MAAP 3.0B/BWR REVIEW

Technical Evaluation Report 3

Severe Accident Containment Modeling

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1.0 INTRODUCTION

This report concentrates on MAAP's ability to model those phenomena associated with severe accident containment challenges. BWR type containment designs are considered. Also discussed are the remedial strategies available to the plant operator as well as passive safety features such as pressure suppression. 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 CONTAINMENT MODELING

For the primary containment the failure modes are either pressure or temperature driven. The sources of energy available to produce a challenge are:

- stored energy of the corium
- chemical energy produced from Core-Concrete Interaction (CCI) and the possible effects of water addition
- combustion of CO and H_2 produced from core-concrete interactions and other chemical reactions such as oxidation of Zr or Cr. This can include energy released by fires.
- radioactive decay energy

For pressure concerns, the mass of gas is important. Besides the steam and H_2 which may be ejected from the vessel once breach occurs, CCI will liberate H_2O and C_2O which can be reduced to H_2 and CO. This gives the major gaseous constituents in the containment as: H_2, H_2O, CO_2, CO and N_2. The nitrogen being initially present in the atmosphere whether or not the containment was inerted.

The above discussion summarizes the important mass and energy sources. The gaseous mass released by the concrete is modeled in CORCON Mod 2[1] to occur during the ablation of the concrete. Typically concrete begins to melt at around 2000°F[2].

In a previous report[3] we discussed the need of a severe accident analysis code to predict the initial boundary conditions for the containment challenge phase of accident progression. Included in the initial conditions were the temperature, constituents, flow rate and mass of

the corium ejected from the Reactor Pressure Vessel (RPV). The temperature has an effect on the first three sources of containment energy. In particular, the chemical energy (reaction energy and reaction rate) is strongly effected by this parameter. For the zirconium-water reaction it is interesting to note that the heat of reaction decreases (becomes less exothermic) as the temperature of the materials increases. The temperature also has a major effect on the gas generation rate from the core-concrete attack. The flammability of the combustible gases is also a function of temperature[4].

The constituents of the ejected material have an effect on all the energy sources and can represent an immediate challenge to the containment especially if there is substantial amounts of non-condensible hydrogen ejected which will only be cooled by an intact pressure suppression system. If a large amount of steam is present this could help create an inert environment (Mark III's are not N_2 inerted).

While there are substantial energy sinks in the form of concrete, steel, and equipment in the containment; their response times vary and hence the mass flow rate of the ejected material can result in pressure spikes beyond the containment failure threshold. All energy sources are effected by the mass of their contributing constituents.

Having shown how the vessel failure characteristics can effect the mass and energy in the containment, let us now discuss the significant issues involved in this accident phase.

If the RPV fails under high pressure conditions, which might occur for long term station blackout scenarios, the molten corium may take the form of small droplets which will directly heat the atmosphere. This direct containment heating (DCH) can result in a pressure spike. One might argue that for BWR's DCH is not a problem because the pressure suppression function will function on a quicker time scale than the DCH mechanisms. The argument is that the pressure spike should be no greater than that produced by a LOCA.

In a LOCA, the pressure suppression function is also activated but the spike is caused by the amount of energy entering the drywell being greater than that being transported to the suppression pool or absorbed by the steel in the drywell. The inertia associated with vent clearing aggrevates the problem, but it is the vent sizing which is of major importance. For DCH it is not known what the RPV failure size will be, nor can it be assured that a bypass path around the pool will not exist. Bypass paths can include failed safety relief valve lines, floor drain lines, as well as vents. It is also possible that the pool will be saturated at the time of RPV failure. It is also possible that the vessel will depressurize at the upper head region well before the lower head fails. Consequently DCH is not a resolved issue.

Steam explosions are also of concern. This phenomena does not require a pressurized vessel at the time of RPV breach. The molten corium is assumed to result in rapid energy transfer to the water. The resulting pressure spike may cause structural damage, but there appears no accurate way to predict what conditions are necessary for steam explosion to occur and what the consequences might be if one occurs.

Perhaps one of the most significant phenomena is corium attack on structures in the pedestal region. This can take the form of steel attack for a Mark I design or Core-Concrete Interaction (CCI) for Mark II and III type containments. There is the belief that steel melt-through is probable for a Mark I unless water is added to the pedestal region before corium attack. There are recommendations for operation action to add water to the containment for this reason. Clearly the mass, temperature and composition of the corium released from the RPV strongly influences the attack.

In the area of CCI, it appears that the scientific community does not agree on the significance of when or if a corium pool will stratify into different layers (such as oxide and metals) or whether it will be homogeneous. The pool configuration can have an effect on where in the pool the energy source is located and its density. If stratification is assumed, much of the Zr, Fe and Cr oxidation would occur in the metal layer, while much of the radioactive decay heat would be in the heavy oxide layer. Also it is possible to postulate

that a solid crust could be formed between two liquid oxide layers when heat transfer, power density and physical properties are considered. The formation of eutectics, with their latent heat of fusion, will alter the available energy for concrete attack, water boiloff, or containment atmosphere heatup. How any crust (internal to the corium pool or on its peripherals) may effect heat transfer to water, atmosphere or concrete, is a matter of importance. Such a crust could also redu' ' the concrete ablation rate or effect the passage of gases up through the corium pool. The latter having an effect on increasing the mass of non-condensible gases in the containment atmosphere, and the generation of radioactive aerosols as the gaseous bubbles burst at the surface of the corium pool-atmosphere interface.

Other significant issues include how the core debris will spread across the drywell floor and whether it is coolable with containment sprays. One argument which is frequently echoed is that without cooling, containment failure is inevitable. One issue which should be resolved is whether water addition will produce a pressure spike due to steam generation which may result in containment overpressure failure. This could possibly occur at a time when the public may be evacuating the area around a stricken plant. A given amount of energy will produce a greater pressure rise due to the sensible heating of a gas than the gaseous mass addition due to boiling. Yet the heat transfer rates, and hence momentary pressurization rates, may be higher for boiling if the mass of the water addition (for a given configuration of the molten debris) is not enough to quench the debris below the water's saturation temperature. What shape or configuration the debris takes on in the containment can then be an important modeling parameter. What the heat transfer coefficient is for debris coolability, whether due to gas or water is a significant parameter on this issue.

A companion issue to debris pool coolability is how containment sprays and their heat removal capability is modeled. In many BWR containment designs the sprays will not remain as droplets as they will impinge on equipment and piping to form films.

In Mark III containment designs the containment volume is larger than the Mark I and II

designs so that igniters are used (as opposed to inerting) to control any combustible gases (H_2 and CO) generated under a core meltdown accident. The amount of combustible gases generated, the initiation of combustion and the degree of burn completeness are important parameters. These items are obviously more important if the AC power for the igniter is unavailable.

Venting is an emergency operating procedure action taken to protect the containment from overpressurization. For inerted containment (i.e., Mark I and II's) the containment atmosphere may be H_2 rich at the time of venting. When the containment atmosphere is vented into the air it is possible to produce H_2 combustion. This can result in a fire (possibly of the electrical cables or lube oil) if the H_2 combustion occurs next to such a fuel source. The amount of fission product material released to the environment could be increased due to the resulting pressure driving force. It is important to know whether H_2 stratification in the containment occurs to a large enough degree that by judicious choice of a vent path one may avoid combustion. The ability to predict natural circulation in the containment would help address this.

In the foregoing we have presented what are the present significant issues involved with severe accident containment modeling without discussing how MAAP or MELCOR address them. That is the topic of chapter three of this report. It should be evident that all these issues are reducible to how the four sources of energy in the containment are modeled.

The containment challenge accident phase supplies the timing of fission product release and energetics to give the source term predictions needed in any Individual Plant Evaluation (IPE). It is synergistically coupled with fission product transport. Without accurate modeling of the energy sources in the containment, one would not be able to correctly predict the driving force (in the form of gaseous mass flow) to carry the fission products to the environment. It is the coincidence of a large source of fission products coupled with a strong driving force, at the time of containment failure, that will result in a severe source term for a given accident. Predicting the time at which the containment fails (or doesn't

fail), and with what available driving force is one-half of this all important coincidence. The fission product source available at this time is the other and it will be addressed in the next TER.

3.0 MODELS AND ANALYSIS

As with other MAAP models, the containment control volume configuration is fixed. Figure I presents a MAAP representation of a Mark II primary containment. MELCOR affords the user greater flexibility and Figure II is one represention of a Mark II containment. As can be seen these models are not substantially different. MELCOR has an explicit representation of the downcomers while MAAP models the dynamics that may occur in the downcomers, but does not represent them in a separate control volume. The MELCOR model also has an upper and lower cavity control volume while MAAP models only the upper cavity. This modeling differences could have an impact if corium preferentially relocats to the lower cavity, because communication from this region to the rest of the wetwell is typically through manways. Nine Mile Unit II has downcomers in the pedestal region and other Mark II's have floor drains, which could allow for this type of preferential mass transport. This would impact pressurization, local corium power density and corium quenching. Both MAAP and MELCOR have provisions to allow for pressure-suppression bypass, wetwell to drywell vacuum breakers, containment venting, sprays and containment failure.

For each of the following major models discussed in this chapter, we have summarized differences between MAAP and MELCOR in Table I.

3.1 Direct Containment Heating (DCH)

MELCOR has no DCH model at the present time. MAAP does model DCH in the PWR version, but not in the BWR version. The PWR DCH model is more of a parametric study tool than a detailed model. The corium is assumed to be in thermal equilibrium with the cavity atmosphere, and the energy transport rate is limited essentially by the mass flow into the cavity from the RPV. The CONTAIN code[5] includes consideration of heat transfer time constants on energy transfer.

MAAP does have a model [ENTRAN] to allow for the transport of corium droplets out of the pedestal region and into the drywell if sufficient RPV blowdown forces exist to levitate the molten mass. This has the effect of spreading the corium with its energy into a larger volume.

The DCH issue is an unresolved one at this time, but BNL believes it would be prudent that with the absence of a detailed model, the BWR version of MAAP should allow for at least the same parametric studies to be conducted as can be done with the PWR version. This is especially true for those scenarios where the pressure-suppression function is not functional.

3.2 Steam Explosion

It was noted to in Chapter 2 that steam explosions are difficult to predict. While MELCOR has no steam explosion model, MAAP does attempt to simulate this phenomena. MAAP requires water to be present on the pedestal floor prior to vessel failure [EXVIN]. It will then track the amount of corium contained in a cylinder whose radius is related to the RPV's breach size and whose height is the water height in the pedestal region. If there is at least 1 kg of water and 1 kg of corium present then the corium is assumed to transfer energy to the water until it is cooled to the saturation temperature of the water. This is assumed to occur in one code timestep and only one such event is allowed. No structural damage is assumed.

The MAAP model is parametric in nature. The amount of corium assumed to interact with the water, its energy transfer rate, and the restriction of one explosion and only in the pedestal region justifies this classification. However, the user can use the model to evaluate the effect of corium stored energy (at or close to the user's supplied corium eutectic melt temperature), and various amounts of water available in the pedestal region on containment performance.

3.3 Core-Concrete Interaction (CCI)

This is one of the major modeling efforts in MAAP as well as MELCOR. To make the comparison simpler we will break up the discussion into the different modeling options employed during CCI.

3.3.1 Material Location and Physical Properties

MAAP assumes that the corium melt is homogenous and that the crust has the same composition as the bulk molten pool. MELCOR utilizes the CORCON MOD2 model for CCI and allows the debris pool to be composed of a metal layer sandwiched between two (heavy and light) oxide layers. The material properties of the debris in the MAAP model are also homogeneous with a single melt temperature. The internal energy of the pool is determined by tracking the composition of UO_2, Zr, ZrO_2, carbon steel and concrete. In this manner the solid to liquid fusion energies of the pool constituents are incorporated into the determination of the energy of the molten pool. Other properties such as conductivity, viscosity and density are appropriately weighted.

MELCOR has a range of melting temperatures for each layer or mixture. At temperatures below the solidus and above the liquidus, each layer has its enthalpy or internal energy weighted by the material composition. However, between the liquidus and solidus temperature, a linear extrapolation of enthalpy is used (see Figure 3). As a means of comparison MAAP utilizes a mechanical mixture model as shown in this figure.

Neither model is exact. The presence of such a large mixture of elements is sure to produce quite a complicated phase diagram (map). This effects the containment analysis in how the debris pool energy is allocated. Whether this will be in increasing the atmospheric temperature of the containment, ablating concrete or being retained to produce a phase change is the significant figure of merit.

Because MELCOR employs a solidus-liquidus model for its mixtures one may see the formation of a crust once the layer temperature falls below the liquidus value.

3.3.2 Heat Transfer and Energy Generation Model

Because MAAP uses single value melting temperatures for the debris and concrete, it simplifies the heat transfer modeling process. The heat source due to oxidation are volumetrically distributed in the debris (including the crust). The user supplies a convective heat transfer coefficient between the molten corium and the crust. This is used to determine the heat flux to the concrete. From this a concrete temperature profile is determined in subroutine HTWALL. MAAP's heat transfer correlation indicates that the greater the crust thickness the larger the flux to the concrete, if the corium melt temperature remains constant.

MAAP also tracks the heat into and out of the crust layer (always assumed to be at least 1 mm thick). This is done by assuming a parabolic temperature profile in the crust. MAAP assumes heat transfer is the same to side and bottom surfaces. The top surface, however, must consider radiative and convective heat transfer. Knowing the heat transfer into the crust from the molten debris, the energy generated in the crust, and the heat transferred from the crust to the concrete MAAP can determine whether the crust thickness will grow or not.

BNL is somewhat concerned with the way MAAP determines the heat transfer to the concrete. The algorithm used to calculate the heat flux to the concrete to determine the concrete temperature, and that used to calculate the crust thickness do not appear to be consistent. One needs to know how quickly the crust thickness changes in time to say there is a true problem, however. This will be observed during the MAAP-MELCOR computer run comparisons.

The situation is far more complicated in MELCOR, and we will not go into the details here.

But consider the fact that the energy source in the debris is not uniform but distributed according to the mixture layers with the metal layer getting much of the oxidation reaction energy, and the heavy oxide layer getting much of the decay heat. Users of CORCON have noted the presence of only a thin oxide crust because of the high heat generation rate within it. Further complicating matters with MELCOR is the presence of crusts being formed in the metallic layer, and a non-uniform heat transfer to the sides and bottom of the debris pool.

The heat transfer to the concrete is very important because of the consequences of concrete ablation on reactive gas formation, containment pressurization and fission product aerosol generation. A closer look at the way MAAP handles this including the effects of varying the convective heat transfer term over an order of magnitude (1000-10,000 W/m^2 [7] is recommended). It also may be possible that a homogenized energy source as used in MAAP, is not conservative because in reality the energy may be concentrated at the bottom of the corium pool where the heavy oxides may gravitate. Again, the heat transfer convective term supplied by the user could be used to adjust for this, at least over a narrow time scale.

3.3.3 Chemical Reactions in the Debris Pool

The subroutine METOXA is used in MAAP to determine the chemical reactions and their reaction energies. METOXA made use of other computer codes to formulate its necessary data. First the chemical equilibrium code EQUUS was employed to identify the important reactions. These were then separated into basis and auxiliary reactions. The difference being that a numerical solution is first attempted on the basis reactions, and used to converge with the auxiliary reactions. An interactive process is used until the equilibrium conditions are established for a given time step. The equilibrium constants used in this solution scheme are based on a functional fit to the Gibb's free energy functions of the reactants and products, similar to that used in VANESA. By-in-large MAAP's model assumes an ideal solution of reactants and products such that the presence of other chemical

reactions does not effect the Gibb's free energy functions in determining the equilibrium constants. To correct for this non-realistic assumption MAAP allows the user to adjust the activity coefficients of four compounds. It should be noted that MAAP does not allow the gases coming off the sides of the CCI pool to react. Also MAAP presently does not include chromium oxidation because "... the MAAP mass balance equations do not include Cr^8."

MELCOR does allow the gases released from the sides of the CCI pool to react and does include Cr oxidation. MELCOR utilizes the CORCON MOD2 model for chemical reactions which also solves for the minimization of the Gibb's function. Each phase is treated as an ideal solution. Because most of the chemical reactions occur due to metal oxidation, MAAP and MELCOR would give different results in the location of this energy source with MELCOR having these reactions concentrated in the metal layer. This could heat up the reactants and alter the equilibrium constants. In the meantime if the heavy oxide layer is the primary interface with the concrete it will need to have this chemical reaction energy transferred to it if this energy will effect the ablation process. With MAAP, the chemical energy will immediately have an effect on ablation since the metals are homogenized throughout the CCI pool. It is therefore not clear which model will be conservative in terms of ablation.

3.3.4 Gas Transport and Generation

As already mentioned, the MAAP code does not allow for the reaction of gases released from CCI if they are released from the sides of the CCI pool. Also the MAAP model will create a pool which has straight sides due to the uniform heat transfer coefficient used on the sides and bottom. The surface area of CCI will then be governed by this, and the molten debris swelling which occurs as the gases lower the density of the corium.

In MELCOR it is possible one could get a larger surface area for CCI because the shape of the CCI pool can be non-regular. Also MELCOR allows for the interaction of the side wall released gases even though they are assumed not to form droplets but flow as a film

up along the sidewalls. MELCOR, also allows for corium swell.

3.4 Debris Spread and Coolability

There is a unique Mark II component model in MAAP for debris spread and coolability. The drywell floor has the downcomer connecting the drywell and wetwell mounted within it. The corium would, however, be first relocated to the pedestal floor region before it flowed out to the drywell. MAAP's DCFAIL attempts to simulate this flow and the progressively large flow area (through the corium covering more downcomers) available to the wetwell as the corium spreads. Although the model is simple it is an improvement over a fixed downcomer flow area, and its effect on CCI and spray effectiveness should be clear. I suspect the use of the control theory model of MELCOR would allow for the user to simulate this more if he wished.

Further to deal with the interaction of the corium with the suppression pool water in a Mark II downcomer. MAAP establishes a quenching zone [QUENCH]. Essentially this does not require the entire suppression pool to reach saturation before the corium will produce steaming. Again one would need to utilize the control theory blocks or an increased number of control volumes in MELCOR to construct such a simulation as one presently doesn't exist. BNL believes the phenomena simulated in MAAP to be real and to have an effect on containment pressure response. One more rather unique model in MAAP dealing with debris spread which was discussed in the earlier section on DCH. This involves high pressure blowdown of the RPV. MAAP corium entrainment model [ENTRAN] allows for the phenomenum of corium droplets being removed from the pedestal region by a levitating steam and H_2 gas from the highly pressurized RPV. BNL's concern is that this model assumes all the mass in the pedestal is removed in 0.5 second if the conditions for levitation exist for that period of time. This flow rate may be too large and although the added debris to drywell atmosphere surface area will effect the short term pressurization rate in a conservative way, it may not conservatively handle CCI and its somewhat longer term pressurization rate.

Both MAAP and MELCOR will model the cooling effects of a pool of water above the corium-debris pool. MAAP permits the user to adjust the film boiling coefficient to allow sensitivities studies on the effect of cracks in the upper crust of the debris pool.

To handle natural circulation in the pedestal region MAAP allows flow to enter the lower opening of this region to remove heat there before passing up and out through the upper openings in the pedestal volume. One would be forced to include additional drywell control volumes in MELCOR to simulate this.

3.5 Combustion

The major items to be considered under the combustion topic are:

- ignition
- propagation
- degree of burn completion
- flame speed

Ignition in MELCOR is determined by a user supplied input value. This input value is compared to a code calculated value which is a function of both H_2 and CO mole fractions. Tests are also made to determine whether there are acceptable amounts of O_2 and the inerting gases of CO_2 and H_2O. The limits for these are also user supplied and compared to code calculated values.

MAAP includes lean and rich flammability limits (LFL and RFL) with a dependence on gaseous temperature. Functionally an increase in temperature lowers the fuel requirements for LFL and raises it for the RFL. Since combustion is permissible between these limits the

rise in temperature has the effect of increasing the (combustible mixture) range for flammability. The determination of ignition is based on a user supplied offset of the LFL and RFL. Thereby reducing the acceptable mixture required to a subset of the flammability regime. Figure IV gives an example of the LFL, RFL and the ignition offset.

The effect of an inerting gas such as N_2, H_2O or CO_2 also effect the flammability and ignition regimes. MAAP utilizes user supplied values for both an inerting concentration at an autoignition temperature and the autoignition temperature. This in effect reduces the flammability regime further.

It can be seen that MAAP's model is more sophisticated than MELCOR's. Modelers of IPE's must be careful not always to assume combustion close to the LFL, assuming this to be conservative. One could get a greater pressure increase if the ignition was not allowed until the RFL was reached.

In summary, ignition is determined in MAAP based on a regime developed from an offset of a flammability regime. The flammability is a function of gas temperature on mole function of its constituents. The inert point is determined by the code using a inerting concentration at an autoignition temperature and the autoignition temperature.

In MELCOR, the user supplies the fuel ignition concentration and the requirements for oxygen concentration. He further supplies a requirement for the concentration of inertants to prevent ignition. MELCOR's ignition criteria is not temperature dependent except in the user's prethought in chosing the limits he supplies.

MAAP has different LFL and RFL limits for the direction of propagation. These also effect the degree of burn completion. All downward propagation burns are assumed to be 100% complete [FLAMM]. If the burns are incomplete their burn time is decided in MAAP from the time it takes the spherical flame front to contact the ceiling of the volume the burning occurs within. Contact with the ceiling stops the combustion. The velocity of the flame

front is determined from the solution of the momentum equation. This considers buoyancy and drag.

MELCOR allows the user to input a constant for burn completness, use a concentration dependent correlation or employ a control function relationship which the user supplies. The propagation follows the flow paths. Up, down and horizontal paths are therefore dependent on the control volumes configuration. As with combustion completeness, MELCOR offers the same three options for flame speed: user supplied value, control function or concentration dependent correlation.

Both MAAP and MELCOR afford strong user control over ignition. For flame speed MAAP allows a tunable parameter it calls the "flame flux multiplier" which gives control over combustion rate. MELCOR users can supply their own flame speed as input. For propagation, MAAP users appear to be able to assure a downward complete burn by setting the ignition criteria such that the fuel concentration is higher than that necessary for a downward propagation flame, if not, the size of the volume and the distance to the control volume ceiling limits burn completeness. MELCOR users have full latitude in chosing burn completeness. Propagation in MELCOR is even permitted across control volumes.

The MAAP code is more phenomenalogical than MELCOR in modeling combustion. Still as just described there is a large degree of versatility in the models. It is, however, the pressure that results from the burn and the remaining gas mixture constituents which are important. MAAP will not calculate a detailed pressurization rate but only an average value based on the burn completion and combustion duration. MELCOR does adjust the burning rate.

MAAP's flammability regime should help in its calculations since they are temperature and, therefore, somewhat time dependent.

3.6 Engineered Safety Features and Alternate Systems

MAAP is much more user friendly in modeling the ECCS than MELCOR, with specific models for each major system. In MELCOR the user would have to utilize control theory and a control volume-junction structure to accomplish a similar task. Essentially this is already programmed in MAAP and in a standardized way. The pump models in MAAP include the effect of backpressure on their flow if the discharge is to the RPV. It is not modeled for containment discharge. The MAAP programmed models would have to be manipulated, however, if one wished to observe the effects of some novel accident management strategies. This could be accomplished by choosing a modeled ECCS which had the appropriate suction and discharge locations and giving the prime mover the appropriate head characteristics.

Probably the most important Emergency Core Cooling System (ECCS) for the containment is the Residual Heat Removal System's containment spray mode. Both MAAP and MELCOR have a spray model. MELCOR uses the HECTR code. Both models assume spherical droplets, that they fall at terminal velocity and are isothermal. Further the models allow for condensation and evaporative mass transfer as well as aerosol washout. Unfortunately sprays will not remain as sprays for long in some equipment congested containments. MELCOR might, again at increase control volume nodalization, be able to be adjusted for this. The droplet size user input parameter in MAAP may also be utilized to help improve the results based on this concern.

Containment Venting should not be a problem for either code in terms of mass flow, though MELCOR would have inertia effects and MAAP would not. However, the effect of this modeling difference should be small over the time phase of venting.

With respect to the pressure-suppression downcomer clearance, MAAP has no true inertia model. However, it will smooth the flow between the drywell and wetwell if the Bernouli flow rates yield flows greater than that which would equalize drywell and wetwell differential pressure in less than 2 seconds or 2 global time steps. In effect this tries to account for the lack of inertia in the Bernouli equation. For breach of RPV into the drywell at high

pressure the pressure spike should be predicted within acceptable bounds, especially when one considers the breach size is only an estimate. For the time phase of drywell pressurization due to CCI the pressurization rate will be slow and inertia effects unimportant. Wetwell and drywell vacuum breakers are also easily modeled by these codes.

Containment failure is usually modeled on a pressure or temperature criteria. MAAP does have a containment strain failure model if the user wishes to employ it. Because of the complexity of containment design it would be better to performed detailed auxiliary (non-MAAP) calculations to equate containment failure to an inputed failure temperature or pressure. There will always be an uncertainty related to containment failure or breach size. Typically the user would perform a parametric study of the fission product release or consequences versus a spectrum of failure sizes.

A gas combustion front can be either subsonic or sonic to supersonic velocity and this characteristic defines the difference between a deflagration and a detonation.

While MAAP does not consider detonation, MELCOR will send a message to the output file if conditions for detonation have been reached. This appears to be the extent of detonation modeling in these codes. The pressure spike from detonation can be larger than that for deflagration, but it is much shorter in duration and the MAAP modelers believe because of this the structures would be able to withstand it.[9] The effect on electrical and mechanical penetrations due to a local detonation are therefore neglected.

4.0 SUCCESS CRITERIA

In PRA's it is common to enter a containment event tree (CET) with the various plant damage stages. The product of the CET is "Release Mode" classifications. In the present document we have not covered the decontamination ability of the Reactor Building or Secondary Containment. Since this building offers little in the way of pressure sustaining capability, we will address its modeling in the Fission Product Transport Technical

Evaluation Report which is to follow. We raise this issue now, however, because a CET will include both the ability to maintain containment confinement as well as controlling the severity of the release. This present report covers the former and only part of the latter.

Let us classify the different containment failure modes into early and late. The cause of the failure, other than containment confinement bypass (such as failure to isolate) can be associated with temperature or pressure limits. Direct Containment Heating (DCH), Steam Explosion, Pressure Suppression Bypass, and H_2 Combustion will be classified as early modes. Loss of containment cooling is a late failure mode.

The loss of containment cooling containment failure will be strongly effected by CCI, and the associated modelling of corium relocation. As was previously discussed[10] MAAP and MELCOR may yield considerably different estimates of the temperature, mass and composition of the corium interacting with the concrete. The modeling of CCI, even with the same initial boundary conditions, is quite different in MAAP and MELCOR. Yet, in the long term for the coarse structure of present day CET's both codes should be sufficiently accurate in determining whether containment failure will occur. The timing of the failure and possibly the amount of H_2 produced as a result of CCI will not agree. This could have an effect on the classification of some plant damage states into different release modes. This would translate into a different prediction of the risk associated with a particular initiating event.

Early failure modes are associated with phenomena which can result in rapid pressure challenges to the containment. As already mentioned DCH is not handled by either code.

For Steam Explosion, MAAP does offer a parametric study tool and this can be used to assist in determing the severity of steam explosions if the conditions warrant. The MAAP model should not be the sole means of determining this however. Steam Explosion modeling is especially difficult, not only in terms of when it will occur but even in terms of the size of the interactive zone. As previously mentioned MELCOR has no Steam

Explosion model.

Neither code predicts if the downcomers used in containment pressure suppression will fail. However, they both appear to be able to adequately handle the effects on containment if they are assumed to fail.

In consideration of H_2 combustion failure of the containment, it is the generation of the fuel which appears to be more of a concern than the combustion model itself. Both MELCOR and MAAP appear sufficiently tunable to be used to determine deflagration combustion failure of the containment. There is a large uncertainty of when ignition will occur and for non-igniter plants this uncertainty might well wash out the uncertainty associated with the pressurization rate predicted by the combustion model. Also there is uncertainty in local failures of containment penetrations due either to deflagration or detonation.

In summary, there appears to be as much uncertainty in the predictions of the occurrence of early failure modes of containment failure as there is in modelling their consequences. BNL does believe that DCH parametric model should be included. For steam explosion, suppression pool bypass and H_2 combustion the modeling of their consequences in MAAP appear adequate when compared to their uncertainty of occurrence.

The CCI models in MAAP and MELCOR appear flexible enough to take advantages of experimental progress in this area. The IPE modeller must, however, be judicious in his choice of release modes.

5. RECOMMENDATIONS

As was discussed in the body of this report (Chapter 3) BNL recommends the following:

- Incorporate a DCH model to allow parametric studies to be performed
- Track chromium for its effects during CCI
- Allow user tunability in the amount of CCI gas coming from the concrete sidewalls that will react with the corium debris.
- Supply user guidance for the effect of water addition coolability due to containment sprays which are more like water streams due to equipment interference in the drywell.
- Check for possible inconsistency in the heat transfer correlation used for CCI crust growth and that for concrete heatup.
- Warn user via documentation of the potential for non-conservatism in concrete attack due to entrainment of corium out of the pedestal region during high pressure RPV blowdown.

Now, none of the above recommendations should be considered as fatal problems at this time.

It should be noted that development activity on MAAP for the Advanced Light Water Reactors has resulted in these changes [DOE/ID-10216, Vol. 1, Nov. 1988].

- Unequal sideward and downward erosion rates.

- Allowance for separate metal and oxide layers.

- Incorporation of liquidus-solidus representation for stainless steel, fuel concrete oxide, Zr-Fe.

- Provisions exist for Cr to be tracked separately.

From this it appears as if the MAAP modelers share some of our concerns.

6. REFERENCES

1. R. K. Cole, et al., "CORCON - Mod 2: A Computer Program for Analysis of Molten - Core Concrete Interactions," NUREG/CR-3920, August 1984, p. 40.

2. ibid, p. 14.

3. J. U. Valente, "MAAP 3.0B/BWR Review, Technical Evaluation Report 2, Core Melt Progression," August 1990.

4. "MAAP 3.0B Users Manual," subroutine FLAMM.

5. D. C. Williams, et al., "CONTAIN Analysis of Direct Containment Heating Events in the Surry Plant," ANS Thermal-Hydraulic Division Proceedings of the ANS/ENS International Meeting, October 31 - November 4, 1988, Washington, DC.

6. R. K. Cole, et al., "CORCON - Mod 2: NUREG/CR-3920, August 1984.

7. "MAAP 3.0B Users Manual," subroutine DECOMP, p. 25.

8. ibid, subroutine DECOMP, p. 10

9. ibid, MAAP Appendix 3B/P, "Introduction to Combustion," p. 1.

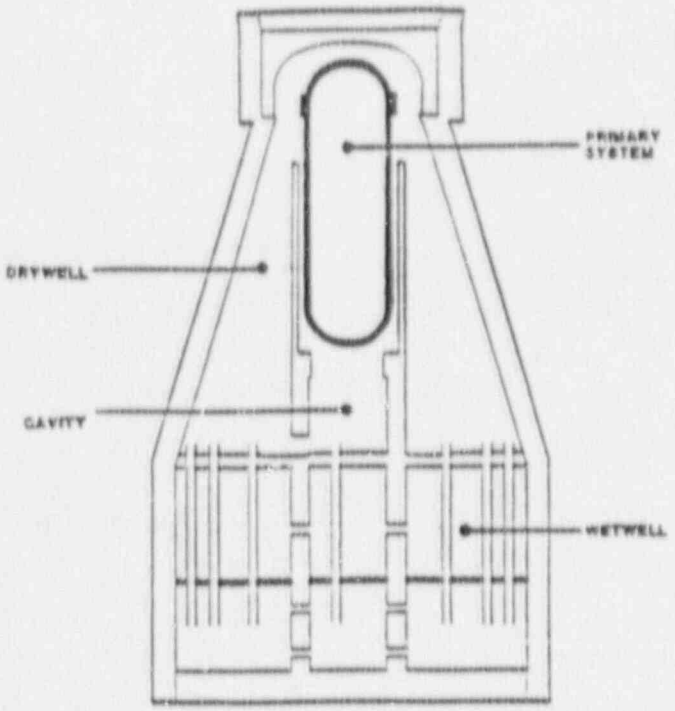
10. J. U. Valente, "MAAP 3.0B/BWR Review, Technical Evaluation Report 2, Core Melt Progression," August 1990.

TABLE 1

	MAAP	MELCOR
DCH	Not modeled	Not modeled
Steam Explosion	- Parametric study model available - A geometrically derived amount of corium is assumed to come to water saturation temperature within one time step. - Reaction occurs in the pedestal region.	Not modeled
Core Concrete Interaction	- 1 Homogeneous layer of corium modeled. - Ideal solution used (activity coefficients set to one) except for four compounds. - Chromium not tracked and hence it has no reaction energy created from it [DECOMP]. - Sidewalls and bottom of CCI crucible are attacked equally. - CCI gases released from sidewalls are not permitted to react with corium debris.	- Uses CORCON MOD2 models. - Allows for a maximum of 3 layers - metal, heavy oxides, light oxides - Each phase (metal and oxides) is treated as ideal solutions. - Cr tracked. - Different attack rates for CCI crucible sides and bottom - Sidewall gas reacts with debris but at different temperatures than bottom gases.
CCI	- H_2O, H_2, O_2, N_2, CO, and CO_2 are tracked. - Utilizes a single melt temperature	- Suppresses all gaseous releases other than H_2O, H_2, CO_2, and CO. - Utilizes a liquidus-solidus transition temperature unique for each layer.

TABLE 1 (Continued)

	MAAP	MELCOR
Combustion	- No detonation modeled. - Ignition - user controlled as offsite of code supplied flammability map. - Inerting values supplied as a concentration at autoignition temperature. This results in reduction of flammability map. - Propagation modeled as a spherical flame front which ceases when it hits a ceiling. Code checks concentrations to determine if downward propagations occur. - Combustion Completeness - Determined by concentration (burn is complete if concentration was large enough for downward propagation) and/or distance to ceiling.	Detonation modeled only by means of output flag. Ignition - user supplied input Inerting - user supplied limits for H_2O and CO_2 - Propagation - up, down and sideward determined by flow paths in burning control volume. Flame can propagate to an adjacent control volume. - Combustion Completeness - takes form of: 1) User input constants 2) User created function 3) Default is NECTR 1.5
Combustion	- Flame speed is determined by the solution of mass and momentum equation.	Flame speed - takes form of: 1) User input constant 2) User created function 3) Default is NECTR 1.5



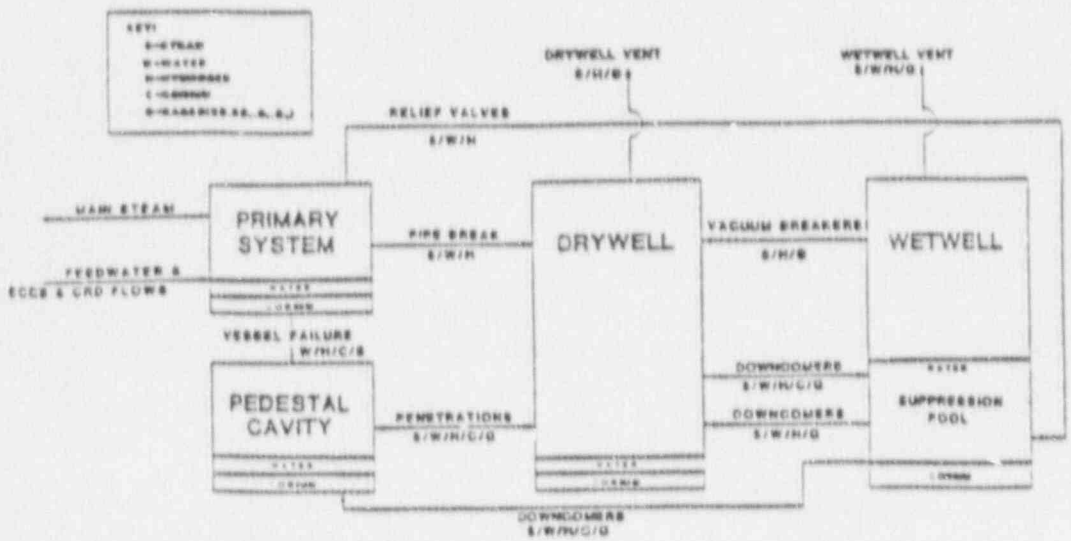


Figure I Susquehanna Mark II Containment

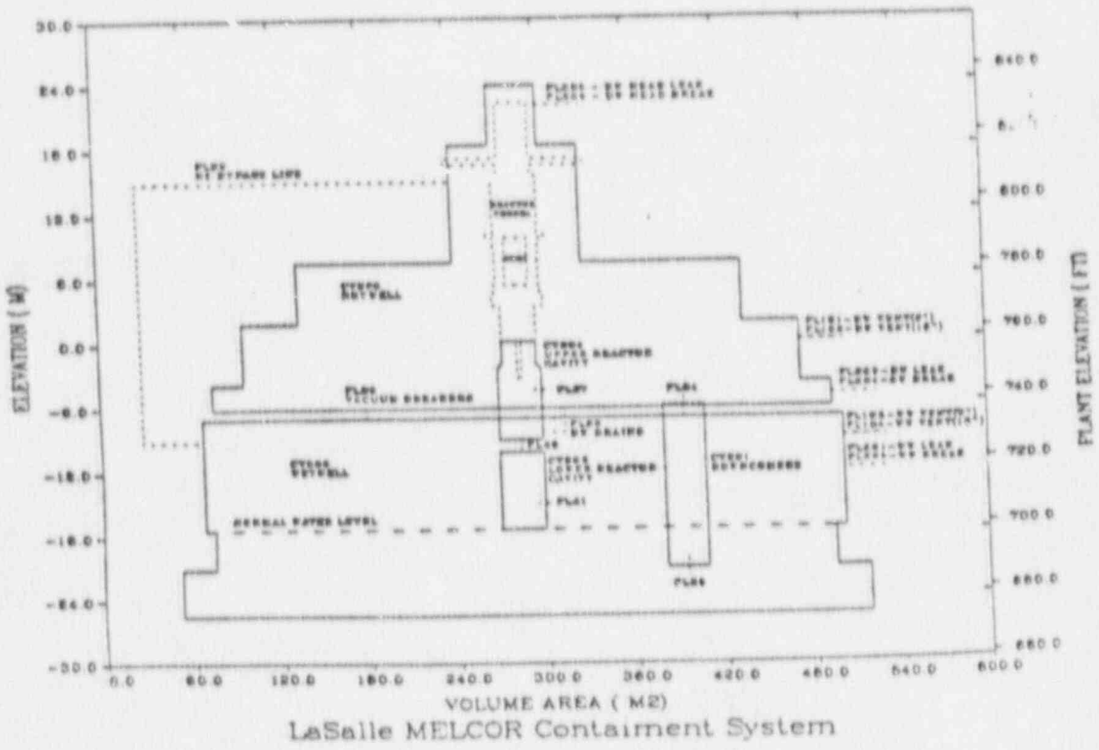


Figure II LaSalle MELCOR Containment System

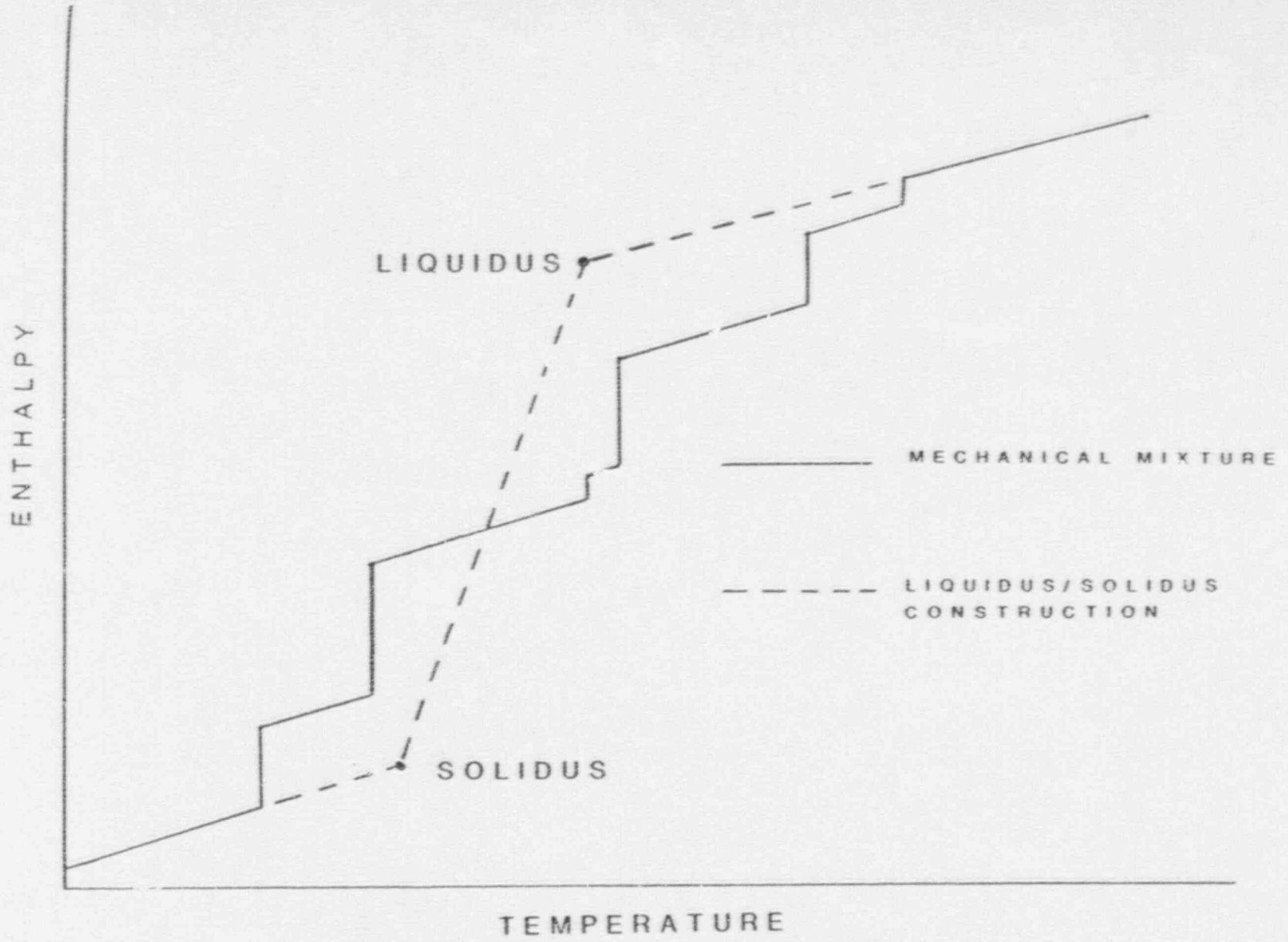


Figure III Two Phase Construction for Mixture

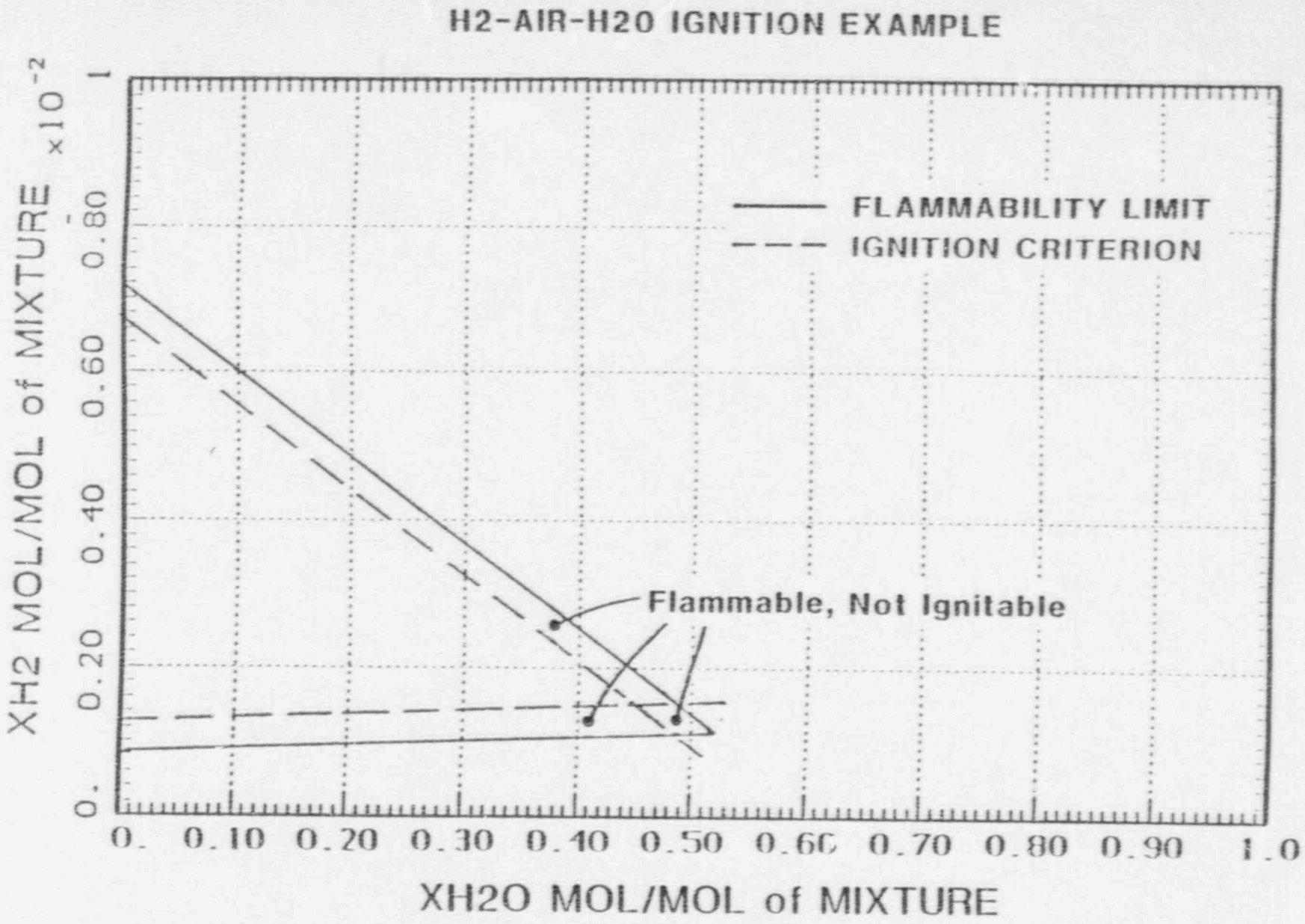


Figure IV H_2-Air-H_2O Ignition Example

MAAP 3.0B/PWR REVIEW

Part 3: Containment Response

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ABSTRACT

This report presents the third part of a preliminary review of the MAAP 3.0B/PWR code. The review covers the thermal-hydraulic response to a containment atmosphere and auxiliary buildings to severe accident conditions. Detailed comments are made on basic assumptions, nodalization, thermal hydraulic modeling and selection of model parameters. Comparisons between the MAAP code and the NRC developed MELCOR code are made.

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ACKNOWLEDGEMENT

This work was conducted under the auspices of the U. S. Nuclear Regulatory Commission (NRC), Division of Systems Research, Accident Evaluation Branch. Mr. Allen Notafranessco is the manager of this project.

The author wishes to acknowledge Dr. H. Nourbakhsh for his review of the MAAP direct containment heating (DCH) model. Thanks are also due to Dr. W. T. Pratt for his comments and review of this report.

I would like to express my appreciation to Kathy Ryan for her excellent preparation and assembling of this report.

1. INTRODUCTION

This report summarizes a preliminary review of the MAAP 3.0B/PWR code. [1] The work was performed under Task 3 of the MAAP Code Evaluation Program. Task 3 of the program deals with MAAP code models for the response of a containment and auxiliary building to severe accident conditions. The review includes phenomena such as corium/water interaction, corium/concrete interaction, combustible gases generation and combustion, direct containment heating, and containment failure modes. An assessment of the models in MAAP for containment safeguard systems (i.e., sprays, fans and ice condensers) is also presented. Comparisons between the MAAP code and the NRC developed MELCOR [2] code are made.

2. PRIMARY CONTAINMENT NODALIZATION AND GENERAL DESCRIPTION

Four PWR plants were selected as reference plants and modeled with the MAAP/PWR code. The Zion, Oconee and Calvert Cliffs plants were selected as representative of large dry containments, and Sequoyah was selected to represent ice condenser containments. The MAAP dry containment model is divided into 4 regions: upper containment (A-compartment), lower containment (B-compartment), cavity (C-compartment) and the annulus region (D-compartment). These compartments are connected by flow paths to simulate forced and natural convection flow, and water drainage. The following materials and gases are specified for each flow path.

Flow Path	Flow Material
A <----> B	Steam/water/gas/hydrogen
B <----> C Annulus	Steam/gas/hydrogen
B <----> C Tunnel	Steam/water/gas/hydrogen/corium
A <----> D	Steam/hydrogen/gas
D <----> B	Steam/hydrogen/water/gas
A <----> C	- Water only (Oconee) - Water/gas (Calvert Cliffs) - None (Zion)

Lower compartment (B) and cavity (C) are connected by two flow paths; namely, the instrument tunnel and the reactor vessel/shield wall annulus. Water and corium can be specified to flow through the tunnel only, but not through the annular passage. However,

for plants with a flow area through the instrument tunnel which is smaller than the area of the reactor vessel/shield wall annulus (i.e., reactors with no lower head penetrations), MAAP allows the debris and water to be dispersed directly to the upper compartment (A) whenever the calculated gas velocity exceeds the entrainment threshold (EVENT flag No. 53). This is done by setting the model parameter No. 13 FCMDA to be 1.

The MAAP ice condenser plant model has two compartments in addition to the 4 compartments in the dry containment model. The additional compartments are the ice condenser (I-compartment) and the upper plenum (U-compartment). These two compartments are located between the lower and upper compartments. Steam, hydrogen and other gases can be specified for the connecting flow paths. The ice condenser compartment also provides water drainage to the lower compartment.

The flow paths defined in MAAP can be connected to form natural circulation loops. For dry containments, MAAP allows one loop between the lower and cavity compartments (loop BC) and another loop between the upper, lower and annulus compartments (loop ABD). For ice condenser containments, a loop between the upper, lower, ice condenser and upper plenum (loop ABIU) is added. The flow rate is determined using an equal-pressure approach, i.e., flow circulation results in pressure equilibrium among the various regions in the containment. The MAAP modeling of loop flow would enhance gas mixing and reduce the localized hydrogen concentration. Assessment of the pre-defined circulation loop should be made by comparing with specifically developed containment codes, such as CONTAIN and HECTR. These codes use dynamic momentum equations and implicit method to compute fluid flow without a pre-defined circulation loop.

Although the major regions of a PWR containment are represented by the MAAP code model, the fixed nodalization and pre-specified flow paths and flow materials do not permit a user to perform a sensitivity study on the effect of nodalization. In many cases, such as natural convection, the flow rate is sensitive to the local fluid density and a finer nodalization would improve the code prediction. Hydrogen mixing is an example.

Computer code simulation of the HDR experiments [3,4] have demonstrated the importance of fine nodalization on predictions of hydrogen distribution in a large containment. An accurate prediction of hydrogen distribution is essential to assess the potential hydrogen combustion mode, such as a localized detonation. The fixed four-compartment nodalization in MAAP may not be sufficient to allow for adequate evaluation of hydrogen distribution under severe accident conditions.

Phenomena treated in various containment compartments are also fixed in the MAAP code as summarized in Table 2-1. From an inspection of Table 2-1 it can be noted that:

(1) All the phenomena modeled in MAAP can be specified in the upper compartment (A);

(2) The containment sprays, DCH and corium/concrete interactions cannot be specified in the annulus compartment (D);

(3) No metal equipment is modeled in the cavity (C) and annulus compartments (D).

The phenomena allowed to occur in pre-specified compartments are reasonable in most cases. However, the exclusion of certain phenomena in some compartments, particularly the annulus region, limits the flexibility of the code. For example, in the Zion plant, a large amount of equipment is located in the annulus and cavity regions. There is 3.4×10^5 Kg of steel (electric cable pans, vent duct, accumulator wails and relief tank walls) in the annulus compartment, and 4×10^4 Kg of steel (various steel structures and vessel bottom in the cavity compartment. These steel structures can not be modeled as heat sink in MAAP code because of the limitations indicated in Table 2.1.

Unlike MAAP code, there is no specific nodalization and no predefined models built into the MELCOR code. MELCOR uses the control volume concept to represent the containment system. Each of the compartments modeled in MAAP for the dry containment

can be represented by a control volume in MELCOR code. (The present version of MELCOR code does not model the ice condenser plant.) In MELCOR, all phenomena can be imposed on any control volume by control functions. This flexibility permits MELCOR to perform many sensitivity studies as needed.

Table 2.1

Phenomena Modeled in Pre-Specified Containment Compartment (MAAP)

Compartment	A	B	C	D	I	U
Containment Failure Location	Yes	No	No	Yes	No	No
Fan Suction	Yes	No	No	No	No	No
Sprays	Yes	Yes	No	No	No	No
DCH	Yes	Yes	No	No	No	No
Corium/Concrete Interaction	Yes	Yes	Yes	No	No	No
Metal Equipment Heat Sink	Yes	Yes	No	No	No	No
Wall Heat Sink	Yes	Yes	Yes	Yes	No	No
H_2 and CO Combustion	Yes	Yes	Yes	Yes	No	Yes
Water Flashing and Rainout	Yes	Yes	Yes	Yes	Yes	Yes
Water Overflow	Yes	Yes	Yes	Yes	Yes	No

Based on PWR subroutine Index given in Volume I, Section 14 of Reference [1].

Note 1. A = upper compartment, B = lower compartment, C = cavity, D = annulus, I = ice condenser, U = upper plenum

2. MELCOR has no restriction on phenomena specified in any compartment. All phenomena modeled in MAAP can be specified in every compartment in the MELCOR code.

3. CORIUM ENTRAINMENT AND CORIUM/WATER INTERACTION

After reactor vessel failure, several subroutines (EXVIN, ENTRAN, PLH2 and PLSTM) are used to estimate the corium behavior and the production of steam and hydrogen during corium/water interactions. Each of the subroutines describes a different mode of corium interaction represented by a different corium configuration. Potential corium configurations range from droplets to a molten pool. BNL expressed concern at the second familiarization meeting regarding the basis for assuming these configurations and the related computational procedure. Each subroutine is discussed in the following sections:

3.1 Subroutine EXVIN

EXVIN computes the amount of steam produced during a steam explosion in the reactor cavity during the initial interaction between debris and water. The time for initiation of an explosion is determined when a column of corium contacts the cavity floor. The maximum quantity of corium involved in the steam explosion is assumed to be the mass in the column extending from the floor to the water surface. The explosion is assumed to occur over a single time-step and the debris is quenched to water saturation. The amount of steam produced is calculated from the amount of energy released as the debris is cooled to the saturation temperature of the water. There is no succeeding explosions and no structural effects involved in the calculation. The MAAP model does not calculate the dynamic force due to the conversion of thermal energy into mechanical energy which could threaten the containment integrity as reported in the studies of steam explosion. Hydrogen generation during a steam explosion is not modeled.

3.2 Subroutine ENTRAN

ENTRAN computes the flow rate of corium and water from the reactor cavity to the containment compartment due to the entrainment or flooding of water and corium in the high speed stream of hydrogen and steam existing the reactor vessel. A constant MAAP

entrainment time (0.5 seconds) is used to determine the entrainment rate. BNL expressed concern about the entrainment model at the second familiarization meeting. The related questions and answer are given below:[7]

Question:

> The entrainment rate of corium and water from the reactor cavity to the containment lower compartment is controlled by the "entrainment time." A constant entrainment time (0.5 S) is used in the code. Should the entrainment time depend on cavity geometry and pressure? Is the entrainment model also used for the DCH calculations?

Answer:

> While the true entrainment time does vary with geometry and pressure, a constant value is used to formulate a rate because the value of the rate is not influential on the transferred mass. This parameter should be set to a value lower than the blowdown time of the vessel to guarantee debris dispersal. It is used to formulate reaction rates from the total amount of material available for reaction, and heat transfer rates from energy transfer needed for equilibration. Thus, the same total change would occur regardless of the selected time constant. In principle, the time constant could influence heat transfer or reactions during DCH, but this is not believed to be important for reasonable entrainment times.

In Reference [6], IDCOR stated that "the transport of core material from the failed RPV to the containment floor is dependent on the shape and size of the cavity (and tunnel(s) where applicable) connecting the lower region of the RPV to the containment region." Based on this position, IDCOR classified PWR reactor cavities into fourteen types according to geometry to express the degree of debris dispersal during a high-pressure melt ejection accident. The classification covers a wide variation in expected debris dispersal. For

example, a type A configuration (such as Zion) would allow large debris dispersal, while a type D configuration (such as Surry) would retain essentially all of the debris in the cavity. Thus, the mass and rate of corium entrainment should depend on the specific cavity configuration of each plant, but this is not reflected by the entrainment model in MAAP. Therefore, the application of the MAAP entrainment model to IPE, in which a plant-specific cavity configuration is involved, should be justified.

3.3 Subroutine PLH2

PLH2 computes hydrogen generation after corium/water contact in the reactor cavity. As described in Reference [7], PLH2 "uses all the corium available at the time of vessel failure (even though some may remain in the vessel) and uses properties for corium in the lower head (even though EXVIN or JET may have been called). PLH2 is also called once in the lower compartment when debris can be entrained to it from the cavity. It is called after a small amount of debris is accumulated, but assumes that all debris in the cavity and lower compartment is available (even though it may not all be entrained) using properties for corium in the cavity (even though DCH may have been called)."

According to the above description, the PLH2 computation procedure involves a large uncertainty on corium mass and properties, which would affect the prediction of hydrogen generation. This model is also used when corium is relocated from the core region into the vessel lower head. There is a large uncertainty on the PLH2 heat transfer model. Comments on the heat transfer model were given in Part 2 of the MAAP/PWR Review Report [5].

3.4 Subroutine PLSTM

PLSTM computes steam production due to the contact of debris with water after the debris relocates into the reactor cavity or is entrained into the upper and lower compartments. The corium configuration in the PLSTM model is assumed to be a molten pool with a crust

layer at the corium/water interface. A major assumption is that the debris crust in contact with the water will crack and allow water ingress. This water ingress results in rapid heat removal from the debris. However, the subroutine imposes several limitations on the heat flux from the debris to the water pool. The limitations are the water addition rate, corium quenching rate, hydrodynamic stability, film boiling and critical heat flux. Three user-specified parameters, i.e., Model parameters No. 8 (HTFB, film boiling heat transfer coefficient), No. 21 (FDROP, droplet critical flow parameter), and No. 33 (FCHF, Kutateladze critical superficial gas velocity) are used to control the corium/water interaction. BNL expressed concern as to how these user-specified parameters were used and what values were recommended. The question and answer related to the PLSTM model are given below:

Question:

Critical heat flux (CHF) and film boiling heat transfer are used in the PLSTM subroutine to compute heat transfer from corium to water pool. A user specified heat transfer coefficient is required to compute the film boiling heat transfer rate. What is the recomm ‹ded value for this coefficient?

The CHF is used to limit the corium/water interaction. Please explain why MAAP excluded the potential formation of a particulate debris bed. The dryout heat flux of a debris bed could be the limiting mechanism for the corium/water interaction.

Answer:

The recommended value for the film boiling heat transfer coefficient (convective portion) is 300 W/M^2K. CHF and film boiling are used by the code, so that the transition boiling regime is not allowed. This regime is instead considered through uncertainty in the CHF itself: the user selects the nominal quenching heat flux as described next.

The functional form of CHF is used to represent heat transfer from debris to water accounting for debris cracking and water ingression. The nominal value of a user-input parameter, FCHF, is set to p.. * the CHF heat transfer rate as a nominal rate during quenching. Since there is uncertainty in corium-water heat transfer during quenching, users should vary FCHF so that the best heat flux varies over a range of between 0.5W/M^2 and 30 MW/M^2. At the low end, this simulates limited debris porosity as a result of quenching. It leads to a low quenching rate, and suggests that under circumstances of thick debris depth and small upwards surface area that complete quenching may not occur. At the high end, extensive fragmentation is modeled, and rapid quenching results. In this case, for containments initially at high pressure, rapid steam generation could threaten containment integrity.

Since debris quenching, steam generation and containment pressurization are obviously very sensitive to these parameters, the selection of the input values must be done with care and in the form of a sensitivity study.

3.5 Summary

The above description indicates that steam and hydrogen generation are computed by several subroutines independently. The quantity of corium involved in the corium/water interaction is controlled by the entrainment model. Each subroutine has its own assumptions related to corium configuration, corium mass and properties. The lack of interaction among these subroutines cause inconsistencies in modeling the physical process occuring during corium/water interaction. The following are examples of inconsistency:

1) EXVIN is called after vessel failure and until corium contacts the cavity floor. Corium is quenched at the end of EXVIN calculation, which implies that the sensible and latent heat of corium are removed and corium is in a solidified configuration. Hydrogen generation and corium relocation are not considered

in the steam explosion model.

2) ENTRAN is called at each timestep after vessel failure to relocate corium from the cavity region to the upper and lower compartments, with no respect to whether EXVIN (steam explosion) has been called. The corium configuration is irrelevant to the entrainment model.

3) PLH2 is called only once after vessel failure for corium located in the cavity and lower compartment. Corium is solidified at the end of a PLH2 calculation, which implies that the sensible and latent heat are removed again. (Recall that the corium has been solidified already at the end of EXVIN calculation.)

4) PLSTM is called at each timestep after vessel failure to compute corium/water interaction. Corium is assumed in a molten state although EXVIN and PLH2 have been called and the corium has been solidified. The sensible and latent heat are to be removed again while the corium/concrete interaction is taking place.

This inconsistent treatment is attempted to maximize the steam production. However, the excessive steam production will increase the containment inertness and reduce the potential for combustion. It will also affect other containment response, such as pressurization and basmat attack, etc. The overall mass and energy balance may not be satisfied.

In MELCOR, ex-vessel debris relocation, heat transfer and oxidation due to corium/water interactions are modeled in the Fuel Dispersal Interaction (FDI) package. Eventually, three types of phenomena will be treated in the FDI package: (1) low pressure molten fuel ejection from the reactor vessel, (2) high pressure molten fuel ejection from the reactor vessel (direct heating), and (3) steam explosion following a low pressure ejection sequence. Currently, the FDI package can only treat a low pressure ejection (mixing phase prior to a

steam explosion). Models for steam explosions and direct heating are not available in the current version of the MELCOR code.

During low pressure ejection, heat is transferred from the molten fuel to the water pool (if present in the associated control volume) as it fragments and falls to the cavity floor. Heat transfer normally occurs by radiation, but a convective lower bound is also included. If a water pool is in the control volume, all of the energy transfer from the molten fuel is used to boil water (no pool heatup, just boiling). If there is not a water pool in the control volume, material passes through FDI without any energy removal.

The model described in MAAP/FDI package would provide a consistent treatment of corium configuration, initial and end states of corium for various corium/water interactions.

4. CORIUM/CONCRETE INTERACTION

Corium/concrete interactions are modeled in two different subroutines in the MAAP/PWR code, namely JET and DECOMP. Subroutine JET treats the decomposition of concrete directly under the reactor vessel when attacked by a corium jet discharged from the reactor vessel. Subroutine DECOMP provides a general treatment of the decomposition of concrete by a molten or solid corium pool. DECOMP is the main subroutine used to model corium/concrete interactions, which could take place in the upper, lower as well as the cavity compartments. The MELCOR code does not have a model for concrete decomposition by direct jet impingement. However, MELCOR incorporates the CORCON-MOD2 model, which is equivalent to DECOMP in MAAP. Although DECOMP and CORCON both model the major phenomena related to corium/concrete interactions, there are significant differences in the assumptions and approximations used in the two codes.

4.1 JET

JET computes the transient ablation rate of the concrete floor in the cavity compartment due to direct contact with a jet of molten corium. The corium stream velocity impinging on the concrete surface is first determined. Knowing the corium velocity, a stagnation point heat transfer correlation is used to compute the heat transfer rate from the corium jet to the concrete, which in turn determines the concrete ablation and gas evolution rates.

Since both JET and DECOMP are used to model concrete decomposition, BNL expressed concern as to how the computational procedures used in the MAAP code for these two subroutines. In response to BNL questions, FAI provided the following description:[7]

> JET is called starting at vessel failure and until all the corium present in the vessel at failure has relocated to the containment, a duration of several seconds for high pressure failure to tens of seconds for low pressure failure.

JET uses the instantaneous flowrate out the failure and corium properties in the lower head. It assumes the debris exits as a stream and contacts the floor in this manner, whether or not water is present in the cavity, maximizing jet erosion.

DECOMP is called after corium contact with the floor and it assumes a pool of debris exists for heat transfer to concrete and to either overlying coolant or the surroundings. Thus, DECOMP could be called while JET is still being called and before entrainment occurs. A minimum debris mass must be present for DECOMP to be called, so after entrainment DECOMP may not be called until more melting in-vessel occurs.

The above description indicates that JET and DECOMP are treated independent of each other and could be called simultaneously. This treatment is an attempt to maximize concrete erosion but it could result in the same small area of concrete (that area in contact with the JET) being eroded in both subroutines.

BNL also raised questions about the presence of water in the cavity when subroutine JET is used.

Question:

Is the JET subroutine limited to the dry cavity situation? No water/corium interaction and jet break-up are modeled in this subroutine.

Answer:

JET is called during the initial corium release after vessel failure whether or not water is present. Jet erosion has no discernable impact on overall code results.

Depending on the jet length/diameter ratio, (i.e., the cavity depth and vessel lower head ablation hole size), hydrodynamic instability could cause the jet to breakup and prevent it from reaching the concrete floor. Thus, the JET model could be invalid for a flooded cavity configuration. Since the JET model does not appear to play a significant role in the overall results of the code, it is suggested that the subroutine be omitted (or modified) to avoid the inconsistencies discussed in this section.

4.2 DECOMP

MAAP assumes that corium/concrete interactions can occur simultaneously in more than one containment region. Hence, MAAP allows the DECOMP subroutine be called by the upper, lower and cavity compartments. In MELCOR, corium/concrete interactions are modeled in the Cavity Package (CAV), which allows an arbitrary number of cavities to be defined (100 are permitted by the input records format). At present, all MELCOR analyses utilize a single cavity for the purpose of modeling corium/concrete interaction. Thus the ability of MELCOR to model corium/concrete interactions in a multiple-cavity configuration has not yet been tested.

4.2.1 Molten Pool Heat Transfer

DECOMP assumes a homogeneously mixed molten corium pool. The concrete slag caused by the melting of concrete is assumed to enter the debris pool immediately and mix with the core debris. The homogeneously mixed model implies a single debris temperature, uniform pool heat convection in all directions, and equal thickness of the bottom and side crusts. (The top crust is treated separately.) The model also results in the same concrete temperature profiles and erosion rates in both sideward and downward directions.

In CORCON, a stratification model is assumed for the molten debris pool. It is assumed that the oxidic species and metallic species in the melt are mutually immiscible. Buoyancy forces are sufficient to separate the molten debris into two phases even in the presence of

vigorous mixing by gases from the decomposition of concrete. In addition to the two layers (metal/oxide), CORCON provides another oxidic layer on the top of debris melt. This less dense oxidic layer is composed of ablation concrete oxides and steel oxides produced by chemical reaction with the concrete-decomposition gases. However, the three-layer configuration (oxide/metal/oxide) is not predicted to last for a long time period. The bottom fuel oxide layer diluted by concrete oxides becomes less dense than the metal layer. At this point it is assumed that the bottom oxide layer moves above the metal layer and form a single oxide layer. The CORCON model predicts different temperatures in each of the layers in the molten pool, non-uniform heat transfer and non-uniform crust thickness in the sideward and downward directions. Consequently, the concrete decomposition and gas release rates are different in the downward direction than the sideward direction in CORCON.

The different assumptions used in the two codes gave rise to the question (and answer) given below:[7]

Question:

> In the DECOMP subroutine, two assumptions are used to compute the erosion rate of the concrete cavity in the downward and radial directions. The two assumptions are (1) no stratification in the molten pool, and (2) uniform heat transfer rate. Please explain the rationale behind these assumptions.

Answer:

> No stratification is assumed in DECOMP because:
>
> 1) When Zr is present, it is soluble in the oxides,
>
> 2) It is unclear whether layers would exist for gas velocities of interest when Zr

is oxidizing.

3) Heat transfer between the layers, if they exist, is highly effective and does not significantly alter the split between heat transfer to concrete versus the surroundings.

4) Chemical equilibrium should occur anyway. Briefly, we do not believe that stratification would have a significant impact on bottom-line results such as total concrete erosion and combustible gas generation.

Uniform sideward and downward heat transfer is assumed because heat transfer coefficients in either direction are nearly equal. The tough part of this problem is quantification of other heat transfer resistances: slag, crust, and gas. It is difficult to relate the unequal erosion observed in, for example, the BETA tests to a reactor case because 1) the height/diameter ratio is quite different, 2) the decay power will be in the oxide and not the metal and stratification may not occur. Thus, this simplification is employed. Ultimately, this assumption should lead to a conservative answer for structural degradation by sideward erosion since the model apparently overpredicts sideward erosion.

Besides the BETA tests, Sandia (the developer of the CORCON code) has cited other experimental evidence[9] to support the multiple-layer approach. The difference in heat transfer in the sideward and downward directions, as claimed by Sandia, is caused by the gas flow between the melt and the concrete. In the downward direction (i.e., on the concrete floor), gas is generated at the boundary and enters the melt; while on the side surfaces, gas forms a flowing film along the melt boundary.

In both DECOMP and CORCON, a quasi-steady model is used for heat transfer calculations. The model assumes that the debris pool temperature adjusts rather quickly so that the internal heat generation balances the heat losses. In DECOMP, the convective heat

loss from the molten debris to its peripheral crust is determined by a user-specified heat transfer coefficient, i.e., model parameter No. 12 HTCMCR. The best estimate, recommended minimum and maximum values are 1000, 500 and 5000 W/m^2-K, respectively. This heat transfer is equal in downward, upward and sideward directions. In CORCON, the multi-layer model permits the code to compute separate temperatures for each layer. The heat transfer to the upper, bottom and side surfaces are computed by different correlations. The presence of bubble agitation is included in the heat transfer correlations. It appears that the CORCON heat transfer model should provide a better estimate of debris temperature than DECOMP. Note that fission product release is strongly affected by the debris temperature.

4.2.2 Effect of Water Layer

Both the MAAP and MELCOR codes allow for a water layer on top of the debris pool in the DECOMP and CORCON subroutines. This water layer is assumed not to interact energetically with the molten materials but rather it serves as an additional heat sink. The presence of a water pool is predicted to cool the top of the melt below the solidification temperature, resulting in a thin solid crust on the surface.

In DECOMP, the corium/water interaction is determined in subroutine PLSTM as discussed in Section 3 of this report. The model assumes that the debris crust in contact with water will crack and allow water ingression. In CORCON, the possibility of crust cracking and water ingress are not modeled. The overlying water pool is modeled only as a heat sink. The heat transfer model in CORCON includes the full boiling curve based on standard pool boiling correlations. No correction is made for the effects of gas injection at the melt/water interface. The water pool as modeled in CORCON does not have a significant influence on the attack of concrete by the core debris.

4.2.3 Corium/Concrete Contact and Heat Conduction in Concrete

One of the large differences between the DECOMP and CORCON models is the treatment of heat transfer at the corium/concrete interface and within the solid concrete. When core debris attacks the concrete, solidification of the melt and melting of the concrete occur at the interface. A thin thermal layer penetrates the solid concrete, within which the complex decomposition reactions take place.

In DECOMP, a direct contact between the core debris and concrete is assumed. The interface temperature of the debris crust and the concrete is equal to the concrete surface temperature, which is the concrete ablation temperature. (DECOMP assumes that concrete melting begins instantaneously upon contact with molten debris.) A one-dimensional heat conduction calculation is performed by subroutine HTWALL for temperature profiles in the solid concrete. Because the heat flux and temperature profiles are the same in both the downward and sideward directions, the erosion rate is also the same in these directions.

CORCON assumes that a stable gas film forms upon initial contact between the molten core debris and concrete. The concrete is separated from the debris by a gas film. The gas film model was modified in CORCON-MOD2, which is the version used in the current version of MELCOR. It is believed that under most conditions, gas release is usually far less than that required to form a stable gas film, and instead, intermittent debris/concrete contact occurs. Therefore, an interface temperature model was implemented in the CORCON-MOD2 code to describe heat transfer at the interface between the core debris and the concrete. The interface temperature predicted by CORCON is closer to the debris temperature than to the concrete surface temperature due to the higher thermal conductivity of the core debris.

The CORCON interface model also included the melting of the concrete and solidification of the core melt. The concrete slag is removed from the interface into the core melt by the rising bu[illegible]gas film model has been retained in the code but is only invoked when the gas [illegible]sufficiently high.

CORCON does not consider heat conduction into the concrete nor the decomposition in advance of the ablation front. Only one-dimensional steady-state ablation is computed.

4.2.4 Solid Pool Treatment

Both DECOMP and CORCON allow the formation of a solidified pool when the crust thickness fills the entire pool. In DECOMP, the treatment of heat transfer in a solidified pool is similar to that in a molten pool. The same heat conduction is calculated for both the side walls and the lower bottom wall resulting in equal erosion in these walls.

The equal concrete erosion model in DECOMP is also not applicable to a solidified debris pool. Because of the rigid debris surfaces, the molten concrete and released gases are likely to form a film between the debris and the uneroded cavity sidewalls. This film represents an additional thermal resistance and would reduce the sidewall erosion rate. Furthermore, the newly eroded concrete will not be able to mix with the rest of the debris and will probably be pushed to the top of the debris where it will form a growing crust. Since the concrete slag crust contains no internal heating, it provides a more effective insulating barrier to upward heat transfer. The insulation effect will influence the internal heat transfer in the solid debris pool. These phenomena are omitted in the DECOMP model. CORCON does predict a top oxide layer which is a mixture of core and concrete oxides and is thus internally heated. This treatment developed for a molten pool is not valid for a solidified pool.

Another important feature related to solidified debris is the mixing and stratification during the transition between molten and solidified debris. DECOMP assumes gross mixing while CORCON assumes stratification. For a conduction-limited solid debris, the most important property that affects the heat transfer process is the thermal conductivity. Since thermal conductivity for the metallic and oxidic phases are at least an order of magnitude different from one another, the difference plays an important role in debris heat transfer. In the CORCON stratification model, the metallic layer has higher thermal conductivity but a

lower decay power source. Hence the metallic layer may solidify while the oxidic layer remains molten. The potential for a partially solidified layer and a molten layer can not be modeled by DECOMP.

4.2.5 Chemical Reactions

In DECOMP, the various oxidation processes are computed in a serial manner, i.e., the Zr/H_2O, Zr/CO_2, Fe/H_2O and Fe/CO_2 reactions are computed sequentially. The steam and CO_2 released from concrete decomposition are first used for the Zr reaction. Iron oxidation begins after the completion of Zr oxidation. Potential oxidation of chromium, a constitute of stainless steel, is omitted.

In MELCOR, the chemical reactions are calculated using the latest version of the chemical equilibrium routine developed for CORCON. An entropy of mixing term is included in the chemical potential of each condensed-phase species. The principal effect is to eliminate the strict sequential oxidation of metallic species as in the DECOMP model. Chromium oxidation is included in MELCOR.

5. COMBUSTION

MAAP models three types of combustion: global (complete), local (incomplete) and continuous burns. A global burn involves the burning of all combustible gases in a compartment. A local burn is initiated by deliberate ignition systems (i.e., igniters) and involves only a fraction of the gas volume in a compartment. The ignition of hydrogen-laden jets is modeled as a "continuous" burn in the MAAP code. This type of burn refers to those circumstances when a very high temperature jet emerges from a potentially inerted region into a cooler, non-inerted region and induces a burn in that region. For example, a hot hydrogen-steam mixture could enter the containment auxiliary building during an interfacing system LOCA (ISL) and cause a hydrogen burn in the auxiliary building. Another example is the entering of a hot hydrogen-steam jet from the reactor cavity region into the containment lower region.

The combustion mode modeled in the MELCOR code is denoted as discrete burn which refers to the burning of combustible gases uniformly in a compartment only after prescribed ignition or propagation criteria are met.

5.1 Ignition Criteria

In the MAAP 3.0B code, the flammability limits are determined by the construction of a combustion diagram. The domain of the diagram consists of both lean and rich flammability limits (LFL and RFL). A power law expression is developed for the flammability limit curve. The flammability limit curve is further modified for elevated temperatures. Limited experimental results have shown that elevated temperatures tend to cause the LFL to decrease and the RFL to increase. The flammability limit curves at various temperatures are used in the MAAP code for upward and downward flame propagations. The upward flame propagation limits are used for the local (incomplete) burn mode, and the downward flame propagation limits are for the global (complete) burn mode. At elevated temperatures, a very small fraction of hydrogen is required to induce a flame propagation.

This situation leads to autoignition model in the MAAP code. The autoignition model assumes that ignition occurs if the mixture temperature is above a critical autoignition temperature (Model parameter No. 71) and the inertant fraction is less than a specified value (Model parameter No. 72). The nominal autoignition temperature is 983K and maximum inerting fraction is 0.75 in the MAAP code.

MAAP code also applies an ignition criterion when igniters are present and active. The flammability limits discussed for upward flame propagation are not alternated when igniters are presented. However, the ignition criterion specified as a mole fraction of hydrogen above (or below) the temperature and steam concentration dependent limits, is an offset to the downward flammability limits. The user-specified ignition criterion is Model parameter No. 73, and the recommended value is zero.

The ignition of hydrogen-laden jet is determined by comparing the gas stream temperature with the user-specified autoignition temperature TJBRN (Model parameter No. 60). If the gas is hotter than TJBRN, the jet is burned as it enters the noninerted compartment if sufficient oxygen is available in the compartment. The recommended value for TJBRN is 1060K.

The ignition and propagation criteria used in the MELCOR code are based on experimental data determined in steam-saturated air at relatively low temperatures and pressures. The criteria are:

a. oxygen mole fraction ≥ 0.05,

b. inertant (steam and CO_2) mole fraction ≤ 0.55, and

c. combustible gas mole fraction must be

$$X_{H_2} + \frac{A}{B} X_{CO} \geq A$$

where

	A	B
Ignition Limits	0.07	0.129
Propagation Limits		
Upward	0.041	0.125
Horizontal	0.06	0.138
Downward	0.09	0.15

The above ignition limits are appropriate when modeling accident sequences with igniters operating. Without igniters, the ignition limits are higher. The MELCOR code increases the ignition limits to A = 0.1 and B = 0.167 for cases in which the igniters are not operating. The propagation limits shown above depend on the spatial relationship of two compartments (i.e., whether the adjacent compartment is located above, below or on the same level as the burning compartment). The concentration limits specified for propagation apply to the adjacent compartments, not the compartment in which the burn originates. The low concentration limit in the upward direction implies that the upward flame propagation is much easier due to the buoyancy force. The criterion for downward propagation implies that the compartment could spontaneously ignite before downward propagation would occur.

In comparison, the MELCOR ignition model is relatively simple; its flammability limits are independent of temperature and inertant fraction if the inertant fraction is less than 55%. The MAAP ignition model requires the flammability limits to be determined by the flammability diagrams which depend on both temperature and inertant fraction. Since both models are empirical and there is only limited experiments at elevated temperatures, the validity of MAAP model and the applicability of the MELCOR model at elevated temperatures must be determined.

It is noted that neither MELCOR nor MAAP model a hydrogen detonation. However, in

the MELCOR code, a warning message that a detonation is indicated in a containment compartment is written out in computer printout, if the following conditions are satisfied:

Molar fraction of H_2 > 0.14

Molar fraction of O_2 > 0.09

Molar fraction of steam < 0.30

The consequence of a hydrogen detonation is not modeled in the code.

5.2 Burn Time and Combustion Completeness

The burn time and combustion completeness are key parameters that determine the quantity of hydrogen reacted and the combustion rate, which in turn determine the energy release rate and containment pressurization rate. In MAAP, the burn time and combustion completeness are obtained by solving the mass and momentum equations for a fireball. MAAP assumes that the spherical fireball expands at the laminar flame speed when buoyancy effects are small. When the fireball is large, its growth is modeled as a plume entraining unburned gases at a rate proportional to its upward velocity. The upward velocity is determined by considering the acceleration of the fireball due to the buoyancy and drag forces. The analytical model involves several parameters, such as entrainment coefficient, laminary flame speed, fireball surface area and drag coefficient. The uncertainties in these parameters are covered by a user-specified flame flux multiplier, model parameter No. 74 FLPHI. The recommended best estimate, minimum and maximum values of the flame flux multiplier are 2, 1 and 10, respectively.

The flame speed correlation used in MAAP is a function of the initial molar fraction of combustible gases (H_2 and CO), the initial molar fraction of diluents (steam and CO_2) and temperature. A graphic presentation of the flame speed at 100°C is given in Figure 5.1.

The flame speed increases linearly with an increased hydrogen fraction, and decreases with an increased steam fraction. Under the expected conditions, the laminar flame speed is generally less than 1 m/s. The correlation is based on the WNRE (Whiteshell Nuclear Research Establishment) experimental data. The experiments covered a hydrogen concentration range of 18% to 65%, steam concentration up to 15% and a temperature range of 25°C to 250°C. It is apparent that the experimental condition does not correspond to the expected containment conditions during accident. A PWR containment is predicted to have a much lower hydrogen concentration and a much higher steam concentration. Furthermore, a turbulent, rather than a laminar, condition is expected in the containment, if sprays and fans are operated.

MELCOR does not model hydrogen combustion as a flame front, instead, it assumes hydrogen burns uniformly in a compartment. Thus, during a burn, a compartment will consist of a homogeneous mixture of burned and unburned gases. The flame speed and combustion completeness are determined by empirical correlations which are derived from a variety of experiments that were performed in the Variable Geometry Experimental System (VGES), Fully Instrumented Test Series (FITS) and at the Nevada Test Site (NTS). No analytical solutions are involved in MELCOR combustion model. The flame speed correlations used in the MELCOR code are functions of the initial mole fraction of diluents and the initial mole fraction of combustible gases. The correlation does not depend on temperature. A graphical presentation of the flame speed is given in Figure 5.2. The flame speed increases linearly with an increased hydrogen fraction, and decreases with an increased steam fraction. For a steam fraction between 20% and 40%, the flame speed is below 5 m/s. Comparison of Figure 5.2 with Figure 5.1 shows that the flame speed predicted by MELCOR is an order of magnitude higher than that predicted by MAAP. This indicates that the empirical correlation used in MAAP is for flame speeds in the turbulent region.

In the MELCOR code the burn time is calculated as the ratio of a characteristic length to the flame speed. The default value of the characteristic length (i.e., flame travel distance)

is the cubic root of the compartment volume. Using the two characteristic lengths of 40 m and 15 m, which correspond approximately to the heights of the upper dome and steam generator compartment, respectively, of the Zion plant, burn times are computed as shown in Figure 5.3. The burn times vary from a few seconds to about 3 minutes depending on the volume size and initial hydrogen concentration.

In MELCOR, the final mole fraction of combustible gases is determined by the combustion completeness model which uses empirical correlations. Combustion is assumed to be complete for combustible gas concentrations at or above 8%. The final combustible concentration may never be reached if the burn is oxygen limited.

Since the burn time and combustion completeness of the MAAP code are obtained by solving the continuity and momentum equations and the solutions are not available, no comparisons with MELCOR results are presented.

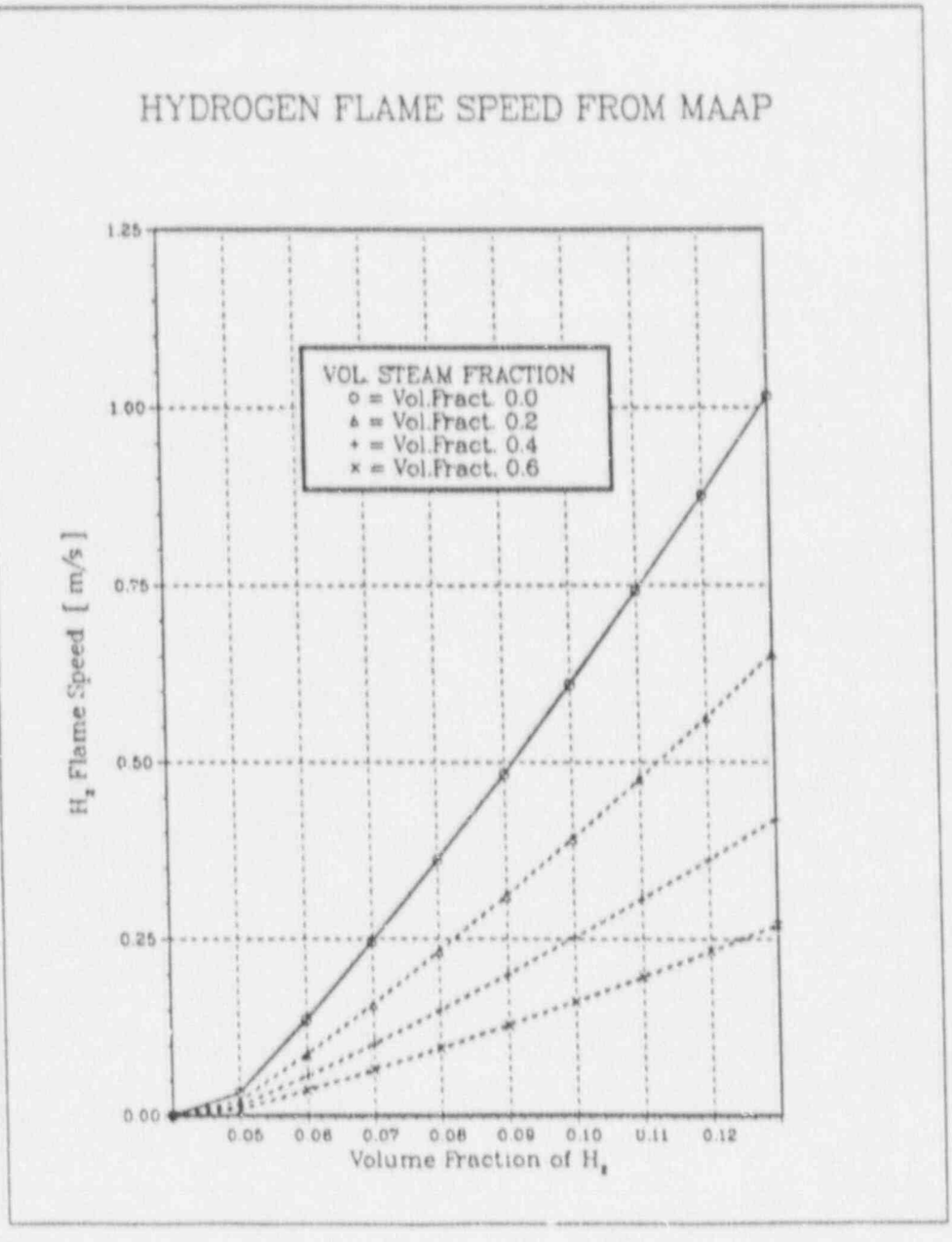

Figure 5.1 MAAP Predicted Flame Speed

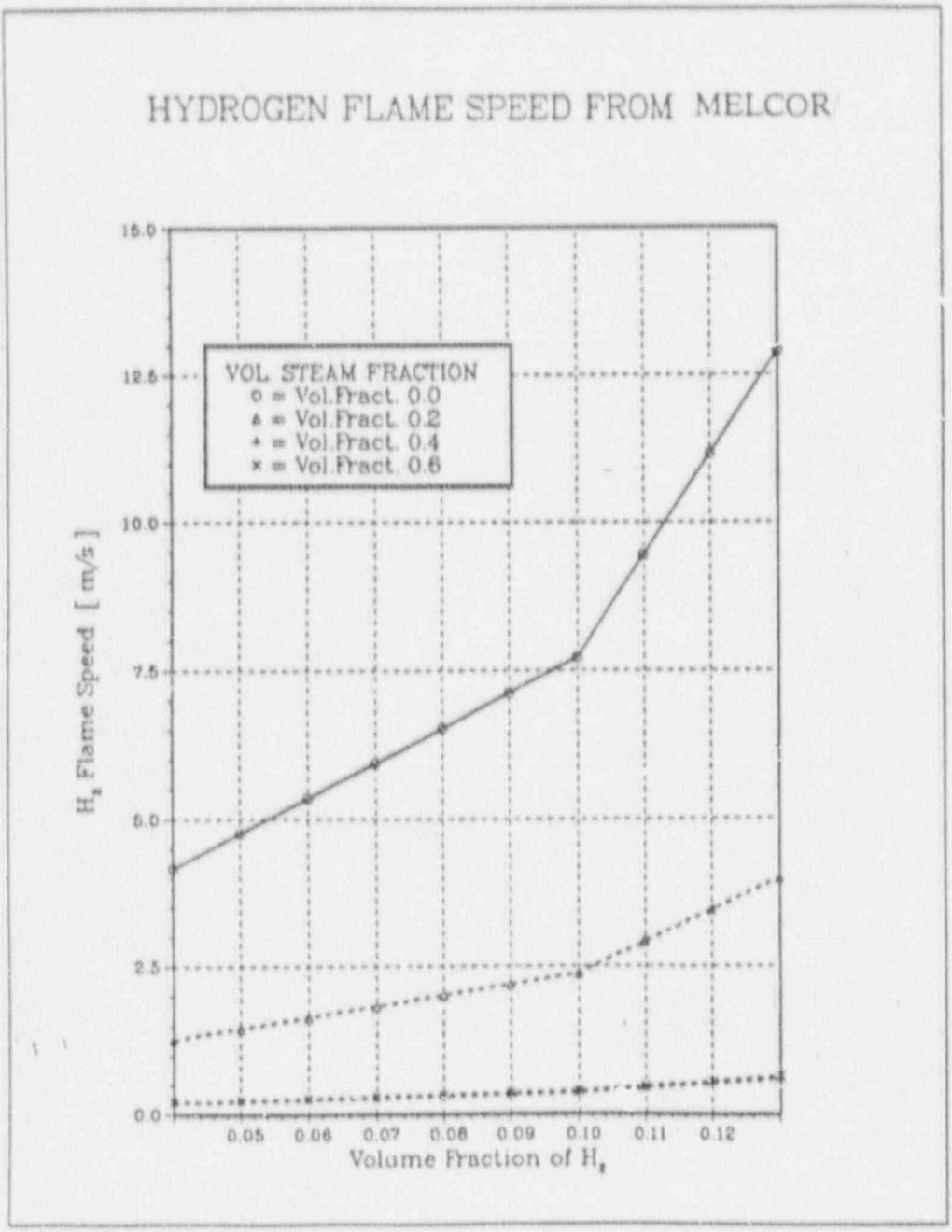

Figure 5.2 MELCOR Predicted Flame Speed

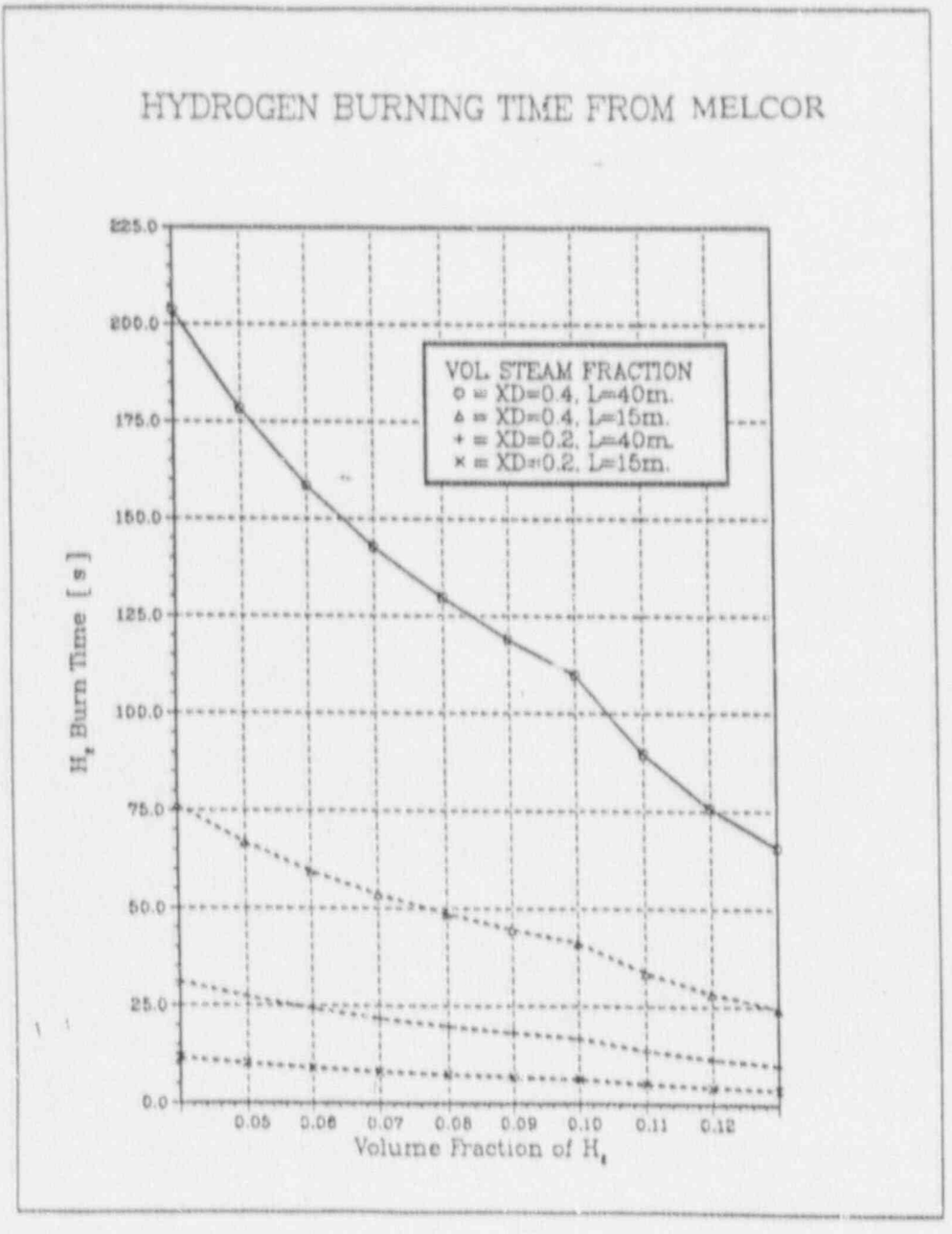

Figure 5.3 MELCOR Predicted Burning Time

6. DIRECT CONTAINMENT HEATING (DCH)

In certain reactor accidents, degradation of the reactor core can take place while the reactor coolant system remains pressurized. In these accidents, molten core debris will relocate to the bottom of the reactor vessel and will start attacking the bottom head of the reactor. When the bottom head of the reactor vessel is breached, the core debris will be ejected under pressure. The ejected materials are likely to be dispersed out of reactor cavity as fine droplets, quickly transferring thermal energy to the atmosphere. In addition, the metal components of the ejected core debris, mostly zirconium and steel, can react with oxygen and steam in the atmosphere to generate a large quantity of hydrogen and chemical energy. This complicated physical and chemical process is known as direct containment heating and may be a significant source of containment pressurization.

MAAP modeling of the DCH process is highly parametric. The flow rates of water, steam and zirconium entrained from the cavity are adjusted for chemical reactions and heat transfer. The thermal and chemical equilibrium of corium entrained out of the cavity with water and gas is assumed. MAAP does not model the oxidation of steel and the highly exothermic reaction of Zr with the oxygen in the containment atmosphere. The Zr/O_2 reaction is particularly important for the upper compartment which is rich in oxygen.

The conditions inside the reactor vessel at the time of vessel failure are very important to the extent of containment pressurization due to DCH. These conditions are determined by the accident sequence and the in-vessel meltdown progression of the core. The kind of information needed to predict the magnitude of DCH are the reactor pressure vessel (RPV), bottom head failure size, the melt mass available for release as well as its temperature and composition, the amount of hydrogen/steam dissolved in the melt, available water mass in RPV, the reactor coolant system (RCS) pressure and the amount of hydrogen in the RCS at the time of vessel failure. The MAAP modeling of some important phenomena such as entrainment/deentrainment are overly simplified and are not physically based. In addition, the DCH subroutine is not called by the CCOMPT subroutine. It appears that DCH is not

modeled for the cavity region.

At the second MAAP familiarization meeting, BNL requested explanations for some aspects of DCH modeling in MAAP. NUMARC has responded to BNL concerns. The question and answer are given below:

Question:

> Please explain why iron oxidation is not included in the MAAP DCH model. BNL analysis has shown that hydrogen generation and energy release due to the oxidation of iron are important parts of the DCH loading.

Answer:

> Iron oxidation is not modeled for several reasons. First, there is little iron in the melt (though this is in part based on user input). Second, while Zr is present in the debris, Fe oxidation will be quite limited. Thus, MAAP assumes Zr oxidation occurs before Fe oxidation. If all the Zr can react, then some Fe may also react, and its relative importance would be related to the amount of Fe present. Since MAAP assumes that little Fe is present, its impact would be small. Steel is added as debris relocates from the core to the lower plenum. The core plate mass available by user input is perfectly ablated at a rate that would remove debris energy above the steel melt point in order to heat the support plate from saturation to melting. Thus, a realistic upper bound to steel addition by this energy balance is computed.
>
> Control material and fission products are added to the mass of debris in the lower plenum as debris leaves the core region, so these are released at vessel failure with the bulk debris. Move of these materials is performed in subroutines HEATFP (melting rate from the core) and PSFP (addition rate to the lower plenum).

The exclusion of Fe oxidation based on the assumption of Fe mass will limit the application of MAAP code. The mass of iron should depend on the accident sequences. The present version of MELCOR code does not have a DCH model and, hence, no comparison can be made.

7. CONTAINMENT SAFEGUARD SYSTEMS

7.1 Containment Sprays

MAAP models containment sprays for the upper and lower compartments. Sprays are not allowed in the annulus region. The code assumes that droplets enter the compartment at an effective height at the terminal velocity and drift downward until either they evaporate or strike a water surface. MAAP does not allow droplets to be carried over to a lower compartment. Using the user-specified nozzle height, initial droplet size, flow rate and temperature, MAAP computes mass and heat transferred from the droplets to containment atmosphere. If the droplets enter at a cold temperature below the dewpoint, moisture in the containment atmosphere will condense on droplets. Droplets can be heated up in the atmosphere and begin to evaporate if the temperature is higher than the dewpoint. The heat and mass transfer by condensation, evaporation and convection are computed by empirical correlations. Only one droplet size can be specified by the user.

In MELCOR, the containment sprays can be modeled in any control volume (i.e., containment compartment) and be carried over to a lower compartment or collected in the containment spray sump. Droplets reaching the bottom of a control volume and not being carried over to other volumes or placed in the sump are put into the pool of the control volume. A droplet size distribution and frequency may be input for every spray source. A maximum of 5 sizes can be specified. Empirical correlations are also used to estimate the heat and mass transfer between the droplets and containment atmosphere.

The MELCOR model is more flexible than MAAP in the treatment of spray source volume, droplet size distribution, and carry over to a lower volume. However, it is expected that differences in the spray models of the two codes will not have a significant effect on the containment thermal-hydraulics, but will affect fission product transport in the containment, particularly due to the treatment of droplet size distribution.

7.2 Fans

MAAP allows the circulation of air by fans from the upper compartment to either the lower compartment or the annulus region. The flow rate and energy transport rate are computed by mass and heat balance. Cross flow and finned tubes are assumed for the fan cooler. The detailed heat and mass transfer calculations involve film-wise condensation on the cooler outer surface, thermal resistance through the tube wall, and convection in the co-current internal flow.

In MELCOR, the suction and discharge of the air flow can be specified separately for any control volume. Heat and mass transfer are also computed for the heat exchangers. Although the details of computation are different from the MAAP code, the general approach of using the conservation laws are similar.

The impact of containment spray and fan models used in the two codes will be evaluated as part of the code comparison exercise.

8. CONTAINMENT FAILURE MODEL

In the MAAP code, the containment failure area and location are user-specified. Failure can occur either in the upper compartment or the annulus region. There are two models which can initiate containment failure. A simple failure model uses a user-specified pressure or temperature as the failure criterion. A more detailed model involves stress and strain analysis. In this model, the containment wall is divided into 3 regions: liner, tendons and rebar. Initially, the elastic deformation due to the containment internal pressure rise is computed. After the yield stress is exceeded, the calculation uses a plastic deformation model. Containment failure is assumed when the resultant stress equals the ultimate stress. The failure is considered as "leak-before-break" if the initial failure is in the liner. The failure is referred to as global failure if the initial failure is in the rebar or tendons. Local failure of a penetration is also considered. The detailed model is obviously more advanced than the simple model. However, no analysis was performed to compare the failure time predicted by the two models. It is not known which model would predict later failure. The failure time is important for fission product transport and offsite consequence analyses. For the IPE applications, a criterion must be provided for the selection of the two models.

MELCOR uses control functions to simulate containment failure. Failure can be initiated by the user-specified pressure, temperature or time. Failure area and location are also user-specified. The control function is equivalent to the simple model available in the MAAP code.

9. AUXILIARY CONTAINMENT

The auxiliary containment model is a new addition to the MAAP code. It is very important for the analysis of containment bypass events. The model does not use the approach of fixed nodalization and pre-defined circulation loop approach used in MAAP for the primary containment. Instead, a node and junction type model was constructed which allows the user to specify the number of control volumes and the number of junctions. A maximum of 9 and 50 are allowed for the control volume and junction, respectively. Multiple junctions, both vertical and horizontal, are allowed for each control volume. The model calculates forced, unidirectional and counter-current natural circulation flows passing through these junctions. Thus, the MAAP model is attempting to treat a very complex flow situation in a multiple region system.

For each control volume, thermal hydraulic properties and the rate of change of these properties are computed. Most of the phenomena which could occur in the primary containment are accounted for, such as combustion, sprays, heat transfer to walls, flashing and rainout, etc. However, it is noted that the model does not include any metal equipment as potential heat sinks in the auxiliary building, i.e., the subroutine HTEQPT is not called.

The most important part of the model is the determination of flow patterns. Three flow patterns are developed: the unidirectional flow (Bernolli flow), purging flow and the counter-current flow. For any junction, a comparison of the three flow rates is made. The Bernolli flow is used for junctions where it exceeds the purging flow. Otherwise, the counter-current flow is used. The Bernolli flow is derived from a simple force balance and is based on the assumption that the gas density is uniform in the control volume, i.e., no stratification in the compartment. The model will introduce some error for situations in which a large temperature and/or concentration variation result in a large density variation. The other two flow models, purging flow and counter-current flow, are derived from empirical correlations.

The experimental base on which the flow models were developed involves a small scale test apparatus. The test tank is 0.55 in square and 0.762 in deep. Salty water and fresh water were used to create the density-driven flow through the small openings in the partition located in the tank. The test tank is essentially a two-volume system. The ratio of density difference to the average density is between 0.024 and 0.17. For ideal gases, the corresponding temperature difference will be in the range of 10 to 68 K for an average temperature of 400 K. This example illustrates the auxiliary building condition at which the empirical correlation could be applied. Of course, other factors, such as geometric scale, multiple volumes, fluid properties and the partition and opening configurations, must be considered in order to test the validity of these empirical correlations.

It should also be pointed out that the experiments used a single-phase fluid (water) in an idealized quasi-steady condition. In the auxiliary building, the atmosphere is expected to contain a large fraction of steam which will condense. In addition, other processes, such as sprays and combustion, could occur in the building. (A hydrogen burn will create a temperature difference much larger than that used in experiments.) Since physical situations in the auxiliary building will be different than the idealized condition employed in the experiments, a scaling study is needed to verify these empirical correlations.

MELCOR using the control volume concept can model the auxiliary building in a similar manner to the primary containment. MELCOR does not have a model which can treat counter-current flow in a junction.

10. ICE CONDENSER PLANT

The compartment nodalization and flow circulation loop of an ice condenser containment have been discussed in Section 2 of this report. MAAP considers the ice condenser as a heat sink for pressure suppression. A simplified model is used to treat the steam condensation and ice melting. The following are the major assumptions used in the model:

1) Ice condenser heat transfer is fully effective and is not degraded until all the ice is melted. The presence of condensate film on heat transfer surface area and the decrease of surface area due to ice melting are ignored.

2) The temperature of steam-air mixture exiting the top of the ice condenser compartment is constant independent of flow conditions. BNL has requested the implications of the constant exit gas temperature. The question and answer are given below:

Question:

In the HICE subroutine, the exit gas temperature is fixed at 100°F. A fixed exist temperature implicitly determines the ice melting rate. What is the range of flow rate within which the assumption of a fixed exit temperature is valid? Is the fixed exit temperature adequate during a very low or high primary system blowdown rate or under conditions where hydrogen burn occurs in the upper plenum?

Answer:

The ice condenser exit gas temperature is set to 100°F to reflect experimental data for high blowdown flow rates. Since the ice melting rate is determined by the steam condensation rate, it is relatively insensitive to selection of a

lower exit temperature, which could result from lower flow rates. That is, the steam mole fraction at 100°F is roughly 5%, whereas its mole fraction would be considerably higher on entry, so that nearly all the steam is already condensed by the model. Therefore, reasonable variation in this exit temperature for lower flow rates would have negligible impact on the ice melt time. It is worth noting that the temperature of the condensate as it exits the ice condenser is assumed equal to the average of the inlet and outlet saturation temperatures (the latter is the exit gas temperature). The sensitivity of the melting rate to this assumption is also believed to be small.

3) The grid and structures used to hold up the ice blocks are not considered as heat sinks. The ice-condenser compartment will not play any role on containment response after the ice is completely depleted.

4) Flow area of the junction between the ice condenser and upper plenum compartments is a function of flow direction. The flow area representing the intermediate deck doors will close if flow reverses. A bypass area which is provided in the design to equalize pressure difference will open. This is modeled by multiplying the normal forward-direction flow area by a user-specified factor when flow reverses. This treatment is also applied to the fan dust dampers.

5) Combustion of hydrogen and carbon monoxide is allowed in the upper planum. However, the event of ice condenser bypass due to the failure of upper plenum caused by combustion can not be modeled by MAAP.

6) Boiling of water pool at the bottom of ice condenser by the dissolved fission product and the decay heat in the gas phase are modeled in MAAP.

Based on the above description, it appears that the simplified model may result in some uncertainties on the predicted steam condensation rate and ice melting rate. The uncertainties should be assessed by sensitivity studies. The lack of flexibility to model the ice condenser bypass event must be solved. The ice condenser bypass event is an important issue as reported in Reference [10].

The present version of the MELCOR code does not have an ice condenser model. Hence, no comparison can be made.

11. SUMMARY

Based on this preliminary review, it appears that the MAAP code can represent containment buildings and important related phenomena reasonably well. Some models contain parameters which allow the user to perform sensitivity studies. The following are specific comments, which have been discussed in more detail in this report:

1) The fixed nodalization and pre-defined circulation loop for the primary containment are restrictive, particularly for an analysis of hydrogen distribution in the containment. The present code structure does not allow a user to identify the potential for a localized detonation, which is potentially an important issue affecting PWR containment performance during severe accidents. It is suggested that the nodalization scheme developed for the auxiliary building be applied to the primary containment.

2) MAAP restricts the number of phenomena that can be modeled in certain containment compartment. For example, sprays, DCH, corium/concrete interaction, and metal equipment heat sinks are not allowed in the annulus compartment. This restriction should be removed.

3) Various corium/water interactions are treated independently and inconsistently by several subroutines (EXVIN, ENTRAN, PLH2 and PLSTM) to maximize the steam production. The excessive steam generation will increase the containment inertness and reduce the potential for combustion. In addition, an over-estimated corium/water reaction results in over cooling of the core debris. It is suggested that these subroutines be modified to provide a consistent treatment of the corium/water interaction.

4) The logic for calculating concrete decomposition by subroutine JET is not consistent with subroutine DECOMP and the corium/water interaction

subroutines (EXVIN, ENTRAN, PLH2 and PLSTM). JET does not play an important role in the overall results of containment performance, it is suggested that this subroutine be either removed or modified.

5) In the treatment of corium/concrete interaction, there are four major differences between the subroutines DECOMP (MAAP) and CORCON (MELCOR): melt stratification, corium/concrete contact at interface, sideward and downward concrete erosion, and heat conduction in the solid concrete. These differences will affect the containment performance (such as combustion, pressurization rate and basmat melt-through) and the fission product release and transport in the containment. The two subroutines must be examined carefully by the code comparison exercise.

6) For hydrogen and CO combustion, the differences between the MAAP and MELCOR treatments are the ignition criterion, burn time and combustion completeness. MAAP relies on an analytical model and MELCOR uses empirical correlations. The impact of the differences must be identified by the code comparison exercise. Hydrogen combustion is an important issue for the PWR dry containment as is considered by the NRC Generic Issue GI 121 [11]. The code predictions would affect the proposed hydrogen control in the PWR dry containment.

7) The MAAP modeling of some phenomena important to DCH such as entrainment/deentrainment are overly simplified and are not physically based. Furthermore MAAP does not consider the oxidation of steel and the highly exothermic reaction of Zr with the available oxygen in the containment atmosphere. It is suggested that the MAAP code be modified to include these reactions.

8) MAAP appears to have an adequate treatment of containment sprays and

fans. However, in comparison with the MELCOR code, the restriction of spray source compartment and spray droplets size distribution imposed by MAAP may have some impact on the fission product transport in containment.

9) The detailed containment failure model based on the strain-stress analysis is a good addition to MAAP. Comparison of the containment failure time predicted by the detailed model and the simple pressure/temperature failure model should be made. A criterion for the selection of failure model should be provided for the IPE studies.

10) The detailed treatment of auxiliary building is a good addition to MAAP code. The auxiliary building model is important for the containment bypass events. Since the model uses empirical correlations to predict the counter-current flow between various compartments, its applicability to containment system must be verified. The experiments employed small, two-volume test apparatus under simplified conditions. The effects of large, multiple-volume with multiple flow paths under conditions of potential hydrogen combustion and steam condensation should be considered.

11) The simplified ice-condenser model is probably adequate for heat transfer caiculation. However, MAAP does not allow a user to model the ice-condenser bypass event, which has been identified as one of the important issues for a ice-condenser plant. It is suggested that the MAAP code be modified to allow the modeling of the ice-condenser bypass event.

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