Sandia National Laboratories

Albuquerque, New Mexico 87185

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to: J. L. Telford and S. B. Burson, USNRC

M Berman Randall K Cole, Jr.

from: M. Berman and R. K. Cole, Jr., 6427

subject: Status of Core Melt Programs -- September-October, 1983

I. Core Melt - Coolant Interactions

1. Presentations and Meetings

Several papers were presented at the International Meeting on LWR Severe Accident Evaluation in Cambridge, Massachusetts (August 28 - September 1): M. L. Corradini and G. A. Moses, "A Dynamic Model for Fuel-Coolant Mixing;" L. S. Nelson, "Steam Explosion Studies with Single Drops of Corium-Related Melts: Ferrous Metals and U- and Zr-Containing Oxides;" M. L. Corradini, D. E. Mitchell, N. A. Evans, "Hydrogen Generation During a Core Melt-Coolant Interaction;" N. A. Evans, "The Effect of Core Melt-Coolant Interactions on Severe Accident Risks in Light Water Reactors." Presentations were made at the Eleventh Water Reactor Safety Research Information Meeting on October 24-28: M. Berman, N. A. Evans, M. S. Krein, "Core Melt-Coolant Interactions: Experiments;" M. Berman, J. M. McGlaun, M. L. Corradini, "Core Melt-Coolant Interactions: Modelling." On October 26, an informal meeting was held between the Sandia FCI team and the cognizant NRC staff (J. Telford, R. Curtis, and R. Wright). FCI experimental and analytical program plans were discussed.

M. L. Corradini attended the Containment Loads Working Group Meeting at Brookhaven on September 15-16. He represented the Core Melt-Coolant Interactions Program and made several presentations on the standard problem calculations and results. N. A. Evans also contributed to this meeting. A Core Melt Information Exchange meeting between the NRC and the Federal Republic of Germany was held at Oak Ridge, Tennessee on October 19-21. Two FCI presentations were made: M. Berman, M. S. Krein, M. L. Corradini, "Core Melt - Coolant Interactions: Overview and Current Experimental Results;" M. L. Corradini, J. M. McGlaun, M. Berman, "Modelling of Fuel-Coolant Interactions."

2. Intermediate-Scale Experiments

(M. S. Krein, M. Berman)

2.1 Introduction

Three steam explosion experiments were performed during the first two weeks of this reporting period. The three experiments included test CM-12, which ended the CM test series, and tests RC-1 and RC-2, which marked the first tests using a rigid container to confine the water. Because the experimental apparatus was destroyed as a result of the explosion produced by test RC-2, no further testing has been possible. An investigation utilizing continuous x-ray observation of an Fe_3O_4/Al thermite burn, in progress, was also begun during this reporting period. The x-ray work was initiated by observed differences in test outcome as an apparent result of variations in one of the melt preparation parameters. This parameter, defined as hold time, is the time between thermite burn termination and melt release.

The results of the three steam explosion experiments, along with the initial test conditions, are discussed below. The preliminary findings of the x-ray studies have also been given.

2.2 Steam Explosion Experiments

2.2.1 Coarse Mixing Test Series - Test CM-12

The purpose of this experiment was to determine if the surface expulsions which had characterized all of the CM series tests were restricted to interactions in nearly saturated water or whether they could also occur in highly subcooled water. The FITS B series did not produce the surface events that have been identified in the CM series, with the possible exception of FITS 6B, which was a low subcooling test. Test CM-12 was therefore set up as a repeat of the FITS 2B experiment, which was a highly subcooled, in-chamber experiment; the objective was to determine if the surface events were primarily limited to hot water tests.

Initial Conditions

The CM-12 experiment was performed using 20 kg of iron-alumina thermite held for 1.5 seconds and delivered to cold water (25°C).

Table 1 lists the initial test conditions.

Table 1
Initial Conditions (CM-12)

1.	Melt	- 20 kg Fe_3O_4/Al
2.	M_c/M_f	- 5.66
3.	Drop height	- 71.5 inches from cylinder down position to water surface.
4.	Water geometry	- 24 x 24 x 12 inches deep-lucite chamber.
5.	Water temperature	- 25°C
6.	Hold time	- 1.5 seconds of the I_3
7.	Crucible lid	- Remained in with "flat drop" release modification to simulate FITS 2B lid entry
8.	External trigger	- None

Note that I_3 is an indicator of burn completion.

Instrumentation

High speed cameras were employed as the only source of data acquisition. Three cameras were used:

1. Low cam - 400 frame/second, 25 mm lens, f5.6/8, #12 shutter, 400 feet VND, 40 seconds film time
2. Hy cam - Looking east, 7500 frames/second, 50 mm lens, f8/11, 400 feet VNX.
3. Hy cam - Looking north, 7,500 frames/second, 100 mm lens, f8/11, 400 feet VNX.

Experiment Control Sequencing

Control sequencing was similar to that used for FITS 2B and is given in Table 2.

Table 2

Experiment Control Sequencing

Time	Event
-5.0 s	Test start
-4.0 s	Tape start
-3.0 s	Visicorder start
-2.0 s	Low cam start
-0-	Ignition
I_3 + 0.0s	Hy cam start (2)
I_3 + 1.5s	Melt drop

Results

Review of the high-speed camera data showed a coherent melt delivery. The crucible lid preceded the melt into the water, although it was angled a few degrees with respect to the water surface. A slight amount of steam was generated upon initial water contact. A surface event occurred at .069 seconds after the melt entered the water and resulted in an upward expulsion of unquenched melt. The upward eruption appeared fairly localized with respect to the water surface--confined to a column with a width less than that of the water surface. The surface event was accompanied by an abrupt increase in the apparent mixing rate of the melt in the water and served to disperse the melt throughout the water chamber. Duration of the surface event was about .013 seconds. Melt penetration depth at the initiation of the surface event was about 20 cm. The melt had been driven near the water chamber base at the time of the surface event termination. A bottom-triggered explosion occurred at .124 seconds of the melt entry - .042 seconds after the melt contacted the water chamber base, and about .055 seconds after the initiation of the surface event. The melt was thoroughly dispersed throughout the water chamber at the time of the explosion. The explosion front traveled through the coarsely mixed region at 600 m/s.

Comparison with Previous Tests

The initial surface event of this experiment resembled, in a general sense, those seen for the hot-water CM series tests. Some differences were, however, observed between the surface event of this experiment and those of low-subcooling tests. The major difference is in the duration of the surface jet; CM-5, for example, produced a surface jet which lasted for about 100 ms and was typical for other low-subcooling tests. The expulsive jet of CM-12, however,

lasted for about 13 ms, much briefer than previous experiments, yet too long to be termed explosive. The surface event of CM-12 was very similar to the event that was seen to precede the bottom-triggered explosion of the cold-water test CM-7. The progression of events and event types for this experiment (CM-12) were not similar to those of the FITS 2B experiment, which produced a single surface-triggered explosion .084 seconds after water entry, and showed no sign of any long duration or nonexplosive expulsion of material. Also, the propagation speed of CM-12 was about a factor of 3 greater than what was observed for the FITS 2 B experiment.

Conclusions

The CM series of tests have demonstrated a rapid expulsion of melt near the water surface. These violent, but nonexplosive events, have not been observed on previous tests. We believe that these expulsions may be explained by either of the following hypotheses: (1) Surface expulsions are common with iron-alumina melts and saturated water. (2) Melt composition, preparation, or delivery, may have changed from the previous tests to produce these surface events.

Note that strong explosions were still observed in several of the iron-alumina/saturated water tests; specifically, CM-8 and CM-9. Explosions were also observed in the two cold water tests, CM-7 and CM-12.

2.2.2 Rigid Confinement Experiments - RC-1, RC-2

The objective of the rigid confinement experiment was to determine what occurred when the expansion phase of the fuel/coolant interaction was radially confined by steel walls. Prior to these confinement experiments, all the FITS and EXO-FITS experiments used lucite water chambers. These lucite chambers offered no structural resistance to the expansion phase of the steam explosion process. Note, however, that Buxton and Benedick had performed steam explosion experiments in large, water-filled steel pipes, buried in the ground. The experimental methods, melt delivery techniques, initial test conditions and instrumentation were sufficiently different that comparison is difficult.

Test RC-2 was a repeat of test RC-1, which had resulted in a nonexplosive interaction--due to the effects of the melt preparation parameter "hold time". The only difference, therefore, between the initial conditions of the two tests was the value of the hold time - 4.0 seconds for RC-1 and 1.5 seconds for RC-2.

Initial Conditions

The initial conditions for the two tests were chosen for their ability to produce energetic steam explosion with the exception of the hold time for test RC-1. Initial test conditions are given in Table 3.

Table 3

Initial Test Conditions, RC-1, RC-2

1. Melt - 20 kg Fe_3O_4
2. M_c/M_f - 5.60
3. Drop height - 70.0 inches from cylinder down position to water surface
4. Water geometry - 22.0 inch diameter x 18.0 inch deep rigid steel chamber
5. Water temperature - 25°C
6. Hold time - RC-1 = 4.0s; RC-2 = 1.5s
7. Crucible lid - left in
8. External trigger - None

The water chamber consisted of a 61 cm OD schedule 60 steel pipe (55.9 cm ID) with bolt flanges on both ends. Total height of the pipe, including the flanges was 94 cm. The pipe was left open on the top, to permit melt entry. The pipe bottom was closed wth a 0.64-cm thick lucite sheet that was glued to the face of the bottom flange. All other parameters were typical of previous experiments in lucite chambers.

Instrumentation

Instrumentation for both experiments included low-speed and high-speed photography and water phase pressure transducers.

Cameras:

1. Low cam, 400 ft/s, 25 mm lens, f5.6/8 400 feet VND
2. East Hy cam, 7000 ft/s, 50 mm lens, f11/8, VNX, 400 ft
3. North Hy cam, 7000 ft/s, 100 mm lens, f11/8, VNX, 400 feet.

Pressure transducers:

(RC-1) 1. Kulite, HKM 375, 10,000 psi, SN 1266-9-218, sensitivity 7.16 x 10^{-3} mv/psi. Amplifier gain = 100. Located 3.0" below the water surface. Mounted in wall.

2. Kulite, HKM 375, 10,000 psi, SN 1266-9-219, sensitivity = 6.64 x 10^{-3} mv/psi. Amplifier gain = 50. Located 14.0" below water surface. Mounted in wall.

(RC-2) 1. Kulite, HKM 375, 10,000 psi, SN 1266-9-219, sensitivity = 6.64 x 10^{-3} mv/psi. Amplifier gain = 100. Located 3.0" below water surface. Mounted in wall.

2. Kulite, HKM 375, 10,000 psi, SN 1266-9-222, sensitivity = 6.90 x 10^{-3} mv/psi. Amplifier gain = 50. Located 14.0" below water surface. Mounted in wall.

2.1.3 Experiment Control Sequencing

Control sequencing was identical for both rigid chamber experiments with the exception of hold time and hy cam starts. The sequencing is shown in Table 4.

Table 4

Experiment Control Sequencing

Time	Event
-5.0s	Test start
-4.0s	Tape start
-3.0s	Visicorder start
-2.0s	Low cam start
- 0 -	Ignition
I_3 + 2.5s (RC-1)	Hy cam start (2)
I_3 + 0s (RC-2)	
I_3 + 4.0s (RC-1)	Melt delivery
I_3 + 1.5s (RC-2)	

Note that I_3 represents the indicator of burn completion.

Results

RC-1

Review of the high-speed film of RC-1 showed a good melt delivery with a minimum of melt breakup prior to water contact. The crucible lid preceded the melt and contacted the water surface face-on. Melt entry velocity was 5.77 m/s.

A small amount of steam was generated at water contact. A surface event began at about .086 s after water entry and continued for about .232 s. The estimated melt penetration at the time of the explosion was 30 cm. The apparent result of the surface event was to eject a large portion of the incoming melt mass upwards - even though 15 kg of coarsely mixed debris was recovered in the chamber. Some of the ejected melt, however, may have fallen back into the water chamber. Of the 15 kg of debris recovered in the chamber, 4.5 kg of it consisted of a single molten slug which appeared to be predominately iron. The remaining 10.5 kg consisted of a loose assortment of spherical particles on the order of a centimeter or less in diameter. The debris will be sieved at a later time.

More than half of the water was found in the chamber following the experiment. The pressure transducers detected no events producing substantial pressures.

RC-2

Melt entry for test RC-2 was very coherent with no indication of excessive melt dispersal. The crucible lid preceded the melt into the water and appeared to impact the water surface face-on. Melt entry velocity, measured from the high film was 5.85 m/s. A surface event occurred .056 s after melt entry and resulted in an upward ejection of the quenched melt. Duration of the surface event was about .130 s. A steam explosion was produced .180 s after the melt first contacted the water surface. The steel water chamber prevented the determination of the trigger location but it probably occurred as melt settled on the bottom. The entire facility, including the water chamber, was lifted about eight feet in the air as a result of the explosion. Also a 1.0-meter diameter circle of the concrete pad underneath the water chamber was crushed and depressed about 15 to 20 cm into the ground. Exit speeds as high as 1000 m/s were observed for at least some fraction of the material. Both pressure transducers were destroyed and severe wall vibration has made a reliable interpretation of their records difficult.

Discussion

The interaction produced by RC-1 was benign and was similar to the types of interactions seen in the hot water CM series test. Although RC-1 was performed in cold water and was, in terms of initial conditions, similar to test CM-12 with the exception of the value of hold time, only limited similarity between the two tests was noted. Both experiments produced the characteristic surface interaction; CM-12, however, progressed from the surface interaction to an energetic steam explosion while RC-1 did not escalate past the surface interaction. Although other factors may be involved, the value of hold time appears to have governed the final outcome of these two experiments.

The peak particle exit velocity of RC-2 ($\simeq$ 1000 m/s), coupled with the destruction of the test apparatus, implies an energy conversion ratio for test RC-2 that may be substantially higher than the conversion ratios that have been determined for previous lucite chamber experiments. A great deal of uncertainty has been involved in the determination of the conversion ratio for RC-2 using the methods and instrumentation that were previously used in the determination of conversion ratios for unconfined experiments. The unexpected result of RC-2 has prompted us to consider new techniques and apparatus for the direct measurement of the work output of a confined steam explosion.

Some variability in the character of the nonexplosive surface event can be found by a comparison of the four cold water experiments performed in the CM and RC test series. Test CM-7, which was performed with the crucible lid removed, and test CM-12, with the lid left on, resulted in very similar surface events followed by vigorous bottom-triggered steam explosions. The surface events of CM-7 and CM-12 were very short in duration, yet not short enough to be termed explosive. Duration of the event in CM-7 was about .020 s, and for CM-12 the surface interaction was about .013 s long. In contrast, the RC experiments experienced surface interactions which lasted about .232 s for RC-1 and .130 s for RC-2. The nature of the surface interaction may be random or it may depend on some factors which cannot yet be identified.

In view of the potential for high levels of direct containment heating as a result of injection of finely fragmented melt particles into the atmosphere from the type of surface event observed in these experiments, a continuing effort will be directed towards understanding the various surface interactions. Current ideas indicate that the

surface interaction may be a function of the nature of the themitically prepared melt as it enters the water. The major argument for this idea is based on the absence of nonexplosive surface interaction during the FITS B series of experiments. Those experiments used a different batch of iron oxide than was used for the CM and RC series of experiments. An x-ray study of thermite burns has been initiated to investigate the nature of the melt just prior to delivery into the water chamber.

2.1.6 Conclusion

The work output of steam explosions similar to the RC-2 experiment may have been underestimated. Of the various phases of a steam explosion, melt entry, course mixing, triggering, propagation, and expansion, the propagation and expansion phases would most likely be affected by rigid confinement. One suggestion is that in an unconfined geometry, the initiation of the expansion phase marks the end of any significant melt-water contact by driving the melt-water system apart. By contrast, the expansion phase of a confined steam explosion may serve to enhance the condition for liquid-liquid contact by driving the liquids together near the walls, rather than apart, thereby allowing more of the melt to participate before escape of the liquids from the interaction region.

3.0 X-ray Observation of Melt Preparation

3.1 Initial Experiments

The results of recent steam explosion experiments, such as the two rigid confinement tests and several of the CM-series tests, have suggested that melt condition upon water entry may influence the final outcome of an experiment. The hold-time parameter has been shown to alter the results of a steam explosion experiment producing, for example, the difference between the results of RC-1 and RC-2. (The hold time for RC-1 was 4.0 seconds and the hold time for RC-2 was 1.5 seconds). It is not known how the hold time affects the FCI. Prior to performing the first x-ray experiment, two theories were put forth to explain how hold time might be affecting the results of the interaction. The first suggestion was that melt temperature may play an important role in the outcome of a fuel-coolant interaction; the bulk temperature of the melt would decrease as a function of the hold time. The time required to produce some temperature drop capable of affecting the outcome of the experiment is unknown as is the temperature drop required. The single drop experiments of Nelson have

shown little dependence on melt temperature in terms of explosibility of iron oxide. Whether the 2.5 second difference in hold time between RC-1 and RC-2 was capable of producing a temperature change which was, in turn, responsible for the results is not known.

The second theory involved the degree of phase separation in the melt prior to water entry. Coupled with the assumption that the oxidic phase of the melt may behave differently than the metallic phase, in terms of explosion triggering and propagation, the relative distribution of species in the melt at water contact may determine the overall nature of the interaction. Since the density of the metallic phase is about two times that of the oxidic phase, the degree of phase separation should be strongly dependent on hold time.

The primary objective of the x-ray investigation therefore, was to visually determine the degree of phase separation as a function of time of the completion of the thermite reaction. A measurement of melt temperature, although not dependent on the x-ray facility or apparatus, was an important secondary objective.

3.1.1 Apparatus and Instrumentation

The x-ray observations were carried out at the Nondestructive Test Facility. This facility contains a Linatian x-ray device which is capable of producing photon energies as high as 10 MeV and at repetion rates of up to 360 hz. The use of a fluorescent screen and video recording equipment produced an image of the reaction with relatively good temporal and spatial resolution. Two optical devices were incorporated in the instrumentation. One of the devices has a response time of 1 millisecond but requires that the emissivity of the melt be known. The second pyrometer has a response time of about 100 milliseconds but, because it is a two-color device, does not require a precise value for the emissivity. The experiments were performed in crucibles similar to those used for the steam explosion experiments.

3.1.2 Results

Three tests have been performed and all three have shown a similar behavior; a vigorous, boiling type of motion was seen to begin immediately after thermite ignition and continue to well after the completion of the reaction. Because of the vigor of the "boiling" no liquid pool was ever observed to form above the advancing burn front. The

vigorous melt action seemed to occur independent of the chemical reaction. Phase separation proceeded rapidly after the melt action had begun to subside--fifteen to twenty seconds after the reaction was complete. The melt remained liquid for quite some time with solidification of the oxidic phase first. No successful temperature measurements have been made.

3.1.3 Discussion

The vigorous melt motion within the crucible appears to be driven by the expansion of gases or vapors within the molten material. Sources for this gas or vapor seem limited to:

a. Boiling of the iron phase of the melt.
b. Boiling or driving off of some impurity - probably associated with iron oxide.
c. Diffusion of gases entrained in the crucible or diffusion of gases through the crucible walls into the melt.
d. Chemical reactions between the melt and the crucible.

The diffusion of gases either from the crucible itself or through the crucible walls seem unlikely. The crucible walls are porous to some degree but it is not known at this time whether or not a quantity of gas, sufficient to produce the observed melt action, could, or even would diffuse through the crucible walls.

The boiling of impurities or the off-gassing of impurities may be the source of the gas generation. The iron oxide used as the major constituent of the thermite mix is an industrial grade that contains certain small quantities of impurities. The boiling of impurities would be consistent with the observed behavior after the reaction was complete. The boiling point of iron is about 3000-3200 K. Heat stored in the oxidic phase may be responsible for maintaining the temperature of the iron at its boiling point for a while after the reaction was complete. An accurate temperature measurement must be made to confirm whether or not the iron was actually boiling.

3.1.4 Conclusion

No phase separation within the time scales representative of hold time seems to occur; the earliest sign of phase separation was observed no earlier than 10-15 seconds after the reaction was complete. The vigorous action of the melt must be understood as it may be responsible for differences in steam explosion results. Future tests will be designed to investigate and define the source of the melt action by a consideration of:

a. Gas diffusion from or through the crucible walls.
b. The boiling or off-gassing of impurities.
c. The boiling of iron.
d. Chemical reactions.

Also a continuing effort to define melt temperature has been planned.

4. <u>Monte Carlo Analysis of Steam Explosions</u>
(M. Berman, D. V. Swenson, A. J. Wickett)

This study was last reported in the March-April bimonthly. Its aims are to provide an uncertainty statement for the conditional probability of containment failure by steam explosions (given core melt) and to identify important contributors to this uncertainty.

A simple parametric model is used to predict the results of an in-vessel steam explosion. Probability density distribution functions are assigned to the uncertain parameters. A value for each parameter is sampled at random from each distribution. The resulting parameter values determine whether containment fails in the model or not. Such trials are repeated many times and the fraction of predicted failures estimates the probability of containment failure conditional on the assigned distributions. The uncertainty in the failure probability is investigated by making different assignments for the probability distributions.

An abstract based on the calculations reported in March-April was submitted in June to the ANS Winter Meeting in San Francisco, 30th October-3rd November 1983.

This concluded that the containment failure probability was very uncertain (calculated values fell in the range 0-33 percent) and that important contributory uncertainties were the amount of molten core participating in an explosion and the conversion ratio. [1]

Following review comments at Sandia these calculations were repeated using different distributions. A topical report was prepared, and drafts were sent to the NRC on July 28 and October 17. [2]

The accompanying tables from the draft report summarize the calculations and numerical results. Each distribution used is flat within the range indicated. The threshold initial velocity for a large missile to fail containment is estimated to be in the range 60-90 m/s, so the numbers in the right hand two columns divided by 10,000 estimate the containment failure probability.

The report concludes that the probabilities of vessel-base failure and containment failure are both uncertain over the whole range from 0 to 1. Four of the most important contributors to the uncertainty in containment failure probability are the conversion ratio, the mass of melt participating in the explosion the likelihood of triggering at high pressure and the failure mode of the vessel top head.

This report is currently undergoing review at Sandia.

References

1. M. Berman, D. V. Swenson, and A. J. Wickett, Monte Carlo Analysis of Steam Explosions, Trans ANS 45, 378-380 (1983).

2. M. Berman, D. V. Swenson, and A. J. Wickett, An Uncertainty Study of PWR Steam Explosions, SAND83-1483, NUREG/CR-3369, draft (1983).

TABLE IV. Main Calculations

	INPUT						CALCULATIONS				FAILURES (per 10,000 trials)			
	Case	Fraction Molten %	Pour Diameter (m)	Pour Length (m)	Slug Condensed Phase Fraction (%)	Conversion Ratio (%)	Mean Explosion Energy (MJ)	Mean Slug Impact Energy (MJ)	Mean Slug Volume (m³)	Mean Slug Mass (1000 kg)	Vessel Bottom	Bolts	Large Missile V>40 m/s	Large Missile V>90 m/s
Full width	1	0-75	0.0-3.4	0.0-3.0	25-100	0-5	504	283	31.5	53.1	2017	466	448	267
All low	2	L(0-25)	L(0.0-1.13)	L(0.-1.)	L(25-50)	L(0.0-1.7)	11	1	9.3	16.7	0	0	0	0
All middle	3	M(25-50)	M(1.13-2.27)	M(1.-2.)	M(50-75)	M(1.7-3.3)	732	400	40.2	61.6	2126	1	1	0
All high	4	H(50-75)	H(2.27-3.4)	H(2.-3.)	H(75-100)	H(3.3-5.0)	3020	2000	22.6	53.0	10000	9987	9987	9959
All	5	L	M	M	M	M	407	211	25.2	28.6	172	0	0	2
Middle	6		L				106	24	16.6	50.3	0	0	0	0
Except	7			L			247	98	24.2	55.1	4	0	0	0
Indiv.	8				L		735	404	69.3	62.0	2087	0	0	0
Low	9					L	248	100	45.0	68.5	5	0	0	0
All	10	H	M	M	M	M	735	364	47.3	92.6	2136	0	0	0
Middle	11		H				1352	683	32.9	43.0	8272	105	105	2
Except	12			H			1070	570	39.0	54.3	5335	62	62	0
Indiv.	13				H		722	396	28.8	62.1	1977	68	68	0
High	14					H	1203	595	31.3	51.9	5804	384	384	84
All	15	L	H	H	H	H	779	434	14.6	22.2	3079	1719	895	0
High	16		L				293	147	19.5	84.0	79	0	0	0
Except	17			L			1116	433	25.1	81.5	5255	460	460	162
Indiv.	18				L		3020	2003	54.6	53.0	10000	4110	4110	4110
Low	19					L	700	392	37.2	87.4	3524	5	5	0
All Low	20	H	L	L	L	L	12	1	34.2	79.4	0	0	0	0
Except	21		H				110	31	38.5	27.3	0	0	0	0
Indiv.	22			H			49	0	19.0	20.5	0	0	0	0
High	23				H		11	1	3.0	16.7	0	0	0	0
	24					H	56	9	9.3	16.7	0	0	0	0

TABLE V. Additional Calculations

	INPUT							CALCULATIONS				FAILURES (per 10,000 trials)			
	Case	Compare with Case Number	Fraction Molten (%)	Pour Diameter (m)	Pour Length (m)	Slug Condensed Phase Fraction	Conversion Ratio (%)	Mean Explosion Energy (MJ)	Mean Impact Energy (MJ)	Mean Slug Volume (m^3)	Mean Slug Mass (1000 kg)	Vessel Bottom	Bolts	Large Missile V>60 m/s	Large Missile V>90 m/s
Heat Content = 0.8 MJ/kg	25	2	L	L	L	L	L	7	1	9.3	16.9	0	0	0	0
	26	3	M	M	M	M	M	484	258	45.3	67.7	220	0	0	0
	27	4	H	H	H	H	H	2259	1320	22.6	53.8	10000	9394	9394	5799
Heat Content = 1.6 MJ/kg	28	2	L	L	L	L	L	15	2	9.3	16.9	0	0	0	0
	29	3	M	M	M	M	M	965	498	35.1	56.1	4118	89	89	18
	30	4	H	H	H	H	H	5109	2865	22.6	53.8	10000	10000	10000	10000
All Un-mixed Melt and Water Above	31	2	L	L	L	L	L	11	1	9.3	16.8	0	0	0	0
	32	3	M	M	M	M	M	106	24	16.6	50.3	2894	0	0	0
	33	4	H	H	H	H	H	3826	2086	22.6	55.8	10000	9993	9993	9966
All Un-mixed Melt and Water Below	34	2	L	L	L	L	L	11	1	9.2	16.7	0	0	0	0
	35	3	M	M	M	M	M	732	424	39.9	59.8	2099	2	2	0
	36	4	H	H	H	H	H	3830	2123	22.4	52.4	10000	10000	10000	9999
Variation of Fraction Molten	37	28	75-100	L	L	L	L	112	1	46.8	111.0	0	0	0	0
	38	10	75-100	M	M	M	M	749	344	54.6	124.0	2252	0	0	0
	39	4	75-100	H	H	H	H	4888	2518	26.8	74.4	10000	9753	9753	9677
Variation of Conversion Ratio	40	2	L	L	L	L	0-5.3	36	5	9.3	16.9	0	0	0	0
	41	3	M	M	M	M	5.3-10.7	2325	1136	26.2	46.4	9284	4304	4295	3053
	42	4	H	H	H	H	10.7-16.0	12292	7211	22.7	53.8	10000	10000	10000	10000
Lower Plenum Failure 500 MJ	43	2	L	L	L	L	L	11	1	9.3	16.9	0	0	0	0
	44	3	M	M	M	M	M	729	243	25.3	49.6	7101	0	0	0
	45	4	H	H	H	H	H	3838	2094	22.6	53.8	10000	9996	9996	9962
Lower Plenum Failure 1500 MJ	46	2	L	L	L	L	L	11	1	9.3	16.9	0	0	0	0
	47	3	M	M	M	M	M	713	490	45.3	67.7	250	0	0	0
	48	4	H	H	H	H	H	3821	2084	22.6	53.8	10000	9994	9994	9953

II. Molten Core/Concrete Interactions
(R. K. Cole, Jr., D. P. Kelly, M. A. Ellis)

1. Presentations

A paper entitled "A Crust Formation and Refreezing Model for Molten-Fuel/Concrete Interactions Codes" was presented at the International Meeting on Light Water Reactor Severe Accident Evaluation at Cambridge, Massachusetts. The paper described the model now contained in the evolutionary version of CORCON and expected to be included in MOD2 when it is released.

A presentation entitled "Status of CORCON-MOD2 Development" was made to the US/FRG Core Melt Technical Exchange Meeting at Oak Ridge, Tennessee which included a description of the freezing model and of a model for (nonexplosive) interactions with an overlying coolant. At the time of the presentation, the latter model was operational, but incomplete in the sense that the effects of ambient pressure on boiling heat transfer were not included.

2. CORCON Development

During the reporting period, a model for interaction with an overlying coolant layer was made operational. The full boiling curve is considered in evaluating heat transfer from the melt to the coolant although, for the problems run to date, only radiation-dominated film boiling has been observed. Addition of coolant has surprisingly little effect on pool behavior in these problems. The melt surface remains extremely hot with heat transfer dominated by radiation. Because the surface radiated to, either the coolant or the above-pool surroundings, is much cooler than the surface of the melt, its temperature (and even its identity) make little difference to the heat flux. In fact, the only significant change in these calculations when coolant is included is that the heat flux, q, from the surface of the pool is converted to a mass flux of q/h_{fg} for as long as the coolant lasts. Of course, this may not be a general result; our experience with the model is still rather limited.

A significant aspect of the implementation of the model into CORCON is that it maintains the implicit nature of the energy equation with respect to inter-layer heat transfer, including vaporization of coolant. It treats both subcooled (nonboiling) and saturated (boiling) coolant. Further, the algorithm includes a consistent treatment for the case where the coolant is depleted (boiled away) during a time step.

As initially implemented, the boiling curve is evaluated at one atmosphere pressure. The extension to include effects of ambient pressure will be made in the near future.

Other changes to the code during the period included conversion to full ANSI77 standard FORTRAN (we believe that no nonstandard code remains). We also introduced a detailed check on conservation of mass and energy within the pool. This was found to be desirable because of the additional complications introduced by boiling of coolant. For our test problems, mass and energy are conserved to within a few times machine round off. No better result is possible for a system in which the total mass and energy change with time because the "error" simply represents the difference in adding up terms in different orders using finite-precision arithmetic.

3. Freezing Model

At the US/FRG meeting, H. Alsmeyer of KfK presented the results of freezing experiments in which a layer of internally heated oil (simulating fuel) was placed over a layer of water (simulating steel) in a dry ice cavity. At sufficiently low-power inputs, the water was observed to freeze from the bottom up. The thickness of the resulting solid crust was a function of power input to the oil. When the crust was thin, gas continued to pass through holes in the ice; when it became thicker, these holes closed up and the crust became impermeable to the gas. This is in agreement with the freezing model in CORCON, although no model for cutting off the gas permeability has yet been implemented in the code. These experiments demonstrate that the CORCON model describes one possible mode of freezing, although other regimes may well exist.

4. Above-Pool Modelling

During this period some time was devoted to the development of a subroutine to predict the gas generation from concrete sidewalls above the melt surface. This involved modification of an existing program we wrote some time ago which employs diffusion theory in a cylindrical enclosure. This calculation involves two-dimensional heat transfer through a participating atmosphere. Because of the design of subroutine ATMSUR, which was coded to facilitate coupling to containment codes, inclusion of this above-pool model was easy. The next step in this effort will include debugging and some scoping calculations.

5. Code Assessment

All tests associated with the MOD1 assessment effort have been completed, and final writing and editing is underway. The major conclusions of this study are summarized below.

This study involved a large number of tests of four basic types: (1) variation of input/initial conditions, (2) numerical stability tests, (3) model sensitivity tests, and (4) selected (specialized) tests of particular code features. Comparisons may be made and conclusions drawn within each of these categories. In general, comparisons between these categories are not meaningful. For example, it would be inappropriate to compare the resulting effects of variations in the initial melt temperature and variations in melt/concrete heat transfer, because the knowledge gained from such an exercise is not useful for code evaluation or future code development. Therefore, this discussion will be structured around the four major areas of tests, without inter-group comparisons.

The section of input/initial conditions tests involved every major input or initial condition required by the code. These tests both demonstrated several user input options not commonly utilized and provided a quantitative comparison of code sensitivity to the various input and initial conditions. The major observations and conclusions drawn from this section of tests include the following:

1. Cavity geometry has a significant effect on the gas composition leaving the molten pool. This is because the gas film adjacent to a wall with an inclination angle greater than 15 degrees is assumed not to chemically react with the melt. For example, a hemispherical cavity produces extremely low amounts of hydrogen and carbon monoxide. This is probably unrealistic.

2. As would be expected, gas generation and basemat penetration are very sensitive to the concrete type. The concretes examined demonstrated that a low ablation temperature does not necessarily imply the greatest capability for gas production.

3. Early deposition of the melt has a significant effect on the results since the decay heat is changing rapidly during this time, while delays in melt deposition (beyond this initial period) have much less of an effect.

4. The initial temperature of the concrete surface significantly influences the heat of ablation calculation. High surface temperatures reduce the heat of ablation resulting in increased cavity erosion.

5. As expected, the concrete ablation temperature is the primary controlling factor in the ablation process, both qualitatively and quantitatively.

6. Concrete emissivity plays a limited role in affecting overall results.

7. An initial melt temperature below the ablation temperature of the concrete results in an execution error (overflow condition). High initial melt temperatures significantly increase concrete ablation and gas generation.

8. The oxidic phase transition calculation considers two components which are (UO_2 and ZrO_2) and (concrete and all other oxides). The properties of the latter component are assumed to be that of the concrete specified in the problem. This clearly breaks down when significant portions of the oxidic phase are made up of other oxides.

9. The metallic phase transition calculation considers three components: Fe, Cr, and Ni. Other metals may be present which are considered in chemical reactions, but for the purposes of the phase transition calculation the melt is normalized so that the three constituents, Fe, Cr, and Ni make up 100 percent of the melt. This is clearly a problem when large quantities of metallic zirconium are present.

10. The key parameter in the internal decay heat calculation is the ratio of the core operating power to the core size.

11. The code results are insensitive to atmospheric conditions, including chemical composition, pressure, temperature, and volume. In fact, the chemical composition and volume of the atmosphere do not enter into any active calculations.

12. The code results are relatively insensitive to the emissivities of the metallic and oxidic phases.

13. Reduction of the emissivity of the surroundings about the pool surface from 1.0 to 0.5 increased concrete ablation by roughly 10 percent.

The next section of tests addressed the numerical stability of the overall code and selected models which are known to be sensitive to the time step value. The following observations and conclusions were made for this section of tests:

14. For the base case problem, a time step value of 30 s appears to be the optimum. Lower values (down to 1 s) result in very little change in code output. Higher values (up to 300 s) result in significant changes in code output. A plot of computation time versus time step was constructed and presented in Figure 20.1.

15. A long-time run (15 hours) was performed which revealed abrupt changes in heat transfer coefficients due to sudden increases in viscosity attributed to the two-phase slurry viscosity multiplier.

16. The cavity/shape change model is explicit in time. Time step values too large result in normal body point projections which may cross adjacent rays giving erroneous results.

17. The principal results of the code are fairly insensitive to the number of rays employed, that is, to the resolution of the cavity geometry.

18. The user should choose the origin of the ray system so that it maximizes the number of rays which intersect the cavity surface as close to perpendicular as possible.

The next section of tests investigated the sensitivity of the code to the major areas of heat transfer modelling and the calculation of material and transport properties. The following observations and conclusions were made:

19. Melt/Concrete Heat Transfer
    Changes in the values of the gas-film heat transfer coefficients for all three regimes, bubbling film, laminar flowing film, and turbulent flowing film are compensated by radiative heat transfer due to the effect of the gas film/melt interface temperature. Therefore, as long as a gas film is assumed to be present, the convective modelling of heat transport across the film has limited influence on the results.

20. Pool Layer Heat Transfer
The code results are the most sensitive to this area of heat transfer modelling. Particularly, increases in layer-to-layer interfacial heat transfer resulted in decreased cavity recession because of the high-melt surface temperature maintained which resulted in large increases in radiative heat transfer from the melt surface to the surroundings. The partition of the decay heat generated in the melt appears to be significantly influenced by this model.

21. Pool Surface Heat Transfer
The principal results are only moderately sensitive to changes in the effective, convective, and radiative heat transfer coefficient.

22. Transport Properties
Mixture viscosity has a significant effect on the calculation of heat transfer coefficients.
The viscosity modelling in CORCON-MOD1 allows abrupt jumps in viscosity causing unrealistic layer temperature behavior. Specifically, sudden increases in viscosity can result in decreased heat transfer coefficients and thermal isolation of the oxidic layer with a characteristic temperature rise. There are two aspects of the viscosity modelling which contribute to this behavior. First, the change from a low-silica to a high-silica oxidic mixture model has no transition, but simply calls a new model at 15 percent silica content resulting in viscosity increases of an order of magnitude in some cases. The second and more frequently observed problem is the use of a two-phase slurry viscosity multiplier which is activated when any interface temperature falls below the liquidus temperature. It is recommended that these models be modified or replaced.
Much like viscosity, the thermal conductivity plays a major role in the calculation of heat transfer coefficients. The models in CORCON appear to give reasonable values and are continuous, well-behaved functions of melt composition. The temperature dependence of thermal conductivity is neglected.
Compared to the viscosity and thermal conductivity, the surface tension has a moderate effect on the code results.

23. Material Properties
Layer-to-layer interfacial heat transfer coefficients and layer bulk-to-side heat transfer coefficients are sensitive to layer density. Particularly, increases in layer density result in increased downward flow of heat in the melt and significant increases in cavity ablation.
Variations in the gas film material properties, both density and specific heat, had little influence on the principal code results.

The final section of tests involved a set of specialized tests specifically designed to probe suspected modelling areas and assumptions in the code. The following observations and conclusions were made:

24. Tests of the chemical equilibrium model; for example, complete depletion of a metallic component by oxidation, showed this package to be susceptible to fatal errors because of nonconvergence. This model tracks many trace species as well as the principal ones resulting in a tremendous scaling problem. When this model converges (which is almost all the time), it gives good answers and is very flexible. However, it is considered overkill.

25. CORCON determines layer orientation solely by layer densities. Therefore, the code allows layers to move around as the ordering of the layer densities dictates. For the majority of cases, CORCON places the heavy oxides (UO_2 and ZrO_2) on the bottom for about one hour, with the metal and concrete oxide layers above. Tests showed that the initial layer orientation is, in fact, important to the overall results. It has a significant effect on radial/axial recession behavior. When the fuel oxides are initially at the bottom, the metallic layer is "insulated" in terms of axial heat transfer, so large radial recession occurs. This large radial recession was absent in the tests where the metals immediately went to the bottom of the melt and stayed there. As would be expected, the generation of gases was also influenced by layer orientation.

Copy to:
M. L. Corradini, U. Of Wisc.
M. Cunningham, NRC, RES
R. T. Curtis, NRC, RES
R. Denning, BCL
G. A. Greene, BNL
C. N. Kelber, NRC, RES
J. T. Larkins, NRC, RES
G. Quittschreiber, NRC, ACRS
D. F. Ross, NRC, RES
Z. R. Rosztoczy, NRC, NRR
M. Silberberg, NRC, RES
T. P. Speis, NRC, RES
D. Squarer, EPRI
R. C. Vogel, EPRI
D. Swanson
T. G. Theofanous, Purdue
R. W. Wright, NRC, RES
6400 A. W. Snyder
6420 J. V. Walker
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6427 D. P. Kelly
6427 M. S. Krein
6427 B. W. Marshall, Jr.
6427 L. S. Nelson
6427 O. Seebold
6444 J. M. McGlaun
6444 S. L. Thompson
6427 M. Berman (3)
6444 R. K. Cole, Jr.