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Analysis of Main Steam Isolation Valve Leakage in Design Basis Accidents Using MELCOR 1.8.6 and RADTRAD

Randell O. Gauntt, Tracy Radel, Michael A. Salay, and Donald A. Kalinich

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Analysis of Main Steam Isolation Valve Leakage in Design Basis Accidents Using MELCOR 1.8.6 and RADTRAD

Randell O. Gauntt, Tracy Radel, Donald A. Kalinich
Reactor Modeling & Analysis Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0156

Tracy Radel
Risk & Reliability Analysis Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0156

Michael Salay
Office of Nuclear Regulatory Research
United States Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Abstract

Analyses were performed using MELCOR and RADTRAD to investigate main steam isolation valve (MSIV) leakage behavior under design basis accident (DBA) loss-of-coolant (LOCA) conditions that are presumed to have led to a significant core melt accident. Dose to the control room, site boundary and LPZ are examined using both approaches described in current regulatory guidelines as well as analyses based on best estimate source term and system response. At issue is the current practice of using containment airborne aerosol concentrations as a surrogate for the in-vessel aerosol concentration that exists in the near vicinity of the MSIVs. This study finds current practice using the AST-based containment aerosol concentrations for assessing MSIV leakage is non-conservative and conceptually in error. A methodology is proposed that scales the containment aerosol concentration to the expected vessel concentration in order to preserve the simplified use of the AST in assessing containment performance under assumed DBA conditions. This correction is required during the first two hours of the accident

while the gap and early in-vessel source terms are present. It is general practice to assume that at ~2hrs, recovery actions to reflood the core will have been successful and that further core damage can be avoided. The analyses performed in this study determine that, after two hours, assuming vessel reflooding has taken place, the containment aerosol concentration can then conservatively be used as the effective source to the leaking MSIV's. Recommendations are provided concerning typical aerosol removal coefficients that can be used in the RADTRAD code to predict source attenuation in the steam lines, and on robust methods of predicting MSIV leakage flows based on measured MSIV leakage performance.

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Introduction

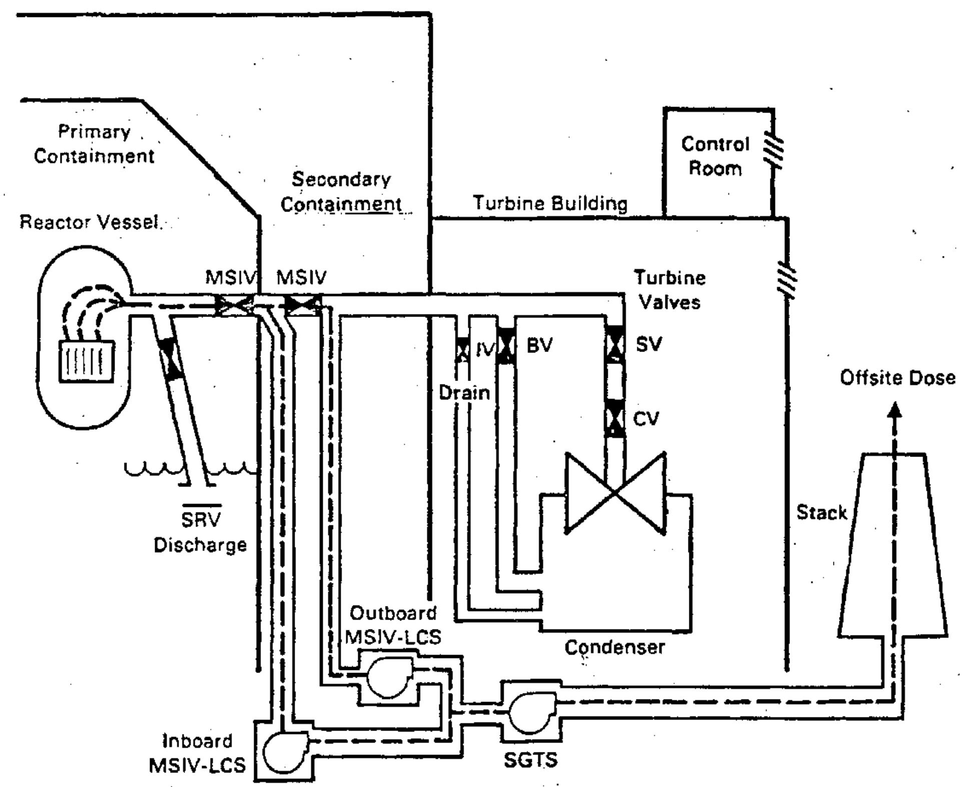
The focus of this work is to evaluate current practices and propose revisions as necessary for the technical basis and regulatory requirements concerning main steam isolation valve (MSIV) performance for boiling water reactors (BWRs) under accident conditions. Current regulatory guidelines for evaluating MSIV performance are described in USNRC Regulatory Guide 1.183 [1] titled "Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors." This regulatory guide addresses the use of the NUREG-1465 [2] alternative source term (AST) in the evaluation of containment performance under design basis accidents (DBAs)*. This guideline articulates a defense in depth principal by prescribing radiological containment requirements for hypothetical core damage accidents resulting from a design basis event, such as a loss of coolant accident (LOCA). The defense in depth aspect follows from the assumption that core damage with significant release of fission products results from a design basis accident, where, by definition, a design basis accident is an event wherein safety systems are designed to preclude just such a core melt event. The requirements for this safety approach are prescribed in the Code of Federal Regulations under title 10, parts 50 and 100 addressing allowable radiological dose to the reactor control room and to the site boundary. The federal code prescribes that a core damage event involving significant release of fission products from the core must be considered in the design of containment systems. Note that Reg. Guide 1.183 addresses many aspects of containment performance for both pressurized and boiling water reactors, and that MSIV performance in BWR's is only one aspect of the regulatory guide's scope.

Motivating this study is a long-standing technical question as to the applicability of the alternative source term prescription, being a stylized source term of radionuclides to the reactor *containment*, to the evaluation of radionuclide releases through MSIV leakage, since the main steam lines are directly connected to the reactor *vessel*, not the containment. Some background leading up to this issue will now be provided.

* It should be pointed out that the regulatory guide only references the portion of NUREG-1465 associated with the gap and early in-vessel release periods and does not employ the entirety of the NUREG-1465 source term.

1 Background

Boiling water reactors operate by boiling water in direct contact with the Zircaloy-clad reactor fuel rods and passing this steam directly through the power turbines by means of large main steam lines as shown in Figure 1-1. Because of this potential direct pathway from the core region to the environment, two main steam line isolation valves, one inboard of the containment boundary and one outboard, are included on each steam line to isolate the containment boundary from the environment in the event of a core damage accident. Anticipating some leakage from these MSIVs, a leakage control system (LCS) is often included to pull off leakage through the valves and route this effluent to the stacks to reduce on-site dose consequences in the control room and dilute releases from the site. Some licensees have removed previously installed leakage control systems having obtained regulatory relief on MSIV leakage requirements. The main steam line isolation valves are quite large and have a documented history of leaking beyond their design specifications and requiring costly maintenance and overhaul to maintain design specification leak rates [3]. In some cases, credit for fission product deposition in the condenser system has been taken whenever the condenser system has been seismically qualified.



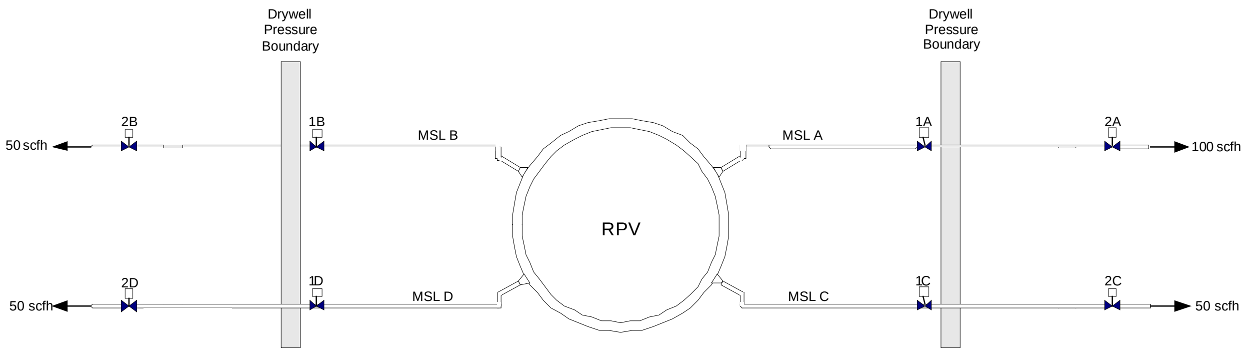


Figure 1-1 Schematic of BWR vessel. steam line and turbine, including location of MSIV's and Leakage Control System (LCS) (the LCS is designed to control leakage from MSIV and vent to stacks).

As seen in the Figure 1-1, the pathway of fission products release from a damaged core to the containment must be either by safety relief valve venting to the wetwell, by venting to the drywell through a break in one of the 4 main steam lines, or more circuitously through a recirculation line or bottom vessel drain line break, depending on the type of design basis accident under consideration. In any event, the source of fission products to the MSIVs is principally from the reactor vessel. Admittedly, if the DBA under consideration is a main steam line break of one steam line between the vessel and the inboard MSIV, then this particular pathway would draw from the drywell volume, while the remaining three intact steam lines would continue to draw from the reactor vessel.

Historically, the leakage of radioactivity through leaking MSIVs has been based on an assumed airborne concentration (Curies/ft^3) of radioactive particles or gas that are available to flow through the valves and a characterized leak rate (ft^3/hr) for the valves. The leak rate of the valves is estimated based on a standard test wherein the space between the inboard and outboard valves (see Figure 1-1) is pressurized to a design specified pressure with air or nitrogen, and a leak rate inferred by the observed gradual depressurization of this intermediate space. The valve design-specified leak rate characterized at standard conditions can then be appropriately scaled to accident conditions to infer a leakage of radioactivity to the environment, providing an appropriate airborne concentration can be determined.

The July 2000 version of Regulatory Guide 1.183 follows previously adopted convention by assuming that the concentration of airborne radioactivity is roughly approximated by the radioactivity released to the containment divided by the containment volume. (Item 6.1 in Appendix A of Reg. Guide 1.183) This idealized view presumes that the radioactivity is released from the fuel, transported out of the vessel, and equilibrated with the drywell volume (and possibly the wetwell volume as well) and that this equilibrated atmosphere subsequently flows through the leaking MSIVs. Additionally, the Regulatory Guide generally permits that natural deposition and aerosol settling processes may be considered in the containment and by implication in regions upstream of outboard MSIVs to reduce in time the airborne activity reaching the MSIVs.

The concept of the drywell space being the source to the MSIVs in the current Regulatory Guidelines can be partially understood in terms of the historical usage of the now-retired TID source term [4], where the release was presumed to be instantaneous. Instantaneously released fission products would be swept by steam advection from the vessel to the drywell where mixing and equilibration with the drywell volume could be expected; however, the major advance introduced by the NUREG-1465 revised source term relative to the TID source term was that the release from fuel was not instantaneous, but instead protracted over time in distinct phases. The NUREG-1465 AST in fact described the time phased release of fission products to the *containment* from the vessel, accounting for the facts that release from the fuel is gradual and occurring over a period of hours, that not all fission products released from the fuel find their way to the containment, some being deposited within the reactor primary system, and that some of these fission products that are retained within the vessel structures can subsequently become re-suspended by revaporization driven by continued decay heating of structures in the vessel.

The NUREG-1465 source characterizes the radioactivity that escapes the fuel and vessel and enters the containment, but does not inform us on the distribution of fission products that have not yet escaped the vessel. In reality, as determined by best estimate analyses, the vessel becomes an ongoing source of airborne radioactivity to the drywell or wetwell (via steam line breaks or SRV venting) as well as the MSIVs on unbroken steam lines as long as release from overheated fuel is taking place and until vessel reflooding and accident recovery takes place. Figure 1-2 illustrates the two conceptual views. After accident recovery and vessel reflooding, the release from the fuel is terminated and the airborne radioactivity in the vessel will be swept into the drywell by the steam generated in the reflooding process, producing vessel airborne concentrations that can be lower than in the drywell region, as illustrated in Figure 1-3.

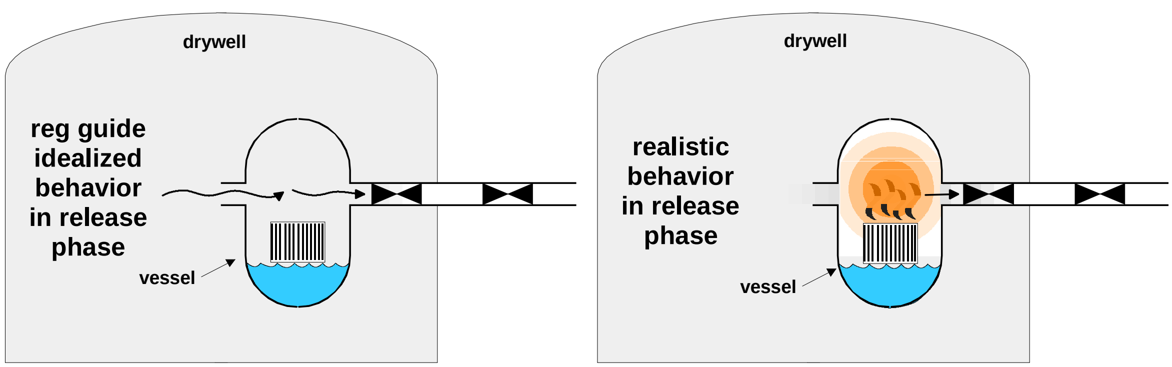


Figure 1-2 Idealized regulatory model of airborne fission products (left) compared to realistic prediction of airborne radioactivity (right) during release phase of a DBA with core damage. Note, source of airborne activity emanates from core (right) more so than the drywell (left).

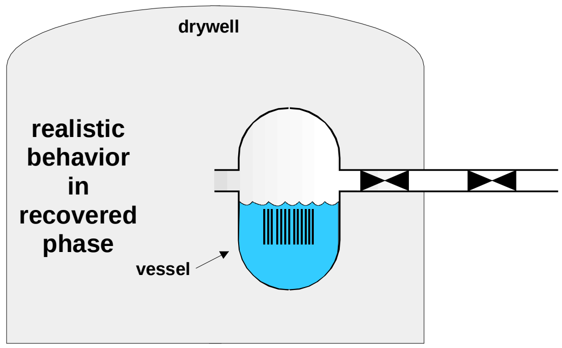


Figure 1-3 Qualitative distribution of airborne activity in post-recovery (reflood) phase of DBA core damage accident.

This misconception or oversimplification in viewing fission product transport from overheated fuel has led to subsequent important conceptual errors in analysis such as proposed use of drywell sprays to reduce airborne radioactivity (as illustrated in Figure 1-4) or equilibrating drywell and wetwell airspace volumes to achieve the same effect, when neither of these processes can directly affect the airborne concentration within the reactor vessel where a continuous source of fission products issues from the overheated fuel. In short, what is needed to evaluate MSIV leakage is a source term to the *reactor vessel steam dome* (which feeds the steam lines) and not a source term to the *containment*.

In order to examine more realistically the behavior of airborne radioactivity in the BWR where design basis accidents with core damage have taken place, the MELCOR code has been applied to make best estimate predictions of fission product release and transport behavior in the vessel and containment systems and the resulting leakage to the environment through leaking MSIVs. Prior to this study two other studies have been performed for Mk-I and Mk-III containment systems (Peach Bottom and Grand Gulf) [5,6]. Using MELCOR 1.8.5, these analyses explored two LOCA DBA scenarios, a recirculation line break and a main steam line break, and compared fractional releases of radionuclides to the environment to those typically produced using the simplified methodology outlined in Regulatory Guide 1.183. Since the MELCOR analyses performed in these studies did not calculate actual dose from released radioactivity, the findings were not conclusive; however, the analyses did indicate that the airborne concentrations in the vessel steam dome could exceed considerably the airborne concentrations in the drywell during the first 2 hours of the accident.

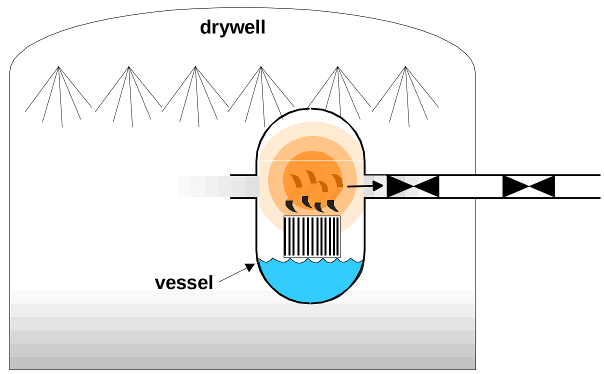


Figure 1-4 Illustration of drywell spray effect on airborne radioactivity in drywell and reactor vessel.

The following sections describe various analyses that have been performed in order to evaluate the conservatism or non-conservatism of the current regulatory guidelines and to establish the technical basis for any recommended revisions of the current regulatory guidelines. The principal new technical information on which these proposed revisions are based are updated full plant MELCOR analyses of two basic design basis accidents. These are described generally in Section 1.1, and in more detail in subsequent sections.

1.1 Full Plant MELCOR Analyses

The present study revisits the analyses reported in references [5,6] using Version 1.8.6 of the MELCOR code with the intent of characterizing releases of radioactivity through leaking MSIVs and then applying these releases in the RADTRAD [7] code in order to calculate the resulting dose to the control room (CR), exclusion area boundary (EAB), and low population zone (LPZ). These calculated doses are then compared to two industry submittals to highlight potential differences by the various methodologies. Analyses are performed using MELCOR 1.8.6 for Mk-I and Mk-III containments for two LOCA DBA scenarios, a recirculation line break and a main steam line break. Both break scenarios are modeled with and without containment spray operation. The effect of including the steam condenser in the release pathway was also investigated with respect to its potential for added radionuclide retention. These analyses are intended to provide a physics-based analysis accident progression, fission product release and transport, and MSIV leakage for the purpose of establishing the technical basis for a simplified regulatory treatment for MSIV performance assessment that corrects for the deficiencies described previously. While these analyses are intended to be essentially “best estimate,” for the purposes of informing regulatory guide recommendations, the analyses are altered in some cases to produce outward flow through the leaking MSIV’s, as described in Section 2.1.1. It is expected that these changes will have a minimal effect on the results. In the remainder of this report, these calculations will be referred to as “full plant analyses” to differentiate them from separate analyses that were performed on the main steam line geometry only. The MELCOR plant models, sequence progression assumptions, and sequence results are described in Section 2.

The MELCOR analyses are characterized as “best estimate” in the sense that physics-based models are used to predict fully integrated and self consistent sequence progression, accounting for primary system thermalhydraulics and thermodynamics associated with LOCA blowdown, core degradation processes such as Zr-steam oxidation and fuel heatup, thermal release of fission products from the fuel, fission product transport and aerosol mechanics. With respect to aerosol mechanics, fission product aerosols are treated using a size-sectional treatment representing the time varying size distribution of the airborne radioactive particles between the limits of 0.1 to 50 micrometers. Treated are agglomeration of smaller particles to form larger particles and a spectrum of deposition processes, including thermophoresis (thermal gradient driven deposition), diffusio-phoresis (steam condensation assisted deposition), and gravitational settling. These phenomena are important in characterizing the transport and deposition behavior of the aerosol particles in terms of so-called “lambda” values (i.e., deposition coefficient) and characterizing these lambda-values for subsequent use in the RADTRAD code are a major focus of this study. The uncertainties in these phenomena are quantified as described in Section 2.1.2 and Section 3.

A principal determination from the full plant analyses is a characterization of the airborne radionuclide concentrations within the vessel upper head region (which feeds the steam lines and MSIVs), and the airborne radionuclide concentration in the drywell (which is used in the current regulatory guidelines as the assumed source to the steam lines and MSIVs). This characterization will be used to scale the drywell airborne concentration determined from the stylized AST (containment source) to a value appropriate for the vessel steam dome. This can be described mathematically as:

$$C_{SD} \approx C_{AST} \times R \tag{1.1}$$

where

C_{SD} = airborne concentration in the steam dome feeding the MSIV leakage,

C_{AST} = airborne concentration in the containment determined from the NUREG-1465 methodology, and

R = the ratio of the steam dome concentration to the drywell concentration determined by the MELCOR full plant analyses.

A slight complication exists in this approach that must now be described. In the time since NUREG-1465 was issued, current MELCOR best estimate predictions on the timing and magnitude of releases from the core to the containment have changed from that described in the NUREG-1465 prescription. In particular, releases to the containment are now found to be delayed in time and to occur at a lower rate. So, in order to account for this difference between current MELCOR predictions of containment airborne concentrations and those determined by the NUREG-1465 methodology, an additional correction is necessary. This is the ratio of current MELCOR-predicted containment airborne concentrations to the NUREG-1465 predicted containment airborne concentrations. Expressed mathematically,

$$C_{SD} \approx C_{AST} \times R_M \times R^* \tag{1.2}$$

where,

C_{SD} = airborne concentration in the steam dome feeding the MSIV leakage,

C_{AST} = airborne concentration in the containment determined from the NUREG-1465 methodology,

R_M = the ratio of the steam dome concentration to the drywell concentration determined by the MELCOR full plant analyses, and

R^* = the ratio of NUREG-1465 containment airborne concentrations to MELCOR containment airborne concentrations.

This normalization (R^*) is necessary because NUREG-1465 containment airborne concentrations, when scaled up by MELCOR steam dome to containment concentration ratios, produces an excessively conservative result. This is described in more detail in Section 6, where NUREG-1465 containment concentrations are adjusted in RADTRAD analyses of MSIV leakage to account for the steam dome source effect on dose calculations.

The MELCOR full plant analyses provided the basic sequence and source term progression information for this study; however, it was also desired that uncertainties in aerosol transport and deposition along the pathway through the steam lines and the MSIV's be considered. The transport and deposition behavior of radioactive aerosol, as they move through the steam lines and valves are characterized in terms of depletion rates (removal coefficients, or lambdas) and filtration efficiencies that are used in the RADTRAD code to account for the source term attenuation factors in the dose rate analysis. A quantification of the variability of these attenuation parameters in the steam lines is desired in order that adequate conservatism be reflected in the values used by RADTRAD to calculate doses. To support this objective, an uncertainty characterization of the deposition rates in the steam lines was performed using Monte Carlo methods, as described in the following section.

1.2 MELCOR Main Steam Line Uncertainty Analyses

In addition to the full plant analyses, separate analyses were made on the aerosol behavior in the main steam line portion of the full plant nodalization. These analyses focused on transport and deposition behavior within the main steam lines, accounting for uncertainties in aerosol transport and deposition mechanics. The uncertainty analysis is aimed at determining likely distributions for aerosol removal coefficients, or the so-called "lambda" values used in the RADTRAD code to calculate attenuation of the airborne radionuclide concentrations within each RADTRAD analysis volume of the release pathway. In these analyses, the full plant thermohydraulics and fission product source entering the vessel steam dome region, as calculated in the MELCOR full plant analyses are used as boundary conditions supplied to a reduced nodalization model of the main steam lines. This is done principally for computation efficiency to facilitate Monte Carlo analyses sampling on aerosol mechanics uncertainty. A number of aerosol deposition physics parameters, considered to be uncertain, are considered in these analyses. The principal product of these analyses are distributions for removal coefficients (lambda's) for various segments of the steam lines, including the inboard, intermediate, outboard and steam condenser elements along the release pathway that are modeled by RADTRAD. Because of mixing, convection uncertainties, and re-evolution, the depletion of source aerosol within the steam line segment inboard of the MSIV is neglected – depletion and deposition in this zone is estimated not to reduce the concentration of aerosol reaching the inboard MSIV due to to convective mixing phenomena. These studies are described in Section 3

1.3 RADTRAD Dose Calculations

Finally, RADTRAD analyses were performed using source terms both from the current Regulatory Guide 1.183 AST methodology, and the best estimate MELCOR analyses. In this portion of the study, a proposed correction to the current regulatory guide methodology is investigated that accounts for the fact that the MSIVs draw their radiological source from the vessel steam dome and not the drywell volume. In essence, since the NUREG-1465 AST is a source term to the containment, a correction is proposed where the vessel steam dome concentration is estimated based on a scaling factor, R, applied to the containment (drywell) concentration. This scaling relationship is determined from comparing drywell to vessel steam dome concentrations observed in the full plant MELCOR analyses, as described earlier in Section 1.1.

1.4 Summary of Strategy for Revising Regulatory Guide

The strategy put forth in this study for revising the regulatory guidelines for estimating MSIV leakage is summarized in the following three figures. The current guidelines allow use of a containment source of aerosol determined from the NUREG-1465 AST to evaluate MSIV leakage as illustrated in Figure 1-5. This work points out that it is the source from the vessel that actually determines MSIV leakage, as illustrated in Figure 1-6, where a MELCOR-predicted source from the vessel could in principal be used to evaluate leakage. This study examines the effect of using a MELCOR source term in a RADTRAD analysis in Section 4. Finally, a strategy is proposed that simulates the MELCOR source during the first 2 hours of the accident, followed by a presumed accident recovery through vessel reflooding, after which the source is provided by ingress of the containment activity into the vessel and towards the MSIV's, the vessel and core sourcing having been effectively terminated by the reflooding actions – this is illustrated in Figure 1-7.

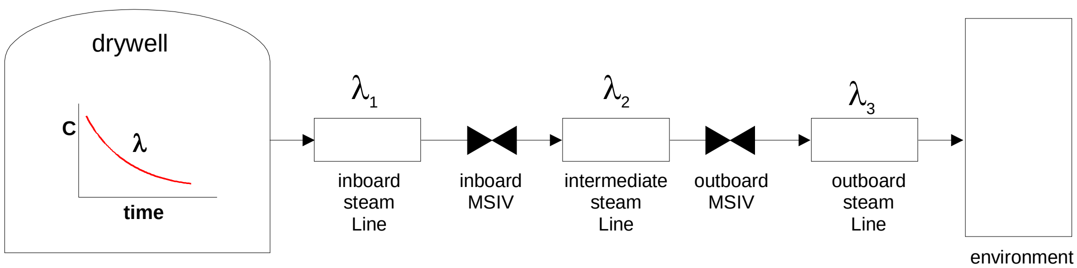


Figure 1-5 Current Reg. Guide 1.183 analysis for dose from leaking MSIV's

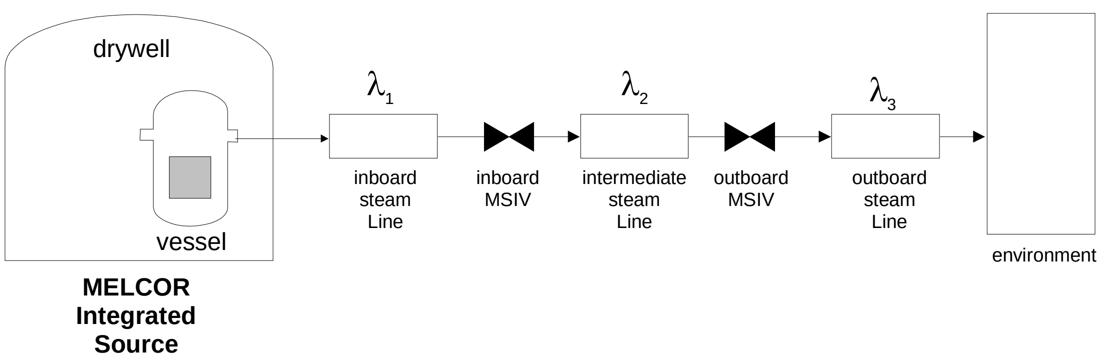


Figure 1-6 RADTRAD analysis using MELCOR source term

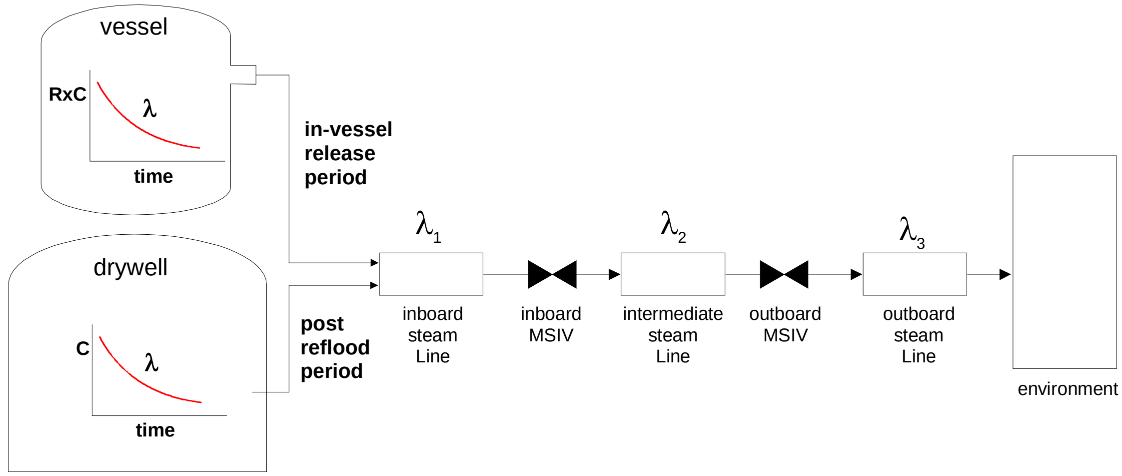


Figure 1-7 Conceptual illustration of modified regulatory methodology to recognize source from vessel steam dome.

1.5 Information Flow Between Models

A variety of different analyses have been performed in this study, sometimes requiring information from one analysis to be used to inform a subsequent analysis. Figure 1-8 illustrates the overall flow of information from each supporting analysis to each dependent subsequent analysis.

One analysis was focused on determining the dose implications of the releases predicted by the full MELCOR sequence analyses, as illustrated by the blue arrows in Figure 1-8. In this analysis, the MELCOR Full Reactor models calculate source term releases (in terms of MELCOR RN classes) to the environment. That information is translated into a form compatible for use by RADTRAD using an Excel worksheet. The RADTRAD code then calculates the doses from this source term using the site specific dispersion (χ/Q) values. This result can be assessed through the time duration for the full plant MELCOR analysis and provide a comparison to doses resulting from a proposed modified regulatory guide methodology.

The MELCOR Full Reactor models also are used to provide the thermo-hydraulic (T-H) information and RN class masses (by aerosol particle size) in the steam dome that are required to run the main steam line (MSL)-only models, as indicated by the red arrows in Figure 1-8. Additionally, the full plant analyses provide information used to scale the drywell airborne radionuclide concentrations appropriately for use in the MSIV leakage analysis. This information is used to establish boundary conditions in the MELCOR MSL-only models.

The MELCOR MSL-only models are run for multiple realizations with various parameters varied (e.g., aerosol physics parameter uncertainty) to ascertain the effects uncertainty on MSL and condenser removal coefficients. Based on the uncertainty analysis results, MSL and condenser removal coefficients are selected.

These removal coefficients are implemented in the RADTRAD MSL-only models. Steam dome-to-drywell radionuclide concentration scaling factors (produced by the MELCOR Full Reactor models) are also implemented in the RADTRAD MSL-only models in order to adjust the containment radioactive airborne concentrations derived from the use of the NUREG-1465 containment source to reflect concentrations in the steam dome that feeds the MSIV's. The RADTRAD MSL-only models are then run to produce doses using BWR core inventory with NUREG-1465 release fractions multiplied by the steam dome-to-drywell radionuclide concentration scaling factors.

Finally, sample analyses for two industry type analyses using RADTRAD and the scaling methodology for use of the AST in MSIV leakage analysis are presented, as indicated by the green arrows in Figure 1-8.

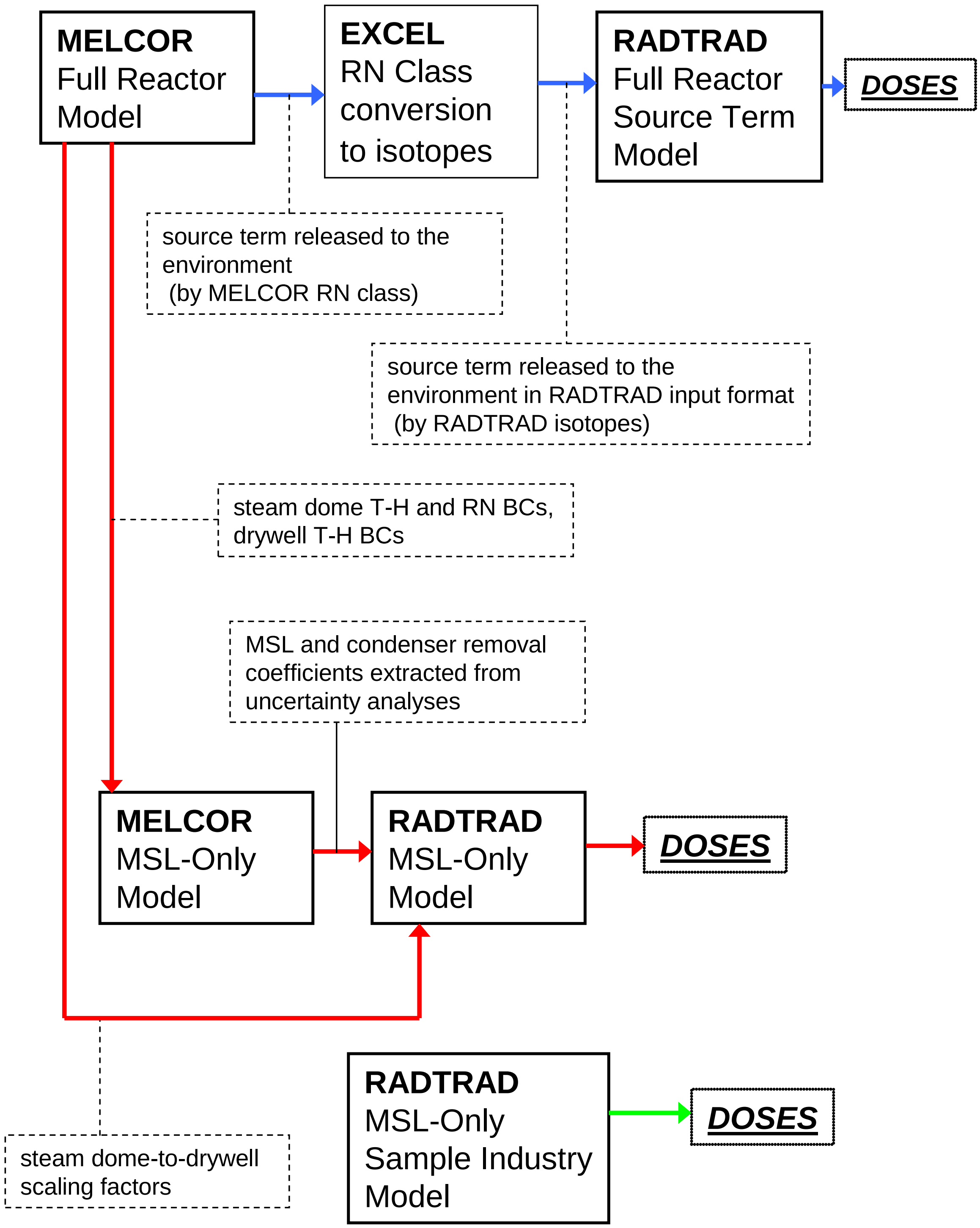


Figure 1-8 Outline of analyses and information flow used in this study.

2 Full Plant MELCOR Analyses

2.1 Description of Full Reactor MELCOR Models

MELCOR calculations to estimate steam dome-to-drywell radionuclide concentration ratios, aerosol removal coefficients in the MSLs, and MSIV leakage source terms were performed using the current state-of-the-art BWR/4 Mk-I and BWR/6 Mk-III MELCOR plant decks developed by Sandia National Laboratories (SNL) for the NRC. MELCOR input data used to develop these models were based on the configuration, geometry and materials of single, representative plants (Peach Bottom and Grand Gulf). Information needed to develop the MELCOR input data were obtained from readily available documents, such as the plant Final Safety Analysis Reports (FSARs) and documentation supporting the Individual Plant Examinations (IPEs). In addition, the models have been configured to conform to current best modeling practices.

The MELCOR nodalization diagrams for the BWR Mk-I and Mk-III models are provided below. Analyses were performed for the following combinations of LOCAs, condenser, and containment sprays.

- Mk-I, main steam line break (MSLB), no sprays,
- Mk-I, MSLB, sprays
- Mk-I, recirculation line break (RLB), no sprays
- Mk-I, RLB, sprays

Mk-III analyses were limited to the RLB and MSLB no containment spray cases.

- Mk-III, MSLB, no spray
- Mk-III, RLB, no spray

The cases were run out to the time of lower head failure. An additional Mk-III RLB case was run in which core sprays were activated 10 minutes prior to the predicted time of lower head failure. This case was run to verify the assumed post-reflood T-H conditions assumed in the MSL-only cases.

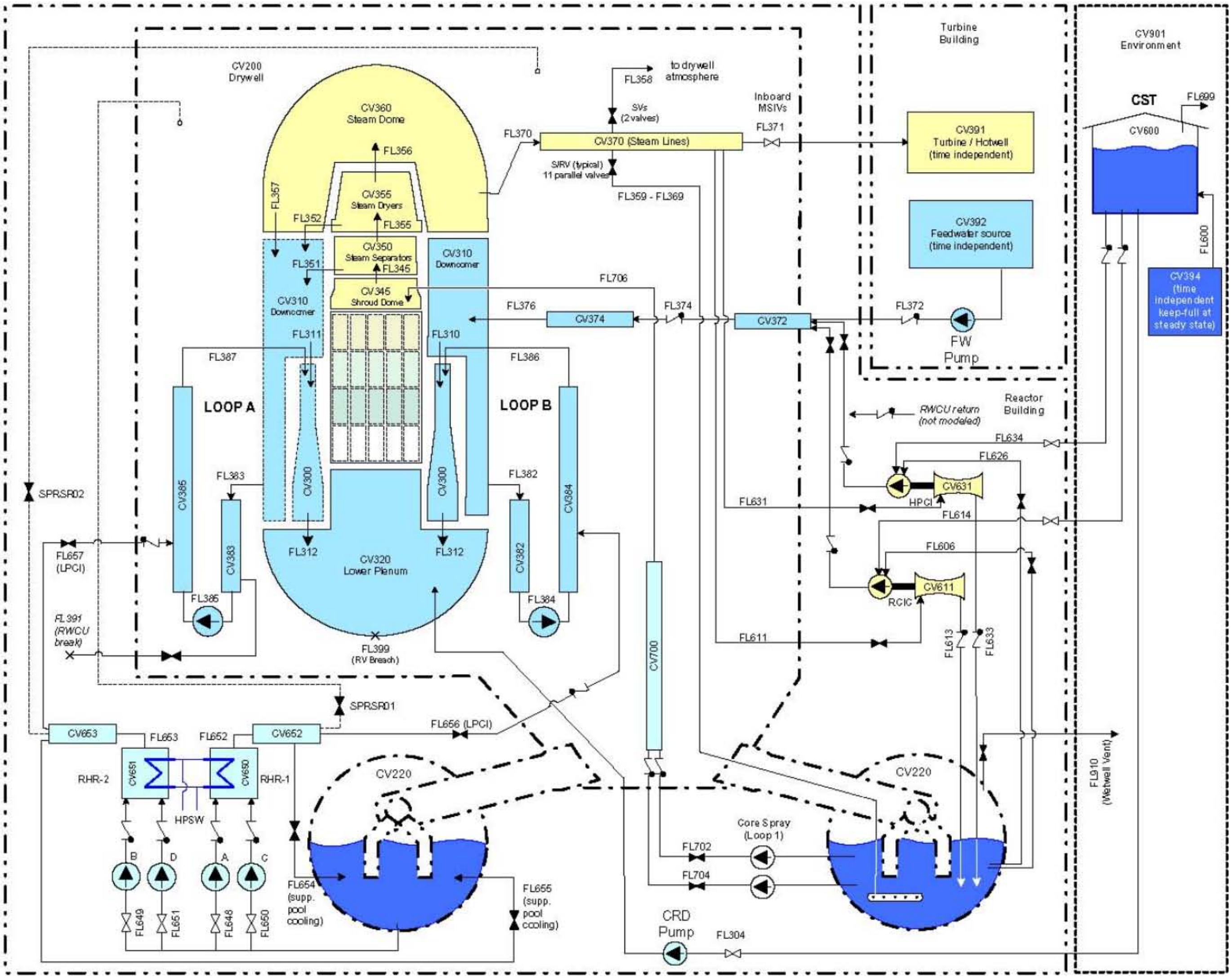


Figure 2-1 BWR Mk-I Reactor Coolant System Nodalization

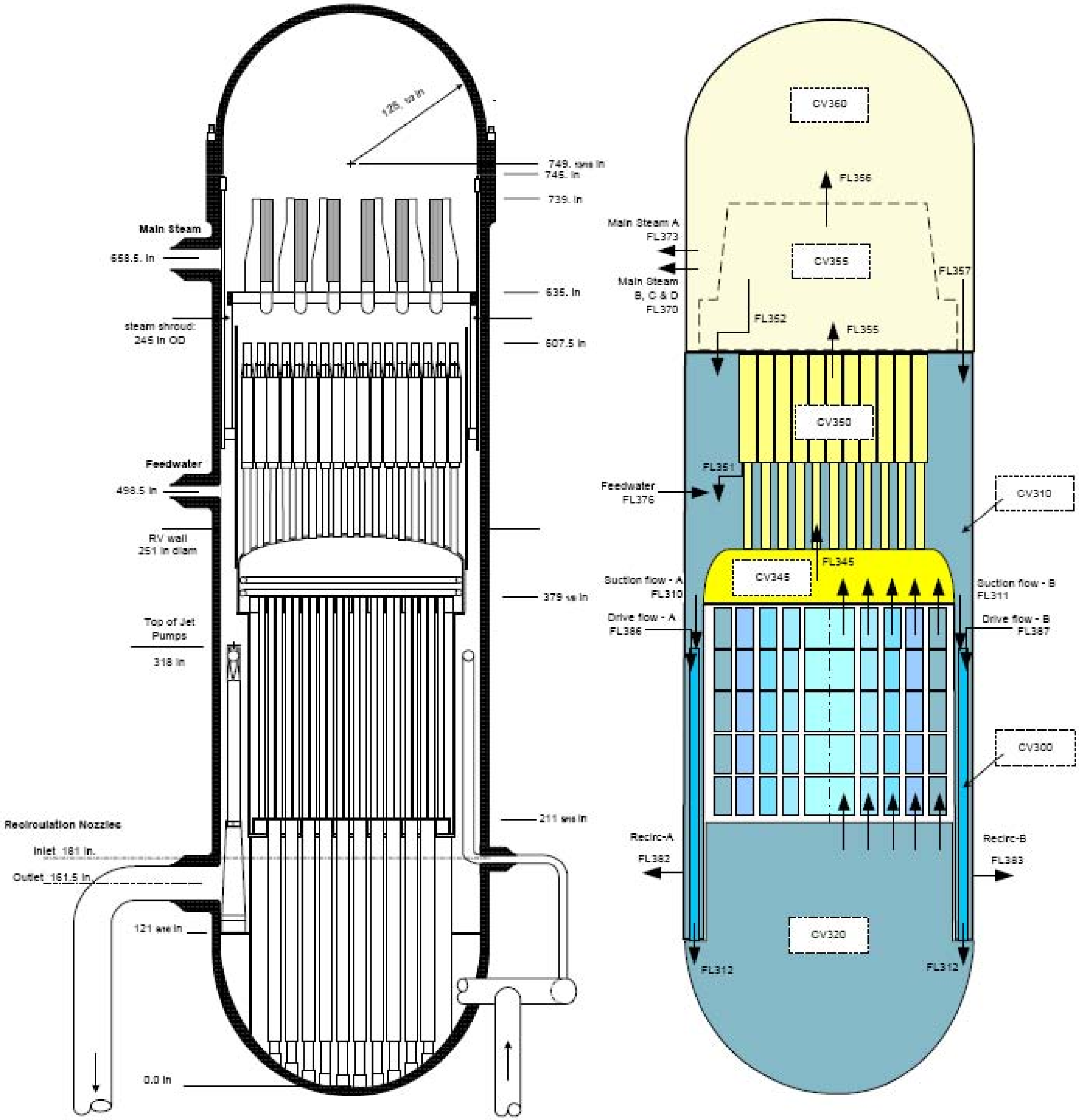


Figure 2-2 BWR Mk-I Reactor Vessel Nodalization Detail

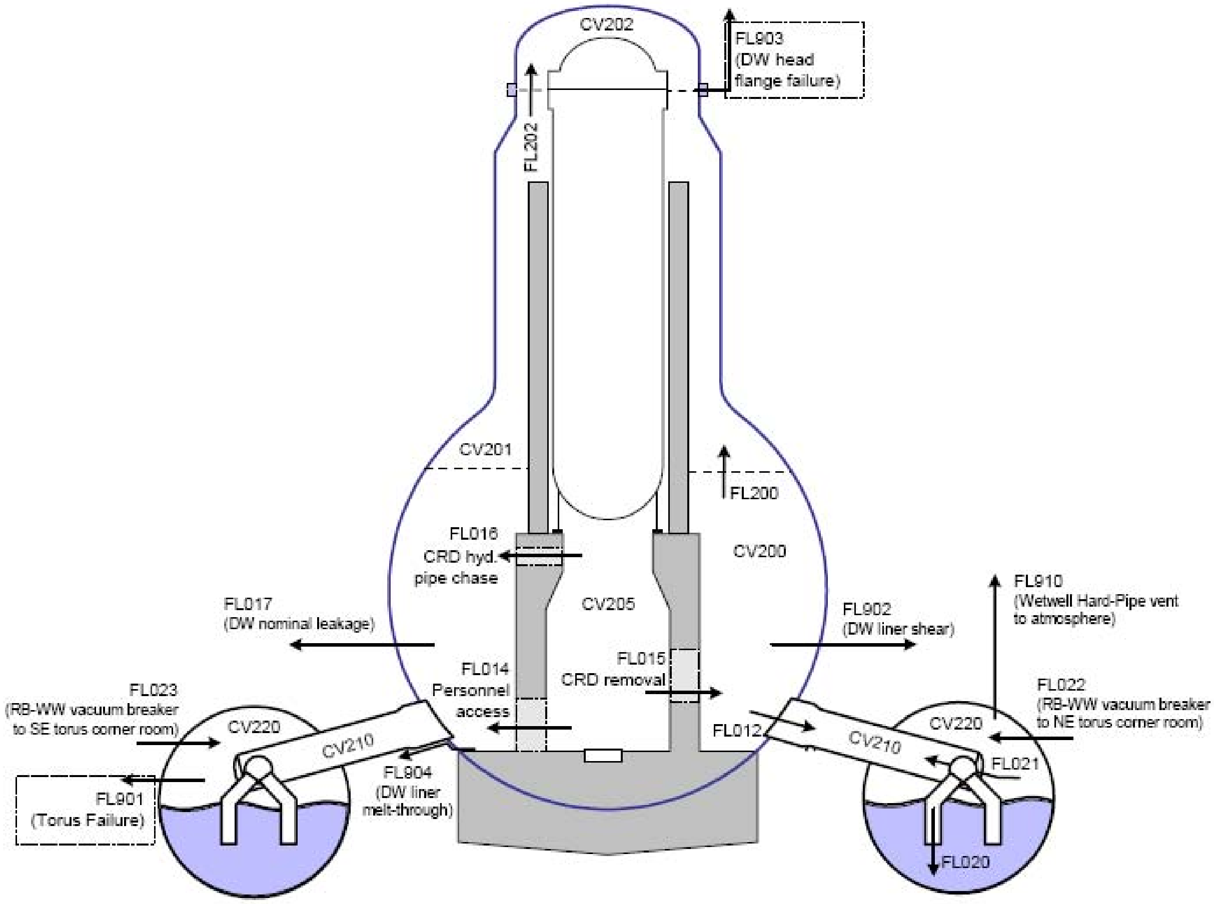


Figure 2-3 MELCOR nodalization used for the Mk-I containment.

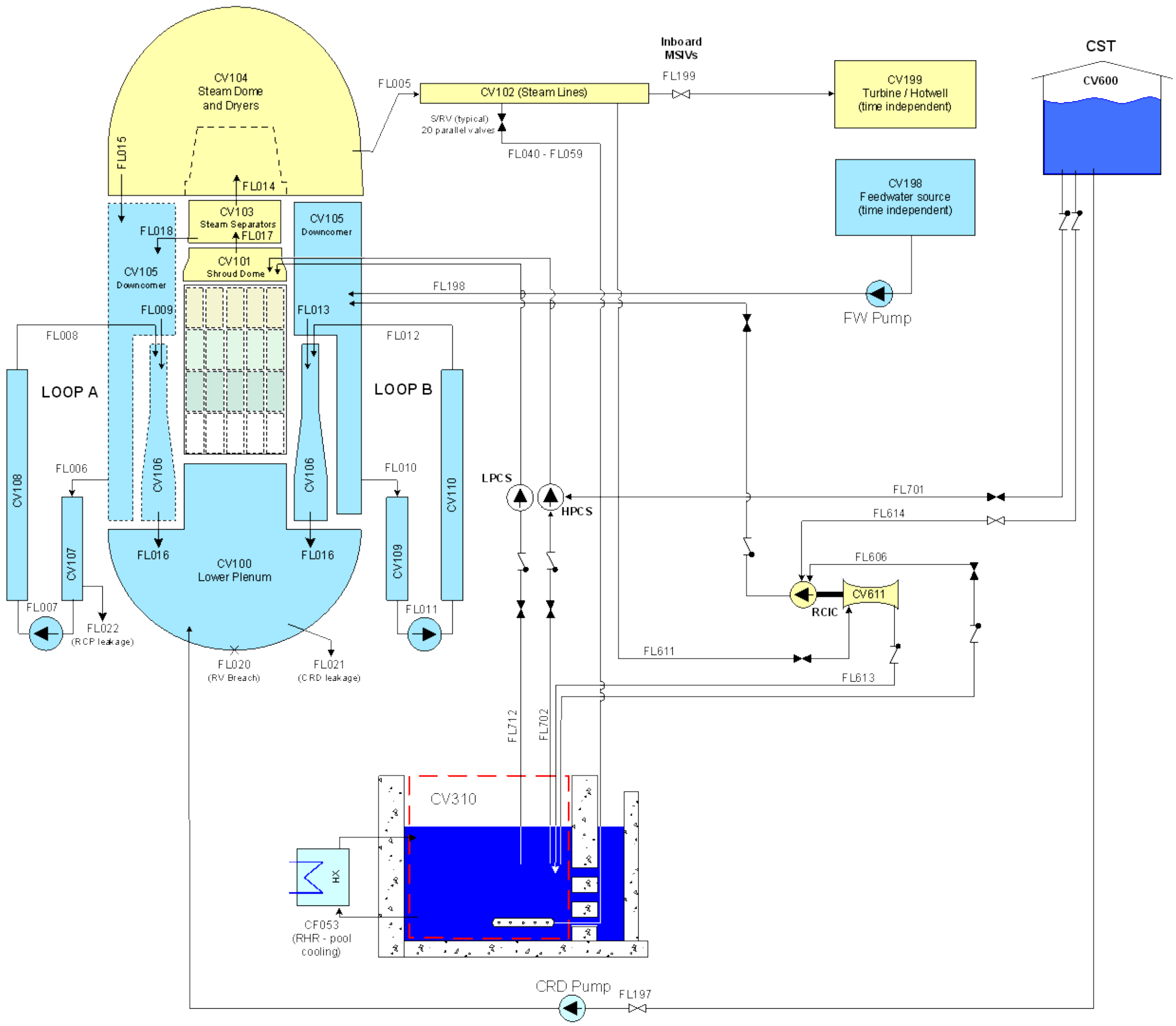


Figure 2-4 BWR Mk-III Reactor Coolant System Nodalization

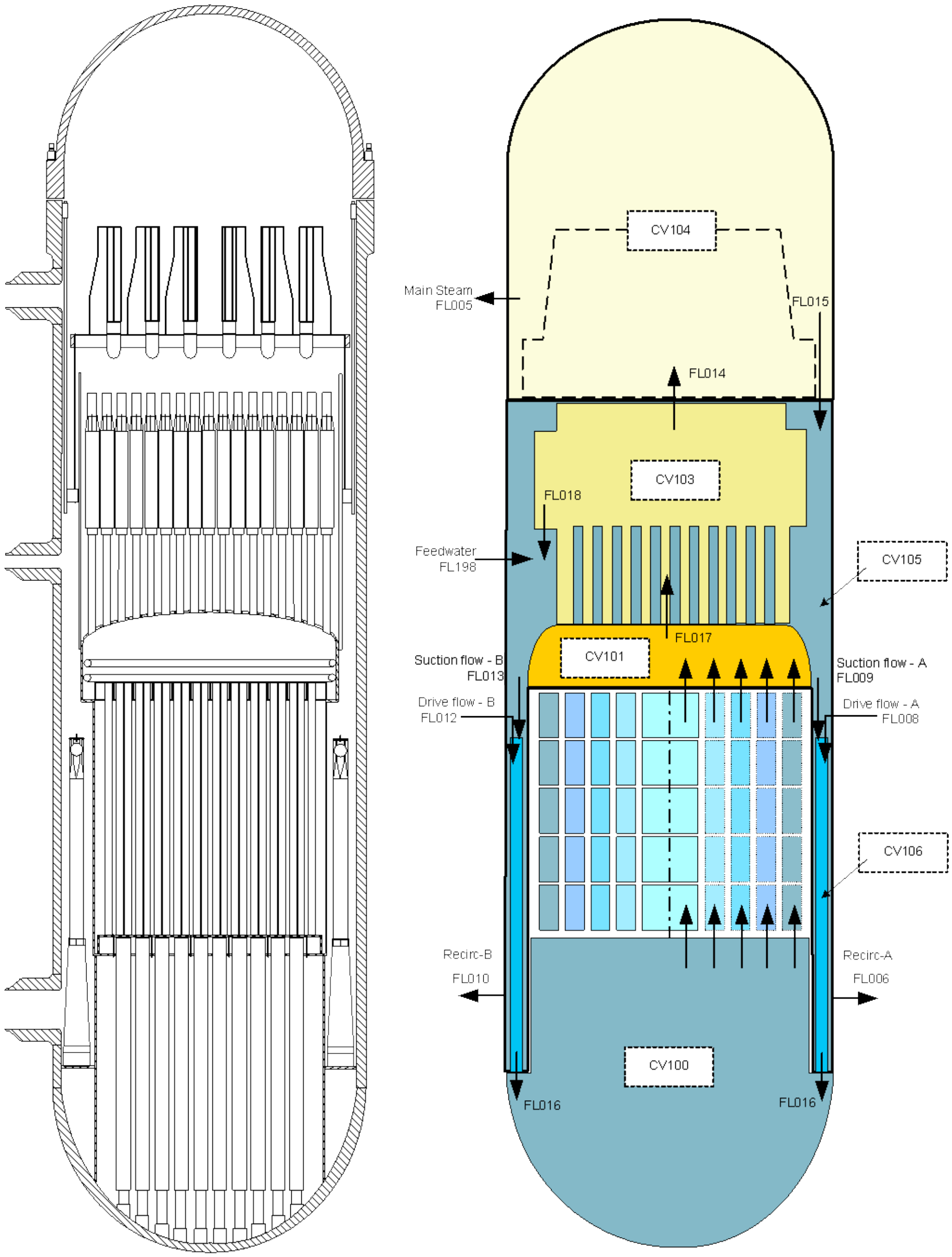


Figure 2-5 BWR Mk-III Reactor Vessel Nodalization Detail

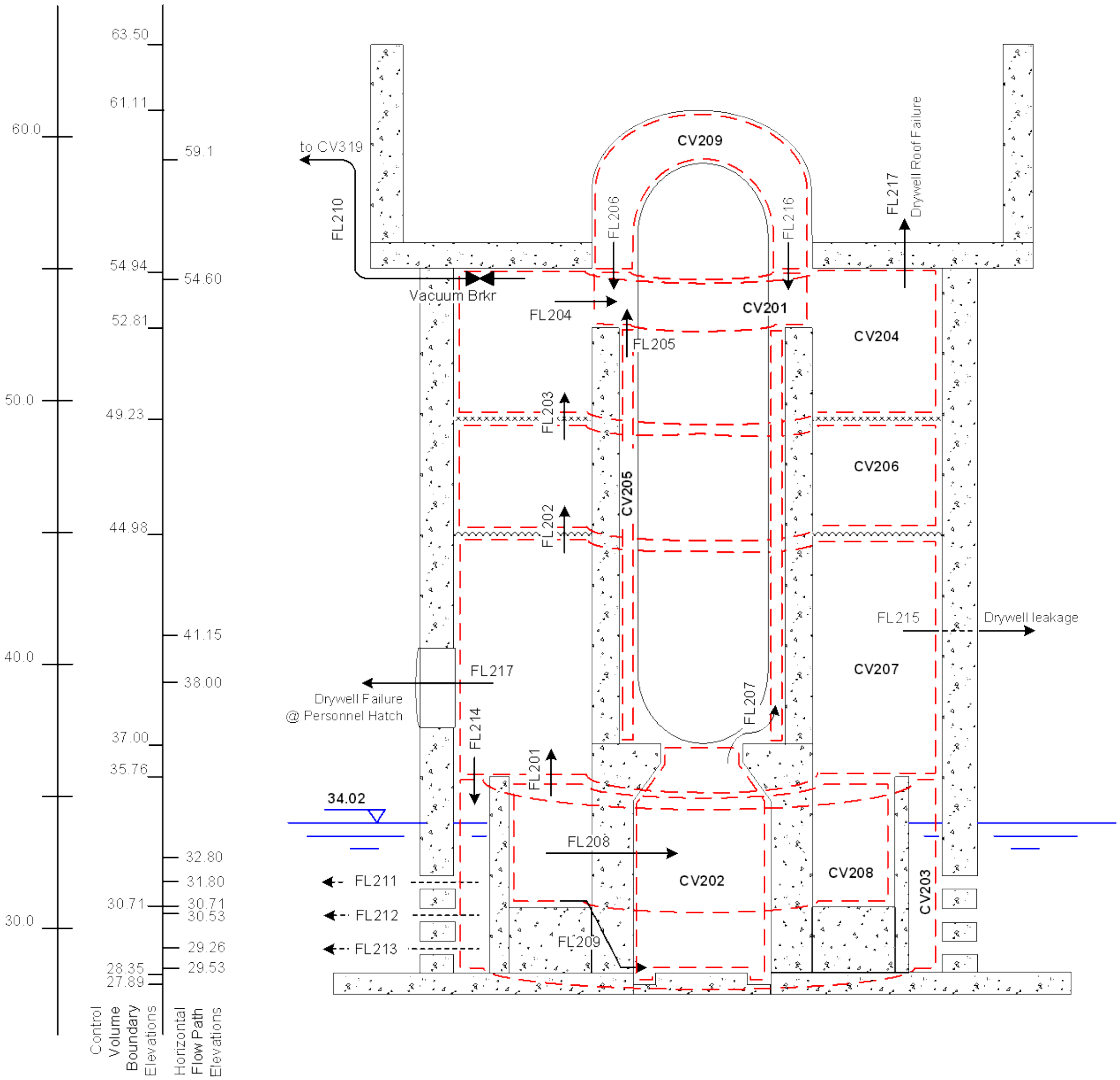


Figure 2-6 Mk-III Drywell Nodalization

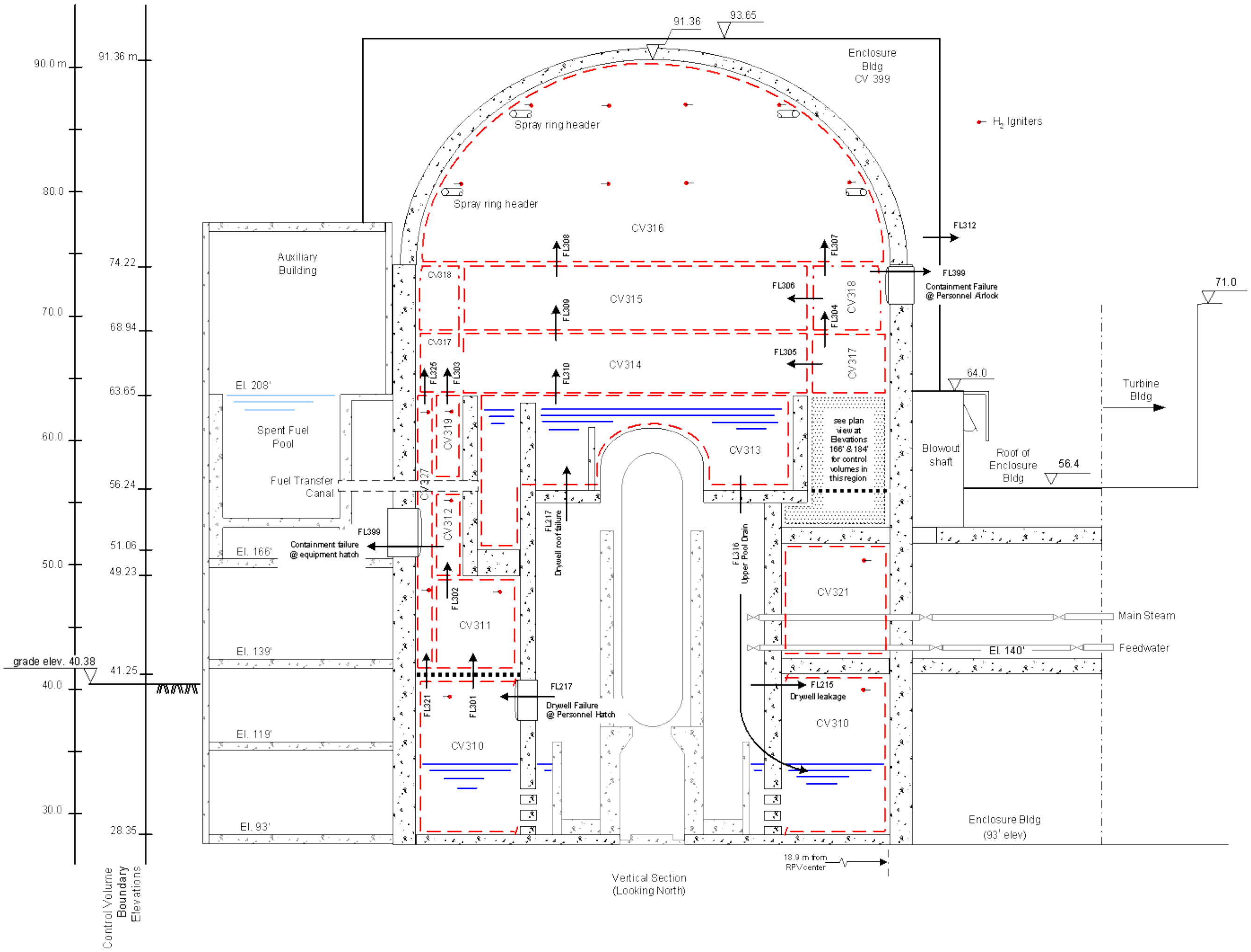


Figure 2-7 BWR Mk-III Containment Nodalization

In this study, each main steam line is modeled separately to allow for different valve leakages on each leg as shown in Figure 2-8 and Figure 2-9. For the cases in which a condenser was included in the model it was added as a control volume connected to the end of the MSLs, modeled as CV860. When used, the condenser was modeled as having 146,996 ft^3 (4162 m^3) at atmospheric pressure and initial temperature of 120F (322K). The deposition horizontal surface area was taken to be the floor area of 252.5 m^2.

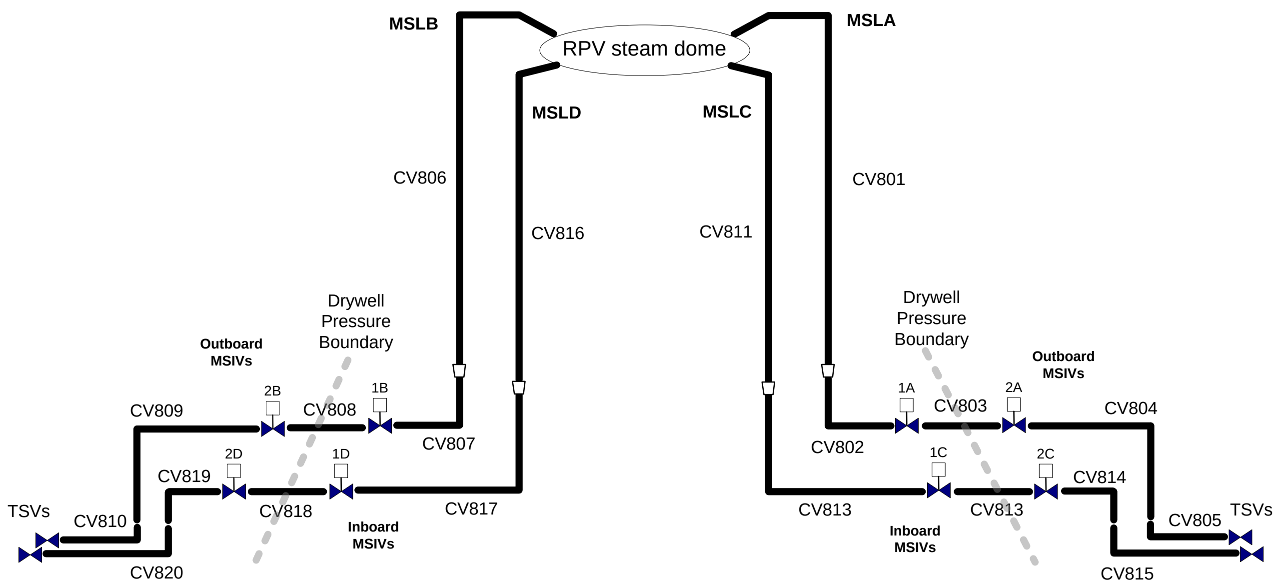


Figure 2-8 BWR Mk-I Main Steam Line Containment Nodalization for MSIV Leakage Calculation

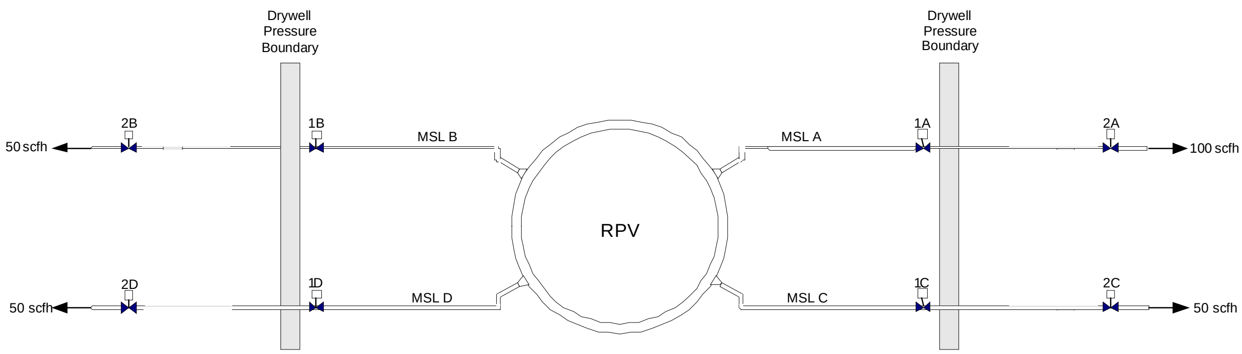


Figure 2-9 BWR Mk-III Main Steam Line Nodalization for MSIV Leakage Calculation

2.1.1 Modifications and Key Assumptions

In the base models the MSIVs close at accident initiation (t = 0 s). This causes the pipe between the MSIVs to be at a higher pressure than the pipe volume between the steam dome and the in-board MSIV. For less than an hour at the beginning of the accident this condition results in back-flow from the in-board MSIV which stops fission products from being passed through the MSLs and on to the environment. The best-estimate base MELCOR model does not account for uncertainties introduced by variations in plant design such as insulation dimensions, MSIV closure times or those from flow recirculation or thermally driven reverse flow, or “chugging [3]”. Because of these uncertainties and to promote MSIV leakage, two modifications were made to the base model: the initiation of closure of the out-board MSIV was delayed by 3 seconds and the heat transfer coefficients of the heat structures of the MSL piping between the steam dome and in-board MSIV were reduced to a low value (0.01 W/(m^2K)) for the first hour after accident initiation in order to thermally decouple the intermediate region gas from the hot steam line walls, and thereby suppress the intermediate region pressurization and reverse flow through the inboard MSIV’s. Additionally, anecdotal evidence[†] has indicated that the inboard MSIV tends to unseat when the down stream pressure exceeds the upstream pressure by about 25 psi, which would tend to prevent high pressure trapped in the intermediate steam line from producing reverse flow through the inboard valve. These adjustments to the MELCOR model produce the anticipated valve outflow conditions, and facilitate comparisons with the RADTRAD approach that specifies outflow conditions. For these calculations, the inboard MSIVs start to close at 0 s and completed closing at 3 s. The outboard valves start to close at 3 s and finish at 6 s. For both valves, the closure rate was constant.

The flow path from the condenser to the environment was modeled as having an area equivalent to that of an MSL. An area of this size provides negligible flow resistance, and is hence conservative with respect to fission product release to the environment.

Leakage past the MSIVs in the Mk-I and Mk-III MELCOR models was defined considering a base technical specification of 11.5 scfh (9.05×10^{-5} m^3/sec) maximum when tested at 25 psig, i.e., with upstream pressure at 39.7 psia (0.172 MPa) and downstream pressure at 14.7 psia (0.101 MPa). Associated upstream temperature was taken to be 59 °F (287.8K).

A standalone MELCOR model was constructed to impose the above conditions on a constricted flow path configured to represent MSIV leak geometry as an orifice, i.e., configured to offer negligible frictional losses. Air was specified as the fluid. The model identified, through trial and error execution, that a flow path with an area of 0.2828 m^2 (the full open area of a main steam line in the Mk-I model) and an open fraction of 5.9926×10^{-7} would flow 1.1×10^{-4} kg/s of air (11.5 scfh taking density at standard temperature and pressure to be 1.2232 kg/m^3).

The base leakage specifications for the MSIVs in the Mk-I models designated for the subject work were:

- 205 scfh (at 25 psig) past the valves in MSL A
- 155 scfh past the valves in MSL B
- Zero leakage past the valves in MSL C
- Zero leakage past the valves in MSL D

The base leakage specifications for the MSIVs in the Mk-III models designated for the subject work were:

[†] Verbal communication with John Ridgely, USNRC.

- 100 scfh (at 25 psig) past the valves in MSL A
- 100 scfh past the valves in MSL B
- 50 leakage past the valves in MSL C
- Zero leakage past the valves in MSL D

Note that these flow areas and open fractions were defined at both the inboard and outboard MSIV locations. As in the standalone MELCOR model, the leakage flow paths in the Mk-I and Mk-III models were configured to offer negligible frictional losses.

The following section presents basic results of the MELCOR full plant analyses, including key accident progression signatures, and airborne concentrations of key radionuclides in the steam dome, drywell and wetwell regions. Ratios of these airborne concentrations are used to provide the scaling parameters to be used in subsequent RADTRAD analyses, as described earlier in Section 1.1.

It should be mentioned that MELCOR does not presently treat wall and surface deposition of elemental iodine from processes other than condensation, this being an area of ongoing research; however, neither does MELCOR introduce any elemental iodine as a result of release from fuel. Rather, it is assumed in MELCOR that all iodine is initially released as CsI. MELCOR can ultimately produce some source of elemental iodine as a result of revaporization of previously deposited CsI onto surfaces where the Cs has been presumed to "chemisorbed," or chemically adhered, to the surface. In this case, iodine alone is evolved in the form of elemental iodine

The nature of leakage pathways and whether they are best treated as orifices or capillary pathways is often discussed in regulatory applications, especially for purposes of calculating releases from containment leakage. It has been common practice by both the NRC and industry to assume orifice geometry. Standard orifice geometry was assumed for the determination of leakage in this report. Because work on aerosol capture in pathways of various geometries suggest that impaction is not a promising mechanism for crediting additional attenuation, impaction was not considered as a removal mechanism for this study.

2.1.2 Calculation of Removal Coefficients

A key result from the MELCOR analysis of full plant behavior is a characterization of aerosol depletion and deposition behavior that is needed by the RADTRAD code to mimic the depletion behavior predicted by MELCOR. While the mechanics of fission product deposition are complex, its net behavior in the containment and in the steam lines is often characterized by the simplified assumption that the overall deposition rate is proportional to the airborne fission product mass in the containment or MSL vapor space.

$$\dot{m}_{dep} = \lambda m \tag{2.1}$$

where

$\dot{m}_{dep}$ - aerosol mass deposition rate
λ - time-dependent aerosol mass removal coefficient
m - aerosol airborne mass in the volume in question

This term is part of the overall generalized aerosol mass balance

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} - \dot{m}_{dep} + \dot{S} \tag{2.2}$$

where

$\frac{dm}{dt}$ - rate of change of airborne aerosol mass in the volume in question
$\dot{m}_{in}$ - rate of airborne aerosol mass entering the volume from other volumes
$\dot{m}_{in}$ - rate of airborne aerosol mass exiting the volume to other volumes
$\dot{S}$ - rate of aerosol source term injection into the volume

For the purpose of calculating MSL removal coefficients, the MSLs have been conceptually divided into three segments (1) between the steam dome and the in-board MSIV, (2) between the in-board and out-board MSIVs, and (3) between the out-board MSIV and the turbine building (or condenser, if modeled). This division is consistent with the typical MSL nodalization used in RADTRAD MSL models. The removal coefficient for each MSL segment is calculated in the MELCOR analyses at each time-step by dividing the aerosol mass deposition rate by the aerosol mass in the vapor space of that MSL segment ($\lambda \approx \dot{m}_{dep} / m$). Likewise, for cases with a condenser, the removal coefficient in the condenser is calculated in the MELCOR analyses by, at each time-step, dividing the aerosol mass deposition rate in the condenser by the aerosol mass in the vapor space in the condenser. From this, an instantaneous removal rate coefficient can be calculated as part of the MELCOR generated results. This instantaneous removal calculated at each time step exhibits transient fluctuations caused by the variations in the parameters that affect it. Among these are fluctuations associated with volume in-flows and out-flows, aerosol source fluctuations, sudden increases in steam generation, and the associated changes in deposition rates from processes such as diffusiophoresis and revaporization of previously deposited fission products. In order to produce coefficients of the form that are consistent with the idealized approach of exponential decay, the instantaneous removal coefficients are averaged in time providing the effective “lambdas”.

2.2 Results from Full Reactor MELCOR Models

Selected results of the MELCOR full reactor model calculations are presented in the following sections.

2.2.1 Mk-I MSLB, No Sprays

The main steam line break full plant analysis for the Mk-I design with no containment sprays operational is described in this section. Figure 2-10 through Figure 2-12 show the pressure response of the vessel and drywell, temperatures in the steam dome and drywell and the core water level. Note that, while the core water inventory is depleted after 2 hours, lower head failure is not predicted until almost 8 hours. This modern view of the accident progression is in significant variance with the view put forth in NUREG-1465 where head failure was assumed to occur at about 2 hours into such an accident. This observation is evidence that the present NUREG-1465 assumptions about the early in-vessel period in terms of release rate and duration are no longer consistent with current best estimate modeling results.

A significant finding in this work is illustrated by comparing the information shown in Figure 2-13 and Figure 2-14. From these figures it can be seen that while there is significantly more airborne *mass* of CsI in the *drywell* during the first 2 hours of the accident, in contrast, the *concentration* of airborne CsI in the *steam dome* is significantly greater than that of the drywell. Since the steamlines are connected to the steam dome and not the drywell, it is the airborne concentration in the steam dome, not the airborne mass in the drywell, that determines the MSIV leakage behavior. Figure 2-15 provides the ratio of airborne concentrations of select radionuclides in the steam dome relative to the drywell in the MELCOR full plant analyses.

Finally, best estimate removal coefficients (lambda values), characterizing the observed deposition of aerosols by gravity settling, thermophoresis and diffusiophoresis for the main steam lines A and B are shown in Figure 2-16 and Figure 2-17. Here one can see that in the first 2 hours, removal coefficients for the inboard and intermediate lines are about 3 hr^{-1}, decreasing to values between 1 and 2 hr^{-1} after 2 hours. The removal coefficients for the outboard lines are always on the order of 1 hr^{-1} or less, due to the very small aerosol particle sizes reaching these regions. Note that the instantaneous removal coefficients at times can show very transient behavior not consistent with the idealized exponential depletion model, as seen for example in Figure 2-16 where at about 2 hours, the removal coefficient suddenly increases from about 1.8 up to a value of 16 to 18, persisting for about a half hour. This temporary increase in apparent removal rate coefficient is driven by events in the core melt progression where core slumping at about two hours drives vigorous steam generation as evidenced by the rapidly dropping core water level at 2 hrs as seen in Figure 2-12. This produces both significantly increased aerosol concentrations in the steam dome region (Figure 2-14), as well as increased diffusiophoretic deposition rates. Other fine structure in the MELCOR-predicted instantaneous removal coefficients can be observed, again owing to the dynamic behavior of core damage progression and hydrodynamic effects.

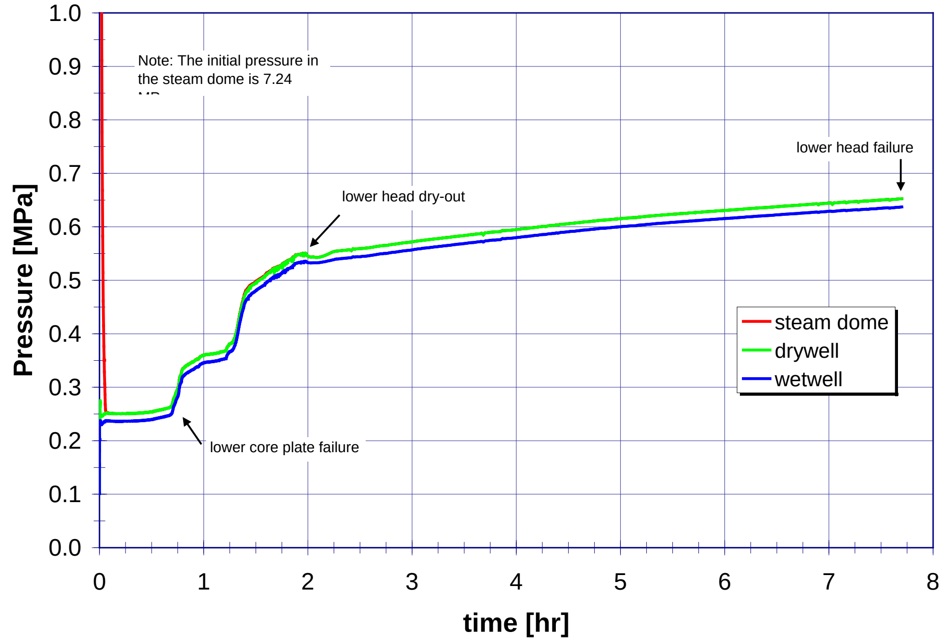


Figure 2-10 BWR Mk-I, MSLB, No Sprays: Steam Dome, Drywell, and Wetwell Pressure

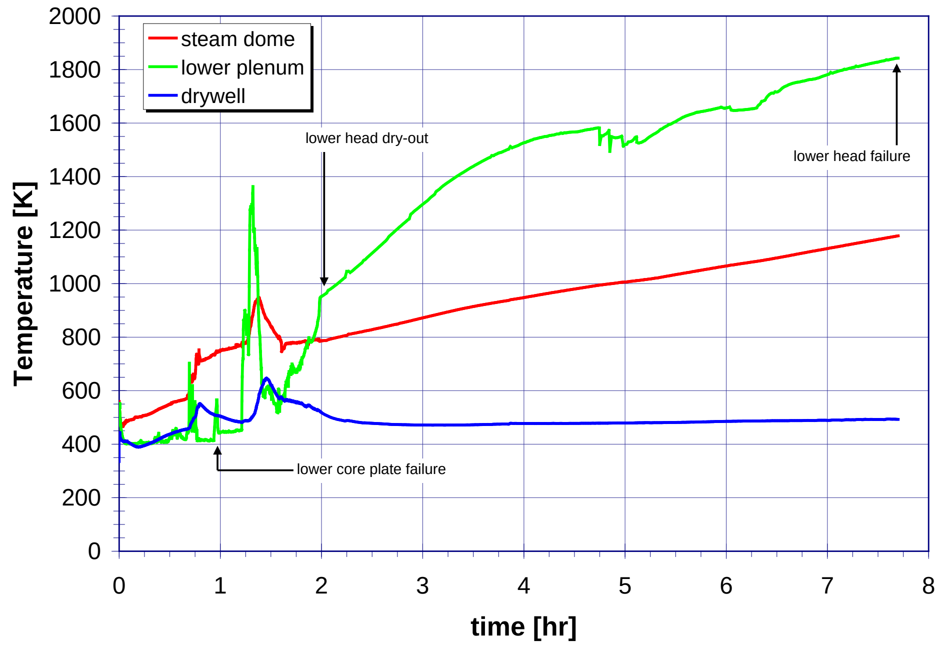


Figure 2-11 BWR Mk-I, MSLB, No Sprays: Steam Dome, Drywell, and Lower Plenum Vapor Temperature

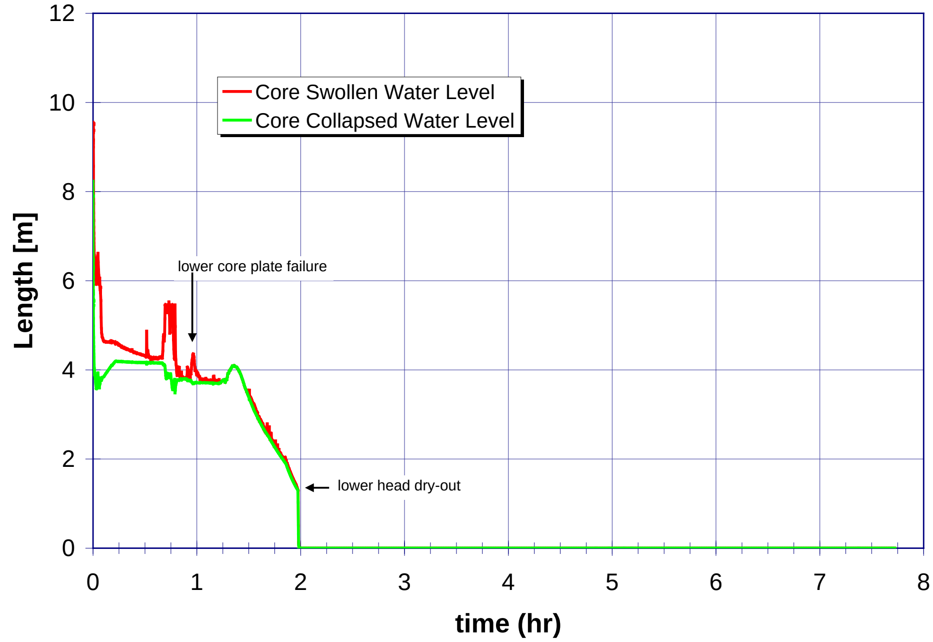


Figure 2-12 BWR Mk-I, MSLB, No Sprays: Core Water Levels

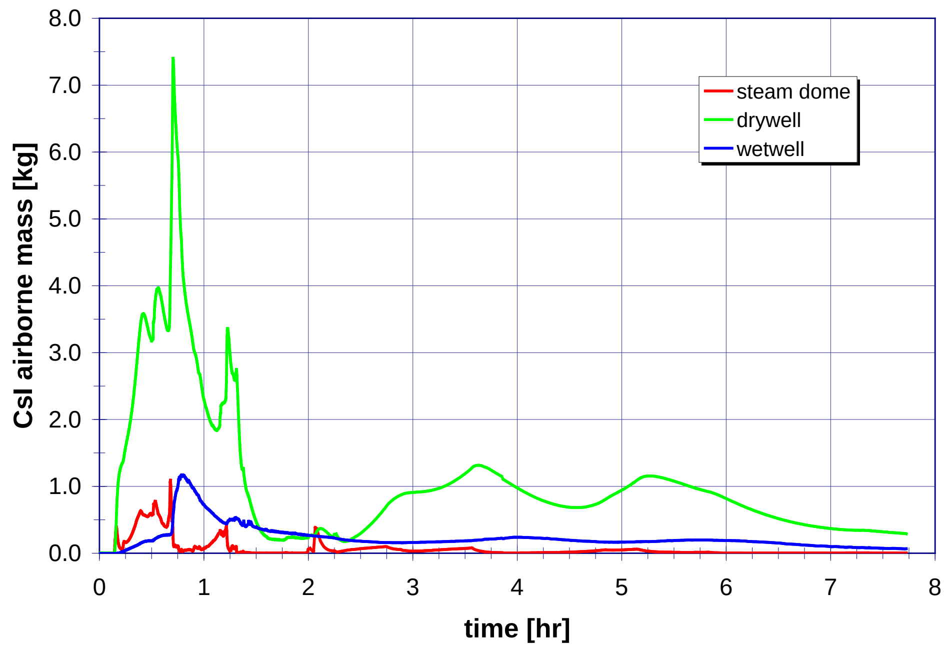


Figure 2-13 BWR Mk-I, MSLB, No Sprays: CsI Mass in the Steam Dome, Drywell, and Wetwell

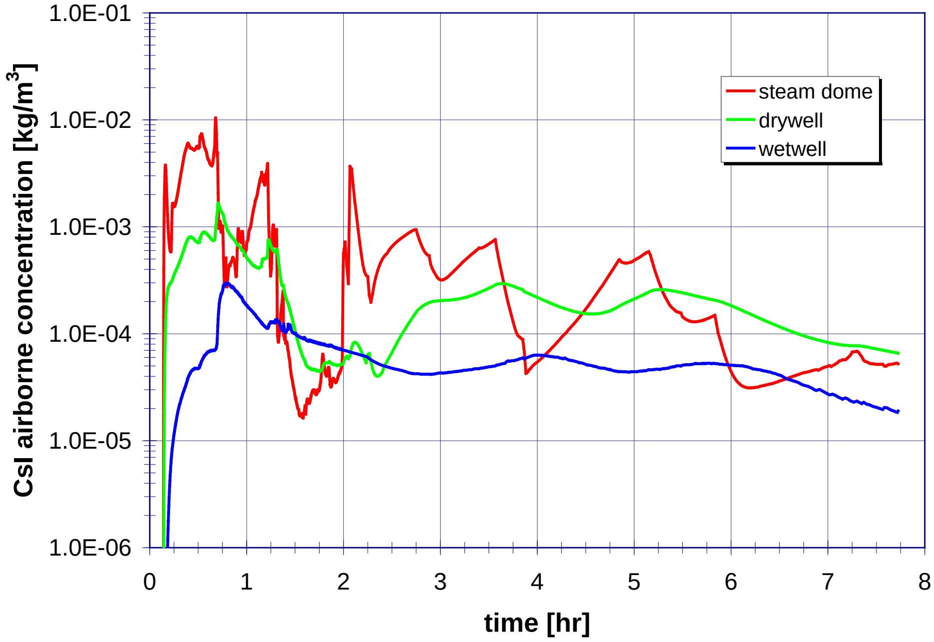


Figure 2-14 BWR Mk-I, MSLB, No Sprays: CsI Concentration in the Steam Dome, Drywell, and Wetwell

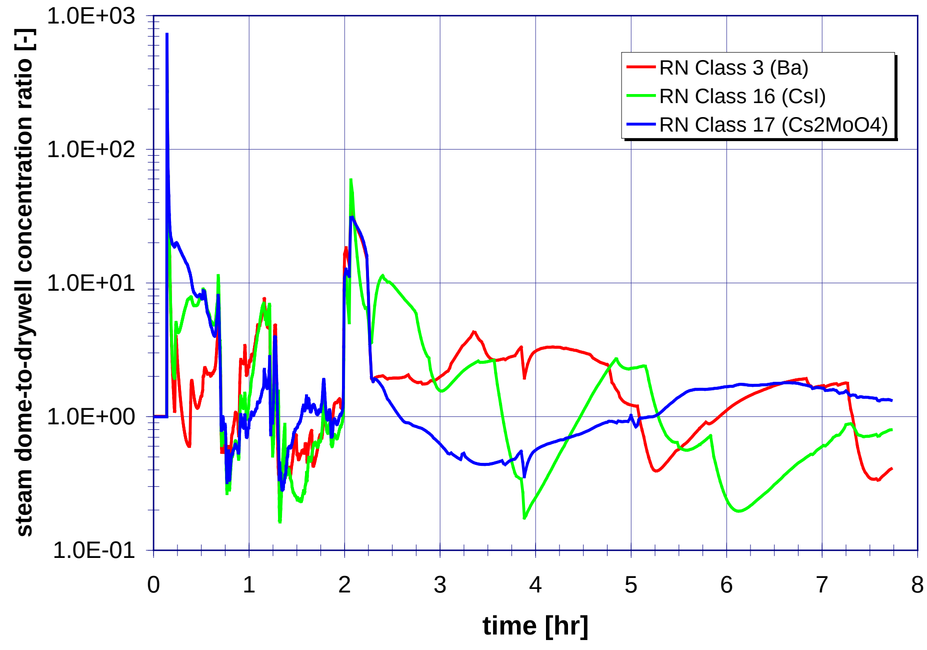


Figure 2-15 BWR Mk-I, MSLB, No Condenser, No Sprays: Steam Dome-to-Drywell Concentration Ratios

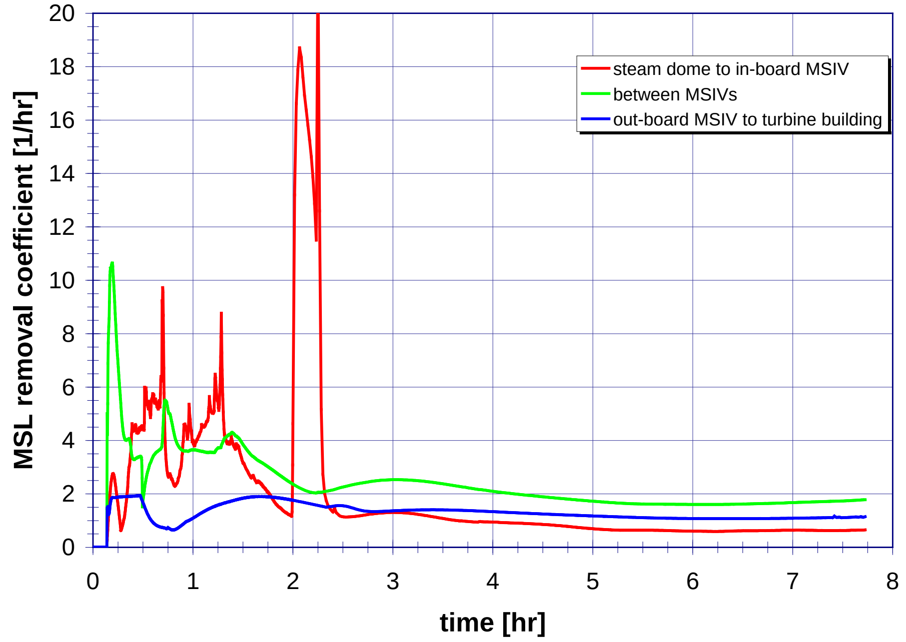


Figure 2-16 BWR Mk-I, MSLB,, No Sprays: MSL-A Removal Coefficients

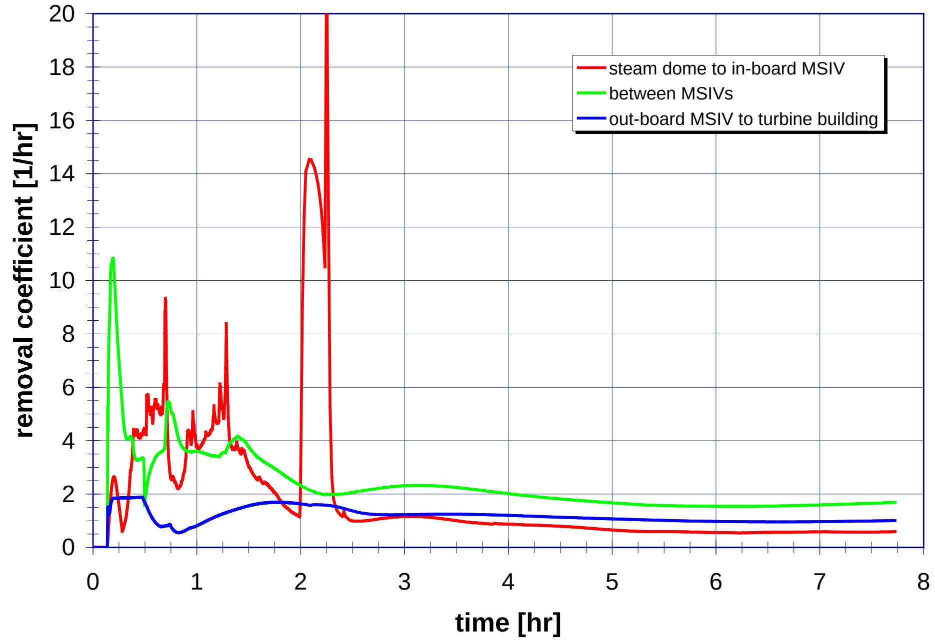


Figure 2-17 BWR Mk-I, MSLB, No Sprays: MSL-B Removal Coefficients

2.2.2 Mk-I MSLB, Sprays

In this section, the automatic actuation of containment sprays at the onset of the accident are examined for the Main Steam Line Break sequence in the Mk-I containment. Results analogous to the previous section are presented here. The purpose of this section is to examine the effect of containment spray actuation on the airborne aerosols in the drywell and in the reactor steam dome, since some license amendment requests have requested credit for aerosol attenuation by sprays in order to reduce the radioactivity escaping through the MSIV's. The basic accident thermal-hydraulic signatures are similar to the cases without containment sprays. These are summarized in Figure 2-18 through Figure 2-20. Again, the drywell airborne total mass exceeds the steam dome mass by a factor of 4 to 5 or more (Figure 2-21), but the steam dome concentration generally exceeds that of the drywell volume by an order of magnitude in the first hour, and a lower factor after 2 hours (Figure 2-22 and Figure 2-23). At times however, steam generation in the vessel can temporarily clear out the steam dome, as occurs between 1.5 and 2 hours. Removal coefficients are summarized for the steam lines in Figure 2-24 and Figure 2-25, again transient behaviors associated with core dynamics and fluctuations in in-vessel steam generation can be observed.

Finally, Figure 2-26 summarizes the effect of containment sprays on the drywell airborne concentrations and on the steam dome aerosol concentrations. From this figure it can be seen that for both the case with sprays and the case without sprays, the steam dome concentrations are essentially the same for the first hour. During this time also there is only a little decrease in the drywell concentration as the aerosol source to the containment from the vessel replenishes the concentrations even as the sprays remove airborne material. After two hours, the drywell sprays significantly reduce the drywell concentrations and would seem also to reduce the steam dome concentrations during this time although the steam dome concentrations still exceed the drywell concentrations. Also after the 2-hour period, the steam dome concentration for the case with no sprays is about an order of magnitude higher than the case with sprays, indicating that after the termination of the early in-vessel release, the containment sprays may encourage outflow from the vessel thereby reducing airborne concentrations in the steam dome.

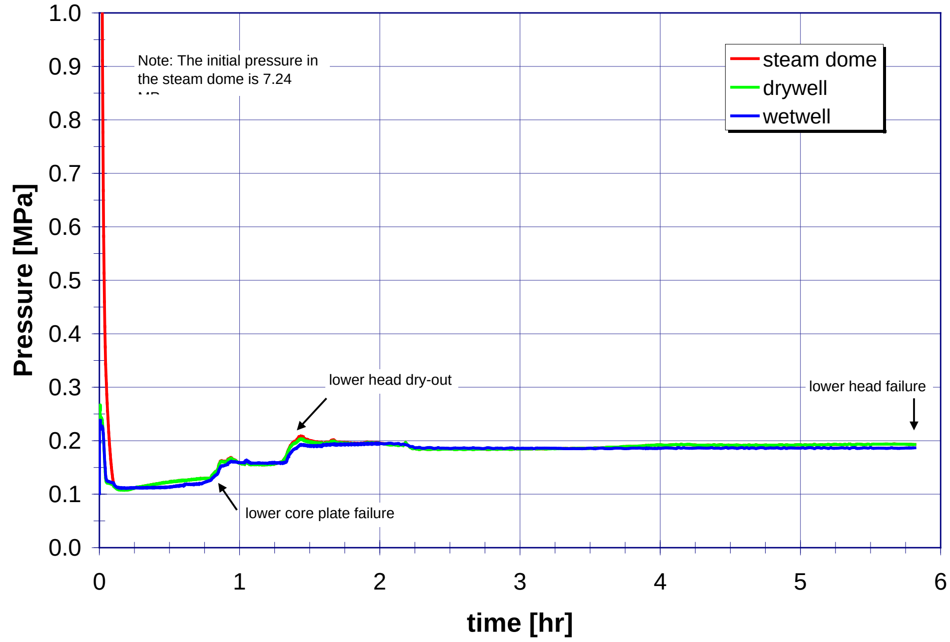


Figure 2-18 BWR Mk-I, MSLB, Sprays: Steam Dome, Drywell, and Wetwell Pressure

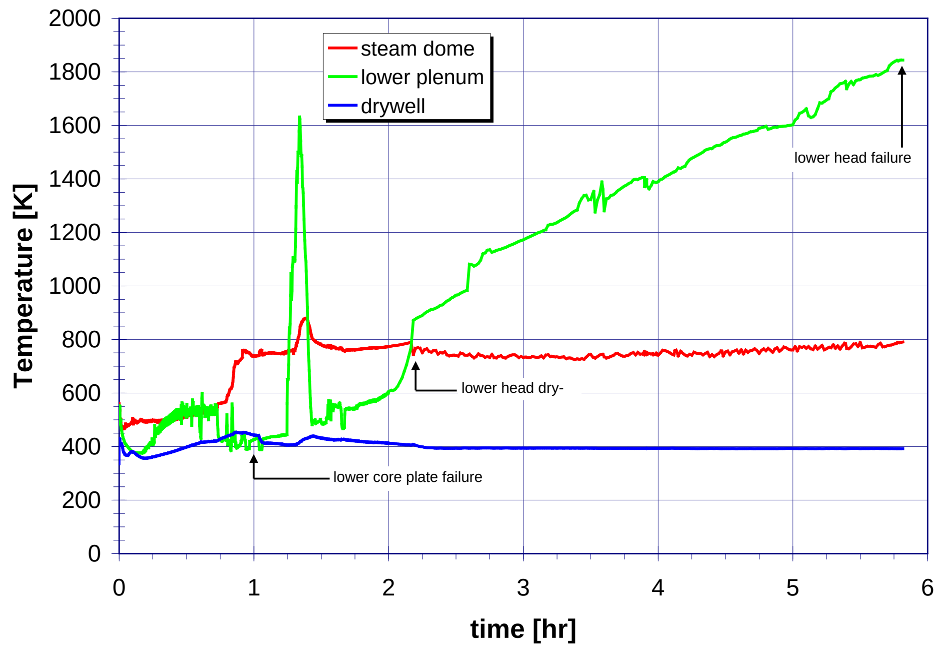


Figure 2-19 BWR Mk-I, MSLB, Sprays: Steam Dome, Drywell, and Lower Plenum Vapor Temperature

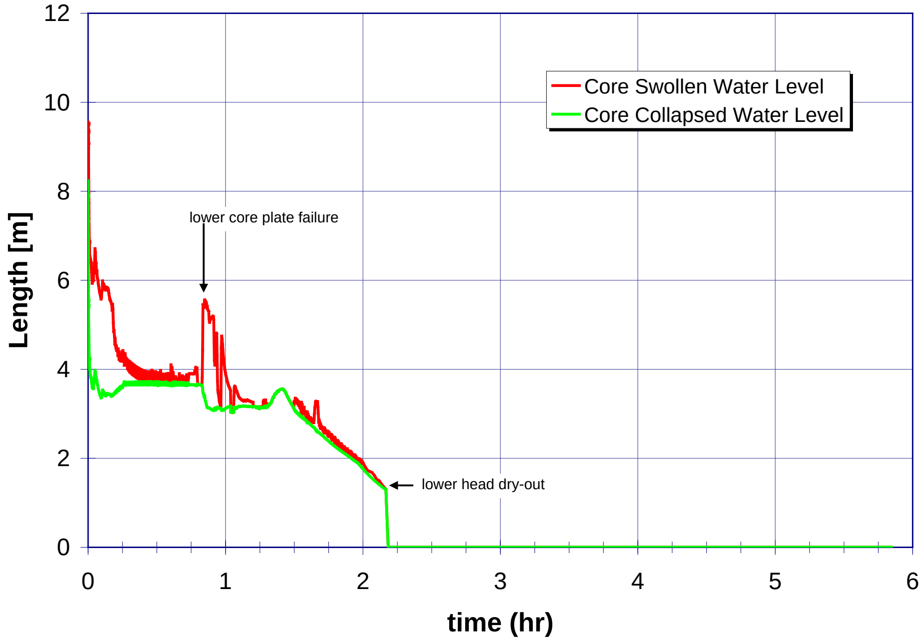


Figure 2-20 BWR Mk-I, MSLB, Sprays: Core Water Levels

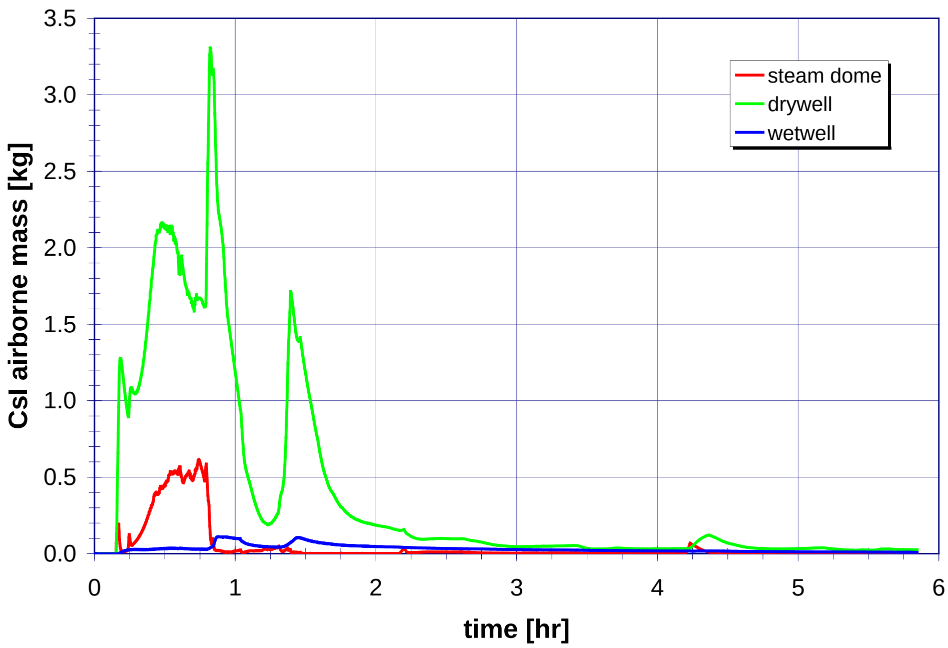


Figure 2-21 BWR Mk-I, MSLB, Sprays: CsI Mass in the Steam Dome, Drywell, and Wetwell

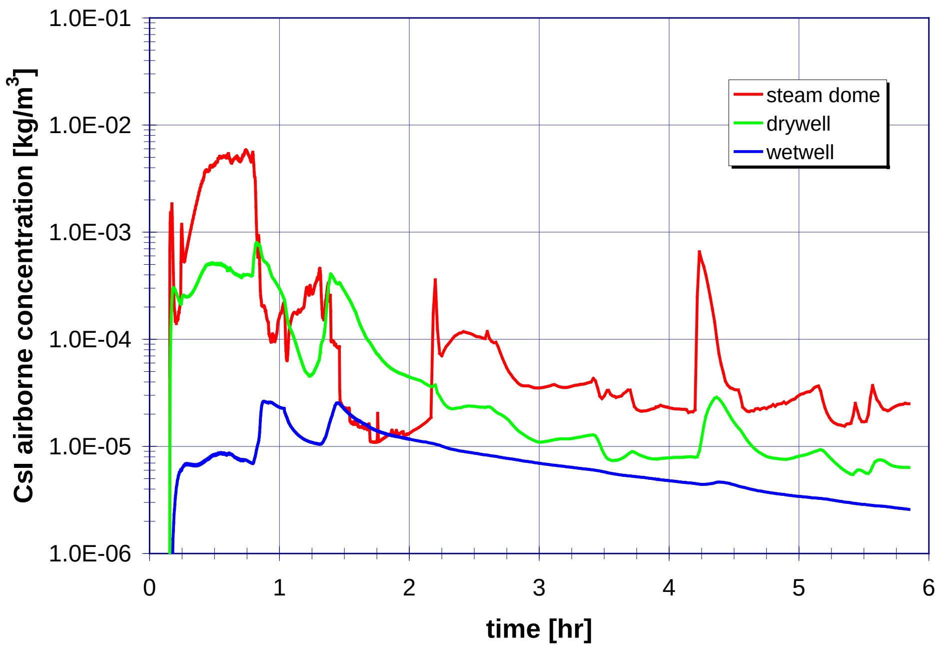


Figure 2-22 BWR Mk-I, MSLB, Sprays: CsI Concentration in the Steam Dome, Drywell, and Wetwell

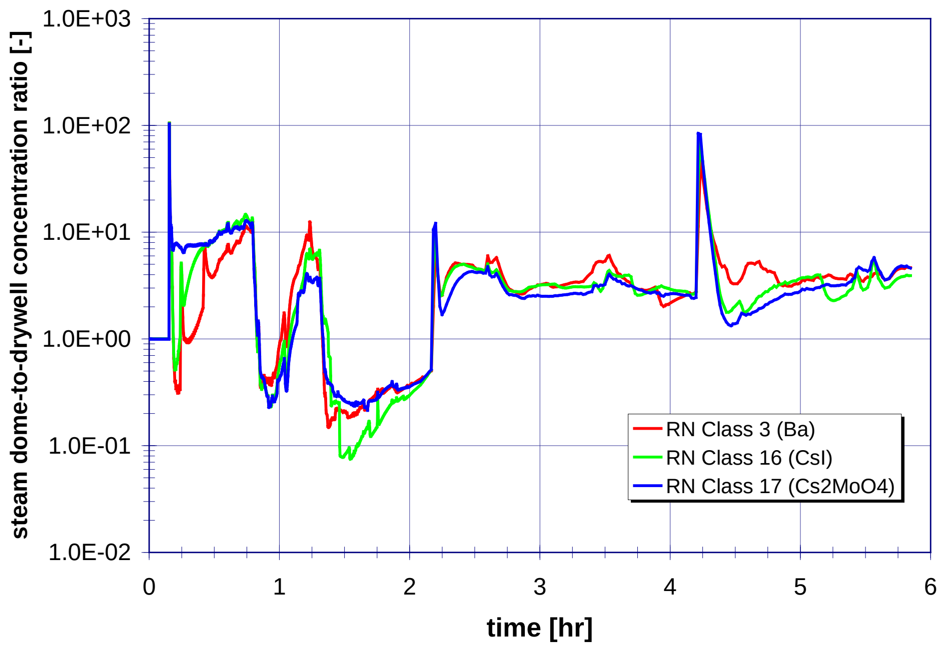


Figure 2-23 BWR Mk-I, MSLB, Sprays: Steam Dome-to-Drywell Concentration Ratios

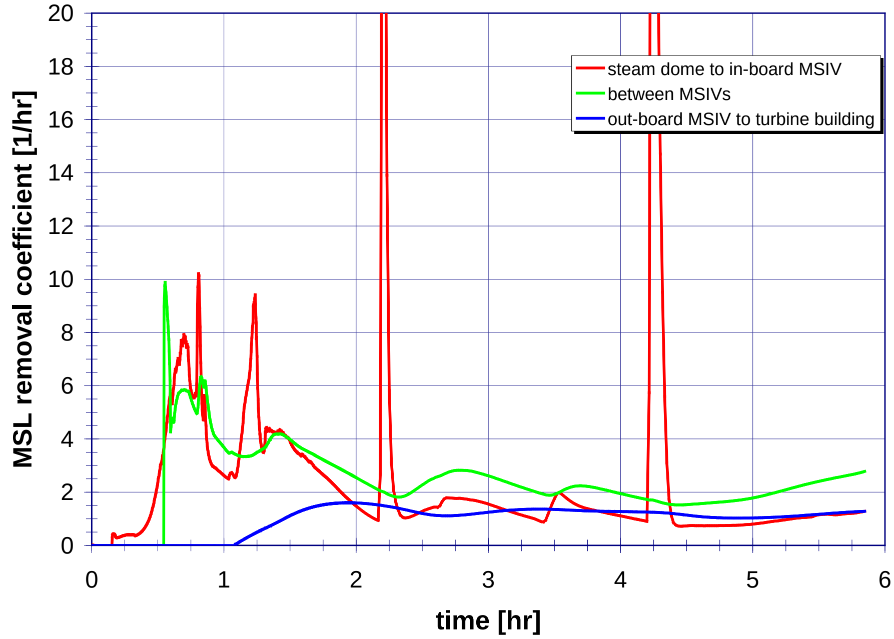


Figure 2-24 BWR Mk-I, MSLB, Sprays: MSL-A Removal Coefficients

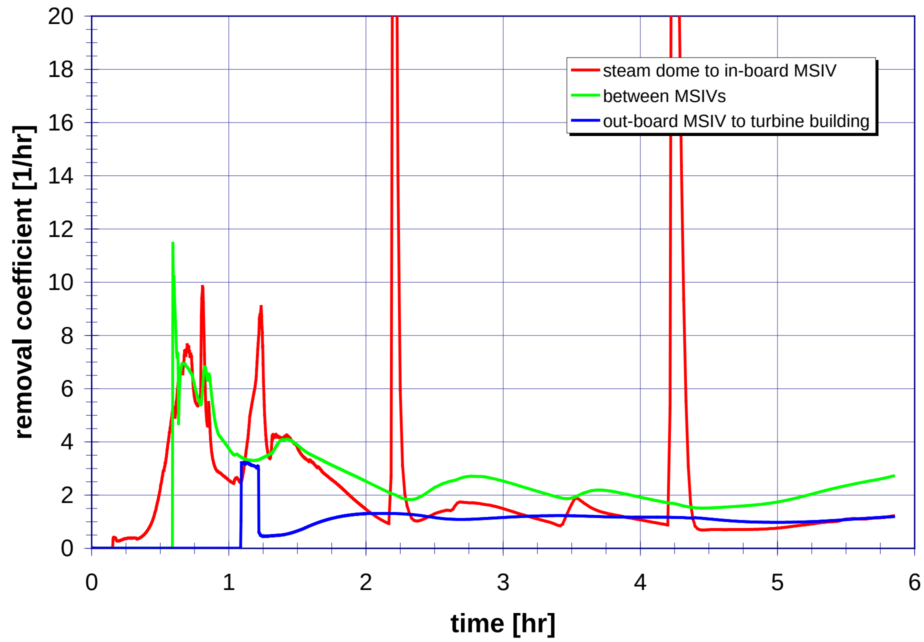


Figure 2-25 BWR Mk-I, MSLB, Sprays: MSL-B Removal Coefficients

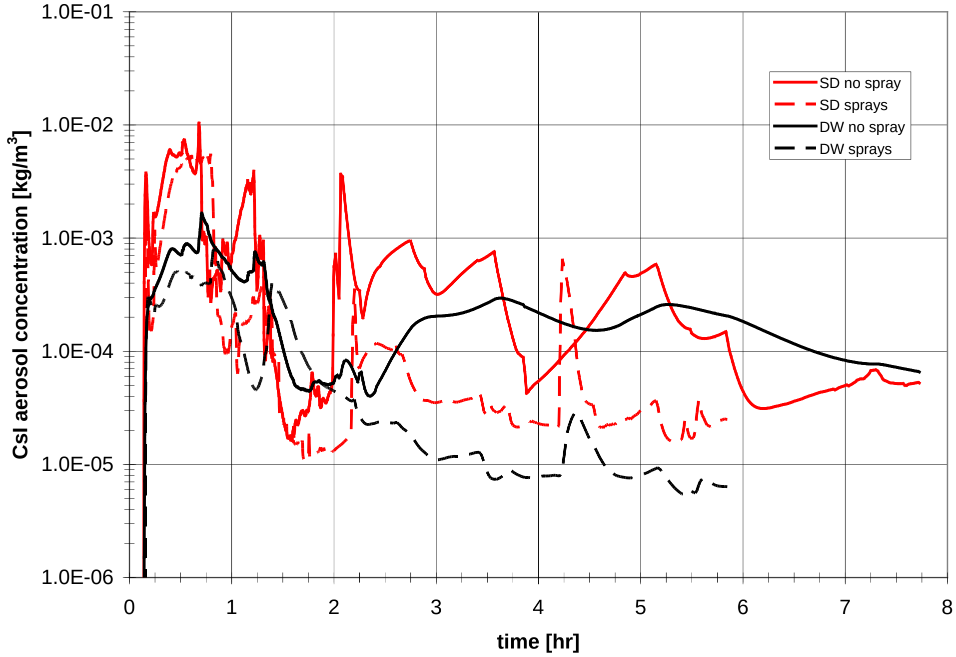


Figure 2-26 BWR Mk-I, MSLB, Comparison of CsI Aerosol Steam Dome and Drywell Concentrations with and without Sprays

2.2.3 Mk-I RLB, Both No Sprays and With Sprays

The following two sections relate the findings for analysis of a recirculation line break in a Mk-I containment, both with and without containment sprays. In these analyses, all steam lines are intact and the breach to the drywell is via the broken recirculation line. The analyses without drywell sprays are presented in Figure 2-27 through Figure 2-34, and the case with drywell sprays are summarized in Figure 2-35 through Figure 2-42. The general characteristics of RLB analyses are similar to the MSLB analyses except for some timing differences in core degradation and vessel failure. A comparison of Figure 2-31 with Figure 2-39 showing CsI concentrations in the steam dome, drywell and wetwell spaces show that steam dome concentrations are again higher than drywell concentrations for both cases with and without drywell sprays, except for brief periods where intense vessel steaming temporarily clears the vessel and steam dome volumes – at these times steam dome and drywell concentrations are similar. Figure 2-43 again summarizes the effect of drywell sprays on the steam dome and drywell aerosol concentrations. Sprays have no appreciable effect on the steam dome concentrations during the first 2 hours of the RLB accident, but after 2 hours, the steam dome concentrations are reduced by about an order of magnitude for the case with sprays, although still an order of magnitude higher than the drywell concentration.

In conclusion, after 2 hours drywell sprays do seem to reduce the steam dome concentrations relative to the no-spray cases; however the steam dome concentrations remain above the drywell concentration in either case.

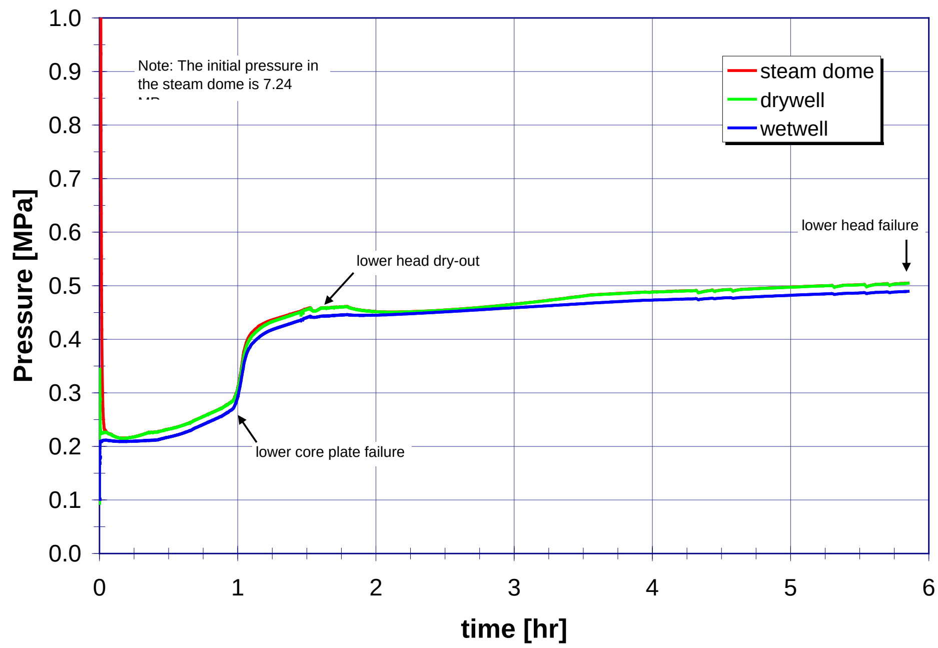


Figure 2-27 BWR Mk-I, RLB, No Sprays: Steam Dome, Drywell, and Wetwell Pressure

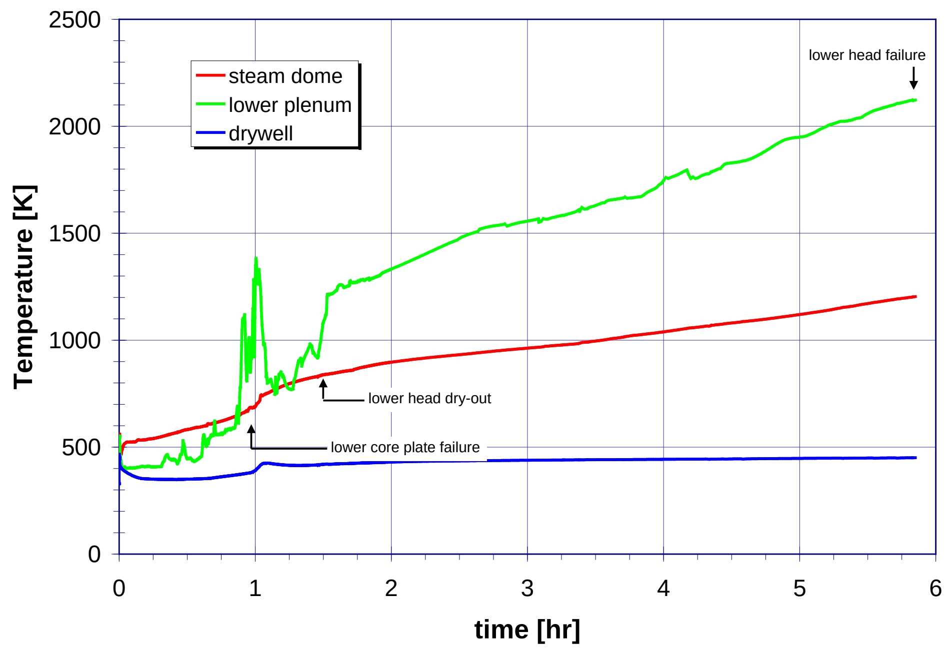


Figure 2-28 BWR Mk-I, RLB, No Sprays: Steam Dome, Drywell, and Lower Plenum Vapor Temperature

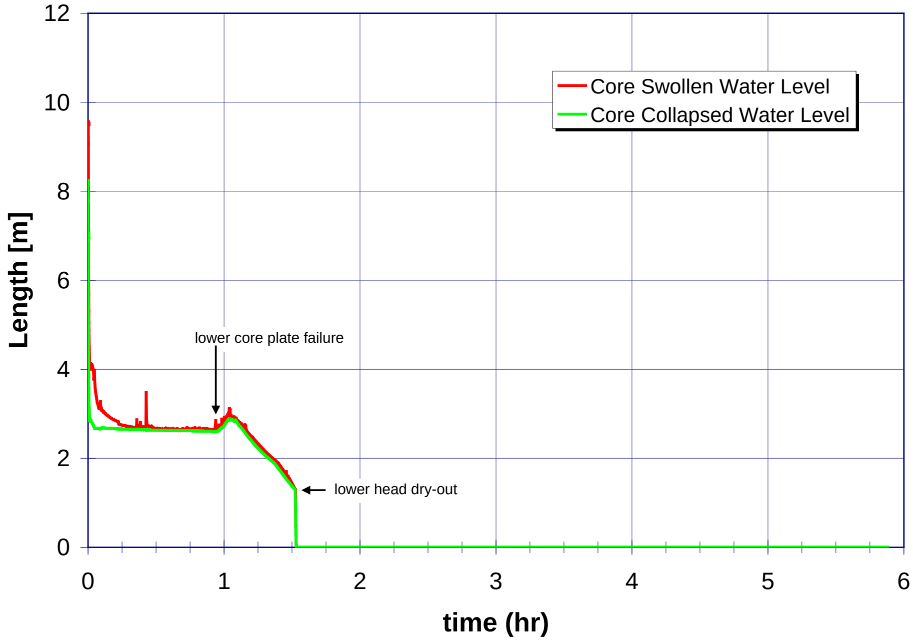


Figure 2-29 BWR Mk-I, RLB, No Sprays: Core Water Levels

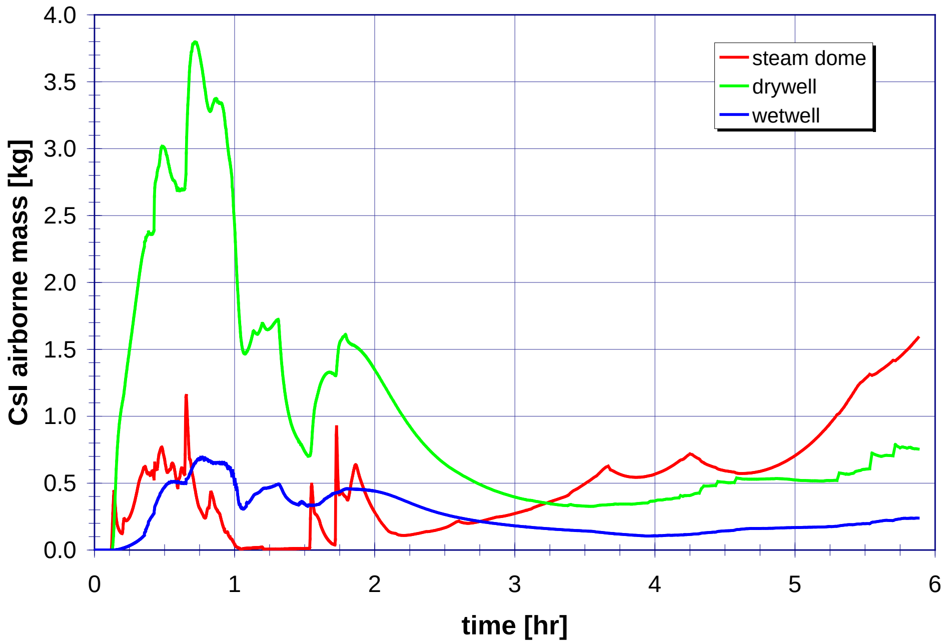


Figure 2-30 BWR Mk-I, RLB, No Sprays: CsI Mass in the Steam Dome, Drywell, and Wetwell

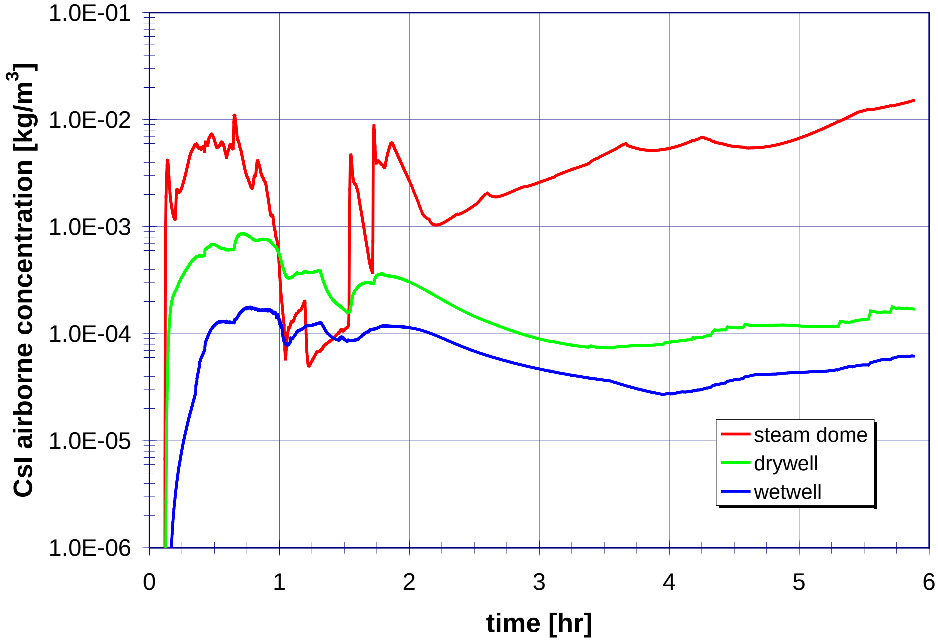


Figure 2-31 BWR Mk-I, RLB, No Sprays: CsI Concentration in the Steam Dome, Drywell, and Wetwell

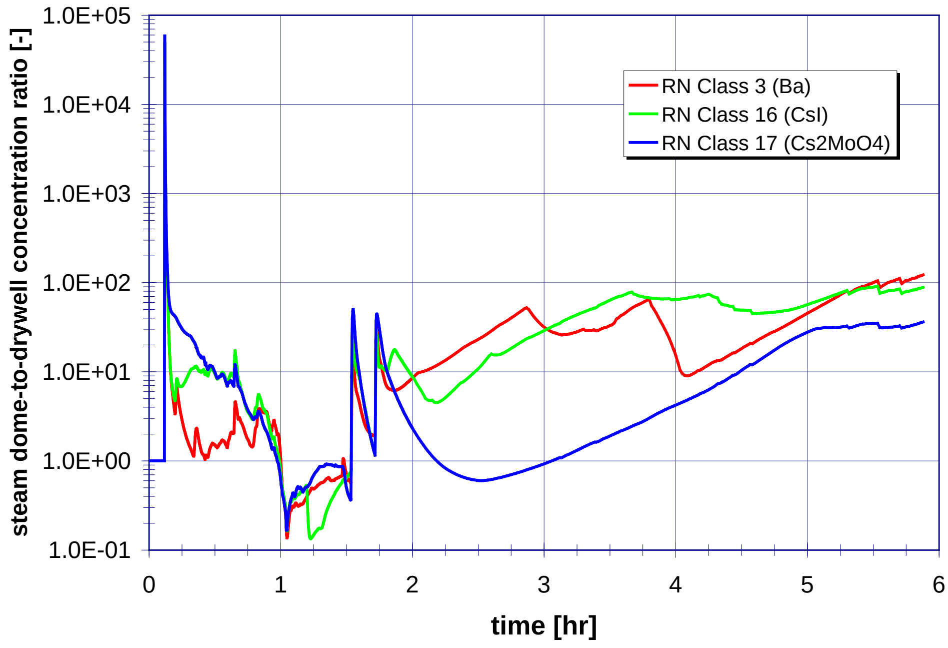


Figure 2-32 BWR Mk-I, RLB, No Sprays: Steam Dome-to-Drywell Concentration Ratios

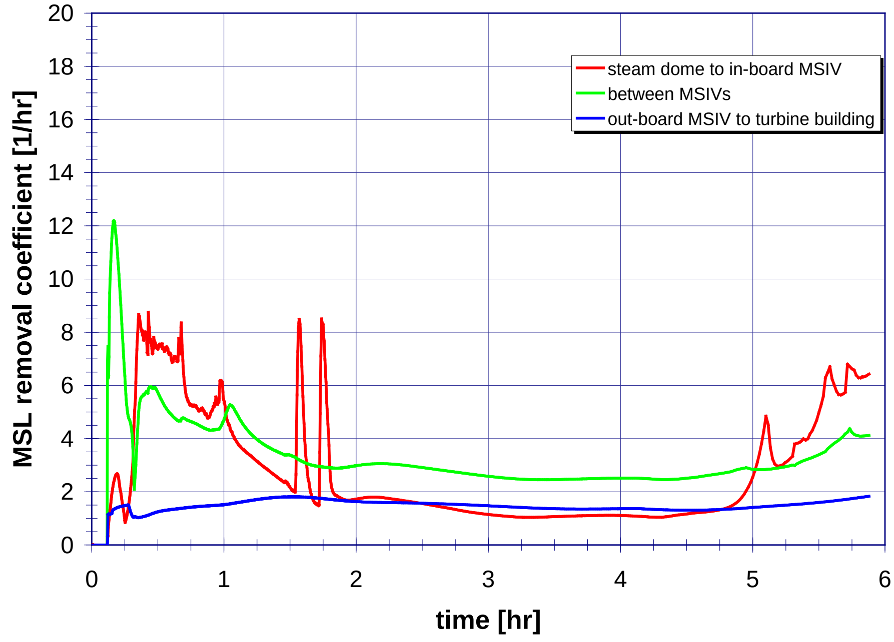


Figure 2-33 BWR Mk-I, RLB,, No Sprays: MSL-A Removal Coefficients

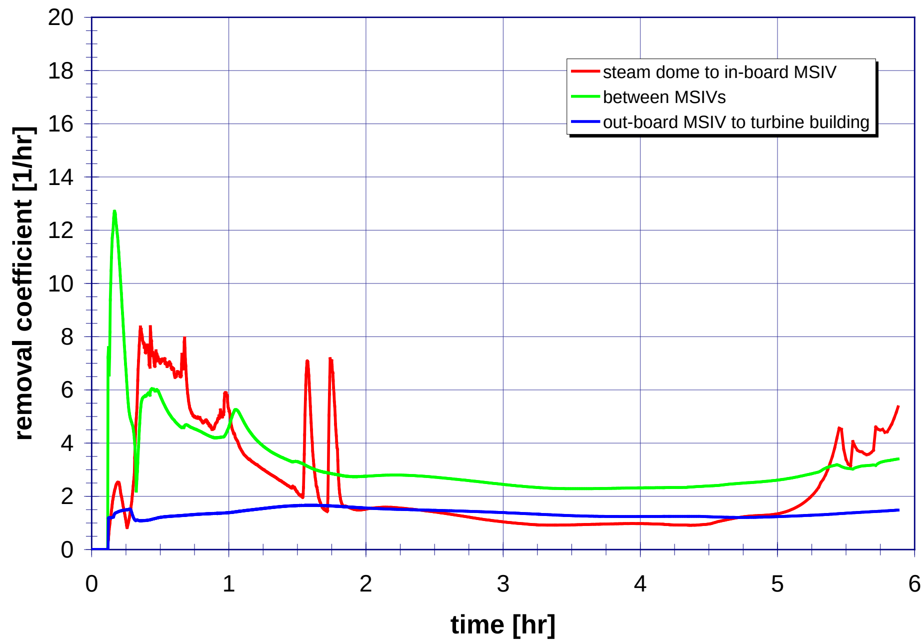


Figure 2-34 BWR Mk-I, RLB, No Sprays: MSL-B Removal Coefficients

2.2.4 Mk-I RLB, Sprays

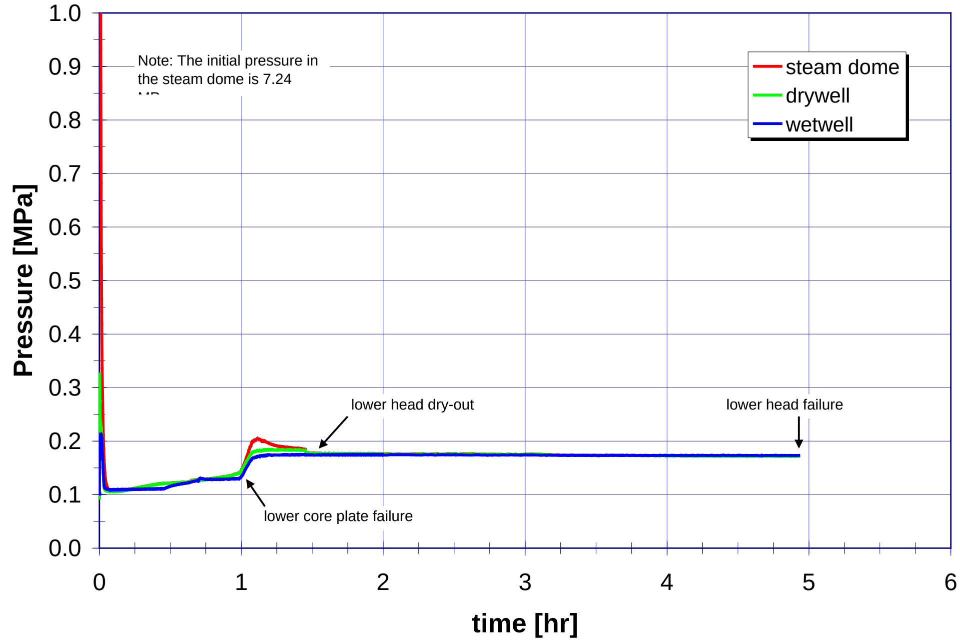


Figure 2-35 BWR Mk-I, RLB, Sprays: Steam Dome, Drywell, and Wetwell Pressure

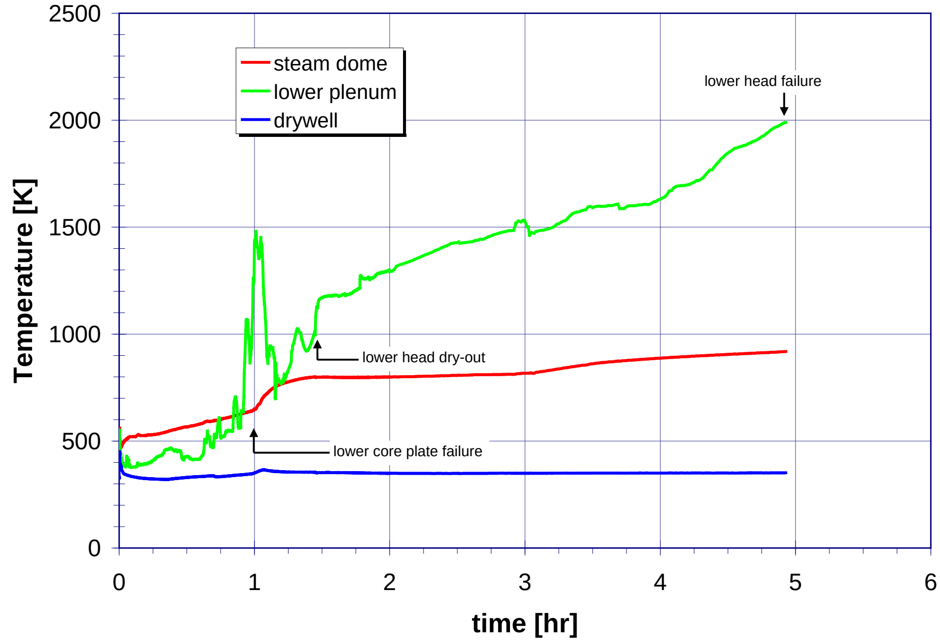


Figure 2-36 BWR Mk-I, RLB, Sprays: Steam Dome, Drywell, and Lower Plenum Vapor Temperature

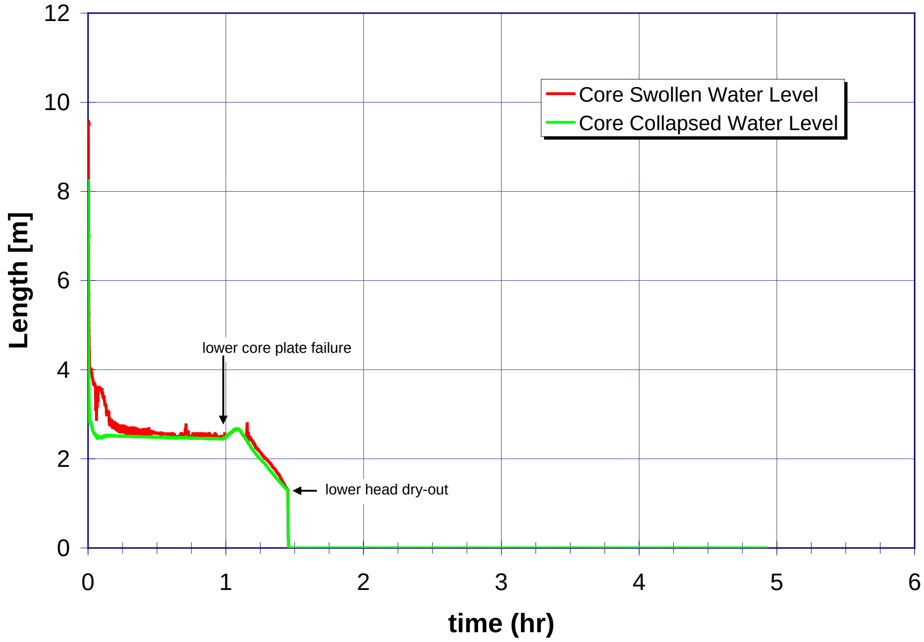


Figure 2-37 BWR Mk-I, RLB, Sprays: Core Water Levels

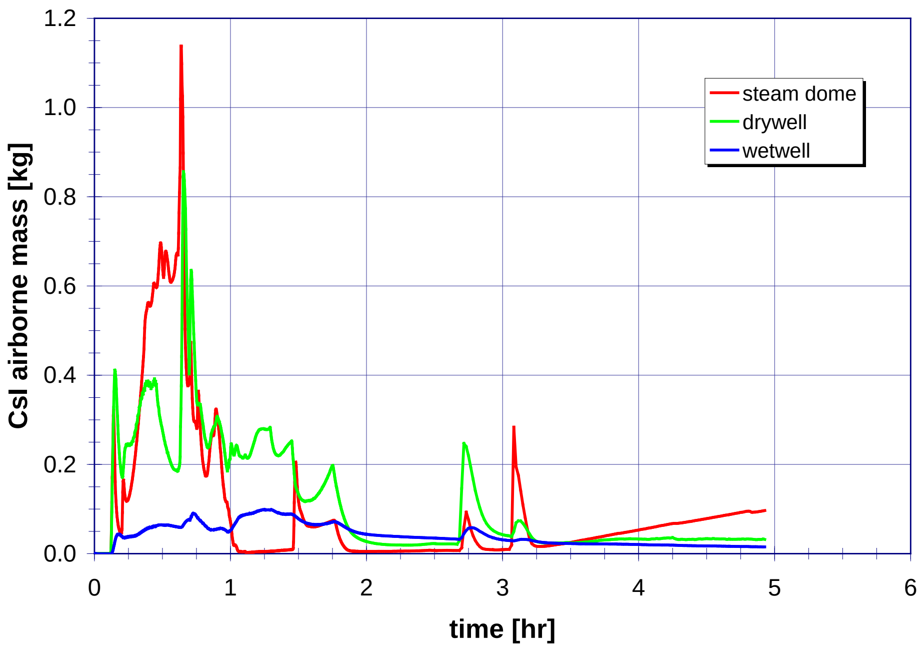


Figure 2-38 BWR Mk-I, RLB, Sprays: CsI Mass in the Steam Dome, Drywell, and Wetwell

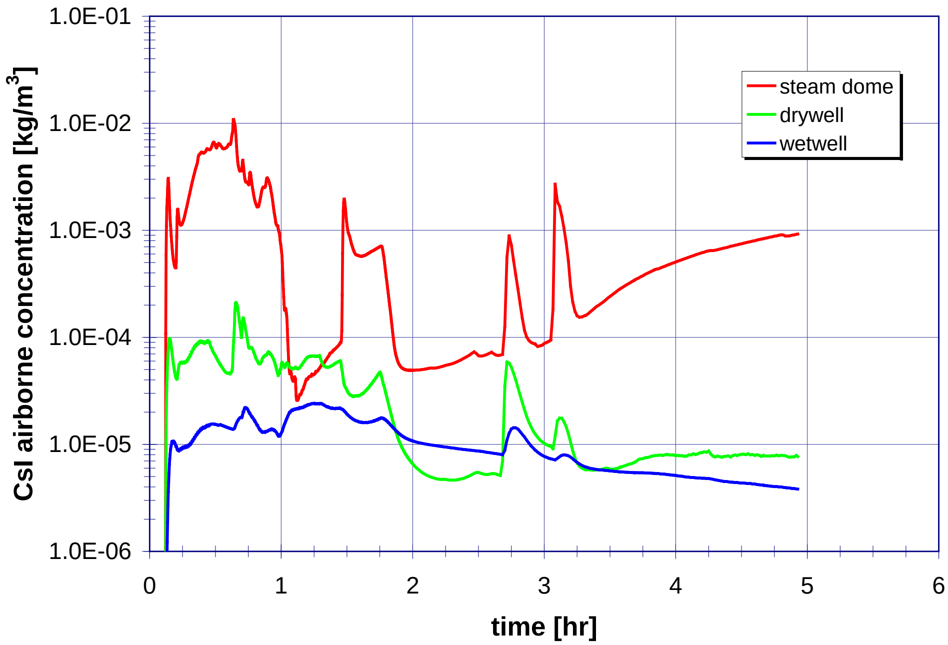


Figure 2-39 BWR Mk-I, RLB, Sprays: CsI Concentration in the Steam Dome, Drywell, and Wetwell

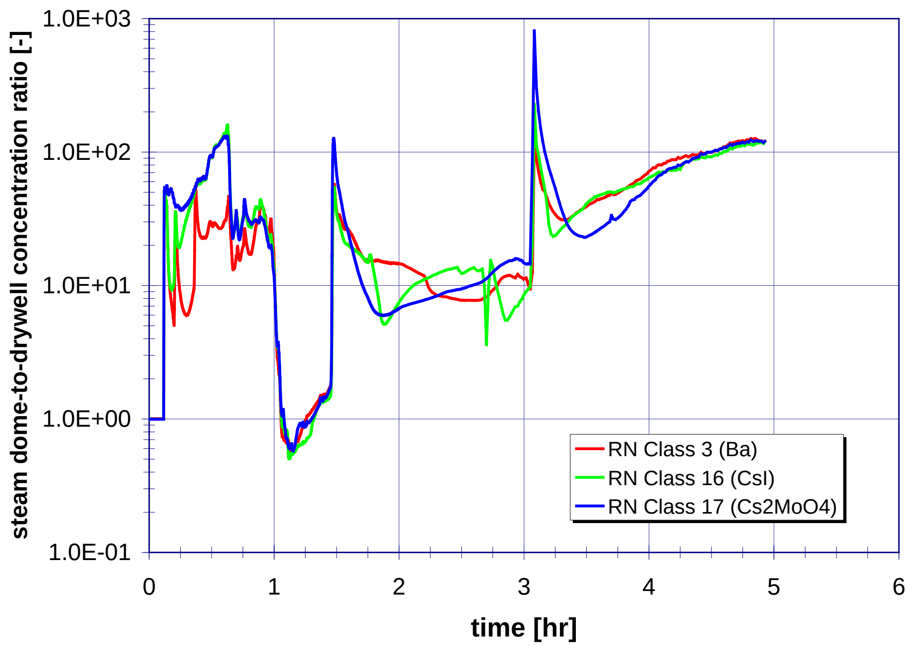


Figure 2-40 BWR Mk-I, RLB, Sprays: Steam Dome-to-Drywell Concentration Ratios

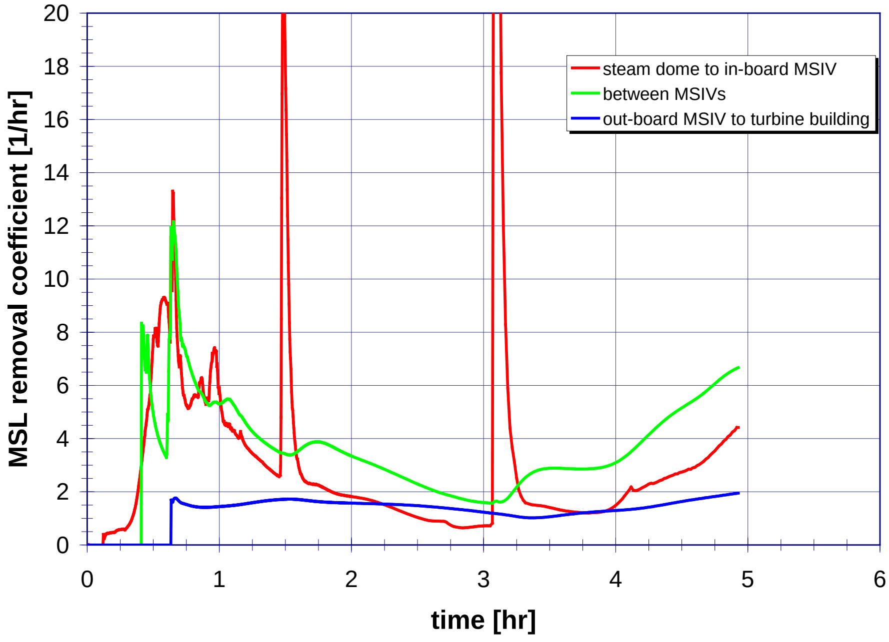


Figure 2-41 BWR Mk-I, RLB, Sprays: MSL-A Removal Coefficients

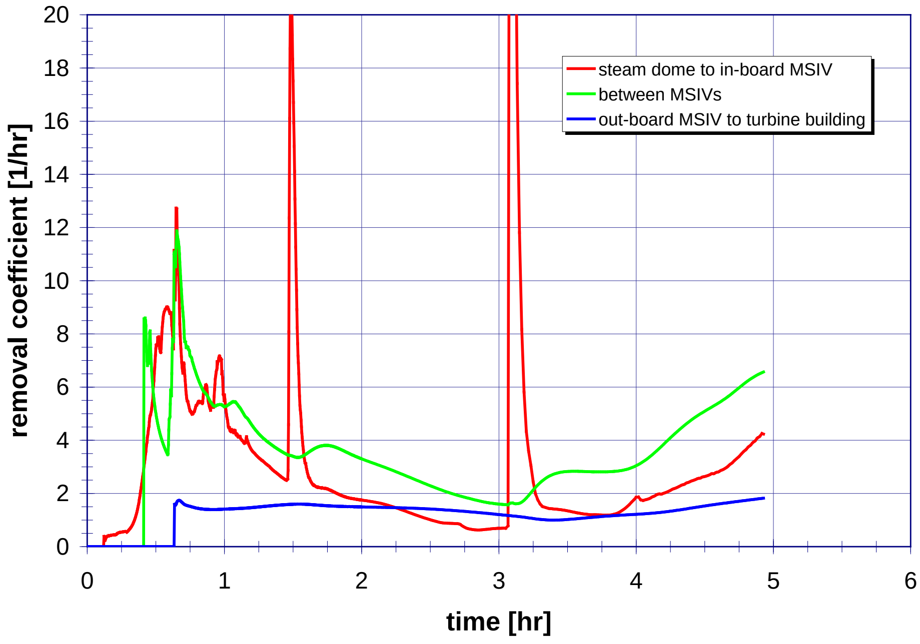


Figure 2-42 BWR Mk-I, RLB, Sprays: MSL-B Removal Coefficients

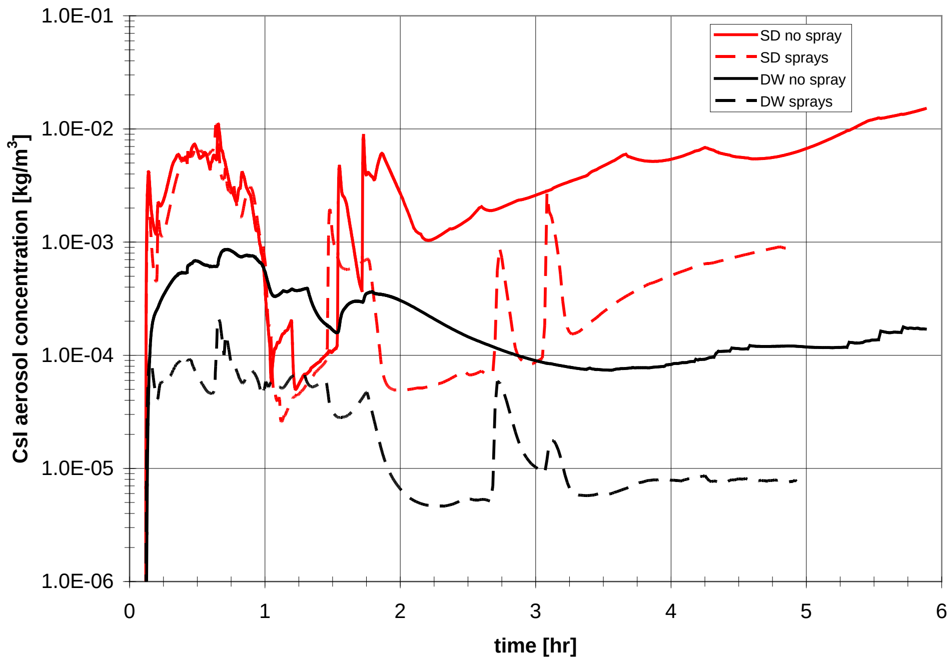


Figure 2-43 BWR Mk-I, RLB, Comparison of CsI Aerosol Steam Dome and Drywell Concentrations with and without Sprays

2.2.5 Evaluation of Post-Reflood Conditions: Effect on Deposition in Steam Lines

One MELCOR analysis for the Mk-III plant was dedicated to including vessel reflood just prior to lower head failure. The purpose of this analysis was to assess deposition processes, in addition to aerosol and thermal hydraulic behavior, after reflood in order to provide guidance for RADTRAD calculations during this time period. Figure 2-44 shows that the airborne mass in the vessel drops by several orders of magnitude following vessel reflooding, while airborne masses in the drywell and wetwell are not significantly altered from their pre-reflood trends. This happens because the core steaming during reflood advects airborne fission products in the reactor vessel into the drywell region and core reflooding terminates any addition fission product source addition from the core. This strongly suggests that following vessel reflooding, that the aerosol concentration in the drywell may be conservatively used as the source to assess MSIV leakage since most airborne activity following reflooding has been transported to the drywell by the escaping steam. At 6639.2 ft^3 the MK-III steam dome volume is approximately 40 times smaller (volume ratio of 0.02459) than the drywell volume. These values can be used to compare the relative fission airborne fission product concentrations provided in this figure.

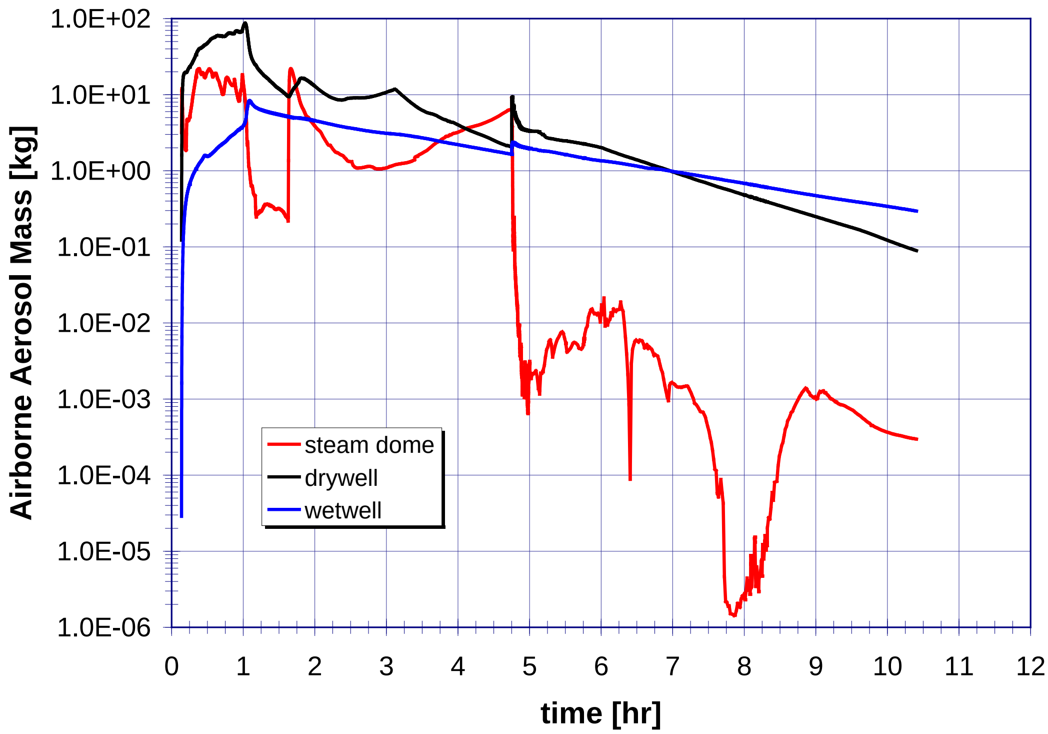


Figure 2-44 BWR Mk-III, RLB, Aerosol airborne mass before and after vessel reflooding.

Figure 2-45 shows the depletion behavior in the first few hours following vessel reflooding. Immediately after reflooding, the removal coefficient (lambda) for the intermediate steam lines is approximately 2.7 hr^{-1}, diminishing to a value of about 1 hr^{-1} after 6 hours. The removal coefficient prior to reflood is quite similar to the earlier analyses presented in this chapter; however, after reflood, the removal coefficient drops owing to the decreasing particle size in the hours following termination of the core source term. Recall that the ongoing pre-reflood core source of aerosols supported a quasi-steady large-diameter component to the vessel aerosol size distribution; after termination of this source, the large particles quickly fall out, leaving only smaller particles and a correspondingly smaller value for the removal coefficient – on the order of 1.0 hr^{-1}.

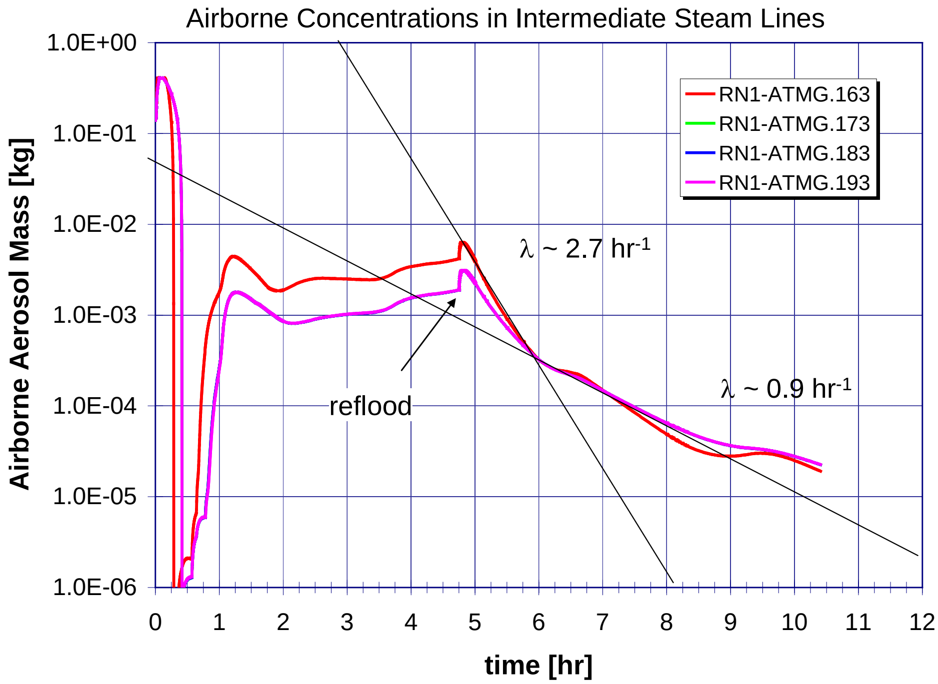


Figure 2-45 Depletion behavior in intermediate steam lines before and after vessel reflooding.

3 MELCOR Main Steam Line Uncertainty Analyses of Removal Coefficients

The results of the MELCOR full plant analyses presented in Section 2 of this report provide information for select DBA sequences for the Mk-I and Mk-III containment designs giving guidance on airborne concentrations in the steam dome and drywell regions as well as their ratio. Other information concerning calculated removal coefficients in the steam dome and steam lines for those analyses were also presented.

A further objective of this study was to explore the potential variability of the removal coefficients as affected by uncertainties in aerosol physics, variability in valve leak area and variances between plant designs in the lengths of steam line piping. In order to estimate these variances, a Monte Carlo method was used to sample over uncertainty distributions estimated for the key uncertain parameters. Since the full fidelity MELCOR model for these plants requires many days of computer execution time, and sample sizes of 150 were desired in order to obtain 95% confidence in the 95th percentile, a faster-running model was developed to explore these uncertainties.

This was done by building a model that consisted of only the reactor steam dome volume, the steam lines, MSIV's and condenser, as shown in Figure 3-1 below. Results from the full reactor MELCOR models (e.g., T-H, airborne radionuclide mass, post-reflood T-H conditions) are used as the boundary conditions to "drive" the MSL-only model such that identical environmental conditions with the full plant MELCOR analysis are maintained in the steam dome volume. It should be pointed out that the MELCOR full plant analyses were calculated out to about 5 hours, whereas the uncertainty analyses performed using the simplified nodalization were calculated out to 24 hours. For the time period beyond 5 hours, the MELCOR thermal hydraulic boundary conditions to the steam dome were held constant, and the aerosol source was terminated to approximate the anticipated effects of reflooding which would effectively cease releases from the core. The residual airborne aerosols in the steam dome after this time are allowed to deplete by gravitational settling.

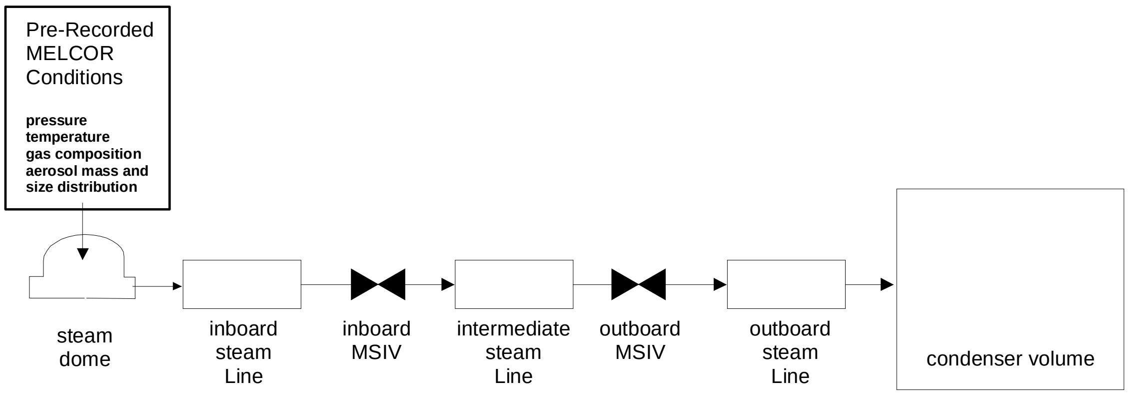


Figure 3-1 Simpified MELCOR model of steam line geometry using full plant model thermal-hydraulic and aerosol sources.

Three separate uncertainty analyses were performed with the Mk-I, MSL model (no sprays, with condenser) using steam dome conditions recorded from the Mk-I RLB scenario described earlier in section 2.2.3. These analyses separately looked at uncertainty in aerosol physics parameters, potential variability in horizontal MSL pipe lengths, and uncertainty in MSIV leakage.

3.1 Aerosol Physics Uncertainties

The following aerosol physics parameters were considered as uncertain in the MSL-only analyses. These are aerosol physics parameters in the MELCOR MAEROS models which affect aerosol settling rate, agglomeration rate and deposition processes. Their distributions were taken from aerosol deposition uncertainty analyses that were previously performed for AP1000 and ESBWR uncertainty analyses. The distributions and their rationale are provided in the following from an earlier report [8] addressing aerosol depletion behavior in the AP-1000 design certification activities. The distributions used to characterize parameter uncertainty were selected based on engineering judgment relative to the degree of certainty held by the authors and, where considerable uncertainty existed, uniform or log-uniform distributions were used.

3.1.1 Chi and Gamma: Aerosol Dynamic and Agglomeration Shape Factors

Both of these parameters were considered to be the same value, and were represented with a non-symmetric Beta distribution as shown in Figure 3-2.

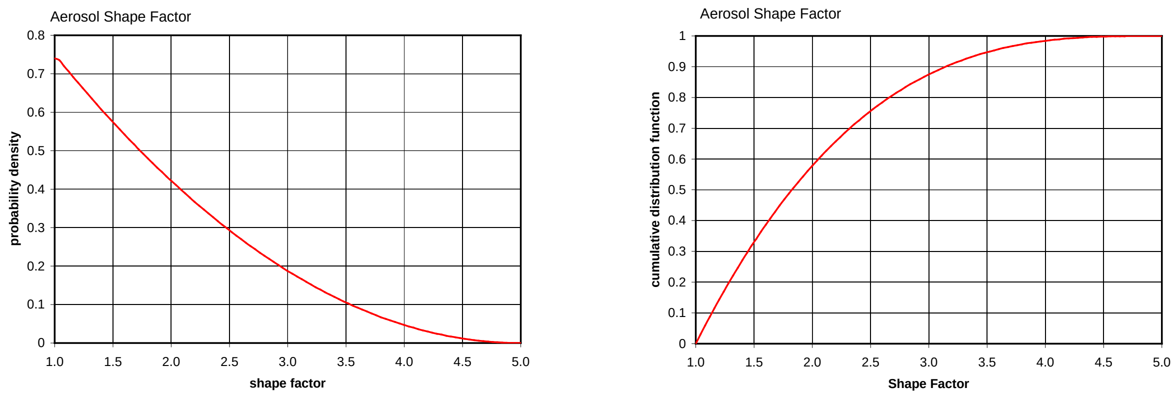


Figure 3-2 Distribution for Chi and Gamma: Dynamic and agglomeration aerosol shape factors.

The particular selection of P and Q (p=1,q=3) produced a distribution that was biased towards 1.0, with diminishing likelihood for Chi and Gamma as the limit of 5 is approached. This specification expresses the belief that the shape factor lies closer to the range of 1 to 3 with diminishing likelihood of having values approaching 5. The lower bound of 1.0 represents perfectly spherical aerosol particles and the upper bound of 5 represents chains of particles. It is rationalized that hygroscopic effects will induce some condensation of moisture on the particles causing the particles to tend towards being spherical and limiting the degree of non-spherical shape.

3.1.2 FSlip: Particle Slip Coefficient in Cunningham Formula

The factor FSlip introduces a correction to the Cunningham slip factor. Its default value in MELCOR is 1.257. Without further justification, since this parameter in MELCOR was specified to 3 places of accuracy, the uncertainty band for this parameter was restricted to lie between 1.2 and 1.3, or roughly a +/- 5% variation, using a Beta distribution as shown in Figure 3-3. The form of the Cunningham factor is shown below.

$$C_m = 1 + \frac{2\lambda}{d_p}\left[F_{slip} + 0.4\exp\left(-1.1 d_p / 2\lambda\right)\right] \tag{3.1}$$

where

λ = mean free path of air at 298 K (~ 0.069 • 10^{-6}m)
F_{slip} = slip factor specified on Input Record RNMS000 (default value of 1.257)
d_p = the particle diameter (m)

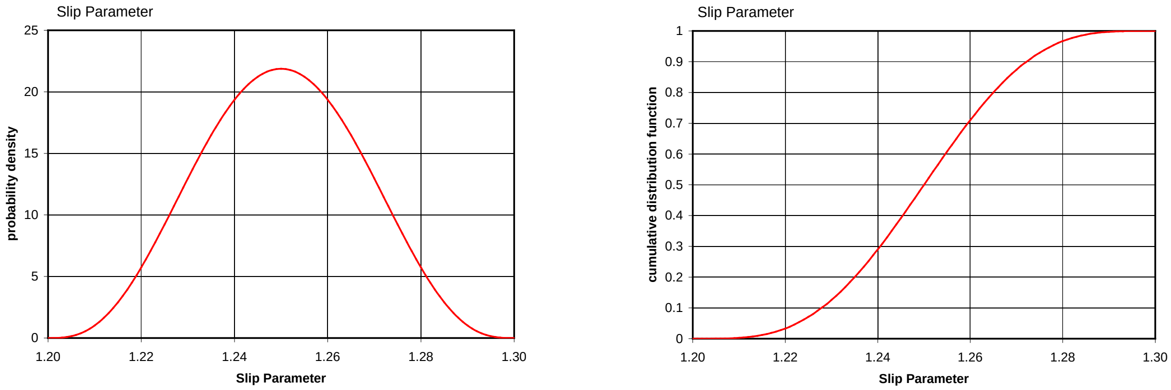


Figure 3-3 FSlip: factor for the Cunningham correction factor.

The Cunningham factor appears in the gravitational settling term,

$$v_{grav} = \frac{d_p^2 \rho_p g C_m}{18 \mu \chi} \tag{3.2}$$

where

v_{grav}	= the downward terminal velocity (m/s)
d_p	= the particle diameter (m)
ρ_p	= the particle density (kg/m^3)
g	= acceleration of gravity = 9.8 m/s^2
C_m	= the particle mobility, or Cunningham slip correction factor, which reduces the Stokes drag force to account for noncontinuum effects.
μ	= viscosity of air at 298 K [~ 1.8 ● 10^5(N ● s/m^2)]
χ	= dynamic shape factor

The factor FSlip also appears in the thermophoretic deposition formulation in MELCOR, discussed later.

3.1.3 Fstick – Sticking probability for Agglomeration

The rate of agglomeration is affected by the probability that a collision between two particles results in the two particles actually sticking together. Often this factor is taken as 1.0; however, this may depend on the wetness of the particles and could be influenced by electrostatic phenomena; like-charged particles that might otherwise collide and stick may instead fail to collide as their distance of separation closes. The uncertainty for this parameter was specified as shown in Figure 3-4 using a Beta distribution (p=2.5, q=1) where values nearer to 1.0 are favored. The median value for the sticking probability is 0.88.

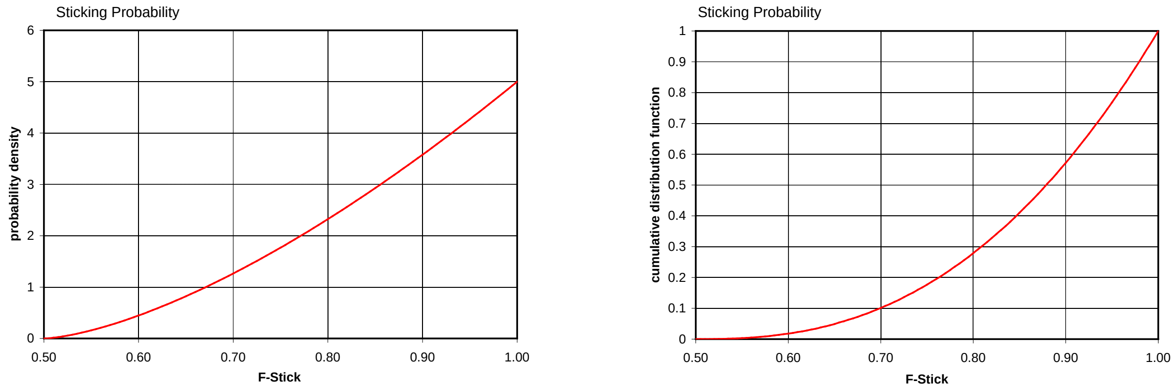


Figure 3-4. Fstick: agglomeration sticking probability.

3.1.4 Boundary layer thickness for Diffusion Deposition:

The boundary layer thickness used in calculating the deposition by diffusion is nominally specified in MELCOR as 10 micrometers as used in the following expression for Brownian deposition velocity:

$$v_{diff} = \frac{k\,T\,C_m}{3\pi\;\mu\;\chi\;d_p\Delta} \tag{3.3}$$

where

v_{diff}	=	diffusion deposition velocity (m/s)
k	=	Boltzmann constant = $1.38 \bullet 10^{-7}$ (J/K)
T	=	atmosphere temperature (K)
μ	=	viscosity ($N \bullet s/m^2$)
χ	=	dynamic shape factor (CHI)
Δ	=	user-specified diffusion boundary layer thickness specified on Input Record RNMS000 (default value of 10^{-5} m)
C_m	=	Cunningham correction factor

In this uncertainty analysis, this value was considered uncertain between the limits of 5 and 20 micrometers, distributed uniformly as shown in Figure 3-5.

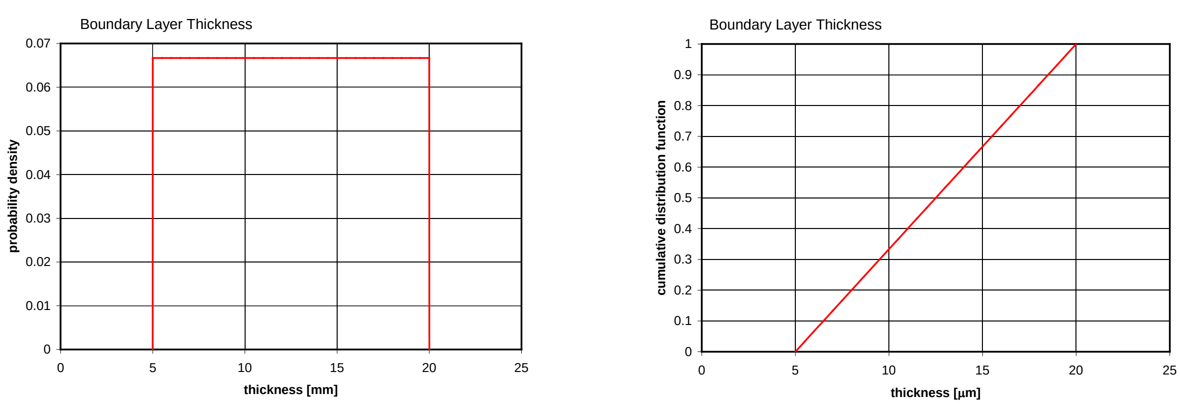


Figure 3-5. DELDF: Diffusion boundary layer thickness.

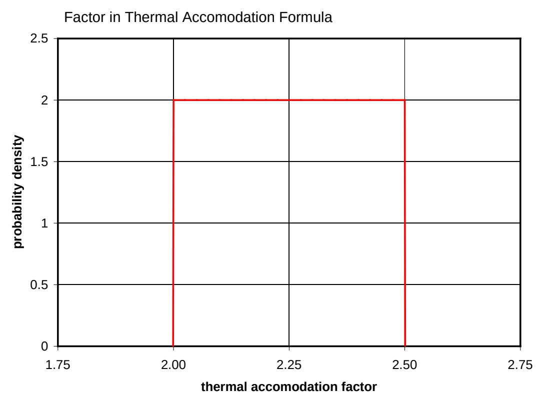
3.1.5 Thermal Accommodation Coefficient for Thermophoresis

The thermal accommodation coefficient in the expression for thermophoretic deposition velocity is accessible in MELCOR via the factor c_t as shown in the equation below
.

$$v_{therm} = \frac{3\,\mu\,C_m\left(c_t\,Kn + k_{gas}/k_p\right)}{2\ \chi\ \ \rho_{gas}\,T\left(1+3\,F_{slip}Kn\right)\left(1+2\,c_t\ Kn + k_{gas}/k_p\right)}\ \nabla T \qquad (3.4)$$

K_n = $2\lambda/d_p$ (Knudsen number)
k_{gas}/k_p = ratio of thermal conductivity of gas over that for aerosol particle and is user-specified (on Input Record RNMS000) – also uncertain in this study
∇T = structure surface temperature gradient (K/m)
ρ_{gas} = gas density (kg/m^3)
T = wall temperature (K)
F_{slip} = slip factor
c_t = constant associated with the thermal accommodation coefficients (specified on Input Record RNMS000 with default value of 2.25)

This coefficient, c_t, was considered uncertain between the limits of 2.0 and 2.5 using a uniform distribution as shown in Figure 3-6 based on the precision of the default value at two decimal places.



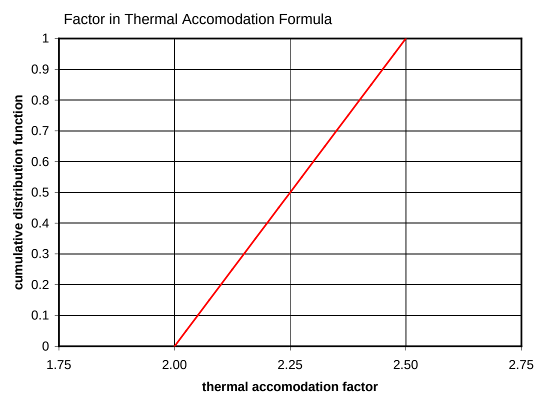


Figure 3-6 Thermal accommodation coefficient in thermophoretic deposition.

3.1.6 Ratio of Thermal Conductivity of particle to gas: TKGOP

Also appearing in the formulation for thermophoretic deposition is the ratio of gas to aerosol particle thermal conductivity, nominally specified in MELCOR as 0.05. This factor is treated as uncertain between the limits of 0.006 and 0.06, based on an inspection of the conductivity of gases (steam, H_2) and aerosol (UO_2, Ag). The range was taken to be distributed log-uniformly owing to the wide range of possible values for this parameter.

Also appearing in the thermophoretic deposition formulation is the factor FSlip, discussed previously in the description of the Cunnningham factor.

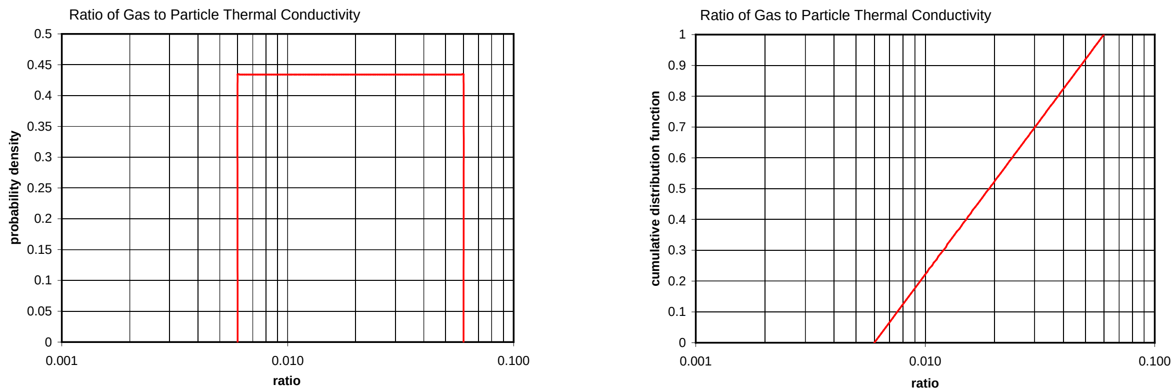


Figure 3-7. TKGOP - Ratio of gas to particle thermal conductivity.

3.1.7 Turbulent Energy Dissipation Factor: TURBDS

The turbulent energy dissipation factor, [default 0.001 m^2/s^3] appears in the agglomeration coefficients in the turbulent shear and turbulent inertial terms [9]. This factor was considered uncertain at +/- 25% as shown in Figure 3-8. A uniform distribution was used with limits between 0.00075 and 0.00125.

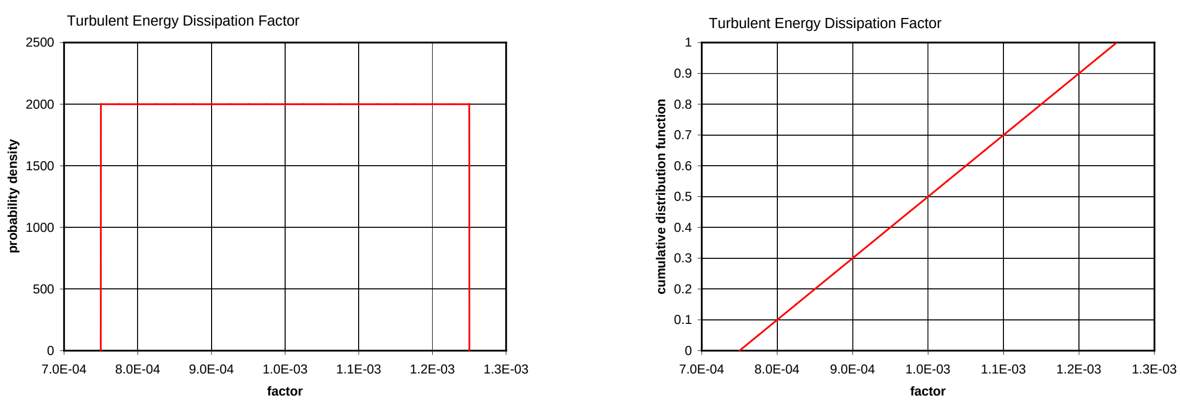


Figure 3-8. Turbulent energy dissipation factor: TURBDS

3.1.8 Multipliers on Heat Transfer and Mass Transfer

The heat and mass transfer coefficients in MELCOR affect the rate of steam condensation, which in turn has a strong effect on the diffusiophoretic deposition calculated for the airborne aerosol in deposition volumes. Since both heat and mass transfer is calculated in MELCOR from the same Nusselt number, we take these two parameters to be correlated. That is, a high heat transfer coefficient should be accompanied by a correspondingly high mass transfer coefficient. These scaling factors for the heat and mass transfer were taken to be roughly 25% above or below the nominal values calculated in MELCOR for the conditions in the containment atmosphere, with diminishing likelihood at the extremes of this range. This belief was represented using a Beta distribution with limits of 0.75 and 1.25, and p and q equal to1.5, as shown in Figure 3-9.

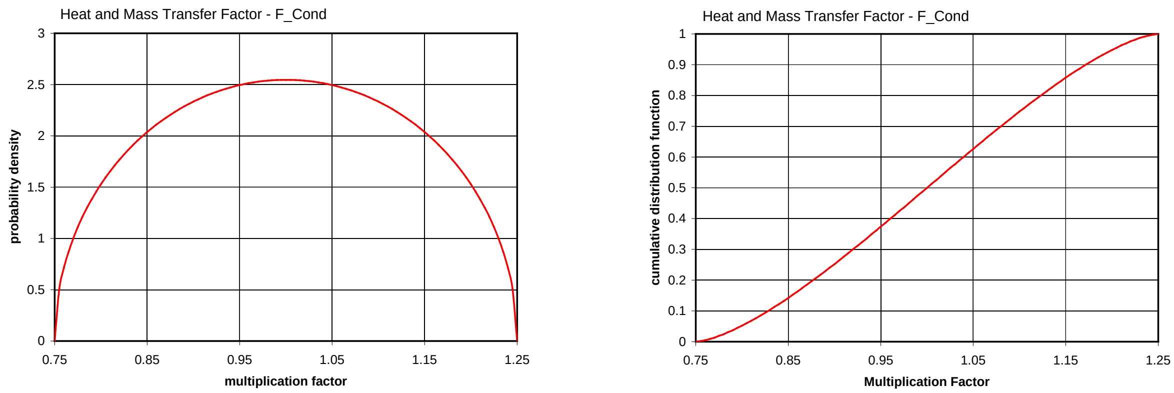


Figure 3-9. Multiplier to heat and mass transfer coefficients for containment shell.

3.1.9 Results of Uncertainty on Aerosol Physics

The aerosol physics parameters treated as uncertain are summarized in the following table. Each of these uncertain parameters was sampled independently (Monte Carlo) to form 150 separate MELCOR analyses. The valve leakage areas for the MSIVs in each loop were set to conform to the assumed leakages as described in 2.1.1. The instantaneous “lambda” values were calculated using the method described in Section 2.1.2 for each section of the MSL illustrated in Figure 3-1, and are displayed in Figure 3-10 through Figure 3-16.

Table 3-1 Aerosol Physics Uncertain Parameters

Aerosol Physics Parameter	Distribution[‡]
aerosol dynamic shape factor/collision factor (-)	Beta: p = 1.0; q = 1.5; min = 1.0; max = 5.0
diffusion boundary layer thickness (m)	Uniform: min = 0.000005; max = 0.0002
slip factor (-)	Beta: p = 4.0; q = 4.0; min = 1.2; max = 1.3
sticking probability (-)	Beta: p = 2.5; q = 1.0; min = 0.5; max = 1.0
thermal accommodation coefficient (-)	Uniform: min = 2.0; max = 2.5
thermal conductivity ratio (-)	log-uniform: min = 0.006; max = 0.06
turbulent dissipation rate	Uniform: min = 0.00075; max = 0.00125
mass transfer coefficient scaling factor (-)	Beta: p = 1.5; q = 1.5; min = 0.75; max = 1.25

[‡] p and q are the two shape parameters that define a beta distribution $f(x,p,q)=\dfrac{x^{p-1}\cdot(1-x)^{q-1}}{\int_0^1 u^{p-1}\cdot(1-u)^{q-1}du}$.

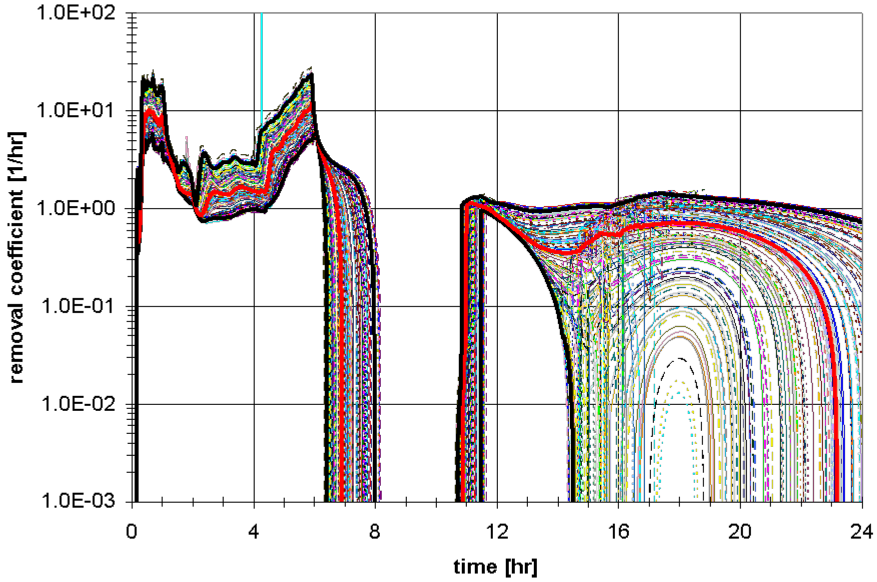


Figure 3-10 Mk-I RLB, Removal Coefficients with Aerosol Uncertainty, MSL-A, In-Board – no sprays, condenser

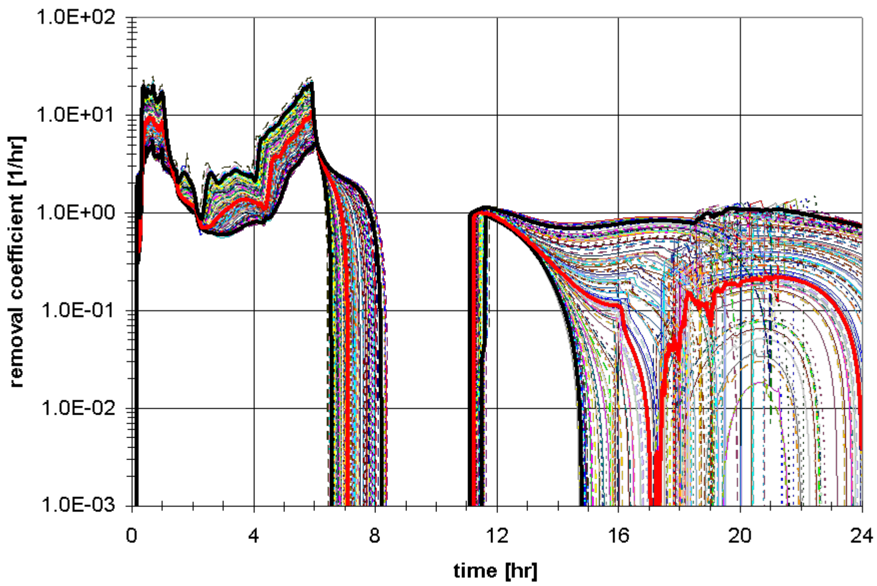


Figure 3-11 Mk-I RLB, Removal Coefficients with Aerosol Uncertainty, MSL-B, In-Board – no sprays, condenser

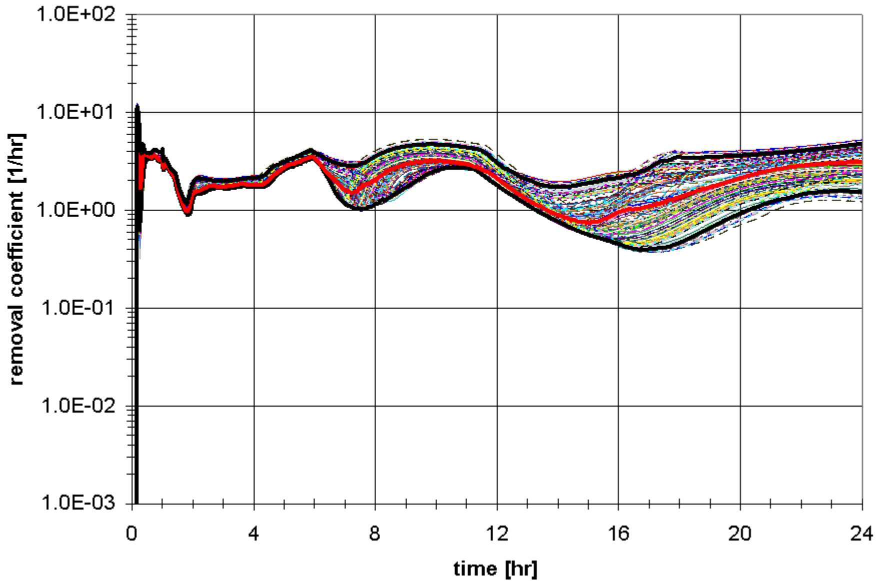


Figure 3-12 Mk-I RLB, Removal Coefficients with Aerosol Uncertainty, MSL-A, Between MSIVs – no sprays, condenser

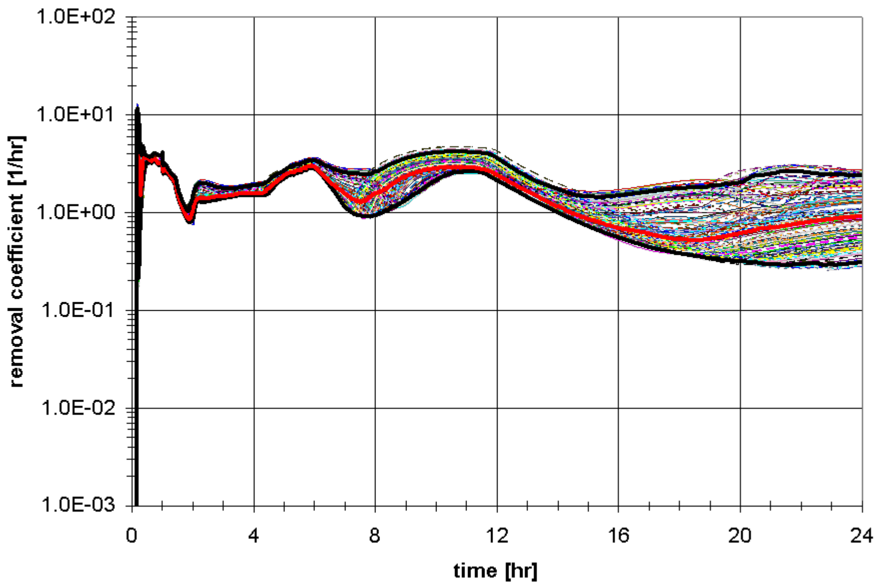


Figure 3-13 Mk-I RLB, Removal Coefficients with Aerosol Uncertainty, MSL-B, Between MSIVs – no sprays, condenser

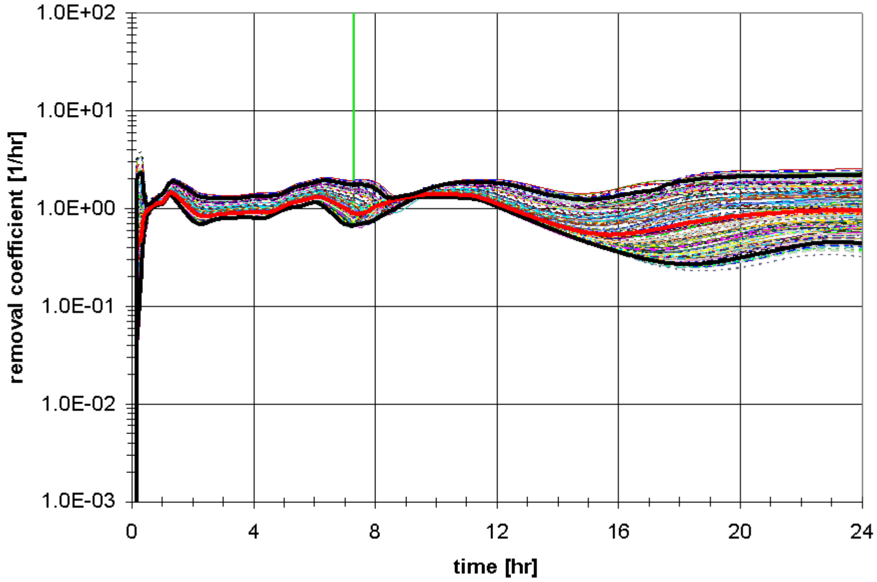


Figure 3-14 Mk-I RLB, Removal Coefficients with Aerosol Uncertainty, MSL-A, Outboard – no sprays, condenser

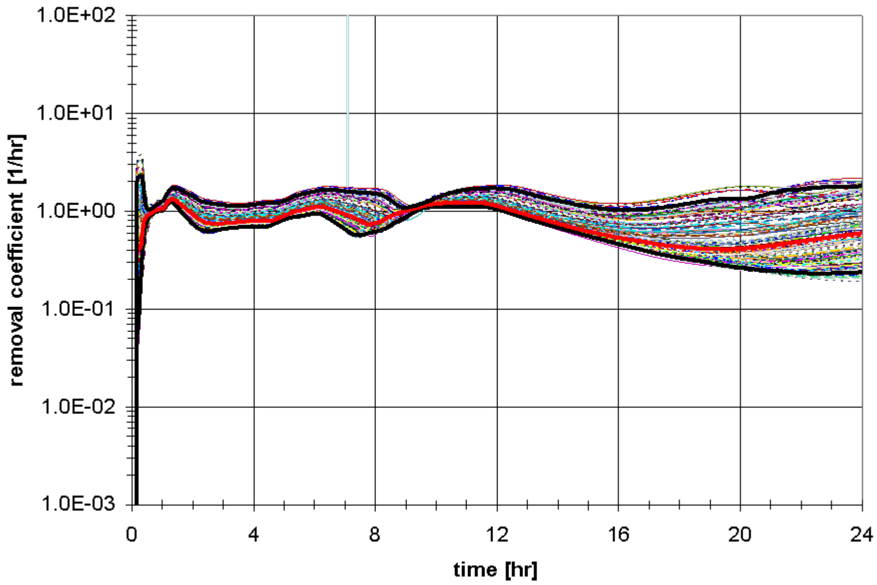


Figure 3-15 Mk-I RLB, Removal Coefficients with Aerosol Uncertainty, MSL-B, Outboard – no sprays, condenser

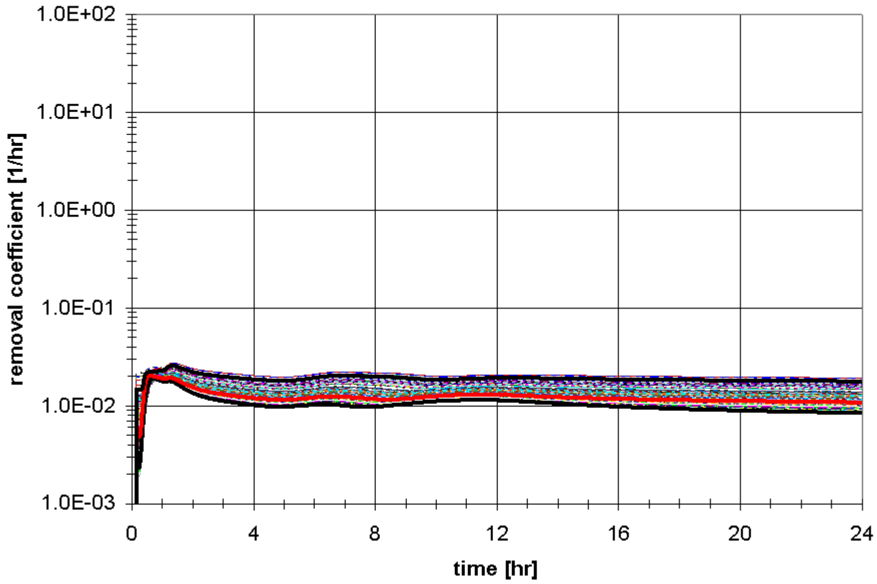


Figure 3-16 Mk-I RLB, Removal Coefficients with Aerosol Uncertainty, Condenser – no sprays, condenser

Table 3-2: Aerosol Uncertainty Analysis MSL and Condenser Removal Coefficients (5th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
MSL-A in-board	2.6	0.85	0.071
MSL-A between MSIVs	2.2	2.0	0.93
MSL-A out-board	0.87	0.99	0.44
MSL-B in-board	2.4	0.77	0.086
MSL-B between MSIVs	2.0	1.8	0.61
MSL-B out-board	0.82	0.84	0.43
condenser	0.014	0.011	0.010

note. removal coefficients are given in 1/hr

Table 3-3: Aerosol Uncertainty Analysis MSL and Condenser Removal Coefficients (50th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
MSL-A in-board	4.4	1.7	0.47
MSL-A between MSIVs	2.5	2.4	1.8
MSL-A out-board	1.0	1.1	0.78
MSL-B in-board	4.1	1.5	0.20
MSL-B between MSIVs	2.4	2.1	0.89
MSL-B out-board	0.94	0.97	0.57
condenser	0.016	0.012	0.012

note. removal coefficients are given in 1/hr

Table 3-4: Aerosol Uncertainty Analysis MSL and Condenser Removal Coefficients (95th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
MSL-A in-board	8.3	3.6	1.1
MSL-A between MSIVs	3.2	3.4	3.1
MSL-A out-board	1.5	1.6	1.8
MSL-B in-board	7.7	3.2	0.88
MSL-B between MSIVs	3.1	3.0	2.1
MSL-B out-board	1.4	1.4	1.4
condenser	0.021	0.019	0.018

note. removal coefficients are given in 1/hr

3.2 Uncertainty in MSIV Leakage Area

The current Mk-I MSIV leakage is calibrated at design leakage conditions. As discussed in Section 3.1.1, this is done by determining the MSIV flowpath open fraction that produces the design leakage at the design pressure. An analysis of uncertainty in MSIV flow was performed by varying the flowpath open fraction between 50% and 150% of the value set by the design leakage conditions. The nominal valve flows for each steam line are as described in Section 3.1.1 (valve A: 205 scfh, valve B 155 scfh). Both valve leak areas were varied in concert so that the minimum flow would correspond to ~75 scfh and the maximum flow would correspond to 410 scfh)

Table 3-5 MSIV Flow Uncertain Parameters

Parameter	Distribution
MSIV flowpath open fraction scaling factor	uniform min = 0.5; max = 1.5

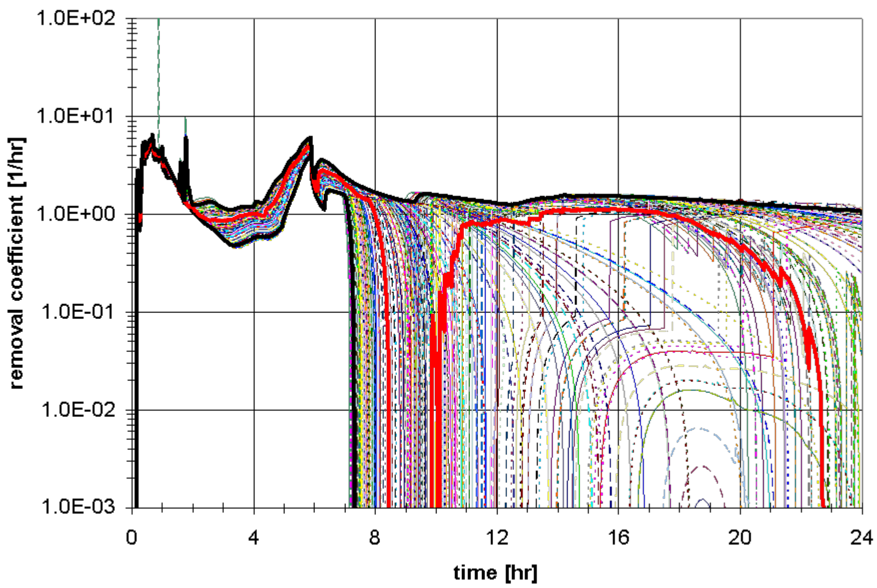


Figure 3-17 **Mk-I RLB, Removal Coefficients with Flow Uncertainty, MSL-A, in-board – no sprays, condenser**

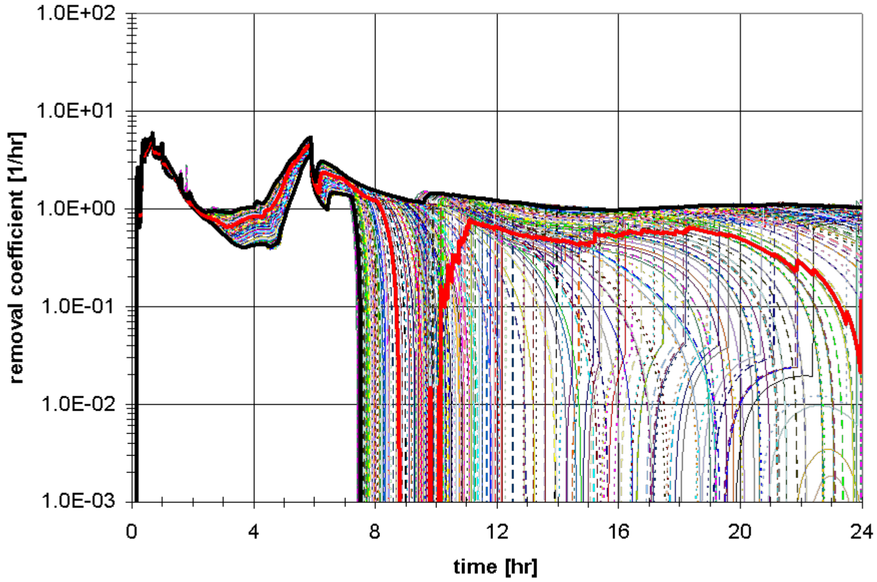


Figure 3-18 Mk-I RLB, Removal Coefficients with Flow Uncertainty, MSL-B, in-board – no sprays, condenser

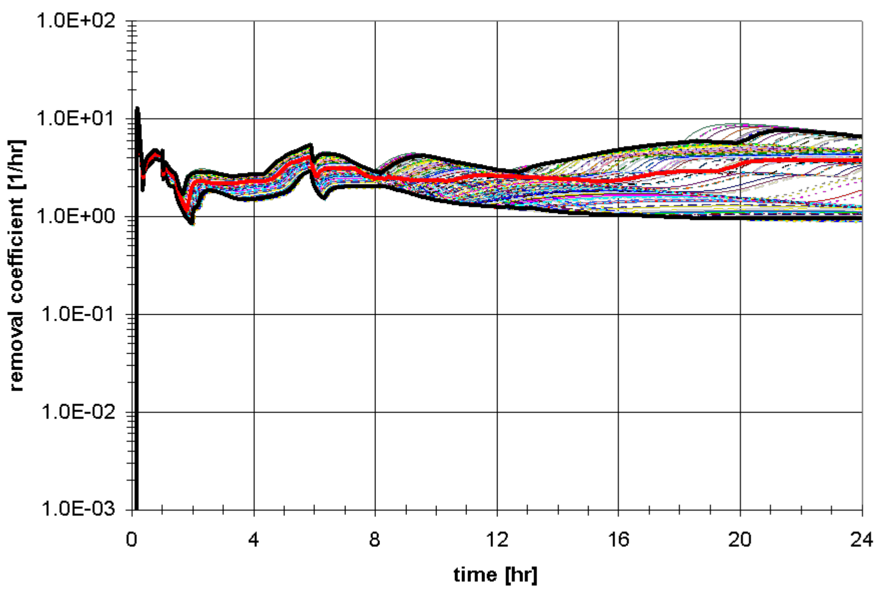


Figure 3-19 Mk-I RLB, Removal Coefficients with Flow Uncertainty, MSL-A, between MSIVs – no sprays, condenser

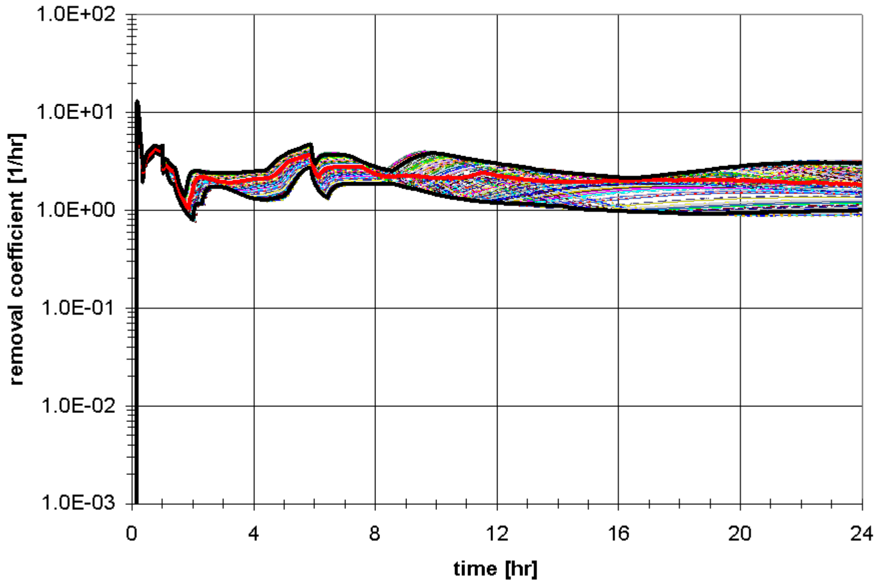


Figure 3-20 Mk-I RLB, Removal Coefficients with Flow Uncertainty, MSL-B, between MSIVs – no sprays, condenser

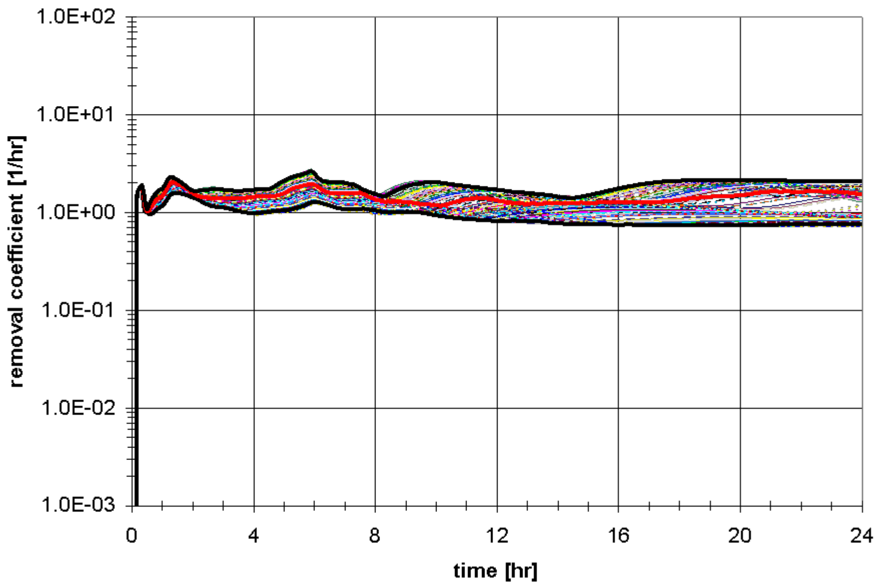


Figure 3-21 Mk-I RLB, Removal Coefficients with Flow Uncertainty, MSL-A, out-board – no sprays, condenser

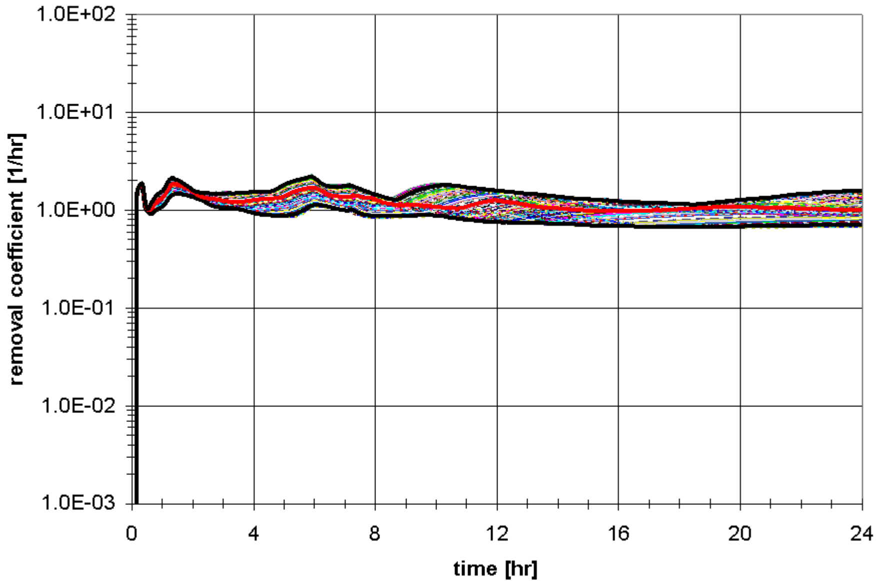


Figure 3-22 Mk-I RLB, Removal Coefficients with Flow Uncertainty, MSL-B, out-board – no sprays, condenser

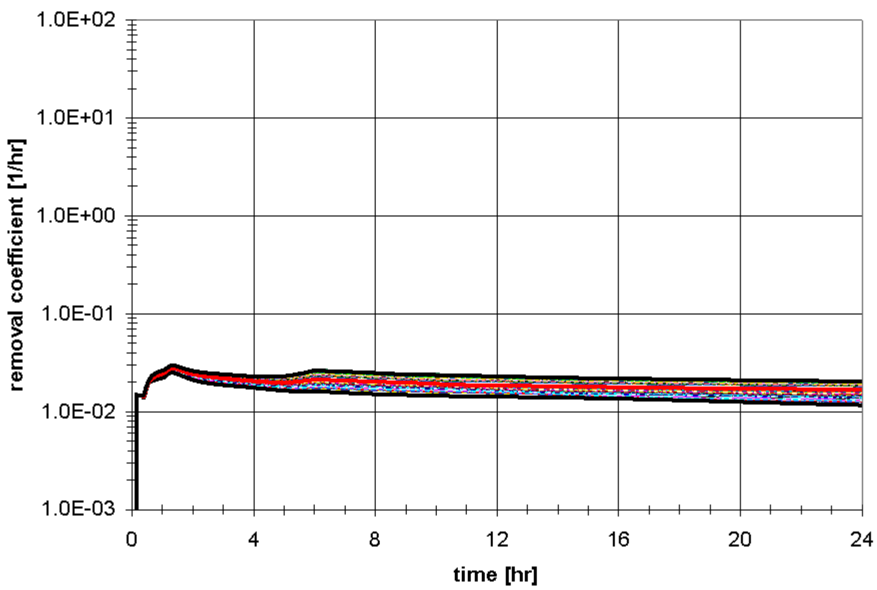


Figure 3-23 Mk-I RLB, Removal Coefficients with Flow Uncertainty, condenser – no sprays, condenser

Table 3-6: Flow Uncertainty Analysis MSL and Condenser Removal Coefficients (5th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
MSL-A in-board	2.5	0.60	0.0
MSL-A between MSIVs	2.8	1.7	1.0
MSL-A out-board	1.3	1.0	0.76
MSL-B in-board	2.4	0.56	0.0
MSL-B between MSIVs	2.7	1.6	1.0
MSL-B out-board	1.2	0.95	0.70
condenser	0.020	0.016	0.013

note. removal coefficients are given in 1/hr

Table 3-7: Flow Uncertainty Analysis MSL and Condenser Removal Coefficients (50th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
MSL-A in-board	2.8	1.2	0.68
MSL-A between MSIVs	3.2	2.6	3.0
MSL-A out-board	1.5	1.4	1.4
MSL-B in-board	2.6	1.1	0.44
MSL-B between MSIVs	3.1	2.4	2.0
MSL-B out-board	1.4	1.3	1.0
condenser	0.022	0.020	0.018

note. removal coefficients are given in 1/hr

Table 3-8: Flow Uncertainty Analysis MSL and Condenser Removal Coefficients (95th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
MSL-A in-board	3.2	1.9	1.4
MSL-A between MSIVs	3.6	3.5	5.5
MSL-A out-board	1.7	1.9	1.9
MSL-B in-board	2.8	1.7	1.1
MSL-B between MSIVs	3.4	3.2	2.6
MSL-B out-board	1.6	1.6	1.3
condenser	0.023	0.024	0.022

note. removal coefficients are given in 1/hr

3.3 Uncertainty in Horizontal Piping Segments

MSL piping lengths vary between the various BWR reactors in the US fleet. To account for this variation the horizontal MSL piping lengths were varied. The horizontal lengths were deemed to be more important than the vertical MSL pipe lengths as aerosol deposition primarily occurs on horizontal, rather than vertical, surfaces. Rather than attempt to build MSL horizontal pipe-length distributions from plant data, scaling factors were defined with sufficiently broad lower and upper bounds. The scaling factors are then used to vary the MSL horizontal pipe lengths. For example, if the in-board scaling factor is equal to 0.5, all of the in-board MSL horizontal pipe lengths are multiplied by 0.5 (i.e., reduced by 50%).

Table 3-9 Horizontal MSL Pipe Length Uncertain Parameters

Parameter	Distribution	Piping Length Distribution [m]	Nominal Piping Length [m]
in-board MSL horizontal length scaling factor	uniform min = 0.1 max = 2.0	uniform min = 1.28 max = 25.6634	12.8
between MSIVs MSL horizontal length scaling factor	uniform min = 0.1 max = 2.0	uniform min = 0.754 max = 15.08	7.54
out-board MSL horizontal length scaling factor	uniform min = 0.1 max = 2.0	uniform min = 8.41 max = 176.8	88.4

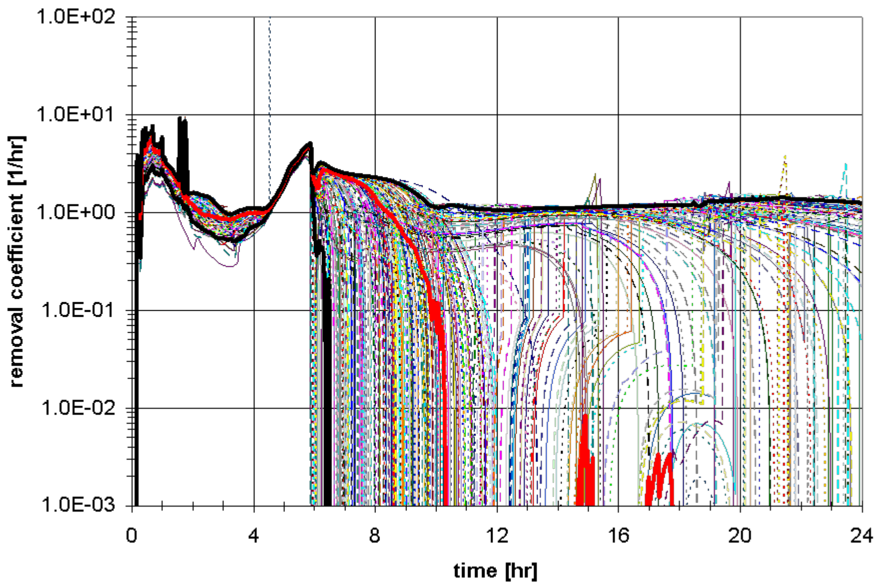


Figure 3-24 Mk-I RLB, Removal Coefficients with Geometric Variability, MSL-A, In-Board – no sprays, condenser

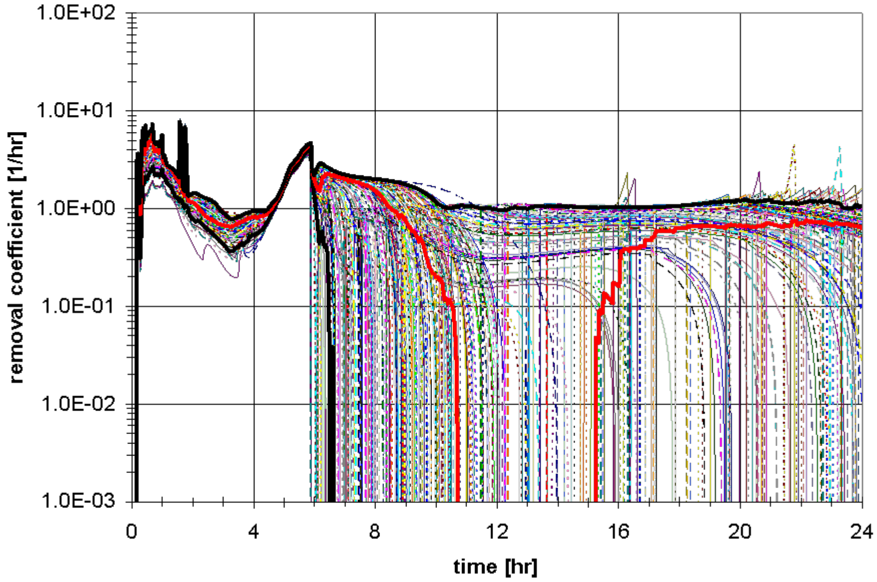


Figure 3-25 Mk-I RLB, Removal Coefficients with Geometric Variability, MSL-B, In-Board – no sprays, condenser

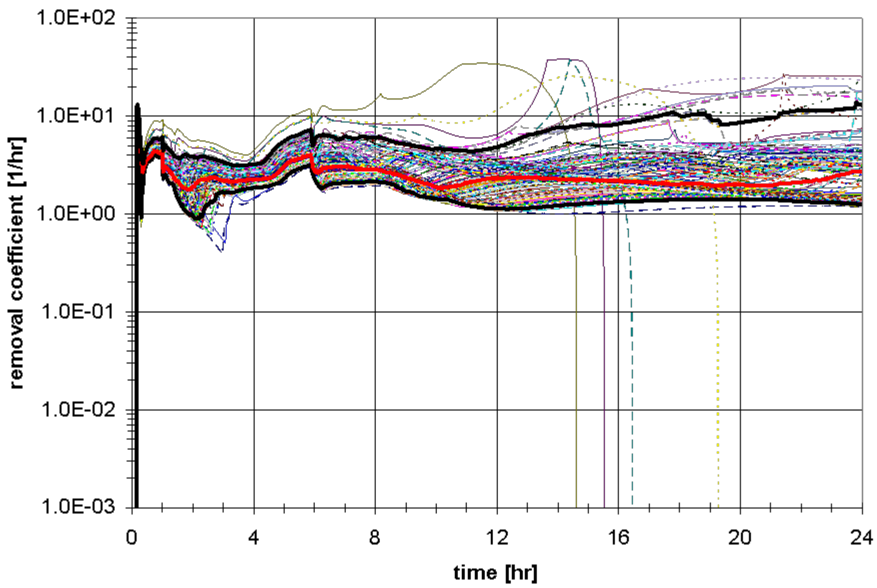


Figure 3-26 Mk-I RLB, Removal Coefficients with Geometric Variability, MSL-A, between MSIVs – no sprays, condenser

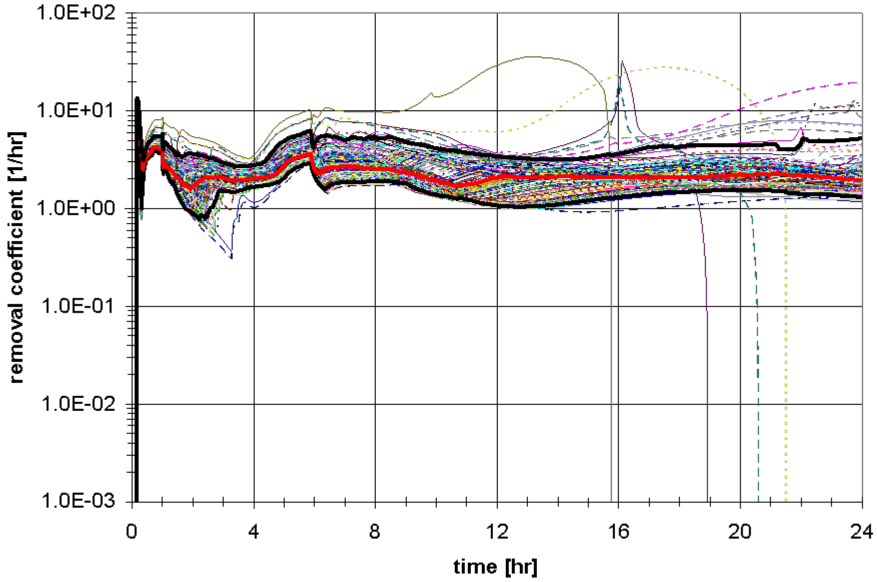


Figure 3-27 Mk-I RLB, Removal Coefficients with Geometric Variability, MSL-B, between MSIVs – no sprays, condenser

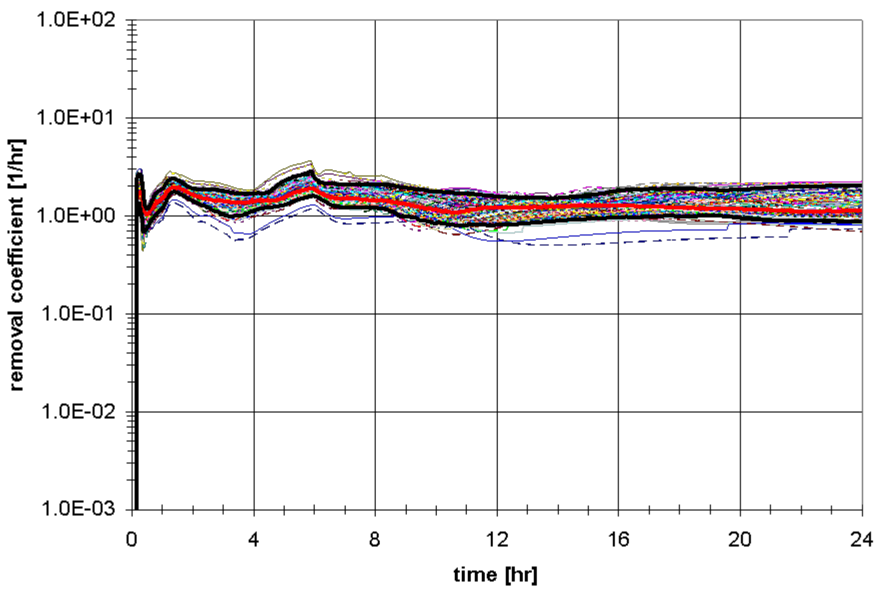


Figure 3-28 Mk-I RLB, Removal Coefficients with Geometric Variability, MSL-A, out-board – no sprays, condenser

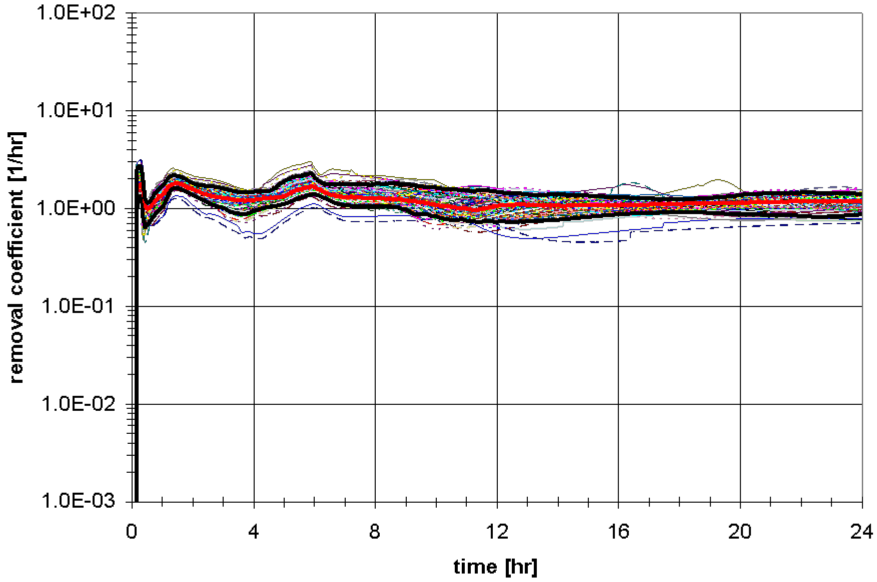


Figure 3-29 Mk-I RLB, Removal Coefficients with Geometric Variability, MSL-B, out-board – no sprays, condenser

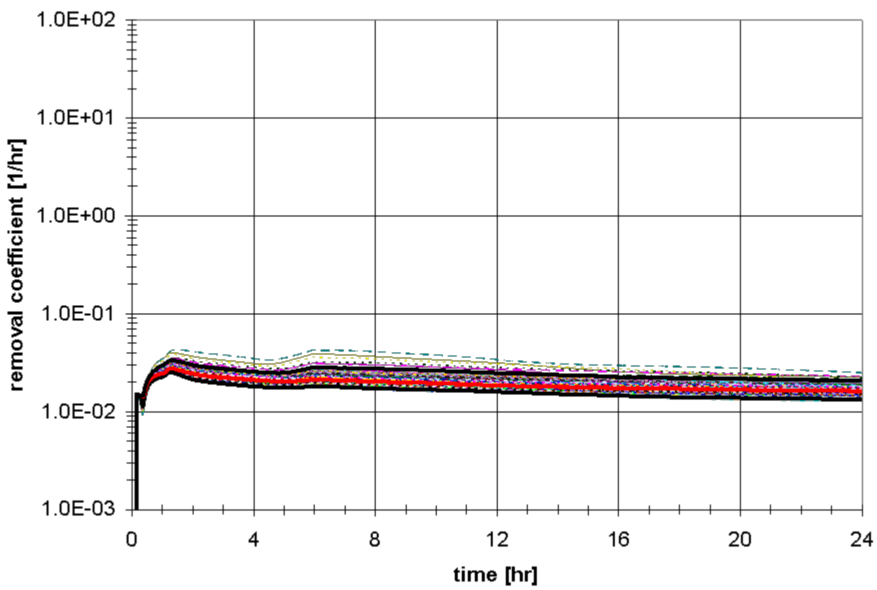


Figure 3-30 Mk-I RLB, Removal Coefficients with Geometric Variability, condenser – no sprays, condenser

Table 3-10: Geometric Variability Analysis MSL and Condenser Removal Coefficients (5th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
MSL-A in-board	1.6	0.55	0.0
MSL-A between MSIVs	2.6	1.8	1.3
MSL-A out-board	1.2	1.1	0.93
MSL-B in-board	1.5	0.50	0.0
MSL-B between MSIVs	2.6	1.6	1.4
MSL-B out-board	1.1	1.0	0.85
condenser	0.020	0.018	0.014

note. removal coefficients are given in 1/hr

Table 3-11: Geometric Variability Analysis MSL and Condenser Removal Coefficients (50th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
MSL-A in-board	2.9	1.2	0.00028
MSL-A between MSIVs	3.2	2.5	2.2
MSL-A out-board	1.5	1.4	1.2
MSL-B in-board	2.7	1.2	0.43
MSL-B between MSIVs	3.2	2.3	2.1
MSL-B out-board	1.4	1.3	1.1
condenser	0.022	0.020	0.017

note. removal coefficients are given in 1/hr

Table 3-12: Geometric Variability Analysis MSL and Condenser Removal Coefficients (95th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
MSL-A in-board	3.8	1.8	1.2
MSL-A between MSIVs	4.7	4.9	9.2
MSL-A out-board	1.9	2.0	1.8
MSL-B in-board	3.5	1.7	1.1
MSL-B between MSIVs	4.5	4.3	4.1
MSL-B out-board	1.8	1.7	1.4
condenser	0.026	0.027	0.022

note. removal coefficients are given in hr^{-1}

3.4 Results from Main Steam Line Uncertainty Analyses

Three uncertainty cases were run using the MELCOR MSL-only model; these included:

- RLB, no sprays, condenser, aerosol physics parameter uncertainty
- RLB, no sprays, condenser, geometric variability
- RLB, no sprays, condenser, MSIV flow uncertainty.

The removal coefficients plots from the cases are given below (see Figure 3-10 through Figure 3-30.

In general, the further away the MSL piping is from the steam dome the lower its removal coefficient. This is due the faster deposition rate of large aerosol particles, which causes them to deposit in the MSL piping closer to the steam dome. The asymptotic drops in the in-board MSL removal coefficients occur at times where the pipe wall temperature is high enough such that deposited fission products are vaporized, causing the deposition rate, and hence the removal coefficient, to become negative. The initial occurrences are driven in part by the elevated gas temperatures associated with the heat-up of the lower plenum prior to lower head failure. The later occurrences are caused by the decay heat from the deposited fission product aerosols.

The 5th, 50th, and 95th values for removal coefficients based on the MSL-only model uncertainty analysis results are provided in Tables 4-13, 4-14, and 4-15. The tabulated values were derived by calculating the integrated average removal coefficient of the percentile of interest (e.g., 5th, 50th, 95th) over the time period of interest (e.g., 0-2 hrs, 2-12 hrs, 12-24 hrs) for each MSL segment (e.g., in-board, between MSIVs, out-board) for both MSLs (e.g., MSL-A, MSL-B) and the condenser from each of the three uncertainty analyses. A simple average was then taken of the results of the three uncertainty analyses for each time period. The MSL-A and MSL-B results were averaged to calculate a single in-board, between MSIVs, and out-board removal coefficient result.

Removal coefficients were calculated for the in-board segments of the MSLs, however it is recommended that no credit (i.e., a removal coefficient of 0.01/hr) be taken for aerosol deposition in this portion of the MSLs. The basis for this recommendation is that at times in the simulation the temperature of portions of the in-board MSL piping are predicted to be high enough to vaporize fission products that had been previously deposited and because of the potential for thermophoretic repulsion: see page 4-15 of reference [3] . This secondary source cannot be easily incorporated into a RADTRAD model, and if the initial deposition (via a non-zero removal coefficient) is credited, the omission of this secondary source would result in an under-prediction of fission products released downstream, and ultimately to the environment.

Decay heat from fission products deposited in the in-board piping can cause natural convection-driven bi-directional flow between the steam dome and the in-board MSLs. While the well-mixed nature of the MSL control volumes does in some fashion capture the enhanced mixing that such flow would cause, it does not address the potential for enhanced bulk transport of fission products from the steam dome into the in-board MSLs. Note that this issue has been previously cited as a basis for not taking credit for aerosol deposition in the in-board MSLs: see page 4-15 of reference [3].

Table 3-13: Recommended MSL and Condenser Removal Coefficients (5th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
in-board	2.2*	0.0*	0.0*
between MSIVs	2.5	1.8	1.0
out-board	1.1	1.0	0.7
condenser	0.018	0.015	0.012

note. removal coefficients are given in hr^{-1}
* calculated values are shown, but a value of 0.0 hr^{-1} is recommended

Table 3-14: Recommended MSL and Condenser Removal Coefficients (50th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
in-board	3.2*	1.3*	0.4*
between MSIVs	2.9	2.4	2.0
out-board	1.3	1.3	1.0
condenser	0.020	0.018	0.015

note. removal coefficients are given in hr^{-1}
* calculated values are shown, but a value of 0.0 hr^{-1} is recommended

Table 3-15: Recommended MSL and Condenser Removal Coefficients (95th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
in-board	4.9*	2.3*	1.1*
between MSIVs	3.8	3.7	4.4
out-board	1.6	1.7	1.6
condenser	0.023	0.023	0.021

note. removal coefficients are given in hr^{-1}
* calculated values are shown, but a value of 0.0 hr^{-1} is recommended

4 RADTRAD Dose Calculations for Full Reactor Models[§]

In this section, the MELCOR source term is converted into estimated doses at the Exclusion Area Boundary (EAB), Low Population Zone (LPZ), and the Control Room (CR). The regulatory limits (set forth in 10 CFR 50.67) to which the RADTRAD dose results are compared are

- 25 rem total effective dose equivalent (TEDE) for the worst two-hour dose at the EAB,
- 25 rem TEDE for the 30 day integrated dose at the LPZ,
- 5 rem TEDE for the 30 day integrated dose in the CR.

The overall purpose of these assessments and comparisons is to evaluate the dose implications of using a source term from a best estimate release analysis. This can be compared to doses estimated using regulatory guidelines methods in order to provide perspective relative to likely degree of conservatism of the simplified regulatory procedures.

4.1 Description of RADTRAD Model for MELCOR Full Plant Decks

A RADTRAD model has been developed to calculate doses from the MSL fission product releases calculated by MELCOR full reactor models. The RADTRAD model consists of a small volume into which the MELCOR-calculated fission product release is input as a source, the environment, and the control room. The source volume is only included because RADTRAD does not allow a source to be placed directly into the environment. The source volume is connected to the environment with a flow path that has a very large volumetric flow rate. This effectively moves the source instantaneously from the source volume to the environment. The model nodalization is shown in Figure 4-1.

[§] MELCOR input data used to develop these models were based on the configuration, geometry and materials of single, representative plants (Grand Gulf and Peach Bottom).

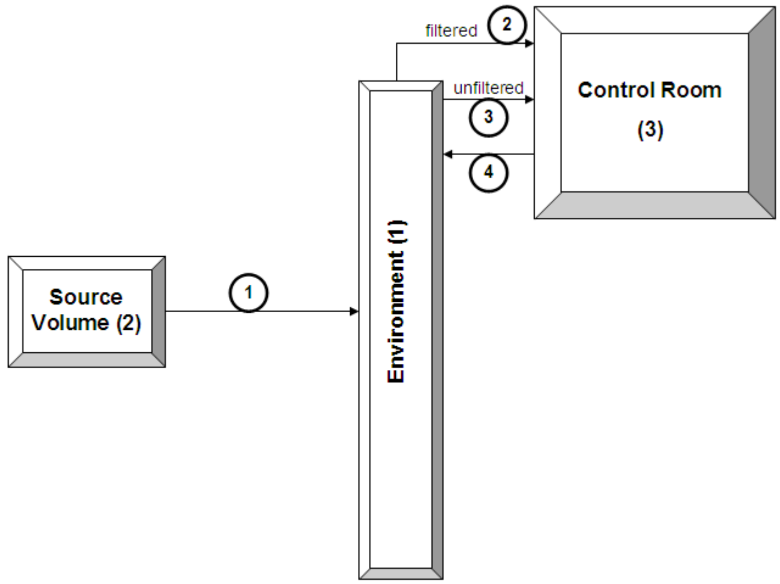


Figure 4-1 Mk-I and Mk-III Full Reactor Source Term Model

The purpose of these full reactor model calculations is to compare early dose results directly from MELCOR to those derived using the proposed methodology. The two sets of results are not expected to match exactly, but they should be comparable and follow similar trends.

4.2 MELCOR to RADTRAD FP Group Conversion

MELCOR and RADTRAD use significantly different accounting schemes to track mass and conservation of radionuclides, with MELCOR using a chemical-family based accounting system and RADTRAD using a radioisotope accounting basis. Importantly, MELCOR accounts for all mass of released materials, both radioactive and stable isotopes as well as the inert mass associated with oxide or hydroxide forms, whereas RADTRAD tracks only selected dose-important isotopes. MELCOR treats all mass in order to account for important aerosol mechanics effects, principally particle agglomeration. In order to map MELCOR predicted fission product source terms into RADTRAD sources, it is necessary to consider the relationship between MELCOR mass inventories and RADTRAD inventories. The following sections describe the mapping methodology used in this study.

To provide context for the description of the fission product release post-processing, a brief discussion MELCOR's and RADTRAD's treatment of fission products is provided.

MELCOR models fission products as a set of radionuclide (RN) classes in which each class is represented by a single chemical compound. For example, while RN class 1 is comprised of a variety of noble gases, it is represented in MELCOR as Xe. Also, certain fission products elements are contained in multiple RN classes (e.g., I is in both the I_2 and CsI RN classes). In contrast, RADTRAD models individual isotopes, but only accounts for 60 fission products that are the most important contributors to dose. Table.4-1 shows the fission product chemical groups used by MELCOR listing the representative element for each group and the fission product elements that correspond to that chemical group. Table.4-2 shows the radionuclides typically considered in RADTRAD, the used inventories of these isotopes for the Mk-I and Mk-III designs, the RADTRAD chemical group to which they belong, and the MELCOR chemical group to which they correspond. The inventories in this table, presented in grams, were converted from the RADTRAD Nuclide Inventory Files (.nif) inventories, in Ci/MW, by using the reactor powers, the decay constants obtained from the half life of each isotope, and the atomic weight of each isotope.

Table.4-1. MELCOR Radionuclide (RN) Classes

RN Class	Name	Representative	Member Elements
1	Noble Gas	Xe	He, Ne, Ar, Kr, Xe, Rn, H, N
2	Alkali Metals	Cs	Li, Na, K, Rb, Cs, Fr, Cu
3	Alkaline Earths	Ba	Be, Mg, Ca, Sr, Ba, Ra, Es, Fm
4	Halogens	I	F, Cl, Br, I, At
5	Chalcogens	Te	O, S, Se, Te, Po
6	Platinoids	Ru	Ru, Rh, Pd, Re, Os, Ir, Pt, Au, Ni
7	Early Transition Elements	Mo	V, Cr, Fe, Co, Mn, Nb, Mo, Tc, Ta, W
8	Tetravalent	Ce	Ti, Zr, Hf, Ce, Th, Pa, Np, Pu, C
9	Trivalents	La	Al, Sc, Y, La, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Cm, Bk, Cf
10	Uranium	U	U
11	More Volatile Main Group	Cd	Cd, Hg, Zn, As, Sb, Pb, Tl, Bi
12	Less Volatile Main Group	Sn	Ga, Ge, In, Sn, Ag
16	Cesium iodide	CsI- – -	CsI
17	Cesium Molybdate	Cs_2MoO_4	Cs_2MoO_4

note: RN classes 13, 14, 18 consist of non-radionuclide aerosol materials

Table.4-2 RADTRAD Nuclide Inventory File Isotopes

Isotope	RADTRAD Chemical Group	MELCOR RN Class	Mk-I Core Inventory (g)	Mk-III Core Inventory (g)
Co-58	7	7	1.701E+01	1.702E+01
Co-60	7	7	5.708E+02	5.708E+02
Kr-85	1	1	3.547E+03	3.487E+03
Kr-85m	1	1	3.562E+00	3.904E+00
Kr-87	1	1	2.040E+00	2.073E+00
Kr-88	1	1	6.479E+00	6.302E+00
Rb-86	3	2	2.826E+00	3.200E+00
Sr-89	5	3	3.395E+03	3.397E+03
Sr-90	5	3	8.223E+04	8.150E+04
Sr-91	5	3	3.694E+01	3.498E+01
Sr-92	5	3	1.128E+01	1.059E+01
Y-90	9	9	2.121E+01	2.106E+01
Y-91	9	9	4.965E+03	5.126E+03
Y-92	9	9	1.477E+01	1.386E+01
Y-93	9	9	4.777E+01	4.539E+01
Zr-95	9	8	7.395E+03	7.677E+03
Zr-97	9	8	8.589E+01	8.466E+01
Nb-95	9	7	4.075E+03	4.227E+03
Mo-99	7	7, 17	3.732E+02	3.778E+02
Tc-99m	7	7	2.982E+01	3.018E+01
Ru-103	7	6	4.599E+03	4.947E+03
Ru-105	7	6	1.525E+01	1.731E+01
Ru-106	7	6	1.823E+04	2.076E+04
Rh-105	7	6	1.149E+02	1.290E+02
Sb-127	4	11	3.833E+01	2.951E+02
Sb-129	4	11	5.416E+00	5.837E+00
Te-127	4	5	3.839E+00	4.303E+00
Te-127m	4	5	1.442E+02	1.608E+02
Te-129	4	5	1.432E+00	1.543E+00
Te-129m	4	5	1.482E+02	2.328E+02
Te-131m	4	5	1.711E+01	1.805E+01
Te-132	4	5	4.444E+02	4.548E+02
I-131	2	4, 16	7.645E+02	7.853E+02
I-132	2	4, 16	1.327E+01	1.361E+01
I-133	2	4, 16	1.730E+02	1.716E+02
I-134	2	4, 16	8.140E+00	8.014E+00
I-135	2	4, 16	5.221E+01	5.179E+01
Xe-133	1	1	1.035E+03	1.023E+03
Xe-135	1	1	3.075E+01	2.968E+01
Cs-134	3	2, 16, 17	1.976E+04	2.223E+04
Cs-136	3	2, 16, 17	9.764E+01	1.156E+02
Cs-137	3	2, 16, 17	1.841E+05	1.704E+05

Isotope	RADTRAD Chemical Group	MELCOR RN Class	Mk-I Core Inventory (g)	Mk-III Core Inventory (g)
Ba-139	6	3	1.094E+01	1.074E+01
Ba-140	6	3	2.358E+03	2.375E+03
La-140	9	9	3.186E+02	3.219E+02
La-141	9	9	2.894E+01	2.894E+01
La-142	9	9	1.116E+01	1.101E+01
Ce-141	8	8	5.558E+03	5.655E+03
Ce-143	8	8	2.354E+02	2.318E+02
Ce-144	8	8	3.980E+04	3.963E+04
Pr-143	9	9	2.248E+03	2.231E+03
Nd-147	9	9	8.012E+02	8.326E+02
Np-239	8	8	8.200E+03	9.982E+03
Pu-238	8	8	3.706E+04	3.921E+04
Pu-239	8	8	6.809E+05	7.774E+05
Pu-240	8	8	1.994E+05	3.205E+05
Pu-241	8	8	2.111E+05	1.895E+05
Am-241	9	9	9.798E+03	7.332E+03
Cm-242	9	9	2.541E+03	2.309E+03
Cm-244	9	9	1.137E+04	2.002E+04

MELCOR does not account for the decay and in-growth of radionuclides[**], while RADTRAD accounts for decay and in-growth of radionuclides once they are released into a volume in the RADTRAD model.

The release rate of a RADTRAD source term is defined by the release timing fraction (.rtf) file. RADTRAD only allows the release rate to be defined as a constant release for three separate time periods. An initial delay in the source term release is also allowed. This delay is used to account for the period between the initiation of the accident (t = 0 hr) and the start of the fission product release to the environment. Conversely, the MELCOR-calculated fission product releases are reported from the model at intervals based on the plot frequency specified in the model (10 s to 180 s).

Also, MELCOR core inventory is a BWR middle-of-cycle (MOC) inventory, which differs both in terms of absolute mass and isotopic composition from the BWR end-of-cycle (EOC) core inventory assumed in RADTRAD.

To account for the different fission product modeling treatments the following post processing steps are applied to a MELCOR-calculated fission product release in order to put it into a RADTRAD-compatible form. This conversion consists of time averaging the MELCOR chemical group releases, distributing the MELCOR chemical group masses among isotopes according to the relative masses of each isotope, scaling to correct for the differences in initial

[**] The MACCS code, developed to calculate consequences from MELCOR-calculated releases, would account for radionuclide decay and in-growth from the time of accident initiation.

core inventories, and decaying the isotopes to account for the reduction of activity at the time of release. Examples from the Mk-I RLB case are used to illustrate the steps.

- Evaluate the MELCOR fission release rate signatures to determine the best fit of the signatures into three release rate periods, and if needed, a delay time before the start of the release.

  For example, based on the release rates shown in Figure 5-2 periods of 0.5 to 2.4 hr, 2.4 to 4.4 hr, and 4.4 to 5.88 hr, with a delay of 0.0 to 0.5 hr are estimated and incorporated in the RADTRAD RTF file.

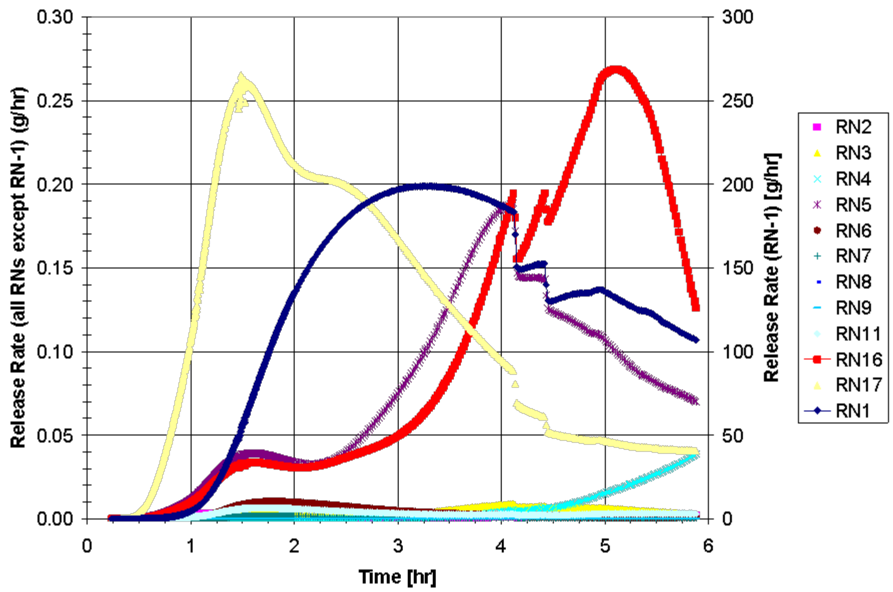


Figure 4-2 Mk-I RLB RN Release Rates

- Calculate the total release of each MELCOR RN class over each time period.

  For example, based on the integrated release output from MELCOR, 124.3 g of RN class 1 were released between 0.5 and 2.4 hr.

- Determine the mass of Cs, I, and Mo contained in MELCOR RN classes 16 (CsI) and 17 (Cs_2MoO_4) and add those masses, respectively, to the RN class 2 (Cs), 4 (I_2), and 7 (Mo) masses.

  For example, between 0.5 and 2.4 hr there are 9.6E-06 g of RN class 4 (I_2) released, and 0.0420155 g of RN class 16 (CsI) released. 49% of the mass of RN class 16 is I (i.e., 0.02061 g). This I mass is added to RN class 4, yielding a total release mass of I_2 over the period of 0.0206069 g.

- Sum the RADTRAD initial core inventory isotope masses by groups that correspond to the MELCOR RN classes. This is done for RN classes 1 through 9, and 11. The other RN classes either are non-radioactive (e.g., RN class 14) or there are no corresponding isotopes in the RADTRAD inventory (e.g., RADTRAD has no U isotopes in its inventory, hence RN class 10 is omitted).

  For example, for MELCOR RN class 1, the sum of the Kr-85, Kr-85m, Kr-87, Kr-88, Xe-133, and Xe-135 in the RADTRAD BWR initial core inventory (for a power level of 3528 MWth) is 4632.9 g.

- Calculate the ratio of the mass of isotopes in each RN class in the RADTRAD initial core inventory to the mass of isotopes in the MELCOR initial core inventory (see Table 4-3).

  For example, the mass of isotopes in the RADTRAD BWR initial core inventory (for a power level of 3528 MWth) that correspond to the MELCOR RN class 1 is 4632.9 g, while there are 531,540.9 g in the MELCOR RN class 1 initial core inventory. Therefore the ratio of the RADTRAD to MELCOR initial core inventory masses for RN class 1 is 4632.9 / 531,540.9 = 0.00870.

- Scale the MELCOR fission product releases, to account for the differences between the RADTRAD and MELCOR initial core inventories, by multiplying the mass of each RN class released in each time period by its respective ratio of RADTRAD to MELCOR initial core inventory masses.

  For example, the ratio of the RADTRAD to MELCOR initial core inventory masses for RN class 1 is 0.00870 and the RN class 1 mass released between 0.5 and 2.4 hr is 124.3 g. Therefore the scaled release mass is 0.00870 x 124.3 g = 1.081 g.

- Calculate the ratio of each RADTRAD isotope to the total mass of all of the isotopes in its equivalent MELCOR RN class. This ratio is used to convert the mass from MELCOR groups to the Isotope masses.

  For example, there are 3548.5 g of Kr-85 in the RADTRAD Mk-I initial core inventory (for a power level of 3528 MWth). Therefore the ratio of Kr-85 to the total mass of the isotopes that correspond to RN class 1 is 3548.6 / 4632.9 = 0.767. The same result can be obtained using the ratio of the corresponding isotope masses provided in Table.4-2 ($=M_{Kr\text{-}85}/(M_{Kr\text{-}85}+M_{Kr\text{-}85m}+M_{Kr\text{-}87}+M_{Kr\text{-}88}+M_{Xe\text{-}133}+M_{Xe\text{-}135})$*) or the ratio of the products of the molecular weights, half lives, and activities (in Ci/Mw) provided in previous Nuclide Inventory Files .*

- Calculate the masses of the individual isotopes of each scaled MELCOR RN class released in each time period. Decay each isotope by half the duration of the time period plus the time previous to the time period (e.g., for a period between 2 and 5 hr a decay time of 3.5 hr would be used).

For example, the ratio of Kr-85 to the total mass in RN class 1 is 0.767 and between 0.5 and 2.4 h the scaled release mass is 1.081 g. Therefore the pre-decay release mass of Kr-85 is 0.829 g. Simple decay is accounted for over a time of 0.5 hr + 0.5 x (2.4 – 0.5) hr = 1.45 hr, which yields a scaled, decayed release mass of Kr-85 of 0.829 g.

The post-processing steps can be described by the following equation

$$m_i^k = m_{cls(i)}^k \times Rc_{cls(i)} \times Ri_i \times \exp\left[-\lambda_i t^k\right] \quad (4.1)$$

where

- m_i^k - mass of the i[th] isotope released over the k[th] release period
- $m_{cls(i)}^k$ - mass of the MELCOR RN class containing the i[th] isotope released over the k[th] release period, accounting for the mass of Cs, I, and Mo being moved from RN classes 16 and 17 mass to RN classes 2, 4, and 5.
- $Rc_{cls(i)}$ - ratio of the RADTRAD to MELCOR initial core inventory masses for RN class containing the i[th] isotope
- Ri_i - ratio of the i[th] isotope to the total mass of all isotopes in the RADTRAD initial core inventory that are in the corresponding MELCOR RN class
- λ_i - radioactive decay constant of the i[th] isotope
- t^k - decay time for the k[th] release period

Table 4-3 Ratio of RADTRAD to MELCOR Initial Core Inventory

MELCOR RN Class	Mk-I Ratio [-]	Mk-III Ratio [-]
1	0.009	0.005
2	0.727	0.446
3	0.374	0.238
4	0.051	0.031
5	0.015	0.011
6	0.067	0.042
7	0.013	0.009
8	0.765	0.617
9	0.018	0.031
11	0.007	0.021

Note: Accounts for the mass of Cs, I, and Mo being moved from RN classes 16 and 17 to RN classes 2, 4, and 5.

4.3 RADTRAD Results

Selected results of the full reactor model source term RADTRAD predictions are presented here, along with comparisons against results from sample industry RADTRAD models obtained from industry reports submitted to the NRC [12,13.

4.3.1 Mk-I Results

When using the MELCOR-predicted releases to the environment directly as the source to RADTRAD, the resulting predicted doses are limited to the amount of time that the MELCOR simulation was run. This ranges from 4.9 hours to 7.7 hours. Thus, a comparison cannot be made between the LPZ and CR limits and the results from the MELCOR full models. These comparisons will be available with the steam line model discussed later in the report however. Table 4-4 compares the worst 2 hour doses at the EAB for the Mark 1 cases examined.

Table 4-4 Worst 2 Hour TEDE Doses at EAB for Mk 1 Using MELCOR Release to Environment

	EAB worst 2 hr (rem)
10 CFR 50.67 Limit	25
Representative Industry Sample analysis	3.48
RLB	10.66
RLB (sprays)	4.06
RLB (cond)	0.11
RLB (cond and sprays)	0.04
MSLB	2.90
MSLB (sprays)	2.09

The following two figures are the integrated doses at the LPZ and the control room out to 6 hours. Some of the cases only run out close to 5 hours. The dose for the LPZ will flatten out when the simulation has reached the end of the MELCOR source term.

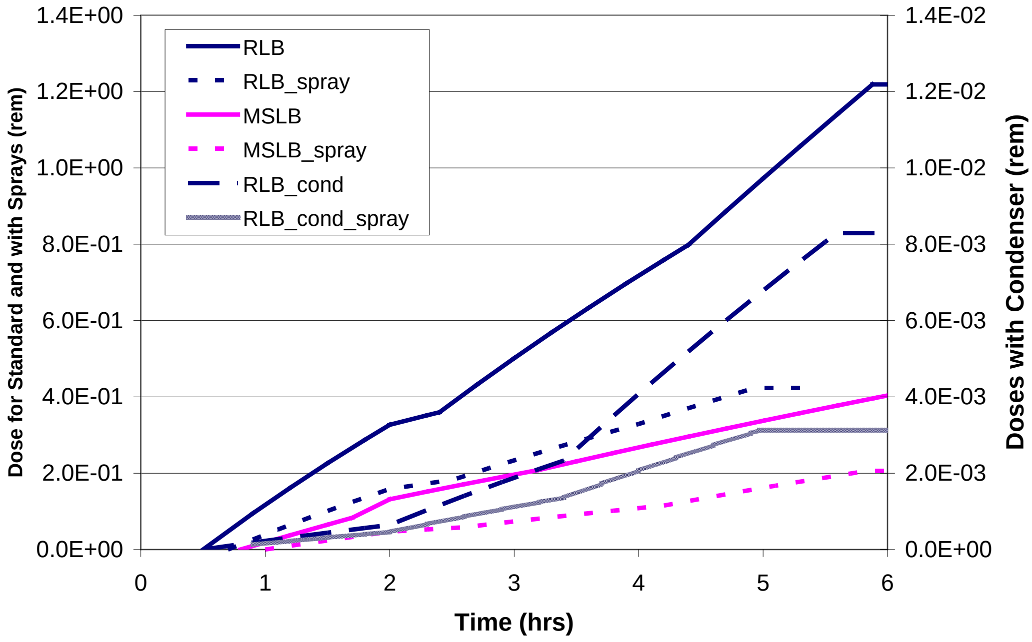


Figure 4-3 LPZ Integrated TEDE for Mk 1 MELCOR Full Model Cases, Notice that the two simulations with condensers use the scale on the right which is lower by a factor of 100.

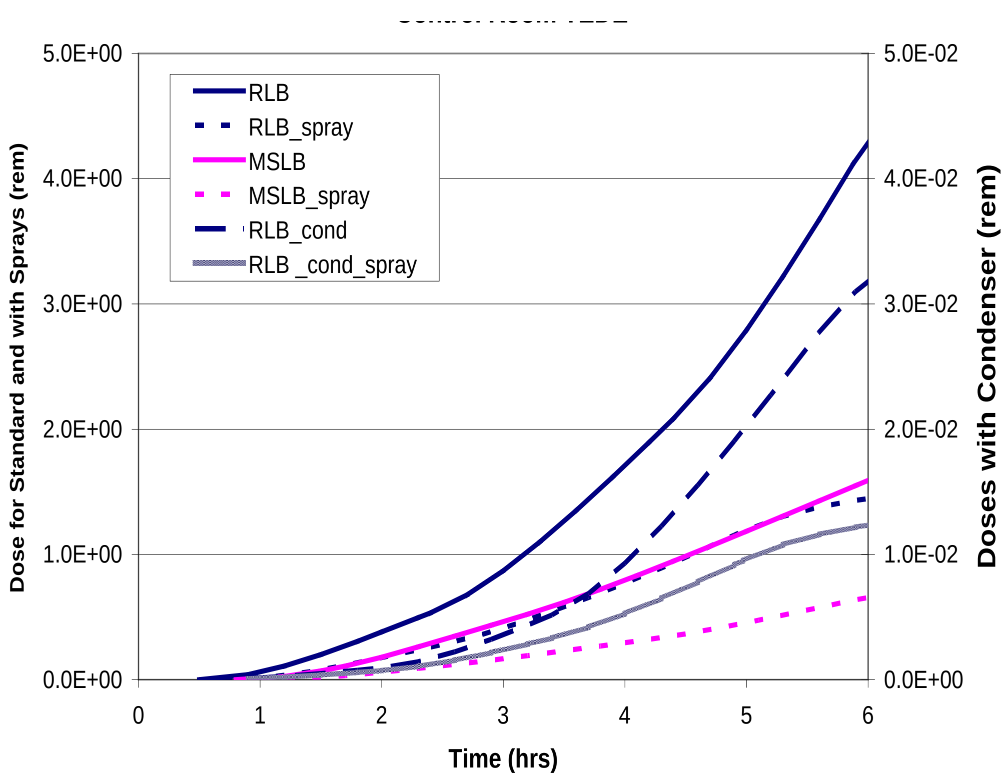


Figure 4-4 Control Room Integrated TEDE for Mk 1 MELCOR Full Model Cases. Notice that the two simulations with condensers use the scale on the right which is lower by a factor of 100

Some insight on the LPZ and CR doses can be gained by comparing them to representative industry calculations without sprays at 5 hours. This comparison is summarized in Table 4-5. The values were taken within 0.1 hours of 5 hours, varying depending on the timesteps within the problem. The RLB analyses produce doses that are larger somewhat than the representative industry value – other cases are closer to the industry value.

Table 4-5 A Comparison of the MELCOR Full Model TEDE Doses to Comparative Industry Calculation without Sprays for LPZ and CR near 5 Hours

RLB(sprays) and RLB(cond) values taken at 4.9 hours, MSLB(sprays) taken at 5.1 hours, the remaining cases were at 5 hours.

	LPZ near 5 hours (rem)	CR near 5 hours (rem)
Representative Industry Sample analysis	0.27	0.99
RLB	0.97	2.79
RLB (sprays)	0.42	1.17
RLB (cond)	0.01	0.02
RLB (cond and sprays)	0.00	0.01
MSLB	0.34	1.19
MSLB (sprays)	0.17	0.48

4.3.2 Mk-III Results

The Mk-III parameters for control room size, flow rates between control room and environment, filter efficiencies, and dose conversion factors were taken from Reference 13. The RADTRAD model labeled "MSIV LEAKAGE RADTRAD RUN" only examines leakage out to 0.3 hours. In order to obtain values out to at least 72 hours, the parameters from the "ESF LIQUID LEAKAGE RAPTOR RUN" and ESF LIQUID LEAKAGE RADTRAD RUN" were used. These parameters seemed to match the initial values in the MSIV leakage RADTRAD run and closely resembled the parameters in the Mk-I studies.

The geometry of the sample Mk-III differs from that of the Mk-I in that there is no piping modeled past the outboard MSIV in MELCOR. This would suggest that the dose will be higher than that of the Mark I, which includes more than 90 meters of piping past the outboard MSIV.

The Mk-III worst 2 hour integrated EAB TEDE results can be found in Table 4-6. The values are approximately 14 rem, still within the 10 CFR 50.67 limit of 25 rem. The LPZ and control room integrated TEDE doses can be seen in Figure 4-5. The control room TEDE has already surpassed the 5 rem TEDE limit after only 4 hours, but the LPZ limit is well below the 25 rem TEDE limit and appears to be flattening out. The result from the Mk-III sample industry model is not considered comparable because it includes a leakage control system. Therefore it is not provided in the table.

Table 4-6: Worst 2 Hour TEDE Doses at EAB for Mk-III Using MELCOR Release to Environment
Notice that the doses are both approaching the 10 CFR limit.

	EAB worst 2 hr (rem TEDE)
10 CFR 50.67 Limit	25
RLB	14.36
MSLB	14.73

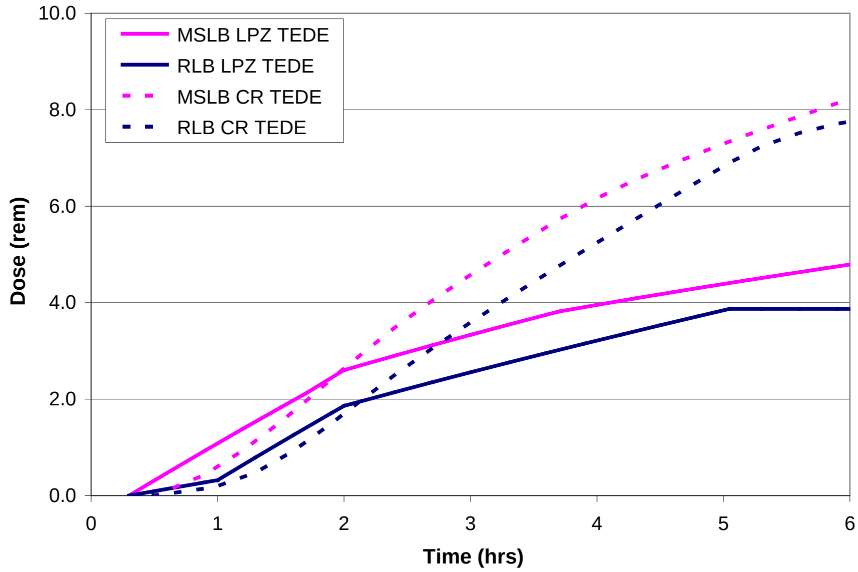


Figure 4-5 Control Room and LPZ Integrated TEDEs for Mark 3 MELCOR Full Model Cases *Notice that the control room doses have exceeded the 5 rem TEDE limit at about 3 hours.*

5 RADTRAD Dose Calculations for Main Steam Line Models

5.1 Description of RADTRAD Main Steam Line Models

The RADTRAD MSL models are examples for how the recommended MSL and condenser removal coefficients and the steam dome-to-drywell concentration ratios would be implemented into RADTRAD. These models are structurally similar to the RADTRAD models currently used by the NRC and licensees to evaluate MSIV leakage consequences and use values for control room size, containment leakage, flow rates between control room and environment, and control room filters from the licensee models. Representative RADTRAD models for Mk-I and Mk-III dose analyses were taken from industry reports submitted to the NRC [12,13]. The RADTRAD input decks used for the MK-I case are provided in Appendix B.

One difference between the Mk-I MSL-only model and the industry sample model is that the MSL-only model uses three steam line volumes rather than two. This is to accurately represent the hold-up in each of these volumes. There are three volumes for both the RLB and the MSLB cases because it was determined that the most conservative approach would be to assume, for the MSLB case, that the break occurs in a non-leaky line, making the geometry the same as that for the RLB case. Therefore, the inboard section is still needed to represent hold-up in the MSLB case.

The reference industry sample model also uses filter efficiencies rather than lambdas. It was discovered during this study that filter efficiencies are not completely equivalent to removal coefficients for all situations, and that their application to volumes that have non-steady state concentrations can result in non-conservative releases. Hence, removal coefficients are used in the MSL models in lieu of filter efficiencies. There were also sprays within the reference model which will not be used in these models.

RADTRAD version 3.03 is limited to modeling no more than ten volumes. As can be seen in Figure 5-1 to Figure 5-4, the RADTRAD MSL models are comprised of more than ten volumes. This was accomplished by breaking the RADTRAD MSL model into two separate submodels, where each submodel contains only one MSL. The submodels are run individually, and the principal of linear superposition was used to add the dose results from the submodels to get the total dose at the EAB, LPZ, and control room.

Another limitation of RADTRAD is that the source partitioning can only be specified once in the input file. So to work around this there are three source volumes modeled. This is to create multiple time-intervals at which to apply the steam dome-to-drywell ratio. Each of the source volumes will only be connected to the model for a specified length of time, with only one source volume connected at any given time, again using a superposition approach.

The nodalization of the models is shown in Figure 5-1-Figure 5-4. The geometry is similar for the Mk-I and Mk-III with a few exceptions. The Mk-III has three lines with MSIV leakage and no outboard line section. This may result in some differences between the Mk-I and Mk-III models, as the outboard line represents nearly 70% of the main steam line length in the Mk-I geometry. The neglected section of pipe in the Mk-III however is shorter than in the Mk-I, so the differences may not be large.

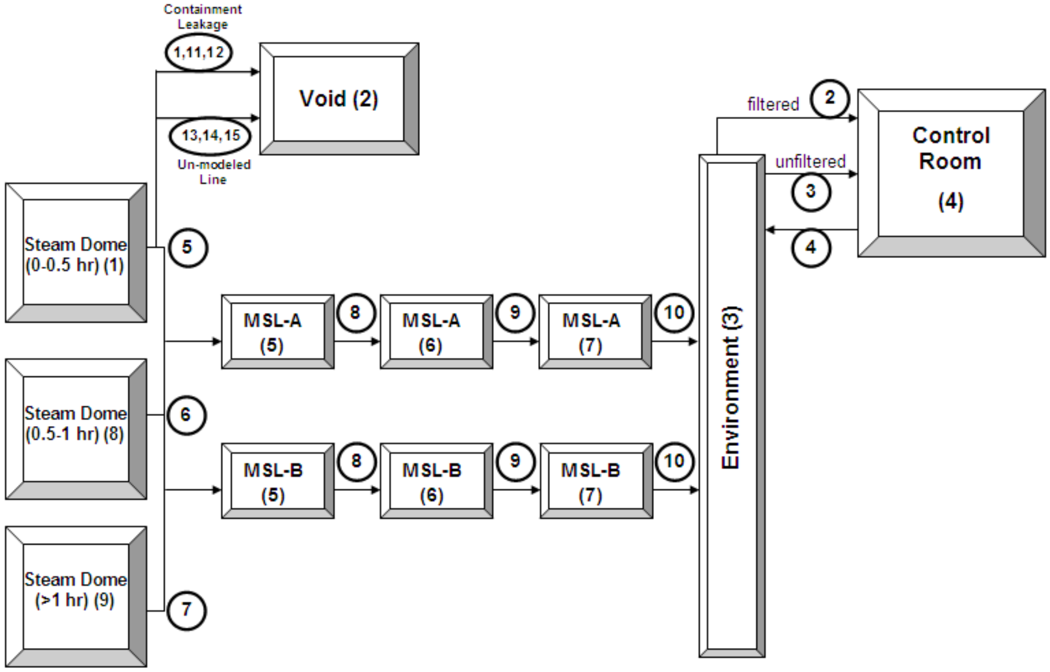


Figure 5-1 Mk-I (RLB and MSLB), No Condenser

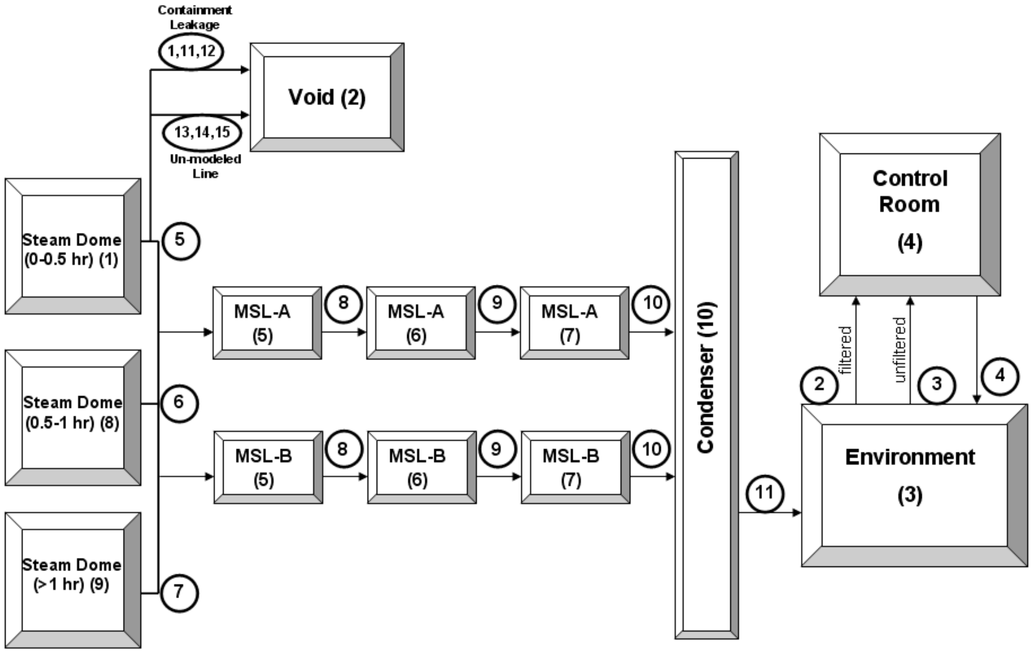


Figure 5-2 Mk-I (RLB and MSLB), With Condenser

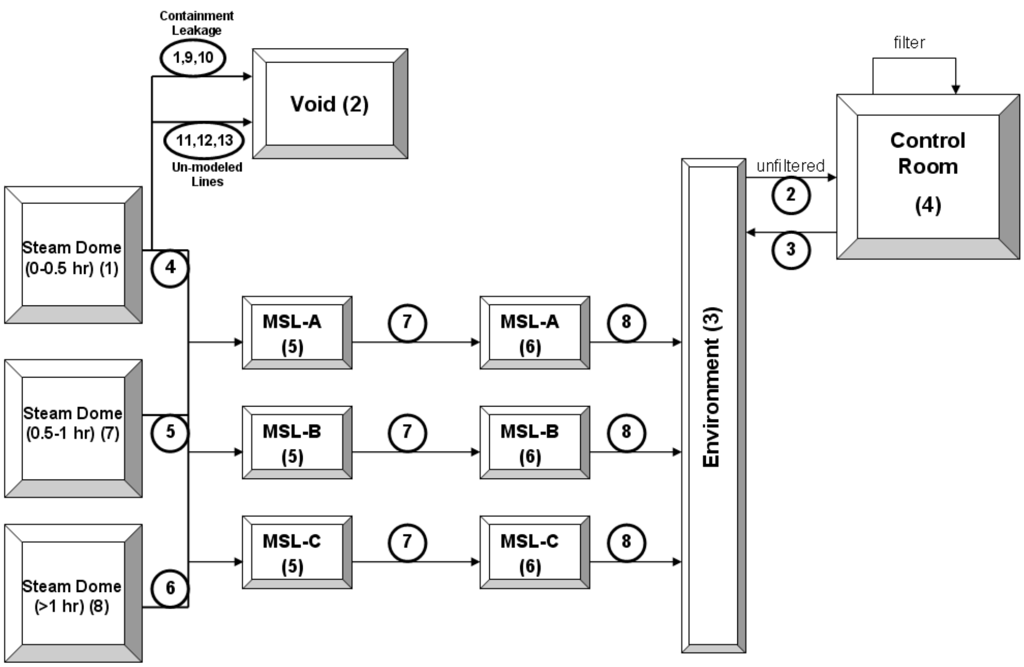


Figure 5-3 Mk-III (RLB and MSLB), No Condenser

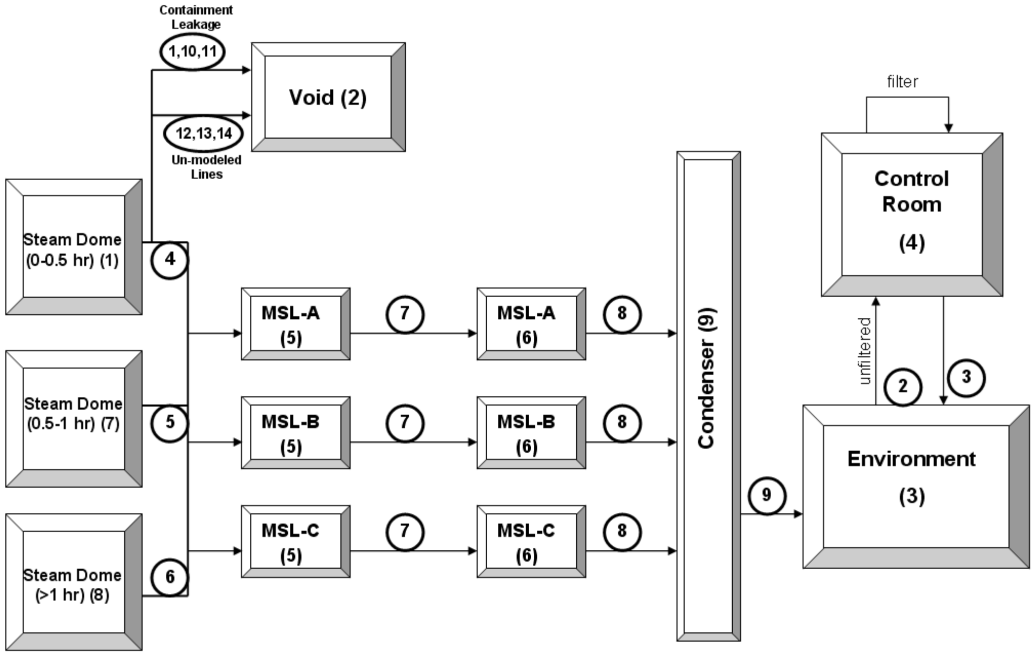


Figure 5-4 Mk-III (RLB and MSLB), With Condenser

5.2 Steam Dome-to-Drywell Ratio

The initial approach for using the steam dome-to-drywell concentration ratio calculated by the MELCOR full reactor models was to use the highest ratios of all of the RN classes. Evaluation of this initial approach found that this significantly overestimated the source term. This was due to the highest ratio of all of the RN classes being very conservative in comparison to the ratios for the RN classes of the isotopes that are most important to dose. Also the drywell concentration in RADTRAD is very different from that in the MELCOR full reactor model.

To address the first issue, the bounding steam dome-to-drywell concentration ratio of the three RN classes that contribute the majority of the dose RN2 (Cs), RN3 (Sr), and RN4 (I) will be used to scale the source term input into RADTRAD.

The drywell concentrations for these three RN classes are different between the MELCOR best estimate calculation and the RADTRAD-AST based calculation because of to the differences in source release rates. Figure 5-5 compares the masses of Cs, Sr, and I in the drywell for both RADTRAD and MELCOR in the Mk-I RLB scenario. Since both analyses model the same drywell volume, this comparison is equivalent to comparing concentrations. Notice that the RADTRAD mass is much higher than that in MELCOR. This difference in airborne concentrations (or mass in this case) illustrates the need for the factor R^*, described earlier in Equation (2-2), to normalize AST-predicted airborne concentrations with MELCOR best estimate predictions. This normalization is necessary in order to avoid excessive conservatism associated with using the AST in this application.

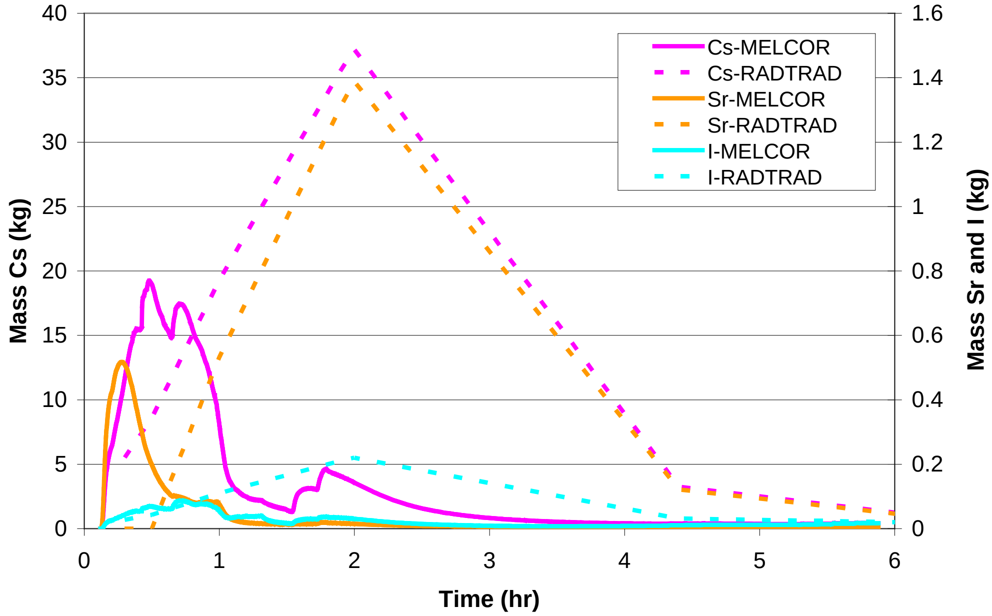


Figure 5-5: Mass of Cs, Sr, and I in RADTRAD and MELCOR Drywells for Mk-I RLB Case

Rather than de-convolve the R_M and R* factors separately, for expediency, they have been derived as their product. That is, the scaling factor is produced as simply the ratio of MELCOR-predicted stream dome concentrations to the RADTRAD-AST predicted drywell concentration. This combined factor is shown in Figure 5-6 for RN class 2, 3, and 4. From the graph, it was determined that an average ratio between 0 and 0.5 hr and 0.5 to 1 hr would be sufficient to characterize the source term. A ratio of 1 after 1 hr was found to be bounding. RN-2 had a limiting ratio of 15.24 for the first 30 minutes, and RN class 4 had a limiting ratio of 6.64 for the following 30 minutes. These ratios will be used in the RADTRAD MSL models for the Mk I to scale the NUREG-1465 derived source term.

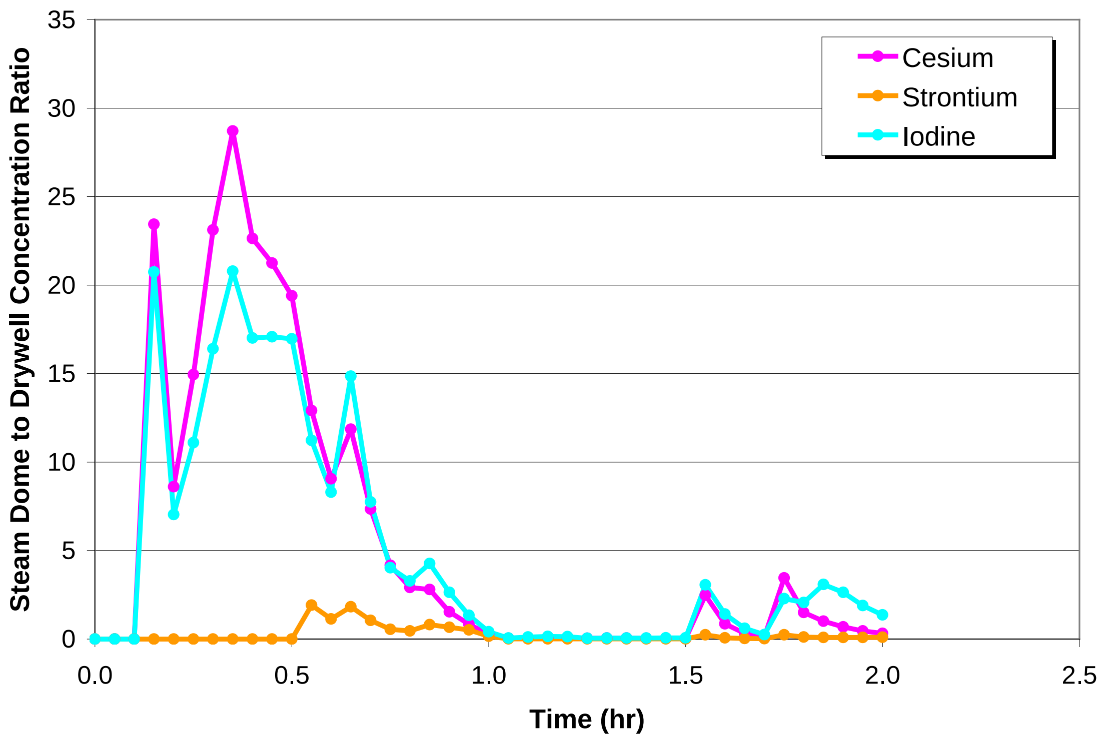


Figure 5-6: Ratio of MELCOR Steam Dome to RADTRAD Drywell for Cs, Sr, and I in Mk-I RLB

Table 5-1: MELCOR Steam Dome to RADTRAD Drywell Ratio for Various Time Intervals for Mk-I RLB

time (hr)	**Cs**	**Sr**	**I**
0.0-0.5	15.24	-----	11.87
0.5-1.0	6.33	0.81	6.64
1.0-2.0	0.59	0.06	0.95

When the steam dome-to-drywell ratio for the Mk-III was examined similarly, it was significantly higher than that of the Mark I. While the steam dome concentrations for the two MELCOR models were similar, the RADTRAD drywell concentration for the Mk-III was much lower than that of the Mk-I. This is a result of the drywell volume for the Mk-III being about 70% larger than that of the Mk-I. The two RADTRAD model core inventories are similar, but when a similar source is placed into a much larger volume the concentration will be lower by a ratio of the volumes. Figure 5-7 shows the ratio of steam dome to drywell for the Mk-III. Notice that the scale on this figure is double that of the Mk-I figure. The average ratios for the same time periods as in Table 5-1 can be found in Table 5-2.

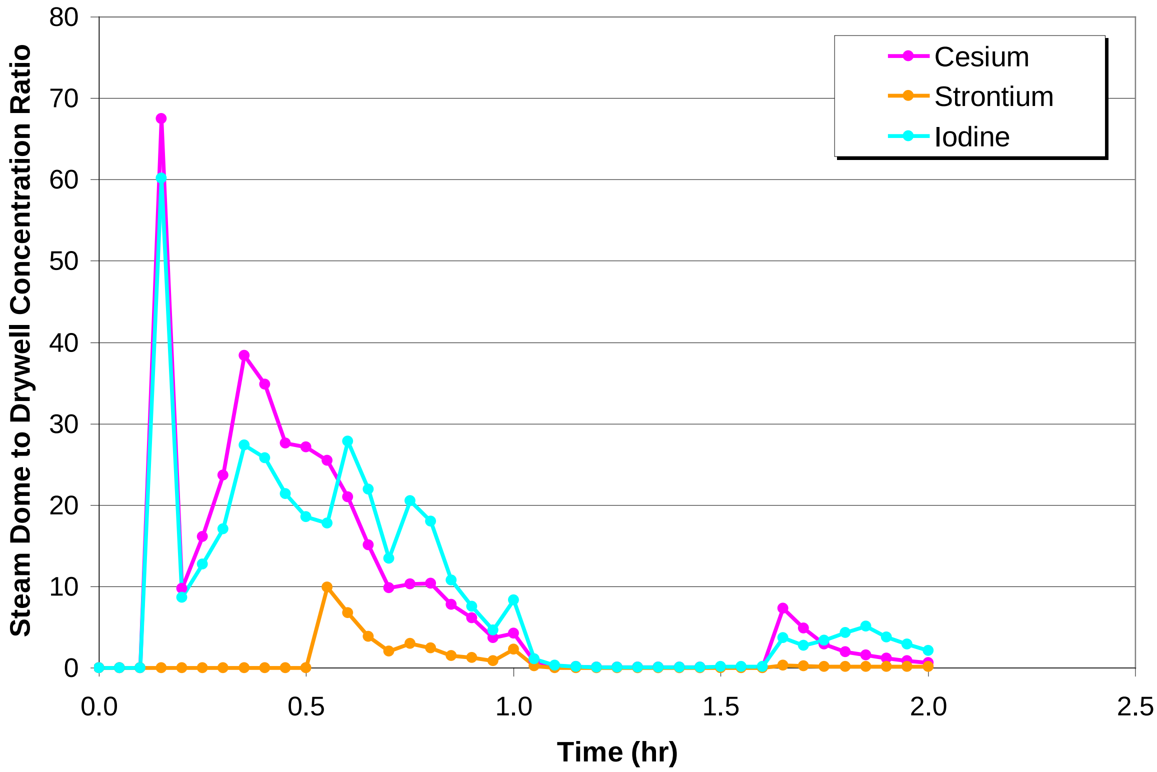


Figure 5-7: Ratio of MELCOR Steam Dome to RADTRAD Drywell for RN Class 2, 3, and 4 in Mk-III RLB

Table 5-2: MELCOR Steam Dome to RADTRAD Drywell Ratio for Various Time Intervals for Mk-III RLB

time (Hr)	Cs	Sr	I
0.0-0.5	21.43	-----	16.90
0.5-1.0	11.61	2.57	14.45
1.0-2.0	1.14	0.14	1.56

These two tables correspond to the Powers 10% aerosol removal by natural processes model for BWR drywells. Values are 20% higher when using the Powers 50% model.

To approximate the effect of a larger drywell increasing the concentration ratio, the ratios determined earlier are multiplied by a scaling factor related to the drywell volume. This scaling factor calculated as the ratio of the drywell volume for the geometry under consideration to the drywell volume that was used to obtain the original ratios (1.59E+05 ft^3 for the Mk-I drywell). For the Mk-III model the scaling factor is calculated to be 1.698. Therefore, the effective steam dome to drywell fission product concentration ratios used for the Mk-III will be:

- 0-0.5 hr: 15.24 * 1.698 = 25.88
- 0.5-1 hr: 6.64 * 1.698 = 11.28

In general, we conclude that this drywell scaling factor should be generally applicable to other BWR containment geometries, such as Mk-II designs.

The steam dome to drywell ratios were implemented in RADTRAD by determining the source concentration using the provided ratios, determining the fraction of AST release that would result in this concentration when placed in the source volume used in RADTRAD, and scaling the AST release to the source volume using these fractions.

In order for the model to represent the physical flow paths of the main steamline connections, the source volume is given the volume of the steam dome for the first two hours (after 2 hrs it is assumed that the vessel has been reflooded with an assumed equilibration of steam dome and drywell FP concentrations). As a result, the radionuclide releases must be scaled according to this volume in order to get the desired concentration within the steam dome. The volumes used for the steam dome, which are taken from the MELCOR models, are 3.7116E+03 ft^3 for the Mk-I and 6.6392E+03 ft^3 for the Mark III. The precise values used for these volumes are not important because the concentrations are scaled to them.

The ratio of steam dome volume to drywell volume for the Mk-I was 0.02334, and the ratio for the Mk-III was 0.02459. Therefore, the final fraction of the source that was placed in each of the modeled steam domes is shown in Table 5-3. Although the steam dome to drywell ratios for Cs and I in the MK-III RLB case are somewhat greater than 1 during the period from 1 to 2 hours, the ratio of steam dome-to-drywell concentration was taken to be 1 for times greater than 1 hour in the calculation of the source fractions (i.e. the source term fraction entering the steam dome after 1 hour is set equal to the steam dome to drywell volume fraction). Because the concentration in the steam dome is expected to drop below that of the drywell upon reflood and remain less than that of the drywell for some period before eventual equilibration with the drywell concentration, a value of 1 is expected to be conservative if the ratio was averaged beyond 2 hours.

Table 5-3: Source Term Fractions to be Placed in Steam Dome Volumes for Mk-I and Mark III

	Mark I	Mark III
Steam Dome 1 (0-0.5 hr)	0.35575	0.63638
Steam Dome 2 (0.5-1 hr)	0.15500	0.27737
Steam Dome 3 (> 1 hr)	0.02334	0.02459

5.3 Removal Coefficients

The removal coefficients (lambdas) used in the steam line only RADTRAD models are those determined by the MELCOR MSL model uncertainty studies. The inboard lambdas are set to zero (see discussion in Section 7.4). The 50^{th} percentile removal coefficients used for the RADTRAD simulations are shown in Table 3-14.

5.4 MSL Flow Rates

The methodology for calculating flow rates for the RADTRAD models is similar to the approach used by Metcalf [10]. The method is based on equations for orifice flow such as described by Bird, Stewart and Lightfoot [11].

The mass flow rate of an ideal gas through a nozzle is given by:

$$w = A \cdot \sqrt{2 P_{up} \rho_{up} \cdot \left(\frac{k}{k-1}\right) \cdot \left[\left(\frac{P_{dn}}{P_{up}}\right)^{\frac{2}{k}} - \left(\frac{P_{dn}}{P_{up}}\right)^{\left(\frac{k+1}{k}\right)}\right]} \qquad (5.1)$$

where

w = mass flow rate
A = area of nozzle
P_{up} = upstream pressure
P_{dn} = downstream pressure
ρ_{up}= upstream density
ρ_{dn}= upstream density, and
$k = C_p/C_v$ specific heat ratio.

The downstream pressure which results in the maximum flow rate using this equation is referred to as the critical pressure, P_{cr}, and is given by:

$$P_{cr} = P_{up} \cdot \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}. \qquad (5.2)$$

The mass flow rate remains constant with any further reduction of the downstream pressure beyond the critical pressure. Therefore, whenever $P_{dn} < P_{cr}$, the downstream pressure, P_{dn}, in equation 6.1 should be replaced by the critical pressure given in equation 6.2.

These equations can be used to:

1. determine the flow area given the mass flow rate of a given gas and pressures and temperatures on either side of an orifice, and to:
2. determine the mass flow rate of a specified gas given the flow area and pressures and temperatures on either side of an orifice

The flow rate at accident conditions is determined using essentially these two steps.

The first step in the process of determining MSIV leakage under accident conditions is the determination of the flow area that would produce the observed leakage of air during the valve leak testing. Properties for air, the MSIV test conditions, and the limiting mass flow rate are used in the nozzle flow equation to determine a flow area, A. The limiting mass flow rate for this calculation can be obtained by multiplying the limiting volumetric leakage at standard conditions by the air density at the standard conditions. The accident leakage rate is then determined by a subsequent application of the same equation using the calculated leak area, steam properties instead of air properties, and accident pressures and temperatures. The calculated accident mass flow rate can be converted to volumetric flow, which is used as input for RADTRAD, at different locations along the steam lines using the local density.

Although these equations are sufficient to determine the accident leakage rate in the event that a single MSIV closes, further calculations are required for the situation when both MSIVs close in order to account for the fact that both valves do not experience the same pressure difference and for the fact that the gas can be heated by the steam lines, which is especially significant for the volume between the MSIVs due to the potential pressurization of this volume. A detailed explanation of the methods used to determine flow rates for the case when both MSIVs close is provided in the calculation below.

5.4.1 Example calculation

For the determination of the volumetric flows for the pathways connecting the volumes in RADTRAD, Metcalf's approach was followed, including the following major simplifying assumptions:

1. both valves experience the same pressure difference, the drywell/steam dome to atmospheric pressure difference.
2. that the different temperatures upstream of the MSIVs can be used to determine the different volumetric flow rates through the valves

The assumptions and values used in this example are for the purposes of demonstrating the methodology only. Ideally, the temperature and pressure expected upstream of each MSIV should be used in the determination of flow through that valve. The determination of bounding values for accident pressures and temperatures on either side of the MSIVs would require a more thorough heat transfer analysis than was applicable for this study.

Metcalf's analysis essentially assumes both valves see the same pressure drop and that critical flow limits leakage. Downstream of the outboard valve, the volumetric flow is determined by converting the outboard valve volumetric flow at its upstream pressure and temperature to volumetric flow at the temperature and pressure estimated for conditions downstream of the outboard valve using the standard ideal gas relation that PV/T remains constant. This produces an increased volumetric flow since the gas is expanding significantly after exiting the outboard valve under the assumed pressure conditions. Using the Imperial units employed by Metcalf, the method is reiterated as follows:

1. Determine a flow area using the test pressure, air properties, and allowable leakage.
2. Use this area to calculate a flow rate for steam at accident conditions for the inboard portion of the MSL and the inboard MSIV.
3. Calculate the increase in volumetric flow for the outboard MSIV due to an increased temperature in the volume between the MSIVs.
4. Determine the flow rate outboard of the MSIVs at standard atmospheric pressure (P_{atm}).
5. Verify that the assumed conditions indeed resulted in sonic flow.

The critical pressure and a mass flow per unit area (G = *w/A*) were determined using equations 6.2 and 6.3, respectively. Equation 6.3 is simply equation 6.1 rewritten on a per unit area basis with specific volume, $\nu = 1/\rho$, used in place of density. Once the allowable leakage has been converted to a mass flow rate under the test conditions using the ideal gas law and specific volume for air (Equation 6.4), this mass flow rate can then be divided by the calculated G to obtain the leakage flow area (Equation 6.5).

$$G = \sqrt{2 \times g_c \times \frac{k}{k-1} \times \frac{P}{\nu} \times \left(\left(\frac{P_{cr}}{P} \right)^{\frac{2}{k}} - \left(\frac{P_{cr}}{P} \right)^{\frac{k+1}{k}} \right)} \tag{5.3}$$

$$\text{leak rate limit}\left[\frac{lbm}{s} \right] = \text{leak rate limit}[scfh] \times \frac{P_{atm}}{P_{test}} \times \frac{1}{\nu \left[\frac{ft^3}{lbm} \right]} \times \frac{1[hr]}{3600[s]} \tag{5.4}$$

$$\text{A}\left[\text{ft}^2\right] = \frac{\text{leak rate limit}\left[\frac{\text{lbm}}{\text{s}}\right]}{\text{G}\left[\frac{\text{lbm}}{\text{s} \cdot \text{ft}^2}\right]} \tag{5.5}$$

Note that when using SI consistent units, the conversion factor g_c is not required.

The mass flux (mass flow rate per unit area) of steam through the inboard MSIV at accident conditions is determined with Equations 6.2 and 6.3 using parameter values that are consistent with those at the accident conditions. The pressure downstream of this valve, however, is assumed to be atmospheric. The pertinent parameters that differ between accident and test conditions are the specific volume, the pressure and temperature on which it depends, and the ratio of specific heats (1.3 for steam versus the 1.4 for air). This newly calculated G can then be multiplied by the specific volume at those conditions and the flow area calculated earlier (Equation 6.6) to determine the volumetric flow through the inboard MSIV.

$$\text{leak rate}\left[\frac{\text{ft}^3}{\text{s}}\right] = \text{G}\left[\frac{\text{lbm}}{\text{s} \cdot \text{ft}^2}\right] \times \text{A}\left[\text{ft}^2\right] \times \nu \left[\frac{\text{ft}^3}{\text{lbm}}\right] \tag{5.6}$$

The pressure between the MSIVs is expected to be closer to the inboard MSL pressure than to ambient. Metcalf assumes that the pressure upstream of the outboard valve is the same as the pressure upstream of the inboard valve. The gas temperature between the MSIVs, however, is assumed to be higher because the steamlines are still near operating temperature. Metcalf has assumed that the gas temperature upstream of the inboard valve is close to the drywell temperature but MELCOR analyses show that this is not the case. With approximately the same pressure as the inboard MSL, the velocity, and also volumetric flow if equal leakage areas are assumed in both MSIVs, is assumed to increase by the ratio of the sonic velocities of the two valves (Equation 6.7) . Therefore, to estimate the volumetric flow rate through the outboard

MSIV, the volumetric flow rate calculated for the inboard MSIV should be multiplied by the ratio calculated using this equation. Since all other parameters in this equation are equal for both volumes (i.e. identical primed and non-primed values) because the same gases are being compared, this sonic velocity ratio becomes the square root of the temperature ratio.

$$\frac{v_{sonic}^{'}}{v_{sonic}} = \frac{\sqrt{(k'-1)\frac{C_p^{'}}{M'}T'}}{\sqrt{(k-1)\frac{C_p}{M}T}} = \sqrt{\frac{(k'-1)C_p^{'}MT'}{(k-1)C_pM'T}} \tag{5.7}$$

The prime in this equation in this calculation indicates conditions upstream of the outboard MSIV (i.e. the volume in between the MSIVs) and the unprimed parameters refer to conditions in the main steam line upstream of the inboard MSIV. M refers to the molecular mass.

The MSL piping downstream of the out-board MSIV will be at atmospheric pressure but the temperature is assumed to be nearly the same as between the MSIVs. The volumetric flow outboard of the MSIVs can be determined using the standard ideal gas relation, PV/T=constant. To determine the volumetric flow rate outboard of both MSIVs, the multiplier calculated by Equation 6.8 should be multiplied by the volumetric flow rate calculated for the outboard MSIV.

$$\left(\frac{P_{inboard}}{P_{atm}}\right)\left(\frac{T_{outboard}}{T_{inboard}}\right) \tag{5.8}$$

In this equation, the *inboard* subscript refers to the gas between the MSIVs and the *outboard* subscript refers to the gas outboard of the outboard MSIV. The volumetric flow rate through the outboard MSIV could alternatively also have been determined using the ideal gas relation.

For the representative Mk-I reactor a test pressure of 25 psig (39.7 psia) was used [12]. The allowable leakage was 205 scfh from one steamline and 155 scfh from a second line. Using these values, flow areas of 3.35E-5 ft^2 and 2.53E-5 ft^2 are calculated for the respective leakage rates. The accident conditions from the drywell are 63.8 psia and a saturation temperature of 296.7° F. The temperature in the volume between the MSIVs was assumed to be 551° F [12]. The pressure in this volume is also expected to be higher than in the drywell for a short period of time but this was neglected for conservatism as was done by Metcalf. Therefore, the pressure between the MSIVs is assumed to be the same as that in the in-board MSL (63.8 psia). The outboard MSL is assumed to be at atmospheric pressure and 551° F. The flow rates calculated for the MK-I design using these conditions and the equations discussed earlier are summarized in Table 5-4.

Table 5-4: Mk-I Main Steamline Flow Rates for RADTRAD Calculations

	Technical Specification Leak Rate Limit (scfh)	Flow Rate for Inboard MSIV and Inboard MSL (cfh)	Outboard MSIV Flow Rate (cfh)	Flow Rate Outboard of MSIVs (cfh)
Line A	205	113.92	131.68	660.58
Line B	155	86.13	99.56	499.46

The representative Mk-III documentation lists a test pressure of 26.2 psia which yields a down stream critical pressure somewhat less than atmospheric. As a result, the standard atmospheric pressure was used in place of critical pressure for Equation 6.4. The allowable leakage for the Mark III, considered to be 100 scfh in the two shortest lines and 50 scfh for the next shortest line, yields flow areas of 3.06E-5 ft^2 and 1.53E-5 ft^2 for the 100 scfh and 50 scfh flows, respectively. The accident conditions are assumed to be at the test pressure of 26.2 psia and a saturated temperature of 242.5° F. Once again, the standard atmospheric pressure, instead of the critical pressure, was used as the downstream pressure in Equation 6.4 for both valves. The vapor temperature in the MSL between MSIVs was assumed to be 500° F with a pressure of 26.2 psia. There is no appreciable amount of outboard piping in the Mk-III steamline, therefore an outboard line is not modeled. Although no outboard section of piping is modeled , the flow outboard of the MSIVs needs to be calculated to determine the volumetric flow from the condenser, which was assumed to be at atmospheric pressure. The flow out of the condenser was assumed to have the same temperature as the area between the MSIVs (500°F) for the purpose of calculating the volumetric flow rate. The flow rates calculated for the MK-III design using these values are summarized in Table 5-5.

Table 5-5: Mk-III Main Steamline Flow Rates for RADTRAD Calculations

	Technical Specification Leak Rate Limit (scfh)	Flow Rate for Inboard MSIV and Inboard MSL (cfh)	Outboard MSIV Flow Rate (cfh)	Flow Rate Outboard of MSIVs (Condenser Out Flow) (cfh)
Line A	100	101.29	118.41	246.69
Line B	100	101.29	118.41	246.69
Line C	50	50.65	59.20	123.35

5.5 Unchanged Model Parameters

Parameters not discussed above were taken from the Peach Bottom [12] and Grand Gulf [13] alternative source term documentation for the Mk-I and Mk-III models respectively. No attempt was made to validate assumptions used in these models. The models were used as presented in the documents with one exception. The Mk-III model for Grand Gulf credited a main steamline leakage control system (MSLCS). Since recent industry submittals typically do not credit leakage control systems, the Grand Gulf model was altered to consider a leakage pathway without the MSLCS.

These parameters include the removal mechanisms in the drywell. For the Mk-I, the 10% Powers model option is used [14]. For the Mk-III , both iodine and aerosol removal coefficients were calculated according to NUREG/CR-0009, reference 27 in the Grand Gulf document [13]. These removal coefficients were compared with using a 10% Powers model and the results were found to be similar, less than 5% difference at 30 days.

Each reference document also sited a time at which the pressure in the drywell has dropped to a point to allow a reduction in the flow rates. For the Mk-I this time was given as 38 hours after the start of the accident, and for the Mk-III it was given as 24 hours.

Leakage from the source term volumes was also included in the models. For the Mk-I this represented 0.7% containment volume per day which was reduced to half after 38 hours. For the Mk-III 3000 cfm representing drywell bypass flow, scaled by the ratio of the steam dome volume to the drywell volume, was used. This value was reduced by half at 24 hours corresponding with the pressure drop in the drywell.

The flows between the environment and the control room were also taken from the reference documents. The Mk-I model has two flows into the control room, one filtered and one not and one unfiltered flow out of the control room. The Mk-III model has one unfiltered flow into the control room and one unfiltered control out of the control room, but unlike the Mk-I it also has recirculating filters on the control room volume.

The other parameters taken from the reference documents were the dose location and simulation parameter values. These include the χ/Q values, occupation factors, breathing rates, and simulation time step sizes.

Iodine removal values were taken from the Peach Bottom reference document. This was a filter of 50% on elemental iodine for each portion of the line that was credited. Consistent with current practice, no organic iodine removal is credited. In the Mk-I models this was two filters on each line. For the Mk-III this was one filter because the inboard portion is not credited and there is not a significant portion of piping modeled downstream of the outboard MSIV. With the treatment of gaseous iodine removal being uncertain, results will be given for the discussed filter configuration as well as no removal of elemental iodine within the steamlines.

Something unique to the Mk-I was a mixing of the drywell and wetwell volumes at 2 hours. The Mk-III documentation discussed mixing the drywell and lower containment volumes, but did not actually use this technique for the MSIV leakage calculation. In the Mk-I simulation, rather than adding a wetwell volume, there was simply a reduction in flow out of the source volume by the ratio of the drywell volume to the total volume of the wetwell and drywell. Through additional RADTRAD simulations, this method was shown to be conservative relative to actually mixing the volumes. The reduction in flow method was maintained in the following calculations because the condenser simulation was already at the 10 volume limit in RADTRAD, preventing the addition of a wetwell volume.

5.6 Main Steam Line Model Results

A summary of the main steam line model results for both the Mk-I and Mk-III models with and without condensers can be found in Table 5-6. For the cases with condensers, none of the doses exceed the 10 CFR limit. However, for the cases without condensers the control room doses far exceed the limit as do the EAB 2 hour integrated doses. The LPZ limit is not exceeded in the case of the Mk-I, but is in the case of the Mk-III. So the Mk-III without a condenser exceeds the dose limits at all three locations.

Table 5-6: Summary of TEDE Dose Results for Mk-I and Mk-III Steam Line Models (Elemental Iodine and Aerosol Removal Included, No Organic Iodine Removal Included)

	EAB, worst 2 hour integrated dose (rem)	**LPZ, integrated dose after 30 days (rem)**	**CR, integrated dose after 30 days (rem)**
10 CFR 50.67 Limit	25	25	5
Mk-I, No Condenser	49.5	8.6	57.7
Mk-I, Condenser	1.0	0.4	3.8
Mk-III, No Condenser	88.1	27.5	71.9
Mk-III, Condenser	0.5	0.4	1.4

The results for the simulations without elemental iodine removal can be seen in Table 5-7. There is not a large difference in the dose, but some increase is apparent. Because the dose results predominantly from the large concentration of aerosols, the difference between the elemental iodine removal case and the no-elemental-iodine-removal case is small.

Table 5-7: Summary of TEDE Dose Results for Mk-I and Mk-III Steam Line Models (No Elemental or Organic Iodine Removal Included, Aerosol Removal Included)

	EAB, worst 2 hour integrated dose (rem)	**LPZ, integrated dose after 30 days (rem)**	**CR, integrated dose after 30 days (rem)**
10 CFR 50.67 Limit	25	25	5
Mk-I, No Condenser	57.7	11.1	86.4
Mk-I, Condenser	1.4	0.62	7.0
Mk-III, No Condenser	142.4	42.6	117.8
Mk-III, Condenser	0.88	0.67	2.7

The LPZ and CR integrated doses out to 30 days and 24 hours are shown in Figure 5-8 through Figure 5-11. The results from all of these plots include iodine removal. It is apparent from the shape of the 30 day figures that the condenser serves as a significant hold-up volume that allows for decay and removal of activity and slowly releases the activity over a longer time period.

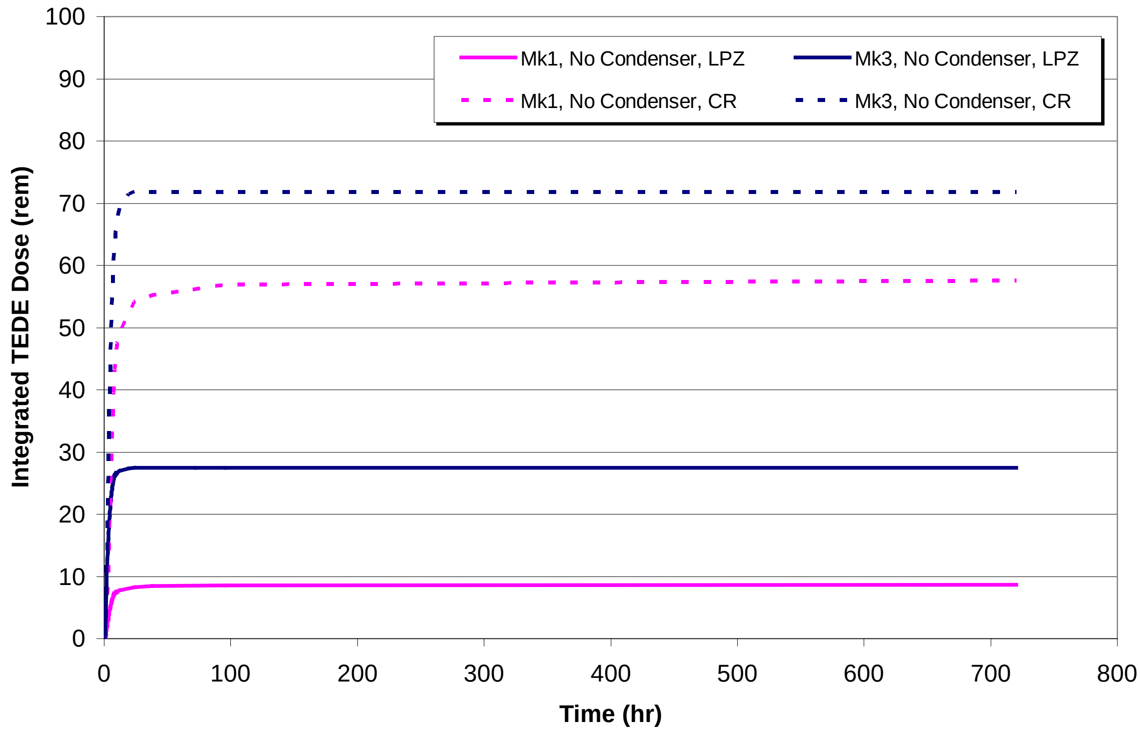


Figure 5-8: Integrated Control Room and LPZ TEDE for No Condenser Cases out to 30 Days

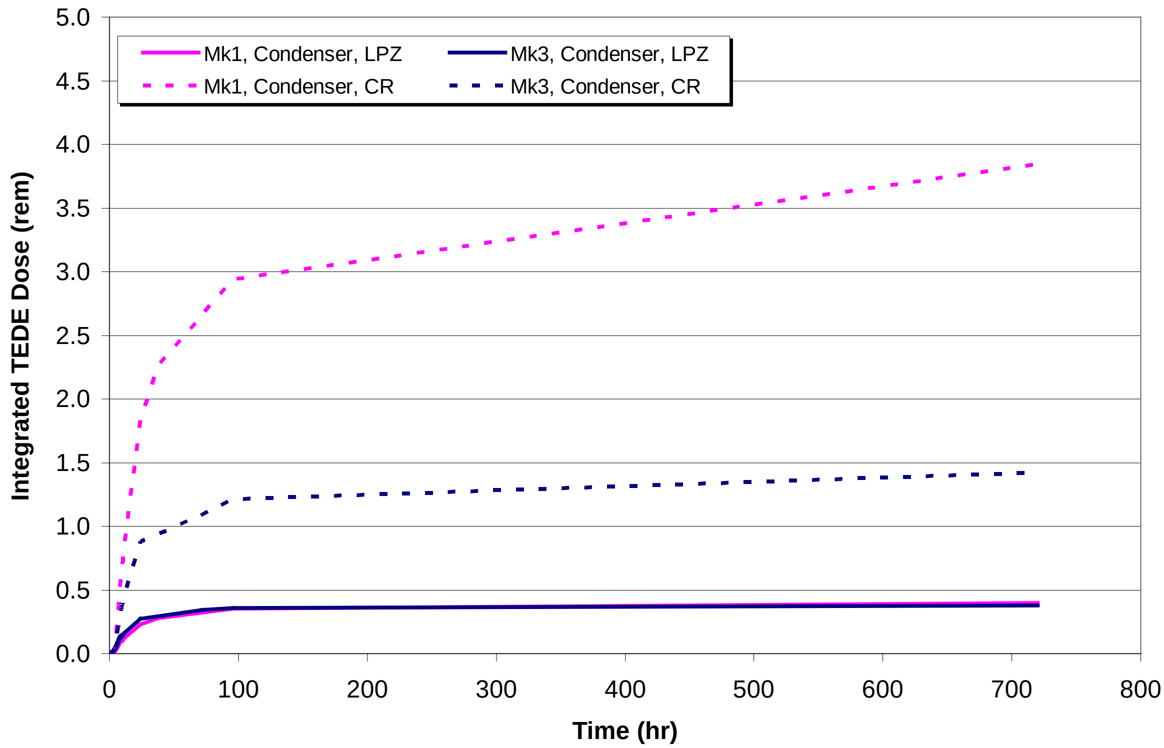


Figure 5-9: Integrated Control Room and LPZ TEDE for Condenser Cases out to 30 Days

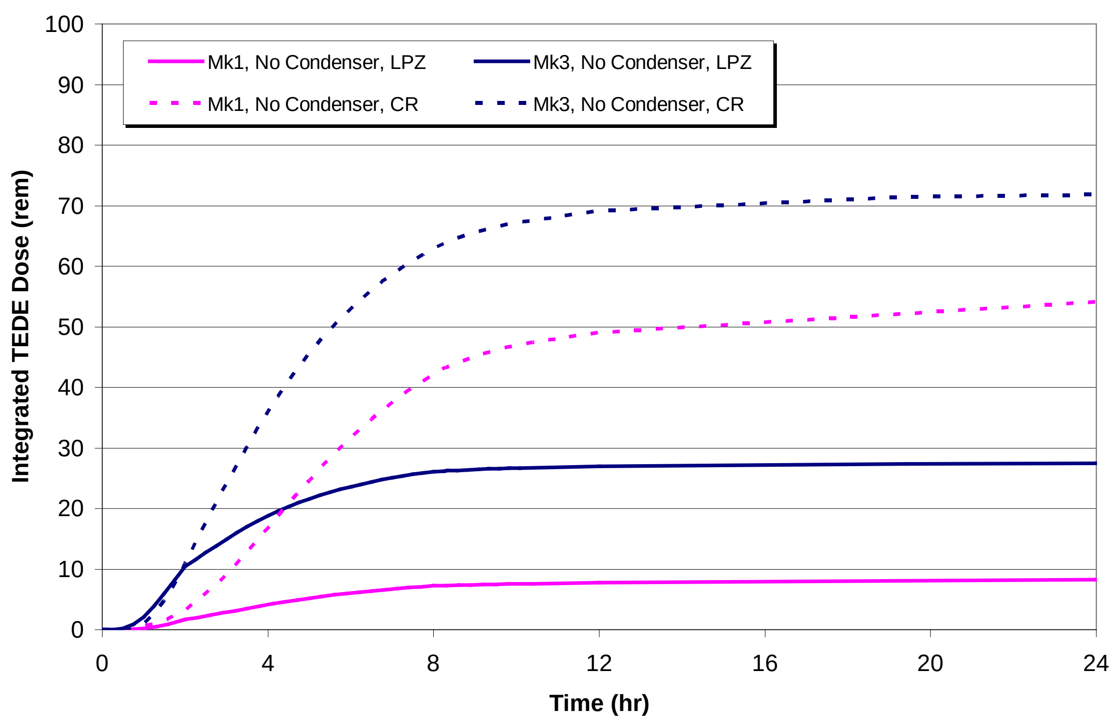


Figure 5-10: Integrated Control Room and LPZ TEDE for No Condenser Cases out to 24 Hours

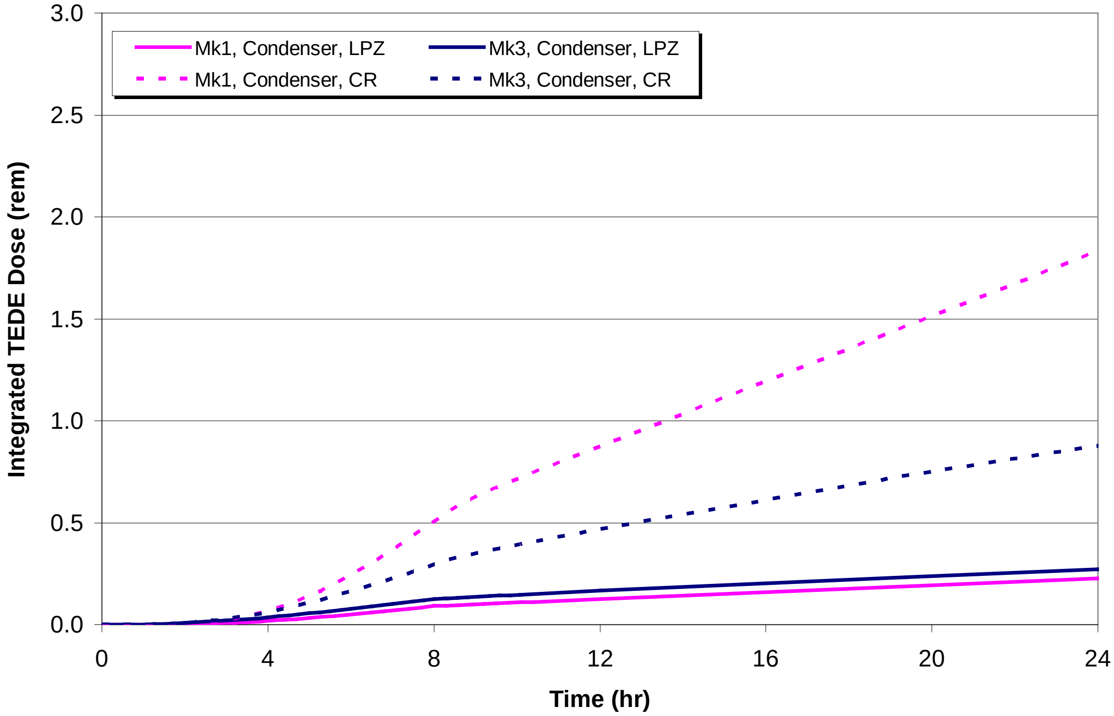


Figure 5-11: Integrated Control Room and LPZ TEDE for Condenser Cases out to 24 Hours

The integrated doses for the LPZ at 2 hours compared with the full model results at two hours are higher by a factor of nearly 5.5. The CR doses at 2 hours are higher by a factor of between 4.9 and 8.7 when compared with the full model doses. It was thought that much of this difference is due to ignoring deposition in the inboard sections of the main steamline. In order to investigate this further, the cases were each run with MELCOR derived lambdas for the inboard portions of the lines.

The results compared with the methodology proposed as well as the MELCOR values can be seen in Figure 5-12 and Figure 5-13. Notice that when the inboard lambdas are included in the simulation there is much better agreement between the Full Model and the MSL-Only Model. At 2 hours this difference is approximately a factor of 2.3 for the EAB and LPZ and 3.3 for the CR. These differences also decrease slightly by the time the simulations reach 5 hours.

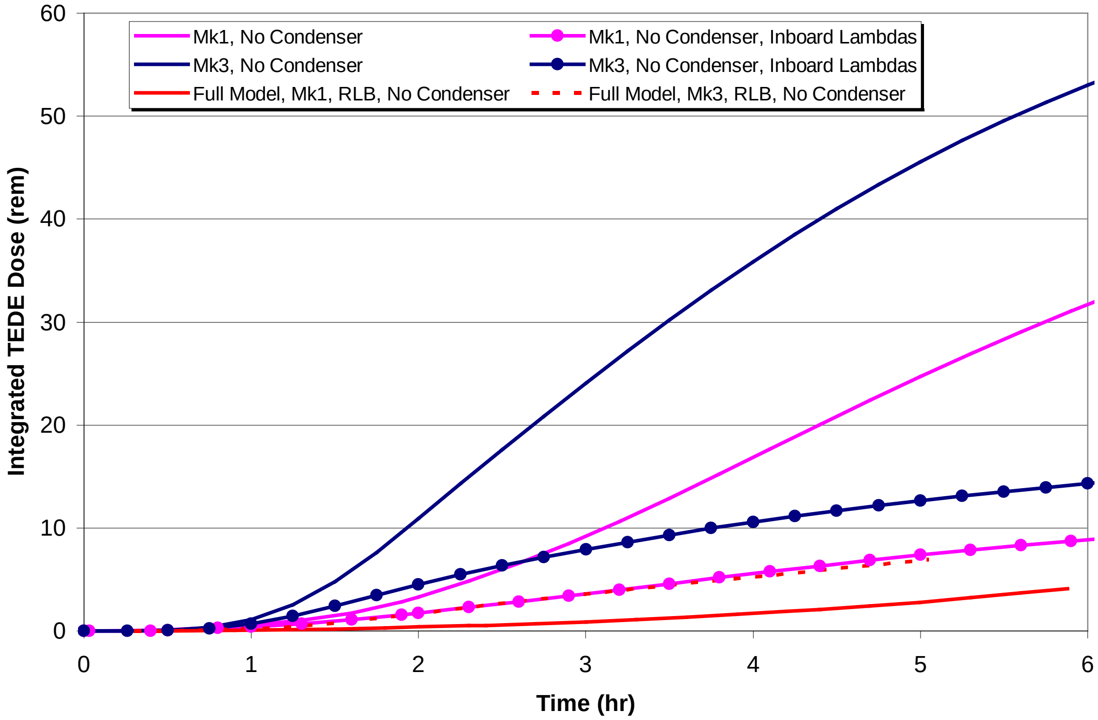


Figure 5-12: Comparison of CR Integrated TEDE with and without Inboard Lambdas to Full Model Results for Mk-I and Mk-III No Condenser Cases

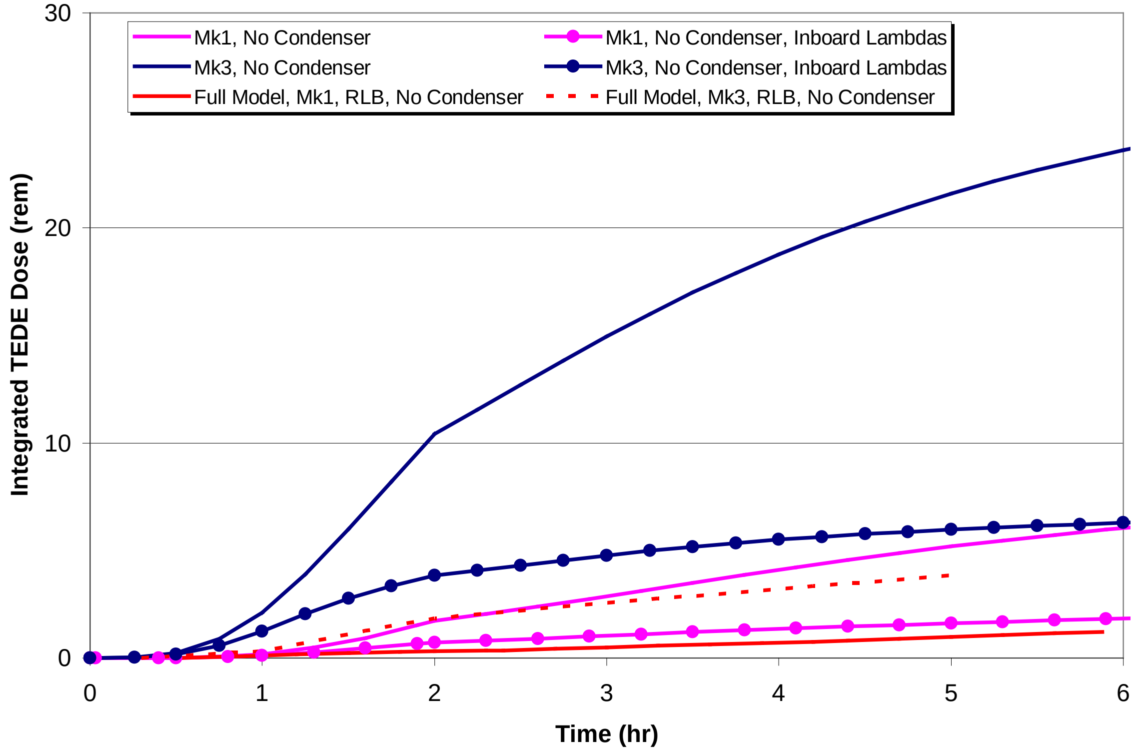


Figure 5-13: Comparison of LPZ Integrated TEDE with and without Inboard Lambdas to Full Model Results for Mk-I and Mk-III No Condenser Cases

5.7 RADTRAD Reference Industry Model

There is no reference model for the Mk-III reactor because in the document used as a source for all representative Mk-III values [13], the MSIV leakage calculation was only carried out to 18 minutes. Since we want to model a "representative" Mk-III, our calculations were carried out to the standard 30-days.

The Mk-I model used for comparison is from the Peach Bottom Analysis Number PM-1077. The title of this report is "Post-LOCA EAB, LPZ, and CR Doses Using Alternative Source Term (AST)." [15] The RADTRAD geometry for this analysis can be found on Page 84 and 85 of the report as Figures 4 and 5. They are shown here as Figure 5-14 and Figure 5-15.

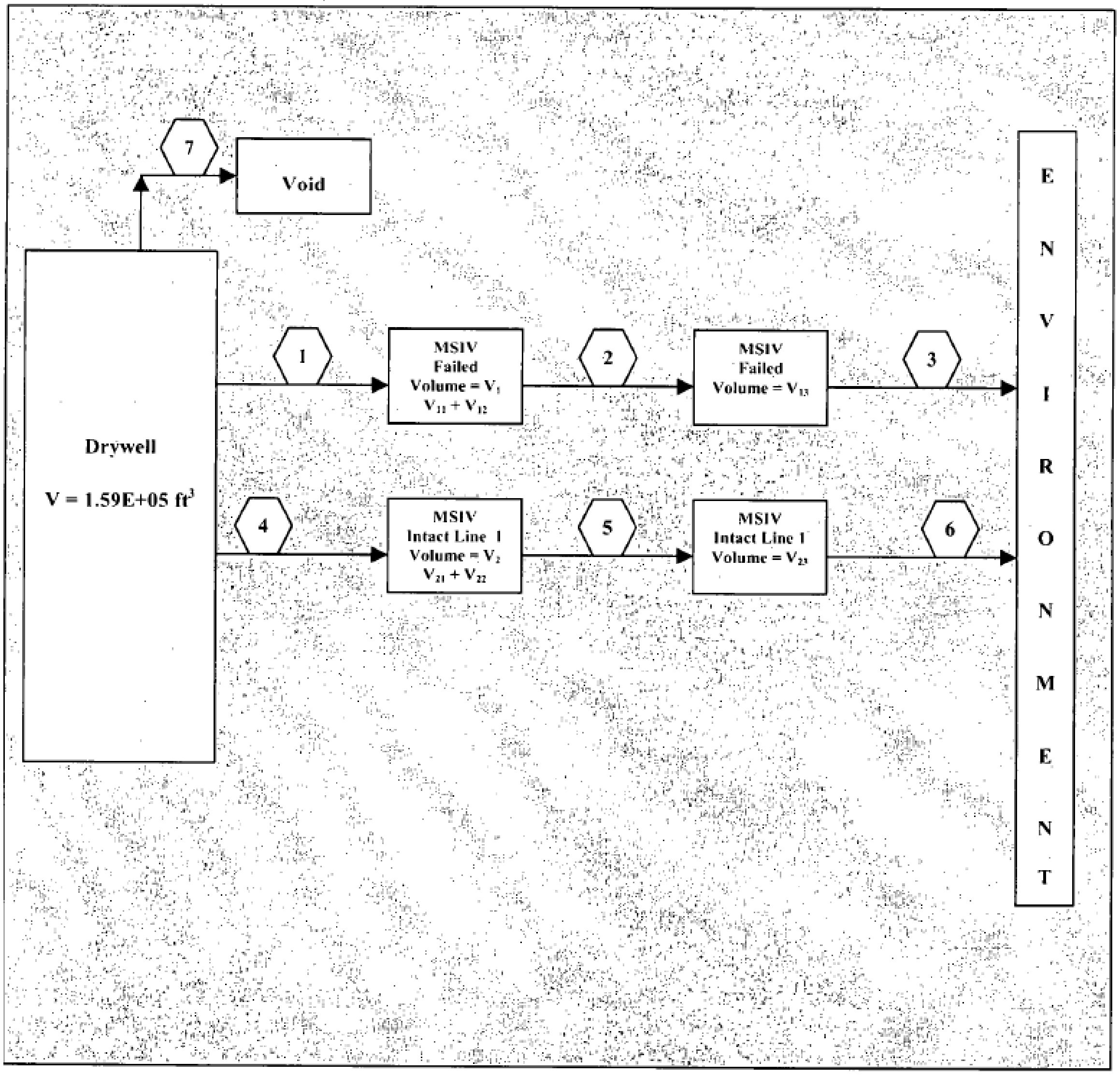


Figure 5-14 Part 1 of Peach Bottom RADTRAD Model, Mark 1 Comparison

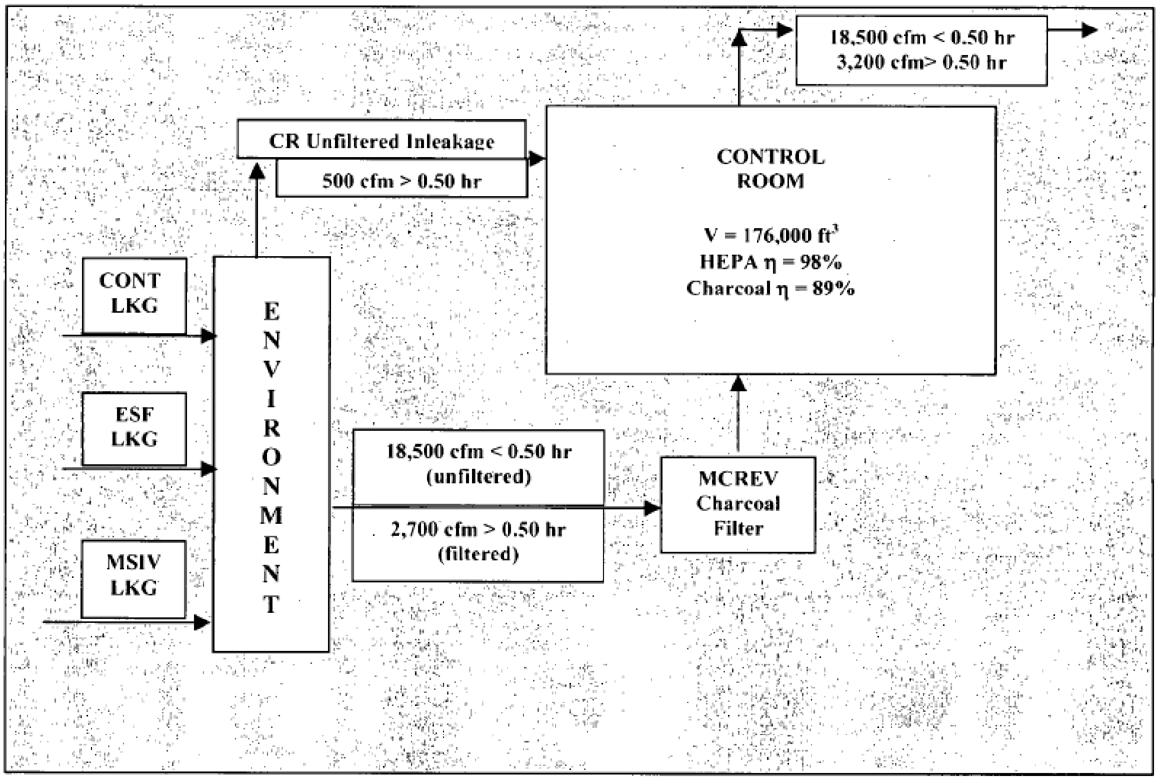


Figure 5-15 Part 2 of Peach Bottom RADTRAD Model, Mark 1 Comparison

The results for the MSIV leakage model start on page 135 of the report. The worst two hour dose for the exclusion area boundary (EAB) is 3.48 rem. The integrated dose out to 30 days for the low population zone (LPZ) is 0.99 rem. The integrated dose out to 30 days for the control room (CR) is 4.36 rem. All are within the regulatory limits.

In examining the input for this case, it was found that the Peach Bottom analysis credited wall deposition of iodine in the drywell using the RADTRAD containment spray model. To have results appropriate for comparison later in this study, a case identical to the Peach Bottom analysis was run in RADTRAD but without wall deposition..

6 Summary and Recommendations

6.1 *Recommendations for the Application of Steam Dome-to-Drywell Concentration Ratios to RADTRAD Calculations*

MELCOR best estimate analyses of two DBA initiated accidents where significant core melting and fission product release has occurred have been explored to evaluate MSIV leakage behavior for two widely deployed BWR containment designs, Mk-I and Mk-III. These analyses have shown that, during the first two hours of such an accident, the airborne fission product aerosol concentrations in the reactor vessel significantly exceed those in the drywell. Since the atmosphere in the reactor vessel supplies the effluent that ultimately leaks through the MSIV's, not the atmosphere in the drywell volume, these findings conclude that the current regulatory guidelines permitting the use of the fission product concentration in the drywell atmosphere during the first two hours prior to assumed vessel reflood is non-conservative for the purposes of evaluating the dose resulting from MSIV leakage, in addition to being conceptually inaccurate.

This study has investigated means of adapting the current regulatory *containment* source term for application to MSIV leakage analysis by means of scaling factors, accounting for differences in vessel fission product concentration and containment concentrations, and for differences in the NUREG-1465 derived containment concentrations compared to current best estimate derived containment concentrations. The developed scaling methodology preserves the simplified approach currently described in the regulatory guide by maintaining use of the AST; alternatively, detailed physics-based computer codes such as MELCOR, could be used to analyze source term release and transport.

Based on this work, it is recommended that the NUREG-1465 drywell fission product concentrations be scaled based on the time-phased scaling factors presented in Table 5-1 and Table 5-2 for application to Mk-I and Mk-III containments when determining the fission product concentration that is the source for MSIV leakage. These tables correspond to the Powers 10% aerosol removal by natural processes model for BWR drywells. The scaling ratios are approximately 20% higher when using the Powers 50% model. The differences in scaling factors for Mk-I and Mk-III are predominantly a result of the differences in the drywell volumes alone. Therefore, extension of these recommendations to Mk-II or containments with different volumes can be justified by scaling the steam dome to drywell fission product concentration ratios by drywell volume (if the drywell volume is larger, then a larger scaling factor is required to obtain correct vessel concentration). This is a generic recommendation concerning the appropriate airborne concentration for evaluating MSIV leakage. A methodology for accomplishing this recommendation using RADTRAD has been demonstrated, using RADTRAD techniques such as superposition to accommodate the time-phased behavior of the releases; however, other code-based methods could be used to accomplish the same objective.

6.2 Recommendations for Sprays in RADTRAD Calculations

The MELCOR Full Reactor model results show that the activation of drywell sprays reduces the fission product release to the environment by reducing the drywell pressure. This pressure reduction decreases the MSIV leakage flow rates thus reducing fission product release. It also increases the flow rate between the steam dome which moves additional fission products out of the steam dome into the drywell. This increase did not, however, appreciably reduce the fission product concentration observed in the steam dome for approximately 1 hour in the cases that were studied.

While drywell sprays can clearly reduce containment leakage, and indirectly reduce MSIV leakage by lowering drywell pressure, it is recommended that sprays not be credited for any reduction of the airborne concentration in the vessel supplying MSIV leakage during the first two hours, since, as discussed earlier, it is the vessel, not the drywell, that is the source of fission product concentration available for MSIV leakage.

Following a presumed recovery by vessel reflooding at two hours, drywell sprays can be credited for reducing the concentration of containment aerosols flowing back into the vessel and to the MSIV regions. Additionally, it would seem reasonable to allow credit for the pressure reduction resulting from the use of containment sprays, thereby reducing the MSIV pressure difference and the flow rate through the valves, provided adequate engineering analysis of containment response to sprays and valve leakage as a function of pressure drop is performed.

6.3 Recommendations for Removal Coefficients in RADTRAD Calculations

Removal coefficients were calculated for the in-board segments of the MSLs. It is recommended, however, that no credit be taken for aerosol deposition in this portion of the MSLs. The basis for this recommendation is that at times in the simulation the temperature of portions of the in-board MSL piping are predicted to be high enough to vaporize fission products that had been previously deposited. This secondary source cannot easily be incorporated into a RADTRAD model, and if the initial deposition (via a non-zero removal coefficient) is credited, the omission of this secondary source would result in an under-prediction of fission products released downstream, and ultimately to the environment.

There have also been questions raised regarding decay heat from fission products deposited in the in-board piping that could cause natural convection-driven bi-directional flow between the steam dome and the in-board MSLs. While the well-mixed nature of the MSL control volumes does, in some fashion, capture the enhanced mixing that such flow would cause, it does not address the potential for enhanced bulk transport of fission products from the steam dome into the in-board MSLs. Note that this issue has been previously cited as a basis for not taking credit for aerosol deposition in the in-board MSLs – see page 4-15 of reference [3].

Recommended removal coefficients based on the MSL-only model uncertainty results are given in the following tables, repeated for convenience from Section 4. The 50% values shown in

Table 6-2 reflect mean tendencies and could be used to avoid conservatism; alternatively, the 5% values in the previous table reflect a greater degree of conservatism.

Table 6-1: Recommended MSL and Condenser Removal Coefficients (5th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
in-board	2.2*	0.0*	0.0*
between MSIVs	2.5	1.8	1.0
out-board	1.1	1.0	0.7
condenser	0.018	0.015	0.012

note. removal coefficients are given in hr^{-1}
* calculated values are shown, but a value of 0.0 hr^{-1} is recommended

Table 6-2: Recommended MSL and Condenser Removal Coefficients (50th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
in-board	3.2*	1.3*	0.4*
Between MSIVs	2.9	2.4	2.0
out-board	1.3	1.3	1.0
condenser	0.020	0.018	0.015

note. removal coefficients are given in hr^{-1}
* calculated values are shown, but a value of 0.0 hr^{-1} is recommended

Table 6-3: Recommended MSL and Condenser Removal Coefficients (95th Percentile)

MSL section	0 - 2 (hr)	2 - 12 (hr)	12+ (hr)
in-board	4.9*	2.3*	1.1*
Between MSIVs	3.8	3.7	4.4
out-board	1.6	1.7	1.6
condenser	0.023	0.023	0.021

note. removal coefficients are given in hr^{-1}
calculated values are shown, but a value of 0.0 hr^{-1} is recommended

6.4 Recommendations for Post-Reflood Conditions in RADTRAD Calculations

The results from the Mk-III RLB case in which core sprays were activated 10 minutes before lower head failure indicate that the re-introduction of water into the core generates sufficient steam such that the vast majority of fission products in the steam dome and, to a lesser extent, in the drywell are swept into the wetwell, which effectively prevents them from being available for release to the environment via MSIV leakage. This same behavior is also seen in the Mk-I results at the time of lower core support plate failure.

Based on this observation, we recommend that the scaling factors be set to unity following the first two hour period where scaling factors are used to adjust the AST-based containment concentrations to reflect vessel concentrations. This conservatively assumes that the drywell and steam dome environments are well mixed after vessel reflood takes place.

Deposition properties after reflood should be based on the characteristics of the containment aerosol (i.e size effects). In the single analysis that explored post-reflood conditions it was observed that the intermediate pipe deposition lambdas decreased over time following reflood owing to the change in size distribution brought about as the larger particles fall out. These depletion trends were not significantly different from the 5% results reported in Table 6-1 (~1 hr^{-1}). More analyses may be required to summarize the physical effect of decreasing lambda with decreasing particle mean diameter; however, the trends reported in this report serve as a minimal basis for recommending smaller lambdas in the hours and days following reflood.

6.5 Recommendation for the Influence of Flow Rates on MSL and Condenser Removal Coefficients

The results from the MELCOR MSL RLB flow uncertainty case show that there is some relationship between flow rates in the MSLs and the removal coefficient. However, this relationship is also highly dependent on the point in time of the accident progression. This is due to the influence of the aerosol particle size distribution on the removal coefficient. The current results do not support the development of a quantitative relationship between MSL flow and MSL or condenser removal coefficients.

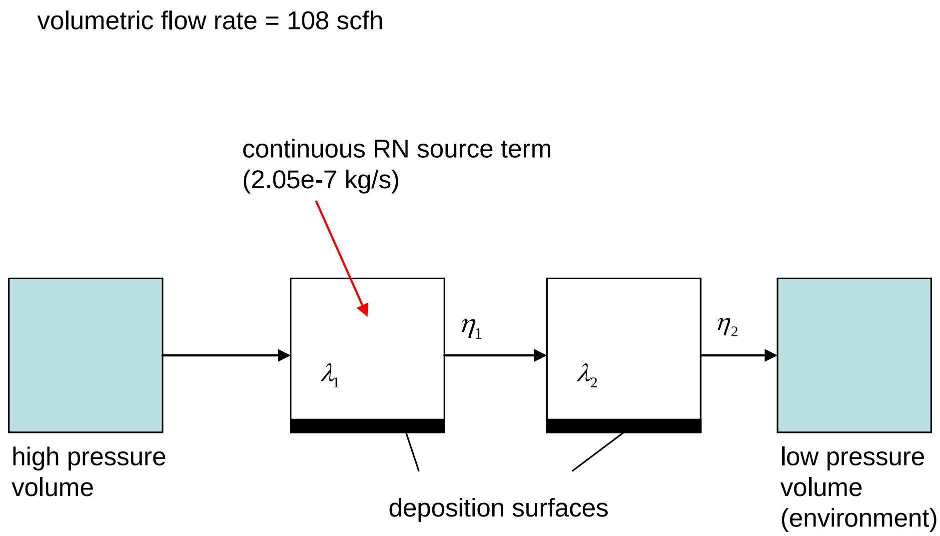
6.6 Recommendation Regarding the Use of Effective Filter Efficiencies for RADTRAD MSL Modeling

In the RADTRAD code the user has the option of specifying either removal coefficients to volumes or filter efficiencies to the flowpaths that connect the volumes. While these two treatments have been deemed equivalent [NRC 1998], this is only true in the specific case where the nuclide storage term is zero (i.e., steady-state conditions). The two options in RADTRAD for treating deposition are both empirical, and each represents very different fundamental views of physics. While a particular filter efficiency can be selected that in the end reflects the degree of holdup and removal of aerosols in a flow path, it cannot mechanistically represent the operative physics. To explore this further a small test problem, with geometry and conditions representative of MSIV leakage flow through steamlines, was investigated as described in the following.

A small MELCOR test problem was developed to evaluate the error in using filter efficiencies rather than removal coefficients under transient conditions. As shown in Figure 7-1, the problem consisted of four volumes: (1) a constant-pressure volume which was set to drive a constant 108 SCFH through down-stream flowpaths and volumes; (2) a volume [high-pressure] in which a single RN aerosol class was introduced at a constant continuous rate (2.05e-7 kg/s), this volume also contains a floor heat structure which provides a deposition location for gravitationally-settled aerosol particles; (3) a volume with floor heat structure; and (4) and a constant-pressure volume [environment] which was set to drive a constant 108 SCFH through up-stream flowpaths and volumes.

The test problem was run out to the time at which a steady-state concentration was reached (i.e., the slope of the curve of integrated RN mass in the environment is constant). Removal coefficients (lambda) and effective filter efficiencies (Feff) were calculated for the problem per the equations in the figure. An identical test problem model was then built for RADTRAD. That model was then run for two cases: (1) using the removal coefficients for the volumes; and (2) using the effective filter efficiencies for the flowpaths. The results were then compared to the MELCOR-predicted RN release to the environment. As shown in Figure 7-2, the case using the filter efficiency under-predicted the RN release (compare the blue curve with the black curve), while the case using the removal coefficients predicted an identical release to the MELCOR test problem result (compare the red dashed curve with the black curve).

Based on these results, it is recommended that deposition in MSL pipes only be modeled in RADTRAD using removal coefficients and that the optional modeling method of using effective filter efficiencies applied to flowpaths not be used unless an actual filtering process is being represented.



$$\lambda = \frac{1}{m}\dot{m}_{dep}$$

$$\eta = \frac{\dot{m}_{dep}}{\dot{m}_{dep} + \dot{m}_{out}}$$

Figure 6-1 MELCOR and RADTRAD Nodalization for Evaluating Effective Filter Efficiencies and Removal Coefficients

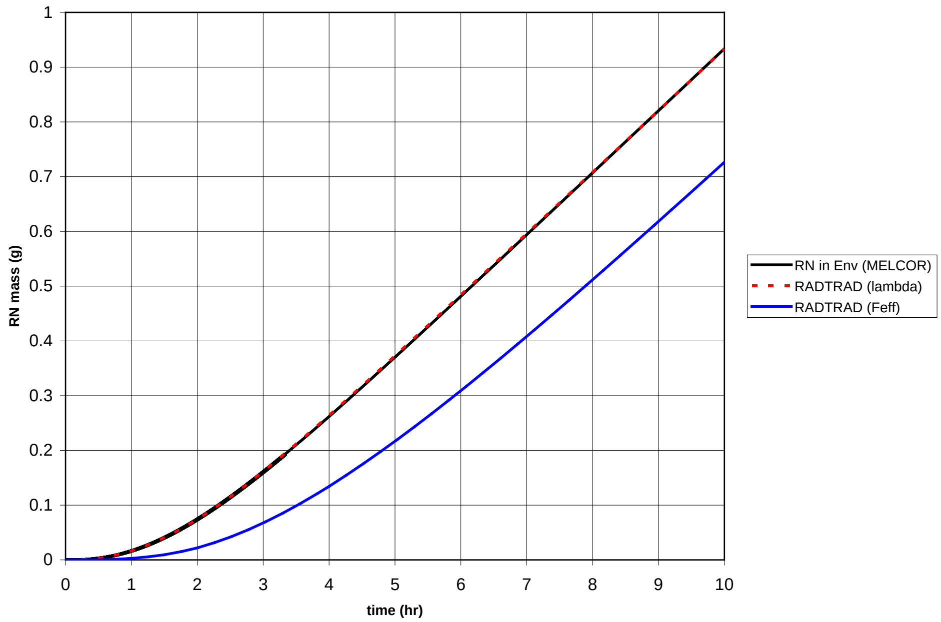


Figure 6-2 Evaluation of Effective Filter Efficiencies and Removal Coefficients --Comparison of MELCOR and RADTRAD RN Mass Releases.

6.7 Recommendation Regarding Calculation of MSIV Leakage Flow

It is recommended that analysis of valve leakage flow be generally based on the flow predicted using nozzle-flow theory as described in many fundamental text books such as Bird, Stewart and Lightfoot [11]. The flow equations described earlier in section 5.4, accommodate critical or sub-sonic flow and serve as a defensible means of analyzing both test leakage behavior and the scaling of these measured flows to the flows that would be expected under accident conditions.

The temperature and pressure expected upstream of each MSIV should be used in the determination of flow through that valve. The determination of bounding (conservative) values for the pressures and temperatures upstream of the MSIVs were not part of this study. Therefore, the temperatures and pressures used in the example are solely for the purposes of demonstrating the methodology and should not be taken as recommended values for MSIV leakage or as representative of the conditions upstream of the MSIVs.

7 Appendix A – Additional Mk-III Containment Analyses

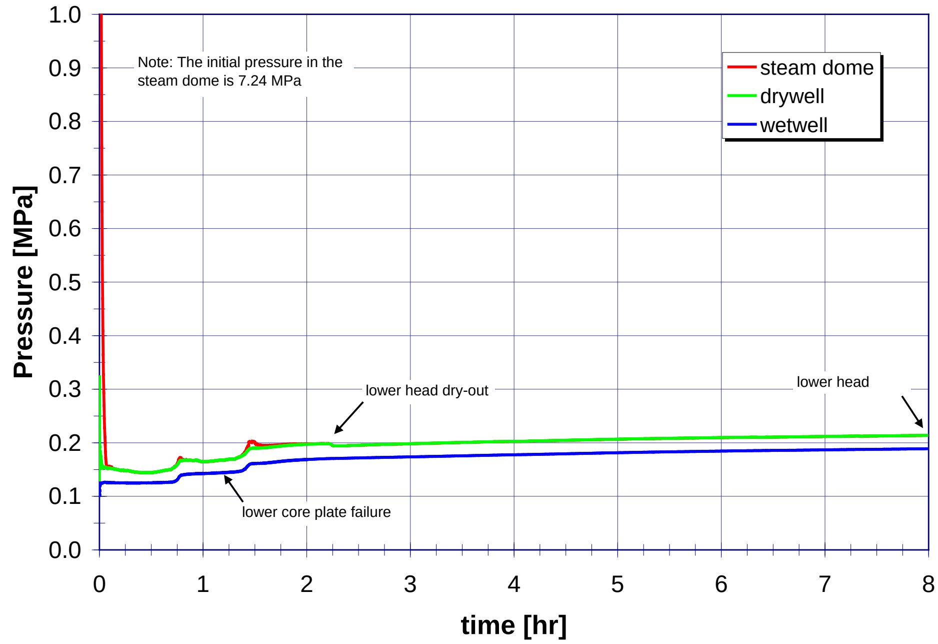


Figure 7-1 BWR Mk-III, MSLB, No Sprays: Steam Dome, Drywell, and Wetwell Pressure

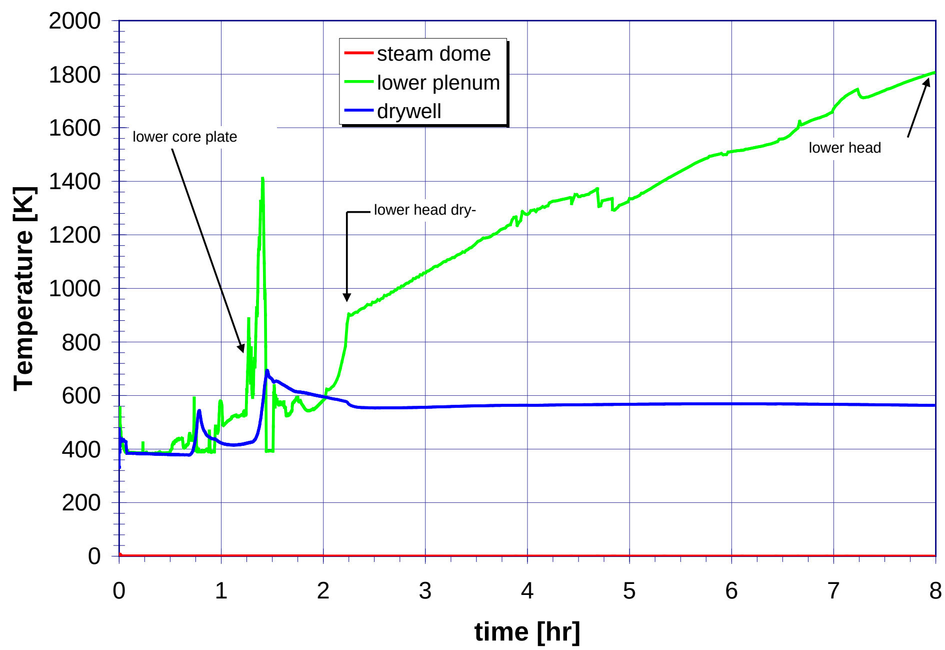


Figure 7-2 BWR Mk-III, MSLB, No Sprays: Steam Dome, Drywell, and Lower Plenum Vapor Temperature

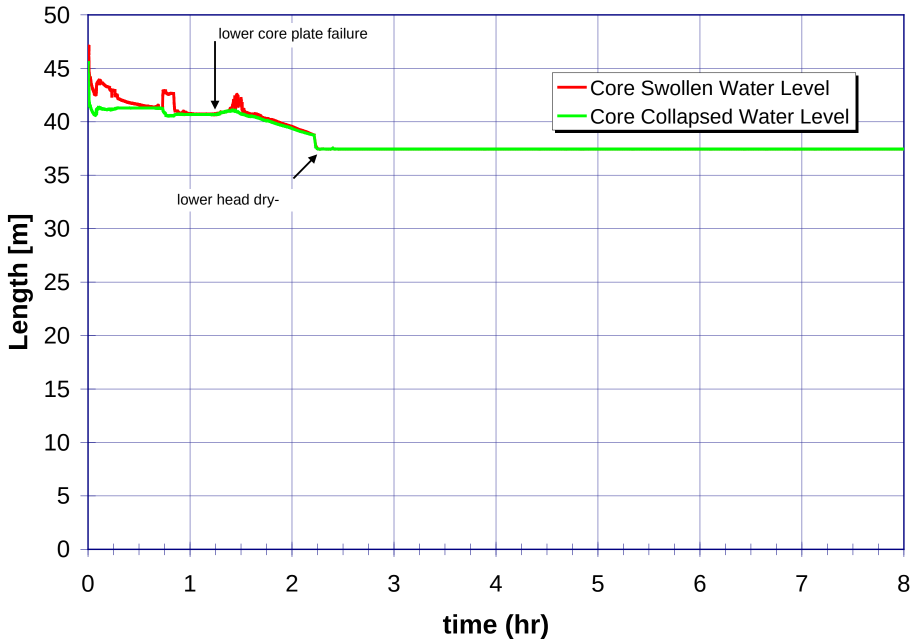


Figure 7-3 BWR Mk-III, MSLB, No Sprays: Core Water Levels

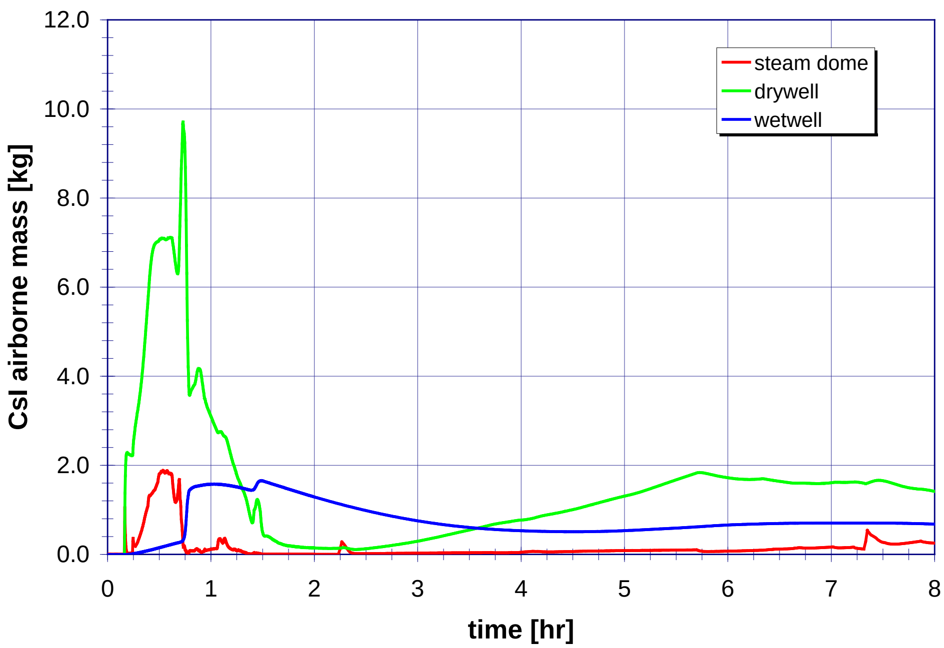


Figure 7-4 BWR Mk-III, MSLB, No Sprays: CsI Mass in the Steam Dome, Drywell, and Wetwell

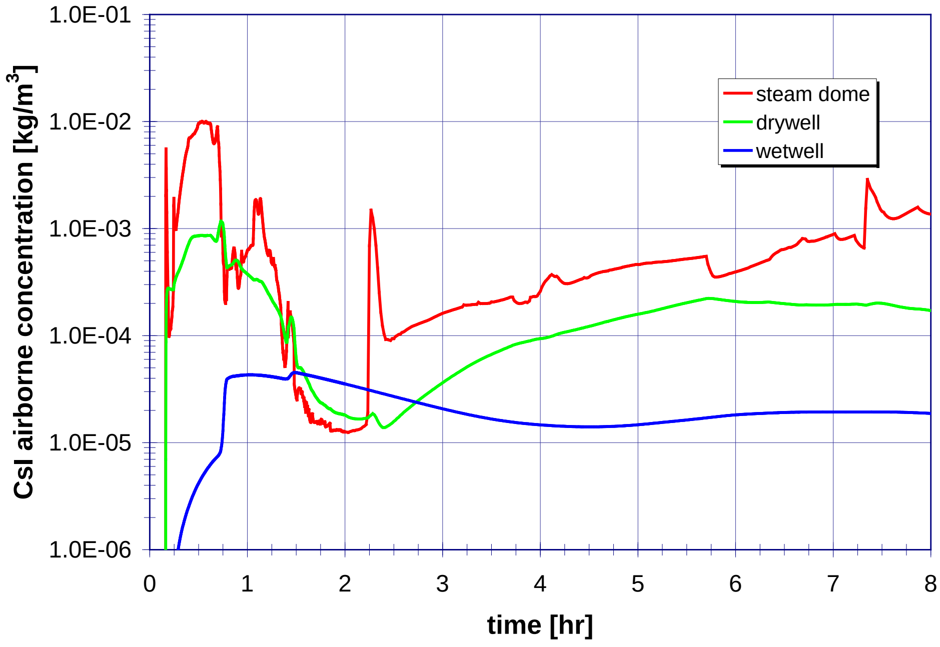


Figure 7-5 BWR Mk-III, MSLB, No Sprays: CsI Concentration in the Steam Dome, Drywell, and Wetwell

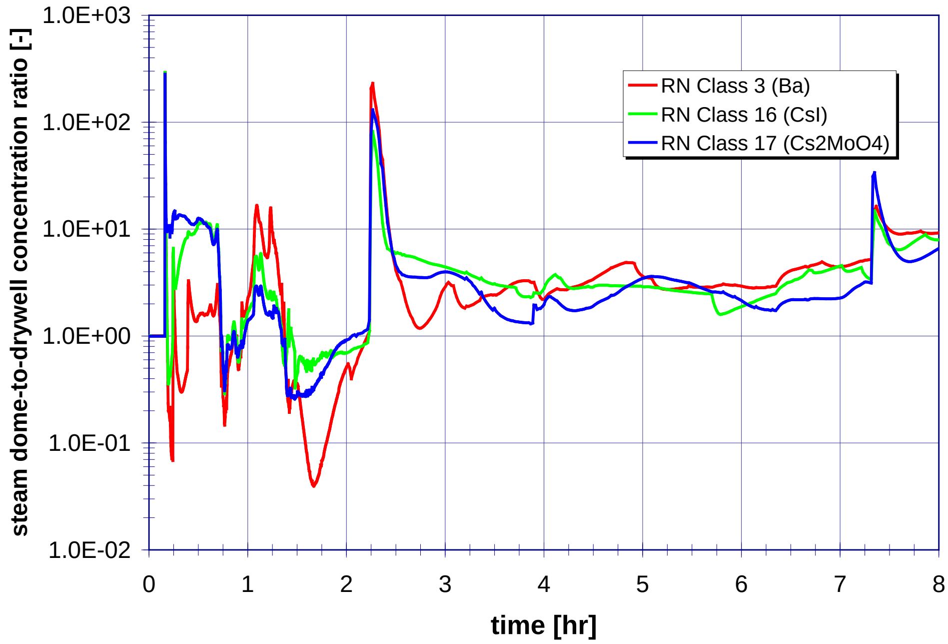


Figure 7-6 BWR Mk-III, MSLB, No Condenser, No Sprays: Steam Dome-to-Drywell Concentration Ratios

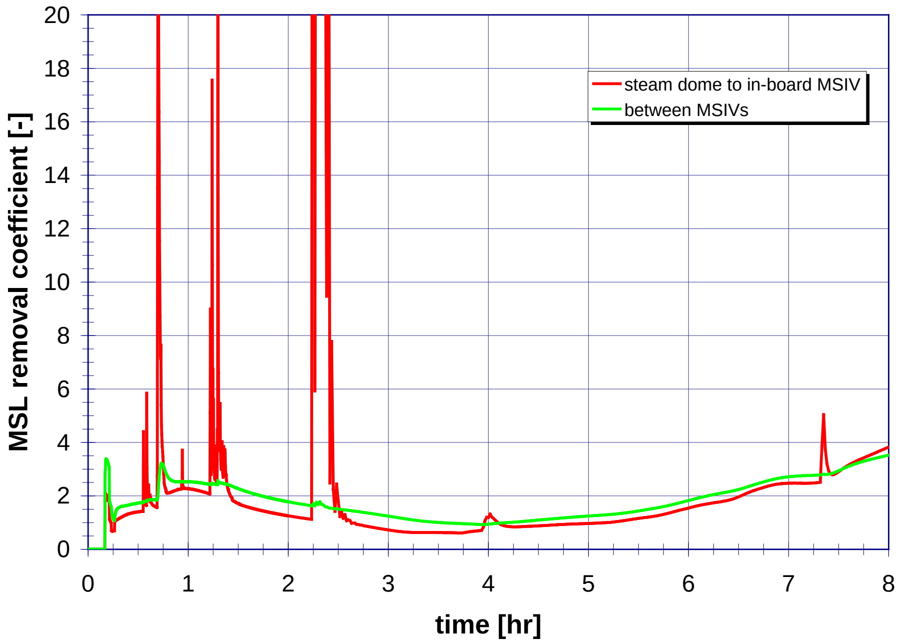


Figure 7-7 BWR Mk-III, MSLB,, No Sprays: MSL-A Removal Coefficients

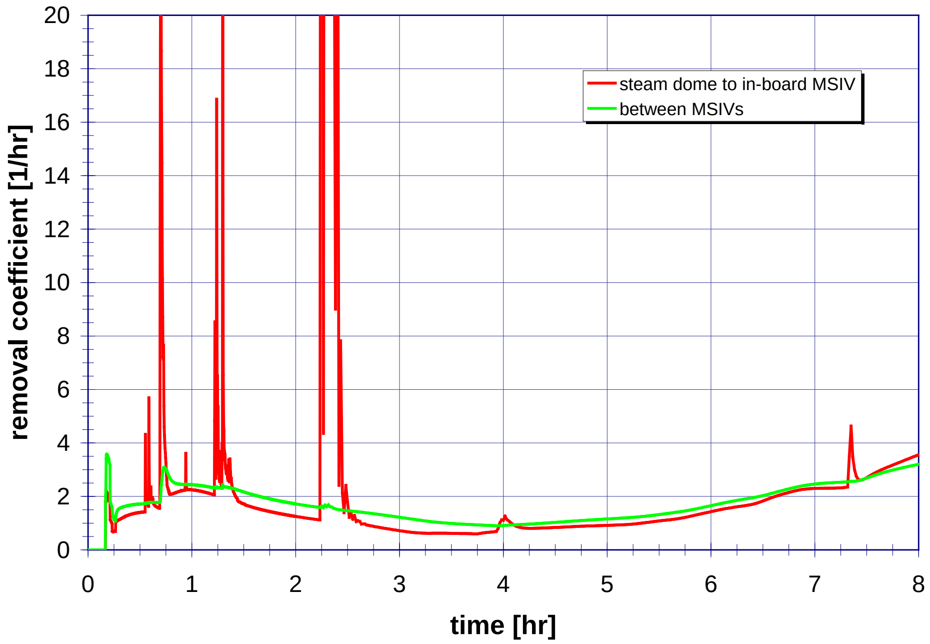


Figure 7-8 BWR Mk-III, MSLB, No Sprays: MSL-B Removal Coefficients

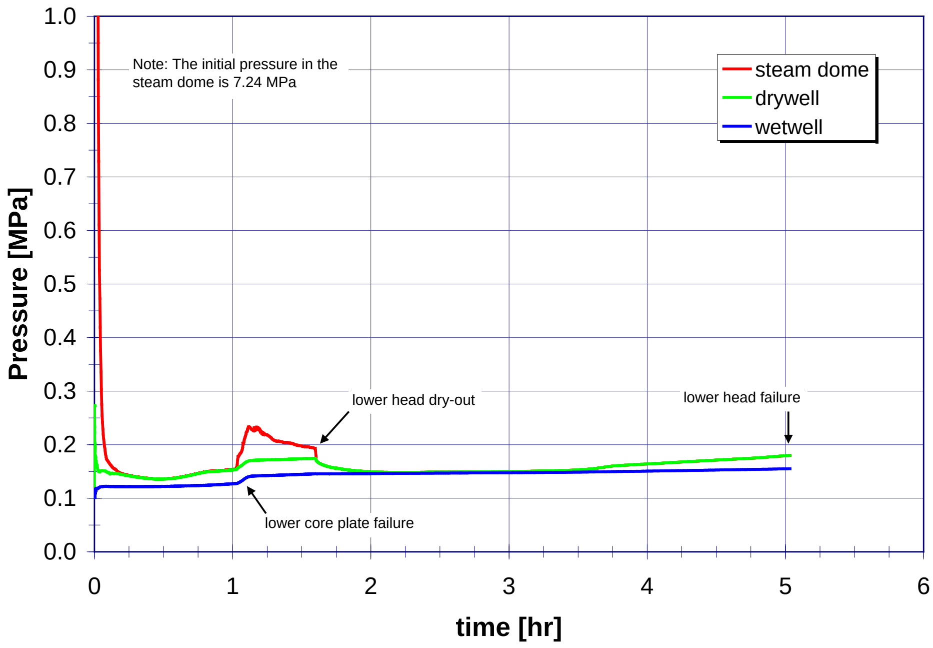


Figure 7-9 BWR Mk-III, RLB, No Sprays: Steam Dome, Drywell, and Wetwell Pressure

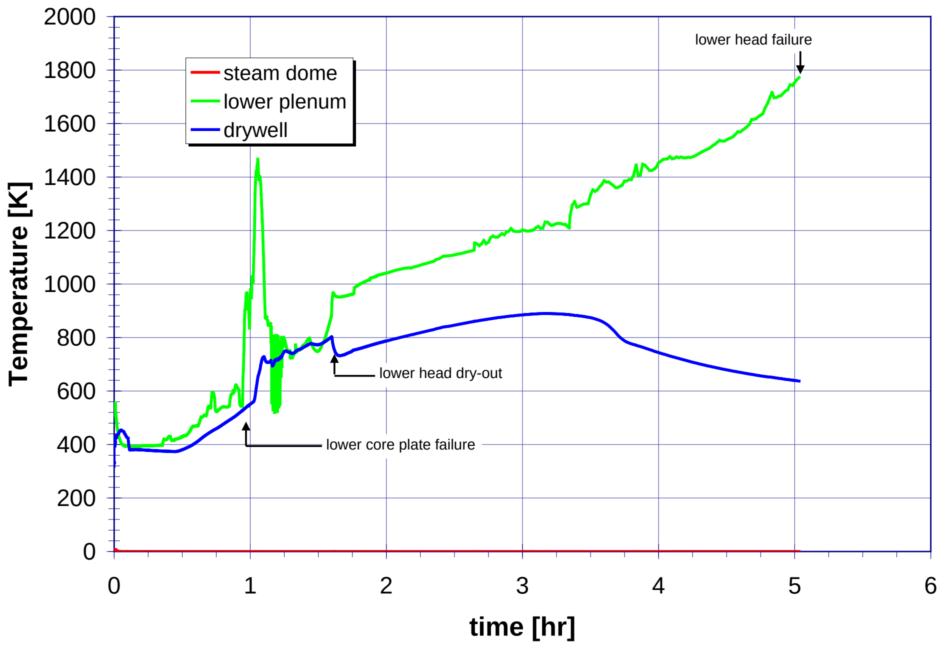


Figure 7-10 BWR Mk-III, RLB, No Sprays: Steam Dome, Drywell, and Lower Plenum Vapor Temperature

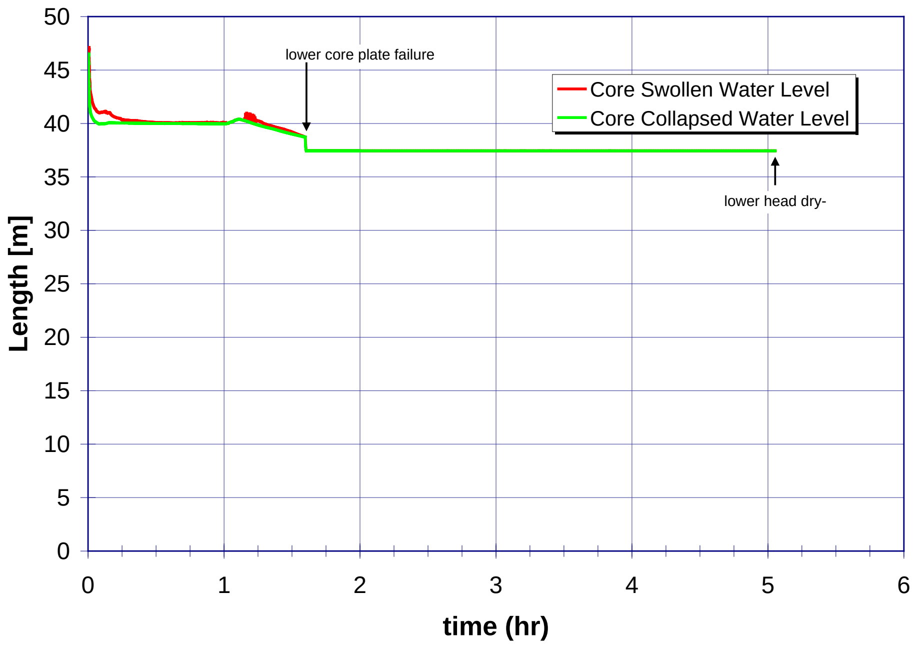


Figure 7-11 BWR Mk-III, RLB, No Sprays: Core Water Levels

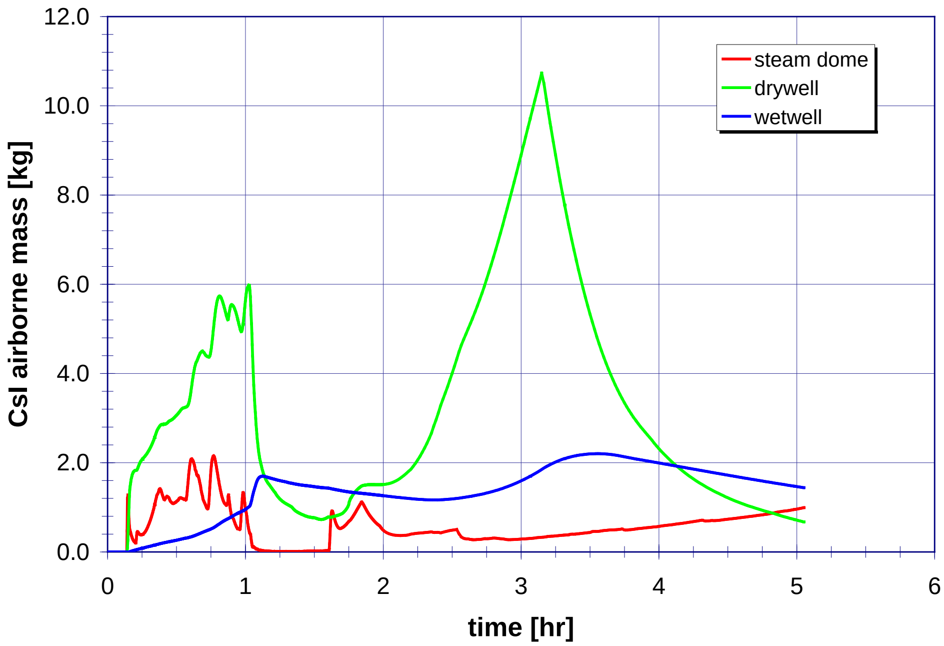


Figure 7-12 BWR Mk-III, RLB, No Sprays: CsI Mass in the Steam Dome, Drywell, and Wetwell

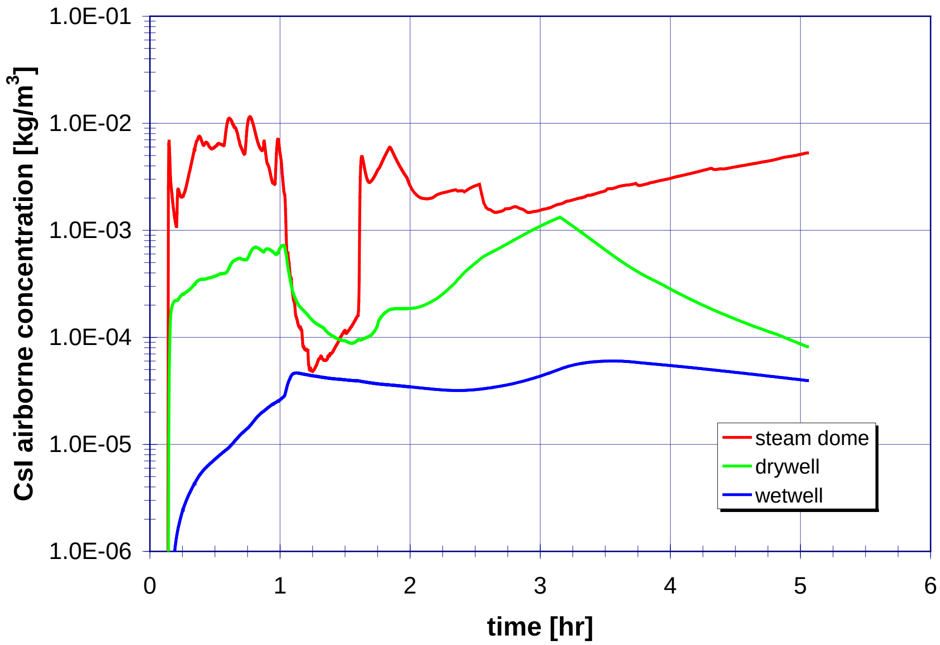


Figure 7-13 BWR Mk-III, RLB, No Sprays: CsI Concentration in the Steam Dome, Drywell, and Wetwell

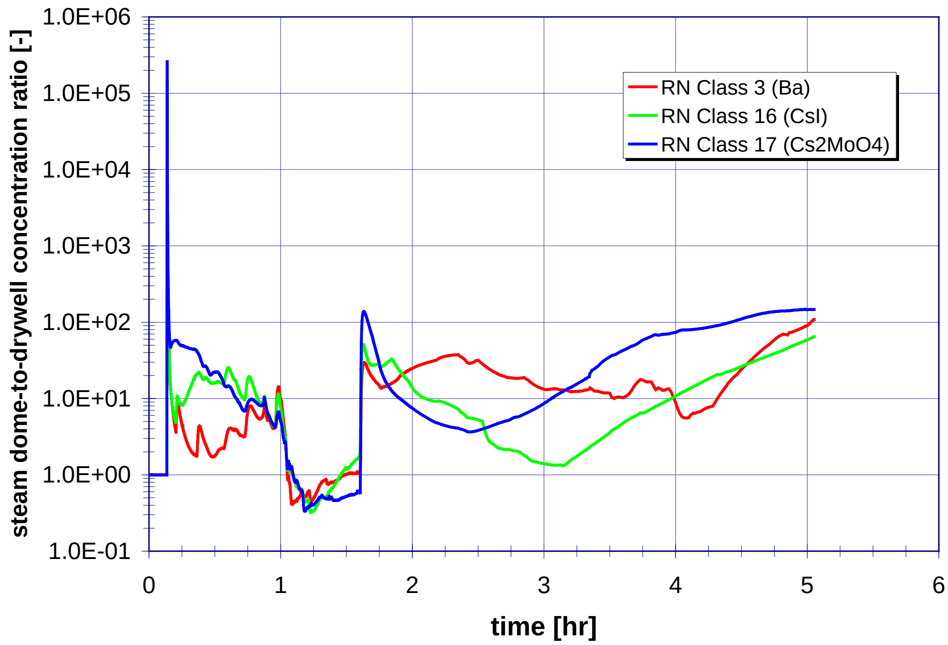


Figure 7-14 BWR Mk-III, RLB, No Condenser, No Sprays: Steam Dome-to-Drywell Concentration Ratios

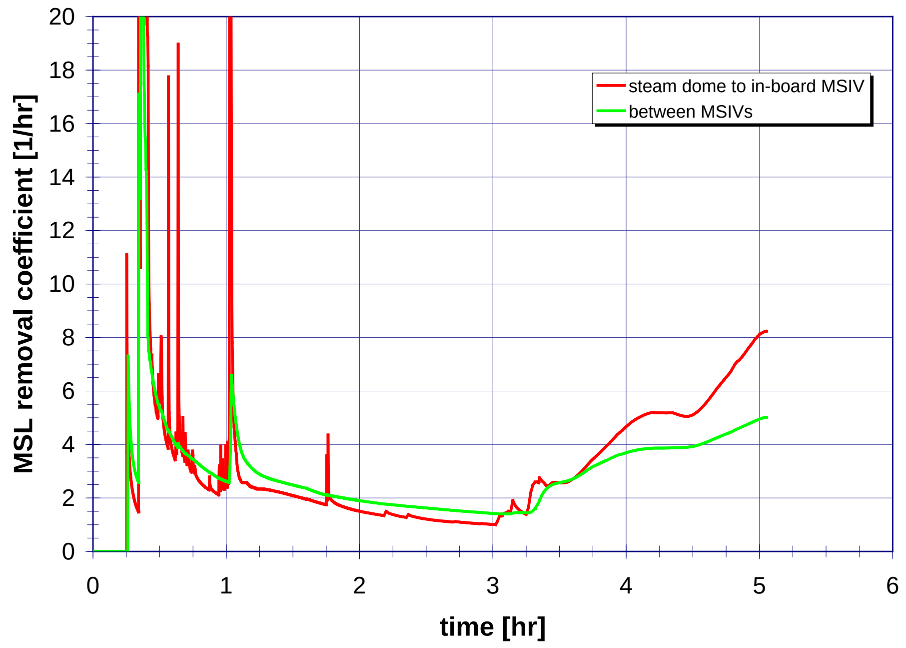


Figure 7-15 BWR Mk-III, RLB,, No Sprays: MSL-A Removal Coefficients

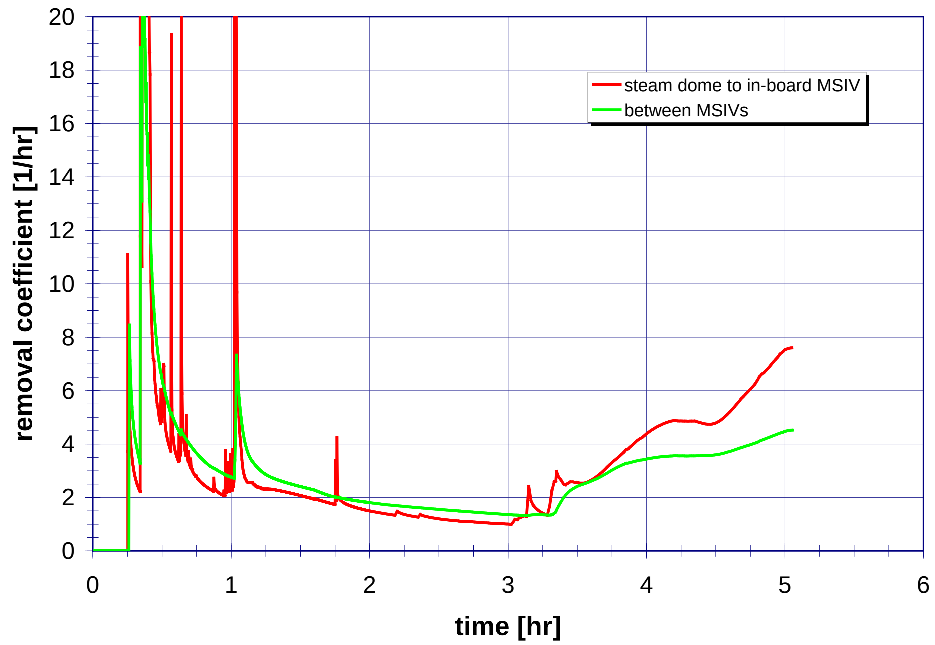


Figure 7-16 BWR Mk-III, RLB, No Sprays: MSL-B Removal Coefficients

8 Appendix B – RADTRAD MK-I Input Files

8.1 RTF file

```
Release Fraction and Timing Name:
 BWR, RG 1.183, Table 1 Section 3.2
 Duration (h):   Design Basis Accident
  0.5000E+00  0.1500E+01  0.0000E+00  0.0000E+00
 Noble Gases:
  0.5000E-01  0.9500E+00  0.0000E+00  0.0000E+00
 Iodine:
  0.5000E-01  0.2500E+00  0.0000E+00  0.0000E+00
 Cesium:
  0.5000E-01  0.2000E+00  0.0000E+00  0.0000E+00
 Tellurium:
  0.0000E+00  0.0500E+00  0.0000E+00  0.0000E+00
 Strontium:
  0.0000E+00  0.2000E-01  0.0000E+00  0.0000E+00
 Barium:
  0.0000E+00  0.2000E-01  0.0000E+00  0.0000E+00
 Ruthenium:
  0.0000E+00  0.2500E-02  0.0000E+00  0.0000E+00
 Cerium:
  0.0000E+00  0.5000E-03  0.0000E+00  0.0000E+00
 Lanthanum:
  0.0000E+00  0.2000E-03  0.0000E+00  0.0000E+00
 Non-Radioactive Aerosols (kg):
  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
 End of Release File
```

8.2 NIF file

```
Nuclide Inventory Name:
 Peach Bottom (PBAPS) AST - in Ci/MW
 Power Level:
  0.1000E+01
 Nuclides:
  60
 Nuclide 001:
Co-58
  7
 0.6117120000E+07
 0.5800E+02
 0.1529E+03
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 002:
Co-60
  7
 0.1663401096E+09
 0.6000E+02
 0.1830E+03
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 003:
none     0.0000E+00
none     0.0000E+00
Nuclide 004:
Kr-85m
  1
 0.1612800000E+05
 0.8500E+02
 0.8313E+04
Kr-85    0.2100E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 005:
Kr-87
  1
 0.4578000000E+04
 0.8700E+02
 0.1633E+05
Rb-87    0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 006:
Kr-88
  1
 0.1022400000E+05
 0.8800E+02
 0.2303E+05
```

```
Rb-88    0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 007:
Rb-86
  3
 0.1612224000E+07
 0.8600E+02
 0.6518E+02
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 008:
Sr-89
  5
 0.4363200000E+07
 0.8900E+02
 0.2798E+05
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 009:
Sr-90
  5
 0.9189573120E+09
 0.9000E+02
 0.3178E+04
Y-90     0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 010:
Sr-91
  5
 0.3420000000E+05
 0.9100E+02
 0.3801E+05
Y-91m    0.5800E+00
Y-91     0.4200E+00
none     0.0000E+00
Nuclide 011:
Sr-92
  5
 0.9756000000E+04
 0.9200E+02
 0.4017E+05
Y-92     0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 012:
Y-90
  9
 0.2304000000E+06
 0.9000E+02
 0.3272E+04
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 013:
Y-91
  9
 0.5055264000E+07
 0.9100E+02
 0.3448E+05
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 014:
Y-92
  9
 0.1274400000E+05
 0.9200E+02
 0.4029E+05
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 015:
Y-93
  9
 0.3636000000E+05
 0.9300E+02
 0.4526E+05
Zr-93    0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 016:
Zr-95
  9
 0.5527872000E+07
 0.9500E+02
 0.4489E+05
Nb-95m   0.7000E-02
Nb-95    0.9900E+00
none     0.0000E+00
Nuclide 017:
Zr-97
  9
```

```
 0.6084000000E+05
 0.9700E+02
 0.4657E+05
Nb-97m   0.9500E+00
Nb-97    0.5300E-01
none     0.0000E+00
Nuclide 018:
Nb-95
  9
 0.3036960000E+07
 0.9500E+02
 0.4512E+05
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 019:
Mo-99
  7
 0.2376000000E+06
 0.9900E+02
 0.5078E+05
Tc-99m   0.8800E+00
Tc-99    0.1200E+00
none     0.0000E+00
Nuclide 020:
Tc-99m
  7
 0.2167200000E+05
 0.9900E+02
 0.4447E+05
Tc-99    0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 021:
Ru-103
  7
 0.3393792000E+07
 0.1030E+03
 0.4202E+05
Rh-103m  0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 022:
Ru-105
  7
 0.1598400000E+05
 0.1050E+03
 0.2908E+05
Rh-105   0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 023:
Ru-106
  7
 0.3181248000E+08
 0.1060E+03
 0.1730E+05
Rh-106   0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 024:
Rh-105
  7
 0.1272960000E+06
 0.1050E+03
 0.2752E+05
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 025:
Sb-127
  4
 0.3326400000E+06
 0.1270E+03
 0.2896E+04
Te-127m  0.1800E+00
Te-127   0.8200E+00
none     0.0000E+00
Nuclide 026:
Sb-129
  4
 0.1555200000E+05
 0.1290E+03
 0.8638E+04
Te-129m  0.2200E+00
Te-129   0.7700E+00
none     0.0000E+00
Nuclide 027:
Te-127
  4
 0.3366000000E+05
 0.1270E+03
 0.2873E+04
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
```

```
Nuclide 028:
Te-127m
  4
 0.9417600000E+07
 0.1270E+03
 0.3855E+03
Te-127   0.9800E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 029:
Te-129
  4
 0.4176000000E+04
 0.1290E+03
 0.8501E+04
I-129    0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 030:
Te-129m
  4
 0.2903040000E+07
 0.1290E+03
 0.1267E+04
Te-129   0.6500E+00
I-129    0.3500E+00
none     0.0000E+00
Nuclide 031:
Te-131m
  4
 0.1080000000E+06
 0.1310E+03
 0.3869E+04
Te-131   0.2200E+00
I-131    0.7800E+00
none     0.0000E+00
Nuclide 032:
Te-132
  4
 0.2815200000E+06
 0.1320E+03
 0.3821E+05
I-132    0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 033:
I-131
  2
 0.6946560000E+06
 0.1310E+03
 0.2687E+05
Xe-131m  0.1100E-01
none     0.0000E+00
none     0.0000E+00
Nuclide 034:
I-132
  2
 0.8280000000E+04
 0.1320E+03
 0.3881E+05
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 035:
I-133
  2
 0.7488000000E+05
 0.1330E+03
 0.5556E+05
Xe-133m  0.2900E-01
Xe-133   0.9700E+00
none     0.0000E+00
Nuclide 036:
I-134
  2
 0.3156000000E+04
 0.1340E+03
 0.6165E+05
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 037:
I-135
  2
 0.2379600000E+05
 0.1350E+03
 0.5192E+05
Xe-135m  0.1500E+00
Xe-135   0.8500E+00
none     0.0000E+00
Nuclide 038:
Xe-133
  1
 0.4531680000E+06
 0.1330E+03
 0.5491E+05
```

```
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 039:
Xe-135
  1
 0.3272400000E+05
 0.1350E+03
 0.2228E+05
Cs-135   0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 040:
Cs-134
  3
 0.6507177120E+08
 0.1340E+03
 0.7280E+04
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 041:
Cs-136
  3
 0.1131840000E+07
 0.1360E+03
 0.2027E+04
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 042:
Cs-137
  3
 0.9467280000E+09
 0.1370E+03
 0.4538E+04
Ba-137m  0.9500E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 043:
Ba-139
  6
 0.4962000000E+04
 0.1390E+03
 0.5084E+05
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 044:
Ba-140
  6
 0.1100736000E+07
 0.1400E+03
 0.4896E+05
La-140   0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 045:
La-140
  9
 0.1449792000E+06
 0.1400E+03
 0.5019E+05
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 046:
La-141
  9
 0.1414800000E+05
 0.1410E+03
 0.4640E+05
Ce-141   0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 047:
La-142
  9
 0.5550000000E+04
 0.1420E+03
 0.4532E+05
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 048:
Ce-141
  8
 0.2808086400E+07
 0.1410E+03
 0.4492E+05
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 049:
Ce-143
  8
```

```
 0.1188000000E+06
 0.1430E+03
 0.4427E+05
Pr-143   0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 050:
Ce-144
  8
 0.2456352000E+08
 0.1440E+03
 0.3596E+05
Pr-144m  0.1800E-01
Pr-144   0.9800E+00
none     0.0000E+00
Nuclide 051:
Pr-143
  9
 0.1171584000E+07
 0.1430E+03
 0.4293E+05
none     0.0000E+00
none     0.0000E+00
none     0.0000E+00
Nuclide 052:
Nd-147
  9
 0.9486720000E+06
 0.1470E+03
 0.1838E+05
Pm-147   0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 053:
Np-239
  8
 0.2034720000E+06
 0.2390E+03
 0.5397E+06
Pu-239   0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 054:
Pu-238
  8
 0.2768863824E+10
 0.2380E+03
 0.1796E+03
U-234    0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 055:
Pu-239
  8
 0.7594336440E+12
 0.2390E+03
 0.1200E+02
U-235    0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 056:
Pu-240
  8
 0.2062920312E+12
 0.2400E+03
 0.1288E+02
U-236    0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 057:
Pu-241
  8
 0.4544294400E+09
 0.2410E+03
 0.6182E+04
U-237    0.2400E-04
Am-241   0.1000E+01
none     0.0000E+00
Nuclide 058:
Am-241
  9
 0.1363919472E+11
 0.2410E+03
 0.9528E+01
Np-237   0.1000E+01
none     0.0000E+00
none     0.0000E+00
Nuclide 059:
Cm-242
  9
 0.1406592000E+08
 0.2420E+03
 0.2388E+04
Pu-238   0.1000E+01
none     0.0000E+00
none     0.0000E+00
```

```
 Nuclide 060:
 Cm-244
   9
  0.5715081360E+09
  0.2440E+03
  0.2602E+03
 Pu-240   0.1000E+01
 none     0.0000E+00
 none     0.0000E+00
 End of Nuclear Inventory File
```

8.3 PSF files

8.3.1 MSL A

```
Radtrad 3.03 4/15/2001
 Mark1, MSIV Leakage Model, RLB, condenser
 Nuclide Inventory File:
 c:\program files\radtrad303\defaults\pbs_def.nif
 Plant Power Level:
  3.5280E+03
 Compartments:
  10
 Compartment 1:
 Steam Dome 1
   3
  3.7116E+03
   0
   0
   0
   1
   0
 Compartment 2:
 Void/Un-modeled Line
   3
  1.0000E+05
   0
   0
   0
   0
   0
 Compartment 3:
 Environment
   2
  0.0000E+00
   0
   0
   0
   0
   0
 Compartment 4:
 Control Room
   1
  1.7600E+05
   0
   0
   0
   0
   0
 Compartment 5:
 MSL-A Volume 1
   3
  3.2800E+02
   0
   0
   0
   1
   0
 Compartment 6:
 MSL-A Volume 2
   3
  7.5000E+01
   0
   0
   0
   1
   0
 Compartment 7:
 MSL-A Volume 3
   3
  9.1700E+02
   0
   0
   0
   1
   0
 Compartment 8:
 Steam Dome 2
   3
  3.7116E+03
   0
```

```
  0
  0
  1
  0
Compartment 9:
Steam Dome 3
  3
 3.7116E+03
  0
  0
  0
  1
  0
Compartment 10:
Condenser
  3
 1.4700E+05
  0
  0
  0
  1
  0
Pathways:
 16
Pathway 1:
Steam Dome 1 to Void (Cont)
  1
  2
  4
Pathway 2:
Filtered Intake to Control Room
  3
  4
  2
Pathway 3:
Unfiltered Inleakage to Control Room
  3
  4
  2
Pathway 4:
Control Room Exhaust to Environment
  4
  3
  2
Pathway 5:
Steam Dome 1 to MSL-A Volume 1
  1
  5
  1
Pathway 6:
Steam Dome 2 to MSL-A Volume 1
  8
  5
  1
Pathway 7:
Steam Dome 3 to MSL-A Volume 1
  9
  5
  1
Pathway 8:
MSL-A Volume 1 to MSL-A Volume 2
  5
  6
  1
Pathway 9:
MSL-A Volume 2 to MSL-A Volume 3
  6
  7
  2
Pathway 10:
MSL-A Volume 3 to Condenser
  7
 10
  2
Pathway 11:
Steam Dome 2 to Void (Cont)
  8
  2
  4
Pathway 12:
Steam Dome 3 to Void (Cont)
  9
  2
  4
Pathway 13:
Steam Dome 1 to Void (Line)
  1
  2
  1
Pathway 14:
Steam Dome 2 to Void (Line)
  8
  2
  1
Pathway 15:
Steam Dome 3 to Void (Line)
```

```
  9
  2
  1
Pathway 16:
Condenser to Environment
 10
  3
  1
End of Plant Model File
Scenario Description Name:

Plant Model Filename:

Source Term:
  3
  1   3.5575E-01
  8   1.5500E-01
  9   2.3343E-02
c:\program files\radtrad303\defaults\fgr11&12.inp
c:\program files\radtrad303\defaults\bwr_dba.rft
  0.0000E+00
  1
  9.5000E-01   4.8500E-02   1.5000E-03   1.0000E+00
Overlying Pool:
  0
  0.0000E+00
  0
  0
  0
  0
Compartments:
 10
Compartment 1:
  1
  1
  0
  0
  0
  0
  0
  3
  3
  1.0000E+01
  1
  1
  0.0000E+00   0.0000E+00
Compartment 2:
  0
  1
  0
  0
  0
  0
  0
  0
  0
Compartment 3:
  1
  1
  0
  0
  0
  0
  0
  0
  0
Compartment 4:
  1
  1
  0
  0
  0
  0
  0
  0
  0
Compartment 5:
  0
  1
  0
  0
  0
  0
  0
  1
  4
  0.0000E+00   0.0000E+00
  2.0000E+00   0.0000E+00
  1.2000E+01   0.0000E+00
  7.2000E+02   0.0000E+00
  0
Compartment 6:
  0
  1
  0
  0
```

```
  0
  0
  0
  1
  4
  0.0000E+00   2.9000E+00
  2.0000E+00   2.4000E+00
  1.2000E+01   2.0000E+00
  7.2000E+02   0.0000E+00
  0
Compartment 7:
  0
  1
  0
  0
  0
  0
  0
  1
  4
  0.0000E+00   1.3000E+00
  2.0000E+00   1.3000E+00
  1.2000E+01   1.0000E+00
  7.2000E+02   0.0000E+00
  0
Compartment 8:
  1
  1
  0
  0
  0
  0
  0
  3
  3
  1.0000E+01
  1
  1
  0.0000E+00   0.0000E+00
Compartment 9:
  1
  1
  0
  0
  0
  0
  0
  3
  3
  1.0000E+01
  1
  1
  0.0000E+00   0.0000E+00
Compartment 10:
  0
  1
  0
  0
  0
  0
  0
  1
  4
  0.0000E+00   2.0000E-02
  2.0000E+00   1.8000E-02
  1.2000E+01   1.5000E-02
  7.2000E+02   0.0000E+00
  0
Pathways:
 16
Pathway 1:
  0
  0
  0
  0
  0
  0
  0
  0
  0
  0
  1
  4
  0.0000E+00   0.0000E+00
  3.3300E-02   7.0000E-01
  3.8000E+01   3.5000E-01
  7.2000E+02   0.0000E+00
  0
Pathway 2:
  0
  0
  0
  0
  0
  1
  4
```

```
   0.0000E+00      1.8500E+04      0.0000E+00      0.0000E+00
0.0000E+00
   3.3300E-02      1.8500E+04      0.0000E+00      0.0000E+00
0.0000E+00
   5.0000E-01      2.7000E+03      9.8000E+01      8.9000E+01
8.9000E+01
   7.2000E+02      0.0000E+00      0.0000E+00      0.0000E+00
0.0000E+00
   0
   0
   0
   0
   0
   0
 Pathway 3:
   0
   0
   0
   0
   0
   1
   4
   0.0000E+00      0.0000E+00      0.0000E+00      0.0000E+00
0.0000E+00
   3.3300E-02      0.0000E+00      0.0000E+00      0.0000E+00
0.0000E+00
   5.0000E-01      5.0000E+02      0.0000E+00      0.0000E+00
0.0000E+00
   7.2000E+02      0.0000E+00      0.0000E+00      0.0000E+00
0.0000E+00
   0
   0
   0
   0
   0
   0
 Pathway 4:
   0
   0
   0
   0
   0
   1
   4
   0.0000E+00      1.8500E+04      0.0000E+00      0.0000E+00
0.0000E+00
   3.3300E-02      1.8500E+04      0.0000E+00      0.0000E+00
0.0000E+00
```

```
   5.0000E-01      3.2000E+03      1.0000E+02      1.0000E+02
1.0000E+02
   7.2000E+02      0.0000E+00      0.0000E+00      0.0000E+00
0.0000E+00
   0
   0
   0
   0
   0
   0
 Pathway 5:
   0
   0
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   3.3300E-02   1.0000E+00   1.8987E+00
   5.0000E-01   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   3.3300E-02   1.0000E+00   1.8987E+00
   5.0000E-01   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   3.3300E-02   1.0000E+00   1.8987E+00
   5.0000E-01   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   0
   0
   0
   0
   0
   0
   0
 Pathway 6:
   0
   0
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   5.0000E-01   1.0000E+00   1.8987E+00
```

```
  1.0000E+00   1.0000E+00   0.0000E+00
  3.8000E+01   1.0000E+00   0.0000E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  5.0000E-01   1.0000E+00   1.8987E+00
  1.0000E+00   1.0000E+00   0.0000E+00
  3.8000E+01   1.0000E+00   0.0000E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  5.0000E-01   1.0000E+00   1.8987E+00
  1.0000E+00   1.0000E+00   0.0000E+00
  3.8000E+01   1.0000E+00   0.0000E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  0
  0
  0
  0
  0
  0
  0
Pathway 7:
  0
  0
  1
  6
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   0.0000E+00
  1.0000E+00   1.0000E+00   1.8987E+00
  2.0000E+00   1.0000E+00   1.0530E+00
  3.8000E+01   1.0000E+00   5.2648E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  6
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   0.0000E+00
  1.0000E+00   1.0000E+00   1.8987E+00
  2.0000E+00   1.0000E+00   1.0530E+00
  3.8000E+01   1.0000E+00   5.2648E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  6
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   0.0000E+00
  1.0000E+00   1.0000E+00   1.8987E+00
  2.0000E+00   1.0000E+00   1.0530E+00
  3.8000E+01   1.0000E+00   5.2648E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  0
  0
  0
  0
  0
  0
  0
Pathway 8:
  0
  0
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   1.8987E+00
  2.0000E+00   1.0000E+00   1.8987E+00
  3.8000E+01   1.0000E+00   9.4935E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   1.8987E+00
  2.0000E+00   1.0000E+00   1.8987E+00
  3.8000E+01   1.0000E+00   9.4935E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   1.8987E+00
  2.0000E+00   1.0000E+00   1.8987E+00
  3.8000E+01   1.0000E+00   9.4935E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  0
  0
  0
  0
  0
  0
  0
Pathway 9:
  0
  0
  0
  0
  0
  1
```

```
   6
   0.0000E+00       0.0000E+00       0.0000E+00       0.0000E+00
0.0000E+00
   3.3300E-02       2.1946E+00       0.0000E+00       5.0000E+01
0.0000E+00
   2.0000E+00       2.1946E+00       0.0000E+00       5.0000E+01
0.0000E+00
   3.8000E+01       1.0973E+00       0.0000E+00       5.0000E+01
0.0000E+00
   9.6000E+01       1.0973E+00       0.0000E+00       0.0000E+00
0.0000E+00
   7.2000E+02       0.0000E+00       0.0000E+00       0.0000E+00
0.0000E+00
   0
   0
   0
   0
   0
   0
 Pathway 10:
   0
   0
   0
   0
   0
   1
   6
   0.0000E+00       0.0000E+00       0.0000E+00       0.0000E+00
0.0000E+00
   3.3300E-02       1.1010E+01       0.0000E+00       5.0000E+01
0.0000E+00
   2.0000E+00       1.1010E+01       0.0000E+00       5.0000E+01
0.0000E+00
   3.8000E+01       5.5050E+00       0.0000E+00       5.0000E-01
0.0000E+00
   9.6000E+01       5.5050E+00       0.0000E+00       0.0000E+00
0.0000E+00
   7.2000E+02       0.0000E+00       0.0000E+00       0.0000E+00
0.0000E+00
   0
   0
   0
   0
   0
   0
 Pathway 11:
   0
   0
   0
   0
   0
   0
   0
   0
   0
   0
   1
   4
   0.0000E+00   0.0000E+00
   3.3300E-02   7.0000E-01
   3.8000E+01   3.5000E-01
   7.2000E+02   0.0000E+00
   0
 Pathway 12:
   0
   0
   0
   0
   0
   0
   0
   0
   0
   1
   4
   0.0000E+00   0.0000E+00
   3.3300E-02   7.0000E-01
   3.8000E+01   3.5000E-01
   7.2000E+02   0.0000E+00
   0
 Pathway 13:
   0
   0
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   3.3300E-02   1.0000E+00   1.4356E+00
   5.0000E-01   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   3.3300E-02   1.0000E+00   1.4356E+00
   5.0000E-01   1.0000E+00   0.0000E+00
```

```
  3.8000E+01   1.0000E+00   0.0000E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   1.4356E+00
  5.0000E-01   1.0000E+00   0.0000E+00
  3.8000E+01   1.0000E+00   0.0000E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  0
  0
  0
  0
  0
  0
  0
Pathway 14:
  0
  0
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  5.0000E-01   1.0000E+00   1.4356E+00
  1.0000E+00   1.0000E+00   0.0000E+00
  3.8000E+01   1.0000E+00   0.0000E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  5.0000E-01   1.0000E+00   1.4356E+00
  1.0000E+00   1.0000E+00   0.0000E+00
  3.8000E+01   1.0000E+00   0.0000E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  5.0000E-01   1.0000E+00   1.4356E+00
  1.0000E+00   1.0000E+00   0.0000E+00
  3.8000E+01   1.0000E+00   0.0000E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  0
  0
  0
  0
  0
  0
  0
Pathway 15:
  0
  0
  1
  6
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   0.0000E+00
  1.0000E+00   1.0000E+00   1.4356E+00
  2.0000E+00   1.0000E+00   7.9614E-01
  3.8000E+01   1.0000E+00   3.9807E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  6
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   0.0000E+00
  1.0000E+00   1.0000E+00   1.4356E+00
  2.0000E+00   1.0000E+00   7.9614E-01
  3.8000E+01   1.0000E+00   3.9807E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  6
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   0.0000E+00
  1.0000E+00   1.0000E+00   1.4356E+00
  2.0000E+00   1.0000E+00   7.9614E-01
  3.8000E+01   1.0000E+00   3.9807E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  0
  0
  0
  0
  0
  0
  0
Pathway 16:
  0
  0
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   1.1010E+01
  2.0000E+00   1.0000E+00   1.1010E+01
  3.8000E+01   1.0000E+00   5.5050E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   1.1010E+01
  2.0000E+00   1.0000E+00   1.1010E+01
```

```
  3.8000E+01   1.0000E+00   5.5050E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   1.1010E+01
  2.0000E+00   1.0000E+00   1.1010E+01
  3.8000E+01   1.0000E+00   5.5050E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  0
  0
  0
  0
  0
  0
  0
Dose Locations:
  3
Location 1:
Exclusion Area Boundary
  3
  1
  2
  0.0000E+00   4.2500E-04
  7.2000E+02   0.0000E+00
  1
  2
  0.0000E+00   3.5000E-04
  7.2000E+02   0.0000E+00
  0
Location 2:
Low Population Zone
  3
  1
  6
  0.0000E+00   4.8100E-05
  2.0000E+00   2.0800E-05
  8.0000E+00   1.3700E-05
  2.4000E+01   5.4900E-06
  9.6000E+01   1.4900E-06
  7.2000E+02   0.0000E+00
  1
  4
  0.0000E+00   3.5000E-04
  8.0000E+00   1.8000E-04
  2.4000E+01   2.3000E-04
  7.2000E+02   0.0000E+00
  0
Location 3:
Control Room
  4
  0
  1
  2
  0.0000E+00   3.5000E-04
  7.2000E+02   0.0000E+00
  1
  4
  0.0000E+00   1.0000E+00
  2.4000E+01   6.0000E-01
  9.6000E+01   4.0000E-01
  7.2000E+02   0.0000E+00
Effective Volume Location:
  1
  6
  0.0000E+00   1.1800E-03
  2.0000E+00   9.0800E-04
  8.0000E+00   4.1400E-04
  2.4000E+01   2.9000E-04
  9.6000E+01   2.2600E-04
  7.2000E+02   0.0000E+00
Simulation Parameters:
  6
  0.0000E+00   1.0000E-01
  2.0000E+00   5.0000E-01
  8.0000E+00   1.0000E+00
  2.4000E+01   2.0000E+00
  9.6000E+01   8.0000E+00
  7.2000E+02   0.0000E+00
Output Filename:
C:\Program Files\radtrad303\MSIV Models\Mk1_Cond_final_a.o0
  1
  1
  1
  0
  0
End of Scenario File
```

8.3.2 MSL B

```
Radtrad 3.03 4/15/2001
 Mark1, MSIV Leakage Model, RLB, condenser
 Nuclide Inventory File:
```

```
c:\program files\radtrad303\defaults\pbs_def.nif
Plant Power Level:
 3.5280E+03
Compartments:
 10
Compartment 1:
Steam Dome 1
  3
 3.7116E+03
  0
  0
  0
  1
  0
Compartment 2:
Void/Un-modeled Line
  3
 1.0000E+05
  0
  0
  0
  0
  0
Compartment 3:
Environment
  2
 0.0000E+00
  0
  0
  0
  0
  0
Compartment 4:
Control Room
  1
 1.7600E+05
  0
  0
  0
  0
  0
Compartment 5:
MSL-B Volume 1
  3
 3.0300E+02
  0
  0
  0
  1
  0
Compartment 6:
MSL-B Volume 2
  3
 6.9000E+01
  0
  0
  0
  1
  0
Compartment 7:
MSL-B Volume 3
  3
 9.3900E+02
  0
  0
  0
  1
  0
Compartment 8:
Steam Dome 2
  3
 3.7116E+03
  0
  0
  0
  1
  0
Compartment 9:
Steam Dome 3
  3
 3.7116E+03
  0
  0
  0
  1
  0
Compartment 10:
Condenser
  3
 1.4700E+05
  0
  0
  0
  1
  0
Pathways:
```

```
 16
Pathway 1:
Steam Dome 1 to Void (Cont)
  1
  2
  4
Pathway 2:
Filtered Intake to Control Room
  3
  4
  2
Pathway 3:
Unfiltered Inleakage to Control Room
  3
  4
  2
Pathway 4:
Control Room Exhaust to Environment
  4
  3
  2
Pathway 5:
Steam Dome 1 to MSL-B Volume 1
  1
  5
  1
Pathway 6:
Steam Dome 2 to MSL-B Volume 1
  8
  5
  1
Pathway 7:
Steam Dome 3 to MSL-B Volume 1
  9
  5
  1
Pathway 8:
MSL-B Volume 1 to MSL-B Volume 2
  5
  6
  1
Pathway 9:
MSL-B Volume 2 to MSL-B Volume 3
  6
  7
  2
Pathway 10:
MSL-B Volume 3 to Condenser
  7
 10
  2
Pathway 11:
Steam Dome 2 to Void (Cont)
  8
  2
  4
Pathway 12:
Steam Dome 3 to Void (Cont)
  9
  2
  4
Pathway 13:
Steam Dome 1 to Void (Line)
  1
  2
  1
Pathway 14:
Steam Dome 2 to Void (Line)
  8
  2
  1
Pathway 15:
Steam Dome 3 to Void (Line)
  9
  2
  1
Pathway 16:
Condenser to Environment
 10
  3
  1
End of Plant Model File
Scenario Description Name:

Plant Model Filename:

Source Term:
  3
  1   3.5575E-01
  8   1.5500E-01
  9   2.3343E-02
c:\program files\radtrad303\defaults\fgr11&12.inp
c:\program files\radtrad303\defaults\bwr_dba.rft
  0.0000E+00
  1
  9.5000E-01   4.8500E-02   1.5000E-03   1.0000E+00
```

```
Overlying Pool:
  0
  0.0000E+00
  0
  0
  0
  0
Compartments:
 10
Compartment 1:
  1
  1
  0
  0
  0
  0
  0
  3
  3
  1.0000E+01
  1
  1
  0.0000E+00   0.0000E+00
Compartment 2:
  0
  1
  0
  0
  0
  0
  0
  0
  0
Compartment 3:
  1
  1
  0
  0
  0
  0
  0
  0
  0
Compartment 4:
  1
  1
  0
  0
  0
  0
  0
  0
  0
Compartment 5:
  0
  1
  0
  0
  0
  0
  0
  1
  4
  0.0000E+00   0.0000E+00
  2.0000E+00   0.0000E+00
  1.2000E+01   0.0000E+00
  7.2000E+02   0.0000E+00
  0
Compartment 6:
  0
  1
  0
  0
  0
  0
  0
  1
  4
  0.0000E+00   2.9000E+00
  2.0000E+00   2.4000E+00
  1.2000E+01   2.0000E+00
  7.2000E+02   0.0000E+00
  0
Compartment 7:
  0
  1
  0
  0
  0
  0
  0
  1
  4
  0.0000E+00   1.3000E+00
  2.0000E+00   1.3000E+00
  1.2000E+01   1.0000E+00
```

```
  7.2000E+02   0.0000E+00
  0
Compartment 8:
  1
  1
  0
  0
  0
  0
  0
  3
  3
  1.0000E+01
  1
  1
  0.0000E+00   0.0000E+00
Compartment 9:
  1
  1
  0
  0
  0
  0
  0
  3
  3
  1.0000E+01
  1
  1
  0.0000E+00   0.0000E+00
Compartment 10:
  0
  1
  0
  0
  0
  0
  0
  1
  4
  0.0000E+00   2.0000E-02
  2.0000E+00   1.8000E-02
  1.2000E+01   1.5000E-02
  7.2000E+02   0.0000E+00
  0
Pathways:
 16
Pathway 1:
  0
  0
  0
  0
  0
  0
  0
  0
  0
  0
  1
  4
  0.0000E+00   0.0000E+00
  3.3300E-02   7.0000E-01
  3.8000E+01   3.5000E-01
  7.2000E+02   0.0000E+00
  0
 Pathway 2:
  0
  0
  0
  0
  0
  1
  4
  0.0000E+00      1.8500E+04      0.0000E+00      0.0000E+00
0.0000E+00
  3.3300E-02      1.8500E+04      0.0000E+00      0.0000E+00
0.0000E+00
  5.0000E-01      2.7000E+03      9.8000E+01      8.9000E+01
8.9000E+01
  7.2000E+02      0.0000E+00      0.0000E+00      0.0000E+00
0.0000E+00
  0
  0
  0
  0
  0
  0
 Pathway 3:
  0
  0
  0
  0
  0
  1
  4
```

```
   0.0000E+00       0.0000E+00       0.0000E+00       0.0000E+00
0.0000E+00
   3.3300E-02       0.0000E+00       0.0000E+00       0.0000E+00
0.0000E+00
   5.0000E-01       5.0000E+02       0.0000E+00       0.0000E+00
0.0000E+00
   7.2000E+02       0.0000E+00       0.0000E+00       0.0000E+00
0.0000E+00
   0
   0
   0
   0
   0
   0
 Pathway 4:
   0
   0
   0
   0
   0
   1
   4
   0.0000E+00       1.8500E+04       0.0000E+00       0.0000E+00
0.0000E+00
   3.3300E-02       1.8500E+04       0.0000E+00       0.0000E+00
0.0000E+00
   5.0000E-01       3.2000E+03       1.0000E+02       1.0000E+02
1.0000E+02
   7.2000E+02       0.0000E+00       0.0000E+00       0.0000E+00
0.0000E+00
   0
   0
   0
   0
   0
   0
 Pathway 5:
   0
   0
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   3.3300E-02   1.0000E+00   1.4356E+00
   5.0000E-01   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   1
   5
```

```
   0.0000E+00   1.0000E+00   0.0000E+00
   3.3300E-02   1.0000E+00   1.4356E+00
   5.0000E-01   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   3.3300E-02   1.0000E+00   1.4356E+00
   5.0000E-01   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   0
   0
   0
   0
   0
   0
   0
 Pathway 6:
   0
   0
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   5.0000E-01   1.0000E+00   1.4356E+00
   1.0000E+00   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   5.0000E-01   1.0000E+00   1.4356E+00
   1.0000E+00   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   5.0000E-01   1.0000E+00   1.4356E+00
   1.0000E+00   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   0
   0
   0
   0
   0
```

```
  0
  0
Pathway 7:
  0
  0
  1
  6
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   0.0000E+00
  1.0000E+00   1.0000E+00   1.4356E+00
  2.0000E+00   1.0000E+00   7.9614E-01
  3.8000E+01   1.0000E+00   3.9807E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  6
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   0.0000E+00
  1.0000E+00   1.0000E+00   1.4356E+00
  2.0000E+00   1.0000E+00   7.9614E-01
  3.8000E+01   1.0000E+00   3.9807E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  6
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   0.0000E+00
  1.0000E+00   1.0000E+00   1.4356E+00
  2.0000E+00   1.0000E+00   7.9614E-01
  3.8000E+01   1.0000E+00   3.9807E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  0
  0
  0
  0
  0
  0
  0
Pathway 8:
  0
  0
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   1.4356E+00
  2.0000E+00   1.0000E+00   1.4356E+00
  3.8000E+01   1.0000E+00   7.1780E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   1.4356E+00
  2.0000E+00   1.0000E+00   1.4356E+00
  3.8000E+01   1.0000E+00   7.1780E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   1.4356E+00
  2.0000E+00   1.0000E+00   1.4356E+00
  3.8000E+01   1.0000E+00   7.1780E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  0
  0
  0
  0
  0
  0
  0
Pathway 9:
  0
  0
  0
  0
  0
  1
  6
  0.0000E+00      0.0000E+00      0.0000E+00      0.0000E+00
0.0000E+00
  3.3300E-02      1.6593E+00      0.0000E+00      5.0000E+01
0.0000E+00
  2.0000E+00      1.6593E+00      0.0000E+00      5.0000E+01
0.0000E+00
  3.8000E+01      8.2965E-01      0.0000E+00      5.0000E+01
0.0000E+00
  9.6000E+01      8.2965E-01      0.0000E+00      0.0000E+00
0.0000E+00
  7.2000E+02      0.0000E+00      0.0000E+00      0.0000E+00
0.0000E+00
  0
  0
  0
  0
  0
  0
Pathway 10:
  0
  0
```

```
   0
   0
   0
   1
   6
   0.0000E+00       0.0000E+00       0.0000E+00       0.0000E+00
0.0000E+00
   3.3300E-02       8.3244E+00       0.0000E+00       5.0000E+01
0.0000E+00
   2.0000E+00       8.3244E+00       0.0000E+00       5.0000E+01
0.0000E+00
   3.8000E+01       4.1622E+00       0.0000E+00       5.0000E-01
0.0000E+00
   9.6000E+01       4.1622E+00       0.0000E+00       0.0000E+00
0.0000E+00
   7.2000E+02       0.0000E+00       0.0000E+00       0.0000E+00
0.0000E+00
   0
   0
   0
   0
   0
   0
 Pathway 11:
   0
   0
   0
   0
   0
   0
   0
   0
   0
   0
   1
   4
   0.0000E+00   0.0000E+00
   3.3300E-02   7.0000E-01
   3.8000E+01   3.5000E-01
   7.2000E+02   0.0000E+00
   0
 Pathway 12:
   0
   0
   0
   0
   0
   0
   0
   0
   0
   0
   1
   4
   0.0000E+00   0.0000E+00
   3.3300E-02   7.0000E-01
   3.8000E+01   3.5000E-01
   7.2000E+02   0.0000E+00
   0
 Pathway 13:
   0
   0
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   3.3300E-02   1.0000E+00   1.8987E+00
   5.0000E-01   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   3.3300E-02   1.0000E+00   1.8987E+00
   5.0000E-01   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
   3.3300E-02   1.0000E+00   1.8987E+00
   5.0000E-01   1.0000E+00   0.0000E+00
   3.8000E+01   1.0000E+00   0.0000E+00
   7.2000E+02   1.0000E+00   0.0000E+00
   0
   0
   0
   0
   0
   0
   0
 Pathway 14:
   0
   0
   1
   5
   0.0000E+00   1.0000E+00   0.0000E+00
```

```
  5.0000E-01   1.0000E+00   1.8987E+00
  1.0000E+00   1.0000E+00   0.0000E+00
  3.8000E+01   1.0000E+00   0.0000E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  5.0000E-01   1.0000E+00   1.8987E+00
  1.0000E+00   1.0000E+00   0.0000E+00
  3.8000E+01   1.0000E+00   0.0000E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  5.0000E-01   1.0000E+00   1.8987E+00
  1.0000E+00   1.0000E+00   0.0000E+00
  3.8000E+01   1.0000E+00   0.0000E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  0
  0
  0
  0
  0
  0
  0
Pathway 15:
  0
  0
  1
  6
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   0.0000E+00
  1.0000E+00   1.0000E+00   1.8987E+00
  2.0000E+00   1.0000E+00   1.0530E+00
  3.8000E+01   1.0000E+00   5.2648E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  6
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   0.0000E+00
  1.0000E+00   1.0000E+00   1.8987E+00
  2.0000E+00   1.0000E+00   1.0530E+00
  3.8000E+01   1.0000E+00   5.2648E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  6
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   0.0000E+00
  1.0000E+00   1.0000E+00   1.8987E+00
  2.0000E+00   1.0000E+00   1.0530E+00
  3.8000E+01   1.0000E+00   5.2648E-01
  7.2000E+02   1.0000E+00   0.0000E+00
  0
  0
  0
  0
  0
  0
  0
Pathway 16:
  0
  0
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   8.3244E+00
  2.0000E+00   1.0000E+00   8.3244E+00
  3.8000E+01   1.0000E+00   4.1622E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   8.3244E+00
  2.0000E+00   1.0000E+00   8.3244E+00
  3.8000E+01   1.0000E+00   4.1622E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  1
  5
  0.0000E+00   1.0000E+00   0.0000E+00
  3.3300E-02   1.0000E+00   8.3244E+00
  2.0000E+00   1.0000E+00   8.3244E+00
  3.8000E+01   1.0000E+00   4.1622E+00
  7.2000E+02   1.0000E+00   0.0000E+00
  0
  0
  0
  0
  0
  0
  0
Dose Locations:
  3
Location 1:
Exclusion Area Boundary
  3
  1
```

```
  2
  0.0000E+00   4.2500E-04
  7.2000E+02   0.0000E+00
  1
  2
  0.0000E+00   3.5000E-04
  7.2000E+02   0.0000E+00
  0
Location 2:
Low Population Zone
  3
  1
  6
  0.0000E+00   4.8100E-05
  2.0000E+00   2.0800E-05
  8.0000E+00   1.3700E-05
  2.4000E+01   5.4900E-06
  9.6000E+01   1.4900E-06
  7.2000E+02   0.0000E+00
  1
  4
  0.0000E+00   3.5000E-04
  8.0000E+00   1.8000E-04
  2.4000E+01   2.3000E-04
  7.2000E+02   0.0000E+00
  0
Location 3:
Control Room
  4
  0
  1
  2
  0.0000E+00   3.5000E-04
  7.2000E+02   0.0000E+00
  1
  4
  0.0000E+00   1.0000E+00
  2.4000E+01   6.0000E-01
  9.6000E+01   4.0000E-01
  7.2000E+02   0.0000E+00
Effective Volume Location:
  1
  6
  0.0000E+00   1.1800E-03
  2.0000E+00   9.0800E-04
  8.0000E+00   4.1400E-04
  2.4000E+01   2.9000E-04
  9.6000E+01   2.2600E-04
  7.2000E+02   0.0000E+00
Simulation Parameters:
  6
  0.0000E+00   1.0000E-01
  2.0000E+00   5.0000E-01
  8.0000E+00   1.0000E+00
  2.4000E+01   2.0000E+00
  9.6000E+01   8.0000E+00
  7.2000E+02   0.0000E+00
Output Filename:
C:\Program Files\radtrad303\MSIV Models\Mk1_Cond_final_b.o0
  1
  1
  1
  0
  0
End of Scenario File
```

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Mail Stop 7 E18
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Washington, DC 20555

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