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August 24, 2010

Ms. Cynthia K. Bladey
Chief, Rules, Announcements, and Directives Branch
Office of Administration
U.S. Nuclear Regulatory Commission
Washington, DC 20555–0001

Subject: Supplemental Information to Nuclear Energy Institute Comments Submitted on January 20, 2010 on U.S. Nuclear Regulatory Commission Draft Regulatory Guide DG-1199, "Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors" (*Federal Register* of October 14, 2009, 74 FR 52822).

Project Number: 689

Dear Ms. Bladey:

This letter provides supplemental information to comments of the Nuclear Energy Institute (NEI)[1] submitted on January 20, 2010, on behalf of the nuclear energy industry on U.S. Nuclear Regulatory Commission (NRC) draft regulatory guide DG-1199 (proposed Revision 1 to NRC Regulatory Guide 1.183), in response to the subject Federal Register notice.

Our January 20 submittal included Comment No. 103, which reads as follows:

"Based on the data presented in [SAND2008-6601] for steam dome temperature, it does not appear that the temperature of the steam dome would be sufficiently low relative to that of the steam lines to produce a steam-hydrogen-fission gas mixture with a density greater than that of the steam in the lines. Accordingly, mixing between the steam dome and the steam lines may not be very

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[1] NEI is the organization responsible for establishing unified nuclear industry policy on matters affecting the nuclear energy industry, including the regulatory aspects of generic operational and technical issues. NEI's members include all utilities licensed to operate commercial nuclear power plants in the United States, nuclear plant designers, major architect/engineering firms, fuel fabrication facilities, materials licensees, and other organizations and individuals involved in the nuclear energy industry.

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Template = ADM-013
Add = R. Carpenter (RGC1)
M Case (MJC)
M. Blumberg (WMB1)

efficient. The absence of efficient mixing (in concert with activity deposition along the leak path) may produce a large fission product concentration difference between the steam dome and the portion of the steam lines adjacent to the inboard MSIVs. Given this condition, considering the drywell as the source (even with credit for drywell sprays but without credit for steam line deposition up to the inboard MSIVs) may produce a more conservative dose result than using the actual steam dome/steam line pathway. RECOMMENDATION: If this is the case, then the requirement for activity concentration adjustment factors and the recommendation against credit for drywell sprays should be deleted from the final regulatory guide."

Input to this comment was provided by representatives from AREVA NP serving on an NEI nuclear energy industry task force formed to review and develop comments on DG-1199. Subsequent to the submittal of our January 20 comments, AREVA NP has published analytical results (attached) that provide further support for the recommendation made in Comment No. 103. As stated in the conclusions of the analysis, the results "contradict the conclusion reached in DG-1199 regarding the need for dose-rate multipliers to compensate for the activity concentration in the steam dome being greater than that in the drywell."

While we recognize that the noticed period for submittal of comments on DG-1199 has elapsed, we also note that the subject Federal Register notice reiterated the NRC's long-standing policy regarding public comments on regulatory guides:

"Comments received after [the noticed] date will be considered if it is practical to do so, but the NRC is able to ensure consideration only for comments received on or before this date. Although a time limit is given, comments and suggestions in connection with items for inclusion in guides currently being developed or improvements in all published guides are encouraged at any time."

Consistent with this policy, we are providing the attached information for consideration by the NRC staff in finalizing the current proposed Revision 1 to Regulatory Guide 1.183 because it represents new and substantive information that supplements our previously submitted comments and is directly relevant to resolving a significant change being proposed in the draft revision to the regulatory guide.

We appreciate your consideration in this matter. If you have any questions regarding our comments or the attached material, please contact me at 202.739.8111; rla@nei.org.

Sincerely,

Ralph Andersen

Ralph L. Andersen

Attachment

BWR Steam Line Radionuclide Concentration Distribution following a DBA LOCA

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Abstract

A generic, time-dependent Boiling-Water Reactor (BWR) steam line radioactivity concentration distribution – following a design-basis Loss of Coolant Accident (LOCA) – was calculated. The results demonstrate that the radioactivity concentration at a point immediately upstream of an intact BWR main steam isolation valve (MSIV) is substantially lower than that in the reactor vessel (RV) steam dome during the time that the dome concentration exceeds that of the drywell. The results presented in this paper supplement and clarify the insights presented in the NRC DG-1199 [(6)] and in the supporting Sandia Report [(2)]. They also contradict the conclusion reached in DG-1199 regarding the need for dose-rate multipliers to compensate for the activity concentration in the steam dome being greater than that in the drywell.

The current revision of RG 1.183 permits the assumption that the drywell is the source of MSIV leakage. The implied assumption, therefore, is that the time-averaged activity concentration within the drywell is the same as (or greater than) that at the first-closed MSIV. DG-1199, on the other hand, claims that the radionuclide concentration at the first-closed MSIV is the same as that in the RV steam dome <u>and</u> that this concentration substantially exceeds (over relevant averaging periods) that in the drywell. The MELCOR 1.8.6 model from the Sandia Report on which that claim is based, however, does not include the potential for density-driven, counter-current flow in a series of stacked control volumes and, therefore, cannot quantify the potential for stratification in vertical steam lines adjacent to the RV.

The dose-rate multipliers, if implemented, would have a significant impact on the MSIV leakage dose contribution, thus potentially affecting BWR plant modifications already implemented to remove MSIV leakage collection systems (LCS) and to increase allowable MSIV leakage rates in many operating BWRs.

A LOCA was investigated with the intact steam lines modeled using the Modular Accident Analysis Program, Version 4 (MAAP4) "Aux Bldg" modeling capability. Thus, the potential for trapping clean steam in the predominantly vertical steam line runs between the RV and the inboard MSIVs was evaluated. The analysis demonstrates that it is acceptable to assume that the activity concentration at the steam line leak point is that of the drywell.

The issue of RV vs. drywell activity concentration was addressed cursorily in a paper by Metcalf [(1)] in 2002. However, since this issue was perceived as already resolved in the 2000 issuance of RG 1.183, an in-depth assessment was not performed. Rather, steam line deposition issues that were not addressed (or not completely addressed) in the 2000 issuance of RG 1.183 were the subjects of that paper. In this regard, this paper may be viewed as an extension of Metcalf 2002.

1 Introduction and Background

The purpose of the brief study described in this paper is to clarify some technical issues raised in References [1] and [2] related to radioactivity leaking to the environment via the main steam lines of a Boiling Water Reactor (BWR) after a core-damage accident. In particular, this paper addresses the treatment of such leakage in a Design-Basis Accident (DBA) environment. DBAs are analyzed simplistically in order to have the analysis be as transparent as possible and to ensure that the results are conservative. Conservatism in this instance means that the activity leaked via this pathway in an actual core-damage accident would be less (and probably far less) than that calculated to be leaked in the DBA analysis of a similar event. The allowable leakage rate for testing the Main Steam Isolation Valves (MSIVs) is established by this DBA analysis.

Appendix A of Reference [3] presents a set of assumptions acceptable to the NRC for analyzing the offsite and Control Room radiation doses associated with a DBA Loss-of-Coolant Accident (LOCA). The DBA-LOCA is one in which there is assumed to be significant damage to the core; i.e., the Emergency Core Cooling System (ECCS) function is initially degraded in some unspecified way. It is further assumed that the ECCS function is restored at some later point in time so that the core debris is successfully cooled in-vessel; and, therefore, no vessel failure occurs. In this respect, the DBA-LOCA addressed in Reference [3] is similar to the accident at Three Mile Island (TMI). However, the Reference [3] DBA-LOCA differs from the accident at TMI in that its Alternative Source Term (AST) magnitude and start-of-release timing is assumed to be initiated by a large rupture of Reactor Coolant System (RCS) piping rather than the small, stuck-open relief valve that occurred at TMI. The assumption of a large-break LOCA (even though it may be less likely than a small-break LOCA) results in an earlier activity release than that seen at TMI, and it also minimizes retention of activity by deposition within the RCS. Both of these factors tend to make the large-break LOCA assumption conservative, at least for the postulation of the activity release to the containment (i.e., the DBA-LOCA source term). The assumed AST duration of release, however (as opposed to the start of release), is more characteristic of a range of core damage accidents, including small-break LOCAs (refer to References [4] and [5]).

One potential non-conservatism in Reference [3] is permission to assume that the source of the MSIV leakage is the drywell (i.e., the containment compartment housing the reactor vessel) rather than the reactor vessel (and in particular, the upper plenum of the reactor vessel), itself. Since the source term specified in Reference [3] was specifically developed in References [4] and [5] as the release **from the RCS to the containment**, it makes perfect sense *prima facie* to make such an assumption. The implied justification for this assumption, however, is that the release from the reactor vessel to the drywell over time must occur in such a way that the activity concentration reaching the MSIV leak point – under the assumption that the drywell is the source – is at least as great as that reaching the MSIV leak point for the actual case of the reactor vessel upper plenum being the source. Otherwise, the analysis may not be adequately conservative.

This issue was addressed cursorily in Reference [1], but the focus of Reference [1] was the discussion of steam line deposition issues that were not fully developed or finalized in Reference [3]. Since the acceptability of assuming the drywell as the source of MSIV leakage had already been established in Reference [3] when Reference [1] was prepared, Reference [1] discussed the matter only briefly and at a superficial level.

This study, as a follow-on to Reference [1], examines in more detail the likelihood that treating MSIV leakage in accordance with Reference [3] (with the drywell as the assumed source) could be non-conservative. This question of conservatism is important because Reference [6] (a proposed revision of Reference [3] with Reference [2] as part of the justification for that proposed revision) essentially suggests that if the Reference [3] assumption (drywell as the source for MSIV leakage) is used, MSIV leakage dose-rate multipliers are necessary during the first part of the accident (i.e., during the first half of the two-hour release period specified in Reference [3]) in order to restore adequate analytical conservatism. The effective multipliers being suggested are approximately 15 to 25 for the 0 – 0.5 hour portion of the two-hour release phase, and about half that for the 0.5 – 1.0 hour portion. While References [1] and [2] are in general agreement that in the long-term, assuming the drywell as the source is conservative (e.g., for the Control Room and Low Population Zone (LPZ) doses), the two-hour Exclusion Area Boundary (EAB) dose could be substantially increased by the use of these multipliers. It is also the case that a significant fraction of the total 30-day Control Room dose can be realized early in the event when Control Room isolation, emergency filtration, and remote air intakes are not yet in operation. For plants where this is the case, such multipliers may also significantly increase the Control Room dose.

The acceptability of designating the drywell as the source of MSIV leakage is naturally coupled to assumptions regarding how radioactivity is removed from the drywell in the DBA-LOCA analysis. Obviously, the greater the degree of conservatism in how that removal is handled in DBA-LOCA analysis, the greater the degree of acceptability of the drywell/source assumption.

Generally, only natural removal (and possibly removal by sprays) is considered in the drywell prior to the end of the two-hour activity release phase. After that, uniform mixing with the wetwell gas-space volume is permitted but only if justified. Even if uniform mixing with the wetwell gas-space is credited after the end of the release phase, credit for suppression pool scrubbing of activity during the transfer of that activity from the drywell to the wetwell is strongly discouraged by Reference [3] and is generally not credited. Since the time period of concern for the MSIV leakage source issue is only the first hour of the two-hour release phase, questions about how drywell activity removal is handled analytically beyond the end of the release phase are really moot. Nevertheless, when one is evaluating the conservatism of the drywell as the source of MSIV leakage, one must recognize that actual severe accident progression analyses (e.g., those done with MAAP4, Reference [7]) show that some transfer of activity from the drywell to the wetwell (and associated suppression pool scrubbing) is occurring even during the release phase. If that fact contributes to activity concentrations in the drywell being identified as being less than activity concentrations in the reactor vessel upper plenum in analyses using MAAP4 or MELCOR (Reference [8] as used in Reference [2]), then an unfair bias may be introduced in comparing concentrations. In other words, wetwell transfer and suppression pool scrubbing are real, and these effects can lower the activity concentration in the drywell. However, for conservatism, these effects are not credited in DBA-LOCA dose analysis; and when comparing the drywell and reactor vessel upper plenum concentrations for purposes of assessing an appropriate source for MSIV leakage, these effects should not be taken into account. If, for example, the MELCOR analysis presented in Reference [2] included these effects (as it most likely did), then any activity in the wetwell gas-space or the suppression pool in those analyses should be added back into the drywell when the drywell activity concentration comparison is made to the activity concentration in the reactor vessel upper plenum. Such an adjustment would make the comparison more relevant for DBA-LOCA purposes.

The study discussed in the next section makes use of MAAP4. MAAP4 was selected for this study because of the availability of its counter-current, density-driven flow model.

Such modeling has proven to be important in the analysis of core-damage reactor accidents because of the presence of superheated steam and hydrogen (contributing to large gas density variations) in both the reactor vessel and in the containment. Similar modeling has been used to study fire propagation in buildings (Reference [9]) where oxygen may only be able to reach compartments through the same openings in which combustion gasses and smoke are being vented, thus limiting the severity of the fire.

The relevance of counter-current, density-driven flow modeling to the problem at hand is established by the geometry of the steam lines. The steam lines are connected to the upper plenum of the reactor vessel and then drop down vertically along the outside of the reactor vessel shield wall many tens of feet before reaching a horizontal run containing the safety/relief valves. Then, there is a second drop of many tens of feet before turning to run horizontally up to the inboard MSIV. In DBA-LOCA dose analysis, activity removal in the steam lines upstream of the inboard MSIV is generally ignored because of the possibility that the initiating pipe rupture could occur at the inboard MSIV; and in that event, the steam lines up to the inboard MSIV would be bypassed when considering the drywell as the source of the MSIV leakage. While its true that the remaining steam lines (usually three in number) would be intact up to the inboard MSIV, it is also usually the case that a single failure of an MSIV to close is postulated in one line and it is also the case than one line is usually assumed to be leaking at a rate greater than the others. (This skewing of the assumed leak rate arises because of the typical specification of allowed leak rate: a maximum total value for all steam lines together and a maximum value for a single steam line). The limiting case, then, is the assumption that the line with the rupture (assumed to be at the inboard MSIV) is also the line with the greatest leak rate and the line with one MSIV failed open. This set of assumptions makes the limiting line so greatly dominant in terms of dose contribution that the question of deposition in the other steam lines up to the inboard MSIVs becomes largely irrelevant; and for simplicity, such deposition is simply ignored.

In the next section, the application of MAAP4 to the determination of the relative activity concentration at the MSIV leakage point (considering both the drywell and the reactor vessel upper plenum as the source) is presented.

2 MAAP4 Analysis

Both Reference [1] and Reference [2] reach the conclusion that in the long term (beyond approximately one hour), assuming the drywell to be the source of MSIV leakage is conservative. However, Reference [2] makes an interesting observation that during the first half of the two-hour DBA-LOCA activity release, the activity concentration in the reactor vessel upper plenum may exceed (by large factors) the activity concentration in the drywell. This fact gives rise to a concern that short-term doses (the EAB dose and possibly a significant fraction of the Control Room dose) may be under-predicted by the assumption that the drywell is the source of the MSIV leakage. However, the key question is not whether the upper plenum concentration is greater than that of the drywell. Rather, the key question is whether the concentration at the inboard MSIV location is greater than that of the drywell for situations in which the steam lines are intact. That is the question being addressed by this study, and MAAP4 is the primary analytical tool that will be used to investigate what the answer to that question might be.

2.1 Approach

The approach used in this study is to perform MAAP4 analyses with a steam line modeled as two or three vertical sections so that the mixing between the steam line and the upper plenum of the reactor vessel is better represented than in the MELCOR model of Reference [2].

One may note that the MELCOR results of Reference [2] were extended out in time to vessel failure, which occurred approximately six to eight hours after the start of the accident. Such extended times to vessel failure are relatively new developments. As described in the next section, vessel failure was expected in Reference [5] (and its supporting documents) within approximately two hours of the start of a significant release of activity to the containment. The longer time to vessel failure blurs the distinction in Reference [5] between the early in-vessel and late in-vessel radioactivity release phases (with the first being included in the AST and the second being excluded). Nevertheless, there is precedent for how MELCOR and AST cases can be properly compared, and this precedent is discussed further in the next section.

2.2 Defining a Time Frame of Interest

One of the major achievements of the AST of Reference [3] is the introduction of timing as a consideration in the assumed accident release. Prior to the introduction of the AST, the assumption was made in DBA-LOCA dose analysis that the total core-damage activity release appeared instantaneously in the containment at the start of the accident (Reference [10]). While this assumption had the appearance of being conservative, the conservatism could be lost if credit were taken for mitigating effects that actually depend on the activity being present in the containment at t = 0. For example, for plants using vapor suppression containments (BWR containments with suppression pools or ice condenser containments), the reality is that most of the steam condensation occurs early in the LOCA well before the onset of core damage. If one assumes, artificially, that the activity is released instantaneously into the containment, then the effectiveness of activity removal due to steam condensation (for BWRs, the so-called "suppression pool scrubbing" phenomenon) may be considerably overstated. In fact, when the activity release begins, condensation rates will likely be only a small fraction of what they are during RCS blowdown at the beginning of the accident. One must take care, therefore, to make sure that thermal-hydraulic phenomena are credited only when the relative timing of activity releases and thermal-hydraulic phenomena are coupled in a reasonably predictable way.

This question of timing comes into play when comparing drywell and reactor vessel upper plenum activity concentrations. The overheating of the core begins when the water level in the core drops to a point where steam generation and cooling of the uncovered portion of the core (by steam generated in the lower, covered portion of the core) is no longer sufficient to prevent cladding oxidation and an acceleration of the core heatup. Depending on the rate of coolant loss, this point may be reached over a wide range of times. However, once the process is begun, there is a certain repeatability of what happens next. First, the highest power portions of the core will experience the greatest rate of heatup with significant cladding oxidation and production of hydrogen. Then, liquefaction of the inner regions of the core will begin while outer regions are still heating up, followed by downward relocation of liquefied core material and other core debris, with additional steam being generated as core debris begins to interact with residual water at the bottom of the reactor vessel. Cladding oxidation, fuel liquefaction, and downward relocation of debris will continue (or even accelerate) until the cooling of the core debris is restored by reflooding. At this point, a very large amount of steam and hydrogen will be generated as the considerable sensible heat that has been accumulating in the core debris is released and steam is available for the oxidation of cladding that was previously steam-starved. As the core debris is cooled, the fission product release from the core debris will cease or greatly slow. Accumulated activity in the reactor vessel upper plenum will be flushed out into the containment, and the transfer of activity from the reactor vessel upper plenum into the steam lines will essentially come to an end.

The timing of these thermal-hydraulic phenomena and the fission product release are coupled by the time-at-temperature of the core and the core debris. The precise timing of the core damage progression, the associated steam and hydrogen production, and the gas composition and thermodynamic state in the reactor vessel (in particular, in the reactor vessel upper plenum) is uncertain. Different models for core debris relocation will produce somewhat different timing with respect to the interaction of the core debris with residual water and with restored ECCS flow. However, the bottom line is similar: when the overheated core debris experiences cooling (either temporarily or permanently), a dramatic increase in steam and hydrogen flow through the upper plenum will generally occur.

In the MELCOR analyses presented in Reference [2], the effects of core debris/coolant interaction on the radioactivity transport are clearly evident. Consider Figure 1, a reproduction of Figure 2-13 of Reference [2], showing the distribution of CsI mass in the reactor vessel upper plenum ("steam dome"), the drywell, and the wetwell for a large main steam line break (MSLB) LOCA without ECCS in a Mark I containment BWR.

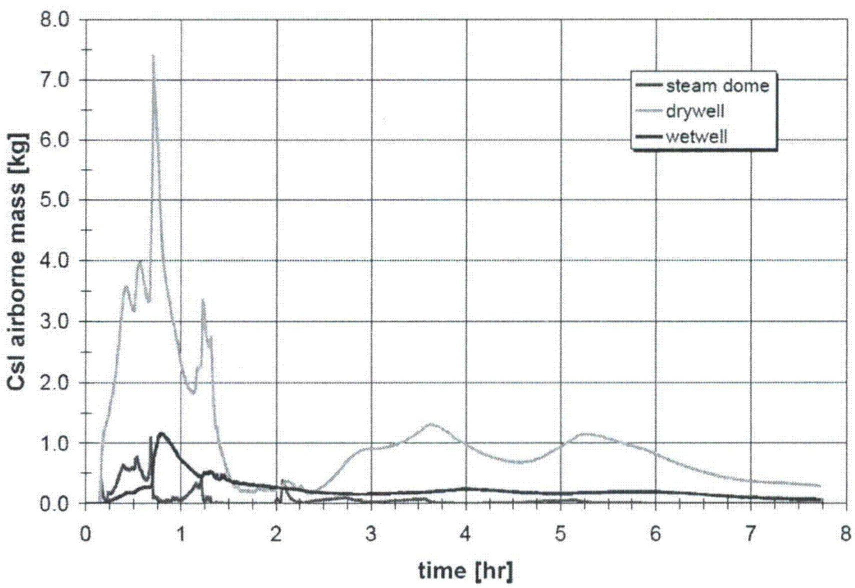

Figure 1 - Reproduction of Figure 2-13 from Reference [2]

Note the dramatic increase in drywell and wetwell airborne CsI mass, and the corresponding decrease in steam-dome mass (more than one order of magnitude) that occurs at about 0.7 hours. This point in time is just before lower core plate failure as seen in Figure 2, a reproduction of Figure 2-12 of Reference [2]:

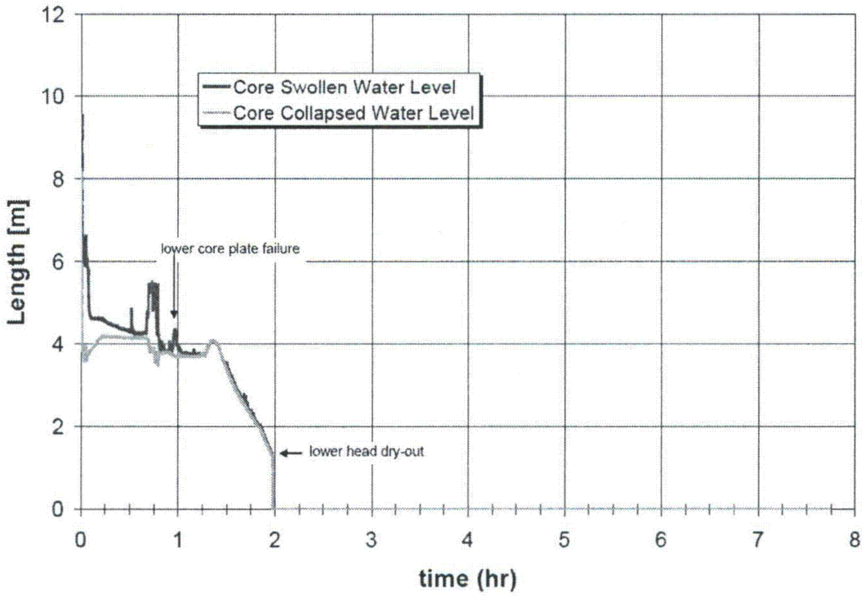

Figure 2 - Reproduction of Figure 2-12 from Reference [2]

In Figure 2, one may observe the significant steam generation just before core plate failure (the dramatic increase in the boiled-up level of the core while the actual core level is decreasing. This is the kind of thermal-hydraulic event that occurs as core debris relocates downward and comes in contact with residual water. Then a quiescent period follows until about 1.2 hours when the complete boil-off of the water in the vessel begins. During this quiescent period, the airborne activity increases in the steam dome and decreases in the containment. The steam dome activity then drops by more than two orders of magnitude between 1.2 and 2.0 hours as the core water level slowly decreases due to boil-off. Finally, the activity in the steam dome increases immediately after dry-out and then decreases, increases, and decreases to a limited degree over a period of nearly six hours until vessel failure. According to Figure 3, a reproduction of Figure 2-14 of Reference [2] showing the CsI airborne concentration corresponding to Figure 1, the steam dome concentration during this t = 2+ hour period at times exceeds that of the drywell; and at times, it is less.

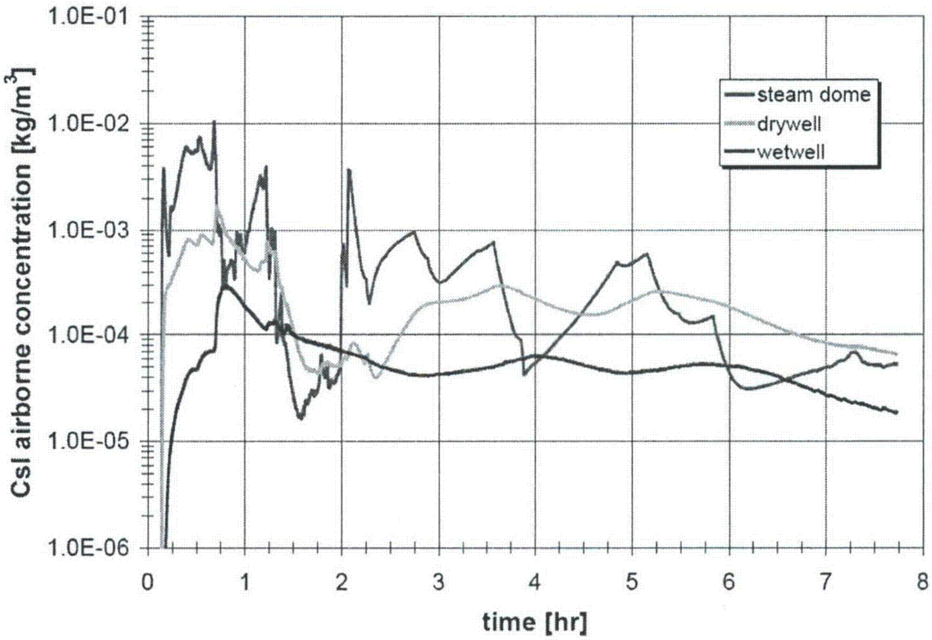

Figure 3 – Reproduction of Figure 2-14 from Reference [2]

For purposes of redefining the BWR DBA-LOCA source term (i.e., developing a replacement for Reference [10]), the core reflood and core debris cooling were assumed to occur in time to preclude vessel failure such that the ex-vessel and late in-vessel release phases described in Reference [5] could be justifiably excluded from the Reference [3] AST (Reference [11]). The early in-vessel releases were assumed to start 30 minutes after the first gap release (for BWRs, 32 minutes after the initiating pipe rupture), and the duration of the early in-vessel release was set at 1.5 hours. This duration was determined as follows (from Reference [5]):

> *"During the early in-vessel release phase, the fuel as well as other structural materials in the core reach sufficiently high temperatures that the reactor core geometry is no longer maintained and fuel and other materials melt and relocate to the bottom of the reactor pressure vessel. During this phase, significant quantities of the volatile nuclides in the core inventory as well as small fractions of the less volatile nuclides are estimated to be released into containment. This release phase ends when the bottom head of the reactor pressure vessel fails, allowing molten core debris to fall onto the concrete below the reactor pressure vessel. Release durations for this phase vary depending on both the reactor type and the accident sequence. Tables 3.4 and 3.5, based on results from Reference 16* [NUREG/CR-4881, Reference [4] of this document], *show the estimated duration times for PWRs and BWRs, respectively."*

The durations identified for the BWR early in-vessel release phase in Table 3.5 of Reference [5] varied from 1.1 hours to 2.2 hours with low-pressure accident sequences averaging about 1.6 hours and high-pressure accident sequences averaging about 1.4 hours. The assumed reflood was judged to be needed before these times to keep the vessel intact and to limit the activity release to that corresponding to the gap + early in-vessel release phases of Reference [5].

In Reference [12], comparisons were made between DBA-LOCA dose analyses done with the AST (and using the DBA-LOCA transport and environmental release methodology) and parallel DBA-LOCA dose analyses based on MELCOR-generated releases to the environment. The MELCOR-generated source term (release to containment) was more rapid than the AST specification, so the ECCS restart/core reflood was assumed to occur earlier than at t = 2 hours (actually, in less than half that time) in order to terminate the MELCOR release and have the releases to the containment be the same for both cases. Even though the assumed reflood in MELCOR had to be advanced to less than one hour after the start of the accident (less than one half the duration of the AST gap + early in-vessel release), the MELCOR analysis was considered to be representative of the AST. This is because the AST timing was chosen to be representative of a wide-range of core-damage accidents, not one accident in particular. Moreover, the AST release magnitude (e.g., 30 percent of the iodine core inventory for BWRs) was chosen independent of any particular event or its timing. Thus, the initiation of debris cooling at t < 1 hour to limit releases to the containment (in order to match the specified AST release to containment) for the MELCOR large-break LOCA with degraded ECCS was not seen as being inconsistent with the AST; it was the magnitude of the release to the containment rather than the exact timing that defined the AST, so there was no inconsistency.

Figures 1 and 3 show only airborne activity; i.e., they do not show activity in the suppression pool. Since no data are provided regarding activity in the suppression pool, that activity can only be estimated. In Figure 1, one may observe (as pointed out earlier) the substantial decrease in drywell activity beginning at about 0.7 hours and occurring again at about 1.3 hours due to large generation rates of steam and hydrogen. The rates of decrease are seen to be of the order of four per hour (hour^{-1}) for the first decrease and 10 hour^{-1} for the second decrease. These decreases are much too rapid for natural deposition (typically one hour^{-1} or less). It's likely that drywell-to-wetwell flow is accounting for the greatest part of these decreases. But one sees no corresponding increase in the wetwell airborne CsI mass (it, too, is decreasing, although not nearly as rapidly). One may assume, therefore, that about 7.0 kg of CsI has accumulated in the suppression pool during these thermal-hydraulic events. Were this CsI (and the ~0.2 kg in the wetwell airspace for t = 2 hours) added back into the drywell (as would be the case for a DBA-LOCA analysis where no credit is taken for drywell-to-wetwell flow prior to the end of the AST release phase), the CsI concentration in the drywell would be about an order of magnitude greater than that seen in Figure 1. (Since the drywell volume of this model is about 4500 m^3, the ~7.2 kg of CsI would add ~1.6E-3 kg/m^3 to the drywell CsI concentration, if the estimated suppression pool CsI inventory is correct. This would <u>not</u> be the case, however, if drywell sprays were credited; and this situation is addressed in Section 3.2.)

Another way of assessing Figures 1 and 3 is that for the plant modeled in the MELCOR analysis, the total amount of CsI available is about 36 kg. In the DBA-LOCA AST, 30 percent of that (10.8 kg) is assumed to be released into the drywell over a two hour period. The corresponding maximum peak concentration at the end of the release phase would be 2.4E-3 kg/m^3 if no activity removal were considered. The actual peak is somewhat less because of activity removal that is ongoing in the drywell, even while the release phase continues.

The transient activity in the drywell for a BWR DBA-LOCA may be easily estimated by using the 10th percentile removal rates from Reference [13] for a BWR. If these removal rates are used, and the drywell CsI concentration is superimposed on Figure 3, the following (Figure 4) result is obtained (with the DBA-LOCA concentration represented by the solid black line).

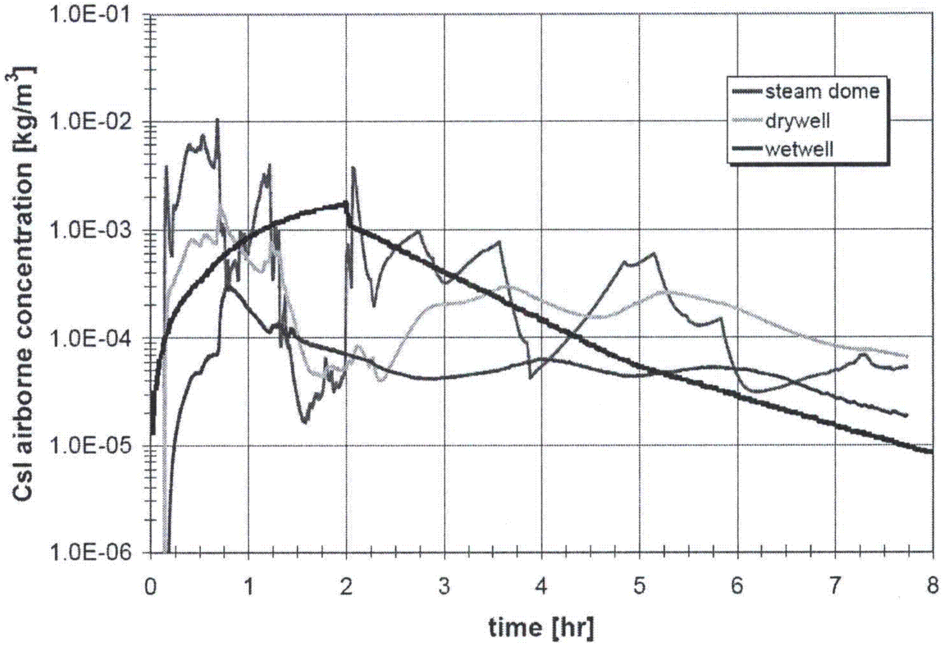

Figure 4 – Figure 3 with DBA-LOCA (No Sprays) CsI Airborne Activity Superimposed

Here it can be seen that the calculated peak CsI airborne concentration for the DBA-LOCA (in the drywell) is actually about 1.8E-3 kg/m^3 rather than the 2.4E-3 kg/m^3 based on the total AST release (see previous page). In other words, about 25 percent of the release has settled out by the end of the release period. Note also the step decrease in the DBA-LOCA drywell concentration occurring at t = 2 hours when the drywell activity is assumed to mix uniformly with the drywell + wetwell volume.

There are a number of points to be made concerning Figure 4:

- First, at t = 2 hours the drywell DBA-LOCA CsI concentration is very close to the MELCOR result as long as the suppression pool and wetwell estimated inventory is added to that in the drywell (i.e., the 1.6E-3 kg/m^3 equivalent CsI mass estimated to be in the suppression pool + the ~7E-5 kg/m^3 in the wetwell reduced by the drywell-to-wetwell volume ratio of about 1.67 + the ~5E-5 kg/m^3 in the drywell = 1.7E-3 kg/m^3). In other words, the MELCOR total release to the containment is very similar to that of the DBA-LOCA. The peak MELCOR concentration at t = 0.7 hours is also very close to the peak DBA-LOCA concentration 1.3 hours later. Both of these observations are consistent with the MELCOR cases run in support of Reference [12].

- Second, Figure 4 demonstrates the steam dome activity concentration concern quite well (which is the central issue being addressed by this study). During the first ~ 1.3 hours, the steam dome CsI concentration substantially exceeds that of the drywell for both the DBA-LOCA and the MELCOR case. For the DBA-LOCA analysis, the worst two hours – in terms of airborne CsI available for leakage from the drywell – would appear to be from about one hour to about three hours. This would be a typical time for the worst two-hour EAB dose to be calculated for an actual DBA-LOCA analysis. If the source were the steam dome, however, the worst two-hour period would appear to be from about 0.2 hours to about 2.2 hours, and the dose could be several times higher for the steam dome case (based on integrated area under the curve from 0.2 to 2.2 hours for the steam dome and from one to three hours for the heavy black line of the DBA-LOCA drywell.
- Third, one may note that the MELCOR drywell concentration actually increases after about 2.3 hours (along with the concentration in the steam dome, which increases sharply about 0.3 hours earlier). These increases are indicative of a second release that appears to make the MELCOR-calculated release to containment after t = 2 hours substantially greater than the AST (since the release up to t = 2 hours appears to be virtually identical to the AST). For consistency with the AST, the MELCOR reflood should probably have been initiated at about t = 0.7 hours, or shortly thereafter, when the activity release to the containment was approximately equal to that of the AST (as was the case in the MELCOR analyses supporting Reference [12]). Certainly, the assumed reflood should not be postponed beyond t = 2 hours.

The situation is similar for the case of the recirculation system large-break LOCA. Figure 5 is identical to Figure 4 except it is based on Figure 2-31 of Reference [2] for the recirculation system large-break LOCA instead of the MSLB. Once again, the solid black line is the drywell airborne CsI concentration for the DBA-LOCA.

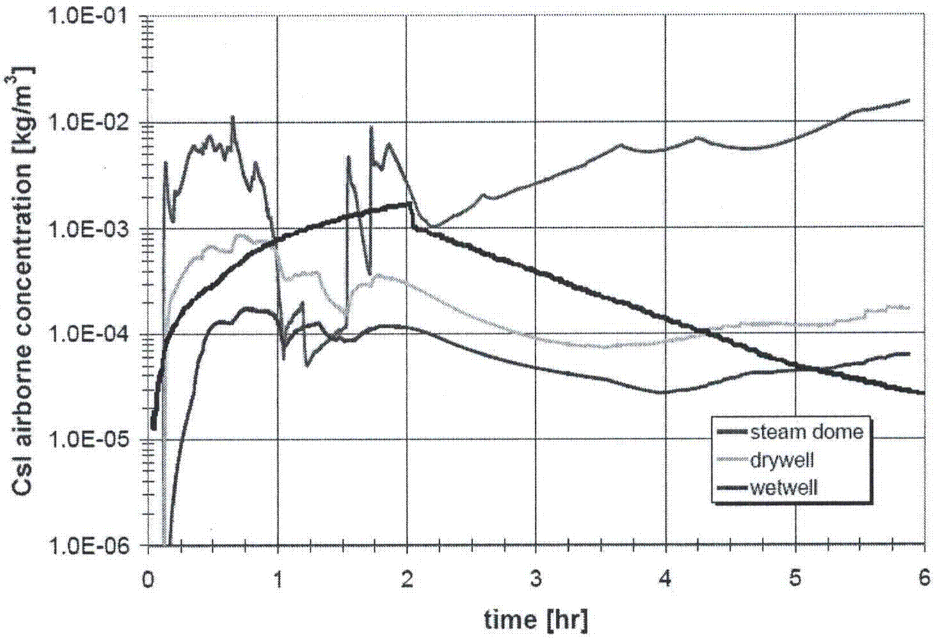

Figure 5 – Reproduction of Figure 2-31 from Reference [2] with DBA-LOCA (No Sprays) CsI Airborne Activity Superimposed

For the recirculation system break, the MELCOR analysis shows about 3.8 kg of CsI airborne in the drywell at the peak time of ~ 0.7 hours with an additional 0.7 kg of CsI in the wetwell. If this were all in the drywell, the CsI concentration would be about 1.0 kg/m^3, about 60 percent of that for the steam line break, and less than the peak for the DBA-LOCA. However, the MELCOR analysis results indicate that at least another 2.0 kg of CsI is added before t = 2 hours. It's difficult to tell from the Reference [2] figures, exactly when the total MELCOR-generated CsI release to the containment for the recirculation system break would exceed 10.8 kg (30 percent release). It would likely take longer than the estimated 0.7 hours for the MSLB, but could still be less than t = 2 hours because of uncertainty about how much activity is in the suppression pool.

One interesting fact is that the MSLB drywell and wetwell pressure plot (Figure 2-10 of Reference [2]) shows a nearly constant 0.02 MPa (approximate) pressure difference between the drywell and the wetwell. This is the pressure difference corresponding to vent submergence and suggests that vent flow is ongoing continuously. The corresponding plot for the recirculation system break (Figure 2-27 of Reference [2]) shows no differential pressure from t = 2 to t = 3 hours. It's likely, then, that between t = 2 and t = 3 hours, no vent flow is occurring; and the concentration reductions seen in Figure 5 (which parallel those of the DBA-LOCA) are nothing but natural deposition at a rate of one hour^{-1}, or less. It appears that vent flow begins again at t ≈ 3 hours and that the drywell and wetwell concentrations begin to increase at that time. Without more data, these observations are somewhat speculative, but the point is simply this: when the CsI activity released to the drywell is such that reflood will result in a final release equal to 30 percent of the iodine core inventory, then that is when the reflood should be assumed in the MELCOR analysis (as was done in Reference [12]). If any other assumption is made, then the issue at hand is not the question of steam dome vs. drywell radioactivity concentration; rather, it is the question of redefining the AST to be something different from (and greater than) the 30 percent iodine release to the drywell specified in References [3] and [5].

Observation:
Because of the extended time to vessel failure now predicted by MELCOR, the MELCOR analyses are extended out in time to a point where the release of radioactivity to the drywell exceeds (or is likely to exceed) the AST specification. If the results beyond that point in time were used, it would amount to a redefinition of the AST.
Recommendation:
The MELCOR cases should involve an assumed reflood time so that the integrated CsI release to the drywell matches the AST.

The above observation and recommendation being made, one must point out that the NRC in Reference [6] (making reference back to Table 5-3 of Reference [2]) is not calling for any adjustment in the drywell concentration for MSIV leakage beyond t = 1 hour. Therefore, the NRC appears to be in agreement with this point, even though the MELCOR runs were extended out in time (beyond the AST magnitude) in Reference [2] and show steam dome concentrations in excess of those for the DBA-LOCA.

The time frame of interest, then, may reasonably be assumed to be less than t = 2 hours (the duration of the AST release) for the MELCOR cases. However, in no case should the time frame be less than the time it takes for the release to containment (after reflood) to equal 30 percent of the core inventory of iodine.

2.3 MAAP4 Input and Modeling Decisions

The Parameter File used in the study is the standard Mark I containment file distributed with MAAP4 (i.e., PEACH4.PAR, Reference [14]).

Only the MSLB case with degraded ECCS (no low-pressure systems), without sprays, was run. This allowed economy of effort since the purpose here is (1) to provide insights pointing the way to resolution of the MSIV leakage source issue and (2) to present information pertaining to the MSIV leakage source issue only to the same level of detail and scope as other, similar issues were treated in Reference [1]. It is not the purpose of this paper to present an exhaustive study of all aspects of the problem.

The cases were run for 12,500 seconds. This run time is sufficient to ensure that at least 30 percent of the iodine inventory is released to containment (see Section 2.2 for further discussion of the AST CsI release to containment).

Reference [2] suggests that the MSLB flow area for the MELCOR analyses is 0.2828 m^2. This is equivalent to an ID of 600 mm, or, just under 24 inches. The steam line ID given in Reference [14] is 0.508 m or 20 inches. It is not clear why the diameters are so different. However, this discrepancy turns out to be relatively unimportant because of modeling challenges regarding the MSLB in MAAP4 that are discussed more fully below.

The cross-sectional area of a 0.508 m diameter steam line is ~ 0.2 m^2. The total length of steam line between the reactor vessel and the inboard MSIV is assumed to be 31 m (i.e., 100 feet) for purposes of this study. Once again, the exact dimensions are not important. With a length of 31 m and a cross-sectional area of 0.2 m^2, the total volume is 6.2 m^3. The elevation of the main steam line centerline at the upper head (UH) junction is 62.35 m according to Reference [14]. (Note that in MAAP4 terminology, the "upper head" is the same as the "steam dome." Another term that is used interchangeably is "upper plenum.")

When the model was started, it was planned that as many as six control volumes would be used in the nodalization of the main steam line with the first volume horizontal and the rest vertical. The first volume was assumed to 17 feet in length (5.2 m) with the remaining five adding up to 83 feet (25.3 m). This placed the centerline of the inboard MSIV at approximately elevation 36.9 m, and the bottom of the main steam line control volume "stack" at about elevation 36.8 m (using the elevation datum of Reference [14]). The volume of the stack would be a total of 5.1 m^3 and the volume of the first control volume ~ 1.1 m^3.

The first run attempted was with a MSLB break area of 0.2 m^2 and two main steam line control volumes modeled as extensions of the containment using the generalized Auxiliary Building modeling and generalized opening features of MAAP4 (AGO(1) = 0.2 m^2 between the reactor vessel UH and the main steam line). The junction between the two main steam line control volumes (the first being the horizontal volume with a volume of 1.1 m^3 connected to the reactor vessel UH and the second being a vertical volume of 5.1 m^3) was also set at 0.2 m^2. The inboard MSIV leakage area was set at 1.4E-6 m^2, the area of a circular hole approximately 1.3 mm in diameter. This is the leakage area that will pass 100 scfh at test conditions or approximately 50 cfh under accident conditions. The same leakage area was assigned to the drywell (DW).

This first case executed successfully. However, when the vertical steam line control volume was divided into two control volumes (2.55 m^3 apiece with a 0.2 m^2 junction connecting them) to provide a total of three main steam line control volumes, the run behaved erratically and failed to end normally. It's judged that the combination of three small control volumes in series (with uni-directional and counter-current flow between them) and a large break, created problems with the numerical integration solution. With limited time and resources to pursue this investigation (e.g., with better time-step control), the base case was changed. The break area for the LOCA (ALOCA in MAAP4 terminology) was reduced to 0.1 m^2; and for this break size, both the two-control volume and the three-control volume runs executed normally. These two runs (MSLB-2CV and MSLB-3CV) are the runs that support the remainder of this study. Note that, for these runs, the MSIV leakage pathway with the source being the drywell and the MSIV leakage pathway with the source being the steam lines were modeled simultaneously in parallel (since the leakage is minimal, doubling the leakage has little effect on the rest of the problem). In order to identify the leakage due solely to drywell leakage (i.e., the drywell considered as the source for MSIV leakage), each run was repeated with the steam line leakage point flow area set equal to zero.

Observation:

The MAAP4 code did not execute normally when three small main steam line control volumes (connected by 0.2 m^2 junctions) were combined with a full-area (0.2 m^2) MSLB.

Recommendation:

The development of a stand-alone computer code to model the steam lines may be advisable. The total volume of the modeled main steam line is small (about 5 percent of the volume of the reactor vessel upper plenum) with a very small exchange rate with the environment (approximately 1 percent per hour of the upper plenum volume). The MAAP4 model results could establish the boundary conditions for the main steam line model and could also provide comparative results for MSIV leakage treated with the drywell as the source. The stand-alone model could make use of the same counter-current flow modeling feature as that incorporated in MAAP4 or used in other studies such as Reference [9]. By decoupling the main steam line model from the MAAP4 code, the impact of more control volumes could be studied as well as direct comparisons with MELCOR results. Reference [2] describes the use of a similar concept (MELCOR MSL-only models).

The main steam lines were modeled without a sedimentation area. The walls of the steam line control volumes were treated as isothermal with the temperature set to that of their normal operating condition. The potential for fission product heating and revaporization is discussed in Section 3.2.2.

The MAAP4 power level was left the same as Reference [14]; i.e., 3293 MWt. This is in contrast to the MELCOR power level of 3528 MWt. The containment volumes from Reference [14] are as follows:

```
VOLRB(1)        240.0  M**3
VOLRB(2)       4841.0  M**3
VOLRB(3)        496.5  M**3
VOLRB(4)       6801.1  M**3
```

The first two volumes are the pedestal and the drywell, respectively. The third volume is the vent system which contains 42.7 m^3 of water (the water initially in the vents). Therefore, the effective volume of the drywell is the sum of the first three control volumes less the 42.7 m^3 of water in the vents or about 5535 m^3. This is 23 percent greater than the 159,000 ft^3 assumed in the MELCOR model. The wetwell volume includes the volume of the suppression pool which is initially 3416 m^3.

2.4 MAAP4 Results

The two MAAP4 cases presented in this section are identical except for the number of main steam line control volumes (either two or three). Key event code times are as shown in Table 1.

Note in Table 1 that the runs were ended very shortly after the relocation of core debris to the lower plenum (i.e., the reactor vessel lower-head region). At this time, a significant increase in steam generation occurred, and the activity concentration in the reactor vessel UH decreased dramatically. As will be discussed later, the runs are not identical because the size and number of the steam line control volumes affect time-step control; and this, in turn, can have small impacts on the calculated accident progression.

Table 1 – Key Event Code Times

Event	Description	Time - seconds MSLB-2CV	MSLB-3CV
256:T	BREAK IN PRIMARY SYSTEM (LOCA)	0	0
64:T	REACTOR SCRAMMED	0.569	0.569
30:T	CORE UNCOVERED	2454.685	2591.660
36:T	CORIUM PRESENT IN LOWER PLENUM	11992.09	11899.19
END		12500	12500

The noticeable impact of the smaller main steam line control volumes (MSLB-3CV case) on time-step control is reflected in the ~ 5 percent difference in time-of-core-uncovery (and a much smaller difference in the time-of-relocation of core debris to the lower plenum). Such differences are larger than one would desire, but using three coupled control volumes totaling only 6.2 m^3, with 0.2 m^2 junctions between them, represents a difficult condition for the numerical solution. The behavior of key thermal-hydraulic variables, however, shows good agreement between the two cases.

Figure 6 presents thermal-hydraulic data for the drywell and the second main steam line control volume (SL2), including pressure, temperature, and hydrogen mole fraction. SL2 is the control volume that leaks to the environment.

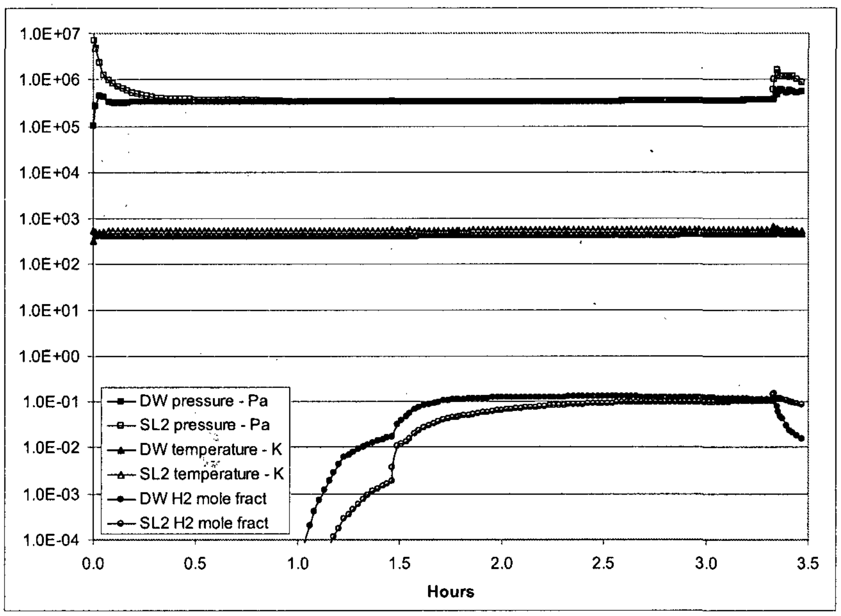

Figure 6 – Thermal-Hydraulic Data for MSLB-2CV

Similar data for MSLB-3CV are presented in Figure 7. In this case, SL3 is the control volume that leaks to the environment (downstream of SL1 and SL2). Only the temperature and pressure plots for control volume SL2 are shown on Figure 7; the corresponding plots for control volume SL3 are essentially identical.

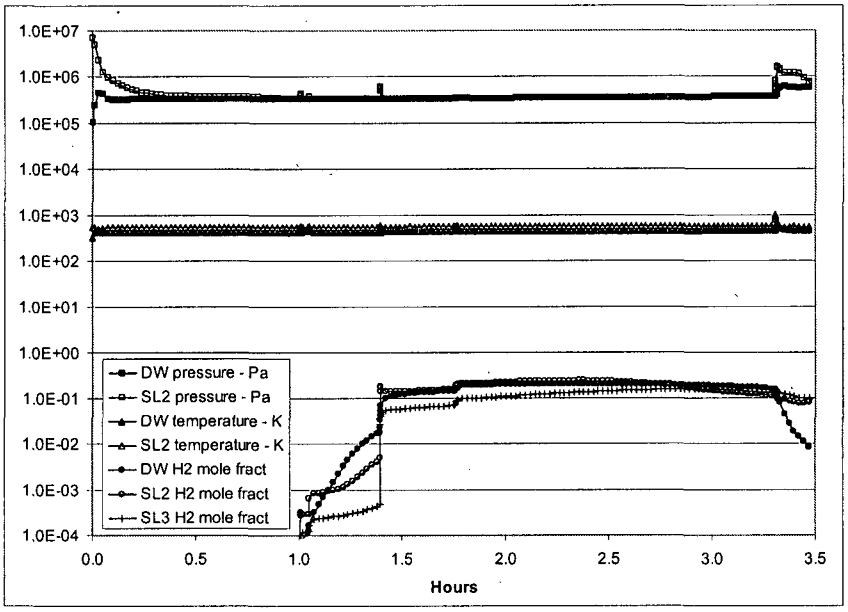

Figure 7 – Thermal-Hydraulic Data for MSLB-3CV

The CsI activity release to the containment for these two cases (expressed as a fraction of core inventory) is shown in Figures 8 (MSLB-2CV) and 9 (MSLB-3CV). As with the thermal-hydraulic plots, they are very similar. Also shown is the AST iodine release delayed by the time of core uncovery from Table 1, and a few points showing the small amount of activity in the UH.

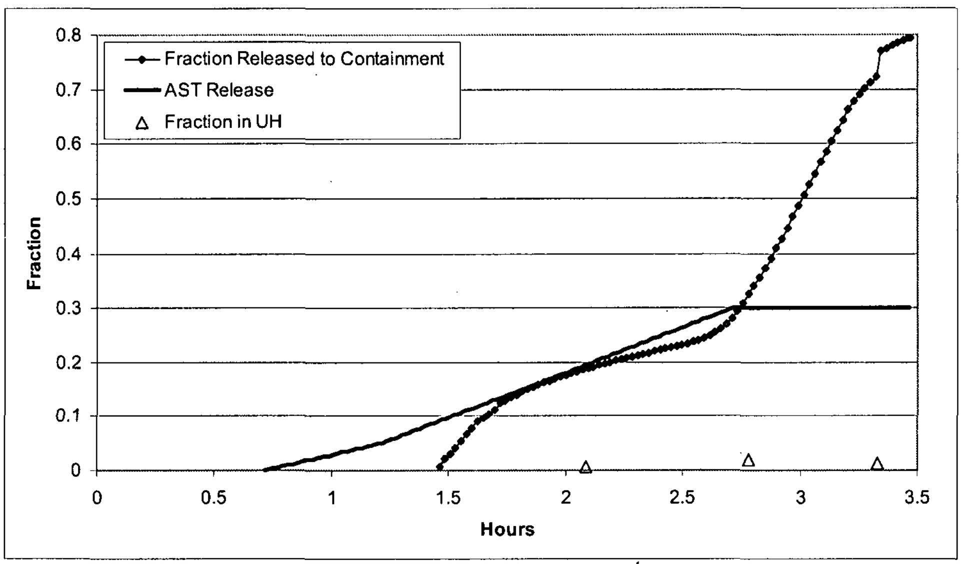

Figure 8 – CsI Release to Containment (Including Suppression Pool) – MSLB-2CV

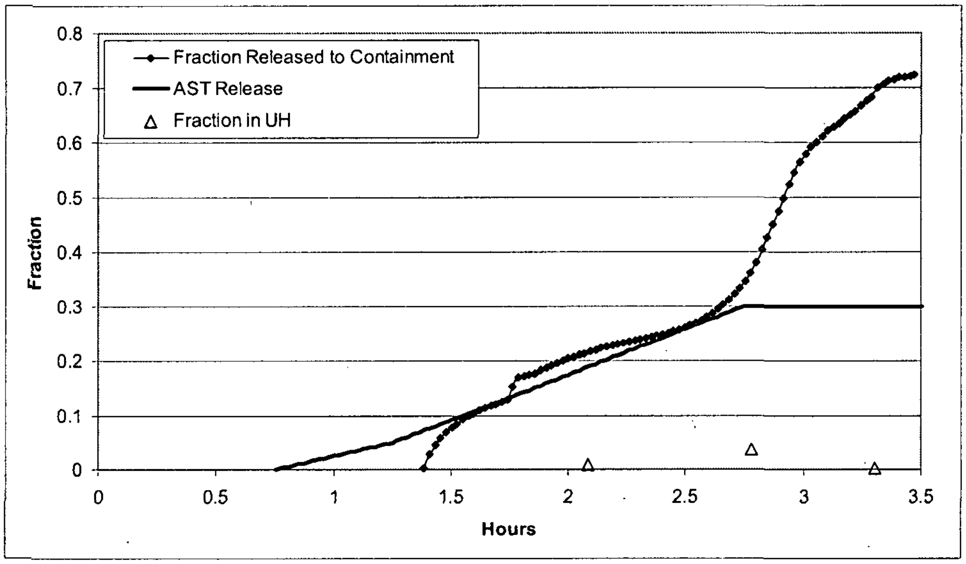

Figure 9 – CsI Release to Containment (Including Suppression Pool) – MSLB-3CV

Note that for the first case, the time from core uncovery (2455 seconds) to the time the CsI activity in the containment reaches 30 percent (9835 seconds) is 7380 seconds or about 2.05 hours. For the second case, the difference is 6984 seconds or about 1.94 hours, once again, about 5 percent difference in the timing between the cases. Although the start of release is delayed because of the 0.1 m^2 break (and because HPCI and feedwater are available for a short time in the MAAP4 model), the release to the containment is similar to the AST (about two hours from core uncovery to the point where 30 percent of the iodine has been released into containment).

With respect to the ratio of airborne CsI concentration (UH to that in the drywell), the results are as follows.

Table 2 –CsI Airborne Ratios for Reactor Vessel Upper Head and Drywell

Hours	2CV UH to DW Airborne CsI Concentration Ratio*	3CV UH to DW Airborne CsI Concentration Ratio*
1.4	66	71
2.1	7.9	12
2.8	9.5	16
3.3	4.2	0.9
3.5	1.5	1.6
*Using MELCOR ratio of UP/DW volume = 0.02334		

Junction mass flows (unidirectional and counter-current) for the relevant junctions (UH to SL1, SL1 to SL2, and SL2 to environment for MSLB-2CV and UH to SL1, SL1 to SL2, SL2 to SL3, and SL3 to environment for MSLB-3CV) are shown on Figures 10 and 11, respectively. Mixing flows are provided for flows between SL1 and SL2 for MSLB-2CV and between SL1 and SL2 and SL2 and SL3 for MSLB-3CV.

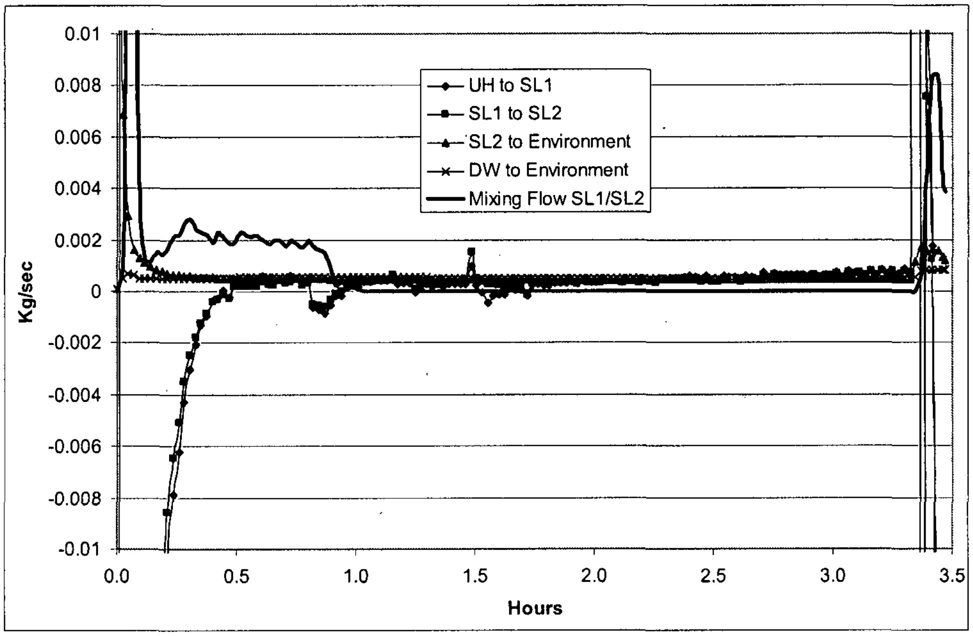

Figure 10 – Junction Mass Flowrates for MSLB-2CV

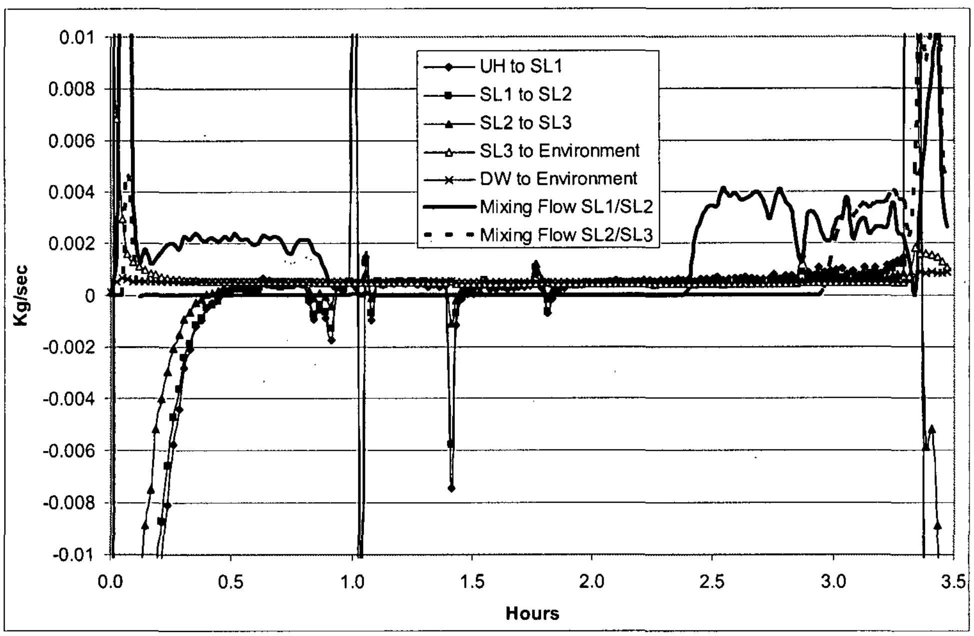

Figure 11 – Junction Mass Flowrates for MSLB-3CV

The final pieces of relevant information taken from the MAAP4 runs are the Noble Gas (NG) and CsI releases from each pathway (DW as the source of MSIV leakage vs. SL2 or SL3 as the source for MSIV leakage). This information is presented in Figure 12 for the limiting MSLB-3CV case.

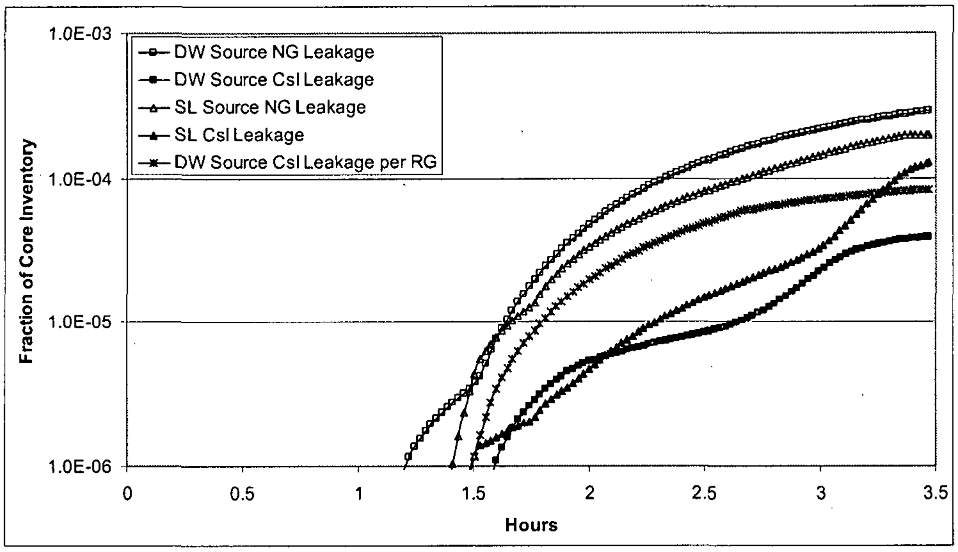

Figure 12 – NG and CsI Release to Environment for DW or SL as Source – MSLB-3CV

Note that, for this case (as well as for the nearly identical MSLB-2CV), the total CsI release to containment at 12,500 seconds (3.5 hours) is well in excess of the 30 percent release representing the AST release to containment (see Figure 9). Therefore, the environmental release values at 12,500 seconds are conservative (i.e., it would have been a correct interpretation of the AST specification of Reference [3] to have imposed core debris cooling and an end to the release at ~ 2.7 hours such that the CsI release to containment would not have exceeded 30 percent).

The last series, "DW Source CsI Leakage per RG," represents the MAAP4-calculated CsI release to the environment, but with the drywell airborne CsI determined using DBA-LOCA methodology. In other words, the release to the drywell for this case begins at about t = 1.0 hour and reaches the 30 percent value for CsI at about 2.7 hours. For the AST, it was explained in Section 2.2 that – using Reference [3] and Reference [13] methodology – about 25 percent of the activity released will have settled out by the end of the two-hour release duration. Using the same removal calculation as that applied in Section 2.2 for the AST, and assuming

- that the gap-release phase lasts ~ 0.2 hours and
- that the early, in-vessel release phase lasts 1.5 hours for purposes of applying the Powers 10th-percentile-removal coefficients from Reference [13] to the MAAP4-calculated CsI release to containment,

about 81 percent of the MAAP4-calculated CsI release remains airborne at t = 2.7 hours (about 8.1 kg of CsI). However, crediting all of the actual, MAAP4-calculated removal mechanisms (including flow from the drywell to the wetwell during core degradation), the MAAP4-calculated airborne activity in the drywell at the same point in time (at 2.7 hours corresponding to a 30 percent CsI release to containment) is less than one-third of the total release (about 3.0 kg of CsI).

The "DW Source CsI Leakage per RG" is the MSIV leakage that would occur with (1) the drywell assumed to be the source and (2) the activity removal from the drywell atmosphere assumed to be that established by the NRC regulatory guidance presented in References [3] and [13]. The CsI environmental release calculated in this way at $t \approx 2$ hours after the core is uncovered (i.e., at $t = 2.7$ hours) is about six times greater than the CsI release to the environment calculated by MAAP4.

2.5 Comparison of Results

Any direct comparison of MAAP4 and MELCOR results needs to take into account that the MAAP4 break size is only 35 percent that of the MELCOR model, the MAAP4 power level is only 93 percent that of the MELCOR model, and the MAAP4 drywell volume is 23 percent greater than that of the MELCOR model. Fortunately, direct comparisons are not necessary to obtain meaningful results.

The most meaningful result is the comparison of the mass of NG and CsI leaked during the time frame of interest (given an identical leak path flow area for each of the two pathways).

The time frame of interest must bound the ~ 2.7 hours it takes for the MAAP4 CsI release-to-containment to exceed the 10.1 kg (30 percent iodine release-to-containment). Ten thousand seconds exceeds that time; and, therefore, is designated the time frame of interest for the MAAP4 cases.

A second important comparison is the period of time in which mixing flows between steam line control volumes is suppressed.

2.5.1 Comparison of MAAP4 Cases

The key comparison is that provided by Figure 12. Here, one can see that the MSLB-3CV case run with the assumed source for the MSIV leakage being the drywell produces a noble gas leakage within the time frame of interest that is 1.55 times greater than that produced with the steam line (i.e., control volume SL3) assumed to be the source. (Note that the steam line leakage is estimated by subtracting the drywell-pathway noble gas leakage from the noble gas leakage for the combined drywell + steam line base case MSLB-3CV). For CsI, however, the situation is the opposite. The case run with the assumed MSIV leakage source being the drywell produces a leakage within the time frame of interest of just over 50 percent of that produced with the steam line assumed to be the source. This result, however, fails to recognize that the proper comparison is one in which the reference drywell activity is that consistent with the DBA-LOCA methodology (prohibiting, for example, credit for the transfer of activity from the drywell to the wetwell during the release period). When the proper comparison is made, the MSLB-3CV case run with the drywell as the assumed MSIV leakage source produces a CsI leakage (within the time frame of interest) 2.8 times greater than that produced with the steam line assumed to be the source. Therefore, the case with the drywell assumed to be the source is more limiting for both NG and CsI releases.

It was expected that of the two control volume arrangements, the more limiting would be the MSLB-2CV case. For the specific MAAP4 runs made, however, the CsI leakage at $t = 2.78$ hours (10,000 seconds) is very slightly greater for the MSLB-3CV case. The reason for this is interesting, and points to the limitations of using MAAP4 with these very small control volumes as the vehicle for this study

Comparing Figures 10 and 11, one may note that the MSLB-2CV plots do not exhibit the apparent flow instabilities that the MSLB-3CV plots display. Since the only difference between the two MAAP4 models is the breaking up of control volume SL2 in the MSLB-2CV model into control volumes SL2 and SL3 in the MSLB-3CV model, it is likely that time-step control has created slight differences in core melt progression and core debris relocation that have, in turn, lead to the flow instabilities in the MSLB-3CV model. (Numerical convergence demands with the smaller control volumes of the MSLB-3CV model has probably also played a role). The impact of these instabilities can be seen in Figures 13 and 14.

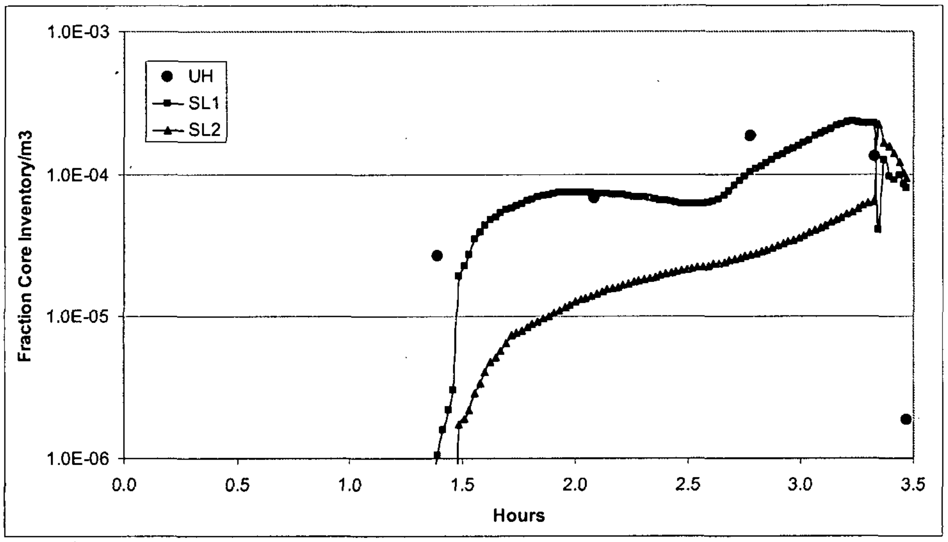

Figure 13 – CsI Concentration in Steam Line Release Pathway – MSLB-2CV

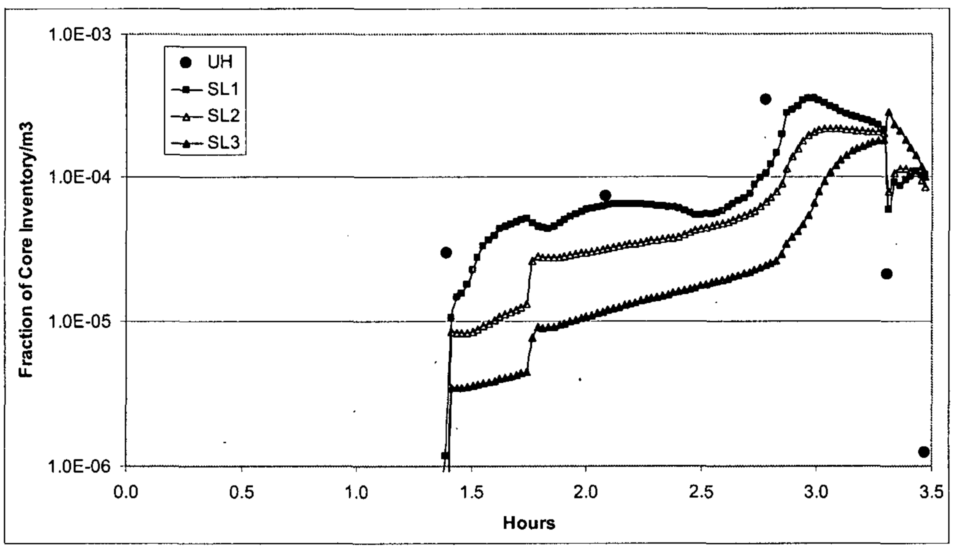

Figure 14 – CsI Concentration in Steam Line Release Pathway – MSLB-3CV

Note the abrupt increases in concentration for the MSLB-3CV case that do not occur for the MSLB-2CV case. However, the difference in CsI release between the two cases is very small through the 10,000 second (2.78 hour) time frame of interest.

It is also worth noting the substantial difference in concentration in both cases between the UH control volume and the control volumes downstream. It would be expected (were it not for the "pumping" of activity into the downstream control volumes in the MSLB-3CV case) that the more control volumes in series, the greater would be the difference between the UH concentration and that at the MSIV leak point. In fact, even with the pumping action, the MSLB-3CV case exhibits a greater ratio of upper head concentration to the concentration in the last steam line control volume than does the MSLB-2CV case as can be seen in Table 3.

Table 3 –CsI Airborne Ratios for Reactor Vessel Upper Head and MSIV Leak Point

Hours	2CV UH to SL2 Airborne CsI Concentration Ratio*	3CV UH to SL3 Airborne CsI Concentration Ratio*
2.1	4.5	6.2
2.8	6.3	14.5
3.3	1.8	0.1
3.5	0.021	0.016
*Using MELCOR ratio of UP/DW volume = 0.02334		

Note that the very small ratio for the MSLB-3CV case at 3.3 hours (relative to that for the MSLB-2CV case) should not be given too much weight. At t = 3.3 hours, the UH concentration is decreasing very rapidly (after core debris location to the lower plenum and interaction with the residual water there), and a small change in time would produce a large difference in this ratio.

Despite the unusual thermal-hydraulic behavior of the MSLB-3CV case, the impact of vertically-disposed steam line control volumes on the activity concentration seen at the MSIV leak point is evident from Table 3. To understand the importance of the vertical run of steam lines that these control volumes represent, compare the junction flow results of Figures 10 and 11. In Figure 10 (junction flows for the MSLV-2CV case) one can see the shutdown of counter-current mixing flow between control volumes SL1 and SL2 beginning a little before t = 1.0 hour and ending at about t = 3.3 hours. In Figure 11, a similar shutdown of the mixing flow occurs between SL1 and SL2, although it ends much earlier (about t = 2.5 hours). What's more important however, is the shutdown of mixing flow between SL2 and SL3 that extends from t = 0.2 hours until about t = 3.0 hours. This means that only unidirectional flow occurs between SL1 and SL2 in the case of MSLB-2CV and between SL2 and SL3 in the case of MSLB-3CV during nearly the entire duration of the time frame of interest (from shortly after core uncovery until well after the CsI release to the containment exceeds the AST-specified 30 percent). Since this unidirectional flow is limited by the MSIV leak rate which is relatively small, large concentration differences along the steam line release pathway would be expected, and Table 3 shows they exist.

In Figures 6 and 7, the H_2 concentration distribution for the steam line control volumes is shown. In Figure 6 for the MSLB-2CV case (two steam line control volumes), the H_2

concentration in the last steam line control volume is less than that in the drywell until core debris enters the lower plenum and a large steam flow cleans out the upper head and causes significant vent flow from the drywell lowering the H_2 concentration. As the upper head gas cools and the H_2 concentration drops, mixing between SL1 and SL2 restarts, lowering the H_2 concentration in SL2, as well, but not as fast as the decrease in the drywell. In a sense, H_2 concentration can be considered a marker for activity concentration since the timing of the hydrogen generation and the volatile fission product release are very similar. So for the MSLB-2CV case, one would expect activity releases via the steam line pathway (relative to those via the drywell release pathway) to become greater after t = 3.3 hours than before. In fact, this is the case. But consider Figures 7 and 14 for the MSLB-3CV case. In Figure 7, the SL2 H_2 concentration somewhat exceeds that of the drywell throughout the time frame of interest. The higher H_2 concentration in SL2 (than that seen in MSLB-2CV) promotes an earlier restart of mixing between SL1 and SL2 (at $t \approx 2.5$ hours when the SL2 CsI concentration in Figure 14 is seen to approach that in SL1), but the SL3 H_2 concentration remains nearly constant until the decreasing H_2 concentration in SL2 permits mixing between SL2 and SL3 to restart at $t \approx 3.0$ hours (closing the gap between the SL3 and SL2 activity concentration in Figure 14). This behavior is of interest and is discussed in greater detail in Section 2.6.

2.5.2 Comparison to MELCOR Results

As noted in Section 2.5, there are a number of complications in making direct comparisons between the MELCOR results of Reference [2] and the MAAP4 results presented in this paper, mostly because of the timing of the core degradation and activity release. However, qualitative comparisons are possible to illustrate the similarity of the upper plenum concentration issue.

Figure 15 is a reproduction of Figure 2-15 of Reference [2] showing the steam dome-to-drywell concentration ratio for three fission product groups including that for CsI.

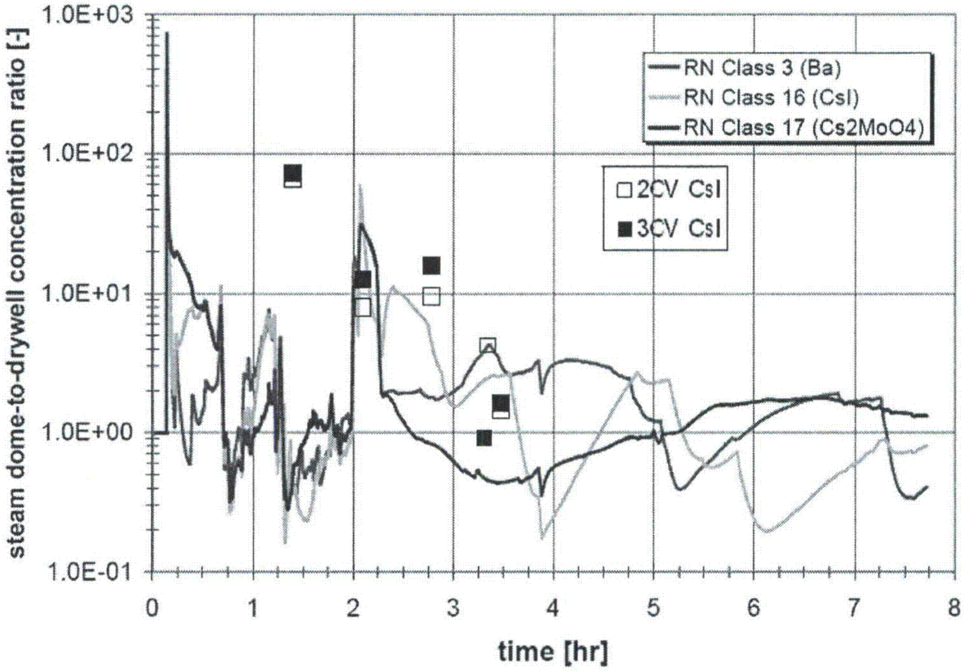

Figure 15 – CsI Concentration Ratio UH (Steam Dome) to DW – MAAP4 vs. MELCOR

Included in Figure 15 is the UH-to-DW CsI concentration ratio from the MAAP4 cases. Note the qualitative similarity between the MAAP4 results and that of Reference [2], although the MAAP4 data are shifted in time by about one hour. This shift is due to the smaller break size and slightly lower power level of the MAAP4 cases resulting in a longer time to the start of activity release. However, the MAAP4 cases have captured the same issue; i.e., the UH concentration being at least an order of magnitude higher than the drywell concentration during the ~ two hour period of release, particularly during the first hour (which for the MAAP4 cases begins at about t = 1.0 hour).

2.6 Interpretation of Results

The issue raised by Reference [2] regarding the need to consider the potential impact of assuming that the MSIV leakage originates in the upper plenum (or "steam dome" or "UH") of the reactor vessel is valid. This issue was addressed superficially in Reference [1]. In this study, it has been addressed in more detail but still not exhaustively.

- The comparison of upper plenum and drywell concentrations for MELCOR or MAAP4 analyses are, by themselves, not sufficient to resolve the question of what the impact would be of considering the upper plenum to be the source of MSIV leakage. The reason for this is that the upper plenum is not actually the source of MSIV leakage; the source is actually the portion of the steam line immediately upstream of the inboard MSIV (assuming the steam line is intact - if the line is ruptured, then the source would be the drywell).
- There can be concentration differences between the upper plenum and the steam line. To properly quantify the concentration differences along the steam line, particularly the vertical runs, unidirectional flows due to MSIV leakage and

pressure variations within the reactor vessel and mixing flows due to density differences need to be properly calculated. MAAP4 is able to do this; however, there are analysis challenges when small steam line control volumes are coupled to a large break in the reactor coolant system.

- The generation of superheated steam and hydrogen accompanying the volatile activity release tends to suppress mixing in the vertical runs of the steam lines. The greater the number of control volumes included in the vertical runs, the greater the resolution of the hydrogen and activity concentration gradients. The reduced activity concentration at the MSIV leakage point during the period of time that the MAAP4 (or MELCOR) reactor vessel upper plenum concentrations exceed those of the drywell mitigates those higher vessel concentrations. However, consideration needs to be given to the potential for the same mixing limitations maintaining high activity concentrations at the MSIV leak point even after the activity concentration in the reactor vessel upper plenum has been greatly reduced by the quenching of core debris. This point is discussed further in Section 3.1.
- The MELCOR and MAAP4 analyses can be carried out too long – beyond the point in time when the release from the reactor vessel to the drywell exceeds the defined AST. Reflood should be assumed to occur in time to limit the release to the drywell to 30 percent of the iodine per Reference [3]. Precedent for doing so was established in Reference [12]. The time period of interest in the case of the 0.1 m^2 MSLB assumed in the MAAP4 analyses was less than t = 10,000 seconds. Beyond that point, the iodine release to the drywell significantly exceeds that of the AST of Reference [3], and reflood should be assumed.
- The MELCOR and MAAP4 drywell concentrations reflect flow from the drywell to the wetwell during core degradation, suppression pool scrubbing, and deposition associated with condensation as well as sedimentation. These effects greatly deplete the airborne activity in the drywell. However, per Reference [3], they are not credited in DBA-LOCA analyses. The result is that at the end of the release in MAAP4 (and apparently also for MELCOR), the activity airborne in the drywell is ~ 20 – 30 percent of the integrated release while for the DBA-LOCA, it is ~ 70 – 80 percent. This difference needs to be taken into account when evaluating the need to assume the steam line to be the source of MSIV leakage rather than the current Reference [3] assumption of using the drywell.
- In the comparisons presented in Section 2.5, no credit was taken for drywell sprays. However, no credit was taken for sedimentation in the steam lines up to the inboard MSIVs, either. These are viewed as mutually exclusive effects (i.e., only one or the other should be credited), and the relative magnitude of these effects (as well as the justification and limitations regarding their credit) is addressed in Section 3.2.

3 Additional Considerations

The 0.1 m^2 MSLB-initiated core melt evaluated in Section 2 provides insights into how considering the steam line to be the source of MSIV leakage would differ from considering the drywell to be the source of MSIV leakage. There are some obvious short-comings of this brief study, however; and these are discussed in this section.

3.1 Behavior of Trapped Activity in the Steam Lines beyond the Time Frame of Interest

Beyond a certain point in time (that corresponding to a core debris cooling event that dramatically reduces the activity concentration, the H_2 concentration, and gas temperature in the upper head), the activity concentration in the downstream steam line control volumes may for a short time exceed that of the upper head as mixing is sequentially restarted though the vertical stack of steam line control volumes. This effect is seen in the last row of entries of Table 3.

What this means is that while there is a benefit of suppressed mixing between the vertically-oriented control volumes during the time frame of interest, there is also a period of time after the core debris quench that the activity concentration at the MSIV leakage point will be significantly greater than that of the upper head and even of the drywell. This is seen in Figure 16.

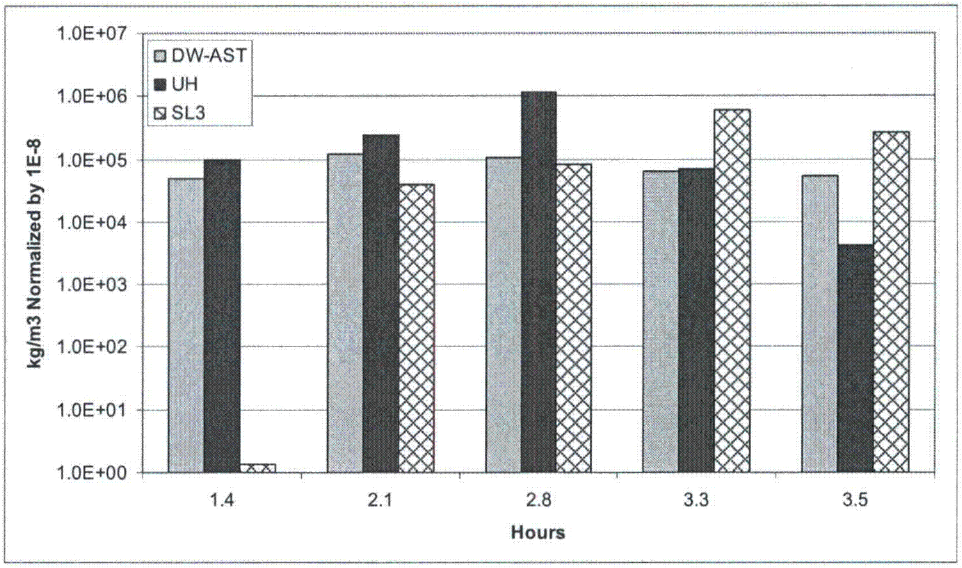

Figure 16 – CsI Concentration in DW, UH, and SL3 – MSLB-3CV

Figure 16 also shows the drywell concentration corresponding to the AST with the start of release delayed (as depicted in Figure 9 and as permitted by Reference [3] for a break smaller than the largest break).

When considering Figure 16, one must recognize that by 2.8 hours, the AST release to the containment is complete and the MAAP4-calculated CsI release to containment has already exceeded the AST value of 30 percent. Therefore, the debris quench that occurs at t = 3.3 hours due to core debris relocation in the MAAP4 calculation should have been forced to occur not later than about 2.8 hours (by restarting the ECCS) to limit the MAAP4-calculated CsI release to containment to 30 percent. Nevertheless, even if the behavior in question occurs well after the time frame of interest, it's worth pointing out the significant increase in the CsI concentration in SL3 even as the CsI concentration is decreasing in both the drywell (slowly) and in the upper head (rapidly) due to the core debris quench.

Even if the debris quench had been forced to occur a half-hour earlier, some similar increase in the reactor vessel pressure and compression of the gas and activity in the steam line (with a corresponding increase in the activity concentration at the MSIV leakage point) would have occurred (although the absolute values would certainly have been less than that shown in Figure 16). If the decrease in the SL3 CsI concentration continued at the same rate as that shown in Figure 16 between 3.3 and 3.5 hours (due primarily to mixing with the relatively activity-free upstream control volumes after the core debris quench), the projected CsI release rates for the SL3 source vs. the AST drywell source would be as shown in Figure 17.

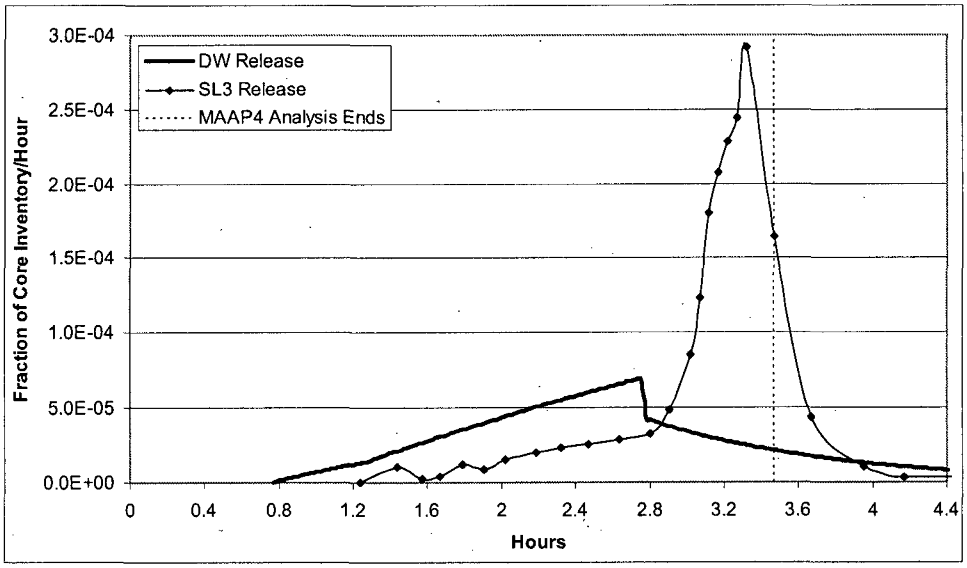

Figure 17 – CsI Release Rate to Environment – AST vs. MSLB-3CV (Projected)

This figure is difficult to interpret. At the end of the 2.78 hour (10,000 second) time frame of interest, it's clear that the AST drywell source bounds the leakage from the steam line control volume SL3 (the actual MSIV leakage point). This fact was already evident from the MAAP4 results presented and discussed in previous sections. What is less clear is the effect of the activity trapped in the steam line which is reduced only by leakage to the environment or by mixing back with the upstream control volumes.

At the end of the MSLB-3CV case (t = 3.5 hours), the integrated release for the AST (with the drywell assumed to be the source of MSIV leakage) would be about 80 percent that of SL3 (representing the integration of the plots on Figure 17). Beyond t = 3.5 hours, it appears from Figure 17 that the integrated release difference between the two pathways (drywell vs. steam line) might even become slightly greater. However, it must be remembered that by t = 3.5 hours, the total release to the containment for the MAAP4 cases is ~ 2.5 times greater than the 30 percent release to containment corresponding to the AST. One must conclude, therefore, that it would be very unlikely for the steam line pathway to become limiting (even with the trapping of activity in the steam line after the quenching of the core debris taken into account) if the release via the steam line pathway would be, at most, 50 percent greater for an extended MSLB-3CV (relative to the drywell pathway with the AST) while, at the same time, there would be ~ 2.5 as much CsI "in play" relative to the AST specification. However, confirming calculations are warranted (calculations in which ECCS is restored at a point in time that limits the CsI release to containment to 30 percent but which continues to track activity trapped in the steam line until it is has either been released or has mixed back in with the reactor vessel and containment volumes).

Observation:

Even if the CsI release to containment is limited to the 30 percent core inventory specification of the AST by timely reflooding of the damaged core, additional activity will remain trapped in the steam lines between the reactor vessel and the inboard MSIVs. This activity could leak to the environment and needs to be included in the total for the steam line release pathway.

Recommendation:

When comparative studies are made of the drywell vs. steam line release pathways and the ECCS reflood is initiated at a point in time that limits the iodine release to containment to 30 percent, provision must be made to account for the activity trapped in the steam lines.

3.2 Credit for Sprays vs. Credit for Steam Line Deposition up to Inboard MSIV

The analyses discussed in Section 2 consider neither sedimentation in the steam lines nor credit for drywell sprays. When evaluating the conservatism of choosing either the steam lines or the drywell to be the source of steam line leakage, the relative benefits of these effects needs to be taken into account, because both could be credited in the DBA-LOCA analysis. One thing seems certain, however: it would be non-conservative to give full credit for both effects. That is, either the activity makes its way to the leak point of the MSIV via the drywell (e.g., by a MSLB as the initiating event) or the activity makes its way to the MSIV leak point via the main steam line. It's unlikely (because of the thermal-hydraulic conditions within the reactor vessel during in-vessel core degradation) that a large fraction of the MSIV leakage would reside for a while in the drywell (to be depleted by drywell sprays) and then reach the MSIV leak point via the steam lines (experiencing deposition in that pathway). So the question at hand is which effect is less favorable in terms of its dose reduction. Is it possible that by crediting drywell sprays, the conservatism of choosing the drywell to be the source of MSIV leakage (to the extent it exists) could become a non-conservatism? Or would credit for activity removal in the intact steam lines up to the leaking MSIVs be of even greater benefit than drywell sprays?

3.2.1 Activity Removal Rate Comparison

Activity removal by sprays can be easily described by using the particulate removal expression for sprays found in Reference [15]; i.e.,

$$\lambda = 1.5*(Q_{spray}/V)*H*(\varepsilon/D)$$

The ε/D value is given as 10 m^{-1} initially (one percent removal efficiency for a 1 mm droplet). After a DF of 50 is achieved (i.e., two percent of the released mass remaining airborne), the ε/D value is reduced to 1 m^{-1}. A typical value for Q_{spray}/V (volumetric spray flowrate divided by the drywell volume) for a BWR drywell would be ~ 0.2 $hour^{-1}$ (i.e., a spray flowrate equal to ~ 20 percent of the drywell volume per hour taking into account spray impingement on the shield wall, other internal structures, and equipment). A typical <u>average</u> spray fall height (H) for a BWR drywell (once again, taking into account the congestion inside the drywell) would be about 10 feet or 3 m. For these values, $\lambda = 1.5*0.2*3*10 = 9$ $hour^{-1}$. This is a typical BWR drywell spray activity removal rate calculated in accordance with Reference [15].

The BWR AST source (S) during the in-vessel release phase is 0.25 of the core inventory of iodine over a 1.5 hour period or S = (0.25/1.5) = 0.17 fraction/hour. During steady-state (which would be reached very quickly for a removal rate $\lambda = 9$ $hour^{-1}$), the fraction of the core inventory airborne in the drywell (A_{DW}) would be $A_{DW} = S/\lambda = 0.17/9 = \sim$ 0.02 (two percent). Therefore, immediately after the end of the in-vessel release phase, the spray removal rate would decrease from 9 $hour^{-1}$ to 0.9 $hour^{-1}$ (based on the DF of 50 having been reached), roughly equivalent to the rate of removal by ordinary sedimentation.

One can estimate the average airborne CsI in the drywell during the AST release period to be about 11 percent of the core inventory without spray credit. Therefore, since the fractional depletion rate after the release has ended is similar for both sprays and sedimentation, the reduction of CsI leakage associated with drywell sprays would be about a factor of 5 to 6 (equivalent to filtering the particulate in the leakage to the environment by 80 - 85 percent).

Estimating the impact of deposition in the steam lines is equally straightforward. There are two horizontal sections in the steam lines between the reactor vessel and the inboard MSIVs, one for the Safety-Relief Valves (SRVs) and one leading from the outside of the shield wall/reactor vessel pedestal to the inboard MSIVs. Assuming together they total 1/3 of the assumed steam line length of 100 feet (from the reactor vessel to the inboard MSIVs) and that the two horizontal runs are equal in length, each horizontal run would be approximately 16.5 feet or 5.0 m in length. The assumed diameter is 0.508 m.

Assuming the activity is well-mixed in each of these two horizontal runs and that there is no activity deposited in the vertical runs that connect them to the reactor vessel and to each other, the two horizontal steam line segments can be regarded as two control volumes in series. For each well-mixed control volume at steady state, the activity entering the steam line segment in question (expressed as a fraction of core inventory per unit time) is $C_{SL}Q_{leak}$ where C_{SL} is the concentration of the fraction of the core inventory airborne in the steam line immediately upstream of the segment and Q_{leak} corresponds to the assumed 50 cfh (4E-4 m^3/sec) MSIV leakage rate (equivalent to 100 scfh). The activity sedimentation rate is $F_{sed} = C'_{SL}v_{sed}DL$ where v_{sed} is the sedimentation velocity, D is the steam line diameter (~ 0.5 m), L is the segment length (assumed to be 5 m), and C'_{SL} is the well-mixed concentration within the steam line segment. The activity that leaks is $C'_{SL}Q_{leak}$ and the removal efficiency is $\varepsilon = \{1 - C'_{SL}/C_{SL}\}$. Since $C_{SL}Q_{leak} = C'_{SL}v_{sed}DL + C'_{SL}Q_{leak}$, $C_{SL} = C'_{SL}*(v_{sed}DL/Q_{leak} + 1)$; and the steady-state (or zero accumulation) removal efficiency is $\varepsilon = \{1 - 1/(v_{sed}DL/Q_{leak} + 1)\}$. The ratio $v_{sed}DL/Q_{leak}$ is the ratio between what deposits and what leaks.

The steam line sedimentation velocity is the key parameter. Reference [16] recommends a sedimentation velocity of 1.17E-3 m/sec if well-mixed control volumes are assumed, but Reference [1] concluded this was too high for control volumes in series with the drywell as the source, even if the drywell were unsprayed, and suggested 6.8E-4 m/sec for the first control volume and 2.6E-4 m/sec for the second control volume. The decrease from 6.8E-4 m/sec for the first control volume to 2.6E-4 m/sec in the second control volume (based on 97percent removal in the first control volume) may be too conservative for removal efficiencies less than 97 percent in the first control volume, but that decrease is what will be assumed here.

For the first control volume, $v_{sed}DL/Q_{leak}$ = 6.8E-4*0.5*5/4E-4 = 4.25 and $\varepsilon = \{1 - 1/(4.25 + 1)\}$ = ~ 80 percent. For the second control volume, $v_{sed}DL/Q_{leak}$ = 2.6E-4*0.5*5/4E-4 = 1.625 and $\varepsilon = \{1 - 1/(1.625 + 1)\}$ = ~ 60 percent. For the two control volume in series, the overall removal efficiency would be ~ 92 percent.

In Section 2, it was shown that the average drywell airborne CsI concentration during the time frame of interest would be greater than that at the MSIV leak point. Let the two concentrations be assumed to be equal and equal to C_{ref} with no credit for sprays and no credit for steam line sedimentation. Sprays would reduce that concentration to ~ 0.17 to 0.2 C_{ref}. Steam line sedimentation, on the other hand, would reduce that concentration to less than 0.1 C_{ref}.

Numerically, one can point out that the average airborne CsI activity in the drywell during the AST release period would be about 0.02 of the core inventory of iodine (about 0.72 kg). For a drywell volume of 4500 m^3, the airborne concentration would be about 1.6E-4 kg/m^3. From Figure 3, one may pessimistically estimate the average airborne concentration in the steam dome (even over the first hour only) to be ~ 5E-3 kg/m^3. With deposition in the horizontal steam line segments, this value becomes 4E-4 kg/m^3 at the MSIV leakage point; and with a factor of ~ 5 concentration gradient in the vertical steam line segments (between the reactor vessel and the MSIV leakage point – see Table 3), the concentration becomes equal to approximately one half the drywell's 1.6E-4 kg/m^3 at the MSIV leakage point. And this evaluation does not credit the effect of drywell sprays reducing the steam dome concentration.

What this evaluation shows is that crediting deposition in the steam lines has a more favorable impact that crediting drywell sprays. If the drywell leakage pathway is more limiting than the steam line release pathway with neither sprays nor steam line sedimentation between the reactor vessel and the inboard MSIV credited, than the crediting of both effects will only make the drywell leakage pathway more limiting.

Observation:

Credit for sedimentation in the horizontal portions of the steam line between the reactor vessel and the inboard MSIV produces a reduction in the steam line CsI concentration that exceeds the reduction in drywell CsI concentration produced by credit for drywell sprays.

Recommendation:

When applying the AST for MSIV leakage dose assessment, credit may be taken either for deposition in the steam lines between the reactor vessel and the inboard MSIV or for drywell sprays but not for both.

3.2.2 Fission Product Heating of Steam Line

Reference [2] raises the issue of fission product heating of the steam line and the potential for revaporization of the activity trapped therein. This effect has the potential of upsetting the observation just made above.

MAAP4 assigns the value of 0.17 as the fraction of total decay power attributable to the CsI/RbI fission product group. The CsOH/RbOH group is assigned the value of 0.01. In other words, for the purposes of this discussion, only CsI/RbI (MAAP4 Group 2) needs to be considered.

The overall decay power of the core inventory of fission products and actinides may be identified as QCORE from the MAAP4 output. At the end of the time frame of interest, QCORE = 3.3E7 Watts or about one percent of the full core power. Of this, one would expect about 5.6E6 Watts to be generated by Group 2.

The amount of Group 2 (i.e., CsI) mass leaked to the environment via the steam line pathway by the end of the time frame of interest is about 2.3E-5 (as a fraction of core inventory). If all of this activity were instead deposited in one steam line, the power generated by that activity would be ~ 130 Watts. One may assume that a quarter of this power would escape the steam line piping as unattenuated gamma radiation, so the power remaining within the piping to raise the temperature of the pipe wall or to be dissipated by mixing flow back into the reactor vessel, leakage flow, or conduction through the pipe wall and insulation would be about 100 Watts (~ 340 BTU/hour).

Treating the heat-up as adiabatic and assuming the pipe wall to be 0.05 m thick, the mass of steel in each meter of steam line length would be about 1500 lbm. The heat capacity would then be about 150 BTU/°F per meter of steam line length. Even if all of the deposition occurred in the first horizontal segment (assumed to be 5 m in length), the heat load would be about 70 BTU/hour per meter, and the temperature rise in the steel would be about 0.5°F/hour. Of course, this assumes a uniform heat-up across the assumed 5 cm thickness of the pipe wall. However, even if all of the energy were deposited in the first cm, the heat-up would be about 2.5 °F/hour. Overall, it seems unlikely that deposition of such a small amount of activity will bring about significant heat-up and revaporization within the steam line.

3.3 Advancement of Contamination by Sedimentation and Diffusion

The study presented in Section 2 demonstrates that stable stratification in the vertical steam line runs within the drywell will contribute to the suppression of mixing between the reactor vessel and the steam lines and that a significant activity concentration gradient will exist between the reactor vessel upper plenum ("steam dome" or "upper head" using the terminology of Reference [2] and MAAP4, respectively). In the absence of mixing (i.e., assuming plug flow), the contamination will advance at the rate of the flow velocity.

For an assumed 100 scfh (approximately 50 cfh or 4E-4 m^3/sec) flow in a steam line with a cross-sectional area of about 0.2 m^2, the flow velocity is about 2E-3 m/sec. For comparison, the 50th percentile aerosol settling velocity from Reference [16] is about 60 percent of this value. Therefore, for leak rates very much less than 100 scfh or where very high aerosol mass concentrations in the reactor vessel upper plenum or steam lines have caused significant particle agglomeration and an increase in the sedimentation velocity, it may be necessary to consider airborne particulate or gaseous activity overtaking the contaminated "front" due to settling or diffusion.

3.4 Break Size and Location Effects

As noted in Section 2.3, compromises had to be made with respect to the number of cases run (break locations) and the break size. Other break locations and break sizes should be examined to make sure that the MAAP4 results presented in Section 2.4, compared in Section 2.5, and interpreted in Section 2.6 are representative.

4 Observations, Recommendations, and Conclusions

Specific observations and recommendations have been made throughout this document where appropriate. The general conclusions are summarized in this section.

The Sandia Report (2) raised a valid issue regarding the need to consider the potential impact of assuming that the MSIV leakage originates in the BWR steam dome. This issue was addressed superficially in Metcalf's paper at the 27th Nuclear Air Cleaning and Treatment Conference (1). The recent DG-1199 (6) conclusion regarding the need for dose-rate multipliers to compensate for the activity concentration in the steam dome being greater than that in the drywell has a significant impact on the MSIV leakage dose contribution, thus potentially affecting BWR plant modifications already implemented to remove MSIV leakage collection systems (LCS) and to increase allowable MSIV leakage rates in many operating BWRs. The Sandia work was based on the MELCOR code, and the calculation for the time-dependent distribution of radioactive concentration in the steam lines needs to be further evaluated.

A brief, generic, time-dependent study of BWR steam line radioactivity concentration distribution following a design-basis Loss of Coolant Accident (LOCA) was performed with the MAAP4 code. There can be concentration differences between the steam dome and the steam line. The MAAP4 code can properly quantify the concentration differences along the steam line, particularly the vertical runs, unidirectional flows due to MSIV leakage and pressure variations within the reactor vessel, and mixing flows due to density differences.

It was also observed during the study that MELCOR cases in the Sandia Report [(2)] predicted vessel failure later in time resulting in a release of activity likely to exceed the AST [(3)] specifications. The MELCOR results beyond the point in time at which the release to containment equals the AST would amount to a redefinition of the AST. The MELCOR cases should involve an assumed reflood time so that the integrated CsI release to the drywell matches the AST.

The MAAP4 results demonstrate that the concentration at a point immediately upstream of an intact BWR main steam isolation valve (MSIV) is substantially lower than that in the reactor vessel (RV) steam dome. These results supplement and clarify the insights presented in the NRC DG-1199 [(6)] and in the supporting Sandia Report [(2)]. They also contradict the conclusion reached in DG-1199 regarding the need for dose-rate multipliers to compensate for the activity concentration in the steam dome being greater than that in the drywell.

When comparing concentrations in the steam dome or steam line to those in the drywell to ascertain if the assumption that the drywell is the source of MSIV leakage is acceptably conservative, one must consider that the AST treatment restricts credit for drywell-to-wetwell flow during the release, strongly discourages credit for suppression pool scrubbing, and greatly limits credit for natural deposition. Therefore, the comparison should be made to the AST drywell concentration, not to that predicted by MELCOR or MAAP4 (for which drywell activity depletion mechanisms are fully active).

The brief study presented in this paper provides insights into how considering the steam line to be the source of MSIV leakage would differ from considering the drywell to be the source of MSIV leakage. There are some obvious short-comings of this brief study, however; and these were discussed in the paper. The near future development of a stand-alone computer code to model the steam lines may be advisable. The total volume of the modeled main steam line is small (about five percent of the volume of the reactor vessel upper plenum) with a very small exchange rate with the environment (approximately one percent per hour of the upper plenum volume). The MAAP4 model results could establish the boundary conditions for the main steam line model and could also provide comparative results for MSIV leakage treated with the drywell as the source. The stand-alone model could make use of the same counter-current flow modeling feature as that incorporated in MAAP4 or used in other studies [(9)]. By decoupling the main steam line model from the MAAP4 code, the impact of more control volumes could be more easily studied as well as direct comparisons with MELCOR results. The Sandia Report [(2)] describes the use of a similar concept (MELCOR MSL-only models).

5 References

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