

# Sandia National Laboratories

Albuquerque, New Mexico 87185

date: October 15, 1983

to: T. J. Walker and S. B. Burson, USNRC

*M. Berman* *R. K. Cole, Jr.*

from: M. Berman and R. K. Cole, Jr., 6441

subject: Status of Core Melt Programs -- July-August, 1983

## I. Core Melt -- Coolant Interactions

### 1. Intermediate Scale Experiments (M. Berman, N. A. Evans, M. S. Krein)

#### 1.1 CM Tests, EXO-FITS

Four tests in the EXO-FITS OM series using an oxidic melt have been performed as shown in Table 1. Significant development work was required to obtain a reasonably satisfactory iron oxide melt from a thermite process. A mixture of iron powder and potassium perchlorate produced molten iron oxide by the following reaction, with the KCl product driven off as a vapor:



Initially, this reaction was too vigorous and most of the molten material was ejected through the crucible vents. The addition of a small amount of iron oxide ( $\text{Fe}_3\text{O}_4$ ) to the initial mixture was highly influential in slowing down the reaction rate, and acceptable melts could be prepared with burn times of the order of 60 seconds. This allowed the removal by vaporization of the potassium chloride without available venting problems, but the dense white cloud (KCl vapor) around the test site produced viewing difficulties, which were partly alleviated by using a large fan to assist in dispersing the cloud.

The unanticipated results of the CM tests led us to suspect that the rapid oxidation of the metallic component of the melt might be strongly influencing the triggering and/or propagation of the explosive and non-explosive interactions that were observed. The result of the OM tests, with no metal in the melt, strongly reinforce that suspicion.

Table 1. OXIDIC MELT-WATER INTERACTION (EXO-FITS-OM)

Test (date)	Thermite loaded (kg)	Iron Oxide delivered (kg)	Coolant dimen- sions square x deep (m)	Coolant- mass/ Melt mass ratio	Coolant Temper- ature (°C)	Drop Height (m)	Results
OM-1 (7/28/83)	20	~10	0.44x0.36	~8	28-30	0.64 (no cru- cible lid)	Premature melt entry into water (several kg) resulted in an explo- sion which destroyed the water chamber.
OM-2 (8/2/83)	18	~9	0.53x0.36	~11	~20	0.64 (no cru- cible lid)	Explosion, with signif- icant upward propa- gation through coarse mixed region.
OM-3 (8/4/83)	20.5	~10	0.61x0.36	~10	~20	0.64 (with cru- cible lid)	Similar to OM-2, but deeper penetration of melt into coolant, and apparently more vigor- ous explosion.
OM-4 (8/9/83)	20	~10	0.61x0.61	~22	90	0.79 (no cru- cible lid)	Surface interaction, followed by strong bottom-triggered explo- sion. Persisting smoke problem.

Violent and unambiguous explosions occurred in all OM tests, regardless of water temperature or the presence or absence of the crucible lid. In the first three tests, strong explosions occurred in cold water. In the fourth test, a double explosion occurred in nearly saturated water. This iron oxide/saturated water pair resembled the previous CM-7 test which used iron-alumina/cold water as a fuel/coolant simulant; both resulted in double explosions with a long time interval between the two explosions.

The recent CM and OM tests have illustrated the complex interactions that are possible for various molten fuel/coolant simulant pairs. In previous tests, the independent variables that have proved to be important included: ambient pressure, water mass, temperature and depth, fuel mass, fuel-coolant mass ratio, and possibly drop height (equivalent to melt entry velocity). Although small-scale tests showed a strong dependence on melt composition (especially metal vs oxide), it was believed that above a given melt volume threshold (about 0.5 liters for iron-alumina or corium A+R), a mixed metal-oxide fuel simulant would readily explode. For that reason, the iron-alumina thermite was believed to be a good simulant of corium, and was used extensively. Current tests indicate a distinct possibility that the metallic and oxidic components of the melt may behave differently. Hence, separate test series using purely oxidic and purely metallic melts appear essential for understanding this compositional effect. We have developed an iron oxide melt that appears to work reasonably well. Although we currently have no capability for preparing pure metal melts at the FITS site, we have begun some of the design work.

Recent tests also indicate that contact geometry may play a role in CMCIs. The presence of intervening structure or crusts may affect the mixing, triggering and propagation of explosions. Such scenarios are certainly possible during reactor accident CMCIs.

Small-scale single droplet tests showed that fuel temperature was not an important parameter unless either: crusts have completely covered the molten fuel; or temperatures are so high that dissociation of water and the production of noncondensable gases inhibit film collapse and triggering. Although we believe that this observation should still apply at large scale, a separate investigation of the effect of melt temperature may still be necessary.

Several independent variables that might influence CMCIs have not been investigated at all to date. Some of these would include the effects of reactor geometries (lower plenum structures and clutter, downcomer vent paths, rigid container walls, etc.), the effects of very high ambient pressures, and the effects of very large scales.

## 1.2 ACM Tests, EXO-FITS

The CMCI program has always planned to investigate the interactions that might occur in alternate contact modes (reflood, sprays, etc.). In July, George Greene met with us to discuss some recent experiments he conducted at Brookhaven. When water was poured on molten lead, bismuth, or Wood's metal, vapor explosions were frequently observed. To support these observations, and to investigate the potential for such explosions using iron-alumina thermite-generated melts, we quickly performed two scoping experiments in the ACM series (Alternate Contact Mode). In the first of these tests, a violent explosion occurred after only about 0.5 liters of water had been poured on the melt. In the second test, no explosion occurred. These tests will be discussed in more detail in the next bimonthly.

## 2. Computer Simulation of Steam Explosions (M. J. McGlaun)

Several calculations were performed to investigate the effect of confinement of the liquid water. Each calculation was a modification of the FITS 9B simulation run number 2.06. The 2.06 calculation was felt to simulate most of the early-time measured data.

In the first calculation, number 3.01, the lucite walls confining the liquid water were replaced by rigid walls. The lucite walls were not simulated in the 2.06 calculation. The rigid walls forced the liquid water to move upward rather than radially as in calculation 2.06. The calculation was run to 12+ ms, at which time the kinetic energies had peaked. Table 2 contains the peak kinetic energies of the materials involved.

The second calculation, number 3.02, was identical to 2.06 except for the addition of a layer of liquid water above the mixing region. The layer was as thick as the liquid water on the sides of the mixing region. The mixing region was completely surrounded by liquid water. This resulted in increased kinetic energy in the liquid water and decreased kinetic energy in the steam and air. The calculation was run to 11+ ms, at which time the kinetic energies had peaked at the values shown in Table 2.

The third calculation, number 3.03, was identical to 2.06 except for the removal of the pedestal where the container of liquid water sat. This removed any confinement from around the liquid water/mixing region. In this calculation the liquid water/mixing region was initially suspended in mid-air. Much of the high pressure steam from the mixing region vented downward. In earlier calculations, the rigid base prevented downward venting. This resulted in a larger kinetic energy in the steam, and a lower kinetic energy in the liquid water. The pressure profiles in the air above the mixing region were very similar to those seen in the original 2.06 calculation. The

calculation was run to 11+ ms, at which time the kinetic energies had peaked, as shown in Table 2. Note that the peak kinetic energy for all materials is generally less than the sum of the individual peaks for each material because they occurred at different times.

Table 2. COMPARISON OF CSQ CALCULATIONS

Calculation number	2.06	3.01	3.02	3.03
Mass of water in mixing region (kg)	36	36	36	36
Mass of water not in mixing region (kg)	100	100	134	100
Melt energy (MJ)	53	53	53	53
Energy deposited in mixing region (MJ)	25.2	25.2	25.2	25.2
Peak K. E. in liquid water (MJ)	0.85	0.32	1.10	0.74
Peak K. E. in steam (MJ)	0.65	0.57	0.33	0.78
Peak K. E. in air (MJ)	0.14	0.11	0.032	0.14
Peak K. E. (MJ)	1.50	0.85	1.37	1.50

3. CMCI Modelling - a Critique of the paper "Interpretation of Large-Scale Vapor Explosion Experiments with Application to LWR Accidents", by H. K. Fauske and R. E. Henry (M. L. Corradini, M. Berman)

During this time period we completed the SARRP work requested by Dr. A. Benjamin of Division 6413. We are also continuing in our development of models to understand steam explosion phenomena. At the end of August the International Meeting on LWR Severe Accident Evaluation was held in Cambridge, Massachusetts. We presented a number of papers in the area of fuel-coolant interactions. Other researchers in this area presented their results and findings. One paper in particular was presented (Interpretation of Large Scale Vapor Explosion Experiments with Application to LWR Accidents, H. K. Fauske, R. E. Henry) which advanced some unique ideas on fuel-coolant mixing phenomena. At this time, we feel a brief critique of this work is needed.

The major tenets of this paper were that "large quantities (many tons) of the molten fuel and the coolant must be finely intermixed prior to any significant energy transfer," and that "premixing on such a scale can readily be ruled out on the basis of first-principle arguments," thereby negating the need for larger-scale experiments. The basis of these conclusions is that "the presence of large subcooling (reflected in the increase in  $q_{CHF}$ ), relatively lower melting point (reflected by a decrease in  $q_{FB}$ ) and higher fuel superheat ( $\Delta T_g$ ) contribute to the large predicted difference in 'explosivity' potential between the current thermite/water system tests (i.e.



referring to Sandia FITS tests) and the LWR system (i.e. corium/saturated water).<sup>\*</sup> To examine these conclusions in detail one must look at the differences between the thermite/water systems used in the FITS experiments and the 'actual' corium/saturated water LWR system. To do this let us first list the various constituents of each system, its properties and possible initial conditions. Then let us look at each point in reverse order; i.e. first  $\Delta T_g$ , then  $q_{fg}$ , then  $q_{CHF}$ .

The properties of the two thermite fuel/water systems and the 'actual' corium/saturated water LWR system are given in Table 3 along with what one presumes the authors of the paper assumed for their study.

Before we discuss the models presented in Fauske's paper let us look at the 'actual' corium fuel he seems to use in his calculations and that used in FITS tests and likely to be in the reactor. Note first that a single melting point has been assigned to corium, namely 2800 K. According to Reference 1, the melting point of stoichiometric  $UO_2$  is 3133 K; stoichiometric  $ZrO_2$  melts at 2946 K. A eutectic melting point occurs at 2825 K. Hence, it appears that Fauske has assumed an approximately equal mixture (on a molar basis) of fully oxidized  $UO_2$  and  $ZrO_2$ . It is our belief that the MAAP code frequently predicts only about 20% of the zirconium is oxidized prior to core slumping for many accidents. Under those conditions, one would expect to find a melt composed of a non-stoichiometric ternary mixture of uranium, zirconium and oxygen. Such mixtures show a range of melting temperatures from as low as 1800 K to as high as 3133 K.<sup>1</sup> One could also expect to find significant fractions of molten stainless steel in "typical LWR coriums". Hence, it is not an exaggeration to consider that the uncertainty in corium melting temperatures covers a range in excess of 1300 K (excess depends on superheat), and that actual temperatures will depend on accident scenario.

Fauske assumes a maximum fuel superheat of 400 K, corresponding to a maximum  $T_f$  of 3200 K. If the mixture were indeed composed only of the two stoichiometric oxides,  $UO_2$  and  $ZrO_2$ , then the maximum melt temperature would not exceed 3200 K.<sup>1</sup> 400 K of superheat would correspond to  $T_f = 3600$  K. If unoxidized zirconium metal was available, temperatures could greatly exceed 3200 K if steam were available to oxidize the metal. The heat of reaction is significant, and would be released coincident with the molten fuel-coolant interaction. If steel were present, its rapid boiling at about 3200 K\* might tend to limit the maximum fuel temperature. However, the steel would also be available for exothermic reactions with steam.

<sup>\*</sup>We have reviewed eight references for the boiling point of iron and found values ranging from 3000 K to 3273 K! The National Bureau of Standards currently uses 3135 K, information received via telephone.

Table 3. FUEL-COOLANT PAIRS CONSIDERED

Property	FITS IRON-ALUMINA	FITS IRON-OXIDE	FITS CORIUM-A+R	ACTUAL CORIUM	CORIUM IN FAUSKE PAPER
Fuel	$\text{Fe-Al}_2\text{O}_3$	$\text{Fe}_3\text{O}_4$	$\text{UO}_2\text{-ZrO}_2\text{-SS}$	U-O-Zr, SS	$\text{UO}_2, \text{ZrO}_2$
Composition	55w/o, 45w/o		53w/o, 17w/o, 30w/o	UNKNOWN*	Not given
Melt Temp (K)	1800, 2300	1800	2750-2800, 1800	1800-3100, 1800	2800
Density <sup>+</sup> (kg/m <sup>3</sup> )	3800	3500	7000	Depends on comp.	Not Given
Specific Heat <sup>+</sup> (J/kg-K)	1060	880	587	Depends on comp.	Not Given
Thermal Cond. <sup>+</sup> (W/m-K)	22	4	6.5	Depends on comp.	Not Given
Emissivity <sup>+</sup>	0.5-0.7	0.7	0.5-0.7	Depends on comp.	1
Heat of Reaction (MJ/kg H <sub>2</sub> )	16	---	20	20 for SS 150 for Zr	Neglected
Fuel Temp (K)	2700-3200	> 2000	2700-3200	1800-3600	2800-3200
Coolant	Water		Water	Water	Water
Initial Temp <sup>#</sup> (K)	280-367		280-300	298-620	373

# In the FITS hot water tests the water temperature has been raised to saturation at Albuquerque ambient pressure (0.83 b).

+ Homogeneous average quantities.

\* Actual corium may be a complex mix of the quaternary U-O-Zr-SS system, depending on the extent of Zr oxidation before melting & stainless-steel structure melted.

Furthermore, by neglecting the presence of stainless steel in the "corium," credit could not be taken for the latent heat of evaporation of the steel. Overall, we concluded that the fuel temperature could range from 1800 K to 3600 K or higher.

The water used in the FITS and earlier Buxton-Benedick tests ranged from highly subcooled to saturated. Explosive and non-explosive interactions were observed throughout all temperature ranges. Furthermore, as discussed in this bimonthly and previous ones, melt composition plays a major role. In this bimonthly, we note that an energetic double explosion was observed for a purely oxidic melt in saturated water.

Now let us address the other reasons individually. First, it is asserted that the length scale for premixing is on the order of 1 cm. Fauske bases this value on the notion that hydrodynamic fragmentation due to relative velocities causes the rapid fuel breakup ( $T^+ = 3$ ); see Eq. 1 of the paper. This is curious considering one still does not know the actual fuel fragmentation mechanism; in fact, Fauske has historically rejected hydrodynamic fragmentation and instead proposed a breakup mechanism due to spontaneous nucleation. Therefore, the quoted length scale is highly arbitrary because it depends on the mechanism and an assumed breakup time of 1 ms and a relative velocity of 100 m/s. We think that the premixing scale may be much larger or smaller depending on the initial conditions and geometry (1 mm to 0.2 m).

Second, Fauske contends that the time to solidification of the fuel surface must be considered as the limit to premixing. At that time premixing would stop because the fuel would begin to solidify. He suggests this time is given by (his Eq. 2)

$$t \equiv \frac{1}{\pi a_{t_f}} \left[ \frac{k_f (T_f - T_{fm})}{q_{FB}} \right]^2$$

where  $a_{t_f}$  is the fuel thermal diffusivity

$k_f$  is the fuel thermal conductivity

$T_f$  is the fuel temperature

$T_{fm}$  is the melting temperature

and  $q_{FB}$  is film boiling heat flux (Fauske Eq. 4).

$$q_{FB} = \sigma (T_{fm}^4 - T_{sat}^4) + h_f (T_{fm} - T_{sat})$$



where  $\sigma$  is the Stefan-Boltzmann constant  
 $\epsilon$  is the fuel emissivity  
 $T_{sat}$  is the coolant saturation temperature  
 $h_f$  is the film boiling heat transfer coefficient

Now using his assumptions,  $\epsilon = 1$ ,  $T_f - T_{fm} = 200$  K for 'actual', and  $q_{FB} \sim 3$  MW/m<sup>2</sup>, one concludes that the 'actual' corium/saturated water system has much less time (factor of 60) than the thermite/water system for mixing before solidification occurs. This conclusion is very questionable precisely because of these assumptions. The emissivity is probably not one but rather  $\sim 0.5$ . The amount of superheat for the fuel could be as little as 200 K or as great as 1800 K for reasons discussed previously. The actual film boiling heat flux is the same for both fuel systems because their temperature range and emissivities are similar (1.5 to 3 MW/m<sup>2</sup>). Now if one uses Fauske's criterion of Table 1

$$\left( \frac{q_{FB\_LWR}}{q_{FB\_THERMITE}} \right)^2 \left( \frac{(T_f - T_{fm})_{THERMITE}}{(T_f - T_{fm})_{LWR}} \right)^2$$

we get that the ratio of premixing time up to fuel solidification for thermite to 'actual' corium ranges between 0.1 to 10. This implies that the available time for premixing can be more for corium or less when compared to the FITS thermite system.

As noted previously, the Fauske/Henry paper completely neglected the effects of chemical reactions. If we account for steel and zirconium oxidation we must remember that the fuel can actually heat up rather than cool down due to metal oxidation. Nelson presented experimental evidence of this possibility at the Cambridge meeting. This suggests that realistically the 'actual' corium could heat up and the limit to the mixing time would not be fuel solidification at all, at least for the metallic fraction.

Finally, Fauske compares the potential for intermixing for an 'actual' corium/saturated water system and the thermite/water system by comparing the film boiling heat flux,  $q_{FB}$ , and the pool boiling critical heat flux,  $q_{CHF}$ , for each system. His point is that because water is subcooled in some FITS tests (not all), then  $q_{CHF} > q_{FB}$  and mixing is allowed to occur; in the actual corium/saturated water system,  $q_{FB} > q_{CHF}$ , and mixing is not allowed. This conclusion is questionable on two counts. First, it is a dubious assertion that the pool boiling critical heat flux is the proper measure to compare fuel film boiling heat flux against. What is so important about  $q_{CHF}$ ? It is only important insofar as it represents a

qualitative limit of steam outflow from the fuel-coolant mixture and water inflow (counter-current, one-dimensional). The actual limit to counter-current steam-water flow into the mixture is the vapor/gas mass flux, not the energy it carries. The major fallacy is that during mixing the fuel and coolant may not mix by counter-current steam outflow and water inflow. Rather, steam flows out the top of the mixture and water flows in from the sides and bottom of the mixture (an unambiguous experimental observation). This inherent difference calls into serious question the use of  $q_{CHF}$  as a measure of the ability of a fuel-coolant system to mix. Rather, fuel and coolant liquid fluidization by the steam mass flux upward may be the limit to mixing. We have already developed models for this situation indicating that substantially more mixing is possible than Fauske contends (see "A Dynamic Model for Fuel-Coolant Mixing", M. L. Corradini, G. A. Moses, Cambridge Meeting).

Second, even if one assumes  $q_{CHF}$  is a reasonable measure of mixing to compare  $q_{FB}$  to, one finds Fauske's comparison to be erroneous. Earlier, we emphasized that  $q_{FB}$  is actually the same for the thermite or 'actual' corium system (1.5 to 3 MW/m<sup>2</sup> depending on  $\epsilon$ ); this is an obvious error in Fauske's analysis. Additionally, new experiments at Sandia (EXO-FITS CM and OM series, a total of 13 experiments to date, many with saturated water) indicate that mixing does occur with thermite/saturated water system even when  $q_{FB} > q_{CHF}$ . Steam explosions have also been observed in saturated water with oxide melts (OM tests) and iron-alumina (reference 2). Thus, the supposed limit to mixing requiring that  $q_{FB} < q_{CHF}$  for fuel-coolant system is invalidated.

This suggests to us that the thermite/water systems (subcooled and saturated water, iron-alumina and corium-A+R) are excellent simulants for the 'actual' corium in a core melt accident.

One final comment should be made. In the final sentence of the paper, Fauske says that the "vanishingly low 'explosivity'" potential indicated for the LWR system is consistent with experimental findings: no propagating vapor explosions have been observed with the corium/saturated water system." In fact, at the FITS facility, no such experiments have yet been attempted. Our observations of the explosivity and conversion ratios of corium A+R/cold water systems led us to believe that they were extremely similar to the iron-alumina/water systems. Explosions have been observed for iron-alumina/saturated water.<sup>2</sup> Since corium tests are much more expensive than iron-alumina, such test are performed less frequently. However, higher priority will be assigned to corium/saturated water tests in future experiment planning.

## II. Molten Core/Concrete Interactions

(R. K. Cole, Jr., D. P. Kelly, M. A. Ellis)

### 1. CORCON Development

Our code-development efforts during this period concentrated on resolving the convergence problems in the crust-formation/freezing calculation which were described in our May-June letter. This involves an iterative calculation to determine the thickness and temperature of the liquid portion of a crusted layer. Through modification of the backup "bound-and-bisect" algorithm which is used when the primary Newton iteration fails, we were able to obtain a solution in all cases tried, including those for which the previous method failed. While the possibility of future problems remains, we believe the present solution procedure is probably adequate, and will move on to implementation of the other models required for CORCON-MOD2.

During a meeting with Brad Burson and George Greene (BNL) in July, several decisions were reached concerning further code development efforts. It was determined that a stable overlying coolant layer should be included, despite George's observation of vapor explosions in some simulant experiments, and that chemical reactions should be included between the flowing gas film and the melt (in current versions of the code, only gas bubbles are permitted to react). These modifications should be relatively straight-forward; in particular, much of the structure and logic for the coolant layer is already included (but bypassed) in the code. If possible, interfacial heat-transfer relations will be modified to include the results of the BNL simulant experiments and the phase diagram for oxidic mixtures improved.

We also agreed that current CORCON validation will have to be based on the available transient test data. Because the duration of these tests is typically comparable to the time necessary to achieve the quasi-steady ablation regime assumed in CORCON modelling, this will require the inclusion of a transient concrete-response model. There are models in existence (notably SLAM, the Sandia Limestone Ablation Model) which include the effects of water migration. However, the detailed two-dimensional concrete-recession calculation in CORCON would make application of these models extremely expensive both in computing time and storage. There is a possibility that a simpler transient-conduction representation might be adequate. The decision on what model should be incorporated was deferred pending the outcome of scoping calculations with SLAM.

### 2. Assessment

During this reporting period the final set of input/initial conditions tests was completed. These included the following

tests: (1) mass of oxidic species, (2) mass of metallic species, (3) core size and operating power, (4) atmospheric gas volume, (5) atmospheric gas pressure, (6) atmospheric gas temperature, (7) chemical composition, (8) oxidic phase emissivity, (9) metallic phase emissivity, and (10) surroundings emissivity.

The first two tests which examined the specification of the oxidic and metallic phase compositions brought to our attention the major shortcomings associated with the phase transition calculations for both oxidic and metallic mixtures. The oxidic mixture phase diagram is constructed by considering a binary mixture whose components are ( $\text{UO}_2$  and  $\text{ZrO}_2$ ) and (concrete and all "other oxides"). For the latter component, the properties of either a user-specified or one of the three default concretes is used. This clearly is questionable when a large quantity of "other oxides" are present in the melt, for example, iron oxides from in-vessel oxidation of molten structural materials.

For metallic mixtures, CORCON-MOD1 consider three principal constituents: Cr, Fe and Ni. The liquid-solid phase transition is calculated by a simple fit to the ternary phase diagram for this mixture. The presence of other elements in the metallic phase are ignored, and the mixture normalized so the sum of the mole fractions of these three constituents equals one. Clearly, any metallic melt which contains a large fraction of any metal other than Cr, Fe, and Ni will result in a great deal of uncertainty regarding the accuracy of the phase transition calculations. The most probable case where this could be a problem is the presence of metallic zirconium from molten fuel rod cladding. For most cases, the zirconium is considered to be almost entirely oxidized prior to deposition of the melt into the reactor cavity.



References

1. "Core-Meltdown Experimental Review," NUREG-0205, SAND74-0382 (Revision), March 1977.
2. L. D. Buxton, W. B. Benedick, "Steam Explosion Efficiency Studies," NUREG/CR-0947, SAND79-1399, December, 1979.

Copy to:

M. L. Corradini, U. of Wisc.  
M. Cunningham, NRC, RES  
J. L. Telford, NRC, RES  
R. W. Wright, NRC, RES  
D. F. Ross, NRC, RES  
T. P. Speis, NRC, NRR  
Z. R. Rosztoczy, NRC, NRR  
R. T. Curtis, NRC, RES  
R. Denning, BCL  
C. N. Kelber, NRC, RES  
J. T. Larkins, NRC, RES  
A. Marchese, NRC, NRR  
J. F. Meyer, NRC, NRR  
G. Quittschreiber, NRC, ACRS  
M. Silberberg, NRC, RES  
D. Swanson  
T. G. Theofanous  
G. A. Greene, BNL  
D. Squarer, EPRI  
6400 A. W. Snyder  
6422 D. A. Powers  
6424 K. D. Bergeron  
6425 W. J. Camp  
6425 W. Frid  
6425 A. J. Wickett  
6425 M. F. Young  
6440 D. A. Dahlgren  
6441 M. Berman (3)  
6441 D. P. Kelly  
6441 M. S. Krein  
6441 B. W. Marshall  
6441 L. S. Nelson  
6441 R. K. Cole, Jr.  
6444 J. M. McGlaun  
6444 S. L. Thompson