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MELCOR ANALYSES OF SEVERE ACCIDENT SCENARIOS IN OCONEE, A B&W PWR PLANT[*]

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ABSTRACT

This paper presents the results and insights gained from MELCOR analyses of two severe accident scenarios, a Loss of Coolant Accident (LOCA) and a Station Blackout (TMLB) in Oconee, a Babcock & Wilcox (B&W) designed PWR with a large dry containment, and comparisons with Source Term Code Package (STCP) calculations of the same sequences. Results include predicted timing of key events, thermal-hydraulic response in the reactor coolant system and containment, and environmental releases of fission products. The paper also explores the impact of varying concrete type, vessel failure temperature, and break location on the accident progression, containment pressurization, and environmental releases of radionuclides.

INTRODUCTION

MELCOR is a fully integrated computer code, being developed for the U.S. Nuclear Regulatory Commission (NRC) by Sandia National Laboratories (SNL), that models all phases of the progression of severe accidents in light water reactor (LWR) nuclear power plants.[1] The code has been developed to the point where integrated calculations of some severe accident sequences in both boiling water reactors (BWRs) and pressurized water reactors (PWRs) can be completed. BWRs analyzed using MELCOR include LaSalle, Grand Gulf, Peach Bottom, and Muhleberg, all GE designs; PWRs analyzed until this study include Surry, Zion, and Beznau (all Westinghouse designs). Brookhaven National Laboratory (BNL) has a program sponsored by the NRC to verify and apply MELCOR to severe accident analyses for several LWR plant types.

This paper presents the results from MELCOR analyses of two accident scenarios, a LOCA and a Station Blackout (denoted as TMLB in WASH-1400), in Oconee, a B&W designed PWR with a large dry containment,[2] and comparisons with STCP calculations of the same sequences.[3] The LOCA sequence is initiated by a pipe break about 3 inches in diameter in the RCS piping. The high pressure and low pressure injection systems of the emergency core cooling system fail; therefore, the RCS inventory cannot be maintained. Core meltdown occurs at low RCS pressure. The engineered containment safety systems are also assumed to fail, leading to containment failure late in the accident sequence due to long-term generation of steam and non-condensable gases from core-concrete interactions. The TMLB sequence is initiated by a loss of offsite power with a loss of the power conversion system, followed by failure of the onsite emergency power. The emergency feedwater system and the high head auxiliary feedwater system also fail, preventing a supply of feedwater to the steam generators. The feed and bleed method for establishing decay heat removal fails, leading to boil-off of the RCS inventory. Core meltdown occurs at high RCS pressure. These sequences are representative of sequence classes that have often been determined to be important contributors to the risk from severe accidents in PWRs.[4,5]

MELCOR calculations were carried out to 61 hours for the LOCA sequence and 53 hours for the TMLB sequence. The results include predicted timing

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of key events, pressure and temperature histories in the reactor coolant system and containment, hydrogen production, evolution of steam and non-condensible gases from core-concrete interactions, and environmental releases of fission products.

The results of some sensitivity calculations with MELCOR are also presented, which explore the impact of varying concrete type, vessel failure temperature, and break location, on the accident progression, containment pressurization, and environmental source terms.

MELCOR PLANT MODEL

The Oconee plant is modeled for MELCOR, as shown in Figure 1, with 24 control volumes, 33 flow paths, and 78 heat structures. The reactor core is nodalized into 14 axial segments and 3 radial rings. Levels 3 through 14 comprise the active core region, and levels 1 and 2 are in the lower plenum. The core plate is in level 2. The current Oconee model uses simplified nodalization of the steam generator secondary side. Also, the pressurizer SRV and PORV valves discharge directly into containment. Each Oconee cold leg is modelled using 2 separate control volumes and structures, and 2 parallel flow paths. The operation of core flooding tanks and internal vent valves is also modeled.

The containment is assumed to fail in the annular compartment at a pressure of 160 psia (1.103 MPa) with a break area of 7 ft^2 (0.65 m^2). Both these values are consistent with STCP assumptions. Containment leakage is also modeled, based on information from the FSAR that the maximum leak rate at 59 psig pressurization is 0.25% of containment volume per day. The impact of this leakage on containment pressurization and environmental releases was found to be negligible. MELCOR does not currently model direct containment heating (DCH), hence, while there is a rapid increase in pressure upon vessel failure, the increase is not as dramatic as would be calculated by a DCH model. Vessel failure is triggered by a user specified threshold temperature, with a default value of 1273.15K. The physical basis for this default value is provided later under "SENSITIVITY CALCULATIONS."

RESULTS AND COMPARISONS WITH STCP

For the MELCOR calculations, the maximum allowable timestep was gradually allowed to grow, to a maximum of 7 seconds for t > 120,000 seconds. The CORSOR model was selected for fission product release from fuel, and the cavity concrete composition was assumed to be basaltic.[8]

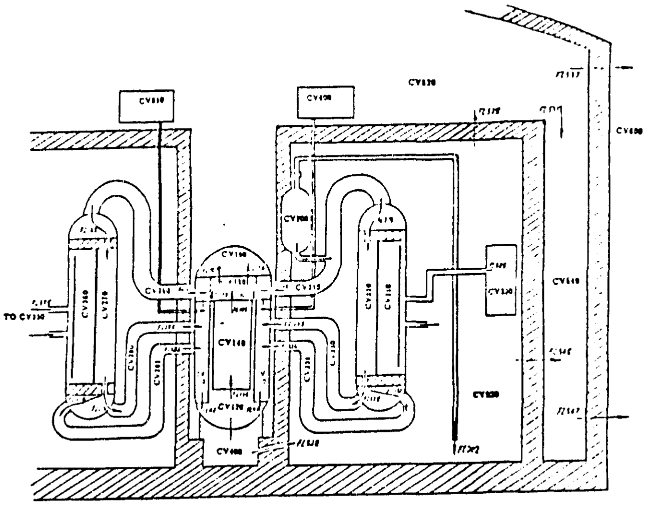

Figure 1 MELCOR Nodalization of the Oconee Plant

LOCA

The calculation was performed using MELCOR version 1.8DNY. The computing time required for 220,000 seconds of problem time was approximately 275,000 seconds on a VAX 6450 machine (WARP ≈ 0.8).

Table 1 summarizes the MELCOR and STCP predicted timing of key events during a LOCA sequence initiated by a break in a hot leg of the main coolant piping. The initial phase of the sequence consists of loss of coolant out of the break and boil-off, until the water level drops to the top of the core (core uncovery). There is good agreement between MELCOR and STCP calculated times of core uncovery. The accumulators start injecting water into the annulus when the RCS pressure drops below 600 psig. MELCOR calculates a slightly slower depressurization rate and hence the accumulators discharge a few minutes later than for STCP. MELCOR predicts melting and relocation to start earlier than STCP. This could be because melting is calculated in MELCOR to occur as the melting point of each component is reached. Thus, steel would melt first, followed by Zircaloy clad, and finally UO_2. STCP, on the other hand, does not distinguish between the

Table 1 MELCOR and STCP-Predicted Timing of Key Events for a LOCA (3-inch hot leg break) Sequence in Oconee

Key Event	Time (min)	
	MELCOR	STCP
Core uncovery	15.0	16.0
Accumulators empty	29.9	21.6
First gap release of fission products	27.3	--
Start melt and relocation	70.7	80.5
Core collapse	96.7(Ring 2) 98.8(Ring 1) 127.4(Ring 3)	107.1
Lower plenum dryout	108.3	124.5
Lower head failure	113.2(Ring 1) 123.1(Ring 2) 133.0(Ring 3)	164.4
Start concrete attack	120.0	164.4
Hydrogen burns begin	162.2	--
Containment failure	2720.8	1074.9
End calculation	3667.0	1366.0

different core components. MELCOR models the core as 3 radial rings and predicts partial core collapse to occur in stages while STCP calculates gross core collapse.

After failure of the lower core plate the core debris relocates into the lower plenum. Heat transfer from this hot debris (T > 2100K) rapidly boils away the remaining water inventory, and causes lower plenum dryout at 108.3 minutes. With water gone, the debris quickly heats up the lower head inner surface and penetrations, until a penetration failure is predicted in ring 1, followed by failure in the other rings. Failure of the lower head allows debris ejection into the cavity. Note that MELCOR calculations assume vessel failure to occur when the temperature of the penetrations reach 1273.15K (default value). The STCP calculation, on the other hand, assumed that gross failure of the lower head due to ablation would be the governing mode, based on depressurized conditions in the reactor vessel. STCP predicts vessel failure later than MELCOR.

MELCOR calculates a more gradual release of core materials into the cavity, so that even after vessel failure in all 3 rings, there is a substantial amount of fuel still left in the core, whereas STCP essentially releases the entire core inventory at the time of vessel failure. This results in a less vigorous core-concrete interaction for MELCOR, and a more gradual pressurization of the containment, leading to containment failure much later than for STCP.

The RCS becomes open to containment following vessel breach, and its pressure then rises in accordance with containment pressurization, until it drops to atmospheric pressure following containment failure. The discharge of water from the accumulators into the vessel, recovers the core level, and delays lower plenum dryout by a few thousand seconds. Water leak rate out of the broken pipe as calculated by MELCOR varies from a maximum of 250 kg/s to zero in about 800 seconds, while the steam continues to leak out until about 8000 seconds. This is similar to the behavior calculated by STCP, except that the maximum flow rate is about 220 kg/s and drops to zero at about 7800 seconds. The total hydrogen produced in-vessel is calculated as 300 kg, of which less than 250 kg is produced prior to vessel failure. MELCOR predicts 27.5% of the total zircaloy clad mass to react with steam. The STCP calculated value of 25-26% agrees closely with the MELCOR prediction.

Figure 2 shows the containment pressurization, including the partial pressure of steam and hydrogen. Clearly the steam pressure is the dominant factor, leading to containment failure. Figure 3 shows the gas temperature in the multi-compartment containment, which reaches 450 K (350°F) at the time of containment failure. Even though containment failure times are very different, the gas temperature calculated by STCP is also 350°F. Thereafter, MELCOR calculates a sharp temperature rise in the containment due to core-concrete interactions and a reduced mass of gas remaining inside. Temperatures are much higher in the cavity. Except for the initial period up to vessel breach, for most of the transient, the cavity is dry. Cumulative mass of gases leaked out of the containment is calculated to be 275,000 kg (mostly steam).

MELCOR calculations show much greater concrete erosion due to core-concrete interaction in the axial direction. This is contrary to STCP results which show greater overall radial penetration of concrete.

Table 2 shows the fractional distribution of fission products in various regions of the plant and the environment at the end of the calculation from both MELCOR and STCP. A comparison of environmental releases shows that MELCOR calculates lower release fractions of Sr, La, Ce, and Ba, while STCP calculates lower release fractions of I, Cs, and Te. The differences

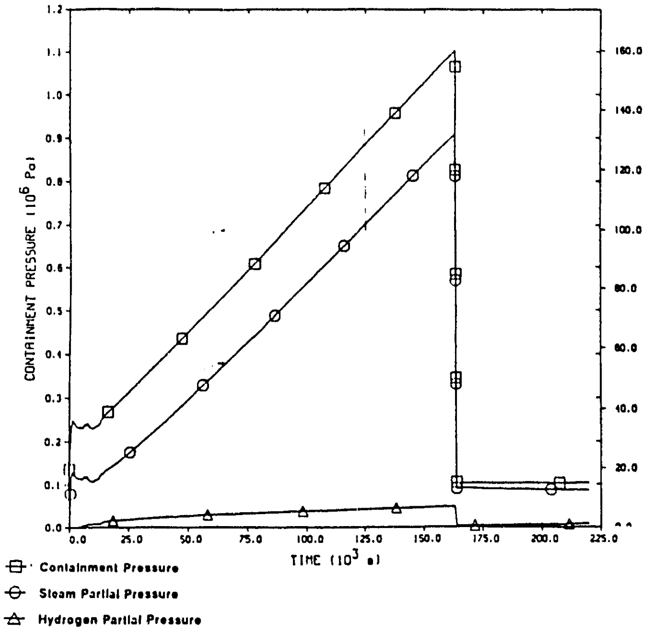

Figure 2 Containment Pressure History - LOCA

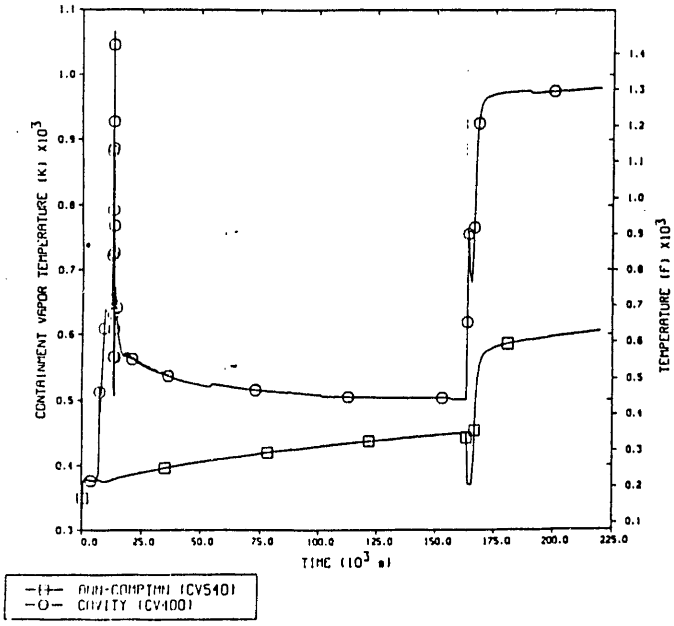

Figure 3 Temperature of Atmosphere in Cavity and Containment - LOCA

are small (less than a factor of 5) for Cs, Sr, and Ba. MELCOR predicts significantly higher release of I (order of magnitude), while STCP predicts significantly higher release of La and Ce (2 orders of magnitude). The lower refractory releases from MELCOR occur because MELCOR calculates debris ejection into the cavity over a much longer period of time, which results in less vigorous core-concrete interactions than STCP, and hence, larger retention of the refractory fission products in the cavity. This can be clearly seen from Table 2.

Station Blackout (TMLB)

The reference calculation used MELCOR 1.8.1. The computing time required for 190,000 seconds of problem time was 550,000 seconds on a VAX 6450 machine (WARP ≈ 0.35).

Table 3 summarizes MELCOR and STCP predicted timing of key events during the TMLB sequence in Oconee. There is good agreement between MELCOR and STCP calculated times of core uncovery. MELCOR calculates clad failure in ring 1 at 71 minutes, releasing the gap inventory of fission products. The transient proceeds at high pressure. MELCOR predicts melting and relocation to start somewhat earlier than STCP, but the relocation is more gradual, and MELCOR predicts core collapse and vessel failure much later than STCP, and staggered over a fairly long period. Note that MELCOR does not model any influence of pressure on vessel failure.

The discharge of borated water from the accumulators depends on reactor vessel depressurization to 600 psig. As this can only occur for the TMLB sequence following vessel failure, the timing calculated by MELCOR is later than STCP. The flooding of accumulator water does not significantly help to recover the core inventory (as in the LOCA sequence) since much of this water flows out of the opening at the bottom of the vessel.

Following debris ejection to the cavity, MELCOR calculates a pressure surge to 43 psi (0.2 MPa) that is significantly below the containment failure threshold of 160 psi (1.1 MPa). The containment fails late in the sequence due to long-term generation of steam and non-condensible gases from core-concrete interactions. STCP, on the other hand, calculates early containment failure, following vessel breach. The reason for this difference could be three-fold. Firstly, there is currently no model for DCH in MELCOR, and hence, no rapid pressurization on vessel failure. Secondly, the staggered failures of vessel penetrations as calculated by MELCOR, followed by gradual release of core material into the

Table 2 Fractional Distribution of Fission Products in Plant and Environment for LOCA (3-inch hot leg break) in Oconee

	RCS		Containment		Cavity		Environment	
Species	**MELCOR**	**STCP**	**MELCOR**	**STCP**	**MELCOR**	**STCP**	**MELCOR**	**STCP**
I	9.92E-2	8.7E-2	0.840	0.9015	0.0	0.0	0.154	1.15E-2
Cs	6.73E-2	8.43E-2	0.887	0.9042	0.0	0.0	5.40E-2	1.15E-2
Te	1.95E-2	0.1808	0.966	0.4634	3.70E-3	0.3527	1.12E-2	3.1E-3
Sr	2.13E-2	1.5E-4	0.321	0.6153	0.658	0.3843	9.24E-5	2.4E-4
Ru	2.0E-2	0.0	1.16E-4	2.9E-6	0.98	1.0	3.25E-7	3.1E-9
La	2.01E-2	0.0	5.51E-2	0.1176	0.925	0.8824	4.40E-7	4.7E-5
Ce	2.0E-2	0.0	3.06E-5	0.1574	0.98	0.8425	4.85E-7	5.7E-5
Ba	2.13E-2	3.1E-3	0.321	0.3465	0.658	.6501	9.24E-5	3.2E-4

Table 3 MELCOR and STCP-Predicted Timing of Key Events for TMLB Sequence in Oconee

Key Event	Time (min)	
	MELCOR	**STCP**
Steam generator dryout	13.4(12% remains)	13.9
Core uncovery	57.7	58.3
First gap release of fission products	71.1	--
Start melt and relocation	75.0	83.1
Core collapse	135.9(Ring 1) 137.1(Ring 2) 199.9(Ring 3)	108.3
Lower plenum dryout	139.0	112.9
Lower head failure	138.9(Ring 1) 139.1(Ring 2) 201.0(Ring 3)	117.5
Start concrete attack	138.9	149.0
Accumulators empty	140.0	117.5
Hydrogen burns begin	145.2	117.5
Containment failure	2854.4	117.6
End calculation	3166.7	750.5

cavity over an extended period leads to more gradual containment pressurization, while STCP calculates the ejection of all core material to the cavity on vessel failure. Finally, while STCP does not model DCH, an energetic containment event was assumed to occur following vessel failure, which resulted in a large steam spike, together with hydrogen combustion, sufficient to fail the containment.[4]

The RCS pressure remains high during core melt progression, controlled by the operation of SRVs and PORVs on the pressurizer. On vessel breach, the RCS pressure drops sharply and then follows the containment pressurization, eventually dropping to atmospheric pressure after containment failure.

The total hydrogen produced in-vessel is calculated as 575 kg, of which about 250 kg is produced during the in-vessel phase (170 kg prior to vessel failure in ring 1, and the rest thereafter). The zircaloy clad mass reacted with steam is calculated as 29%, compared with the STCP calculated value of 36%.

Figure 4 shows the containment pressurization, which is predominantly due to steam partial pressure. The initial pressure spikes are caused by internal pressure spikes in the reactor vessel, that are transmitted to the containment via the pressurizer SRVs. Figure 5 shows the gas temperature in the multi-compartment containment which reaches 450 K (350°F) at the time of containment failure. STCP calculates early containment failure, which gives less time for the containment to heat up, and the gas temperature is about 250°F prior to containment failure. The steam spike and H_2 combustion increase the temperature rapidly to 900°F at the time the containment is predicted to fail.

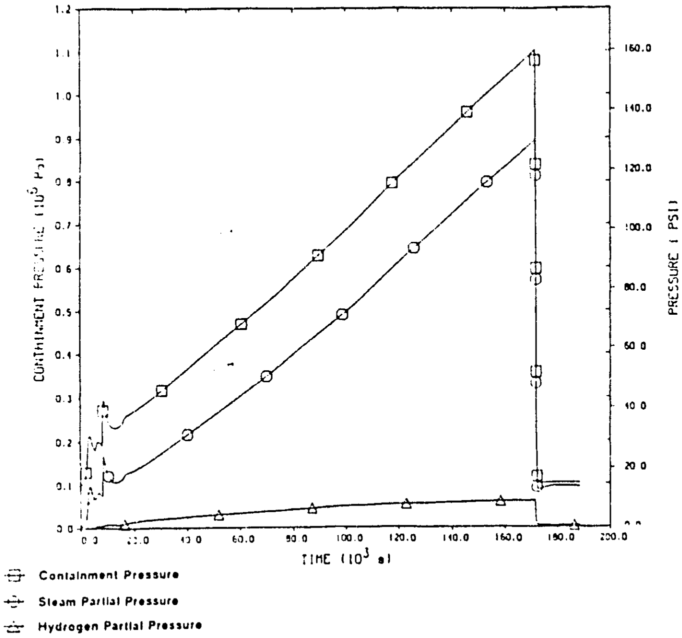

Figure 4 Containment Pressure History - TMLB

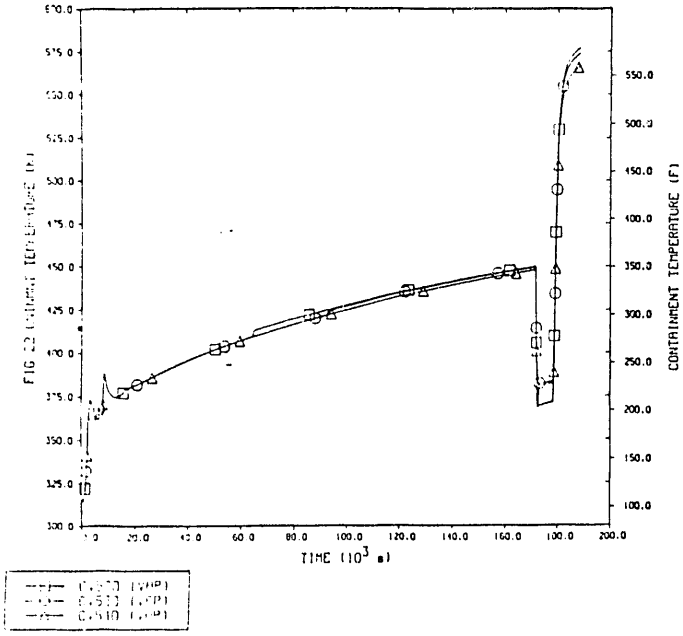

Figure 5 Temperature of Atmosphere in Containment - TMLB

Except for the initial period up to vessel breach, for most of the transient, the cavity is dry. The cumulative mass of gases from the containment is calculated to be almost 275,000 kg (mostly steam).

Table 4 shows the fractional distribution of fission products in various regions of the plant and the environment at the end of the calculation from both MELCOR and STCP. A comparison of environmental releases shows that MELCOR consistently calculates lower release fractions for all radionuclide groups. The lower volatile releases from MELCOR are primarily because STCP calculates early containment failure and hence, early releases of all volatile species without time being available for removal mechanisms such as deposition. The lower refractory releases from MELCOR occur mainly because MELCOR calculates debris ejection into the cavity over a much longer period of time, which results in less vigorous core-concrete interactions than STCP, and hence, larger retention of the refractory fission products in the cavity. This can be clearly seen from Table 4.

SENSITIVITY CALCULATIONS

Concrete Type

The concrete material in Oconee is described in the FSAR [2] as "marble aggregate", which could imply limestone, but is listed as basaltic in reference 8. For the LOCA sequence the only significant impact of concrete type is on the containment failure time, which is almost 10 hours earlier for limestone concrete. This is because limestone concrete releases significantly larger quantities of non-condensibles (CO_2 and CO) that increase containment pressurization. The environmental releases of radionuclides for both concrete types are very similar, the maximum difference being a factor of 4.5 (Lanthanum, being higher for limestone concrete). This difference is well within numerical uncertainties of the code.

Lower Head Failure Temperature

For the LOCA sequence, a pipe break in the RCS causes early depressurization of the reactor vessel, and the core melt progression occurs at low pressure. The reference MELCOR calculation described earlier assumed vessel failure to occur when the temperature of the penetrations reached 1273.15K (default value). This threshold value is lower than the melting temperature of steel and is based on assumptions of stress-related failure of penetrations. The STCP calculation, on the other hand, assumed that gross failure of the lower head due to ablation would be the governing mode, based on

Table 4 Fractional Distribution of Fission Products in Plant and Environment for TMLB in Oconee

	RCS		Containment		Cavity		Environment	
Species	**MELCOR**	**STCP**	**MELCOR**	**STCP**	**MELCOR**	**STCP**	**MELCOR**	**STCP**
I	2.45E-2	0.5814	0.975	8.76E-2	0.0	0.0	1.01E-3	0.331
Cs	1.72E-2	0.7056	0.982	6.44E-2	0.0	0.0	7.63E-4	0.23
Te	6.07E-3	0.2006	0.929	0.2924	6.13E-2	0.4192	3.68E-3	8.78E-2
Sr	0.238	5.2E-4	0.321	0.1744	0.524	0.8225	9.25E-5	2.6E-2
Ru	1.14E-2	0.0	7.22E-3	2.8E-8	0.981	1.0	1.01E-7	4.4E-7
La	1.23E-3	0.0	3.62E-2	1.9E-3	0.963	0.9981	2.02E-6	8.1E-5
Ce	2.27E-4	0.0	1.65E-4	3.9E-3	1.0	0.996	5.69E-7	5.7E-5
Ba	0.238	9.8E-3	0.238	1.44E-2	0.524	0.876	9.25E-5	4.3E-3

depressurized conditions in the reactor vessel. It is not clear what threshold temperature for failure was used in the STCP model. Based on lower head failure studies reported by EG&G [9], a reasonable threshold temperature for gross lower head failure would be 1500 K or greater.

Calculations were made assuming vessel failure temperatures (T_{pfail}) of 1273.15K (default), 1500K, and 1700K. Events up to melt initiation are unaffected by the temperature assumption. The impact of increasing T_{pfail} is to delay the occurrence of lower head failure and initiation of core-concrete interactions. However, the predicted containment failure time seems to increase for 1500 K and then decrease for 1700K. The earlier containment failure for 1700K could be attributed to a hotter debris being ejected to the cavity, causing more vigorous core-concrete interactions and more rapid pressurization of the containment.

The effect of T_{pfail} on environmental releases was minimal for the basaltic concrete calculations, all releases being within a factor of 2 of each other. For limestone concrete, most releases were very similar, the maximum deviation being limited to a factor of 4.6, which is well within the calculational uncertainties of the code.

Break Location

This section examines the impact of break location on predicted timing of key events and containment pressurization in Oconee, by simulating a LOCA sequence initiated by a break in a cold leg pipe.

Table 5 compares the timing of key events. The timings up to vessel failure are similar, for both break locations, except that for the break in a cold leg, the accumulators discharge into the vessel earlier, indicating a more rapid depressurization of the RCS due to greater loss of coolant out of the break. The maximum flow rate out of the cold leg break is 275 kg/s (250 kg/s for the hot leg break), and cumulative mass flow out of the break into containment is about 153,000 kg (17,000 kg more than for the hot leg break). Boil-off of a larger mass of water in the containment causes more rapid pressurization leading to earlier containment failure. The total mass of gases released from core-concrete interactions at the time of containment failure is less for the cold leg break due to less time available prior to containment failure.

Table 6 compares the radionuclide release fractions into the environment. The impact of break location is seen to be minimal for the refractory species. The lower release fraction of Ru could also be a result of round-off error, the number being so small. However, the volatile species I, Cs, Te all exhibit about an order of magnitude lower environmental release fractions, because of substantially greater retention in the RCS, for the break in a cold leg. This result was expected since the pathway to the break for the fission products is via the steam generator, where substantial retention occurs.

Table 5 Impact of Break Location on Timing of Key Events - LOCA

Key Event	Time (min)	
	Break in Hot Leg	Break in Cold Leg
Accumulators empty	29.9	22.5
First gap release of fission products	27.3	24.3
Start melt and relocation	70.7	71.0
Core collapse	96.7 (Ring 2)	98.7 (Ring 2)
	98.8 (Ring 1)	104.5 (Ring 1)
	127.4 (Ring 3)	126.6 (Ring 3)
Lower plenum dryout	108.3	111.9
Lower head failure	113.2 (Ring 1)	120.0 (Ring 1)
	123.1 (Ring 2)	127.5 (Ring 2)
	133.0 (Ring 3)	133.0 (Ring 3)
Start concrete attack	120.0	128.1
Hydrogen burns begin	162.2	120.3
Containment failure	2720.8	2489.3
End calculation	3667.0	2833.3

Table 6 Impact of Break Location on Environmental Release Fractions - LOCA

Species	Break Location	
	Hot Leg	Cold Leg
I	0.154	6.56E-3
Cs	5.4E-2	4.01E-3
Te	1.12E-2	1.59E-3
Sr	9.24E-5	9.30E-5
Ru	3.25E-7	1.57E-11
La	4.40E-7	.4.79E-7
Ce	4.85E-7	5.73E-7
Ba	9.24E-5	9.30E-5

The presence of vent valves in the reactor vessel upper plenum provides a potential pathway for steam to exit from the break. However, these valves open only for about the first half-hour of the transient closing thereafter due to the depressurized conditions. Hence, most of the coolant flow from the reactor vessel to the cold leg break still passes through the steam generator.

CONCLUDING REMARKS

Since MELCOR has not been used until this study, to calculate source terms for B&W PWR plants, this study has been useful in evaluating the ability of MELCOR to successfully simulate various accident sequences and calculate source terms to the environment from a B&W plant. In fact, this application did lead MELCOR into uncharted territory where new code errors were uncovered and communicated to the code developers,resulting in the creation of new updates to the code. Such analyses will be able to guide MELCOR towards maturity as a severe accident/source term analysis tool for PRA studies of current LWR plant designs, which is one of the key targeted applications for MELCOR.

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