FNP-PAL-052

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September 21, 1979

Mr. Robert L. Baer, Chief
Light Water Reactors Branch No. 2
Division of Project Management
U.S. Nuclear Regulatory Commission
7920 Norfolk Avenue
Bethesda, Maryland 20852

P. B. Haga
Director
Plant Analysis & Licensing

Re: Docket No. STN 50-437; Revision 2
to OPS Report 36A59

Dear Mr. Baer:

Transmitted herewith are seventy (70) copies of Revision 2 to Offshore Power Systems Topical Report 36A59, "FNP Core Ladle Design and Safety Evaluation". This revision responds to the comments of Sandia Laboratories transmitted by your letter of June 5, 1979. The content of Revision 2 also reflects the discussions which took place in a meeting between Offshore Power Systems, the NRC Staff and Sandia personnel on July 24, 1979.

Very truly yours,

P. B. Haga

P. B. Haga

/lel

CC: V. W. Campbell
P. B. Haga

Attachment

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Offshore Power Systems Responses to
ACRS Letter Dated July 25, 1979

ERRATA

p. 4 Change "fire" to "fibre" in line 12.

p. 7 Change "critique of" to "critique (Reference 15) of" in line 12.

p. 10 Change "Figures 9 and 10" to "Figures 12 and 13" in line 17.

p. 11 Change "Figure 10" to "Figure 13" in line 2.

p. 13 Add "(Reference 9)" to the end of line 3 of the response.

p. 16 Replace with new page.

p. 23 Change "ZrO_2 anchor bricks" to "ZrO_2." in line 13 of the response.

p. 27 Change "1700°C" to "1690°C" in line 10 of the response.

p. 30 Change "of - quartz to - quartz" to "of - quartz to quartz" in line 21.

p. 40 Change "subcritical." to "subcritical and cooled." in line 8.

p. 41 Change "SG Compartment" to "Safeguards Compartment" at the bottom of the page.

p. 50 Change "indirect" to "inadvertant" in line 22.

p. 54 Replace with new page.

p. 56 Change "or" to "on" in line 8.

p. 60 Change "Further, the containment..." to "Further, it was shown in the LPGS that the containment..." in line 7 of the response.

p. 63 Change "reference (12)" to "reference (17)" in line 6 of the response.

p. 66 Change "comments on FES-III" to "comments on the Revised Draft FES-III" in line 6 of the response.

p. 67 Change 30A59 to 36A59 in Reference 2.

p. 68 Change "6130178" to "6/30/78" in the last line.

p. 70 Replace with new page.

p. 72 Delete asterisks (*) from the FNP column (in three places).

p. 72 Change "flow" to "floor" in the second line of note (1).

p. 76 Change item 3 to read "3. SPACE OVER SAFEGUARDS".

Figure 16 Replace with new sheet.

Figure 19 Replace with new sheet.

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Question a.3.(b)

Discuss the consequences of Item 2 with respect to loss of hearth capacity.

Response

The ladle volume was originally established as 980 cubic feet based on core melt constitutents given in Table IV-1 of Reference 2. Ongoing evaluations have shown that a substantial fraction of the reactor vessel and internals may melt during the debris retention period. Table 2 lists the total weight and estimated (molten) volume of steel in the reactor vessel and appurtenances. The ladle volume of approximately 4000 cu ft is adequate to contain the entire fuel assembly volume plus 93% of the total available volume of additional materials listed in Table 2.

The new ladle configuration has been developed within the existing constraints of the reactor cavity steel structure by altering the bend radius of the incore instrumentation from a 12 to an 8 foot radius. Offshore Power Systems believes the change in configuration of the ladle within the major constraints of the existing FNP design demonstrates considerable latitude and flexibility to respond to changes that may be dictated in the more detailed design phase.

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schedule and the 10 operating ships were retrofitted during the first refueling activity, all within the existing hull and compartmentation envelope. Further, the change in mission objectives for the Fleet Ballistic Missile Program resulted in approximately 30 submarines being subjected to major retrofits during conversion from the Polaris to the Poseidon missile launch capability. Finally, the Ship Life Extension Program (SLEP) presently underway by the Navy to overhaul the Forrestal Class Aircraft Carrier is a very extensive retrofitting program to extend the service life of the ship from 25 to 35 years. The estimated cost (approximately 500 million dollars per ship) illustrates the magnitude of changes which can be accomplished on such vessels.

The above examples provide assurance that the FNP can be retrofitted to accommodate changes without degrading the safety or operability of the plant. When comparing the ratio of equipment and distributive system density between the FNP and complex marine vessels, Navy vessels in particular, it is felt that the arrangement of the FNP and the segregation and separation of systems afford a high probability that needed design changes can be accomplished to satisfy future requirements.

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TABLE 2

REACTOR VESSEL AND INTERNALS

WEIGHT AND VOLUME

Source	Weight (lbs)	Volume (ft^3)*
Reactor Vessel	700,920**	1752
Reactor Vessel Head	159,500	399
Studs, Nuts, Washers, etc.	45,100	113
Lower Internals	252,000**	630
Upper Internals	153,000	382
Bottom Mounted In-Core Instr.	12,000	30
CRDM's	74,000	185
R.V. Insulation	1,000	3
U.H.I. Piping	8,300	21
Lifting Rig & Seismic Support	72,000	180
TOTAL	1,477,820	3695

*Steel density of 400 #/ft^3 is assumed.
**Includes the steel listed in Table IV-1 of Report 36A59, reference (2).

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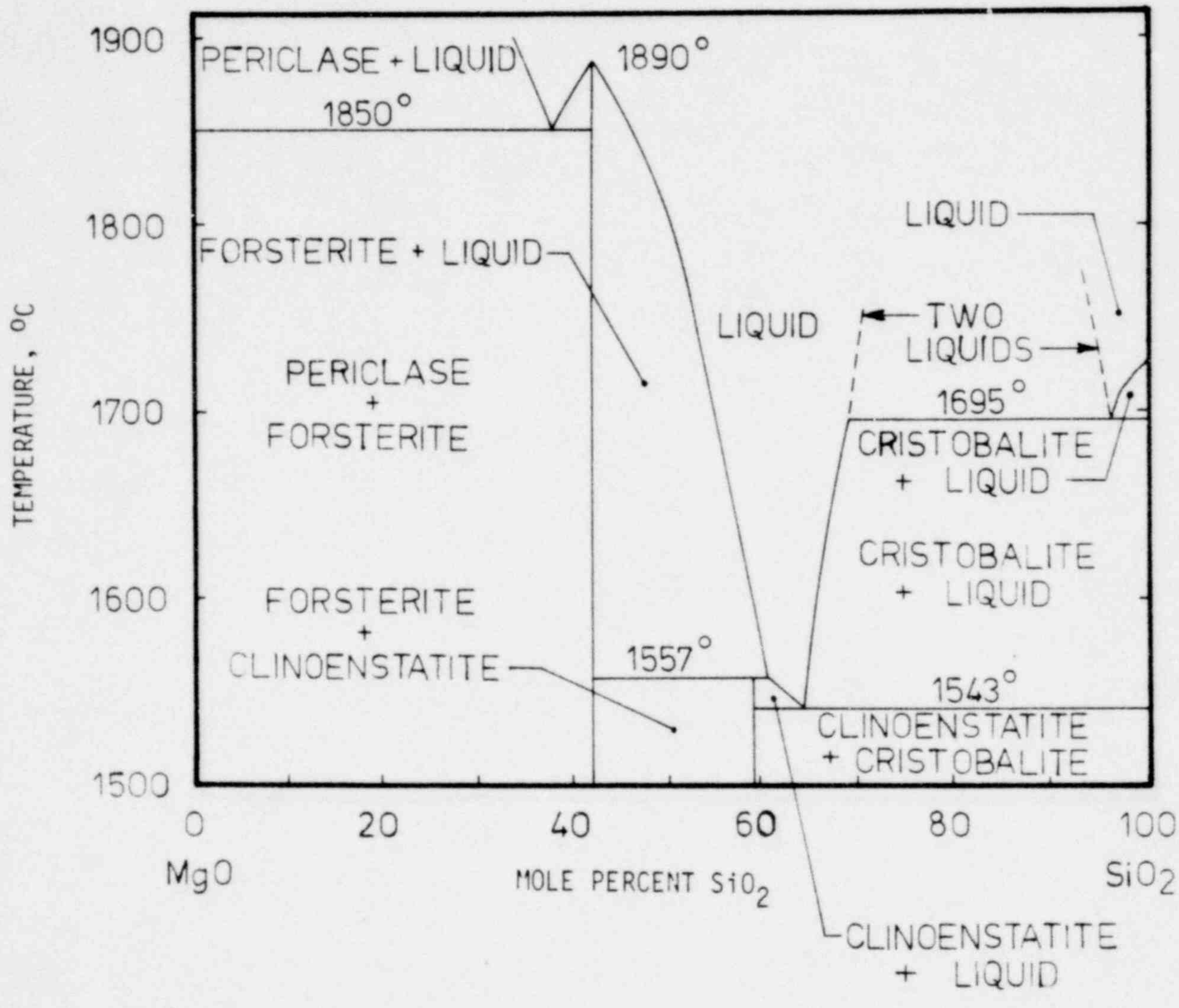

Ref: E. M. Levin, C. R. Robbins, H. F. McMurie, "Phase Diagrams for Ceramists," The American Ceramic Society, Columbus, Ohio, 1964

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Figure 16
MgO-SiO_2 Phase Diagram

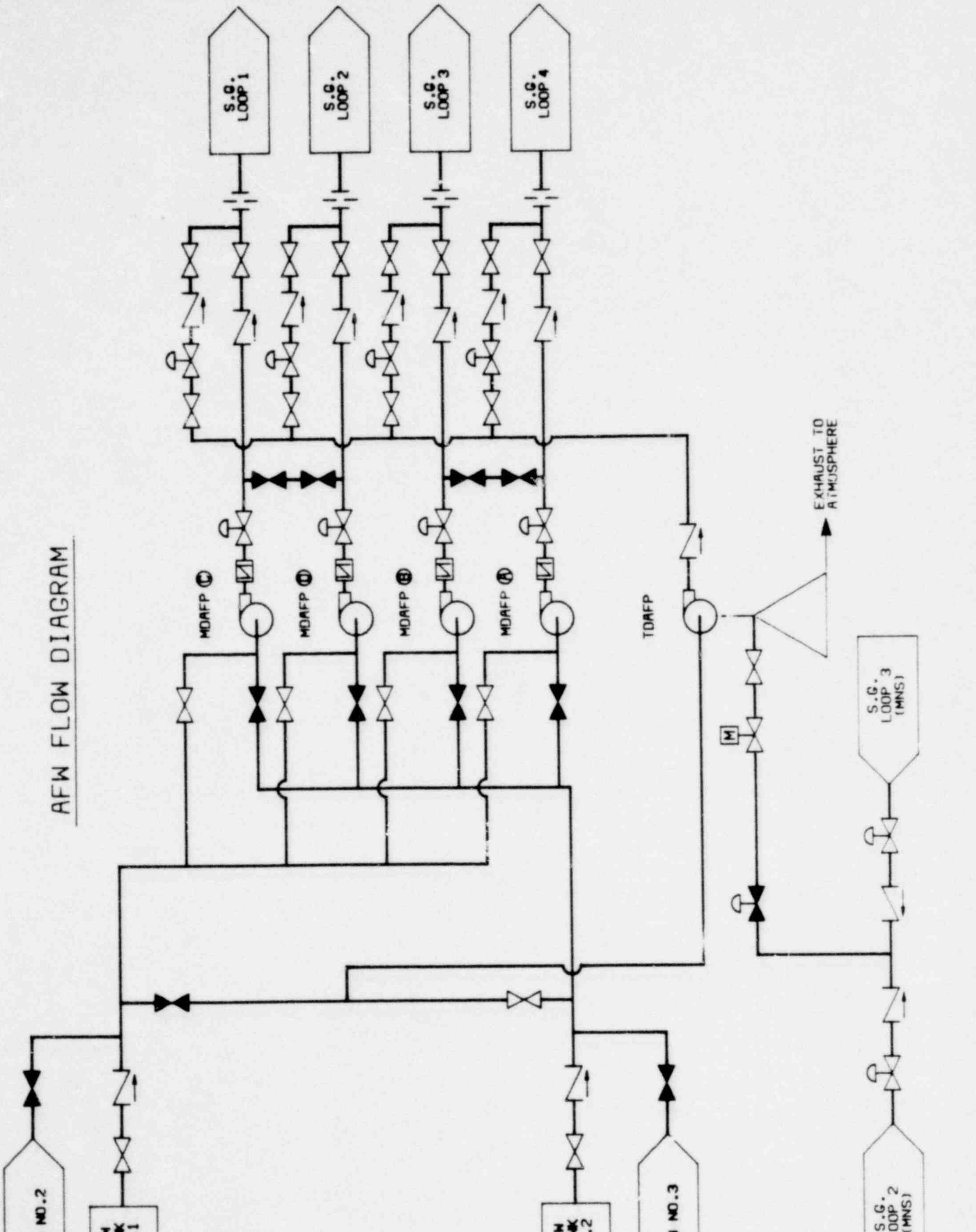

FIGURE 19

AUXILIARY FEEDWATER SCHEMATIC DIAGRAM

Instructions for Entering
Revision 1
in
OPS Report 36A59

1. Replace the Table of Contents page.

2. Replace pages V-1 through V-16 with new pages V-1 through V-21.

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V. TESTING PROGRAM FOR CONFIRMING ADEQUACY OF LADLE DESIGN

V.A Purpose

The purposes of the testing program for confirming the adequacy of the ladle design are:

1. Obtain otherwise unavailable data required to confirm that the core ladle will meet its functional design requirements listed in Section II.

2. Obtain otherwise unavailable data required to confirm that the core ladle does not compromise existing safety.

V.B General

The refractory ladle is being incorporated in the FNP to assist in reducing environmental consequences of a postulated core-melt accident. The ladle is intended to provide a sufficient delay in the time of core melt-through so that effective interdictive action can be instituted to reduce the environmental consequences of such an accident. Because the ladle is not required by the NRC for public health and safety, confirmation of ladle design will be based on realistic rather than highly conservative assumptions, analyses and tests. This is the approach consistantly taken by NRC for the evaluation of environmental consequences and risk.

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V.C Approach

Offshore Power Systems will provide, for evaluation by NRC, the information needed to establish that the core ladle can perform its intended environmental protection function and that the core ladle does not compromise existing FNP safety functions and capabilities. At least three sources can be utilized to obtain the needed information:

1. Applicable experience and technology from the metals refining industry,

2. Test programs sponsored by NRC, DOE or other sources which are planned or already in progress related to high temperatures interactions between molten oxides and refractory materials,

3. A specific core ladle testing program funded by OPS.

The first two sources listed above will be relied on to the extent possible by OPS in assembling the data required to establish the adequacy of the ladle design and in determining the extent of additional ladle qualifications testing to be performed by OPS. Table V-1 identifies the OPS core ladle testing program as it is currently conceived. As detailed design proceeds and as additional information becomes available from related testing programs sponsored by NRC, DOE, or other sources, modifications to the core ladle testing program may be appropriate and if so they will be made after discussion with NRC. In addition, test program results may indicate that certain design concepts or design features are not suitable

for meeting the core ladle functional requirements. If such proves to be the case, appropriate design alterations and additional testing (if needed) will be proposed.

V.D Schedule and Cost

It is Offshore Power Systems' intent to initiate a testing program after an FNP customer is identified.

As indicated in the Table V-1, it is estimated that the testing program can be completed in about 18 months. Offshore Power Systems estimates that it would take about six months to initiate the testing program. At the conclusion of the testing program, the pertinent data would be summarized, evaluated and the evaluation submitted to NRC for their review. Six months is estimated for NRC review and evaluation. The estimated 2-1/2 years from initiation of the testing program to completion of NRC review coincides with the period between customer identification and the need to begin manufacture of major elements of the FNP hull as projected by Offshore Power Systems.

Total estimated cost of the testing program is about $700,000.

V.E Summary of Information Needs and Core Ladle Testing Program

In this section potential information needs in the following four areas are evaluated and discussed:

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1. Physical and chemical interaction between melt debris and the MgO ladle

2. Physical behavior of the MgO ladle

3. Thermal interaction between the ladle and molten core debris.

4. Safety related concerns

The OPS testing program for confirming the adequacy of the ladle design is summarized in Table V-1.

1. Physical and chemical interaction between melt debris and the MgO bed

   a. Eutectic formation for the MgO, UO_2, ZrO_2, FeO multicomponent system

      i. Description

      For current penetration calculations, penetration of MgO is assumed to be a uniform physical melting process which occurs at the temperature of UO_2-MgO eutectic.

      ii. Importance to Ladle

      The rate at which molten core debris erodes or penetrates into MgO is a basic parameter in determining the length of time which a ladle constructed of MgO can delay core debris melt through. If the interaction process occurs at a

significantly lower temperature than that of the $MgO-UO_2$ eutectic, the rate of bed attack may be increased slightly.

iii. State of Knowledge

Phase diagrams are available for Fe_2O_3-M O and UO_2-MgO systems which indicate miscibility of the molten oxides at high temperatures. Phase diagrams for both UO_2-MgO and Fe_2O_3-MgO show eutectics with melting points substantially lower than that of MgO. Formation of a eutectic with an even lower melting point (than UO_2-MgO) when Corium interacts with MgO may be possible.

iv. Information Required

Test data may be needed to insure that lower melting points eutectics do not form for the Corium-MgO system.

b. Effect of MgO Impurities on Grain Boundary Attack

i. Description

Preferential attack of MgO along grain boundaries could produce a higher rate of attack of the MgO by causing erosion of the surface rather than bulk dissolution. Impurities precipitated at the grain boundaries are known to increase the tendency for grain boundary erosion attack.

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ii. Importance to Ladle

Preferential grain boundary attack could increase the rate of MgO loss and decrease ladle retention time.

iii. State of Knowledge

There are some test results that show penetration of MgO grain boundaries by molten UO_2. We know of no specific data on the effect of impurities in the MgO on grain boundary attack.

iv. Information Required

Tests are needed to determine the importance of impurities in MgO on the rate of attack of MgO by molten oxides present in Corium.

c. Enhanced Erosion at Temperatures Below Eutectic Temperatures

i. Description

Erosion or mechanical removal of solid MgO from the ladle surface at temperatures below the eutectic temperature could increase the rate of ladle attack.

ii. Importance to Ladle

Enhanced erosion at temperatures below the eutectic temperature could increase the rate of MgO loss and decrease ladle retention time.

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iii. State of Knowledge

Little data exist for temperatures above 2000°C and below the $MgO-UO_2$ eutectic temperature.

iv. Information Required

One or two medium scale tests are required to confirm that erosion does not lead to enhanced attack at these temperatures.

d. Slag Line Attack

i. Description

See Section IV.E for the description and state of knowledge on this subject.

ii. Importance to Ladle

If a substantial layer of iron oxide (slag) were to form on top of the molten debris in the ladle and if extensive attack at the slag line were to occur, preferential lateral dissolution of the ladle at the slag line could occur thereby reducing melt-through delay times.

iii. Information Required

Available information indicates that slag line attack rates are low in steel making furnaces. Additional confirmatory testing with the mixed oxides present in Corium is required.

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e. High temperature chemical interaction between melt debris and ladle

i. Description

If an exothermic chemical interaction between melt debris and MgO were to occur at high temperatures, the additional energy source could lead to an enhanced rate of ladle attack.

ii. Importance to Ladle

An increase rate of ladle attack could reduce ladle melt-through times.

iii. State of Knowledge

While chemical interactions at temperatures above 2000°C are not expected, definite data are not presently available.

iv. Information Required

Small scale high temperature tests are required to confirm that chemical interactions do not lead to an enhanced rate of attack.

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2. Physical Behavior of MgO Ladle

a. Floatup

i. Description

The refractory ladle described in Section III is constructed of fixed MgO bricks with a density less than half of that of molten debris. If the molten debris penetrates around the bricks and if the bricks are not restrained, they will float on the denser molten debris.

ii. Importance to Ladle

Extensive floatup could lead to relatively rapid penetration of the refractory ladle thereby shortening the melt delay time.

iii. State of Knowledge

Floatup has rarely been experienced in the refractory-lined furnaces and ladles used in the metals refining industry. Like Corium, steel melts are also more dense than the MgO refractories used to contain them. In addition, floatup has not been observed in furnaces used for refining nickel melts whose densities are as high as those of Corium. In the metals refining industries, the refractory linings of furnaces and ladles are usually constructed in an inverted arch shape so that the arch wedging action reduces floatup tendency.

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iv. Additional Information Required

The FNP refractory ladle will be constructed in an inverted arch configuration similar to those normally employed for refractory linings in furnaces and ladles in the metals refining industry. In addition, a tongue and groove brick configuration with staggered layers is planned to further restrict the tendency for floatup. Based on experience in the metals refining industry and the design features incorporated in the ladle to prevent floatup, this subject is considered to be adequately treated and no testing is required.

b. Thermal Shock and Spalling

i. Description

When molten materials at high temperature are poured on refractories at room temperature, large temperatures gradients and thermal stresses are induced. The thermal stresses can lead to cracking and/or spalling.

ii. Importance to Ladle

Fracturing of the brick as a result of thermal shock can reduce the penetration time of the refractory ladle.

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iii. State of Knowledge

In the metals refining industry, melts at high temperatures are poured into furnaces, mixers or ladles that are sometimes cold. Extensive cracking or spalling of refractory lining, which is similar to or more susceptible to thermal shock than high purity magnesite brick, does not occur. Reported results on small scale tests of molten UO_2 interactions with high purity magnesite brick are that "essentially no cracking or spallation was observed".

iv. Information Required

An upper layer of chemically bonded MgO brick which is highly resistant to thermal shock will be used in the FNP. Experience with refractories in the metals refining industry and existing experimental data provide an adequate basis relative to this subject and no further testing is necessary.

c. Mechanical Shock

i. Description

As part of the melt-down process, it is possible for large pieces of debris to fall upon the refractory ladle which may fracture brick.

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ii. Importance to Ladle

Fracturing of the brick as a result of physical shock could reduce the penetration time of the refractory ladle.

iii. State of Knowledge

In the metals refining industry, heavy objects are dropped onto refractory beds of furnaces with impacts equal to or greater than those which could be produced in a core melt accident (see Appendix D). Resulting damage to the refractory material is not such that it impairs its functional capability.

iv. Information Needs

Experience with refractories in the metals refining industry along with appropriate analysis provides adequate information relative to this subject.

d. Crack Penetration by Melt

i. Description

As MgO is heated it expands. A crack may be left between bricks to accommodate brick expansion during heatup (see Section IV). A small gap may continue to exist between some bricks as a result of less than perfect construction or as a result of non-uniform temperatures across the bed. Thus penetration of cracks between bricks by molten debris may occur.

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ii. Importance to Ladle

Extensive crack penetration could lead to brick floatup and enhanced bed penetration.

iii. State of Knowledge

Freezing of the debris melt as it flows into the narrow cracks between bricks is likely to limit crack penetration. Experience from the metals refining industry indicates crack penetration is not a problem although the range of temperatures associated with such application is not as great as may be experienced for a molten core debris ladle. Calculations indicate that the maximum penetration of the core ladle would be about one layer of brick.

iv. Information Required

The extent of crack penetration for a range of crack sizes and temperature needs to be examined.

3. Thermal Interactions Between Ladle and Molten Debris

a. Fractions of available energy lost to radiant upward heating

i. Description

Some fraction of the decay heat energy generated in the molten core debris will be lost to the surfaces surrounding the pool by thermal radiation. This energy will not be available for melting the refractory ladle material.

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ii. Importance to Ladle

Calculations indicate an acceptable ladle life for radiant loss fractions as low as 10%.

iii. State of Knowledge

Models exist for estimating radiant losses for fixed geometries and for known temperatures of the radiating body (pool) and receptor (surfaces above the pool). There is, however, uncertainty regarding the surface temperature of the pool.

iv. Information Needs

Bounding calculations show that a reasonable thickness of refractory material can provide the necessary delay times for conservative assumptions regarding thermal energy radiation losses. Thus additional information is not needed.

b. Relative Rates of Energy Loss into MgO Ladle Laterally and Vertically

i. Description

In current estimates of ladle penetration rates, heat flow per unit area into the MgO from the molten debris pool is assumed to be equal in the horizontal and vertical directions.

ii. Importance to Ladle

With the assumption of equal lateral and vertical heat flow per unit area, the proposed MgO ladle is calculated to provide retention of two days in both the lateral and vertical directions (see Section IV.A). If heat flow per unit area in one direction proves to be substantially greater than the other, a different ladle configuration will be required and can be accomodated within the platform configuration.

iii. State of Knowledge

Energy flow per unit area in the lateral and vertical direction are assumed to be equal. The basis for this assumption was engineering judgment.

iv. Information Needs

Information is needed to determine if energy flow per unit area in the lateral and vertical directions are approximately the same. Approximate values (±10 to 15%) are adequate.

4. Safety Related Concerns

Safety-related concerns listed under item 4 in Table V-1 are discussed in other sections of this report. Specifically, radiation shielding is discussed in Section IV.B, gas generation by bed materials is discussed in Section IV.C, and criteria applied to interaction between the ladle and safety related structures are discussed in Section III.K.

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There are no ladle testing programs associated with safety-related concerns because adequate information currently exists.

V.F. Elements of Planned NRC Test Programs Applicable to FNP Ladle

The Nuclear Regulatory Research Program contains a number of planned tests which will yield information applicable to the FNP refractory ladle. Elements of the program were provided to OPS by the Fuel Behavior Research Branch, Division of Reactory Safety Research of NRC, reference (7). Tests applicable to the ladle have been summarized in Table V-2. The test series are briefly described in the following sections.

1. Furnace Heat Up Tests

   A series of tests is planned in which metal and oxide materials will be heated in small crucibles of candidate core-melt retention materials to temperatures where the metal and oxide mixtures melt. Included will be tests with MgO crucibles, iron-iron oxide and Corium melts. Initial tests will be at temperatures of about 3100°F. Temperatures up to 4000°F are possible in the furnace. Such tests can be used to derive information on slag line attack, MgO penetration rates by oxides and possibly on phase relationships, particularly eutectic formation.

2. Small Scale Inductive Heating Tests (CATH Series)

   In these tests metal-oxide and Corium melts will be inductively heated in small refractory crucibles (Crucibles are 6" OD by 12" high). Included will be tests with MgO crucibles containing iron-iron oxide

melts and Corium melts. Also included will be tests with MgO crucibles with cracks. These tests will provide information on slag line attack, rate of MgO penetration by various oxide melts, and the extent of penetration of cracks by the oxide melts.

3. Large Scale Tests with Inductive Heating

A series of tests in which approximately 440 lbs of steel is heated to approximately 3100°F and then poured into crucibles of various refractory material or concrete has been conducted at Sandia. After pouring, melt temperature is maintained by inductive heating. The test already conducted with a MgO crucible was of limited usefulness since inductive heating was lost early in the test. One additional test with a crucible constructed of alumina cement is planned and another test with a MgO crucible may be conducted. A test with a MgO crucible could provide information on Mgo penetration rate as well as relative rates of energy flow in the vertical and horizontal directions.

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TABLE V-1
SUMMARY OF LADLE INFORMATION NEEDS AND TESTING PROGRAMS

1. Physical and Chemical Interaction Between Melt Debris and MgO Bed

	Information Needed	Type of Test	Estimated Testing Period	Comments or Estimated Cost
a.	Eutectic formation for the MgO, UO_2, ZrO_2, FeO multicomponent system	15 to 20 small scale, sustained heating furnace tests	18 months	250,000
b.	Effect of MgO impurities on rate of penetration by molten debris	5 to 10 small scale, sustained heating furnace tests	6 months	50,000
c.	Potential enhanced attack by erosion at temperatures below eutectic temperatures	2 medium scale tests	6 months	50,000
d.	Potential for slag line attack	1 medium scale test assuming data from (1a) are employed	3 months	25,000
e.	Potential for rapid attack at high temperatures due to chemical interaction between melt debris and MgO	2 - 4 small scale, high temperature tests.	15 months	125,000

2. Physical Behavior of MgO Bed

	Information Needed	Type of Test	Estimated Testing Period	Comments or Estimated Cost
a.	Brick floatup upon contact with high density molten debris	None		Industrial sufficient to establish there is not a problem
b.	Thermal shock with spalling of ladle brick	None		Industrial experience sufficient with addition of resistant top layer of brick

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TABLE V-1 (CONT'D)
SUMMARY OF LADLE INFORMATION NEEDS AND TESTING PROGRAMS

c. Mechanical shock causing degradation of bed	None		Industrial experience shows this is not a problem
d. Extensive melt penetration of cracks beteen brick leading to breakup of bed	3 small scale, sustained heating tests	9 months	50,000
3. Thermal Interaction Between Ladle and Debris			
a. Energy loss due to radiant upward heating	None	-	Treated by by bounding calculations which assume all energy is directed into bed
b. Energy split between the downward and lateral directions	2 medium scale high temperature tests	18 months	150,000
4. Safety Related Concerns			
a. Radiation shielding properties of MgO	None	-	Adequate cross section data can be derived from existing literature
b. Gas generation capability	None	-	Bounding gas generation from top layer of chemically bonded brick can be tolerated. Little if any gas generation from MgO melting.

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TABLE V-1 (CONT'D)

SUMMARY OF LADLE INFORMATION NEEDS AND TESTING PROGRAMS

c. Possible effects of bed on nearby containment pressure boundary under accident conditions	None	-	Possible effects can be adequately treated analytically based on available information

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TABLE V-2

NRC TEST PROGRAM ELEMENTS APPLICABLE TO FNP CORE MELT LADLE

TYPE OF TEST	TEST MATERIALS	APPLICABLE INFORMATION
Furnace Heat-Up Tests	MgO Crucible, $Fe-Fe_2O_3$ Melts MgO Crucible, Corium-$Fe-Fe_2O_3$ Melts	Slag Line Attack, MgO Erosion Slag Line Attack, MgO Erosion, Phase Relationships
Small Scale Inductive Heating CATH-3	MgO Crucible, $Fe-Fe_2O_3$ Melt	Slag Line Attack, MgO Erosion
Small Scale Inductive Heating CATH-4	MgO Crucible with Cracks, Fe Melts	Melt Flow In Flaws and Cracks
Small Scale Inductive Heating CATH-6	MgO Crucible, Corium Melt	MgO Erosion, Slag Line Attack
Small Scale Inductive Heating CATH-7	Alumina Crucible, Corium Melt	Alternate Materials Erosion Rate and Susceptibility to Slag Line Attack
200 Kg Steel Melt with Inductive Heating (HAC-2)	Alumina Cement Crucible, Steel Melt	Alumina Cement Erosion Rates
Incore Test Series		Data on Erosion Rates for Various Crucible - Melt Combinations with Internal Melt Heating

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