MELCOR Assessment at SNL

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1 Introduction

MELCOR [1] is a fully integrated, engineering-level computer code that models the progression of severe accidents in light water reactor (LWR) nuclear power plants, being developed at Sandia National Laboratories for the U. S. Nuclear Regulatory Commission (USNRC). The entire spectrum of severe accident phenomena, including reactor coolant system and containment thermal/hydraulic response, core heatup, degradation and relocation, and fission product release and transport, is treated in MELCOR in a unified framework for both boiling water reactors (BWRs) and pressurized water reactors (PWRs). The MELCOR computer code has been developed to the point that it is now being successfully applied in severe accident analyses, particularly in probabilistic risk assessment (PRA) studies.

MELCOR was the first of the severe accident analysis codes to undergo a formal peer review process. One of the major conclusions of the recent MELCOR Peer Review [2] was the need for a more comprehensive and more systematic program of MELCOR assessment. A systematic program of code assessment provides a number of benefits, including:

1. guidance to the code developers in identification of areas where code improvements are needed (such as coding implementation errors in models, inappropriate or deficient models, missing models, excessive numerical sensitivities),
2. documented evidence to external observers, users, reviewers and project management that the code is modelling required phenomena correctly, and
3. increased general public acceptance that the code adequately treats issues related to public safety concerns.

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A MELCOR verification and validation ("V&V") program was funded at Sandia in 1985-1986 [3]. That limited effort primarily involved containment phenomena. Results from MELCOR 1.0, 1.5.0 and 1.6.0 were compared with experimental data, with more mechanistic codes and with analytical solutions for a number of problems. MELCOR has been used by Sandia to participate in the TMI-2 [4] plant accident, and HDR T31.5 (ISP-23) [5] hydrogen mixing and PHEBUS B9+ (ISP-28) [6, 7] and CORA 13 (ISP-31) [8] core damage standard problem exercises.

Because some assessment is available for MELCOR in the areas of containment thermal/hydraulics and core damage assessment, calculations done at Sandia since the Peer Review concentrate on primary system thermal/hydraulic response, on fission product and aerosol release, transport and deposition, and on integral severe-accident analysis, areas where little or no MELCOR assessment was previously available. Completed and ongoing MELCOR assessment analyses at Sandia, whose results are summarized in this paper, include:

1. the LACE LA4 containment-geometry aerosol deposition test [9],
2. the FLECHT SEASET natural circulation tests [10],
3. the ACRR ST-1/ST-2 in-pile source term experiments [11],
4. the OECD LOFT integral severe accident experiment LP-FP-2 [12],
5. the Marviken-V ATT-2b and ATT-2 aerosol transport and deposition tests in primary system geometries [13],
6. PNL ice condenser experiments 11-6 and 16-11 [14], and
7. PWR TMLB' calculations with and without DCH.

One of the major contributions of this assessment project to the MELCOR effort has been the systematic search for and identification of code features which lead to time step and other numerical dependencies, as summarized in the individual task reports. Nearly all major advances in elimination of these undesirable features during the last year are the result of these systematic studies. Many of the numeric sensitivities have been traced to code problems that would not be readily detected in the single, isolated calculations that are typical of many user applications.

In addition, a number of user guidelines on input modelling and on the adequacy and applicability of default parameter settings are being generated, with details contained in the individual assessment reports. In some cases, these will be included in the preliminary users' guide scheduled for next year. In other cases, the end result is a change in the code documentation or changes to the default variable setting in the code; this latter option seems more effective in the long term because it eliminates the need to document when and why the user should override default settings.

2 LACE LA4 Aerosol Transport and Deposition

The LWR Aerosol Containment Experiments (LACE) program [15] was a cooperative effort to investigate inherent aerosol behavior for postulated accident situations for which high consequences are presently calculated in risk assessment studies because either the containment is bypassed altogether, the containment function is impaired early in the accident, or delayed containment failure occurs simultaneously with a large fission-product release. A series of six large-scale experiments has been conducted at the Containment Systems Test Facility (CSTF) at Hanford Engineering Development Laboratory (HEDL).

The MELCOR code has been used to simulate LACE experiment LA4 [9], an integral aerosol behavior test simulating late containment failure with overlapping aerosol injection periods [16]. In this test, the behavior of single- and double-component, hygroscopic and nonhygroscopic, aerosols in a condensing environment was monitored. Nonhygroscopic MELCOR results were compared to experimental data, and to CONTAIN hygroscopic calculations for LACE LA4 [18]. The reason for the difference in predicted suspended aerosol masses in the two codes is the larger aerosol particles calculated by MELCOR despite the lack of teatment for hygroscopic effects; the reason for the difference in aerosol particle sizes is primarily the larger agglomeration shape factors used in the MELCOR input.

MELCOR calculated the thermal/hydraulic and aerosol response phenomena observed during the LACE LA4 experiment. Figure 2.1 shows the test vessel pressure and the suspended aerosol masses predicted by MELCOR and CONTAIN, compared to experimental data. The lack of any hygroscopic effects in the MELCOR aerosol treatment is visible mostly as the lack of any calculated difference in the behavior of the hygroscopic CsOH and the nonhygroscopic MnO aerosols. MELCOR predicted aerosol particles generally larger than measured, which then settled faster than observed, and consequently less suspended aerosols were leaked and/or plated in the calculation than in the experiment.

The MELCOR LA4 analysis included sensitivity studies on time step effects, wall and pool condensation, radiation heat transfer, number of aerosol components and sections, impact of non-default values of shape factors and diameter limits in the aerosol input, and the degree to which plated aerosols adhere to the walls or are washed off by draining liquid condensate films. The results showed that water should be modelled as a separate aerosol component in this problem, and that more sections (size bins) than the MELCOR default should be used. Including atmosphere-structure radiative heat transfer, even at the relatively low temperatures (300-400K) characteristic of this test, produced better agreement with data, as did using a detailed volume-altitude table reflecting the differences in sump pool liquid surface area with elevation in the elliptical lower head. There was a strong effect on amount of aerosol plated on walls of whether plated aerosol mass was allowed to wash off heat structures with condensate films draining down into the pool, as indicated in Table 2.1. The suspended aerosol results depended most strongly on the value used for the agglomeration shape factor, with a much weaker (but still visible) dependence upon the dynamic shape factor.

Although there has been a lot of discussion recently on numeric effects seen in other MELCOR calculations, no machine dependencies were seen in this problem, and smooth convergence in results with reduced time steps was demonstrated.

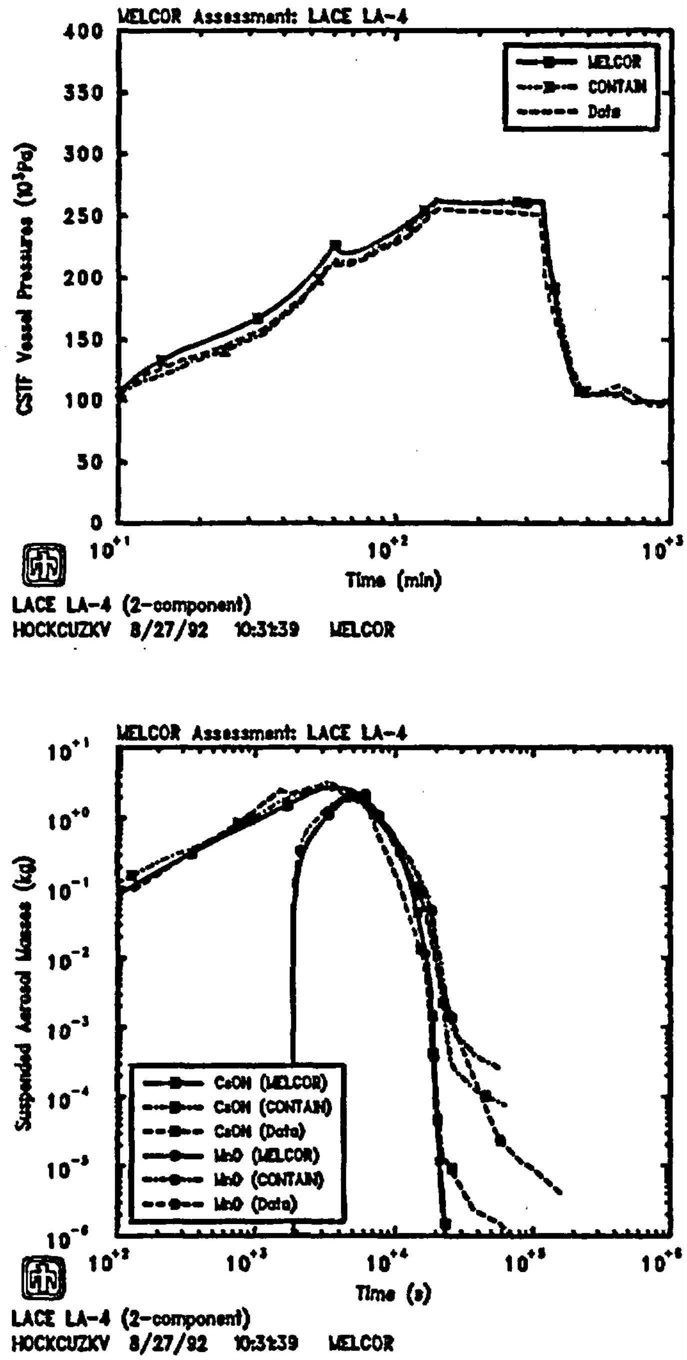


Figure 2.1. LACE LA4 CSTF Vessel Pressure and Suspended Aerosol Masses Predicted by MELCOR, Compared to Test Data and to CONTAIN Results

Table 2.1. LACE LA4 Final Aerosol Deposition

Aerosol Species	Location	Test Data (kg)	Code (kg) Reference ("Sticky")	Default ("Nonsticky")
CsOH	Settled	2.563	2.615	2.841
	Plated	0.304	0.230	0.004
	Leaked	0.007	0.002	0.003
MnO	Settled	1.927	2.153	2.267
	Plated	0.228	0.117	0.002
	Leaked	0.101	0.001	0.002
Sum	Settled	4.490	4.768	5.108
	Plated	0.532	0.347	0.006
	Leaked	0.108	0.003	0.005

3 FLECHT SEASET Natural Circulation

The Full-Length Emergency Cooling Heat Transfer Separate Effects and Systems Effects Test (FLECHT SEASET) program was a cooperative NRC/EPRI/Westinghouse effort to investigate heat transfer and hydraulic phenomena in a Westinghouse PWR primary system. Part of this program [19, 20] consisted of a series of natural circulation tests in a 1:307-scale facility, with prototypic full lengths and full heights. Steady-state single-phase liquid, two-phase and reflux condensation modes of natural circulation cooling were established, and flow and heat transfer characteristics in the different cooling modes were identified. In addition, other tests studied the variation of single-phase liquid natural circulation with changing core power or with different secondary side heat removal capabilities, and the effect of noncondensables on two-phase natural circulation flows.

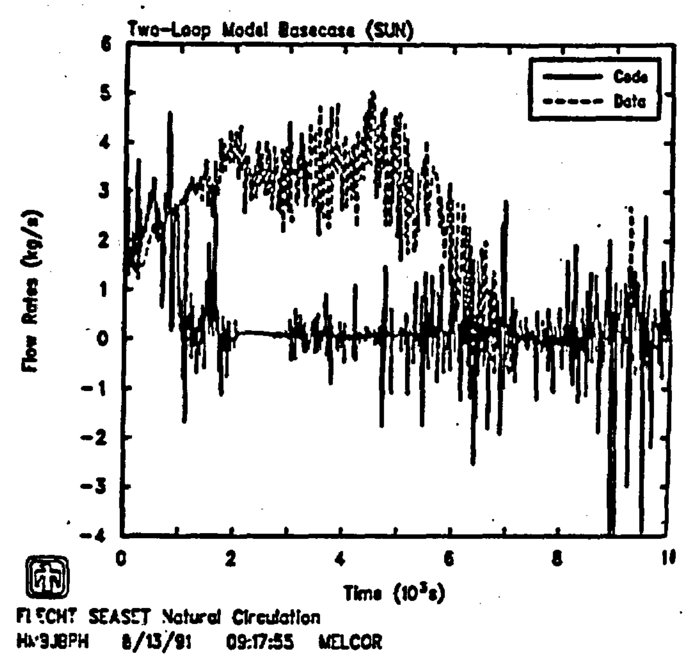
In our assessment [10], MELCOR correctly calculated the thermal/hydraulic phenomena observed during steady-state, single-phase liquid natural circulation, as summarized in Table 3.1. MELCOR predicted the correct total flow rate and the flow split between two unequal loops without any *ad hoc* adjustment of the input. The code could reproduce the major thermal/hydraulic response characteristics in two-phase natural circulation, after a number of non-standard input modelling modifications; MELCOR could not reproduce the requisite physical phenomena with "normal" input models. The natural circulation mass flows predicted in these two cases are shown in Figure 3.1.

One major input model change consisted of subdividing the steam generator U-tubes into stacks of multiple control volumes. The top elevations of the control volumes containing the U-tubes were adjusted to lie above the top of the connecting horizontal flow path opening heights, and small incremental volumes were added in the volume-altitude tables in those control volumes; this is an input trick to ensure that a minimal atmosphere is always present and the

Table 3.1. FLECHT SEASET Single-Phase Liquid Natural Circulation

Parameter	Measured	Calculated
Specified by Input:		
Core Power (kw)	222.4	222.4
Pressurizer Pressure (MPa)	0.930 ± 0.110	0.930
Pressurizer Liquid Subcooling (K)	409.0 ± 1.7	409.0
Pressurizer Liquid Level (m)	0.21 ± 0.50	0.21
SG Pressure (MPa)	0.260 ± 0.110	0.323
SG Collapsed Liquid Level (m)	7.62 ± 0.50	7.62
Calculated:		
Upper Plenum Pressure (MPa)	0.930 ± 0.115	0.932
Core Flow (kg/s)	1.47 ± 0.075	1.41
Upper Plenum Temperature (K)	442.0 ± 1.7	445.3
Lower Plenum Temperature (K)	408.0 ± 1.7	409.4
Intact Loop (IL) Flow (kg/s)	1.11 ± 0.075	1.07
IL Hot Leg Temperature (K)	439.0 ± 1.7	(416.4)†
IL Cold Leg Temperature (K)	408.0 ± 1.7	410.3
Broken Loop (BL) Flow (kg/s)	0.36 ± 0.075	0.34
BL Hot Leg Temperature (K)	437.0 ± 1.7	(417.1)†
BL Cold Leg Temperature (K)	410.0 ± 1.7	409.8

†for MELCOR volume which includes uphill leg of SG U-tubes



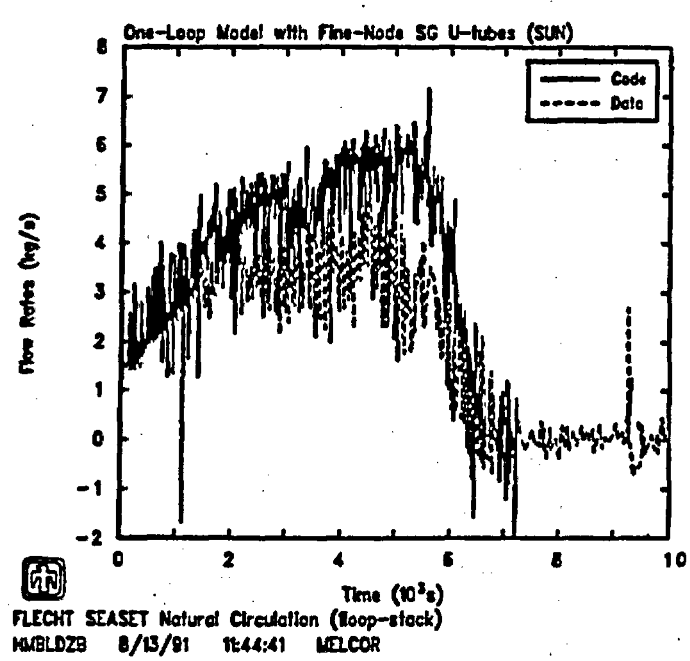


Figure 3.1. FLECHT SEASET Natural Circulation Mass Flows for Initial (top) and Final (bottom) MELCOR Calculations, Compared to Test Data

nonequilibrium physics model always used in the control volume. Other required input changes included enabling the nondefault bubble rise model to account for interactions of bubbles with the pool, and increasing the junction opening heights between vertically-stacked volumes.

With these various input modifications, the correct dependence of mass flow on system mass inventory was obtained; the pressure and temperatures were then calculated to be in good agreement with test data. However, even in this case, the two-phase flow was overpredicted by ~30%, possibly because of incorrect two-phase interface and/or wall friction code models. As in the single-phase liquid natural circulation calculations, the two-phase simulations experienced a lot of subcycling and repeated advancement attempts, and time step cycling.

No significant machine dependencies were seen in sensitivity studies for this problem; however, much smoother two-phase mass flow rates were calculated with a substantially reduced time step.

4 ACRR ST-1/ST-2 Source Term Experiments

The ACRR Source Term (ST) experiments [23, 24] provide time-resolved fission product release data to help validate models and to identify important release mechanisms. ST-1 and ST-2 were performed with the same temperature history, fuel characteristics, hardware configuration, sampling methods, and hydrogen partial pressure; the main difference in the experiment conditions was in the pressure and in the gas velocity through the fueled test section.

MELCOR has been used to simulate both the ST-1 and ST-2 experiments [11],using the CORSOR, CORSOR-M and CORSOR-Booth release models [21, 22]. Both release rates and total releases calculated by MELCOR generally agreed well with test data, as shown in Table 4.1. Both qualitative and quantitative differences between volatile and refractory species were correctly reproduced. The more volatile species (Xe, Cs, I and Kr) were released starting earlier and peaking earlier than the more refractory species (Ba, Sr and Te) and most of the initial inventories were released for the volatiles, while only part of the initial masses present were released for the more refractory species. Very low release fractions were predicted for the most refractory species (U and Zr) which agreed well with the limited test data.

None of the release model options produced consistently better agreement with test data for all species considered. The new CORSOR-Booth model matched the europium test data best, while CORSOR and CORSOR-M significantly underpredicted Eu release. CORSOR-Booth predicted less release of all volatiles than the nearly complete release calculated using either the CORSOR or CORSOR-M options; none of the models predicted the different release fractions measured for the various volatiles. CORSOR-Booth and CORSOR-M underpredicted the releases of refractory species such as Ba, Sr, Zr and U, while the CORSOR results for those species appear in good agreement with test data.

The MELCOR results also were compared directly to the release rate correlations as functions of temperature, using control functions, and to ST-1/ST-2 results obtained by Battelle using their standalone CORSOR code, to verify that the models have been implemented correctly within MELCOR.

Because the release is a very strong function of temperature, it was important to match the experimental temperature distribution as well as possible. Sensitivity studies showed no significant temperature dependence on changes in power, pressure or gas flow (within the experimental uncertainties and variations), or on convective heat transfer coefficients; the temperatures calculated were sensitive to the insulation thermal conductivity and the view factors used in radiation heat transfer from the fuel to the shroud.

Sensitivity studies checking for time step and noding effects, and for machine dependencies, were done. The major problem identified was a machine dependency associated with exponentials and very small numbers; it resulted in significantly different releases being predicted on different machines for refractory species. Other problems associated with differences in round-off of small numbers were also found. All these problems were corrected immediately, and no machine dependencies were found in our final calculations.

5 LOFT LP-FP-2

MELCOR has been used to model experiment LP-FP-2 [25, 26, 27, 28, 29, 30, 31], which simulates many of the primary system and core thermal/hydraulic conditions that would be expected during a PWR V-sequence. The relatively large scale of the test and the extensive instrumentation used make the LP-FP-2 experiment an important integral source of data for qualifying severe accident code predictive capabilities.

Our MELCOR results [12] can be put into perspective best, perhaps, by examining them in relation to the performance of other codes in predicting this very challenging experiment [31]. MELCOR does at least as well as other "best-estimate" (*i.e.*, SCDAP/RELAP5) or integral (*i.e.*, MAAP) codes in predicting the thermal/hydraulic and core responses in this experiment, as shown in Figures 5.1 and 5.2; in fact, MELCOR and MAAP appear to give the best agreement with data, especially for clad temperature histories. Further, MELCOR does at least as well as "best-estimate" fission product codes in predicting the source term (with a number of such codes having to be run in tandem and driven by test data or other "best-estimate" thermal/hydraulic and code damage codes to provide results equivalent to a single, integrated MELCOR calculation), as shown in Table 5.1.

The predicted primary system pressure was generally lower than measured, while the predicted primary system mass inventory was generally higher than measured, but with a large uncertainty on the test data. The pressurizer was predicted to empty within 1min, in good agreement with test data, and the early-time intact-loop mass flow also was calculated in good agreement with measurement, despite the lack of a complicated pump coastdown model in MELCOR. Despite the differences in calculated and observed thermal/hydraulic response, the core uncovery, dryout and onset of clad heatup were calculated in excellent agreement with thermocouple data.

Sensitivity studies on parameters which directly affect the thermal/hydraulic response showed a significant dependence on several break flow modelling parameters, including areas, discharge coefficients and loss coefficients used. Results showed little or no dependence on structural heat transfer, either on the magnitude of the convective heat transfer coefficients or on the correlation sets ("int" *vs* "ext") and characteristic lengths used, on the radiative heat transfer emissivity or path length used, or on the modelling of piping insulation, on bubble rise physics in flow paths, or on secondary system leakage. The sensitivity studies did find a strong dependence on the junction opening heights used in flow paths connecting vertical stacks of control volumes, particularly at the core inlet and outlet.

Table 4.1. Aerosol and Fission Product Vapors Released from Fuel in ST-1

Element	Percent (%)							
	Test Data	VICTORIA[24]	Standalone CORSOR[22]			MELCOR		
			CORSOR	CORSOR-M	CORSOR-Booth	CORSOR[1]	CORSOR-M[1]	CORSOR-Booth
Xe		100	100	100	58.5	98.1-99.3	98.8-99.6	55.6
Cs	71§-56†	94	100	100	58.5	98.1-99.3	98.8-99.6	55.6
Ba	8†+3.2‡	27-39	16.75	0.88	4.1	11.0-14.0	0.48-0.63	4.30
I	38†	81	100	100	58.5	98.1-99.3	98.8-99.6	55.6
Te	<0.2†		19.1¶	100¶	2.0	0.31-0.40	15.2-19.2	2.18
Kr	100		100	100	58.5	98.1-99.3	98.8-99.6	55.6
Sr	5†+ ≤0.43‡		16.75	0.88	4.1	4.07-5.25	0.48-0.63	4.30
Zr	≥0.034‡		0.016	0	0.0026	0.017-0.042	0.00001-0.0002	0.005
Eu	15§-5†		0.024	0	8.4	0.014-0.018	0	8.38
U	0.011‡		0.024	0.007	0.0088	0.014-0.018	0.003-0.004	0.009
Sn			49.03	7.18	4.1	32.9-39.9	4.45-5.73	4.30

[1] values without-with surface/volume correction term
¶apparently not scaled by 1/40
§amount released (measured by gamma scans)
†amount collected (measured by filters)
‡amount collected (measured in water leachates)

Table 5.1. LOFT LP-FP-2 Source Terms

Class	CFM Radionuclide Release (% CFM Initial Inventory)						
	Data ([31])	MELCOR			INEL		Spain
		CORSOR†	CORSOR-M†	CORSOR-Booth‡	CORSOR	FASTGRASS	
1 (Xe)	2.5-2.8	6.977/8.376	8.124/10.74	3.718/1.744	44.5	5.3	9.58
2 (Cs)	2.9	6.976/8.371	8.125/10.74	3.337/1.653	44.5	3.0	8.1
3 (Ba)		0.157/0.192	0.0058/0.0069	0.0150/0.0089	2.22		
4 (I)	5.2	6.973/8.372	8.120/10.73	3.715/1.739	44.5	3.0	8.1
5 (Te)	0.54	0.171/0.267	3.985/6.559	1.880/0.863	1.75	0.058	4.31

†values without/with surface-volume correction term
‡values using low-burnup/high-burnup coefficients

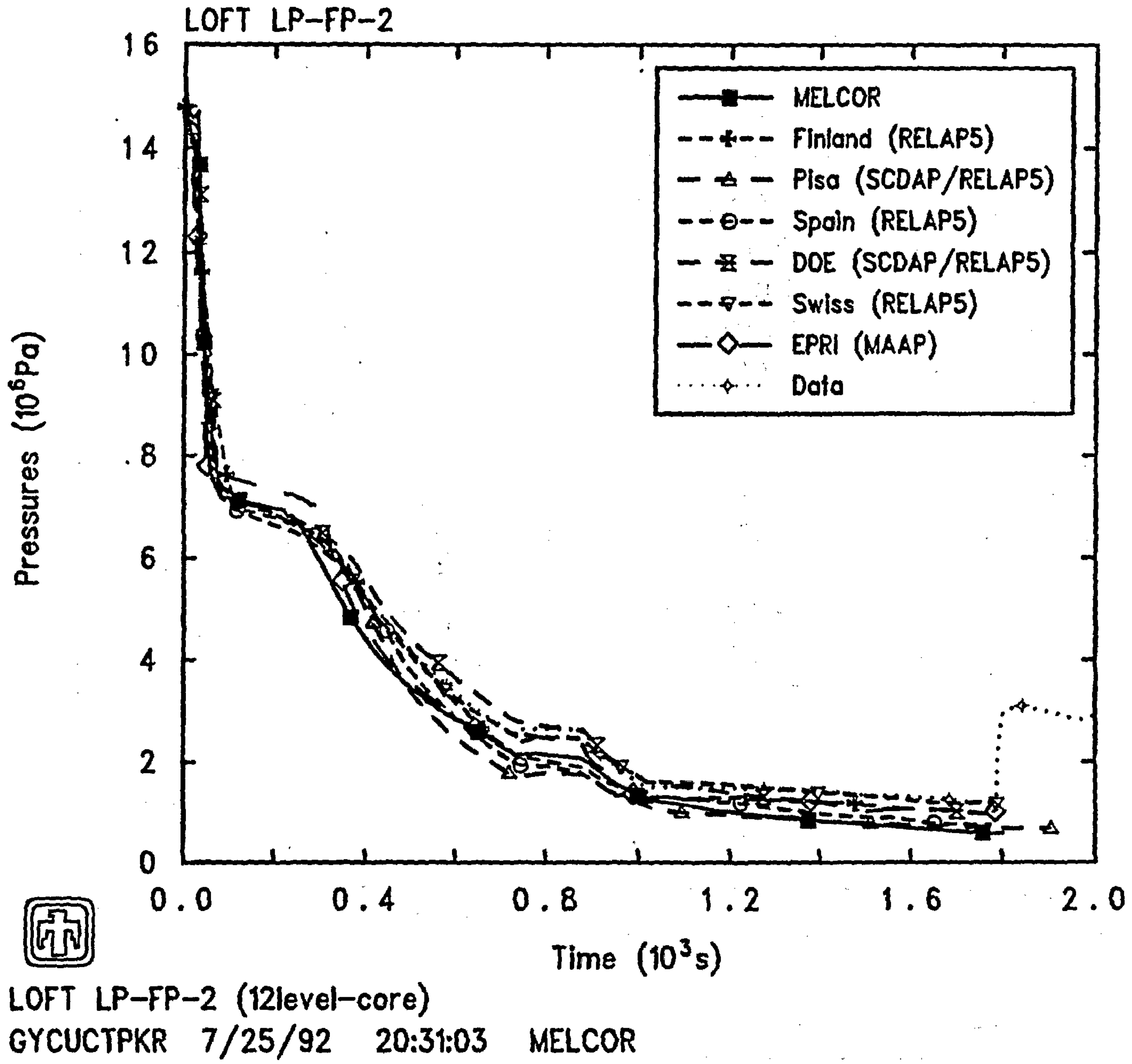


Figure 5.1. LOFT LP-FP-2 Primary System Pressure Predicted by MELCOR, Compared to Test Data and to Results from Other Code Calculations

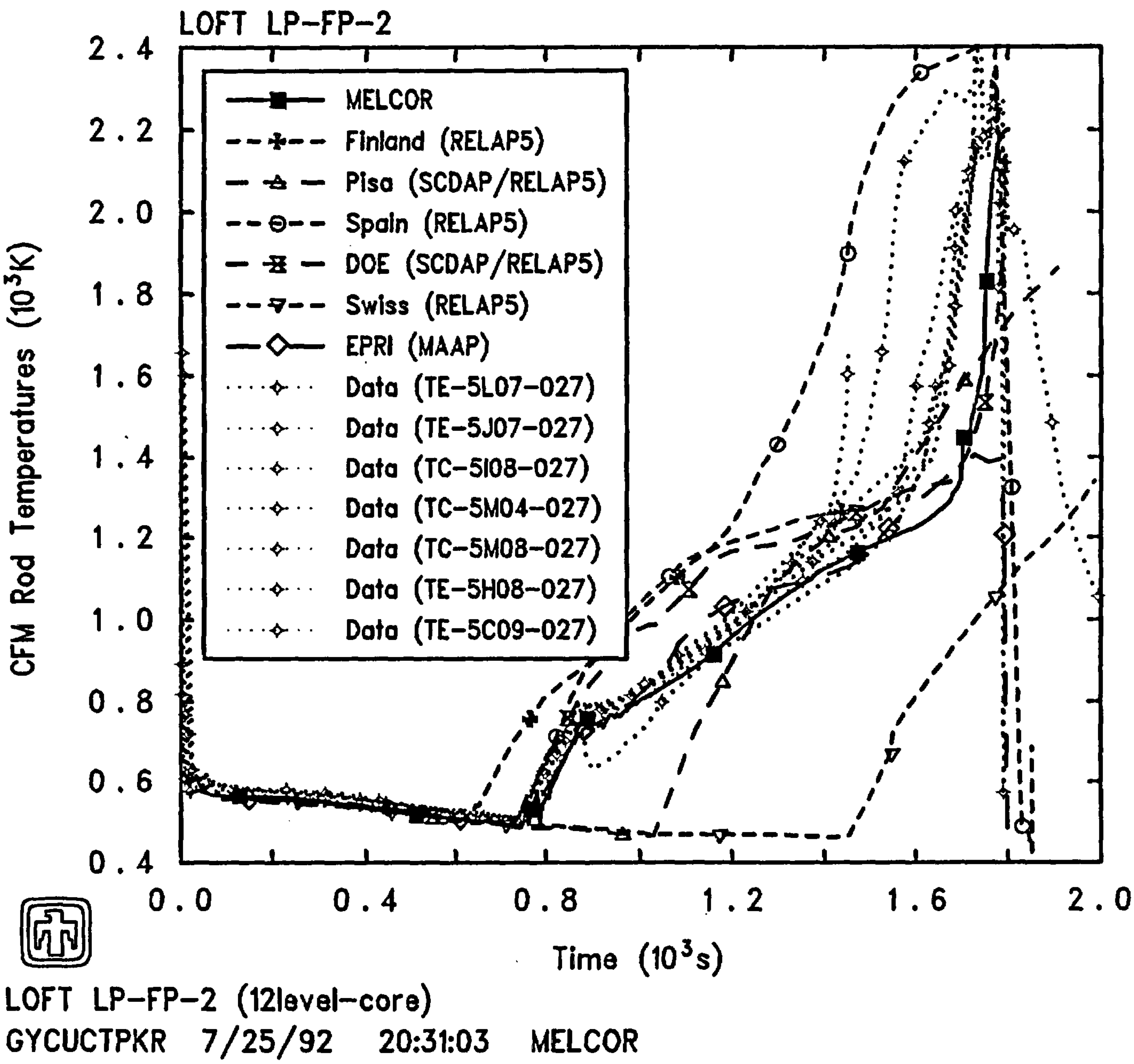


Figure 5.2. LOFT LP-FP-2 CFM Mid-Core Clad Temperature Predicted by MELCOR, Compared to Test Data and to Results from Other Code Calculations

The core heatup predicted was in very good agreement with test data (even to the effect of enhanced core cooling and a partial rewet soon after core dryout and uncovery) until the onset of rapid metal-water reaction late in the transient. This behavior could not be predicted using the default models and parameters in MELCOR, but required changing the temperature switching from a low-temperature to a high-temperature set of Zircaloy oxidation rate constants.

Post-irradiation examination (PIE) of the central fuel module (CFM) [30] concluded that the material relocation and stratification in LP-FP-2 resulted in low-melting-point metallic melts near the bottom of the fuel bundle, a high-temperature $(U,Zr)O_2$ ceramic melt region above this, and a debris bed of fuel pellets near the top of the fuel bundle. The final material distribution in MELCOR is in reasonable qualitative agreement with the test results. A debris bed consisting mostly of solid UO_2 fragments overlies a central region where much of the oxidized and unoxidized Zircaloy clad has refrozen, with the steel in the other structure refreezing at a somewhat lower average elevation and the control rod poison material flowing down to the lower core and core support plate before refreezing. The PIE identified a 79-86% blockage due to material relocation and stratification in LP-FP-2. There is no internal blockage model in MELCOR. With flow blockage approximated *via* input at $\geq$1400s, predicted clad temperatures are in better agreement with data; the agreement might be improved further if the blockage could be modelled as occurring at the "correct" (moving) core elevation, rather than simply at the CFM inlet.

The hydrogen generated in our MELCOR analyses is in good agreement with data. The reference MELCOR calculation, with the inner Zircaloy liner of the insulating shroud assumed to oxidize at the same temperature and rate as the adjacent clad, showed 267g of hydrogen in the BST, while a sensitivity study in which oxidation of the shroud inner liner was neglected gave 218g of hydrogen in the BST. Two experimental data sets are available for comparison. Grab samples from the suppression pool indicating 205$\pm$11g reflect hydrogen generation during the transient because the tank was isolated just prior to reflood; the PIE indicated 63g and 118g of hydrogen, respectively, generated as a result of Zircaloy oxidation in cladding shells and in relocated material in the lower bundle, for a total of ~181g.

Modelling the CFM shroud proved important primarily because of its effect on preventing radiative heat transfer and coolant temperature equilibration in the two parallel, isolated core flow channels. Minor changes were noted as a result of varying Zircaloy melt temperature or core axial noding resolution, eliminating a gaseous diffusion oxidation rate limit or axial conduction, or varying convective heat transfer in the core, refreezing heat transfer coefficient values, minimum oxide shell thicknesses for material holdup or other structure composition (*i.e.*, steel or Inconel).

Significant fractions of the most volatile species (Xe, Cs and I) were released using both the CORSOR and CORSOR-M expressions, with all three classes having nearly equal releases of ~7-11% (with the test data in the lower half of this range, with more I found released than Cs, Xe and Kr). Only the gap inventories were released for the most highly refractory species (*e.g.*, Ce, La and U) for all options, and also for Ru, Mo and Cd in the CORSOR-M version. CORSOR gave higher releases for several classes (Ba, Mo, Cd and Sn, and – to a lesser degree – Ru), while CORSOR-M produced significantly higher release of Te (with data indicating a Te source term somewhere inbetween). CORSOR-Booth predicted significantly lower releases (2-4%) for the most volatile species (Xe, Cs and I) than either of the older CORSOR options, in very good agreement with test data, while the releases of other species (Ba, Te, Cd and Sn) were intermediate between the CORSOR and CORSOR-M predictions. Calculations were done with both the low- and high-burnup CORSOR-Booth default constants, although the CFM fuel in the LP-FP-2 test would clearly lie on the low-burnup side of the expressions.

Different initial gap release times were calculated with the different CORSOR and CORSOR-Booth options in MELCOR, indicating that some differences existed in these source-term sensitivity study calculations prior to clad failure. MELCOR analyses using CORSOR-M (with and without using MELCOR's optional surface/volume correction term) showed identical results up to the time of first clad failure and gap release, but this was not the case in preliminary calculations; a number of code problems had to be identified and corrected to obtain this expected result. We also thought that no differences should exist in calculations varying assorted MAEROS parameters prior to clad failure and subsequent aerosol release, but found that small differences were caused by the effect of the MAEROS input parameter changes on water droplets present in control volume atmospheres during the first portion of the transient (confirmed in a sensitivity study with specification of zero fog density through sensitivity coefficient input.)

Both machine-dependency and time-step studies, and evaluation of the new heat transfer model for partially covered core cells, indicate strongly that additional time step controls must be developed in the COR and/or CVH packages to avoid what appear to be unphysical, numerically-driven liquid level oscillations during core uncovery and dryout, and valve-setpoint over- and undershoots. The Cray, VAX, and SUN and IBM workstations gave very similar results, while the "same" analysis done on a 486-PC gave visibly different results throughout most of the latter half of the transient, primarily due to the increase in both number and magnitude of liquid level oscillations during core uncovery. Increasing the time steps used generally resulted in progressively larger and more numerous liquid level oscillations.

Our results indicate that more separate-effects assessment of MELCOR is needed, particularly for break flow in the early-time thermal/hydraulics and for rapid metal-water reaction during core damage. Numerical effects were significant in both the COR and HS packages for heat transfer under two-phase conditions, in the COR and CVH packages for liquid level oscillations during core dryout, and in the CVH and FL packages for valve setpoint over- and undershoots. New time step control algorithms are now being developed to check and adjust for rapid liquid level changes in control volumes, and for valve setpoint over- and undershoots; preliminary results indicate that these will resolve many of the outstanding difficulties in these LOFT analyses.

This LOFT LP-FP-2 assessment analysis clearly demonstrates MELCOR's ability to fulfill a large portion of its primary intended use, the calculation of severe accidents from full-power steady-state initiation through primary-system thermal/hydraulic response and core damage to fission product release, transport and deposition. After a number of identified code errors were corrected, few nonstandard inputs and no code problem-specific modifications were needed to provide reasonable agreement with test data in all areas considered.

6 Marviken-V ATT-2b/ATT-4 Primary System Aerosol Transport and Deposition

A series of five aerosol transport test (ATT) experiments were done in the large-scale Marviken facility investigating the behavior of vapors and aerosols under typical LWR primary system accident conditions.

MELCOR calculations have been completed for test ATT-2b and are currently underway for test ATT-4. In test ATT-2b [33], the system geometry consisted of a pressurizer and four pipe sections followed by a relief tank, which was used to scrub materials which would otherwise escape the system; the fissium aerosol was injected horizontally, near the bottom of the pressurizer. In test ATT-4 [34], the aerosol was injected into a simulated reactor vessel containing internal structures, whose top was connected by piping to the pressurizer volume and the remainder of the fissium transport system.

The results for test ATT-2b showed that MELCOR could match most of the pressurizer and piping gas and wall temperature histories, after an extra flow path representing internal circulation in the pressurizer was added. Sensitivity studies were done on thermal/hydraulic parameters, such as amount of internal recirculation and wall emissivity, and on aerosol modelling parameters, such as the number of MAEROS components and sections. Both the pressurizer and the downstream piping were subdivided into a number of control volumes as a "best-estimate" model of the facility, and noding studies were done progressively combining volumes until a noding typical of plant calculations was used. Because no data were given on the size of the aerosol particles injected, results have been compared for a range of initial aerosol average diameters; the aerosol deposition results were generally in reasonable agreement with test data when a relatively large initial diameter ($5/mu$m) was assumed.

The MELCOR results for ATT-2b are compared to results from corresponding TRAPMELT2-UK [35, 36, 37], VICTORIA [38] and TRAP-MELT2 [39] analyses in Table 6.1.

Identical calculations for test ATT-2b were run on a Cray, SUN and IBM workstations, VAX and 486 PC, and otherwise identical calculations were run on the SUN using the code-selected time step (generally in the 0.7-0.9s range), and with the user-input maximum allowed time step progressively reduced to 0.5, 0.25, 0.1 and 0.01s. No machine dependencies or time step effects were seen, except for a 5-10% reduction in aerosol deposition using the smallest (0.01s) time step.

7 PNL Ice Condenser Tests 11-6 and 16-11

MELCOR has been used to simulate ice condenser tests 11-6 and 16-11, two of a series of large-scale experiments conducted at the High Bay Test Facility (HBTF) at Pacific Northwest Laboratories (PNL) to investigate the extent to which an ice condenser may capture and retain air-borne particles [40]. Experiment 11-6 was a low-flow test, while experiment 16-11 was a relatively high-flow test; in both tests, ZnS was used as the aerosol and temperatures and particle retention were monitored.

MELCOR results [14] have been compared to experimental data, and also to the results of CONTAIN calculations [41, 42] for these two tests. MELCOR version 1.8LF was used for the final calculations.

Agreement was very good between MELCOR predictions and PNL experimental data. MELCOR particle retention results agreed qualitatively with the data in that the value began at one and decreased quickly, levelled out during the time that the ice was melting, and then finnaly began decreasing again late in the experiment when the ice supply had been exhausted. Quantitative agreement with the experimental results was also excellent, based on the few values given for the experimental particle retention, as shown in Table 7.1. Agreement with

Table 6.1. Cesium Retention in Primary System in Marviken-V Aerosol Trasport Test ATT-2b

		Cesium Retention (% Total Cs Injected)			
Location	Data	MELCOR†	TRAPMELT2-UK‡	TRAP-MELT2¶	VICTORIA§
Pressurizer					
Wall Runoff	1.09				
Bottom	35.04	6.0-37.5			
Lower Wall	3.30	2.1-1.2			
Middle Wall	0.61	2.7-1.6			
Upper Wall	0.60	1.2-0.6			
Top	0.58	0.1			
Total	41.22	12.1-40.8	10-70	87/25/34	27-35
Piping					
LOS4	0.30	0.2-0.1		0.29/0.10/0.11	
LOS5	3.93	12.2-22.1		1.60/0.86/0.94	
LOS6	0.27	1.5-0.6		0.04/0.08/0.05	
Total	4.50	13.9-22.7	10-15	1.9/1.0/1.1	5-10

†0.5-5.0μm range of initial AMMD
‡1-35μm range of initial AMMD
¶0.2/3.4/2.0μm range of initial AMMD
§different pressurizer nodings

temperature data was also excellent, as shown in Figure 7.1, with MELCOR results usually falling within the low-temperature/high-temperature experimental data envelope; the time at which all of the ice in a region melted also was well-predicted by MELCOR.

The MELCOR results were in better agreement with experimental data for particle retention than the CONTAIN results, as indicated in Table 7.1. On average, MELCOR and CONTAIN results were quite similar for the diffuser inlet and outlet temperatures, although differences in nodalization complicate the comparison. Unfortunately, there was no CONTAIN data published or available for temperatures in the ice-condenser region, the region of most interest.

A number of sensitivity studies were performed for each experiment simulation, also. The results of a time step study showed a small time step dependency with the results clearly converging with reduced time steps. No machine dependencies were observed when running the same problems on a Cray-XMP/24, SUN Sparc2, IBM RISC-6000 Model 550, VAX 8650 and 486 PC.

Thermal/hydraulic sensitivity studies examined the effects of varying flow loss coefficients, equilibrium *vs* nonequilibrium thermodynamics, and including SPARC bubble rise physics. Parameters associated with the aerosol input examined through sensitivity studies included number of aerosol components, number of aerosol sections, aerosol particle density and aerosol particle size range. The last set of studies examined the effect of varying input parameters associated with the ice condenser model directly, and included varying the energy capacity of the ice, the ice heat transfer coefficient multiplier, the ice heat structure characteristic length, the number of nodes in the ice condenser heat structure, and radiation heat transfer for the ice condenser heat structure.

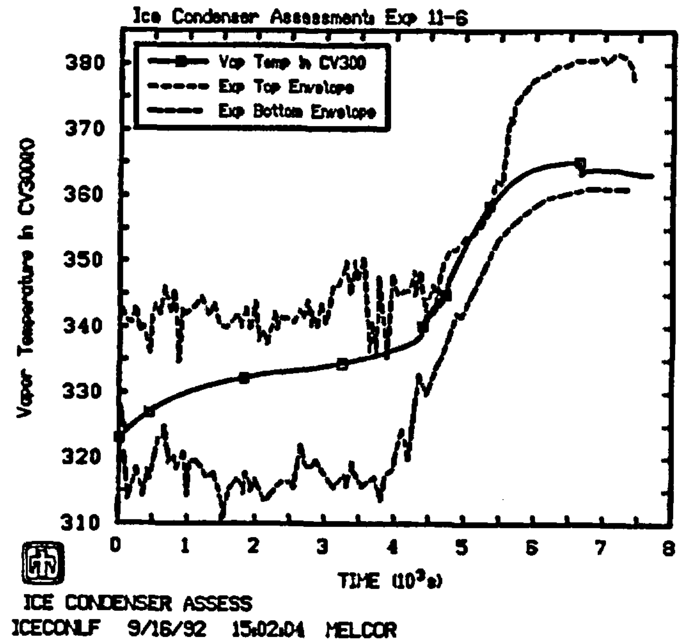
8 Surry TMLB' with and without DCH

As part of the MELCOR Peer Review process [43], Sandia performed and presented a demonstration calculation of a Surry station blackout (TMLB') accident with MELCOR. This was the first fully-integrated PWR severe accident calculation performed with the code (since the TMI analysis only included in-vessel phenomena).

That analysis is continuing, investigating problems identified by the Peer Review (*e.g.*, lack of pressurizer draining prior to vessel breach), evaluating the impact on the results of

Table 7.1. Aerosol Particle Retention in Ice Condenser Tests

	Aerosol Particle Retention (%)					
	Test 11-6			Test 16-11		
Time Period	Data	MELCOR	CONTAIN	Data	MELCOR	CONTAIN
Initial	86	100	-	95.9	100	-
Average	78	80	67.7	93.7	94	89
Final	73	70	67.7	88	91	65



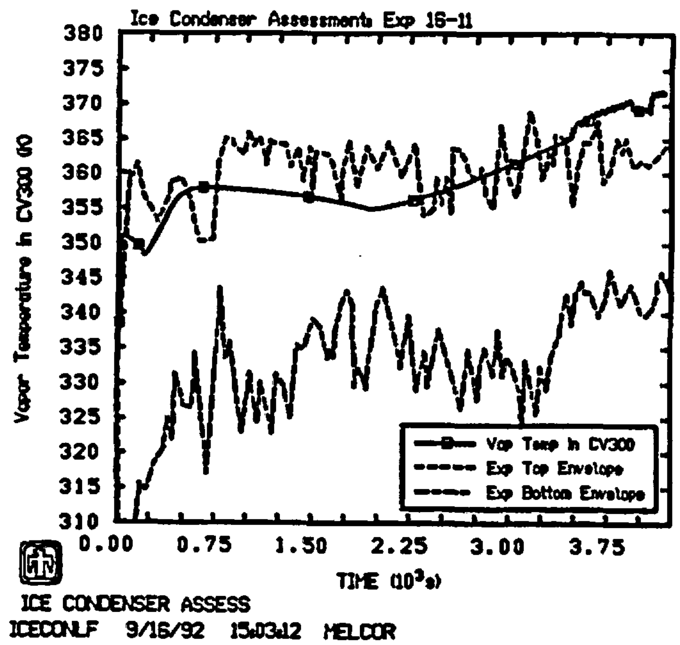


Figure 7.1. Temperatures in Lower Region of Ice Condenser Predicted by MELCOR for PNL Tests 11-6 (top) and 16-11 (bottom), Compared to Test Data Envelope

model improvements and of new models (such as radial debris relocation or direct containment heating due to high pressure melt ejection), and studying noding and modelling sensitivities (for example, comparing releases predicted using the various CORSOR options).

Preliminary sensitivity studies have been done checking for time step and noding effects, and for machine dependencies, and a number of numerics effects have been identified. The reference analysis has been run on a Cray, VAX, SUN and IBM workstations, and 486 PC, and with the code-selected time step and then the maximum allowable time step set by user input to 5, 2.5 and 1s.

In both the machine-dependency and time-step studies, differences were noted early in the transient in the number of times that the steam generator secondary relief valve and, later, the pressurizer PORV cycled. Those differences were traced to differences in over- and undershooting the valve controller setpoint pressures with different time steps and/or different machine accuracies. The tabular function logic was modified to allow step function input, to minimize valves getting caught in a part-open state interpolating between table entries. A time-step controller is now being tested which is intended to limit the time step whenever a valve pressure setpoint is being approached in the control volume. Figure 8.1 shows that this addition to the code's time-step control algorithm significantly decreases the numeric sensitivity, but some small effect still remains to be identified.

The differences seen in timing of key events such as clad failure, core plate failure, lower head penetration failure, *etc.*, in these machine-dependency and time-step studies vary by much smaller times (on the order of 10-100s) than the timestep-variation results presented by BNL to the Peer Review for their Peach Bottom station blackout analysis (which often varied by 1,000-10,000s). A large part of this reduction in numeric sensitivity probably represents the significant efforts of the code developers since the Peer Review in identifying and eliminating numeric sensitivities in MELCOR. Unfortunately, we have no comparable results of time-step studies for the more recent BNL Oconee analyses.

The times of lower core plate and lower head penetration failures are significantly affected by the new debris radial relocation model, with results showing material flowing from all core rings to and through the first core ring to fail the lower core support plate, and then to and through the first ring to fail the lower head. The new direct containment heating model in MELCOR, which models high pressure melt ejection from the vessel into containment, is being used in these PWR TMLB' analyses. Sensitivity studies have been done varying the relative amounts of melt deposited directly in the cavity, in the various containment volume atmospheres, and on various heat structures in the dome, basement and cavity.

A numeric effect recently identified in these PWR demonstration analyses is a big difference (up to 10,000s) in the time that hydrogen burns occur in containment, which in turn can significantly impact on containment failure times and releases to environment, on our machine-dependency and time-step sensitivity studies. This is currently being investigated.

We plan to use a new eutectics model for core material interactions and an in-vessel natural circulation model now being developed for these PWR TMLB' demonstration calculations as soon as available.

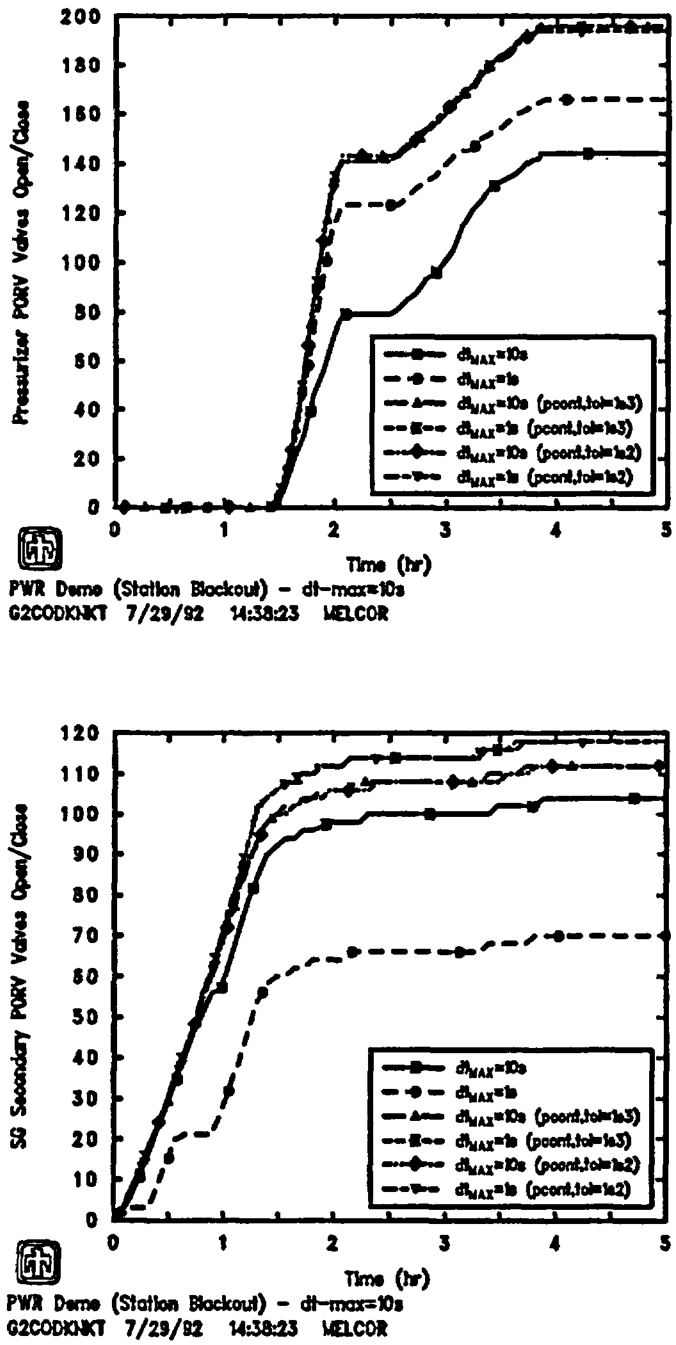


Figure 8.1. SG Secondary and Pressurizer Valve Cycling in PWR TMLB'

9 Summary and Recommendations

The MELCOR assessment program at Sandia is significantly expanding the available MELCOR validation database. A review of MELCOR verification, validation and assessment to date reveals that most of the severe accident phenomena modelled by MELCOR have received or are receiving some evaluation.

Figure 9.1 summarizes the available MELCOR assessment against experimental test data, for in-vessel and containment phenomenology, respectively. Only analyses that are completed or already underway are included; analyses scheduled but not yet begun are not included.

However, in many of these areas, the assessment to date does not cover all phenomena of interest, or is based on a limited number of experiments and analyses which may be insufficient to cover the scales of interest and which may be insufficient to allow identification of experiment-specific problems *vs* generic code problems and deficiencies. Furthermore, there has been no assessment at all of MELCOR for ex-vessel melt phenomena such as core-concrete interactions, debris bed coolability or direct containment heating (although some assessment of the new MELCOR DCH model is planned, and the core-concrete interaction model has had some inherited validation from the standalone CORCON assessment activities). And, although SNL has assessed the new ice condenser model, there has been no assessment against test data for hydrogen burns or for other engineered safety features such as containment sprays and/or fans.

There is no experiment (not even the TMI accident) which represents all features of a severe accident (*i.e.*, primary system thermal/hydraulics; in-vessel core damage; fission product and aerosol release, transport and deposition; ex-vessel core-concrete interaction; containment thermal/hydraulics; and hydrogen transport and combustion), and only the TMI accident is at full plant scale. It is therefore necessary for severe accident codes to supplement standard assessment against experiment (and against simple problems with analytic or otherwise obvious solutions) with plant calculations that cannot be fully verified, but that can be judged using expert opinion for reasonableness and internal self-consistency (particularly using sensitivity studies) and also can be compared to other code calculations for consistency.

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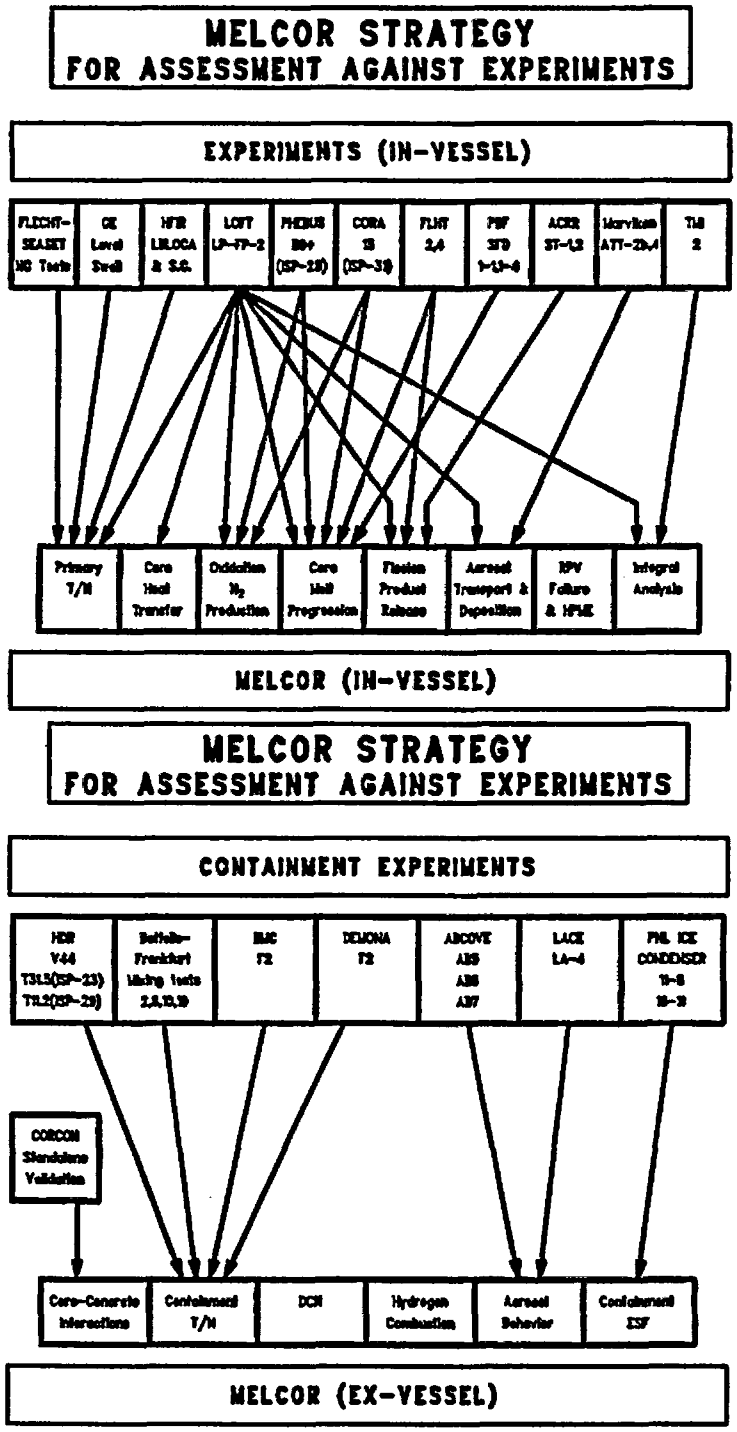

Figure 9.1. MELCOR Phenomena Assessment to Date

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Peak Cladding Temperature in LOFT Large Break Transients[1]

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The fuel centerline temperature data in LOFT large break experiments LP-02-6 and LP-LB-1 were analyzed to determine the bias at peak cladding temperature (PCT) in the cladding exterior surface-mounted thermocouples and the effect of the thermocouple cable on the thermal behavior of the cladding. A statistically determined bias of 11.4 K ± 16.2 K was found in the cladding thermocouples (measured less than actual PCT). The fin effect of the thermocouple cable was determined to be small and within the uncertainty of the data in the blowdown phase of the transients in which PCT occurred. The PCT in LOFT experiments LP-02-6 and LP-LB-1 was determined to be 1104.8 K and 1284.0 K respectively.

Introduction

Data from the Loss-of-Fluid Test (LOFT) Program have been relied upon to quantify the margin of safety inherent in pressurized water reactors during postulated loss-of-coolant accidents (LOCAs). However, questions arose concerning the accuracy of LOFT fuel rod cladding temperature data following the first LOFT large break transient (L2-2)[1] with the core at power. This data was obtained from thermocouples laser welded to the outer surface of the fuel rod cladding. The origin of the concerns was the apparent large cooling of the cladding in the 5 - 15 s interval, during the blowdown phase of the transient, as indicated in the cladding thermocouple data shown in Figure 1. The interval of enhanced cooling subsequently was determined to be real phenomena based on analysis of coolant flow balances which showed that reestablishment of positive core flow can occur[2,3]. This phenomenon was verified through further analytical development and a large break transient (L2-5)[4,5,6] wherein boundary conditions were defined that would prevent the phenomenon from occuring. The cladding temperature in LOFT L2-5 is shown compared to the L2-3 cladding temperature in Figure 2.

The concerns about the cladding temperature data, then, consisted of the following questions:

1. Does a bias exist in the thermocouple measurement of cladding temperature in the thermal-hydraulic conditions of the large break blowdown phase?

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