor system coolant into the auxiliary building. Several design features of the RCS and low pressure interfacing at Sizewell B could influence the retention of fission products, and these must first be considered:-

- i. For the Surry I plant assessed in WASH-1400, the failed check valves are in the LPI lines feeding the cold legs of the RCS (Fig I 4-6 of WASH-1400, reproduced as Fig A.1 of NUREG-0772). The LPI and residual heat removal (RHR) circuits of Sizewell B differ significantly from Surry I, and have been the subject of recent design changes. The V-event is analysed in section 1.6.4.17 of WCAP 9991, and circuit designs shown in Figs 1.6.4.17-1 to -3. Three scenarios are identified (a) failures of 3 series Motor Operated Valves (MOV's) in the RHR suction lines connected to two of the RCS hot legs (b) failures of check valves and MOVs in the high head safety injection (HHSI) system connecting with the four RCS hot legs (c) failures in check valves and operator-actuated MOVs in the LPI lines connecting with the four RCS cold legs. Sequence (a) is assessed to dominate the overall probability of event V by about two orders of magnitude, in contrast with the WASH-1400 situation. Attention will be confined to sequence (a) here. The relevant circuit is shown in Fig 3.1, which reproduces Fig 1.6.4.17-3 of WCAP 9991.

*Footnote: The symbols V, A, S and T are used here as convenient abbreviations for Interfacing, Large-break, Small-break and Transient LOCAs, respectively. No precise correlation with similarly-designated WASH-1400 sequences is implied.

- ii. The Sizewell B capability for ECC includes four, low head safety injection (LHSI) pumps and four HHSI pumps, some of which may still be functional following an interfacing LOCA event. It is assumed that, unless operator action succeeds in isolating the RCS, no attempt would be made to activate the ECCS, since this could be maintained only until the refuelling water storage tank (RWST) became exhausted. A recirculation phase is precluded in the V-event.
- iii. The most probable failure points in the low pressure circuit due to over-pressure have not been identified. High capacity pressure relief valves exist in both the RHR suction lines and LPI lines, affording a possibility of reduced damage to the low pressure circuit. The release path from these valves is routed back to the pressuriser relief tank in the containment. Other possibilities for the RHR suction line route are fracture near the failed interfacing valves, or downstream failures of LP valves which could route the flow to the RHR pump and heat exchanger, RWST or containment spray headers. The influence of the failure point on FP retention is discussed below.

Thermal-hydraulic conditions

The RHR suction line is taken to have diameter 0.3m, so that the primary circuit thermal-hydraulic conditions will be equivalent to a medium-break hot leg LOCA. The phases of the accident will be:

- i. Rapid draining of coolant from the RCS and accumulators, with flashing to steam as the pressure drops. This phase will last about a minute. Gap release of FP may occur, but this can be neglected compared with later phases.

- ii. Core uncovering and heat-up to slump. This is the phase of major volatile FP release (I, Cs, Te). MARCH runs predict an interval of about 20 minutes from beginning of core uncovering until slump. Modelling of FP release rates from the whole core, using the SRD FISREL[14] code, which combines the MARCH thermal history with release rate constants recommended in NUREG-0772 (Chapter 4), suggests that the release of volatile FP will begin after about 10 minutes, and continue at uniform rate up to core slump, when essentially all of the iodine and caesium, and 90% of the Te, will have been released. Other relevant conditions derived from MARCH are:-

Strongly reducing hydrogen/steam atmosphere, $H_2/H_2O > 1$.

Total gas flow rate from core ($H_2 + \text{steam}$), $\sim 140 \text{ mol s}^{-1}$.

Total pressure \sim estimated 0.4 MPa.

Circuit temperatures \sim all $>$ steam saturation temperature ie a dry circuit.

HI is computed to be the dominant volatile inorganic form of iodine exiting the core if reaction with caesium is excluded.

- iii. Core slumping to RPV melt-through. This phase is of short duration, 6-8 minutes. Any volatile FP trapped in the residual water in the lower plenum will be resuspended during or after the boil-dry stage. Some release of the less volatile FPs (Ba, Sr, Sn, La, Ru if air is present) and structural and control-rod materials (Fe, Zr, Ag) as dense aerosol will occur from the dry melt. A minor proportion of this may plate-out on the RPV internals, but it is assumed that the majority will fall back in to the melt, or be swept out on RPV lower head failure.

Fission product retention

The flow path for FP escape from the core passes through the RPV upper plenum, part of the damaged hot leg, and along the RHR suction line to the failure point in the low pressure pipework. Some transport may occur to the steam generators (SG) in the intact and damaged loops, due to convective effects, but this is neglected here. The effects of fission product retention mechanisms in successive regions of the escape route are now considered.

RPV upper plenum

MARCH output suggests temperatures for gases entering the upper plenum rising from 1500 to 2000°C, and average surface temperatures increasing from 500 to 800°C, during the stage of VFP release. Mean residence times are in the range 5 - 10 s. Calculation shows that even if VFP vapours are supersaturated with respect to surface temperatures of upper plenum intervals, mass transport will limit condensation onto these to < 10% in the short residence time. Also, the high final surface temperature is likely to result in re-evaporation of any earlier-deposited FPs. No condensation of VFPs onto structural aerosols is expected. The net retention of fission products in the upper plenum will thus be insignificant.

Hot leg

The residence time here is short, typically < 0.5 s. Gas temperatures in the range 800 - 1000°C, and surface temperatures of 400 - 500°C, are expected from MARCH calculations. Mass transfer limits surface deposition to < 1% in the residence time. The estimated partial pressure of CsOH is 6×10^{-3} MPa, and for CsI about one tenth of this, both being close to the respective SVPs at 700 - 800°C. Little condensation onto structural aerosol is therefore expected. Overall FP retention in the hot leg will be negligible.

RHR system

The potential for fission product retention in the RHR circuit depends strongly on the mode and location of the failure in the LP pipework. Two failure modes need to be distinguished

- a. Fracture of the LP line immediately downstream of the failed MOV which acts as the HP/LP interface. The transport pathway into the auxiliary building then includes only the HP section of the RHR suction line, estimated as 50m of 0.3m i.d. pipework. This pipe enters the auxiliary building in a subterranean duct which may be flooded or partially flooded by water released from the RCS at an earlier phase of the accident.
- b. Disc failure of one or more LP valves interfacing with the RHR and connected systems. The ultimate failure point through which major escape of FP into the auxiliary building will occur is then uncertain. Likely weak spots appear to be the gland seals of the RHR pumps, and the RHR heat exchanger. The important factor for FP retention is that further exposure to sections of cold, wet pipework, possibly including water lutes, is likely.

Since the actual failure mode of the LP system is unidentified, we assume equal probabilities for each of the alternatives (a) and (b) above.

Retention for failure mode (a)

No thermal-hydraulic data is available on conditions in the RHR suction line during the stage of major VFP release from core. During the earlier RCS blow-down phase, most of the reactor coolant will have flowed down this line as a flashing steam-water mixture, the temperature declining with system pressure to a value between 100 and 200°C. The surface temperature will probably remain in this range during later stages, but the gas temperature could be significantly higher, around 400 - 500°C, as the main passage of VFP occurs. Residence time

in the suction line will be only ~2s. Mass transport limits the extent of condensation or plate-out of VFP onto pipe walls to <1%. However, vapours of CsI, CsOH and Te will become supersaturated with respect to aerosol surface temperatures, and substantial condensation onto the structural aerosols can be expected. Negligible deposition of the latter is anticipated in the short residence time. We therefore conclude that, if the fractured RHR suction line vents directly into the auxiliary building atmosphere, no retention of VFP in the RCS and RHR pipework can be expected. A release factor, $F = 1$, then applies.

An alternative possibility is that the pipe chase in the auxiliary building basement through which the RHR line passes from the containment building will be flooded. Escaping gases and fission products may thus encounter a water lute, with effective scrubbing of both volatile inorganic iodine species and aerosols, before release to the auxiliary building atmosphere. As noted in Section 3.1, decontamination factors of 10 or more have been measured for pool scrubbing. However, because in the present situation the pool may be shallow, and large initial temperature differences may exist between the gas and liquid phases, we consider an acceptably conservative decontamination factor of 4 can be applied here. The corresponding release factor is then, $F = 0.25$.

The relative probabilities of dry and flooded release paths in the auxiliary building are difficult to estimate. The flooded situation appears to be the more likely, but in the absence of proper analysis, we ascribe equal probabilities to the two situations. Overall, for failure mode (a), the release factors to the auxiliary building atmosphere of 1 and 0.25 are taken to be equally-weighted.

Retention for failure mode (b)

A significant extension of the flow-path through RHR pipework would result if the initial failure mode of the LP system was disc bursting of one or more LP

valves. Two situations concerning the ultimate failure point of the LP system then have to be considered:-

- i. Failure gives an escape path directly to the auxiliary building atmosphere. The length of the flow path, and residence time, are uncertain, but there is a high probability that sections of the pipework would be immersed in water at around 100°C, and that water pools, and even lutes, might exist. Steam condensation onto the pipe walls, with associated diffusio-phoresis of aerosols, would produce some retention for particulate-borne FP, and condensation onto the aerosols themselves would enhance agglomeration and settling. Volatile inorganic iodine would partition strongly into water pools and surface films. It is impossible to calculate the consequences of these processes, but it appears reasonable, or even conservative, to attribute a release factor, $F = 0.5$, to this situation.
- ii. Failure exposes escaping FP to bulk water. If the failure point of the LP system was in a flooded basement compartment of the auxiliary building, or in the RHR heat exchanger, escaping fission products would be exposed to scrubbing by bulk water at about 100°C. Considerable retention would be expected, and decontamination factors of 4 to 10 might be ascribed, depending on the effective geometry of the situation. For estimation purposes, F values of 0.25 and 0.1 are considered equally probable in this situation.

In the absence of any information on the location of the ultimate LP failure point for failure mode (b), we take the alternative escape paths (i) and (ii) to the auxiliary building atmosphere just outlined to be equally probable.

Summary

The foregoing assumptions on probabilities, and associated estimates of FP retention, may be combined to give an overall distribution for the V-sequence dominated by RHR hot-leg suction line failure as follows:-

Failure mode	(a)		(b)	
Probability	0.5		0.5	
Failure point	Direct	Submerged	Direct	Submerged
Probability	0.25	0.25	0.25	0.25
F	1.0	0.25	0.5	0.25/0.1

Collecting contributions under standard fractions, and rounding-off thus gives

F	1.0	0.5	0.25	0.1	0.05
Probability	0.25	0.25	0.4	0.1	0

3.2.2 Large-break (A) LOCA

Accident description

Guillotine fracture of the hot or cold legs of the RCS initiates this sequence, followed by very rapid depressurisation of the primary circuit with discharge of the coolant into the containment building as a flashing steam-water mixture.

Thermal-hydraulic conditions

These are essentially the same as already described for the V-sequence, with the exception that during the period of major volatile FP release, circuit pressure is expected to be about 0.2 MPa. Core heat-up history, steam and hydrogen flows, fission product release, and chemical conditions differ insignificantly from the V-sequence. Auxiliary Feedwater Supply (AFWS) to the steam generators is assumed to be maintained.

Flow paths from the core

No analysis has been performed of the relative probabilities of hot- and cold-leg fractures. The best current advice available is to assign equal probabilities to the two locations. Similarly, no analysis has been made of the relative probabilities of cold-leg failures in the coolant circulation pump suction leg and the RPV injection leg. However, this latter question is thought to have only a minor impact on the course of a cold-leg break LOCA. For a

hot-leg break, only flow from the core to the break-point through the defective hot-leg needs to be considered. In the case of a cold-leg break, three routes for FP transport from the core to the breach point can be distinguished (Fig 3.2), with differing retention properties:-

a. Lower plenum, downcomer, RPV annulus, cold leg of failed loop. Flow resistance in this path will be determined by the water level in core, lower plenum, and downcomer. TRAC runs for a double-ended cold-leg LOCA suggest that the path becomes dry within a few seconds of the break occurring, but that when the RCS pressure falls below the 4.1 MPa set pressure of the accumulators, (20-30s), partial reflooding will occur. A water lock is expected to exist throughout the release phase of volatile FPs, although instabilities in water level may permit some escape of FPs by this route.

b. Damaged loop. Hot leg, steam generator (SG), cold leg including coolant circulation pump.

FPs will be carried in the flowing steam-hydrogen mixture along this dry route to the failure point. Flow resistance might be expected from the shut-down coolant pump, but TRAC modelling suggests this will be small. This is considered to be a major flow path. Maintenance of the auxiliary feedwater system (AFWS) to the SG is assumed, giving surface temperatures around 280 - 300°C.

c. Three undamaged loops. Hot leg, SG, cold leg, RPV annulus, cold leg of damaged loop.

This path is similar to (b), but additional flow resistance may arise in the RPV annulus due to steam generated from water boiling in the downcomer. TRAC modelling indicates that flow through each of the undamaged loops will be similar to that through the damaged loop.

Because of the considerable uncertainties in defining the flow path from core to the failure point, we consider three alternative scenarios, with different weightings to the alternative routes.

	Routes	(a)	(b)	(c)
Case I		0.5	0.5	0.0
Case II		0	0.5	0.5
Case III		0	0.25	0.75

Of these, Case I is probably pessimistic with respect to FP retention, and cases II and III are expected to be nearer the true situation.

Fission product retention

Hot-leg break

It is clear from the discussion presented for the V-sequence that no retention of volatile FPs can be expected in the upper plenum and hot leg. $F = 1.0$.

Cold-leg break

General considerations

Route (a)

Some scrubbing in the water lute is expected, but trapping by solution will only represent a temporary hold-up, since resuspension is likely following core slumping. We, therefore, set the release factor (F) for all volatile fission products (VFP) escaping by this route to unity, $F = 1.0$.

Route (b) and Route (c)

Upper plenum

MARCH calculations suggest that the surface temperature rises to $> 800^{\circ}\text{C}$ during the VFP release stage. The situation is similar to that for the V-sequence, and no long-term retention of VFP is expected.

Hot leg

Residence time is in all cases short, < 1 s. MARCH output indicates surface temperature $< 500^{\circ}\text{C}$, and gas temperature $< 800^{\circ}\text{C}$, during the main VFP release period, but surface temperature may rise to $> 800^{\circ}\text{C}$ following core slump. Deposited VFPs are thus likely to re-evaporate. Also, mass transfer limits surface deposition to $< 1\%$ in the residence time. Retention in the hot leg will, therefore, be negligible.

Estimated partial pressure of CsOH is 3×10^{-3} MPa, which is close to the SVP at $700\text{--}800^{\circ}\text{C}$, so that little condensation onto structural aerosols is expected.

Steam Generator

Surface temperature of 300°C is assumed, and gas temperature will accommodate to this during passage. Mass and heat transfer do not set any limit to the extent of surface deposition of gas-borne VFPs. This is determined by the residence time t_r and the surface deposition velocity v_d .

Volatile inorganic iodine deposition (HI)

Deposition onto steam generator (SG) tube walls will occur, and attachment to structural aerosols is also possible. These are competing processes, but the relative contributions are difficult to estimate, since no measurements of deposition rates on to particulate have been made. We, therefore, adopt two limiting models:-

- Model i. Deposition onto walls only. This is calculated from the known (A/V) ratio (230 m^{-1}) and estimated residence time t_r , using $v_d = 10^{-4} \text{ m s}^{-1}$.
- Model ii. Deposition onto walls and particulate with equal deposition velocities. The effective (A/V) ratio for particulate is estimated as 200 m^{-1} . The fraction of iodine-loaded particulate retained in the SG

is estimated from the mass-density and residence time using Fig 6-3 of NUREG-0772. The F is then the combined contributions of undeposited gaseous iodine (HI) and released iodine-loaded particulate.

Particulate deposition

Vapours of Cs and Te species will become rapidly supersaturated on entering the SG. Condensation onto the SG tube walls and gas-borne structural particulate will occur, and will be essentially complete in the residence time. The proportion, condensing onto each surface-type should be approximately in the ratio of the effective (A/V) values; a fraction 0.47 is thus estimated to condense onto particulate which represents the maximum F in the event that none of this particulate is retained. Additional retention is estimated from the mass density and residence time using Fig 6-3 of NUREG-0772. We note that resulting F values are in broad agreement with the TRAP-MELT results quoted in Appendix D of NUREG-0772.

Quantitative estimates

The principles outlined above can be used to calculate the release factors for the three cases treated, using appropriate residence times. Results are summarised in the following Table.

Table 3.1				
	F for	Iodine (as HI)		Particulate
		Model i	Model ii	
Case I		0.86	0.88	0.73
Case II		0.55	0.65	0.47
Case III		0.52	0.62	0.47

This procedure generates numbers which lie in only the 1x and 0.5x standard factor bins, and the finally-condensed distribution will clearly be sensitive to the probability assigned to each of the Cases. However, the results are

insensitive to which volatile inorganic iodine deposition model is adopted in this accident. In order to obtain a probability distribution for primary circuit release factors, some choice of weightings for the three cases is needed. This is of necessity fairly arbitrary, but the following choice appears reasonable on the basis of existing evidence:-

Case I 0.2, Case II 0.4, Case III 0.4.

The resulting total probability distributions for the cold-leg break are then:-

F	1	0.5	0.25	0.1	0.05
Iodine (HI), Prob	0.2	0.8	0	0	0
Particulate, Prob	0.2	0.8	0	0	0

Overall distributions

Taking equal probabilities for hot- and cold-leg breaks, the $F = 1$ value for the hot-leg case may be combined with the above distribution for the cold-leg case to derive the following overall distribution for large-break LOCAs.

F	1.0	0.5	0.25	0.1	0.05
Iodine (HI), Prob	0.6	0.4	0	0	0
Particulate, Prob	0.6	0.4	0	0	0

3.2.3 Small-break (S) LOCA

Accident description

A range of break sizes in the hot- or cold-side circuit much smaller than the hot or cold-leg main circuit pipework diameters falls within this description. We limit consideration to those cases where the RCS pressure lies between the secondary side relief pressure (8.2 MPa) and the LPI set pressure (4.1 MPa) during the core-melt phase. This is roughly equivalent to fracture of a pipe of diameter 50 to 100mm connecting to the hot or cold legs, although failures of RPV penetrations of equivalent size fall within the category. Reactor system

coolant is released direct to the containment as a flashing steam-water mixture, and FP release is also direct to the containment.

Thermal-hydraulic conditions

We assume that AFWS is maintained to the SGs. Once the RCS pressure falls below the secondary side relief pressure, two-phase conditions will exist in the primary circuit. MARCH runs suggest that during the latter stages of boil-dry of the core, when major release of volatile FPs occurs, system pressure will be around 6.8 MPa, and total steam plus hydrogen flow will be about 500 mol s⁻¹. Primary steam will be unsaturated in the SGs, and condensation will not occur there, although some condensation may be possible in the cold-leg region of the circuit. The RPV lower plenum and downcomer are expected to remain filled with water until the end of core boil-dry.

Flow path from the core

No analysis is available of the relative probabilities of hot- and cold-side breaks. The cold side has more connections to greater lengths of small-diameter pipework than the hot side, and contains the circulation pump, so that a higher probability of circuit breach in this region is expected. On these grounds, a 1:3 ratio for hot- to cold-side failures is adopted. For hot-side failures, only the flow path from the core to the breach-point needs to be considered. In the case of cold-side breaks, the three possible paths described for the A-LOCA need to be considered (Fig 3.2). The route via the lower plenum and downcomer remains water-filled up to core slump, and since the core boil-dry process is less turbulent in this case than for a large LOCA, we discount this route for FP transport. RELAP modelling of cold-leg small breaks indicates that during the early stages, two-phase coolant flow through all four reactor loops, damaged and undamaged, is on average about equal. However, because of the uncertainties in flow route, we again consider three cases covering the range of possible situations. The weightings assigned to the routes are:

	Route (b)	Route (c)
Case I	1.0	0
Case II	0.5	0.5
Case I+I	0.25	0.75

Fission product release

MARCH output for a small-break LOCA suggests that the core boil-dry stage covers a period from about 40 min to 60 min after accident initiation, terminating in core slump. SRD modelling[14] of whole-core release of VFPs indicates a fairly constant release rate beginning at about 50 min, and continuing to core slump. The fraction of core molten increases roughly in proportion with the VFP release, and simultaneous release of structural aerosol is, therefore, predicted. Hydrogen to steam mole ratios will range from 1:5 to 1:1 during iodine release, and SOLGASMIX calculations[14] show that HI will be the only significant gaseous form of iodine (if CrI is neglected).

Fission Product Retention

Hot-Side Break

Upper plenum

No directly relevant MARCH results on gas and surface temperatures in the RPV upper plenum are available in this case, although indications are that they will not differ greatly from the A-LOCA situation. Average residence time in the upper plenum will be around 40s. Partial pressures of VFP vapours are estimated to be high eg $2-3 \times 10^{-1}$ atm for $(CsOH)$, so that condensation onto upper plenum structures will probably occur during the core heat-up phase. The fraction of VFPs so deposited is limited by mass transfer to $< 25\%$, and these will probably be resuspended when the surfaces heat up following core slump. Similarly, VFP deposition with structural particulate is estimated to be at most a few percent, and this may be resuspended at a later stage. It, therefore, seems reasonable to discount VFP retention in the upper plenum.

Hot leg

Residence times are in the region 5-10 sec, with gas temperature 700-800°C and surface temperature probably <500°C during major VFP release. Estimated vapour pressures ($\sim 10^{-2}$ MPa for Cs species, 10^{-3} MPa for Te species) greatly exceed SVPs, and condensation onto both pipe walls and structural particulate will occur. Calculation shows that mass transport limits the possible deposition onto the walls to <1%. The estimated (A/V) ratio for particulate is around 1000 m^{-1} , and the extent of condensation onto it will be determined by the deposition velocity for the process. Values of 10^{-5} and 10^{-4} m s^{-1} for this parameter yield respectively $\sim 10\%$ and $\sim 50\%$ condensation onto particulate. Similar proportions of iodine may become attached to the structural aerosol. However, insignificant deposition of this aerosol is expected in the residence time (Fig 6-3 of NUREG-0772), so that no overall retention of VFPs in the hot leg can be claimed.

In conclusion, an $F = 1.0$ is adopted for all VFPs in the case of a hot-side break.

Cold-Side Break

Upper plenum and hot leg

The situation will be as described for the hot-side break. No long-term retention of VFP by deposition onto structures in these regions is anticipated. Any VFP still in suspension at the time of core slump will be swept through the system by the steam plus hydrogen generated when the residual water in the RPV lower head boils off. We conclude that in all cases, total transport of VFPs to the steam generators should be assumed.

Steam generators

The gas temperature will accommodate to the wall temperature of about 300°C quite rapidly within the SG tubes. Residence times are much greater than for the V- and A-LOCA situations, due to the higher pressure. Mass and heat transfer do not limit the extent of plate-out here.

Volatile Inorganic Iodine

We again adopt two limiting models for iodine behaviour. In model i, no deposition onto particulate is assumed, and the retained fraction is that deposited on the tube walls in the residence time, taking $v_d = 10^{-4} \text{ m s}^{-1}$. Model ii allows deposition onto structural aerosol with the same velocity as for the walls. Since the estimated (A/V) for particulate here (2000 m^{-1}) greatly exceeds that for the tubes (230 m^{-1}), overall iodine retention is largely determined by the fraction of particulate which deposits in the SGs. This is estimated from the mass density and residence time using Fig 6-3 of NUREG-0772. Iodine (HI) deposition onto particulate in the hot leg is neglected in Model ii.

Particulate

Any VFP vapours not condensed in the hot leg will rapidly do so in the SG, and total condensation of all Cs and Te species can be assumed. The competition between the tube walls and structural particulate surfaces as condensation sinks will be determined by the respective (A/V) values and deposition velocities. In general, the particulate surface will be hotter than the tube walls, and will therefore probably have a smaller deposition velocity. This is likely to be more than offset by the much larger (A/V) value. For the present estimates, equal deposition velocities have been assumed, and the retained fraction of condensed vapours is the sum of that deposited on the walls, and the fraction attached to particulate which is deposited. The latter is estimated from Fig 6-3 of NUREG-0772. In general, this procedure may tend to over-estimate the F_s slightly.

Quantitative Results of cold-side break

The calculated F_s for the three cases are given in the following Table:-

Table 3.2

F for	Iodine (HI)		Particulate
	Model i	Model ii	
Case I	0.21	0.22	0.25
Case II	0.03	0.09	0.10
Case III	0.0	0.09	0.10

To generate probability distributions, relative probabilities must now be assigned to Cases I, II and III. In the absence of definitive information, we weight each of the cases equally. Models i and ii for iodine behaviour are also equally weighted. In this way, the following probability distribution for standard F fractions are produced:-

F	1	0.5	0.25	0.1	0.05
Iodine (HI), Prob	0	0	0.33	0.33	0.33
Particulate, Prob	0	0	0.33	0.66	0

These may be rounded-off conservatively to yield:-

F	1	0.5	0.25	0.1	0.05
Iodine (HI), Prob	0	0	0.4	0.3	0.3
Particulate, Prob	0	0	0.4	0.6	0

Overall Distributions

The value $F = 1$ applicable in hot-side break conditions may be combined with the above distributions for cold-side breaks in the probability ratio 1:3 to derive the following overall release factors for volatile inorganic iodine and for particulate-borne fission products (including CsI):-

F	1	0.5	0.25	0.1	0.05
Iodine (HI), Prob	0.25	0	0.3	0.225	0.225
Particulate, Prob	0.25	0	0.3	0.45	0

3.2.4 Transient T

Accident description

This sequence is characterised by loss of both secondary side and emergency core cooling capability. Natural circulation following reactor trip maintains core decay-heat cooling whilst the SG secondary side boils dry, over a period of about 2 hours. Thereafter RCS pressure and temperature increases until the pressure attains the set value of the pressuriser relief valve (17.1 MPa),

when coolant is vented as steam or flashing steam-water through the relief line to the quench tank. The water saturation temperature corresponding to the relief pressure is 354°C, so that a steam phase will exist in regions of the RCS at higher temperature.

FP Release Path from Core and Thermal Hydraulics

The escape route for volatile FPs from core will be via the upper plenum, hot leg, pressuriser, relief valve, relief line and quench tank (Fig 3.3). When bursting disc pressure is reached on the quench tank, escape of FP into the containment building is possible. Volatile FPs will be released during the latter stages of core boil-dry. MARCH runs show that this will be about 3 hours after accident initiation. Surface temperatures in the upper plenum, and hot leg will be above steam saturation temperature, and this part of the path will be dry. The pressuriser surface temperature may be close to the saturation value, and some steam may condense here, but this will be a minor effect.

Because flow velocities are small, and residence time in the upper plenum and pressuriser are long (>1000 s), the simple plug flow approach adopted in analysing previous sequences must be replaced by one based on well-mixed volumes. The sequence is treated in terms of three time phases.

Phase A. VFP release stage. This is near the end of core boil-dry, and lasts about 30 minutes, terminating in core slump. Flow rates of steam plus hydrogen through the core are small, typically $50-100 \text{ mol s}^{-1}$, and the atmosphere is strongly reducing. If CsI formation is excluded, HI will be the only significant volatile inorganic form of iodine. Essentially all of the iodine, caesium and tellurium is released at this stage.

Phase B. Boil-dry of lower plenum. Following core slump into the residual water in the RPV lower plenum, this water rapidly boils off, in a period of 3-5 minutes. The volume of steam plus hydrogen generated ($> 150 \text{ m}^3$) is sufficient

to sweep any residual VFP vapours and aerosol out of the RPV into the pressuriser. Gas temperature will be close to water saturation temperature at this stage (~360°C), and the temperature of the RPV upper internals will fall.

Phase C. RPV melt-through. When the core debris in the RPV lower plenum has boiled dry, temperatures will rise to exceed the melting point of steel, and melt-through of the RPV lower head will follow within a few minutes (~ 6 min). Gas flow through the system will be negligible at this stage, but convective and radiative heat transfer may heat up the RPV upper intervals to temperatures of 800°C or higher. Some revolatilisation of VFP deposited onto the upper grid plate may occur at this stage. Following RPV melt-through, the system will rapidly depressurise, and any still-suspended FPs will be swept into the containment, together with any fraction of earlier-deposited FP which may become resuspended at this stage.

FP Retention

Iodine (HI)

If it is assumed that iodine deposits onto particulate, as in Model (i) of the preceding discussion, then the retention behaviour is entirely dominated by this process due to the high aerosol densities anticipated, and the behaviour follows that of other particulate.

In the case that Model (i) applies, and only deposition onto walls is allowed, then it is readily calculated that the hot-leg and pressuriser surfaces which would be cool enough to permit deposition have insufficient surface area to retain more than a small fraction (<1%) of the iodine inventory at saturation coverage. Effectively all of the iodine would be released into the relief line. The combined processes of steam condensation in the relief line and scrubbing in the water-lute of the quench tank are expected to effectively partition highly soluble HI into the bulk water phase, and a Decontamination Factor (DF) of at

least 10 can be estimated from calculations and suppression pond experiments. We therefore set the release factor F for volatile inorganic iodine in the Model (i) situation at $F \leq 0.1$.

Particulate

Upper plenum

Phase A.

Gas temperatures are estimated to be in the region of 800-900°C, and internal structure surface temperatures around 500°C, during the stage of major VFP release. Calculated partial pressures of CsOH and CsI of about 0.2 MPa and 0.02 MPa respectively exceed the SVPs corresponding to gas temperature by two or more orders of magnitude. The surface temperature of structural material aerosols co-released with the VFP should be close to the temperature of the surrounding gas in each region, and when hot gases exiting the core mix with cooler gas in the RPV upper plenum, rapid condensation of these VFP vapours onto the aerosols is expected. The partial pressure of Te (~ 0.05 MPa) does not so greatly exceed the SVP, and incomplete condensation onto particulate is anticipated. All the VFP vapours will be greatly supersaturated with respect to wall temperature, and condensation onto the upper plenum structures will also occur.

The residence time in the upper plenum is long, estimated at 1000-1500 s. The initial structural aerosol density at the core exit may be estimated by assuming that the gases passing through molten regions of the core become saturated with the vapours of molten structural and control rod materials, since the flow velocities of carrier hydrogen/steam are low ($\sim 0.01 \text{ m s}^{-1}$). Control-rod silver will be the main contributor, and a mass density of around 1 kg m^{-3} can be derived. Agglomeration and deposition in the upper plenum will rapidly reduce the mass density, and the process will be accelerated by the condensation of VFP onto the aerosol. Estimation of the extent of VFP retention is difficult, due to uncertainties in the deposition velocities for condensation, and the changing aerosol density, but the following is presented as a reasonable approach:-

a. Internal surface deposition

This will probably be mass transfer limited, and in the absence of structural aerosol, significant condensation onto the upper plenum internal structures would be expected. However, since the effective A/V ratio for the aerosol is estimated to be two or more orders of magnitude greater than that for structures ($\sim 5 \text{ m}^{-1}$), condensation onto the aerosol will dominate even if the deposition kinetics are considerably slower for this process. We therefore neglect detailed consideration of condensation onto structures, whilst noting that it will provide additional retention.

b. Deposition with particulate

Two factors enter into the estimate:-

1. The fraction of VFP vapour which condenses onto particulate. For the highly supersaturated vapours CsOH and CsI, condensation will be governed by mass transfer and heat transfer. The intimate mixture of aerosol and vapour ensures that mass transfer processes will be fast, the typical diffusion time to the nearest particle being only a few seconds. Heat transfer of the latent heat to the bulk gas following condensation may then be the rate limiting process, but a simple calculation suggests that the timescale for temperature accommodation is again of the order of seconds. Thus, for the highly supersaturated vapours CsOH and CsI, essentially complete condensation onto particulate is anticipated within 10-20s of entering the upper plenum, and the fraction of these species retained is the same as the overall retention of particulate. For Te, the equilibrium distribution between vapour and condensed states is also expected to be rapidly attained, but in this case it corresponds to a 60-70% condensed fraction.

2. The fraction of particulate which deposits in the upper plenum. In order to estimate this, a crude stepwise calculation of the aerosol history in the upper plenum, treated as a well-mixed volume, has been performed.

Gas flow rates and temperatures were taken from a MARCH run. A structural aerosol mass generation rate increasing linearly with time (and hence roughly with fraction of core molten), to a maximum of 0.1 s^{-1} just before core slump, was employed. For estimation of the extent of aerosol deposition, an algorithm based on Fig 6-3 of NUREG-0772 was used. The following table outlines the results of the calculations, time zero being the onset of VFP release.

Table 3.3

t,s	Fraction of released mass deposited in upper plenum %	Aerosol mass density in upper plenum, $\text{kg m}^{-3} \times 10^3$
300	0.73	0.28
600	50.4	54
900	76.7	81
1200	86.3	95
1500	90.6	108
1800	93.1	118
1950 (core slump)	93.8	123

This calculation takes no account of the effect of condensing VFP in enhancing aerosol deposition, and is therefore considerably conservative. It leads to the following estimate of VFP distribution at the time of core slump (%):-

	Cs,I	Te
Deposited in RPV upper plenum	80	40
Vapour in Core	10	10
Suspended in RPV upper plenum	4	30
Transported out of RPV	6	20

Phase B

On a conservative assumption, the VFP still suspended in particulate or vapour form at the time of core slump will be swept without further deposition into the hot leg and pressuriser. Since the upper plenum structures will be cooled during this period, no resuspension of VFP is anticipated. Flow velocities are too low in the upper plenum to produce significant hydrodynamic resuspension forces on deposited particulate.

Phase C

Heat-up of the upper plenum structures at this stage could produce some volatilisation of deposited VFP, but several arguments suggest that resuspension is likely to be small. Assuming the upper core grid plate remains intact, and attains a temperature of about 800°C, the vapour pressures of VFP compounds will remain quite low ($< 10^{-2}$ atm), and mass transfer limitations will ensure that only small fractions of the deposited masses, at most a few percent, will evaporate in the short time available. Moreover, CsI, CsOH and Te will all be in the liquid state at this temperature, suggesting strong adhesion to surfaces, and little probability of resuspension by hydrodynamic lift during the depressurisation following RPV melt-through. On these grounds, it is proposed that resuspension of VFP deposited in the RPV upper structures during Phase A can be neglected.

Hot leg

Residence time in the hot leg is in the region 30-60s, and negligible deposition of particulate is expected for the aerosol mass densities of 0.1-0.2 kg m⁻³ expected in gas flowing from the RPV upper plenum. Gas temperature will fall somewhat through the hot leg, and further condensation of Te vapour onto particulate will occur. The vapours of Cs, I and Te species will all be highly supersaturated with respect to pipe wall temperature, but mass transfer will limit deposition to <1%.

In summary, no significant VFP deposition is expected in the hot leg.

Pressuriser

Phase A

Data from MARCH calculations, and from NUREG-0772, Appendix D, suggest that the gas temperature here will rise to about 600°C, and the surface temperature to 400°C, during the phase of VFP release. The residence time is estimated to be very long, 2000-3000s. Vapours of any VFP not already condensed, notably Te, will become highly supersaturated here, and essentially complete condensation can be expected. Residual structural/FP aerosol will be the main sink for this condensation, since mass transport will limit the extent of deposition onto the walls to a few percent. The fate of that proportion of VFP which escapes from the RPV will thus be determined by aerosol behaviour in the pressuriser.

No detailed calculations have been performed, but using Fig 6-3 of NUREG-0772[4] as a guide it can be estimated that at least 80% of the aerosol entering the pressuriser during this stage will be deposited there. Total release of Cs and I (to the relief line) by the end of Phase A is thus estimated at less than 1%, and of Te at less than 4%, of core inventory.

Phase B

Following core slump, the rapid steam/hydrogen flow from the RPV lower plenum will sweep the residual VFP suspended in the core and upper plenum into the pressuriser, and drive that proportion of aerosol still suspended in the pressuriser out through the relief valve. The latter process is estimated to release about a further 1% of core inventory of Cs, I and Te into the relief line.

Results of the complex transport, condensation and mixing processes in the RPV upper plenum and pressuriser during this phase are difficult to estimate. Very approximately, though, an aerosol of mass density around 0.5 kg m⁻³ is expected

to be created in the pressuriser, and in the stagnation period between end of boil-dry and RPV melt-through, some 90% is estimated to deposit in the pressuriser.

Phase C

From the foregoing, it follows that at the time of RPV melt-through and circuit depressurisation into the containment building, only some 1-2% of Cs and I core inventory, and about 4% of Te inventory, is expected to be still gas-borne as aerosol in the pressuriser. Further possibilities of trapping of this exist as it flows back through the circuit to the breach point. However, conservatively we estimate the releases of Cs and I at this stage as 2%, and of Te as 4%.

Relief line and Quench Tank

Gas escaping to the relief line experiences a large pressure drop from 17.1 MPa to < 1 MPa on passage through the relief valve. This will produce strong adiabatic expansion cooling, and steam condensation in the relief line is certain. The relief line and quench tank will thus be wet, affording good possibilities of aerosol trapping on surfaces. In addition, if a water lute exists in the quench tank, scrubbing of exit gases will further attenuate aerosol release to the containment, with DFs probably as high as 10. Thus, of the few percent of VFP which are estimated in earlier sections to escape into the relief line, only a minor proportion will reach the containment atmosphere.

Summary

If deposition onto aerosol is neglected, iodine (I₂) is expected to largely escape from the RCS via the pressuriser relief valve, but effective trapping in the quench tank will reduce the gas-borne fraction released to containment to <0.1. Otherwise, iodine will be retained attached to particulate inside the RCS to an extent of > 90%. Other VFP will be trapped within the RCS, condensed on deposited aerosol, to an extent of > 90%. The main release (< 5%) is expected to be on RPV melt through and RCS depressurisation.

Discussion of primary circuit retention

In Section 3 above, the physical mechanisms which can lead to retention of volatile fission products in the reactor coolant system have been reviewed, and an attempt has been made to quantify these mechanisms for specific accident types within the framework of the DPD approach. This analysis identifies many areas in which existing information is incomplete or inadequate, and it has frequently been necessary to apply judgement in selecting values for key parameters. Deficiencies in both probabilistic and physically descriptive data are apparent. A need to modify some aspects of the treatment in the light of improved experimental and computational data may be anticipated, and in several features, such as making no claims for VFP retention in the RPV upper plenum in V, A and S LOCAs, the conclusions may be somewhat conservative. The overall probability distributions derived for the four LOCA-types covered are summarised in Table 3.4.

4. Building Retention

If the fission products, having left the primary circuit, become well-mixed in a building and remain there for some time before leaking to the environment, there is then the possibility that some fraction of them will be retained on the internal surfaces of the building. Three cases are considered in this section:

1. the auxiliary building
2. the containment building without sprays operating and with eventual failures
3. the containment building with sprays operating and without eventual failure.

In the first case the building can stand no overpressure so leakage begins immediately upon release. In the second case the release is dominated by the puff release at the time of containment failure, and to a first approximation the amount released is the amount airborne at this time. In the third case the release is due to the design basis leakage of the containment building.

The present work builds upon a WASH-1400 style study performed by Offshore Power System (OPS) reported in WCAP9991. The building dimensions and output of the MARCH and CORRAL calculations are those given in WCAP9991[9].

4.1 Auxiliary Building Retention in UK1

4.1.1 Introduction

The first estimate methodology allows for no retention in the auxiliary building, so

$$F_A(i) = \phi_A^{(2)}(i)$$

(see Section 2 for definitions) for $i = I$ (inorganic iodine-containing vapours) and $i = p$ (volatile fission produce particulate). Very little modelling of auxiliary building effects has been done in the past. Table 7.3

of NUREG-0772[4] quotes results of a CORRAL calculation, results which imply

$$F_A(I) = 0.52 \quad , \quad F_A(p) = 0.64$$

However the assumptions and parameters on which these calculations are based are not given in the text. Moreover what little is said in the text about the V-sequence accident seems to contradict these numbers. On p7.22 we read:

"The integrity of the auxiliary building would be lost very early in the accident. Little retention of iodine is predicted to occur in the failed building regardless of chemical form".

Again on pA.8 we read:

"The fission products would be released to the atmosphere of the safeguards building in a mixture of hydrogen and superheated steam. For gas generation rates consistent with decay heat, the residence time in the safeguards building would only be a few minutes before release to the environment".

In view of this confused situation, it was decided to base the second estimates on our own scoping calculations, and these are presented below. Broadly speaking it seems that values of $F_A(I)$ and $F_A(p)$ of around 0.5 (close to the values in NUREG-0772) can be justified.

4.1.2 General Approach

Release category UK1 contains only the V-sequence, so we do not have here uncertainties of the first kind (defined in Section 2). What remain uncertain are things like the size and position of the break in the low pressure circuit and the state of damage of the auxiliary building, ie uncertainties of the second kind. In the investigations to be described in this section we do two things. Firstly we consider a simple model for an intact building, taking it to be an empty shell (a conservative assumption) ventilated by the steam coming out of the ruptured primary circuit. Secondly we define four building states

which attempt to represent the spectrum of possible building responses, ranging from complete destruction to the survival of a building within which the fission products can become well-mixed before leaking to the environment. These are:

1. Total Destruction. The fission products vent from the broken pipework directly to the atmosphere.
2. Leaky Shell. There is substantial demolition of internal partitions and of the external walls. Fission products are removed by wind ventilation.
3. Compartment Rupture. Damage is restricted largely to the compartment in which the leak occurs, and is primarily in the external rather than internal walls. The ventilation is dominated by the wind. Physically the situation is like case 2 except that the volumes, areas and ventilation rates are all smaller.
4. Internal Rupture. Here it is the internal rather than the external walls which are the most damaged. Fission products become well-mixed throughout the whole building before leaking out. The ventilation is due to primary circuit gas. This case is the same as the simple case described above except that more internal surface area is assumed here.

Considerations of the design of the building, which is substantially compartmentalized to restrict common-cause failure of the plant it houses, and particularly of the nature of the location of most likely breaks, suggest that most weight should be given to cases 3 and 4.

The modelling of the transport processes uses the assumptions embodied in CORRAL. The consequent omission of particulate agglomeration can be justified on the grounds that, as will be shown later, agglomeration does not become

important till after four hours, whereas typical residence times in the auxiliary building will turn out to be less than one hour. Removal of iodine and particulate are characterised therefore by first order rate constants:

$$\lambda_I = k_I A_I/V, \quad \lambda_p = k_p A_p/V$$

k_I and k_p are deposition velocities, and the geometrical factors are:

V = total volume within which the fission products can become well-mixed on a time-scale short compared with residence times.

A_I = total area available for I_2 plate-out

A_p = total area available for particulate sedimentation.

Values for these factors are estimated below for the different building states. Uncertainties in the building state are believed to be more important than those caused by the choice of CORRAL methodology and of the particular values of k_p and k_I (taken from WASH-1400 modelling of the containment).

To calculate release fractions we need the removal rate constants, λ_I and λ_p and the leak rate N :

$$N = \Theta/V$$

where Θ is the volume flow rate out of the affected volume.

For wind ventilation Θ is

$$\Theta = \psi v_w A_u$$

where v_w is the wind velocity and A_u is the breached area on the upwind side of the building. Henceforth the constant of proportionality ψ is taken as unity, representing the largest possible exchange rate.

4.1.3 Calculations of Release Fractions

These calculations require as input values of k_I , k_p , Θ and the geometric factors V , A_I , A_p . From these we obtain the rates λ_I , λ_p and N . The release fractions are then:

$$F_A(I) = \frac{N}{N + \lambda_I} \quad , \quad F_A(p) = \frac{N}{N + \lambda_p}$$

WASH-1400 quotes for the containment without sprays

$$\lambda_I = 1.38 \text{ hr}^{-1}$$

This value of λ_I is used in conjunction with the appropriate dimensions of the RSS containment to derive suitable deposition velocities.

The containment parameters for the RSS containment are:

$$\begin{aligned} V &= 5.10 \times 10^4 \text{ m}^3 \quad (\text{containment free volume}) \\ A_p &= 1.05 \times 10^3 \text{ m}^2 \quad (\text{floor area}) \\ A_I &= 7.71 \times 10^3 \text{ m}^2 \quad (\text{wall} + \text{dome} + \text{floor area}) \end{aligned}$$

This gives a deposition velocity for iodine of:

$$k_I = 9.13 \text{ m hr}^{-1}$$

The number k_p is a Stokes's law terminal velocity of the particulate. In CORRAL this is calculated from the aerodynamic equivalent diameter (AED) as follows:

$$k_p / (\text{m hr}^{-1}) = 0.109 (\text{AED} / \text{m})^2$$

The AED falls linearly from $15\mu\text{m}$ to $5\mu\text{m}$ in 4 hours, and then is held at this value. A typical calculated residence time ($1/N$) for particulate in the auxiliary building is 0.66 hr, corresponding to $\text{AED} = 13.35\mu\text{m}$. We shall use the settling velocity corresponding to this residence time, namely

$$\begin{aligned} k_p &= (0.109 \times (13.35)^2) \text{ m hr}^{-1} \\ &= 19.43 \text{ m hr}^{-1} \end{aligned}$$

The other parameters depend on the details of the case being considered. We begin with a simple case, in which the building is taken to be an empty shell, so that V is the total building volume, A_p is its floor area, and A_I is the total area of walls, floor and ceiling. Volume and floor area from WCAP9991 are.

$$V = 5.66 \times 10^4 \text{ m}^3$$

$$A_p = 7.15 \times 10^3 \text{ m}^2$$

Making the additional conservative assumption of a square plan, we get a height of 7.92m, so that the total area of walls, floor and ceiling is

$$A_I = 1.70 \times 10^4 \text{ m}^2$$

The flow rate of steam into the building is taken to be that typical of a small break LOCA, during the time of the melt release. This is obtained from the output of the MARCH code:

$$\dot{Q} = 8.49 \times 10^4 \text{ m}^3 \text{ hr}^{-1}$$

Next we have to compile the same input for the four cases de. in 4.12. In case 1 there is no building left, so nothing is required. For the flow rate in case 2, we take

$$v_w = 4 \text{ m s}^{-1} \text{ (a typical UK wind velocity)}$$

$$A_u = 150 \text{ m}^2 \text{ (about a quarter of the area of one wall)}$$

$$\text{giving } \dot{Q} = 600 \text{ m}^3 \text{ s}^{-1}$$

With this amount of ventilation, the fission product cannot be expected to mix with the entire building volume or make use of the entire surface area. Let us take as effective geometric parameters:

$$V' = 14000 \text{ m}^3 \text{ } (\approx 1/4 V)$$

$$A_p' = 2800 \text{ m}^2 \text{ } (\approx (1/4)^{2/3} \times \text{floor area})$$

$$A_I' = 4000 \text{ m}^2 \text{ } (\approx 2 \times \text{area of one wall} + A_p')$$

Finally we assume that the flow, \dot{Q}' , actually affecting fission product is in proportion to \dot{Q} as V' is to V , namely

$$\dot{Q}' = 150 \text{ m}^3 \text{ s}^{-1}$$

These numbers for case 2 are chosen more or less arbitrarily so that scoping calculations can be done for the effects of incomplete mixing in the building.

For case 3 we take a compartment of the same volume and floor area as were affected in case 2, so V and A_p are as above. With a square plan the total surface area is then

$$A_I = 6660 \text{ m}^2$$

The wind velocity is kept the same, but now the breached area is taken as one-tenth of the area of one wall:

$$A_u = 25 \text{ m}^2$$

$$\text{so } \theta = 100 \text{ m}^3 \text{ s}^{-1}$$

Finally for case 4 we take the input of the simple case except for an increase in A_I to take account of surviving internal vertical partitioning. For these calculations we increase A_I by a factor of four.

$$A_I = 6.8 \times 10^4 \text{ m}^2$$

With this input the rates and release fractions are as tabulated:

Case	N/hr^{-1}	λ_I/hr^{-1}	λ_p/hr^{-1}	$F_A(I)$	$F_A(p)$
Simple	1.50	2.74	2.45	0.35	0.38
1	-	-	-	1.00	1.00
2	38.6	2.61	3.89	0.94	0.91
3	25.7	4.34	3.89	0.86	0.87
4	1.50	11.0	2.45	0.12	0.38

If the four cases are given equal weights then the mean releases are

$$\overline{F_A(I)} = 0.73 \quad \overline{F_A(p)} = 0.79$$

If we restrict the possibilities to cases 3 and 4, giving them equal weights we get

$$\overline{F_A(I)} = 0.49 \quad \overline{F_A(p)} = 0.63$$

4.1.4 Conclusions

The numbers presented above suggest the following conclusions:

- a. There is little significant difference between iodine vapour and particle behaviours; the residence times are too short for the effect of the faster removal rate of the former to become apparent.
- b. Given that some sort of building survival is the most likely outcome, the greatest probability should be given to $F = 1/2$, with some weight also in $F = 1$ and $F = 1/4$ to account for the extreme cases.

These conclusions can be expressed in the following DPDs:

F_i	=	1	1/2	1/4	1/10	1/20
$P(F_A(I) = F_i)$		0.2	0.6	0.2	0	0
$P(F_A(p) = F_i)$		0.2	0.6	0.2	0	0

4.2 Containment Retention in UK2, 5 and 6

4.2.1 Introduction

The cases discussed in the present section are characterised by the eventual failure of the containment and the operation only of natural removal processes within the containment. Spray removal is discussed in Section 4.3, in the context of sequences where the containment does not fail. In UK2 there is the possibility of a steam explosion, and containment is failed promptly after failure of the reactor pressure vessel. In UK5 and 6 there is no steam explosion, and the containment fails only after several hours. UK5 has a vaporisation release while UK6 does not.

The effects which cause a decrease in release fractions relative to the point values are similar in all three categories. However in UK2 and UK6 there are possible mechanisms which tend to work in the opposite direction, that is to increase the release fractions. These are treated in the present work as perturbations on the distributions obtained by considering only those additional effects which reduce the release fractions.

The UK5 distributions are therefore taken as representing the effects of the retention mechanisms in all three categories, and these are discussed in 4.2.2, 4.2.3 and 4.2.4. Then in subsection 4.2.5 the release enhancing mechanisms and their likely effects on the distributions are discussed separately.

The release categories are defined in terms of molten core behaviour after the pressure vessel failure and of containment response, whereas the sequences are divided up according to the initiating event. Therefore there is no simple correspondence between release category and accident sequence. This point is examined in 4.2.2. As in the auxiliary building, there are uncertainties in the geometrical factors (areas and volumes) to be used in the modelling of the containment. Increased retention estimates due to more realistic modelling of internal surfaces, together with the dependence of these increases on time of failure, are discussed in 4.2.3. Finally, CORRAL is incomplete in its modelling of aerosol behaviour. By comparing CORRAL results with those of the mechanistic code AEROSIM, the effects of allowing for a spread of particle sizes and for the process of agglomeration are studied, the results appearing in 4.2.4.

In all of the cases considered here the leak rate is small before containment failure, and on failure a sudden puff release is assumed, which releases 95% of the containment contents. Therefore the amount released is dominated by the amount airborne at puff release (except in UK2 where the vaporisation release component is not yet airborne at the time of puff). This simplifies particularly

the calculation of dependence on release time of the mass released, because it can then be estimated from graphs of amounts airborne as functions of time.

4.2.2 Effects of Sequence Uncertainties

No separate effects calculations have been done specifically for UK2; the point values were taken from the RSS, category PWR 1. However, WCAP9991[9] reports calculations for a series of cases involving prompt containment failure and these show little difference between the A, S and T type events. The contributions of uncertainties of the first type described in Section 2.5 are therefore unimportant in UK 2.

For UK5 and UK6 both T and S sequences contribute. Relevant WCAP 9991[9] results are tabulated for sequences with containment failure 4 hours after RPV failure as follows:

UK5 (Vaporization Release)

Sequence	I ₂ release	Cs release
T	6.3×10^{-2}	3.4×10^{-1}
S	4.4×10^{-2}	3.4×10^{-1}
A	3.9×10^{-2}	3.3×10^{-1}

UK6 (No Vaporization Release)

Sequence	I ₂ release	Cs release
T	3.1×10^{-2}	2.5×10^{-1}
S	1.9×10^{-2}	2.5×10^{-1}
A	1.8×10^{-2}	2.6×10^{-1}

Again the differences between sequences are seen to be small.

The results for a four hour failure time were used in this study simply because only in this case had the calculations been done for the three sequences. In fact an eight hour failure is considered to be the minimum plausible for both

UK5 and UK6, and the point values for UK6 are indeed based on an eight hour failure. For UK5 a four hour failure was taken for the point value. For a T-sequence contributing to UK5 the release fractions for eight hour failure are 1.1×10^{-2} and 2.4×10^{-1} for I_2 and Cs releases respectively (WCAP-9997, Table 4.5-13 [9]). Therefore simply by giving weight to realistic failure times in UK5, without invoking any other effects, gives a reduction in the point value.

4.2.3 Effects of Uncertainties in Volumes and Areas

Both iodine and particulate removal rates are of the form:

$$\text{rate} = \text{deposition velocity} \times \frac{\text{Area}}{\text{volume}}$$

Therefore the assumption that the containment is an empty shell is conservative because internal partitioning and equipment increase available area and decrease available volume. Here it is being assumed that internal structure does not alter the deposition velocities. In fact they could disrupt the convection patterns found in an empty building, and thereby increase the boundary layer thickness. Since for I_2 plate-out by diffusion through the boundary layer is rate-determining, the effect of internal structure would be to decrease the deposition velocity. Moreover if the containment is found to be divided into effectively separate well-mixed volumes more detailed modelling would be required.

If the time-dependence of airborne-concentrations is of the form $\exp(-\lambda t)$, and if λ is replaced by an enhanced rate λ' , then the mass airborne and hence available for release will be reduced by a factor, $\exp[-(\lambda' - \lambda)t]$, decreasing exponentially with time of containment failure. To estimate how the effects of increasing λ_I depend on time of failure, a simple fit was made of the iodine releases calculated by OPS[9] for the three failure times in a T-sequences accident. The results were approximated by using

$$\begin{aligned} \lambda_I &= 1.05 \text{ hr}^{-1} && \text{up to end of vaporisation release} \\ &= 0.40 \text{ hr}^{-1} && \text{after vaporisation release} \end{aligned}$$

Then λ_I was increased by a factor of four, giving the following reduction factors for the masses airborne at the stated times.

	Prompt Failure	4 Hours Failure	8 Hours Failure
reduction factor	0.40	0.125	4×10^{-4}

Once again times are measured from the time of pressure vessel failure; prompt containment failure means that it occurs within a few minutes of vessel failure. Note that there is still a reduction for prompt failure because the volatile fission products come into the containment before pressure vessel failure.

We see that for iodine the effect of increasing A_I/V is very sensitive to the failure time assumed.

For the particulate, WCAP9991[9] gives sensitivity studies for increases in A_p/V of factors of $\frac{3}{2}$ and 2 for the four hour and eight hour failure cases. A simple exponential interpolation between point values for four hours and prompt failure enables us to estimate an effective λ_p , and hence what the analogous reductions would be for a prompt failure. The results for reduction factors are:

A_p/V increase	prompt failure	four hours	eight hours
$\frac{3}{2}$	0.83	0.56	0.50
2	0.63	0.31	0.25

The removal rate for particulate in the containment, particularly at the longer times, is much smaller than that for iodine, so these reductions are much less sensitive to time than the iodine numbers.

If the A/V increases discussed above are possible and if this is the only source of release reduction, the reductions achieved are around 0.5 for the particulate cases and for prompt iodine release. For delayed iodine release much greater reductions can be claimed.

4.2.4 Effects of Processes Not Modelled

As well as uncertainties in our knowledge of the physical conditions, there are deficiencies and uncertainties in the modelling of the physical and chemical processes to be taken into account. This is particularly true of the aerosol modelling. In CORRAL each release is characterised by a single radius for particulate material and hence a single rate of fall-out. In the CSE experiment, on which CORRAL is based, the sedimentation rate was found to decrease with time[15], an effect attributed to the faster fall-out of the larger particles. In CORRAL this is modelled by letting the particle radius decrease linearly as a function of time after release. If, however, in actual accident conditions the particle density is high enough to make particle agglomeration an important process, then the population of larger particles will continually be replenished, and λ_p will not fall. The effects of agglomeration are discussed in detail below.

Processes involving steam condensation are also not modelled explicitly in CORRAL although it may be that the effects are implied since the CSE experiments included condensing steam. If steam condenses on particulate material, or if the particles agglomerate with water droplets their size will increase and sedimentation will be faster. If steam condenses on surfaces then particles will deposit on these surfaces, transported there by diffusiophoresis. Results from the German code NAUA, are reported in NUREG-0772 (p 7.27). For the TMLB' accident, going from a dry to a steam atmosphere causes only a 20% reduction in airborne concentration, owing to "the rather short period of condensation predicted by the thermal hydraulic conditions." It is then said, "the effects of condensation could be more significant for sequences other than TMLB'."

The effects of agglomeration have been studied for the T sequence using the SRD aerosol code, AEROSIM[16]. The mass median radius of the source distribution was chosen to be 0.082 μm , corresponding to an AED (aerodynamic equivalent diameter) of 0.532 μm (ie a factor of 30 below the initial size of particulate in CORRAL).

This is the value recommended in the CSNI report on aerosols in reactor safety[17]. The masses released are core inventories predicted using the FISPIN code[10] multiplied by RSS release fractions. The releases were calculated for the four and eight hour failure cases of TMLB' with vaporisation release and the ratios of AEROSIM to CORRAL release fractions for Cs particulate are given below. Also tabulated are the ratios when a four-fold reduction in the masses of all material released is assumed, the significance of which will be explained later.

	4 hour failure	8 hour failure
$F_C(p)$ with standard source release masses	0.77	0.12
$F_C(p)$ with release masses $\times 1/4$	1.94	0.63

The benefit to be gained by agglomeration is strongly time-dependent. CORRAL is quite accurate for the earlier failure (which comes very soon after the end of the vaporisation release), but is larger than predicted by AEROSIM by an order of magnitude at the later time.

A similar picture emerges from a study reported in NUREG-0772 (Figure 7.12, page 7.33). Predictions of mass airborne as a function of time are compared for CORRAL and for four mechanistic codes. The graph is shown schematically as figure 4.1. The mechanistic codes give results lying within a tight envelope. For four hours after the start of the release the CORRAL result lies within that envelope, but from then on falls very much less sharply. By eight hours (that is, six hours after pressure vessel failure) the CORRAL values are an order of magnitude higher.

Figure 4.2 shows the ranges of particle sizes assumed for CORRAL, as compared with the mass median radius (r_{50}) from AEROSIM. For each release in CORRAL the AED starts out at $15 \mu m$, then falls linearly to $5 \mu m$ in four hours and remains at this value thereafter. In AEROSIM r_{50} starts off small, rises to some quasi-steady-state value, from which it slowly declines (this sequence is

*

interrupted by the injection of fresh material by the vaporisation release). After about five hours into the accident the AEROSIM r_{50} goes above the CORRAL radii, and from then on fall-out will be faster in AEROSIM than in CORRAL. What this figure does not show is that AEROSIM predicts a range of particle sizes. The largest particles typically have a radius an order of magnitude above r_{50} . Even when r_{50} is below the CORRAL radii AEROSIM predicts a continually replenished supply of much larger particles falling out much more quickly than does CORRAL.

However, within the spectral source term methodology one must be careful in claiming these reductions due to agglomeration. Probabilities for retention in the three sites, primary circuit, containment and leak path are considered as statistically independent. A probability for containment reduction is claimed regardless of what has already been claimed for primary circuit retention.

Such an approach is all right when removal processes are first order, as they are assumed to be in CORRAL. Then the fractional reduction in concentration does not depend on initial concentration. However, such an assumption is not applicable for a second order process like agglomeration. For this reason AEROSIM calculation has been repeated with all masses of released material reduced by a factor of $1/4$. The results appear on the second line of the above table. The modest agglomeration reduction for four hours is wiped out, and the reduction to 12% at eight hours is replaced by a reduction only to 60%. On the other hand, if we are to consider primary circuit processes, we might legitimately claim an increase in radius along with the decrease in concentration, and this will increase the removal rate again. For example when, with the standard source, the radius is increased from $0.082 \mu\text{m}$ to 0.770 (corresponding to $AED = 5 \mu\text{m}$) the 12% is reduced still further to 4%. The initial radius is an important uncertainty in aerosol calculations. It follows from this discussion that great caution has to be exercised in claiming agglomeration-based containment reductions within the present methodology, because of the dependence of such reductions on the extent of the reduction during primary circuit transport.

4.2.5 Release Enhancing Mechanisms

UK2 involves a steam explosion which may cause a resuspension of material, an effect not included in point value calculations. In UK6 there is no vaporisation release, a fact which may be due to the hot core having been spread widely over the floor of the containment. The resulting thermophoresis effects will hinder particulate and iodine deposition on the floor. Below we give some simple calculations which investigate the best way to represent the effects, within the DPD methodology.

Let the fraction of the total fission product put into the containment airborne at the time of an explosion be ϕ , and for simplicity let us identify this with the fraction released in the absence of resuspension. Therefore $1-\phi$ of the input has been deposited; let us assume a fraction f of this is resuspended and hence released. Then the release fraction with resuspension is

$$\phi' = \phi + (1-\phi)f$$

The values of ϕ' for various values of f are presented below for the behaviour of Cs particulate in UK2. Also given are ratios $\phi'/\bar{\phi}$, where $\bar{\phi} = 0.4$ is the point value.

ϕ		0.4	0.2	0.1
$\phi / \bar{\phi}$		1.0	0.5	0.25
$f = 1/10$	ϕ'	0.46	0.28	0.19
	$\phi' / \bar{\phi}$	1.15	0.70	0.475
$f = 1/5$	ϕ'	0.52	0.36	0.28
	$\phi' / \bar{\phi}$	1.3	0.90	0.70
$f = 1/2$	ϕ'	0.70	0.60	0.55
	$\phi' / \bar{\phi}$	1.75	1.50	1.38

The effect is to concentrate the distribution around the point value.

The effect of deposition retardation due to core spreading can be crudely modelled by a reduction in the effective floor area available. This clearly affects particulate much more than iodine, the latter having area other than floor available to it. So the release enhancement should be attributed much more to the particulate than to the iodine in UK6. As discussed earlier in the context of increases in area, the effects are much greater at longer times. If the small release end of the spectrum is identified with long times to failure, then this end should be affected most. The appropriate way to perturb the distribution is therefore to shift some weight, based on judgement, from the lowest occupied value of F_i to $F_i = 2$.

4.2.6 Summary and Conclusions

The main points made in this section are as follows:

- i. Significant reductions can be obtained solely on the basis of increasing internal areas and decreasing the containment volume, consistent with the specific design parameters.
- ii. The effects of uncertainties in the contribution of accident sequences to release categories are small.
- iii. Weighting longer times to containment failure will decrease UK5 point values, particularly for iodine release, even without A/V increases.
- iv. Point values in UK6 are already for the longer times, so the reductions mentioned in (iii) above (ie those independent of A/V increases) cannot be claimed here.
- v. Particulate agglomeration gives significant reductions in release fractions at the longer failure times, but since the magnitude will depend on what happens in the primary circuit they cannot easily be fitted into the present statistical methodology and hence were not used.

vi. Fission product resuspension in UK2 will tend to concentrate the probability distribution obtained by considering only reduction mechanisms around the point value.

vii. Core spreading in UK6 may shift weight from lower to higher particulate releases, but the effects for iodine will be smaller.

For the purposes of the consequence calculations these conclusions are expressed in the following DPDs. Firstly distributions are constructed to represent the release reducing effects in all three categories. This is attributed unaltered to UK5, where there is no release enhancement. Then this first pair of distributions has a weight of 0.1 shifted from each $F = 1/4$ column to each $F = 2$ column, to represent release enhancement, the result being attributed to UK2 and 6. For the release reductions we look to effects of A/V increases. For inorganic iodine-containing vapour we can expect a factor of 1/2 reduction even for prompt failure. So a weight of 0.4 is attributed to $F = 1/2$ and the rest is spread between 1 and 1/4. For particulate there are reductions between 1 and 1/2 for prompt failure, so 0.4 is assigned to $F = 1$ and to $F = 1/2$, with the rest in $F = 1/4$. The results are:

	$F_i =$	2	1	1/2	1/4	1/10	1/20
UK5							
I	0	0.3	0.4	0.3	0	0	
P	0	0.4	0.4	0.2	0	0	
UK2 and 6							
I	0.1	0.3	0.4	0.2	0	0	
P	0.1	0.4	0.4	0.1	0	0	

It should be noted that for UK5 and 6, which represent cases of delayed containment failure, the arguments presented in Section 4.2.3 show that considerably less conservative distributions can be justified. The enhancements have been expressed in a simple way, maybe one not strictly appropriate for steam explosion resuspension, but the uncertainties involved are such as to make going into greater detail unwarranted.

4.3 Containment Retention in UK12

In this case where the sprays operate and the containment does not fail, the dominant mode of removal is by the sprays.

4.3.1 Spray Removal of I₂

The principal conservatism in the spray modelling of iodine removal in CORRAL is the assumption of a 1% cutoff, ie that 1% of the airborne iodine will not be removed by direct spray action. Because the release to atmosphere is via a small design basis leak rate the amount released depends on the residual amount which remains airborne over a very long time. The point value for iodine release is based on a leak time of 720 hours, and 80% of the amount leaked comes out after 24 hours. If we could claim that sprays and natural processes could get the airborne iodine levels down well below the 1% level at least within 24 hours then something like a factor of 1/5 reduction could be claimed.

4.3.2 Spray Removal of Particulate

In the case of Cs particulate the conservatism seems to be in choice of sequence. OPS model two sequences, an S-sequence where sprays do not come on till after 1 hour into the accident, and an A-sequence where sprays come on almost immediately. The S-sequence result is taken as the point value; the A-sequence result is an order of magnitude down on this. Almost all (99%) of the release in the S-sequence occurs before the sprays come on. These facts suggest that important reductions can be obtained for earlier spray onset times.

4.3.3 Conclusions

The DPDs which have been chosen to express the release reductions discussed above are:

F =	1	1/2	1/4	1/10	1/20
I	0.2	0.35	0.35	0.1	0
P	0.5	0.3	0.15	0.05	0

For iodine vapour the large weight given to $F = 1/2$ and $1/4$ expresses the conservatism of the 1% threshold level assumption and of the choice of 720 hours for leakage. For particulate most weight is still given to the first estimate, but with the distribution tailing away to $F = 1/10$ to allow for earlier spray inception times.

5. Leak Path Retention

There are two distinct cases to be considered here: the leak paths following containment failure, applicable to UK2, 5 and 6, and the paths taken by design basis leaks, that is, those from an unfailed containment, applicable to UK12. To assess what retentions are possible requires a knowledge of the likelihoods of failure modes and the detailed conditions obtaining along the leak paths in the likely modes. As this information is presently not available to us we cannot fully assess the degree of retention possible. However the following comments can be made.

5.1 Leak Paths from Failed Containment

Even without a knowledge of the nature of the leak paths we can at least say that if the paths lead to the auxiliary building rather than directly to the atmosphere then there will be retentions of the sort discussed in Section 4.1. Since the building will receive gas at only the containment pressure rather than at the full primary circuit pressure, building damage should be less than in a V-sequence accident. Therefore let us assign release fractions of between 0.2 and 0.5 to leaks via the auxiliary building and a fraction of 1 to direct leaks. What then can we say about the probabilities associated with these two leaks?

The failures of containment can be divided into missile and overpressure failures. We do not treat basemat failure in this study. It seems that the former have a very small probability, so we give all the weight to the latter. These are divided into failures of seals in the various containment penetrations and gross failures of containment structure. Let x and $(1-x)$ be the respective probabilities of these models. Typically at least 95% of the penetrations go to the auxiliary building, so this is taken as the probability of seal failure which leaks to the auxiliary building. 20% of the total area of the containment wall is bordered by the auxiliary building, so this is taken as the probability of structural failure giving leaks to the auxiliary building. The probabilities are summarised as figure 5.1 in the form of a simple event tree.

The overall split between auxiliary building and direct leaks is

leak to auxiliary building : $P = (0.2 + 0.75x)$

leak direct to atmosphere : $P = (0.8 - 0.75x)$

For illustration, if we take a value of x of about 0.5, ie if structural and seal failures are about equally probable, then the probability of leak to the auxiliary building, and hence of substantial reductions of about 1/2, can be expected.

5.2 Design Basis Leaks

The point to be made immediately for this case is that we can no longer claim auxiliary building retention. Design basis leaks are assumed to pass through the penetrations, so 95% of the material is assigned to the auxiliary building, where all of the 95% is assumed to be removed by ventilation system filters*. This is taken into account in the calculation of the point values, so if we look for mitigation of the point value it is the residual 5% direct leak we must consider.

There is a model, due to Vaughan and discussed in NUREG-0772 (p7.35), for aerosol effects in design basis leaks. However it predicts, not fission product deposition in the leak path, but rather the blockage of the leak by aerosol particles. A mass \bar{m} of aerosol is predicted to leak before blockage. The fraction of core inventory released to the environment depends only on this quantity, and is independent of retentions in primary circuit and containment, unless the leak is so large or the mass airborne in the containment is so small that the mass that would be leaked in the absence of blocking is less than \bar{m} .

The model predicts that for a leak path with circular cross-section of diameter D the value of \bar{m} is:

$$\bar{m} = K D^3$$

* If this assumption is challenged then a X2 entry could indeed be generated for the DPD.

where $K = 50 \text{ g cm}^{-3}$. NUREG-0772 says, "This correlation has been shown to be applicable for a wide range of aerosol types, leak rates, and duct diameters up to as big as 30 cm". Note that the mechanism here is not that envisaged in the approach we have been using. It is not that a significant fraction of the mass is deposited along leak paths. Rather, a small fraction is deposited and blocks the path preventing further leaks of aerosol. Whether or not this also prevents the leakage of gas and particularly I_2 vapour is not clear. This question is important not only for retention of I_2 vapour, but also because if the gas flow is blocked the pressure will increase inside the containment until the particulate plug is blown out.

NUREG-0772 goes on to say, "... applying this correlation to leak path dimensions commensurate with a design leak rate of 0.1 volume percent per day indicates that quite small amounts of aerosol will be leaked before plugging will occur". A similar calculation has been done with Sizewell B data, and the same conclusion was reached, namely the amount of aerosol leaked before plugging is small by comparison with point value aerosol releases. Specifically a 0.2% volume leak rate per day corresponds to choked flow across an area of $7.2 \times 10^{-6} \text{ m}^2$. The area of the direct leak to atmosphere (ie 5% of the total) is then $3.7 \times 10^{-7} \text{ m}^2$. If we conservatively assume this to be via a single circular hole, the diameter is $3.4 \times 10^{-4} \text{ m}$, giving, by the Vaughan model:

$$\dot{m} = 2.0 \times 10^{-6} \text{ kg}$$

Given a mass of 660 kg during the melt release, we get a fraction to the environment of

$$f = 1.7 \times 10^{-8}$$

If all the Cs released comes out during this phase and if it is well-mixed in the 660 kg of material then this f is the fractional release of Cs particulate. The point value for UK12 is

$$f_{Cs} = 1 \times 10^{-6}$$

The simple blockage model reduces the point value by a factor of 1/50.

If the blockage model proves to be applicable to UK PWR degraded core accidents, then it can replace all of the source term modelling, at least for particulates, for UK12. Considerable reductions in the point value may then be expected.

5.3 Conclusions

Assigning probabilities to leak path retentions is still difficult, particularly where auxiliary building effects cannot be claimed. The DPDs chosen for the present are:

F =	1	1/2	1/4	1/10	1/20
Failed Containment					
I	0.4	0.2	0.2	0	0
P	0.3	0.3	0.3	0.1	0
Design Basis Leak Rate					
I	0.1	0.4	0.4	0.1	0
P	0.05	0.15	0.4	0.4	0

In the case of containment failure the weights span the range of possibilities of flow through the auxiliary building, with greater retention being allowed for particulate because of the possibility of partial plugging. The iodine distributions are principally the result of retention in the auxiliary building. For design basis leaks judgement has been used to shift the weight to values lower than for a failed containment reflecting enhanced plugging and retention possibilities in the smaller leakage pathways.

6. The Second Estimate Source Term Release Fractions for Sizewell B

In this section of the paper the primary circuit retention factors derived in Section 3, the auxiliary and containment building retention factors derived in Section 4, and the leak path retention presented in Section 5 are brought together using the methodology of Section 2 to obtain the overall spectral source term probability distributions for Sizewell B. Following a brief discussion of a number of general assumptions and guidelines which were adhered to, the results are given and reviewed. Of the release categories which have been studied hitherto only UK1, 2, 5 and 6 are treated here, and not UK12 for which even the first estimate source terms are small.

In the course of the derivation of the containment and leak path retention factors in Sections 4 and 5 it was demonstrated that variations due to the different accident sequences which contribute to each release category are within the limits of the methods of analysis and can be neglected. This is not the case, however, for the primary circuit retention factors derived in Section 3, where different values were obtained for V (interfacing LOCA), A (large LOCA), S (small LOCA), and T (transient) initiated sequences. In applying the results of Section 3, therefore, account has to be taken of the contribution of different types of accident sequence to the various release categories. From WCAP 9991 it can be seen that:

- release category UK1 contains only V sequences; for this study the pathway considered was the failure of the valves separating the high and low pressure coolant systems.
- UK2 is divided between A(45%), S(39%) and T(16%) type sequences.

- UK5 is divided between A type (8%) and S type (29%) and T type (63%) sequences.
- UK6 is divided between A type (2%) S type (32%) and T type (66%) sequences.

At the time this work was undertaken it seemed probable that UK5 and UK6 would be largely divided between A and S type sequences and the primary circuit retention factors for S type sequences have been used instead of those for the T type. It will be seen from Section 3 that this ensures that the results will err on the conservative side. It was also thought that UK2 would be completely dominated by S type sequences and the results for this category will, in consequence err slightly on the non-conservative side.

A further issue which has to be considered in arriving at the spectral probability distributions for Sizewell B is the physico-chemical form of the fission product iodine. For completeness the possibility that the inorganic iodine might exist as either vapour species (I , I_2 , HI) or the less volatile caesium iodide was envisaged earlier in the paper. Recent evidence on this topic has been reviewed in NDR610[3], where the conclusion is drawn that the most likely form must currently be assessed to be caesium iodide. For present purposes account has been taken of this by treating inorganic iodine as particulate rather than vapour; hence, the spectral probability distributions for iodine becomes identical with those for all the other non-gaseous fission products. However, care must be taken to associate these with first estimate release fractions for iodine based on a particulate model and not with the first estimates in WCAP9991 which are based on a vapour model.

Adopting the same philosophy of using the best current technology new first estimate release fractions for tellurium have also been adopted, based on the recommendation in NDR610 that 85% of this fission product rather than 15% assumed in WCAP9991, escapes from the fuel at the melt release.

Table 6.1 shows the revised first estimate release fractions for inorganic iodine and tellurium, together with the appropriate spectral probability distributions selected from Sections 3, 4 and 5 of the paper for fission product retention during the separate stages of release. The new treatment of the first estimate for tellurium impacts only on UK6 which has no vaporisation release or ex-vessel steam explosion following the melt release. For all the other release categories for which a vaporisation release and/or steam explosion ensures eventually complete release of tellurium from the fuel, the effect is negligible. Separate probability distributions (UK 5A and B, and UK 6A and B) are retained at this stage for the different types of initiating sequence contributing to release categories UK5 and 6.

In Table 6.2 the overall probability distributions obtained by conservative condensation of the partial distributions in Table 6.1 are given*. To obtain the final values for UK5 and 6 the overall distributions for UK 5A and B and UK 6A and B respectively were simply combined in the proportions in which the relevant accident sequences contribute to the release category. This approach is adequate because the range of first estimate release fractions spanned by the different accident sequences within a category is relatively small. From Table 6.2 it can be seen that the overall form of the second estimate probability distributions is such that the probability of source terms as high as the first estimates may be no more than 0.05 to 0.1, depending on the release category. The probability that the release will be less than one tenth of the first estimate is of the order of 0.2 or greater in most instances.

* When these numbers were used subsequently for the consequence calculations the small remaining contributions to the P=2 bin (0.7% in both UK2 and UK6) were moved into the P=1 bin, it being felt that this doubling of the source term was unrealistic except as an artefact of the coarse level of discretization of the spectral distribution.

When the likelihood that the predominant form of inorganic iodine in PWR's is caesium iodide was first identified it was thought by some that this must of necessity substantially reduce estimates of the source term release fraction in severe accidents. The results in Tables 6.1 and 6.2 show that this view needs to be treated with caution in the present state of the art for such calculations. So far as the first estimate release fractions are concerned the depositions of vapour forms of iodine in the containment, as evaluated by CORRAL is much faster than the settling of particulate. Hence, the revised first estimate in Table 6.1 for UK5 and 6 (0.3 and 0.2 respectively) which represent delayed containment failure with no safeguards operating, are much higher than those given in WCAP9991 [9] (0.06 and 0.009 respectively). The means of the spectral release fractions for UK5 and 6, which take account of primary circuit retention, improved calculational methods for containment retention, and leak path retention, are of course lower than the revised first estimates (0.037 and 0.048), but in the case of UK6 is still larger than the WCAP9991 first estimate and in the case of UK5 is only marginally lower. This result may be an artefact of the limitations of the present methods of calculation, and even within those limitations it is a function of the relatively short time to containment failure in UK5 and 6 (8 hours or less) since the removal of inorganic vapour quickly reaches a limit in CORRAL when 1% of the original inventory remains airborne whereas the removal of particulate can continue over very long periods. Nevertheless it is clear that the overall effect reflects the balance of a number of opposing factors of which proper account must be taken.

7. Summary and Conclusions

We have illustrated in the preceding sections how, when account is taken of many conservatisms inherent in the previous approach used to derive fission product release fractions, substantial reduction factors on the point values can be justified. Our analysis, as discussed in Section 6, supports the qualitative contentions of Levenson & Rahn[2], but shows the wide and diverse range of detailed information needed to justify quantitatively the effects for which they have evoked more global arguments.

One or two important questions are highlighted by our treatment. For the sake of completeness, the chemical form of iodine has been deliberately left open. The approach adopted in the RSS, and subsequent studies following the same methodology, was to treat iodine as a volatile inorganic form, apart from a small organic fraction. There has been increasing recognition[4,18] that this is probably incorrect, and that the appropriate chemical release form is as metal iodides, principally caesium iodide. The transport and retention of iodine would then parallel that of caesium and other volatile, particulate-forming fission products. Our treatment shows that similar retentions of the alternative forms would be expected for primary circuit mechanisms. However, significantly different conservatisms are inherent in the CORRAL treatments of volatile inorganic iodine and particulates in the containment, and the leak path retentions to be expected also differ considerably. Overall, it is not possible to conclude that the caesium iodide form offers enhanced possibilities of retention compared with volatile inorganic forms.

The impact of specific features of the plant design can be strong. The position of the failure point in the primary circuit, particularly in the case of a large break LOCA can have a dominant effect upon the amount of fission product

retention which may be claimed in the primary circuit. For cold-leg breaks the flow path will be via at least one steam generator. The interfacing systems LOCA is another example, where the different possibilities between failures in the injection lines connecting to the hot or cold-legs has to be taken into account, as well as the detailed layout of the residual heat removal circuits to establish the possible flow paths. Further, the routing of the circuit within the auxiliary building, and the influence which the point of failure may have on the damage state of the building require specific analysis.

The established approach to facilitating consequence assessment in PRA entails the choice of a limited number of end points, the release categories. These consist of groupings of event sequences for which analyses have produced similar source terms. At the level of detail involved in the conservative treatment of sequences, this approach works well, and the defined point value source term associated with each category will not differ seriously from those derived for any of the contributing sequences. However, the finer level of detail required in the spectral source term approach does not fit so readily within this framework. For example, a conventional release category might contain sequences ranging from a hot-leg large break LOCA to a cold-leg small break LOCA, since primary circuit retention is omitted from the analysis. These sequences have quite different spectral probability distributions, and some choice is therefore required of how to combine the results to generate a distribution for the category overall. The approach adopted will depend on the particular 'pinch point' methodology used to produce the release categorisation, but in the event it may be necessary to subdivide categories to take full advantage of mitigation which can be claimed. It should be pointed out that once a spectral distribution has been derived for a given category, the fact that the point value may then appear a gross overestimate does not imply that the category should be merged with some lower release category. For this study the effect on

the release categorisation has been included by taking suitably weighted contributions from the different accident sequences contributing to each category. This was considered sufficient, consistent with the overall level of uncertainty. In future studies, we anticipate that greater detail will be retained in the final categorisation process.

The method used in this paper represents a step towards providing more realistic less conservative estimates of fission product releases and puts the analysis of uncertainty arising from the release fraction calculations on the same footing as uncertainties arising from other contributions to the risk analysis. The basic structure is a very powerful tool since it can easily accommodate differences in plant (even between reactor types, although here we only address PWR's), and improved knowledge on models as they become available. Changes would simply be reflected in the relative probabilities of each of the discrete fractions. Thus, once a set of 'bins' has been established (they may include many more than treated here), the necessary dispersion and consequence calculations can be performed on a once and for all basis since changes in the conditional probabilities of contributing spectral terms can be examined without having to recalculate all the consequences. It is also not necessary to start from the RSS values in establishing the reduction factors. Indeed this study shows that the RSS categories are very specific to the Surry I plant and 'point values' need to be calculated afresh for different designs as done here. The method allows new calculations to be incorporated easily since the only results needed are the probabilities that these new values are uncertain. In such cases we would expect a distribution around the 'point value' and not skewed as in the present examples. In the long term, an increasing understanding would be exhibited as a narrowing of the distribution, as confidence grew that a particular 'bin' was the most likely.

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Table 2.1 Summary Description of Release Categories

<u>Category</u>	<u>Description</u>
UK-1	This category is used for accident sequences involving core melting, where a containment bypass pathway from the primary circuit to the environment exists. The pathway considered in this study is the failure of the isolation valves separating the reactor cooling system and the low pressure RHR system. It is equivalent to the V sequence of the RSS.
UK-2	This release category is used for over-pressure failure events with a source term reflecting the possible occurrence of a steam explosion, and in which containment sprays are not functioning. It is also used to include those sequences where, although there is no overpressure failure, an isolation failure or small by-pass of the containment occurs.
UK-3	This release category is used for early over-pressure failures where sprays are not functioning. It is also used for sequences where sprays are functional but where containment failure occurs so soon after most of the fission products are released from the reactor system that the sprays are not effective in removing fission products and, in particular, for small-break sequences.
UK-4	This release category is used for over-pressure events with the assumed occurrence of a steam explosion at a time when the spray system is functioning.

Table 2.1 continued

UK-5	This release category is used for late over-pressure failures without sprays operating. Failures are as a result of relatively slow pressure build-up due to loss of containment heat removal capability. It is pessimistically assumed that failure occurs after 4 hours. Cooling of the core debris is lost so that dry-out and vaporisation release occurs.
UK-6	This release category is used for late over-pressure failures without sprays operating. Failures are as a result of relatively slow pressure build-up due to loss of containment heat removal capability, in this case failure is assumed to occur after 8 hours. Debris in the cavity from the molten core remains covered by water so that no vaporisation release occurs.
UK-7	This release category is used for early over-pressure failure events following a large break LOCA with spray systems functional for a significant period before reactor vessel failure.
UK-8	This release category is used for delayed over-pressure failure sequences for which spray systems are functional.
UK-9 and UK-10	These release categories are used for melt-through of the basemat, with and without spray failure, respectively. A release takes place through the basemat and surrounding soil to the environment.
UK11 and UK12	These release categories are used for all degraded core or core melting accidents in which the containment remains intact or for which the system is recovered. UK-11 and UK-12 refer to cases with and without spray failure, respectively. Radioactivity released to the environment would be small, corresponding to that associated only with normal levels of containment leakage.

Table 2.2 Chemical Classes

1. Xenon (Xe) and Krypton (Kr) (noble gases)
2. Organic Iodine
3. Elemental Iodine (I) (halogens)
4. Caesium (Cs) and Rubidium (Rb) (alkali metals)
5. Tellurium (Te)
6. Barium (Ba) and Strontium (Sr) (alkaline earths)
7. Ruthenium (Ru) (noble metals)
8. Lanthanum (La) (refractory oxides, including actinides).

Table 3.4

Summary of primary circuit retention probabilities

<u>Release factor (R)</u>		1	0.5	0.25	0.1	0.05
<u>Sequence</u>						
<u>Interfacing (V) LOCA</u> (RHR suction line)	VI	0.25	0.25	0.4	0.1	0
	P	0.25	0.25	0.4	0.1	0
<u>Large-break (A) LOCA</u> 1:1 Hot:Cold-leg probability ratio	VI	0.6	0.4	0	0	0
	P	0.6	0.4	0	0	0
<u>Small-break (S) LOCA</u> 1:3 Hot:Cold-leg probability ratio	VI	0.25	0	0.3	0.225	0.225
	P	0.25	0	0.3	0.45	0
<u>Transient (T) LOCA</u>	VI	0	0	0	0.5	0.5
	P	0	0	0	0.5	0.5

Note: VI = volatile inorganic iodine (I₂, I, HI)

P = aerosol-borne VFP, including CsI

TABLE 6.1

SOURCE TERM PROBABILITY DISTRIBUTION ESTIMATES FOR SIZEWELL B
DETAILED BREAKDOWN OF CONTRIBUTIONS

RELEASE CATEGORY	REVISED FIRST ESTIMATE FOR IODINE (AS CAESIUM IODIDE PARTICULATE)	REVISED FIRST ESTIMATE FOR TELLURIUM	TRANSPORT PROCESS	FRACTION OF FIRST ESTIMATE SOURCE TERM RELEASES					
				2	1	1/2	1/4	1/10	1/20
UK1	0.5	No Change	Primary Circuit	0	0.2	0.5	0.2	0.1	0
			Auxiliary Building Plate-out	0	0.2	0.6	0.2	0	0
UK2	0.4	No Change	Primary Circuit	0	0.25	0	0.3	0.45	0
			Containment Deposition	0.1	0.4	0.4	0.1	0	0
			Containment Leak Path Deposition	0	0.3	0.3	0.3	0.1	0
UK5A A LOCA	0.3	No Change	Primary Circuit	0	0.6	0.4	0	0	0
			Containment Deposition	0	0.4	0.4	0.2	0	0
			Containment Leak Path Deposition	0	0.3	0.3	0.3	0.1	0
UK5B S LOCA	0.3	No Change	Primary Circuit	0	0.25	0	0.3	0.45	0
			Containment Deposition	0	0.4	0.4	0.2	0	0
			Containment Leak Path Deposition	0	0.3	0.3	0.3	0.1	0
UK6A A LOCA	0.2	0.2	Primary Circuit	0	0.6	0.4	0	0	0
			Containment Deposition	0.1	0.4	0.4	0.1	0	0
			Containment Leak Peak Deposition	0	0.3	0.3	0.3	0.1	0
UK6B S LOCA	0.2	0.2	Primary Circuit	0	0.25	0	0.3	0.45	0
			Containment Deposition	0.1	0.4	0.4	0.1	0	0
			Containment Leak Path Deposition	0	0.3	0.3	0.3	0.1	0

TABLE 6.2
SOURCE TERM PROBABILITY DISTRIBUTION ESTIMATES FOR SIZE/FEL. B - OVERALL VALUES

RELEASE CATEGORY	FRACTION OF FIRST ESTIMATE SOURCE TERM RELEASES*						
	2	1	1/2	1/4	1/10	1/20	
UK1	0	0.04	0.22	0.60	0.06	0.08	
UK2	0.0075	0.0375	0.0765	0.2965	0.166	0.416	
UK5A (Large LOCA)	0	0.072	0.192	0.528	0.132	0.076	
UK5B (Small LOCA)	0	0.03	0.06	0.228	0.169	0.513	
UK5	0	0.034	0.073	0.258	0.165	0.469	
UK6A (Large LOCA)	0.018	0.102	0.222	0.486	0.106	0.066	
UK6B (Small LOCA)	0.0075	0.0375	0.0765	0.247	0.166	0.4655	
UK6	0.0077	0.0393	0.079	0.252	0.165	0.457	

*NOTE: The iodine and tellurium spectral source term release fractions should be evaluated using the above probability distribution with the revised first estimates shown in Table 1.

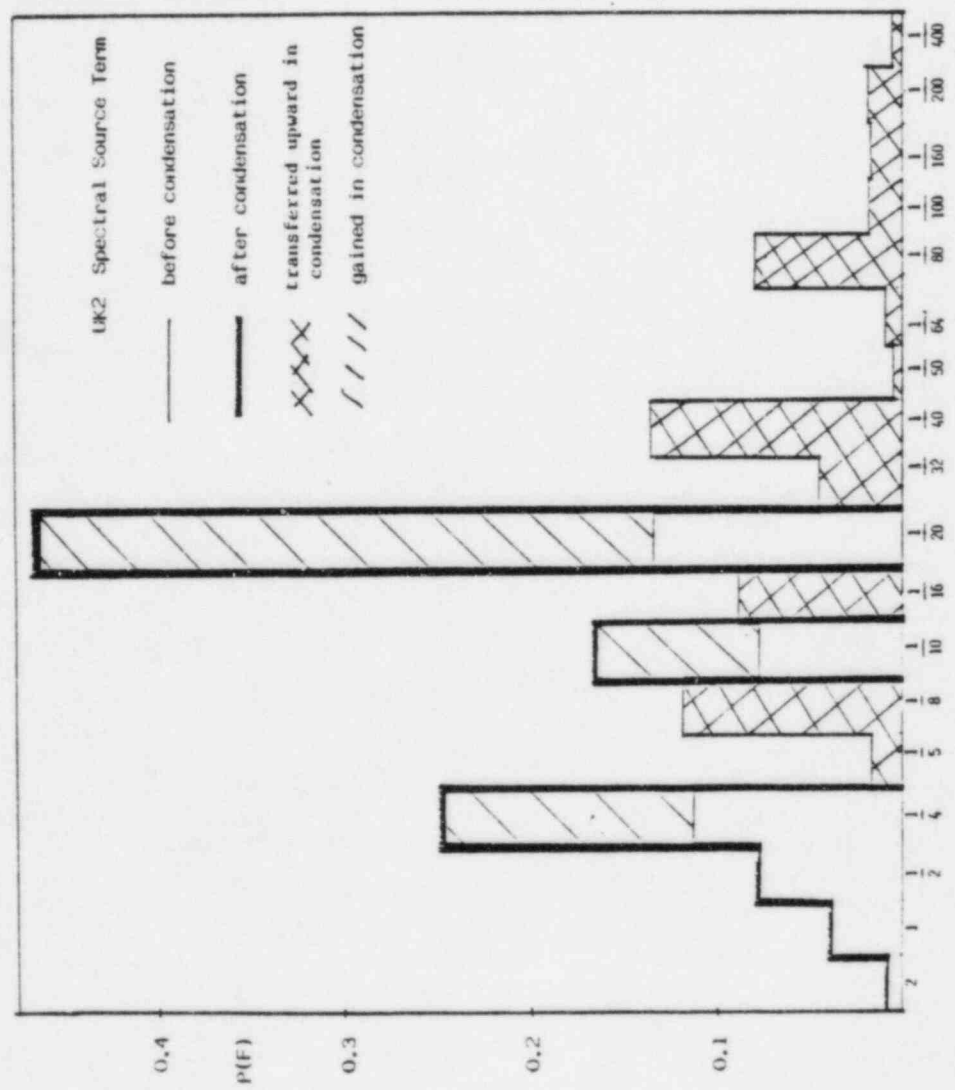
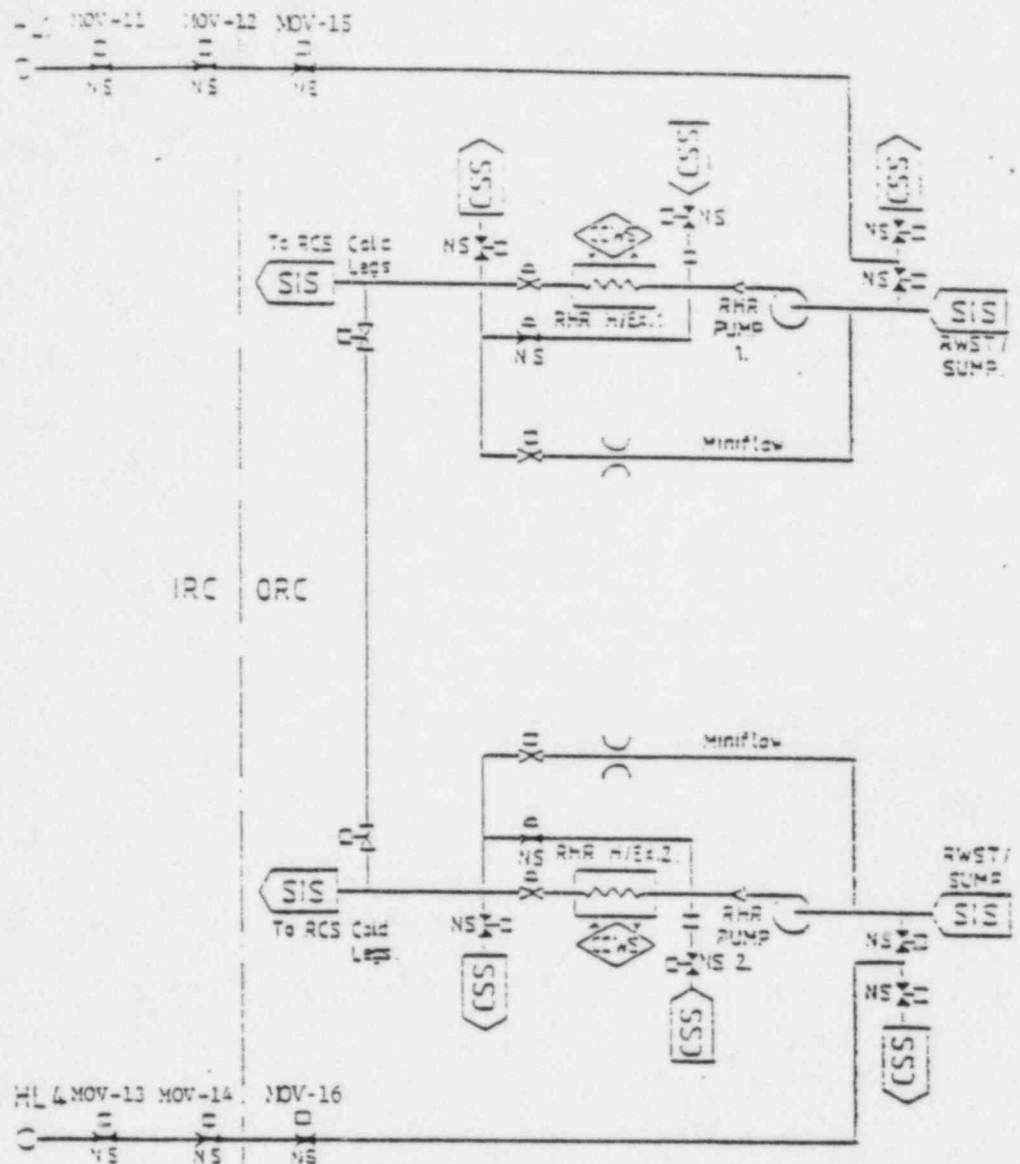


FIGURE 2.1 THE EFFECTS OF CONDENSATIVE CORRELATION



- NOTES - 1. SYSTEM SHOWN ALIGNED FOR NORMAL POWER GENERATION OPERATION. (I.E. ON STANDBY FOR INJECTION MODE).
 2. N.S. DENOTES VALVE NORMALLY SHUT
 3. FUNCTIONAL VALVES ONLY SHOWN

LEGEND: RCS, Reactor Coolant System; HL, Hot Leg;
 SIS, Safety Injection System; IRC, Inside Reactor Primary Containment
 CSS, Containment Spray System; ORC, Outside Reactor Primary Containment
 CWS, Component Cooling Water System.

FIGURE 3.1 ARRANGEMENT OF RHRS

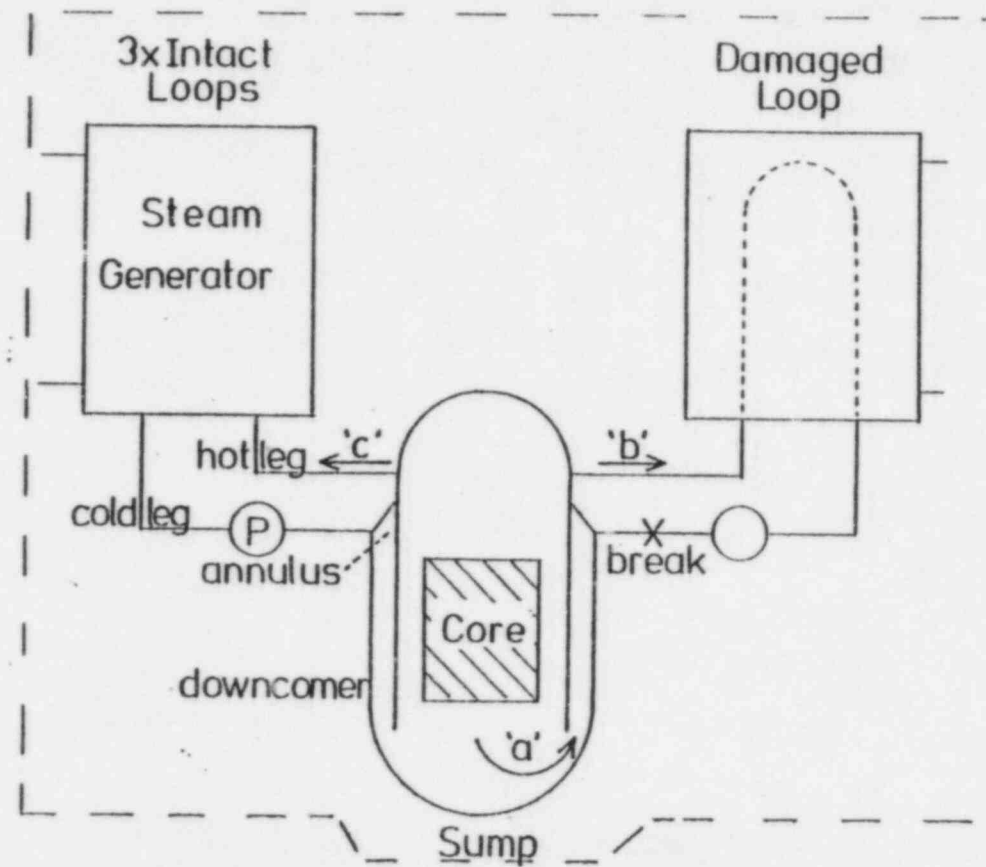


Fig.3.2 Alternative flow routes to cold leg break

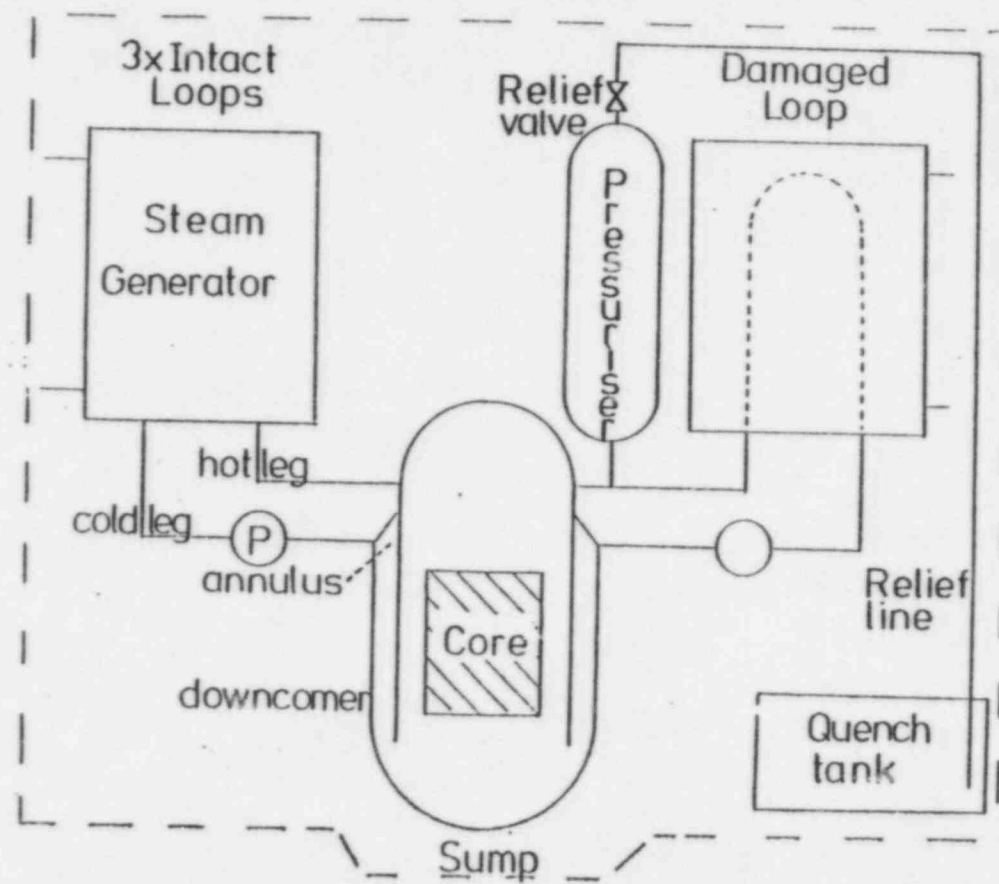


Fig.3.3 Flow route for T LOCA

Fraction of
core
inventory
airborne

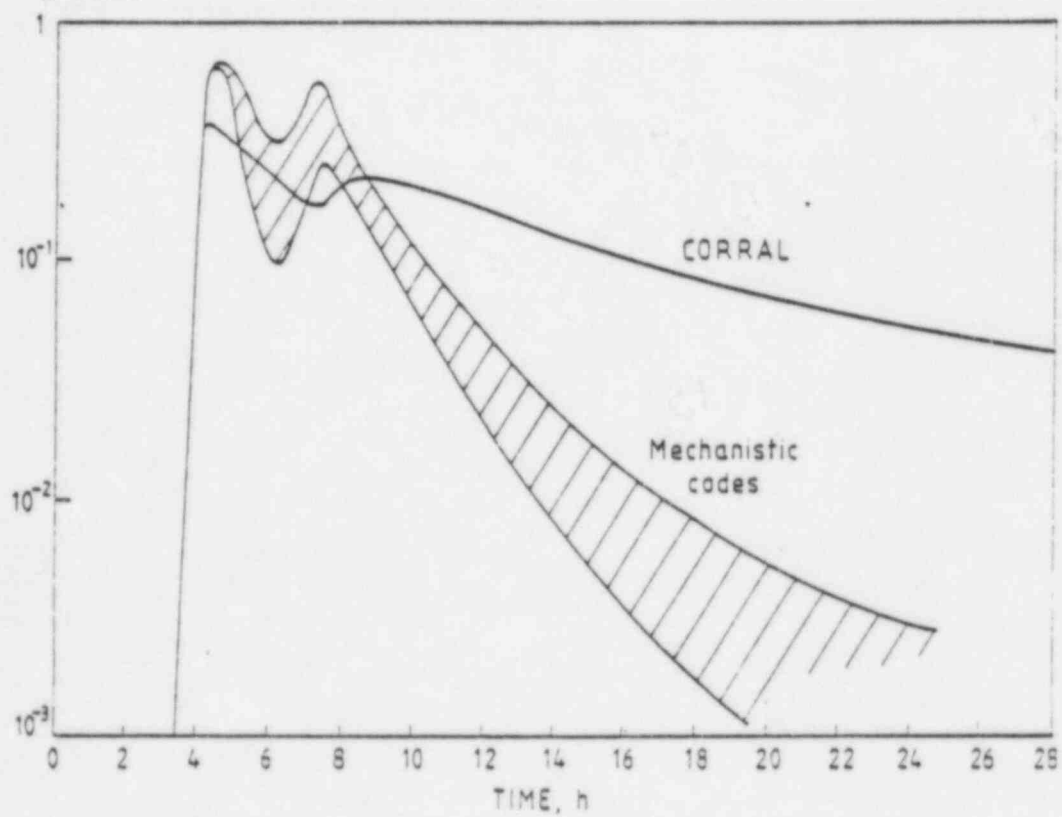


FIG. 4.1 EFFECTS OF AGGLOMERATION CORRAL Vs.
MECHANISTIC CODES

(After NUREG-0772, Fig. 7.12)

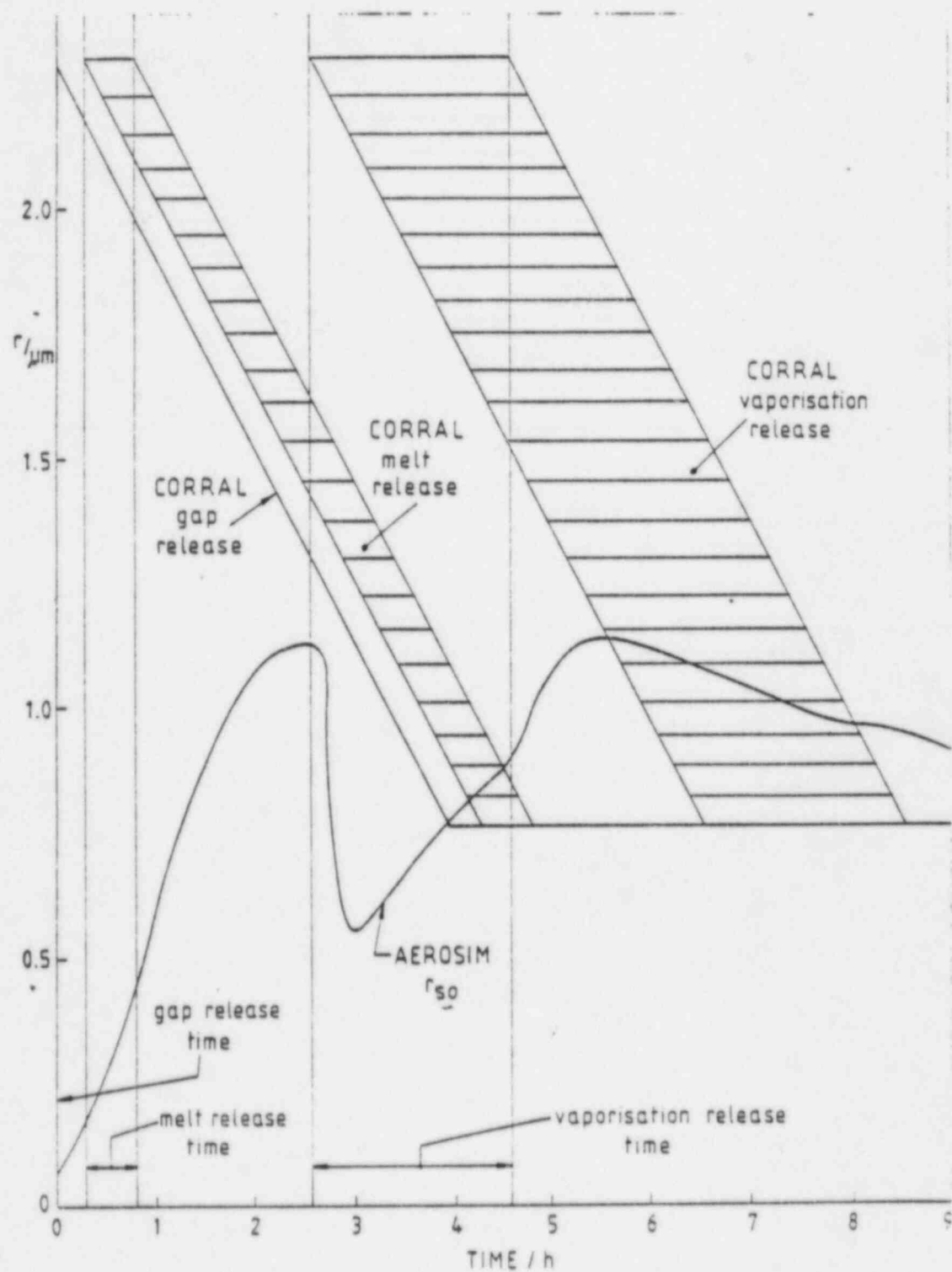


FIG. 4.2 AEROSOL RADII VS. TIME IN A T-SEQUENCE ACCIDENT
T.04

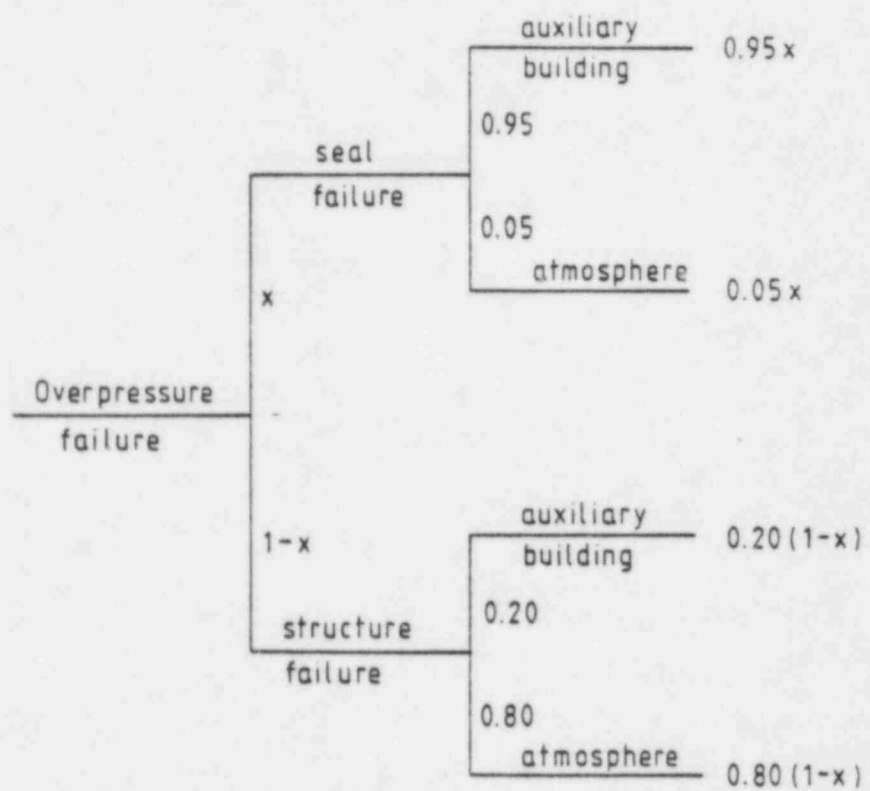


FIG. 5.1 OVERPRESSURE FAILURE
EVENT TREE