MAAP 3.0B/BWR REVIEW

Technical Evaluation Report 4

Fission Product Release and Transport

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1.0 INTRODUCTION

This report is the last in a series of four Technical Evaluation Reports (TER's) on the MAAP severe accident computer code. Prior TER's have concentrated on the accident time phases of:

- Before Fuel Failure
- Fuel Relocation
- Containment Challenges

The topic of the present work is Fission Product Release and Transport. In the course of this report comparison will be made between MAAP and other computational tools with an emphasis on the MELCOR code.

After a discussion of the significant issues associated with this accident time phase, the report will review how MAAP and MELCOR model the pertinent phenomena. We conclude with some thoughts on MAAP's ability to model success criteria and our recommendations.

2.0 SIGNIFICANT ISSUES INVOLVED WITH SEVERE ACCIDENT FISSION PRODUCT GENERATION AND TRANSPORT

The primary goal of a source term code such as MAAP is to supply the release rates of select fission product groups to a consequence code such as CRAC2. The latter code is then used to determine the radiological effect of an accident on the public surrounding the plant. For IPE work, this would be done for all representative sequences used to establish the release category groups. Ultimately the predicted release rates are used to determine overall plant risk.

Presently severe source term codes like MAAP are being enhanced to predict the effect of operator actions associated with various accident management strategies. improve the codes effectiveness in IPE work, because it will allow the modeler to a detail to the event trees used to determine the plant damage states as well as release categories.

To predict release rates correctly, one needs first to determine the source of the fission products. The major fission product sources are at the time of fuel failure and melting in-vessel and during core concrete interaction (CCI). Fission products can be retained in the damaged fuel as well as deposited on solid surfaces or in liquid pools.

Pool scrubbing, condensation and revaporization have been classified as "transition" phenomena. Fission product removal from a gas is also placed under transition.

Besides fission product sources and their transition, to be able to predict their release from the containment one must consider their transport. This necessitates tracking their transport medium while they reside within the containment boundary. Fission products can be carried by liquid corium and fuel solid particulates, as well as, liquid water pools. These are in addition to gaseous medium transport of fission product vapors, and aerosols.

With the full spectrum of the fission products to deal with, the necessity for grouping or classifying the fission products becomes obvious. Classifying by chemical properties appears to be the most appropriate.

To summarize, then, the topic of fission product release and transport is functionally dependent on:

Classification and grouping
Sources
Transport
Transition

The MAAP models for these four items are addressed in Chapter 3. For the moment, however, let us discuss the significant issues associated with them.

The number of fission products groups one wishes to track as well as the total number of fission products one wishes to distribute among these groups is not universally accepted. One wishes to assume that chemical, physical and nuclear properties of the constituents of a group are considered. This includes concerns over what phase they are in (solid, liquid or gaseous), what is their vapor pressure, what fraction of the decay power do they carry with them, and how might they chemically react with other elements which might change their physical and chemical properties. Also of importance is the interface these groups have with the active materials considered in CCI.

How these items are handled can have an effect on energy distribution, and the distribution of each group's mass (along with how much remains airborne to be released to the environment). Specifically, in considering revaporization the accuracy of prediction is a function of being able to predict the right energy distribution between the fission product groups.

The empirical derived functional form of fission product release from the fuel matrix is approximated well by the Arrhenius formulation which utilizes an activation energy. For conditions before fuel melt, the grain size of the oxide pellet is also believed to be of importance. It is possible to fit the empirical data with other functional relationships, sometimes using temperature range dependent coefficients. If the fuel melts completely in a short time, the relationships for fission product release would be expected to yield nearly full FP gaseous release. Rarely, however, will all the fuel melt before containment failure. Also the desire to know the effectiveness of operator actions is driving the industry to reexamine this item for more accurate predictions.

Another factor is the presence of a transport medium at the time of release, and other thermal-hydraulic conditions such as structure temperature when the release is occurring. If the structures are cool, it might result in significant condensation of vapors and possibly liquid aerosol removal from a transport medium as it passes over these structures. These structures would then act as repositories of fission products which may release them when thermal-hydraulic conditions change. Airborne concentrations and gaseous temperature changes associated with the depressurization of the Reactor Pressure Vessel (RPV), or the heat up of the structure due to the deposited fission products decay heat might cause this.

The removal of the gaseous and liquid aerosol fission products from the core can also be effected by their saturation vapor pressure. This could limit their release or cause them to be released as aerosols, which could later vaporize if they are transported to a lower vapor pressure region.

Other than fuel matrix release, the other major release to the gaseous media of fission products will occur during core concrete interaction (CCI). Here the stimulus of the gases released by concrete ablation and the turbulence and heat produced by chemical reactions with the corium pool will free additional fission products.[2]

Transport of aerosol and vapor fission products is effected by gaseous flow. Natural circulation in the RPV, primary and secondary containment will be the dominant mode during most of this accident time phase. Some of the fission products will be transported along with corium relocation. Further, fission products deposited in liquid pools will be transported with their liquid flow.

Fission product transition from one physical form to another will effect the transport and release of fission products. The removal of aerosols and vapors from the gaseous stream will reduce fission product release, and is measured by the FP mass into of a volume divided by the FP mass out of that volume. This is the decontamination factor. There are many processes which can lead to decontamination. The most important are scrubbing by sprays or water pools. Those fission products which are in aerosols form within a gaseous media are usually most strongly effected by sedimentation and impaction. The first of these involves agglomeration or growth of the suspended aerosols accompanied by gravitational settling onto solid structures or liquid pools. The second, impaction, can become important under strong gaseous flow as the aerosols impinge on surfaces. It is also possible that the growth of an aerosols can be effected by water take-up. This should be tracked for hydroscopic aerosols.

Liquid aerosols can be produced from supersaturated vapors. This transition then takes what was once a gas and exposes it to all the aerosol removal mechanisms we have discussed. Fission product vapors can also be condensed on cool surfaces or sprays. Revaporization or evaporation can be a major item of concern. Previously removed (from the gas transport media) fission products may again become available for transport to the environment.

The following chapter will now take these issues in turn and explain how MAAP models them. MELCOR will be used for comparison.

3.0 MODELS AND ANALYSIS

3.1 Classification and Grouping

MAAP tracks 22 specific fission product (FP) species (elements and compounds). These are grouped into 12 chemically similar groups (Table I). The initial mass of the 22 species and user supplied and are grouped, conserving their total number of moles, into the 12 chemical groups. MELCOR, on the other hand, allows the user to create up to 20 material classes, though typically only 15 are used (Table II). These are based on chemical properties and allow for the assignment of the periodic table of elements. It is of interest that for each of these material classes, MELCOR makes a distinction between radioactive mass and fission product mass. When a mass is released from the fuel in MELCOR, it is assigned the appropriate material class based on it being released in elemental form. The mass increment, however, becomes part of the radioactive mass of that material class. MELCOR then assumes the elemental form will take on compound forms. Lets say Cs becomes CsOH. This compound form's mass is then made part of the fission product mass of that material class. In this manner MELCOR may not conserve mass and the fission product properties are those of the material class. The user can specify unique material classes for compounds, such as CsI, if he wishes. A review of Tables I and II, however, indicates that in Table I only Cs takes on dual material classes in MAAP in the form of CsI and CsOH. Therefore, the concern that MELCOR may not correctly represent the appropriate characteristics (vapor pressure for example) for the fission product compounds based on elemental grouping may not be a problem.

Whether the number of fission product compounds MAAP is tracking is sufficient is hard to judge at this point without seeing whether the inclusion of more, such as in MELCOR, would alter the predicted dose produced by the consequence code. In WASH 1400[1], 25 elements were tracked as compared to MAAP's 22. MELCOR's input follows the material classes for initialization of mass distribution. Hence if one wished to include more individual fission products in the material class, it would be wise to check MELCOR's Decay

Heat Package. Here we find that MELCOR uses tabular look-up functions to determine the amount of decay heat produced at any given time by the material classes. This is based on tracking 29 elements over time from a representative ORIGEN run. The end result is that MELCOR supplies a time dependent decay power to each class such that the fraction of the total decay power assigned to each class may vary in time. MELCOR thus has a varying shape as well as amplitude function for decay power.

MAAP on the other hand fixes the decay power fraction for each of its FP groups or classes and varies only the magnitude as a function of time. It has a fixed shape and varying amplitude function.

3.2 Sources

In MAAP no fission products are released from the fuel matrix until fuel damage is predicted to occur. This is usually associated with clad failure. In MAAP and MELCOR, a fuel damage temperature is supplied by the user. In MELCOR, however, fission products located in the gap before fuel damage will be released upon reaching the fuel damage temperature. This is more realistic than MAAP which would have a delay time associated with the release from the fuel matrix to the gap. MELCOR will also allow for fuel damage if the fuel failure criteria has been reached. This is dependent on clad minimum Zr thickness.

Once damage occurs, gap release occurs for MAAP and MELCOR. MAAP classifies the fission product groups into volatile and non-volatile categories and applies different criteria to them. For the volatile fission products, their time release from the fuel is governed solely by an exponential functional relationship of the form.

$$K(t) = Ae^{BT}$$

Where:

K(t)	=	fractional release rate as function of time
A & B	=	constants depending on fission products and piecewise dependent on temperature
T	=	temperature of the fuel

The non-volatiles use an Arrhenius formulation:

$$K(t) = K_o e^{-(Q/RT)}$$

Where:

K_o&Q	=	constants supplied for each fission product
R	=	universal gas constant
T	=	temperature of fuel

There is another limitation on the release rate for the non-volatiles. They can not exceed their individual vapor saturation pressures. One could argue that they would be released as aerosols which is what is effectively done with the volatile fission products, but the constants must not be tuned for this. This can have a major effect on their release if the fuel blockage model[3] is employed, since it could greatly effect the attainment of saturation pressure. It should be noted that MAAP does not allow the presence of aerosols in the core region, and for the volatiles will transport the vapors to the upper plenum where if supersaturation conditions exist will create aerosols.

There is a user option in dealing with Te. It may either be released as a volatile or assumed to be transported out of the core with the corium melt, combined with the unoxidized Zr. It would then be released in the containment as the Zr metal is oxidized during CCI.

The other major source of fission product release occur during CCI. Here MAAP employs the METOXA subroutine group. It determines the chemical equilibrium of the elements and compounds supplied by the corium and steel laden concrete. The gases are assumed to be liberated from the corium pool. Some of these would be tracked in the 12 fission product groups. These would be added to the gas medium. MAAP developers argue that the volatility of some of the fission products is not well understood in such a corium pool as present during CCI. Therefore, they allow for the effect of a non-ideal solution on oxide forms of Sr and Ba as well as Si, K, and Na. By the use of activity coefficients, then, the user can control their release rates.

There are two substantial differences associated with MELCOR. Both involve aerosols. The first deals with the release of aerosols from the core region. MELCOR does not limit release due to vapor pressure in the core for the non-volatiles while MAAP does. For the volatiles, although MAAP has no mass removal limitation on the vapor release, it assumes transport of the vapor to the region above the core region and checks there for supersaturated conditions to create aerosols. Here, however, the total core release conditions are considered and supersaturation conditions may not exist, while they might have in the more active core nodes. Hence, MELCOR may predict aerosol formation when MAAP may not. MELCOR is more phenomenologically correct.

The second major difference is aerosol release from CCI. MELCOR, which utilizes a modified VANESA predicts aerosol release, MAAP doesn't. The bulk of the aerosols released are expected to be of non-radioactive mass, but this will have an effect on radioactive aerosols when these non-radioactive aerosols join them in the containment. It can't be said that MAAP would then be conservative, however. This is because even though

the removal rates from the containment atmosphere may be less in MAAP, there is also less of an aerosol source term and some of this is radioactive. The timing of containment breach and the Core Concrete Interaction conditions have synergistic effects on aerosol release to the environment. Again, MELCOR is more phenomenologically correct.

These two major differences: comparisons of vapor, and aerosol mass distribution in the vessel and containment, will be worthy significant figures of merit for comparison between the two codes.

3.3 Transport

In MAAP, aerosols and vapors are carried with the bulk gaseous flow. This flow is usually H_2, H_2O, CO, CO_2, and N_2 laden. In general, deposited fission products flow with that medium they are deposited in. This can take the form of water or corium transport. This is true for the containment. For the core, water transport of liquid fission products is not modeled. Fission products still bound up with the corium at the time of vessel exit are transported with the exiting corium.

The fission product groups carry decay energy as was discussed in 3.1. MAAP makes a distinction of the energy deposition, however, based on whether we are discussing the containment or the RPV. In the containment regions, gaseous carried FD's heat their transport medium, deposited vapors and aerosols heat a water pool if one is present in the control volume or region they are in. If a water pool is not present, then they directly heat a heat slab.

For the RPV, the airborne vapors and aerosols as well as deposited vapors and aerosols heat a pre-selected heat sink.

MELCOR's transport mechanisms are essentially the same for vapors and aerosols to those of MAAP's. Those fission products which are contained within the mixture or pool region of the control volumes are transported with the mixture whether or not the control volumes are within the core or containment. MAAP's failing in the vessel to transport pool deposited FP may be a concern if in-vessel recovery actions are attempted. Transport of the FP which are retained in the fuel, whether liquid or solid, are relocated with the fuel. This happens while relocation is occurring in-vessel as well as at the time of vessel breach.

Table III also summarizes the way MAAP and MELCOR transmit the fission product decay heat. For airborne fission products, MAAP has different criteria for the containment and vessel regions. For the vessel, this heat can only be deposited to a heat slab. In the

containment, it will heat the air. In MELCOR the user directs what fraction of the airborne FP heat in a control volume will go to the air or surface. In MAAP there are no FP's deposited in the vessel water, and in a containment region deposited fission products heat the water if present or a heat slab. MELCOR retains within a pool the heat produced by the fission products deposited within it. Also, in MELCOR, any fission products deposited on a heat slab can be directed to heat any heat slab or control volume gas.

From the above, MELCOR appears to offer far greater tunability in directing fission product heat. This can be of great importance in effecting FP transport and transition. MAAP appears somewhat limited especially in the vessel. The sensitivity of this failing should be observed during later project tasks. At this time it appears most troublesome for cases involving in-vessel recovery actions, or very slow vessel uncovery (for example having inadequate but some inventory make-up to the vessel). This latter case could allow for substantial water remaining in the vessel during a time of fission product release from the fuel.

3.4 Transition

In MAAP fission product vapors follow their thermodynamic properties of condensation and evaporation. That is, they will condense within the gaseous medium to form aerosols if they become supersaturated. They will also condense on cool heat slabs to form liquids. Revaporization from the heat slabs is also permitted.

MAAP's modeling of aerosol transition, primarily its removal from gaseous transport, has removed the explicit tracking of aerosol size dependence. Essentially MAAP classifies a time frame as either one of steady state aerosol generation, or aging with no source. The simple mass balance equation for the airborne aerosol is then:

$$\frac{dm}{dt} = -\lambda m + m_p$$

Where:

m	≡	mass of aerosol
m_p	≡	source term
$-\lambda m$	≡	removal term with λ being the decay constant

Then for the steady state formulation we have

$$\frac{dm}{dt} = 0 = -\lambda m + m_p$$

and for the aging state with no source

$$\frac{dm}{dt} = -\lambda m$$

MAAP then solves these equations by utilizing the formulations previously discussed

(Section 3.2) to determine "m_p" and by determining the decay constant "λ". MAAP determines the decay constants for a variety of removal mechanisms by determining a functional relationship for "λ" based on numerical experiments which used a size dependent solution for aerosol behavior. The exact solution of λ is determined by solving for two dimensionless scaling parameters "Λ" and "M". These are dependent on geometric and physical properties of the aerosol material such as its viscosity, height of aerosol contained volume, density of aerosol particle material and temperature. In addition there are two user supplied aerosol shape factors. These have defaults supplied by the MAAP developers.

The aerosol physics model also employs combining and interpolation laws. If more than one aerosol removal mechanism is determined to be occurring, it has combining laws on determining the appropriate decay constant for the mass conservation equation. Interpolation is used to treat conditions between steady state and aging. Log-log plots are presented by the MAAP developers to show the comparison accuracy of their interpolation schemes to more detailed aerosol codes products and equipment. From these it appears the MAAP model can do well when there is a nice demarcation between times when a strong source exists and then ceases. In a severe accident condition one would expect times of strong sources mixed with times of weak source. It is not explicitly clear what the degree of accuracy would be for these conditions when reviewed on a linear time plot. MAAP has a model for hydroscopic aerosols which can result in greater sedimentation rates than their dry aerosol model. This wet aerosol sedimentation rate can be user controlled by his choice of the initial seed (dry aerosol) particle size.

There are two other special aerosol removal mechanisms dealt with in MAAP. The first is water spray entrainment. Then model determines a reduction in gaseous suspended aerosols as a function of water spray droplet radius size, its settling velocity and collection efficiency. The last of these is determined by experiment. As previously stated in Chapter 2 of this TER this model must be utilized with a fair assumption on spray droplet size, since containment sprays will impinge on drywell equipment.

Pool scrubbing is the second special component aerosol removal mechanism. Actually the MAAP model also includes pool scrubbing of vapors which when passed through a pool are anticipated to condense to liquid aerosols and also be removed. MAAP's models are based on a functional fit to numerical experiments performed with the SUPRA code. It uses the following parameters:

1) Mode of gas injection (downcomers, side vents, etc.)

2) Geometry (height of pool)

3) Gas condition (steam mass fraction and composition)

4) Pool conditions (subcooled, pressure)

5) Aerosol characteristics (size)

We have indicated that MAAP does not keep track of aerosol particle size during its aerosol transition or removal from the atmosphere calculation. So to be able to correctly utilize the SUPRA data it performs a interpolated table look-up of predefined particle size spectrum which are functions of viscosity, gas temperature, mass generation rate and user tunable shape factors. MAAP effectively calculates a decontamination factor for each particle size and then mass averages these to get a total DF.

The MELCOR code aerosol model characteristics can be found in Table III. It is interesting to note that the MELCOR aerosol mass conservation equations are quite general. They are not limited to the steady state and aging regimes. Further they are sectionalized into aerosol size groups and give the user the flexibility to separately track different compositions. Since MAAP appears to solve the aerosol mass equation for only one large composition of all tracked material groups it would be of interest to see whether MELCOR would yield similar results by just using only one composition as in MAAP and

then comparing this to a case where multiple mass equations (based on multiple compositions) were employed. Of particular concern here is that MAAP may not correctly determine the release functions of aerosol fission products which have different dominant production times. One can envision a late production of a given FP aerosol which is released into an atmosphere of an aging aerosol environment. Here MAAP would shift to steady state continuous source solution [$dm/dt = 0 = -\lambda m + m_{product}$] not considering the potential that the new source of a single composition will have a size section quite different from an aerosol atmosphere which had been going through aging for some time. MAAP would simply remove the new aerosol component using the same decay constant as the aged aerosol. It would however remove it on a rate commensurate with its relative mass composition in the total aerosol atmosphere. The end result, however, may be an overprediction of the newly predirected aerosol's removal rate versus what a sectional code like MELCOR would yield.

4.0 SUCCESS CRITERIA

Unlike the previous TERs[4] which have dealt with specific time phases during an accident sequence, Fission Product Release starts at the time of fuel damage, and can culminate in an environmental source term. The end product of a Level 2 PRA (source term analysis) is the source terms (magnitude and time of release) associated with the Release Category structure chosen. The accuracy of predicting the fission product release success criteria (FPRSC) directly effects the choice of the number of release categories used by the PRA modeler, and the classification of the spectrum of accident sequences into their appropriate release categories. The number of event nodes used, especially in the Containment Event Tree, can be increased based on a source term code which can accurately distinguish fine detail in fission product release and transport (FPR).

In the prior chapters of this TER, we have touched upon the significant issues of FPR, and how MAAP models this subject. Let us now break up our discussion of FPRSC into 3 areas:

- In-vessel success
- In-primary containment success
- Ex-primary containment success

A point of clarification is needed here. In past TER's success criteria could be associated with an event node which asked a binary response question. In plant event trees this may be if the HPCI system is available. Once FPR occurs our success criteria is associated with the level or degree of release to the gaseous transport media. This may require finer detail in knowing the rate at which FPR is occurring so that a level of release can be ascertained before fuel clad damage, fuel melt progression or CCI has been arrested. It is not that timing is not important in the success criteria determinations of the earlier TER's which are

essentially fission product barrier success criteria. But, the emphasis before was whether these barriers remained intact. Now we want to know if they failed, when did they fail, and what is the level of FPR. For the PRA modeler to accomplish this he must for each accident sequence, or its representative, evaluate the plant damage state, containment failure mode and any remedial actions that could attenuate the release through the reactor building to the environment. This latter may include the use of fire protection sprays or controlled venting into the reactor building (location and flow rate). When considering in-vessel arresting of FPR, fuel damage criteria, fuel failure criteria, fission product release rates and vessel decontamination are the significant parameters. The BWR version of MAAP has no true fuel-clad gap release model. So a quick return to adequate core cooling after some clad damage will not be conservatively modeled. If core heat-up continues, MAAP does not always use an Arrhenuis function formulation for its release rate equations. This may not be a problem, but MAAP 3.0B does not consider fuel grain size as a parameter in its rate equation. This is something fuel behavior modelers have considered for some time. The true grain size, however, is not always a simple parameter, it is affected by burnup history (as opposed to the as-fabricated grain size). The effects were considered large enough to encourage the MAAP developers to offer another FPR model which does depend on grain size in their DOE sponsored work.[5] Again from a success criteria standpoint, this would be important in determining the amount of FPR before arresting core heat-up. FPR is a strong function of fuel temperature and quenching the core should abate release from the oxide fuel matrix, though it may fail cladding due to thermal stock. The latter is not modeled in MAAP.

Because fuel failure and its associated relocation is temperature dependent, the adequacy of this model will effect the location and hence temperature employed by the release models to determine FPR rate. It appears, however, that MAAP may be conservative here because fuel may remain at elevated temperatures at its initial location while other predictions (i.e., MELCOR) may have resulted in fuel pellet relocation to a cooler, possibly flooded, location.

If the vessel does fail, the amount of fission products which are retained in the vessel becomes a significant figure of merit. This is strongly dependent on the release rates from the fuel, its transport within the Nuclear Steam Supply System (including flow-through and retention within safety relief valve piping), and its removal from the gaseous carrying media possible due to transition. MAAP's accuracy, but not necessarily its conservatism, may be compromised in that depositing and airborne fission products heat a select heat sink. The airborne fission products could effect flow patterns within the reactor pressure vessel if they were permitted to heat their carrying media directly, as would preferential deposition on the vessel heat sinks. This all has a synergistic effect on the vessel's decontamination factor.

Within the primary containment, conditions can be conducive to aerosol agglomeration and fission product vapor condensation. The rate of these removal mechanisms will be important in determining the effects of their presence when and if the containment is breached. Perhaps most important is the effect of CCI on creating a new source of airborne fission products. This being the case, MAAP's ability to model CCI, and the cooling of the reacting pool are significant. The MAAP developers have made significant changes to the MAAP 3.0B model under review during recent DOE sponsored work.[6] In effect the new CCI model has become more MELCOR like in that the heat transfer correlations have been altered to allow different erosion rates in the downward and sidewall concrete attack. This effects aerosol and vapor release rates from the pool.

The decontamination afforded by sprays and the suppression pool clearly are part of the containment FPR success criteria as their impact is universally agreed to be large.

In the Reactor Building, the aerosol transport modeling is probably the most important parameter. Here, because secondary containment integrity is almost always lost once the primary containment is breached, the measure of success is the reactor building decontamination factor. The multi-compartmental design of this structure makes the flow paths and its effects on aerosol removal mechanisms difficult to predict. The MAAP

modelers now have with MAAP 3.0B a multi-compartment model with control volume connecting junctions which can predict counter-current flows.

The mode of containment failure and its location are typical event nodes in present generation Containment Event Trees, since they are a good measure of the success of decontamination. This can involve the use of operator containment venting procedures.

5.0 RECOMMENDATIONS

For BWR use, MAAP has a number of deficiencies as we have discussed. Concerning FPR, an IPE conducted using MAAP should be able to indicate the weaknesses of a present plant design. The present MAAP version is not believed to accurately represent fuel relocation, clad-pellet gap release or fission product heating within the vessel to make it a tool for predicting FPRSC once melt progression has begun. It may still be effective in estimating the amount of in-vessel fission product release for large core disruptions where the problems mentioned above are masked by the magnitude of the release. We would therefore, not recommend MAAP as the sole tool used in the establishment of FPR success criteria if detailed Release Categories are to be established from it.

In addition to the above, the following are our concerns in MAAP's modeling accuracy for IPE work:

1) Decay heat energy distribution among the 12 FP groups vs. time.

2) The non-component dependence of the aerosol removal model.

3) Release of fission products from the CCI phenomena due to what may be modeling inaccuracies in the collective specific heat of the corium-concrete mixture and heat transfer process.

4) Lack of an aerosol release model from the corium pool during CCI.

6. REFERENCES

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Table I

MAAP Fission Product Species

1. Nobles
2. CsI
3. TeO_2
4. SrO
5. MoO_2
6. CsOH
7. BaO
8. $La_2O_3 + Pr_2O_3 + Nd_2O_3 + Sm_2O_3 + Y_2O_3$
9. CeO_2
10. Sb
11. Te_2
12. $UO_2 + [illegible] + PuO_2$

Table H

Material Classes in MELCOR

Class Name	Representative	Member Elements
1. Noble Gas	Xe	He, Ne, Ar, Kr, Xe, Rn, H, N
2. Alkali Metals	Cs	Li, Na, K, Rb, Cs, Fr, Cu
3. Alkaline Earths	Ba	Be, Mg, Ca, Sr, Ba, Ra, Es, Fm
4. Halogens	I	F, Cl, Br, I, At
5. Chalcogens	Te	O, S, Se, Te, Po
6. Platinoids	Ru	Ru, Rh, Pb, Re, Os, Ir, Pt, Au, Ni
7. Early Transition Elements	Mo	V, Cr, Fe, Co, Mn, Nb, Mo, Tc, Ta, W
8. Tetravalent	Ce	It, Zr, Hf, Ce, Th, Pa, Np, Pu, C
9. Trivalents	La	Al, Sc, Y, La, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Cm, Bk, Cf
10. Uranium	U	U
11. More Volatile Main Group	Cd	Cd, Hg, Zn, As, Sb, Pb, Tl, Bi
12. Less Volatile Main Group	Sn	Ga, Ge, In, Sn, Ag
13. Boron	B	B, Si, P
14. Water	H_2O	H_2O
15. Concrete	---	---

Table III

	MAAP	MELCOR
Classification and Grouping	· Tracks 22 FP elements grouped into 12 material groups. For BWR version structural material such as Zr is not released fr n core material [FPCRP] · The 12 material groups can take on 4 forms · Vapor · Aerosol · Deposited in water pools · Retained in core or corium · Total decay power (amplitude function) is calculated and the distribution of this gross power amongst the 12 material groups (shape function) is non-time variant.	· Nearly the full periodic table of the elements are assigned material groups · User can create up to 20 material groups though 15 is standard. Compounds take on only the elemental properties of one of its constituents only. · Within each material group, MELCOR tracks the mass of the radioactive material and fission product mass · Total mass as transferred from the fuel to the material groups may not be conserved · Release fractions from fuel are a function of the material group they are within · Decay power is both a time dependent amplitude and shape function based on tabular look-up

	MAAP	MELCOR
Sources		
a) Fuel	- No gap release but start of release from fuel matrix1 on user-supplied clad failure temperature - Each tracked fission product has its own release model constants The release model used is a function of whether the isotope is classified as volatile or non-volatile a) The volatile fission products can use either $K(t)=A\exp(BT)$ or Cubicciotti's model (user option) b) The non-volatiles use an Arrhenius formulation $K(t)=K_o\exp(-Q/RT)$	*- Gap release on user supplied temperature or at time of fuel failure which is based on clad zircaloy metal (unoxidized) thickness - User has option of choosing CORSOR or CORSOR-M model for FP release from fuel The CORSOR model is of the form $K(t) = A\exp(BT)$ while the CORSOR-M model is an Arrhenius formulation This release constants are functions of the material group (same constant for each element in a given material group) - Non-radioactive materials, including cladding, canister and control rods follow same release rates as the radioactive FP in their material class [RM-RM-6]
	- Fission products are released as vapors only (no aerosols). Their release can be either: diffusion from the fuel matrix melting or mass transfer the from the core region limited. - Te, at user option, can be released in vessel or out of vessel during CCI	*- Fission products can be released as vapors or aerosols if saturation conditions are exceeded [RN-RM-7] - Te, release in vessel can be reduced by the presence of non-oxidized Zr

Table III (Continued)

	MAAP	MELCOR
b) CCI	· During CCI, oxidation and reduction reactions occur which can not only result in chemical changes but alter the major release of the FP from the corium pool · Documentation appears to support the release only of vapors from the pool · "Once the FP leaves the core in-vessel or core debris ex-vessel, the chemical state as given by the 12 FP groups is frozen" Ba and Sr are two of the major radioactive aerosols one might expect from CCI; these have user input activity coefficients in MAAP for tunability	* · During CCI, a modified VANESA model has been incorporated. This includes: · aerosol generation rates · concentration of aerosols in gaseous release from the pool · Aerosols and vapors are released from the pool. Most aerosols are non-radioactive aerosols, however, these non-radioactive aerosols can have an effect on the aerosol removal mechanisms in the containment.

Table III (Continued)

	MAAP	MELCOR
Transport	· Aerosols and vapors are transported with H_2O and H_2. · Deposited fission products transport with water between containment regions. This is not done between reactor vessel regions · Fission products in the corium, exit vessel with the corium · In containment: - airborne FP heat the air - deposited FP heat a water pool if present, otherwise a selected heat slab · In-vessel regions - airborne and deposited FP heat an individual heat sink	· Aerosols and vapors are transported with H_2O and H_2 · FP products in the pool of a control volume are transported with the pool · Fission products in the core material are transported with it during relocation. This could be in solid or liquid form *· In any control volume: · airborne FP have user supplied split of this heat between the atmosphere or surface of any volume. A water pool is classified as a surface · decay heat from FP deposited on any heat slab can be directed to any heat slab or control volume gas phase · fission products deposited in a pool yield their heat to that pool

Table III (Continued)

	MAAP	MELCOR
Transition	- FAI developed aerosol mass conservation equation utilizing decay terms. Does not track particle (aerosol size) - Separate mass conservation equation not written for each chemical component - Aerosol decay constants exist for: - settling - diffusion phases (steam condensation) - thermophoresis - impaction - hydroscopic aerosol modeling considered to enhance settling - Combining laws for decay constants are employed - Aerosols created from super saturated vapors - User tunable factors include 2 shape factors used in the decay constants and aerosol seed radius used in the hydroscopic aerosol model - Spray removal model - Pool scrubbing model based on functional fit to SUPRA numerical experiments - Aerosol evaporate to keep a vapor saturated, MAAP handles revaporization	- Uses MAEROS which is a sectional aerosol code - it tracks particle size - Separate mass conservation equation written for each chemical component - Coagulation due to: - Brownian Motion - gravity - turbulence - Particle deposition due to - settling - diffusion - thermophoresis - Particle growth due to Condensation of water vapor on particles - User can set all natural classes to a simple component in the solution of the MAEROS sectional solutions. This would accelerate the solution time [RM-RN-p.7] - Aerosols created from supersaturated vapors - Resuspensions of aerosols deposited on surfaces are not predicted in MELCOR - Spray model based on the NECTR code is employed. It removes both aerosols and vapors - Pool scrubbing model exists for aerosols only - Filter model removes aerosols and vapors. Could be used in Reactor Building of BWR - TRAP-MELT2 code equations are utilized to determine condensation and evaporation of vapors from aerosols and heat structures - Aerosols created from supersaturated vapors