10

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

JUN 15 1984

MEMORANDUM FOR: Those on Attached List

FROM: John L. Telford
Containment Systems Research Branch

SUBJECT: MEETING SUMMARY FOR THE MOLTEN-CORE COOLANT INTERACTION RESEARCH REVIEW GROUP

On June 4 and 5, 1984 technical working sessions of the subject research review group were held at the Hilton Hotel, Meeting Room 406, New Orleans, LA. The sessions were attended by: J. Rosenthal, J. Telford, and R. Wright (members) and R. Anderson, G. Bankoff, M. Berman, W. Bohl, M. Corradini, D. Squarer, and T. Theofanous (advisors). The purpose of the review group is given in Enclosure 1 of this letter. An agenda for the meeting is given in Enclosure 2 of this letter.

The meeting discussions included the following.

1. The agenda was modified to allow more time to discuss recent SNL experimental results and four proposed near term experimental test series.

2. Selected areas of NRC-IDCOR disagreement involving steam explosion phenomana resulting from the Harpers Ferry Meeting were briefly discussed as points-of-reference and to establish one need for specific research.

3. Recent SNL experimental results were briefly discussed by M. Berman. The attached information paper, "NRC/Sandia Fuel-Coolant Interactions Program Information Exchange Meeting" was provided to all review group participants.

4. Three proposed experimental test series were discussed as follows:

   a. Large-scale (2000 Kg) facility for open-geometry experiments on coarse mixing and conversion ratio using thermite melts at ambient pressure.

134

b. Extension of the Fully Instrumented Test Site (FITS) closed-geometry experiments to 50 Kg (from 20 Kg) of thermite melts. This series would evaluate six independent variables, as a first effort.

c. Medium-scale (400 Kg) facility for closed-geometry experiments using induction-heated prototypic oxidic and metallic melts. This series would evaluate eight independent variables, as a first effort.

The specific items of discussion, for the record, are given in Enclosure 3 of this letter.

The review group's conclusions are the following.

1. The large-scale (2000 Kg) facility for open-geometry experiments on coarse mixing and conversion ratio using thermite melts at ambient pressure should have first priority and work should begin as soon as possible.

2. The need for the medium-scale (400 Kg) facility for closed-geometry experiments using induction-heated prototypic oxidic and metallic melts may depend on the results of the large-scale (2000 Kg) tests (conclusion 1, above). The dependence is based on whether a limit to mixing is found and the behavior of conversion ratio as melt mass increases.

3. There is a need for a detailed written description of how the conversion ratio will be measured and for an "uncertainty" statement to describe the precision of the conversion ratio measurement.

4. The use of artifical triggers is acceptable if delayed or "late" triggers are used.

5. There is need to demonstrate that the gas in the thermite during the melt formation stage has been allowed to escape before delivery of the molten thermite to the water chamber.

6. There is a need for the review group to meet again within six to nine months to review the actions taken on conclusions 3 and 5 and to discuss in detail the design of the water chamber (geometry) to be used in the large-scale (2000 Kg) tests.

If any of the view group participants would like to add corrections to this summary, please give me a call (301-427-4576).

John Telford

John L. Telford
Research Review Group Chairman
Containment Systems Research Branch

Enclosure: As stated

cc: D. Ross, RES
O. Bassett, DAE
T. Speis, NRR
W. Morrison, DAE
R. Curtis, RES
C. Kelber, RES
M. Silberberg, RES
L. Larkins, RES
B. Burson, RES

DISTRIBUTION LIST FOR MEMORANDUM DATED:

Dr. Richard Anderson
Argonne National Laboratory
9700 South Cass Avenue
Building 208
Argonne, IL 60439

Dr. George Bankoff
Chemical Engineering Department
Northwestern University
Evanston, IL 60201

Dr. Marshall Berman
Sandia National Laboratories
Division 6441
Albuquerque, NM 87185

Dr. William Bohl
112 Paseo Penasco
Los Alamos, NM 87544

Dr. Mike Corradini
University of Wisconsin
1500 Johnson Drive
Madison, WI 53706

Dr. Dave Squarer
Nuclear Safety & Analysis Dept.
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Dr. Theo Theofanous
132 Pathway Lane
West Lafayette, IN 47906

Mr. J. Rosenthal
U.S. Nuclear Regulatory Commission
Mail Stop P-1132
Washington, DC 20555

Mr. R. Wright
U.S. Nuclear Regulatory Commission
Mail Stop 1130-SS
Washington, DC 20555

ENCLOSURE 1

Molten Core-Coolant Interaction Research Review Group

Purpose:

The Group's purpose is to advise in the design and planning of experiments to obtain maximum effectiveness and efficiency. The areas of consideration include: engineering design of the test facilities, measurements and data recording, definition of independent variables and their ranges, and clarity of logic for the test results to provide definitive answers to the hypotheses of interest.

ENCLOSURE 2

AGENDA

Molten Core-Coolant Interaction Research Review Group

MONDAY, June 4, 1984

6:30 p.m.	Introduction	J. Telford
6:40 p.m.	Description of FITS Series	M. Berman
6:55 p.m.	Description of "Large Mass" Series	M. Berman
7:10 p.m.	Discussion of "Large Mass" Series	
8:00 p.m.	Discussion of FITS Series	
8:50 p.m.	Develop Summary Conclusions	
9:00 p.m.	Adjourn	

TUESDAY, June 5, 1984

6:30 p.m.	Introduction	J. Telford
6:35 p.m.	Description of "Enclosed" Series	M. Berman
6:50 p.m.	Discussion of "Enclosed" Series	
8:00 p.m.	Develop Summary Conclusions	
8:45 p.m.	Adjourn	

Enclosure 3

The following are the main items of discussion from the review group meeting held June 4 and 5, 1984. The participant first bringing up the item has been identified.

1. Experiments designed to address the alpha mode-of-failure should have a high priority - T. Theofanous.

2. Different methods of melt preparation may produce melts of different characteristics - D. Squarer.

3. For the large scale (2000 Kg) experiments, consider trying to measure the locations of the steam, water, and melt phases (after contact of melt and water) by using resistivity or acoustic measurements - G. Bankoff.

4. The objectives of all the experimental series could be categorized by three considerations:

   a. Alpha failure mode and mixing,

   b. Steam and hydrogen production and debris characteristics, and

   c. fission product source term - M. Corradini.

5. G. Bankoff discussed some recent calculational results using the Phoenix Code. During the molten fuel-coolant mixing, the code predicts the locations of the melt, water, and steam phases. As an input condition the code was given uniformly spaced 10 cm diameter spheres to represent the melt.

6. T. Theofanous made the following points for the large scale (2000 Kg) experiments:

   a. measure conversion ratio very well,

   b. eliminate the "leading edge" effect (in other words, investigate the effects of melt mass, pour rate, water chamber depth, and water chamber cross sectional area), and

   c. use an integral test approach.

7. For the geometry of the water chamber consider a right cylinder shape - W. Bohl.

8. Experience has shown that the same steam explosion (fuel-coolant interaction) result is not repeatable even for the same test conditions - R. Anderson.

9. The water chamber should have rigid walls - G. Bankoff.

10. To allow photographic coverage with a rigid wall water chamber consider: fiber optics, ports in the water chamber, two mirrors to look into the chamber, and front lighting - R. Anderson.

11. As a comparison, we could consider one or two tests using lucite water chambers followed by one or two tests using rigid wall water chambers - R. Wright.

12. Having X-ray films may be important information on premixing phases. This would imply using lucite water chambers - G. Baknoff.

13. One reasonable partition is to use rigid wall water chambers in 80% of the tests and lucite water chambers in 20% of the tests - T. Theofanous.

14. It would be meaningful to find out if trigger strength is correlated with conversion ratio. This suggests a need to measure trigger strength as well as conversion ration - G. Bankoff.

15. For the extension of FITS closed-geometry experiments using 50 Kg thermite melts, there is a potential problem that 50 Kg is sufficiently small in relation to reactor scale that the melt mass will behave like the leading edge of a larger mass - T. Theofanous.

16. For the medium-scale (400 Kg) experiments the following independent variables were proposed - M. Berman.

    a. melt mass
    b. melt composition (oxidic or metalic)
    c. additional heat beyond melting
    d. water depth
    e. water chambers cross sectional area
    f. water temperature
    g. melt energy velocity
    h. ambient pressure (inside closed vessel)

    The proposed measurements are:

    1. hydrogen generation rate and total amount
    2. steam generation rate and total amount
    3. debris characteristics
    4. conversion ratio
    5. water phase pressure
    6. gas phase pressure

7. base impulse
8. maybe X-ray or gamma-ray films (for coarse mixing)

17. For the medium-scale (400 Kg) experiments, all participants expressed their opinions on the ability of these experiments to solve the related safety issues. The use of an induction melt and 400 Kg mass was favored by some participants. One question was whether 400 Kg is a large enough mass. Most participants did not want to make a decision at this time. The need for these tests may depend on the results of the large-scale (2000 Kg) experiments.

18. D. Squarer had the following sumarry comments

    a. The water chamber (cross section) should be larger than the stream of melt mass.

    b. The cavity structure should be carefully designed (preference for prototypic conditions).

    c. Some tests should use lucite water chambers so that the results can be related to previous experiments.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

JUN 15 1984

MEMORANDUM FOR: Those on Attached List

FROM: John L. Telford
Containment Systems Research Branch

SUBJECT: MEETING SUMMARY FOR THE MOLTEN-CORE COOLANT INTERACTION RESEARCH REVIEW GROUP

On June 4 and 5, 1984 technical working sessions of the subject research review group were held at the Hilton Hotel, Meeting Room 406, New Orleans, LA. The sessions were attended by: J. Rosenthal, J. Telford, and R. Wright (members) and R. Anderson, G. Bankoff, M. Berman, W. Bohl, M. Corradini, D. Squarer, and T. Theofanous (advisors). The purpose of the review group is given in Enclosure 1 of this letter. An agenda for the meeting is given in Enclosure 2 of this letter.

The meeting discussions included the following.

1. The agenda was modified to allow more time to discuss recent SNL experimental results and four proposed near term experimental test series.

2. Selected areas of NRC-IDCOR disagreement involving steam explosion phenomana resulting from the Harpers Ferry Meeting were briefly discussed as points-of-reference and to establish one need for specific research.

3. Recent SNL experimental results were briefly discussed by M. Berman. The attached information paper, "NRC/Sandia Fuel-Coolant Interactions Program Information Exchange Meeting" was provided to all review group participants.

4. Three proposed experimental test series were discussed as follows:

   a. Large-scale (2000 Kg) facility for open-geometry experiments on coarse mixing and conversion ratio using thermite melts at ambient pressure.

b. Extension of the Fully Instrumented Test Site (FITS) closed-geometry experiments to 50 Kg (from 20 Kg) of thermite melts. This series would evaluate six independent variables, as a first effort.

c. Medium-scale (400 Kg) facility for closed-geometry experiments using induction-heated prototypic oxidic and metallic melts. This series would evaluate eight independent variables, as a first effort.

The specific items of discussion, for the record, are given in Enclosure 3 of this letter.

The review group's conclusions are the following.

1. The large-scale (2000 Kg) facility for open-geometry experiments on coarse mixing and conversion ratio using thermite melts at ambient pressure should have first priority and work should begin as soon as possible.

2. The need for the medium-scale (400 Kg) facility for closed-geometry experiments using induction-heated prototypic oxidic and metallic melts may depend on the results of the large-scale (2000 Kg) tests (conclusion 1, above). The dependence is based on whether a limit to mixing is found and the behavior of conversion ratio as melt mass increases.

3. There is a need for a detailed written description of how the conversion ratio will be measured and for an "uncertainty" statement to describe the precision of the conversion ratio measurement.

4. The use of artifical triggers is acceptable if delayed or "late" triggers are used.

5. There is need to demonstrate that the gas in the thermite during the melt formation stage has been allowed to escape before delivery of the molten thermite to the water chamber.

6. There is a need for the review group to meet again within six to nine months to review the actions taken on conclusions 3 and 5 and to discuss in detail the design of the water chamber (geometry) to be used in the large-scale (2000 Kg) tests.

If any of the view group participants would like to add corrections to this summary, please give me a call (301-427-4576).

John Telford
John L. Telford
Research Review Group Chairman
Containment Systems Research Branch

Enclosure: As stated

cc: D. Ross, RES
O. Bassett, DAE
T. Speis, NRR
W. Morrison, DAE
R. Curtis, RES
C. Kelber, RES
M. Silberberg, RES
L. Larkins, RES
B. Burson, RES

DISTRIBUTION LIST FOR MEMORANDUM DATED:

Dr. Richard Anderson
Argonne National Laboratory
9700 South Cass Avenue
Building 208
Argonne, IL 60439

Dr. George Bankoff
Chemical Engineering Department
Northwestern University
Evanston, IL 60201

Dr. Marshall Berman
Sandia National Laboratories
Division 6441
Albuquerque, NM 87185

Dr. William Bohl
112 Paseo Penasco
Los Alamos, NM 87544

Dr. Mike Corradini
University of Wisconsin
1500 Johnson Drive
Madison, WI 53706

Dr. Dave Squarer
Nuclear Safety & Analysis Dept.
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Dr. Theo Theofanous
132 Pathway Lane
West Lafayette, IN 47906

Mr. J. Rosenthal
U.S. Nuclear Regulatory Commission
Mail Stop P-1132
Washington, DC 20555

Mr. R. Wright
U.S. Nuclear Regulatory Commission
Mail Stop 1130-SS
Washington, DC 20555

ENCLOSURE 1

Molten Core-Coolant Interaction Research Review Group

Purpose:

The Group's purpose is to advise in the design and planning of experiments to obtain maximum effectiveness and efficiency. The areas of consideration include: engineering design of the test facilities, measurements and data recording, definition of independent variables and their ranges, and clarity of logic for the test results to provide definitive answers to the hypotheses of interest.

ENCLOSURE 2

AGENDA

Molten Core-Coolant Interaction Research Review Group

MONDAY, June 4, 1984

6:30 p.m.	Introduction	J. Telford
6:40 p.m.	Description of FITS Series	M. Berman
6:55 p.m.	Description of "Large Mass" Series	M. Berman
7:10 p.m.	Discussion of "Large Mass" Series	
8:00 p.m.	Discussion of FITS Series	
8:50 p.m.	Develop Summary Conclusions	
9:00 p.m.	Adjourn	

TUESDAY, June 5, 1984

6:30 p.m.	Introduction	J. Telford
6:35 p.m.	Description of "Enclosed" Series	M. Berman
6:50 p.m.	Discussion of "Enclosed" Series	
8:00 p.m.	Develop Summary Conclusions	
8:45 p.m.	Adjourn	

Enclosure 3

The following are the main items of discussion from the review group meeting held June 4 and 5, 1984. The participant first bringing up the item has been identified.

1. Experiments designed to address the alpha mode-of-failure should have a high priority - T. Theofanous.

2. Different methods of melt preparation may produce melts of different characteristics - D. Squarer.

3. For the large scale (2000 Kg) experiments, consider trying to measure the locations of the steam, water, and melt phases (after contact of melt and water) by using resistivity or acoustic measurements - G. Bankoff.

4. The objectives of all the experimental series could be categorized by three considerations:

   a. Alpha failure mode and mixing,

   b. Steam and hydrogen production and debris characteristics, and

   c. fission product source term - M. Corradini.

5. G. Bankoff discussed some recent calculational results using the Phoenix Code. During the molten fuel-coolant mixing, the code predicts the locations of the melt, water, and steam phases. As an input condition the code was given uniformly spaced 10 cm diameter spheres to represent the melt.

6. T. Theofanous made the following points for the large scale (2000 Kg) experiments:

   a. measure conversion ratio very well,

   b. eliminate the "leading edge" effect (in other words, investigate the effects of melt mass, pour rate, water chamber depth, and water chamber cross sectional area), and

   c. use an integral test approach.

7. For the geometry of the water chamber consider a right cylinder shape - W. Bohl.

8. Experience has shown that the same steam explosion (fuel-coolant interaction) result is not repeatable even for the same test conditions - R. Anderson.

9. The water chamber should have rigid walls - G. Bankoff.

10. To allow photographic coverage with a rigid wall water chamber consider: fiber optics, ports in the water chamber, two mirrors to look into the chamber, and front lighting - R. Anderson.

11. As a comparison, we could consider one or two tests using lucite water chambers followed by one or two tests using rigid wall water chambers - R. Wright.

12. Having X-ray films may be important information on premixing phases. This would imply using lucite water chambers - G. Baknoff.

13. One reasonable partition is to use rigid wall water chambers in 80% of the tests and lucite water chambers in 20% of the tests - T. Theofanous.

14. It would be meaningful to find out if trigger strength is correlated with conversion ratio. This suggests a need to measure trigger strength as well as conversion ration - G. Bankoff.

15. For the extension of FITS closed-geometry experiments using 50 Kg thermite melts, there is a potential problem that 50 Kg is sufficiently small in relation to reactor scale that the melt mass will behave like the leading edge of a larger mass - T. Theofanous.

16. For the medium-scale (400 Kg) experiments the following independent variables were proposed - M. Berman.

    a. melt mass
    b. melt composition (oxidic or metalic)
    c. additional heat beyond melting
    d. water depth
    e. water chambers cross sectional area
    f. water temperature
    g. melt energy velocity
    h. ambient pressure (inside closed vessel)

    The proposed measurements are:

    1. hydrogen generation rate and total amount
    2. steam generation rate and total amount
    3. debris characteristics
    4. conversion ratio
    5. water phase pressure
    6. gas phase pressure

7. base impulse
8. maybe X-ray or gamma-ray films (for coarse mixing)

17. For the medium-scale (400 Kg) experiments, all participants expressed their opinions on the ability of these experiments to solve the related safety issues. The use of an induction melt and 400 Kg mass was favored by some participants. One question was whether 400 Kg is a large enough mass. Most participants did not want to make a decision at this time. The need for these tests may depend on the results of the large-scale (2000 Kg) experiments.

18. D. Squarer had the following sumarry comments

a. The water chamber (cross section) should be larger than the stream of melt mass.

b. The cavity structure should be carefully designed (preference for prototypic conditions).

c. Some tests should use lucite water chambers so that the results can be related to previous experiments.

NRC/SANDIA

FUEL-COOLANT INTERACTIONS PROGRAM

INFORMATION EXCHANGE MEETING

JUNE 4, 1984

NEW ORLEANS, LOUISIANA

MARSHALL BERMAN
SANDIA NATIONAL LABORATORIES

FUEL-COOLANT INTERACTION PHENOMENA INCLUDE

- STEAM EXPLOSION: RAPID HEAT TRANSFER AND VAPOR GENERATION ON A TIME SCALE OF MILLISECONDS.

- STEAM GENERATION: NON-EXPLOSIVE PRODUCTION OF STEAM, GENERALLY BY FILM BOILING.

- HYDROGEN GENERATION: PRODUCED BY THE INTERACTION OF MOLTEN METALS AND STEAM DURING THE FCI.

- DEBRIS BED FORMATION: THE DISTRIBUTION OF PARTICLE SIZES AND THE CHARACTERISTICS OF THE DEBRIS BED FORMED SUBSEQUENT TO THE FCI (POROSITY, STRATIFICATION).

FCI'S CAN OCCUR IN ANY ACCIDENT WHICH INVOLVES SOME MELTING OF THE CORE OR CLADDING MATERIALS.

NRC/SANDIA

FUEL-COOLANT INTERACTIONS PROGRAM

INFORMATION EXCHANGE MEETING

JUNE 4, 1984

NEW ORLEANS, LOUISIANA

MARSHALL BERMAN
SANDIA NATIONAL LABORATORIES

MEETING OBJECTIVES

- FCI RESEARCH RATIONALE
- BRIEF PROGRAM UPDATE
- PLAN FOR RESOLUTION OF ISSUES
- GENERAL DISCUSSION:
  - -EXPERIMENTAL FACILITIES
  - -TEST MATRICES
  - -MODEL DEVELOPMENT
  - -RESEARCH PRIORITIES

FUEL-COOLANT INTERACTION PHENOMENA INCLUDE

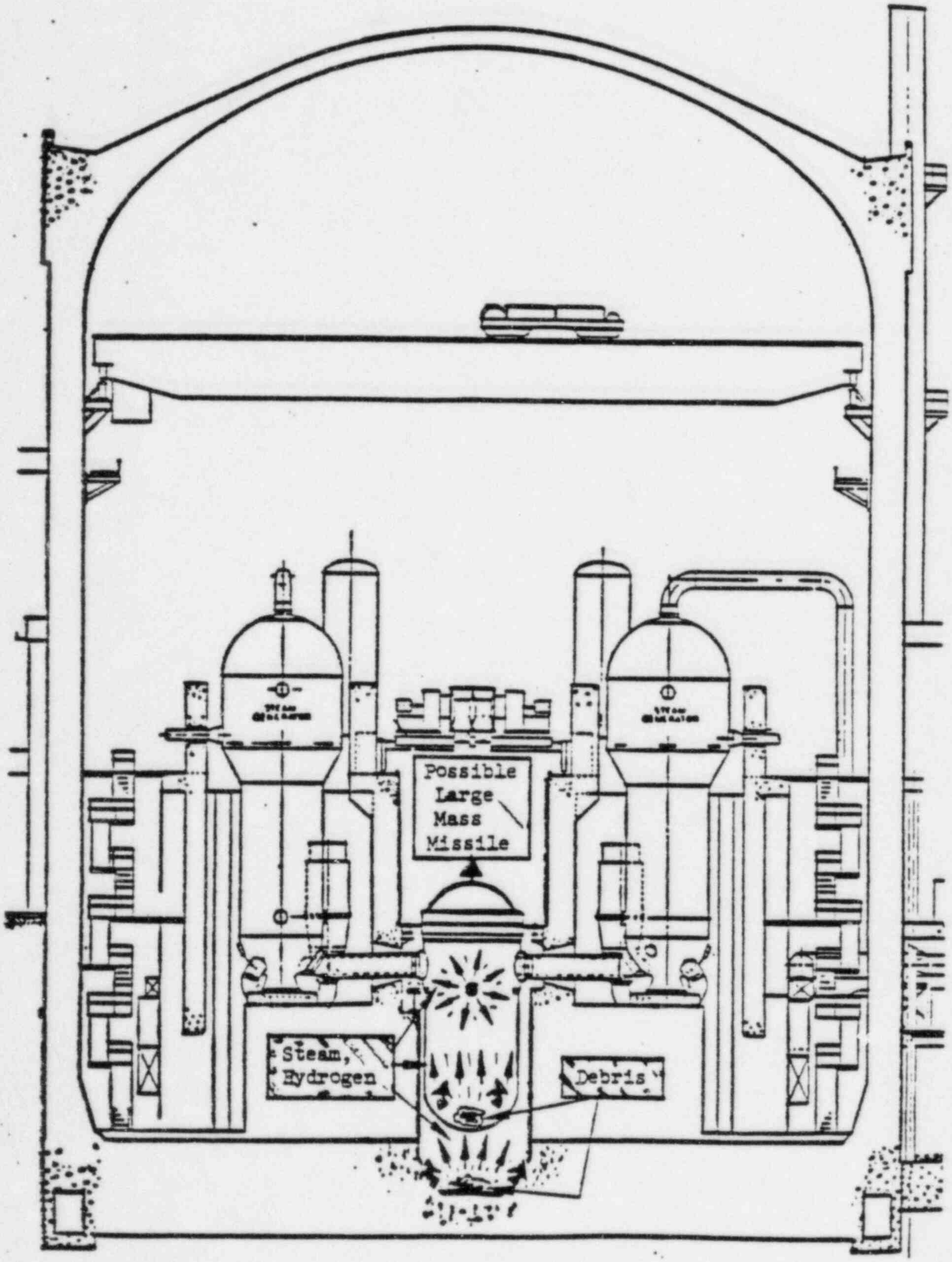
• STEAM EXPLOSION:	RAPID HEAT TRANSFER AND VAPOR GENERATION ON A TIME SCALE OF MILLISECONDS.
• STEAM GENERATION:	NON-EXPLOSIVE PRODUCTION OF STEAM, GENERALLY BY FILM BOILING.
• HYDROGEN GENERATION:	PRODUCED BY THE INTERACTION OF MOLTEN METALS AND STEAM DURING THE FCI.
• DEBRIS BED FORMATION:	THE DISTRIBUTION OF PARTICLE SIZES AND THE CHARACTERISTICS OF THE DEBRIS BED FORMED SUBSEQUENT TO THE FCI (POROSITY, STRATIFICATION).

FCI's CAN OCCUR IN ANY ACCIDENT WHICH INVOLVES SOME MELTING OF THE CORE OR CLADDING MATERIALS.

WHY ARE FUEL-COOOLANT

INTERACTIONS IMPORTANT

FOR REACTOR SAFETY?


Possible
Large
Mass
Missile
Steam,
Hydrogen
Debris

FCI'S CAN OCCUR

- IN CORE BARREL
- IN LOWER PLENUM
- IN REACTOR CAVITY

WATER CAN BE SATURATED OR SUBCOOLED

PRESSURE CAN BE HIGH OR LOW

REACTOR SAFETY ISSUES AFFECTED BY FCIS

1. STEAM AND HYDROGEN GENERATION:

   WHAT ARE THE RATES AND TOTAL MAGNITUDES OF STEAM AND HYDROGEN WHICH CAN BE GENERATED DURING FCIs?

2. DEBRIS CHARACTERISTICS:

   WHAT ARE THE CHARACTERISTICS OF THE DEBRIS PRODUCED BY FCIS, INCLUDING PARTICLE SIZE DISTRIBUTION, POROSITY AND DEBRIS-BED STRATIFICATION?

3. ACCIDENT PROGRESSION AND SOURCE TERM:

   HOW DO FCIs INFLUENCE THE PROGRESSION OF THE ACCIDENT AND THE NATURE OF THE SOURCE TERM (INCLUDING FISSION PRODUCT CHEMISTRY, RELEASE RATE, PARTICLE SIZE AND MORPHOLOGY, AND FP DISPERSAL)? WHAT ARE THE CONSEQUENCES OF FUEL DEBRIS DISPERSAL IN- OR EX-VESSEL BY VIOLENT FCIs?

4. ACCIDENT TERMINATION AND SAFE SHUTDOWN:

   HOW DO FCIs AFFECT THE PROBABILITY OF SUCCESSFUL ACCIDENT TERMINATION BY THE ADDITION OF WATER TO THE MELT? WHAT OPERATOR ACTIONS WOULD INCREASE THE POSSIBILITY OF SAFE SHUTDOWN BY REDUCING THE RISK FROM DANGEROUS FCIS?

5. DIRECT FAILURE:

   WHAT ARE THE PROBABILITIES AND CONSEQUENCES OF DIRECT CONTAINMENT FAILURE BY A STEAM EXPLOSION (α - MODE)?

6. INDIRECT FAILURE:

   WHAT ARE THE PROBABILITIES AND CONSEQUENCES OF INDIRECT CONTAINMENT FAILURE BY FCIs (δ-, γ-, OR ϵ- MODES)?

THESE SAFETY ISSUES ARE ONLY IMPORTANT IF THEY AFFECT:

- THE PROBABILITY AND CONSEQUENCES OF TERMINATED ACCIDENTS
  - \+ FISSION PRODUCT DISPERSAL
  - \+ PRIMARY SYSTEM FAILURE
  - \+ POST-ACCIDENT HYDROGEN REMOVAL
  - \+ NEED FOR EMERGENCY EVACUATION
  - \+ COSTS OF CLEANUP AND PLANT RECOVERY

- THE PROBABILITY AND CONSEQUENCES OF UNTERMINATED ACCIDENTS
  - \+ TIME OF CONTAINMENT FAILURE:

    EARLY VS LATE
  - \+ NATURE OF CONTAINMENT FAILURE:

    SMALL VS LARGE LEAK; OR CATASTROPHIC FAILURE
  - \+ FISSION PRODUCT STATE AT FAILURE TIME:

    QUIESCENT, SETTLED, IN WATER SOLUTION, IN MELT, VS DISPERSED, AEROSOLIZED, VAPORIZED.

SOME NRC AND IDCOR POSITIONS ON FCI SAFETY ISSUES

ISSUE	IDCOR	NRC
MAXIMUM AMOUNT OF FUEL THAT CAN COARSELY MIX IN-VESSEL	100 KG	5000 KG OR MORE
MAXIMUM AMOUNT OF FUEL THAT CAN COARSELY MIX EX-VESSEL	7 KG	16000 KG OR MORE
MULTIPLE EXPLOSIONS AND HIGHLY TRANSIENT FCI PHENOMA	DO NOT OCCUR	NOT MODELED. MAY OCCUR
AMOUNT OF METAL-WATER REACTION THAT CAN OCCUR DURING AN FCI	NEGLIGIBLE	POSSIBLY 30% OR MORE
AMOUNT OF STEAM GENERATED DURING AN EXPLOSIVE OR NON-EXPLOSIVE FCI	NEGLIGIBLE	PRIMITIVE MODELS
COOLABILITY OF DEBRIS BED RESULTING FROM AN FCI	COOLABLE	MAY OR MAY NOT BE
IN-VESSEL FUEL DISPERSION DUE TO A STEAM EXPLOSION	DOESN'T OCCUR	NOT MODELED. MAY OCCUR
BWR GEOMETRY PRECLUDES SIGNIFICANT COARSE MIXING IN LOWER PLENUM	YES	MAYBE, BUT NO DATA
STEAM EXPLOSIONS DO NOT OCCUR AT HIGH AMBIENT PRESSURE	YES	MAYBE, BUT INSUFFICIENT DATA
LOWER PLENUM FAILURE DUE TO A STEAM EXPLOSION	DOESN'T OCCUR	NOT MODELED. MAY OCCUR
ENERGETIC STEAM EXPLOSION IN REFLOOD MODE	DOESN'T OCCUR	NOT MODELED. MAY OCCUR
ENERGETIC STEAM EXPLOSION IN STRATIFIED MODE (WATER ABOVE FUEL)	DOESN'T OCCUR	NOT MODELED. MAY OCCUR
CONTAINMENT FAILURE DUE TO STEAM EXPLOSION	DOESN'T OCCUR	NO MECHANISTIC MODEL
ALTERATION IN EX-VESSEL FISSION PRODUCT SOURCE TERM DUE TO FCIs	NOT IMPORTANT	NOT MODELED
FAILURE OF MARK II PEDESTAL WALL BY EX-VESSEL STEAM EXPLOSION	NOT CONSIDERED	POSSIBLE

FCI RESEARCH RATIONALE

- MANY ASPECTS OF SEVERE ACCIDENTS CAN BE STRONGLY INFLUENCED BY THE NATURE OF THE FCIs.
- UNCERTAINTIES CONCERNING MANY FCI PHENOMA ARE SO LARGE THAT ACCIDENT RISKS CANNOT BE ACCURATELY QUANTIFIED, NOR CAN ACCIDENT MANAGEMENT PROCEDURES BE ACCURATELY DEFINED.
- ADDITIONAL RESEARCH HAS A HIGH PROBABILITY OF REDUCING THESE UNCERTAINTIES.

CORE MELT-COOLANT INTERACTIONS

PROGRAM STATUS

AND

RECENT ACCOMPLISHMENTS

FRAGMENTATION AND MIXING

THE KEY QUESTION FOR FCIs IS:

TO WHAT DEGREE, AND AT WHAT RATE, DOES THE MOLTEN CORIUM FRAGMENT WHEN IT CONTACTS WATER?

POSSIBLE ANSWERS

1. NO FRAGMENTATION: STEAM AND HYDROGEN GENERATION RATES ARE SLOW AND BENIGN. EARLY CONTAINMENT FAILURE IS UNLIKELY OR IMPOSSIBLE.

2. COARSE FRAGMENTATION: (AKA "PREMIXING"); TIME SCALE OF ORDER OF SECONDS; SIGNIFICANT INCREASE IN STEAM AND HYDROGEN GENERATION RATES AND MAGNITUDES. INCREASED POSSIBILITY OF δ-, γ-, AND ϵ- FAILURE MODES.

3. FINE FRAGMENTATION: (AKA "STEAM EXPLOSION"); TIME SCALE OF ORDER OF MILLISECONDS; STEAM AND HYDROGEN GENERATION RATES AND MAGNITUDES CAN BE VERY HIGH. SHOCK WAVES AND MISSILES MAY BE GENERATED. INCREASED POSSIBILITY OF ALL FAILURE MODES, INCLUDING DIRECT FAILURE (α-MODE).

DEGREE AND RATE OF FRAGMENTATION IS A FUNCTION OF MANY VARIABLES SPECIFYING INITIAL AND BOUNDARY CONDITIONS:

1. FUEL PROPERTIES: COMPOSITION, TEMPERATURE, MASS
2. COOLANT PROPERTIES: COMPOSITION, TEMPERATURE, MASS
3. CONTACT MODE BETWEEN FUEL AND COOLANT:
   FUEL INTO COOLANT OR VICE VERSA
   INJECTION GEOMETRY AND RATE
4. NATURE AND STRENGTH OF SPONTANEOUS TRIGGERS
5. INTERACTION CHAMBER: GEOMETRY, SIZE, DEGREE OF CONFINEMENT, INTERNAL STRUCTURES
6. AMBIENT ATMOSPHERE: PRESSURE, RADIATION

FCI PROGRAM TASKS

1. BASED ON CURRENT STATE OF KNOWLEDGE, DEFINE MOST IMPORTANT VARIABLES AND THEIR RANGES.

2. CONDUCT EXPERIMENTS ON THESE VARIABLES, CONSISTENT WITH PROGRAM FUNDING.

3. DEVELOP MODELS TO EXPLAIN AND INTERPRET EXPERIMENTAL RESULTS, AND TO EXTRAPOLATE THOSE RESULTS TO REACTOR SCALES.

CMCI PROGRAM ELEMENTS

1. MECHANISTIC MODEL DEVELOPMENT AND APPLICATIONS.

2. PROBABILISTIC MODEL DEVELOPMENT AND APPLICATIONS.

3. SMALL-SCALE (SINGLE DROPLET) EXPERIMENTS.

4. INTERMEDIATE-SCALE OPEN-GEOMETRY EXPERIMENTS (EXO-FITS).

5. INTERMEDIATE-SCALE CLOSED-GEOMETRY EXPERIMENTS (FITS).

FCI EXPERIMENTAL PROGRAMS

INFORMATION GENERATED

SMALL-SCALE EXPERIMENTS:

- STEAM EXPLOSION TRIGGERABILITY.
- DROPLET FRAGMENTATION.
- CONVERSION RATIO.
- DEBRIS SIZE DISTRIBUTION, CHARACTERISTICS
- HYDROGEN GENERATION RATES.

INTERMEDIATE-SCALE EXPERIMENTS:

- PROBABILITY AND CONSEQUENCES OF STEAM EXPLOSIONS (TRIGGERING, PROPAGATION, EXPANSION, CONVERSION RATIO, SLUG FORMATION AND BREAKUP).
- NON-EXPLOSIVE STEAM GENERATION.
- DEBRIS SIZE DISTRIBUTION, CHARACTERISTICS.
- HYDROGEN GENERATION RATES AND MAGNITUDES.

INTERMEDIATE-SCALE FITS TESTS

EXPER. SERIES	NUMBER OF TESTS	INDEPENDENT VARIABLES: MELT MASS	FUEL/COOLANT MASS RATIO	AMBIENT PRESSURE	FUEL COMPOSITION	MELT ENTRY	CHAMBER GEOMETRY	WATER TEMPERATURE	OTHER (LID, HOLD TIME, ETC.)	CONTACT MODE	FUEL TEMPERATURE		MEASUREMENTS: COARSE MIXING	GAS PHASE PRESSURE	WATER PHASE PRESSURE	HYDROGEN GENERATION	STEAM GENERATION	CONVERSION RATIO	DEBRIS CHARACTERISTICS
MD	19	●				○	○						○		○			○	
FITSA	5			●									○	○	○		○	●	●
FITSG	2							●					○				●		●
MDC	7				●						○		○						
FITSB	9		●				○	○					○	○	○			●	●
FITSC	5			○	○			●					○	○	○	●	●	○	○
CM	12	○	○		?	○	○	●	●		?		○						
OM	4*				●			●	○				●	●+	●		●+	●+	●+
RC	2*						●								●			●+	●+
ACM	2*									●				●+		●+	●+	●+	●+

● PRIMARY VARIABLE
○ SECONDARY VARIABLE
* PRELIMINARY SCOPING TESTS
+ NOT YET MEASURED

FITS-C Test Series

Initial Parameters for the FITS-C Test Series

Test Name	Melt Composition	Melt Mass Del. kg	Water Mass kg	Mass Ratio M_c/M_f	Water Temp. K	Water Subcool. K	Ambient Press. MPa	Water Side Dim. m	Water Depth m	Melt Drop Height m	Melt Entry Vel. m/s	Melt Hold Time s
FITS1C	$Fe+Al_2O_3$	17.[illegible]	112.9	6.6	298	69	0.088	0.610	0.305	1.82	5.59	1.52
FITS2C	Corium A+R	16.0	226.1	13.4	295	72	0.082	0.610	0.610	2.37	6.60	1.43
FITS3C	Corium A+R	11.5	108.1	9.4	297	70	0.081	0.533	0.381	1.82	5.97#	1.52
FITS4C	$Fe+Al_2O_3$	19.0	110.2	5.8	353	74	0.531	0.610	0.305	1.82	5.97#	1.50
FITS5C	$Fe+Al_2O_3$	19.6	110.4	5.6	351	75	0.510	0.610	0.305	1.82	5.97#	1.50

- Indicates that the entry was calculated by $[2 \times g \times h]^{(1/2)}$

Lid status (in/out): IN

All tests conducted in an inerted (Nitrogen) atmosphere.

FITS-C Test Series

Event Classification and Characteristics for the FITS-C Test Series

Test Name	Event Type	Event Time after Melt Entry ms	Explosion Propagation Velocity m/s	Avg/Peak Particle Velocity m/s	Percent of Water Depth at Event
FITS1C	SE	78	415.0	280./379.	100.0
FITS2C	SE	10	N.O.	22.5/29.3	26.4
FITS2C	TR	169			100.0
FITS3C	No events observed				
FITS4C	No events observed				
FITS5C	No events observed				

TR - Nonpropagating trigger SE - Steam Explosion

N.O. - Not obtained.

FITS-C Test Series

Comments and Additional Results for the FITS-C Test Series

Test Name	Melt Width at Entry m	Comments on Test
FITS1C	0.07	Repeat of FITS2B. Some early melt leak. Lost mass was not used in particle diameter calculations.
FITS2C	0.23	Lid trails melt entry by 50 ms. Lid contacts bottom first after passing through melt. Possible partial melt crust formation prior to water contact. Lid/bottom contact may have caused last trigger. Lost mass was not used in diameter calculations.
FITS3C	N.O.	Melt delivery failure. Melt fell in a shower of approximately 500 ms in duration. Lid entered at tail end of melt shower. No events observed from film data.
FITS4C	N.O.	Gas samples lost. No films. Dispersed melt probably caused melt sensor not to respond. Detonator did not fire. Poor melt delivery.
FITS5C	N.O.	No film data. Apparently no explosion. Detonator fired at approximately 200 ms after entry. Probable dispersed melt delivery. Repeat of FITS4C/FITS2B tank/drop geometry.

N.O. - Not Obtained.

FITS-C Test Series

Debris Analysis and Fraction of Metal Oxidized

Test Name	Part. Mass Mean Dia. micrometer	Sauter Diameter micrometer	Total Mass Recovered kg	Lost Mass kg	Fraction of Metal Oxidized Fe_2O_3/ FeO
FITS1C	393.0	231.0	15.89	1.16	0.22/0.33
FITS2C	927.7	549.0	15.68	1.25	0.18/0.26
FITS3C	N.A.	N.A.	11.00	0.50	0.04/0.06
FITS4C	N.A.	N.A.	N.O.	N.O.	N.O.
FITS5C	N.A.	N.A.	19.49	0.07	0.05/0.08

N.O. - Not Obtained. N.A. - Not analyzed at publication.

RECENT EXO-FITS EXPERIMENTS

FY83 - 84

CM:	COARSE MIXING, 12 TESTS
OM:	OXIDE MELTS, 4 TESTS
ACM:	ALTERNATE CONTACT MODE, 2 TESTS
RC:	RIGID CONTAINER, 2 TESTS
FITSD:	IN-VESSEL, 4 TESTS

CM SERIES - COARSE MIXING

I. OBJECTIVE:

INVESTIGATE COARSE MIXING BEHAVIOR TO DISTINGUISH BETWEEN EXISTING MODELS.

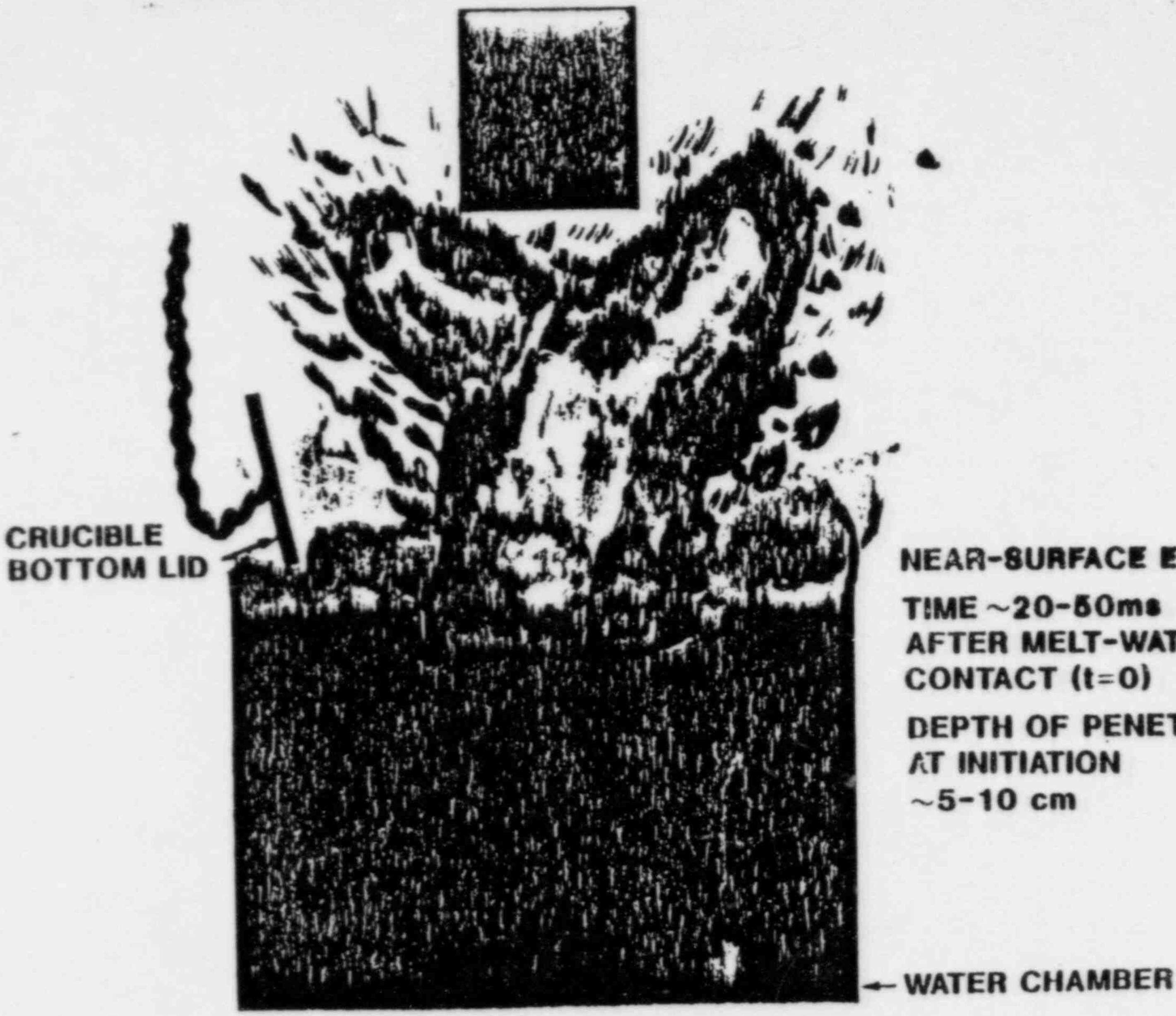
II. SERIES DESCRIPTION:

USE MOLTEN IRON-ALUMINA MELTS (~ 20 KG) AND SATURATED WATER. VARY OTHER PARAMETERS TO QUANTIFY THE DEPENDENCE OF MIXING ON SCALE, GEOMETRY, AND THERMODYNAMIC PARAMETERS. ALSO DETERMINE EXPLOSIBILITY OF FUEL/COOLANT SYSTEM AND MEASURE WATER-PHASE PRESSURES AND CONVERSION RATIO, IF POSSIBLE.

III. STATUS:

SERIES COMPLETED: 12 TESTS.

MELT PENETRATION AND EVENT INITIATION



NEAR-SURFACE EVENTS:

TIME ~20-50ms
AFTER MELT-WATER
CONTACT (t=0)

DEPTH OF PENETRATION
AT INITIATION
~5-10 cm

CM SERIES - COARSE MIXING

IV. RESULTS:

- SURFACE EVENTS OF SUFFICIENT VIOLENCE TO EXPEL MELT FROM THE WATER, AS WELL AS PREVENT SOME MELT FROM ENTERING, OCCURRED IN EVERY TEST.

- RESIDUAL MELT MASSES OF ~ 4 KG WERE NOT EXPELLED, AND FROZE ON THE CHAMBER BOTTOM FOR MOST HOT WATER TESTS.

- THE LATEST DELAY TO AN EXPLOSION EVER OBSERVED OCCURRED FOR THE COLD WATER TEST CM-7 (550 MS AFTER MELT ENTRY). EXPLOSION SEEMED TO OCCUR IN A VERY WATER-LEAN ENVIRONMENT.

- THE PRESENCE OF THE LID SEEMS TO DELAY THE SURFACE INTERACTION.

- LONGER HOLD TIMES SEEM TO CORRELATE WITH GREATER DELAYS IN MELT EXPULSION.

Coarse Mixing Test Series

Initial Parameters for the Coarse Mixing Test Series

Test Name	Melt Mass Del. kg	Water Mass kg	Mass Ratio M_c/M_f	Water Temp. K	Water Subcool. K	Water Side Dim. m	Water Depth m	Melt Drop Height m	Melt Entry Vel. m/s	Melt Hold Time s	Lid in/out
CM 1	18.5	109.7	5.9	358	9	0.305	1.220	0.305	2.44#	1.00	OUT
CM 2	18.0	109.3	6.1	363	4	0.305	1.220	0.305	2.44#	4.00	OUT
CM 3	18.0	437.0	24.3	364	3	0.610	1.220	0.483	3.11	0.68	OUT
CM 4	18.9	218.5	11.6	364	3	0.610	0.610	1.120	4.60	0.68	OUT
CM 5	7.6	218.7	28.7	363	4	0.610	0.610	1.120	4.78	0.75	OUT
CM 6	4.0	218.5	54.6	364	3	0.610	0.610	1.220	4.99	0.81	OUT
CM 7	18.5	169.6	9.2	294	73	0.610	0.457	1.120	4.77	0.65	OUT
CM 8	18.6	218.4	11.7	365	2	0.610	0.610	0.444	3.08	0.66	IN
CM 9	18.6	218.6	11.8	364	3	0.610	0.610	0.444	3.06	0.66	IN
CM 10	18.4	109.3	5.9	366	1	0.610	0.305	1.143	4.60	7.00	OUT
CM 11	18.7	218.6	11.7	366	1	0.610	0.610	1.120	4.68	5.00	OUT
CM 12	18.5	112.9	6.1	298	69	0.610	0.305	1.820	5.89	1.50	IN

- Indicates that the entry was calculated by [2 x g x h]$^{(1/2)}$

Melt composition: iron-alumina

Coarse Mixing Test Series

Event Classification and Characteristics for the Coarse Mixing Test Series

Test Name	Event Type	Event Time after Melt Entry ms	Eruption Duration ms	Explosion Propagation Velocity m/s	Avg/Peak Particle Velocity m/s	Percent of Water Depth at Event
CM 1	ER	30				
CM 2	ER	73				
CM 3	ER	43	41		47/88	7.5
CM 3	TR	56				
CM 4	ER	18	62			12.2
CM 4	TR	59,68,75,89				
CM 4	BC	197				100.0
CM 5	ER	27	119		33/43	13.0
CM 5	BC	252				100.0
CM 6	ER	22	163		20/26	11.0
CM 6	TR	66,88,108,132,159				
CM 6	BC	194				100.0
CM 6	TR	203				
CM 7	ER	43			62/73	49.0
CM 7	SE	69		301	197/—	71.8
CM 7	BC	113				100.0
CM 7	SE	503				100.0
CM 8	ER	37	179			11.8
CM 8	ER	117			41/96	24.6
CM 8	TR	195,202				
CM 8	SE	216				67.2
CM 9	ER	65	40			21.3
CM 9	SE	105			105/350	38.9
CM 10	ER	43	69		18/24	
CM 10	SE	112			37/78	100.0
CM 10	SE	311				
CM 11	ER	52	88		32/—	25.9
CM 11	BC					100.0
CM 12	ER	37				15.8
CM 12	SE	69			103/110	65.6
CM 12	BC	111				100.0
CM 12	SE	125				100.0

ER – Eruption TR – Nonpropagating Trigger SE – Steam Explosion
BC – Melt Contact with Bottom

Coarse Mixing Test Series

Comments and Additional Results for the Coarse Mixing Test Series

Test Name	Residual Mass in Chamber kg	Melt Width at Entry m	Comments on Test
CM 1	N.O.	N.O.	Lid skimmed water surface. High-speed cameras didn't work. Possible weak surface explosion can be seen from low-speed camera.
CM 2	3.80	N.O.	Lid skimmed water surface. Lid stuck in crucible for 1.5 to 2.0 s making hold time 3.5 to 4.0 s. No high-speed films. Water chamber remained intact.
CM 3	4.28	0.33	One nonpropagating trigger occurred at 56 ms after melt entry. The top 1/3 of water chamber fractured.
CM 4	3.50	0.53	Strong 25-30 mph crosswind at test time. Stripped some melt from the falling melt mass. Water chamber destroyed by nonpropagating triggers.
CM 5	3.40	0.28	Eruption velocity seemed to increase approx. 42 ms after eruption began. No triggers observed. A large amount of fine dust-size debris remained in chamber.
CM 6	1.94	0.18	Eruption appeared to be composed of multiple events. Water chamber remained undamaged.
CM 7	N.O.	N.O.	Melt shape was not uniform with a thin arm preceding main melt mass by 13 cm. Second explosion deformed water chamber support stand.
CM 8	N.O.	0.23	Lid entered water perpendicularly. The lid quickly separated from melt and slid off to side. Main center eruption was preceded by steaming. Weak explosion.
CM 9	N.O.	0.26	Lid entered water parallel to surface. Weak explosion.
CM 10	N.O.	0.19	Severe crucible melt leak prior to release at 5 s hold time. Fragments of lid entered with rest of melt. Water was a boiling froth at melt entry.
CM 11	5.80	0.20	No triggers observed. The chamber remained intact.
CM 12	N.O.	0.20	Large water swell due to eruption. Weak first explosion ruptured chamber. Strong second explosion did some mech. damage to stand and test tower. Second explosion began on bottom.

N.O. - Not Obtained.

OM SERIES - OXIDE MELTS

I. OBJECTIVE:

UNDERSTAND CMCIs WITH OXIDIC MELTS.

II. SERIES DESCRIPTION:

USE OXIDIC MELTS (FeO_x, UO_2, ETC.). VARY MELT MASS, WATER VOLUME AND TEMPERATURE, AMBIENT PRESSURE, AND OTHER PARAMETERS. DETERMINE EXPLOSIBILITY OF THIS FUEL/COOLANT SYSTEM. MEASURE PRESSURES, DEBRIS CHARACTERISTICS, CONVERSION RATIO AND COARSE MIXING CHARACTERISTICS.

III. STATUS:

4 TESTS COMPLETED: SATURATED AND SUBCOOLED WATER.

OM SERIES - OXIDE MELTS

IV. PRELIMINARY RESULTS:

- STEAM EXPLOSIONS OCCURRED FOR ALL FOUR TESTS (THREE IN COLD WATER, ONE IN HOT).

- PRESENCE OF LID IN OM-3 DELAYED EXPLOSION (100 MS AT 25 CM PENETRATION FOR OM-3 VS ~ 35 MS AND < 10 CM FOR OTHER THREE TESTS).

- MULTIPLE EXPLOSIONS OCCURRED FOR HOT WATER TEST OM-4. LAST EXPLOSION WAS ~ 490 MS AFTER MELT ENTRY.

- NO NON-EXPLOSIVE SURFACE EVENTS OCCURRED, IN CONTRAST TO CM SERIES.

→ IRON OXIDE MELTS ARE EASILY TRIGGERED AND EXPLODE READILY IN HOT AND COLD WATER.

Oxide Melt Test Series

Initial Parameters for the Oxide Melt Test Series

Test Name	Melt Mass Del. kg	Water Mass kg	Mass Ratio M_c/M_f	Water Temp. K	Water Subcool. K	Water Side Dim. m	Water Depth m	Melt Drop Height m	Melt Entry Vel. m/s	Melt Hold Time s	Lid in/out	Melt Width at Entry m
OM 1	N.O.	66.1	N.O.	298	69	0.43	0.36	0.635	3.53#	3.8	OUT	N.O.
OM 2	9.	100.9	11.2	298	69	0.53	0.36	0.635	3.83	3.8	OUT	0.24
OM 3	10.	131.7	13.2	298	69	0.61	0.36	0.635	3.34	3.8	IN	0.34
OM 4	9.	218.6	24.3	363	4	0.61	0.61	0.787	3.56	5.0	OUT	0.25

- Indicates that the entry was calculated by $[2 \times g \times h]^{(\frac{1}{2})}$

N.O. - Not obtained.

Event Classification and Characteristics, and Comments for the Oxide Melt Test Series

Test Name	Event Type	Event Time after Melt Entry ms	Avg/Peak Particle Velocity m/s	Percent of Water Depth at Event	Comments on Test
OM 1	SE	N.O.	N.O.	N.O.	Some melt ejected through crucible vent holes, fell into chamber, and exploded. Chamber destroyed. Rest of melt released at 3.8 s and fell into empty chamber base.
OM 2	SE	47	193/272	29.2	Poor film visibility due to smoke from thermite burn. Chamber destroyed by surface explosion. Possibility of incomplete thermite reaction.
OM 3	SE	141	785/—	N.O.	Substantial melt leak from bottom of crucible prior to melt release. Poor film visibility. Only one high-speed camera and no low-speed camera.
OM 4	SE	19	332/427	N.O.	Chamber destroyed by surface explosion. Explosions at 198 and 247 ms were local explosions near west wall and did not propagate to entire melt.
OM 4	SE	198	N.O.	N.O.	
OM 4	SE	247	N.O.	N.O.	
OM 4	SE	360	132/184	100.0	

ER - Eruption TR - Nonpropagating Trigger SE - Steam Explosion

N.O. - Not obtained

ACM SERIES - ALTERNATE CONTACT MODE

I. OBJECTIVE:

UNDERSTAND THE PROBABILITY AND CONSEQUENCES OF CMCIs FOR DIFFERENT CONTACT MODES.

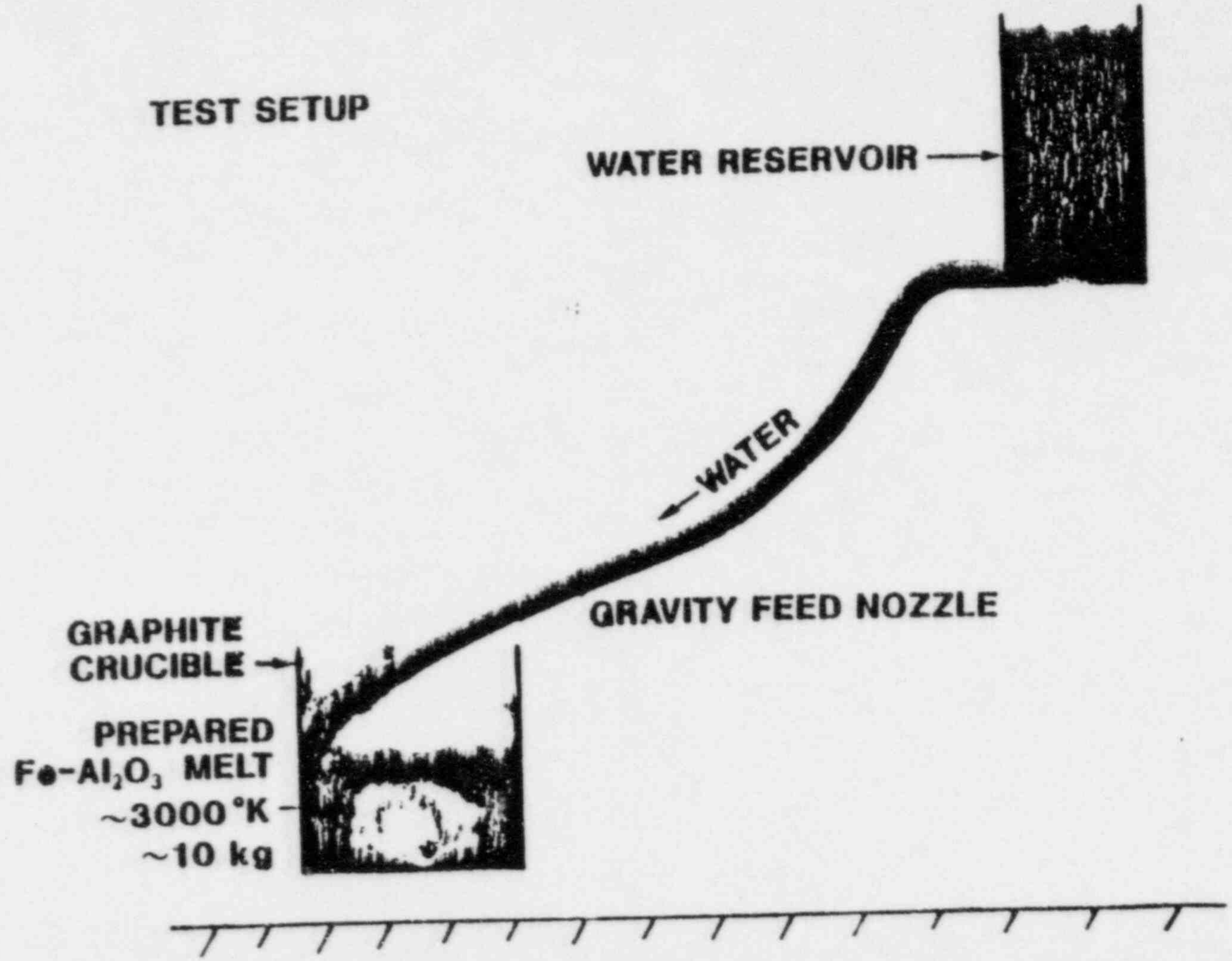
II. SERIES DESCRIPTION:

USING VARIOUS FUEL/COOLANT SIMULANT PAIRS, INVESTIGATE EXPLOSIBILITY AND STEAM AND HYDROGEN GENERATION RATES IN FLOODING AND WATER-INJECTION CONTACT MODES.

III. STATUS:

2 PRELIMINARY SCOPING TESTS COMPLETED.

TEST SETUP



WATER RESERVOIR
WATER
GRAVITY FEED NOZZLE
GRAPHITE CRUCIBLE
PREPARED $Fe-Al_2O_3$ MELT
~3000 °K
~10 kg

ACM SERIES - ALTERNATE CONTACT MODE

IV. PRELIMINARY RESULTS:

- ACM - 1: WATER INJECTED 1 s AFTER COMPLETION OF BURN. VIOLENT EXPLOSION AFTER AN ADDITIONAL 3 S.

- ACM - 2: WATER INJECTED 4.5 s AFTER BURN. NO EXPLOSION. PROBABLE CRUST FORMATION PRIOR TO WATER ENTRY.

- EXPLOSIONS IN REFLOOD MODE ARE POSSIBLE. ENERGETICS ARE UNKNOWN, BUT WILL PROBABLY DEPEND STRONGLY ON INITIAL AND BOUNDARY CONDITIONS.

Alternate Contact Mode Test Series

Initial Parameters for the Alternate Contact Mode Test Series

Test Name	Melt Mass kg	Water Mass kg	Water Temp. K	Water Subcooling K	Ambient Press. MPa	Water Hold Time s
ACM 1	10.0	0.6	298	69	0.083	1.0
ACM 2	18.5	3.8	298	69	0.083	4.5

Melt composition: iron-alumina

Event Classification and Characteristics; and Comments for the Alternate Contact Mode Test Series

Test Name	Event Type	Time after Melt Entry s	Comments on Test
ACM 1	Explosion	3	Delay between end of thermite burn and water-melt contact was 1 s. Explosion occurred at 3 s after water-melt contact. Several minor eruptions before explosion.
ACM 2	No Explosion		Delay between end of thermite burn and water-melt contact was 4.5 s. No explosion observed. Apparent crusting of melt prior to melt-water contact.

RC SERIES - RIGID CONTAINER

I. OBJECTIVE:

UNDERSTAND EFFECTS OF EXPLOSION CONFINEMENT.

II. SERIES DESCRIPTION:

USING VARIOUS FUEL/COOLANT SIMULANT PAIRS, INVESTIGATE THE CHANGE IN EXPLOSION CONVERSION RATIO DUE TO INCREASED CONFINEMENT.

III. STATUS:

2 TESTS COMPLETED. EXO-FITS FACILITY DESTROYED.

RC SERIES - RIGID CONTAINER

IV. PRELIMINARY RESULTS:

RC - 1: IRON-ALUMINA/COLD WATER, HOLD TIME = 4 S; VIOLENT EXPULSION, NO EXPLOSION.

RC - 2: IDENTICAL TO RC - 1 EXCEPT MELT WAS HELD FOR ONLY 1.5 S AFTER THERMITE BURN. STRONG EXPLOSION DESTROYED EXO-FITS CONCRETE PAD AND SUPERSTRUCTURE. WATER PHASE PRESSURE > 700 B.

Rigid Container Test Series

Initial Parameters for the Rigid Container Test Series

Test Name	Melt Mass Delivered kg	Water Mass kg	Mass Ratio M_c/M_f	Water Temp. K	Water Subcool. K	Chamber Diameter m	Water Depth m	Drop Height m	Melt Entry Velocity m/s	Melt Hold Time s
RC 1	19.0	111.7	5.9	298	69	0.56	0.46	1.78	5.77	4.0
RC 2	18.5	111.6	6.0	303	64	0.56	0.46	1.78	5.85	1.5

Melt composition: iron-alumina
Lid status(in/out): IN

Event Classification and Characteristics, and Comments for the Rigid Container Test Series

Test Name	Event Type	Event Time after Melt Entry ms	Eruption Duration ms	Avg/Peak Particle Velocity m/s	Comments on Test
RC 1	ER	86	232	N.O.	Rigid vessel was 94 cm long, 55.9 cm I.D. pipe with 2.5 cm thick walls and a plexiglass bottom. Entry velocity and time estimated using pipe inlet velocity and gravity.
RC 2	ER	56		N.O.	Same vessel as RC 1. Explosion lifted vessel 2 m off ground. Destroyed EXO-FITS test stand and concrete pad. Substantial ground and air shock felt.
RC 2	SE	180		853/1122	

ER - Eruption TR - Nonpropagating Trigger SE - Steam Explosion

N.O. - Not obtained

FITS-D Test Matrix
(Two experimental level, 1/8 rep fractional factorial experiment design)

Test	M_f	d	w	v	SC	P	Water mass-kg M_c	Water/Melt mass ratio M_c/M_f
FITS1D	H	L	H	H	H	H	87	1.7
FITS2D	L	H	L	H	H	H	95	4.8
FITS3D	L	L	H	L	L	H	87	4.4
FITS4D	H	H	L	L	L	H	95	1.9
FITS5D	L	H	H	L	H	L	381	19.0
FITS6D	H	L	L	L	H	L	22	0.44
FITS7D	H	H	H	H	L	L	381	7.6
FITS8D	L	L	L	H	L	L	22	1.1

The following parameters will be held constant during this series:

melt composition	: iron-alumina thermite
melt pour rate	: default
contact mode	: melt into water
chamber confinement	: unconfined, lucite walls
triggering	: spontaneous or absent
melt hold time	: 1.5 sec

Ranges of variable parameters corresponding to H and L values above:

melt mass, M_f	: H = 50 kg, L = 20 kg, actual delivered mass will be less.
water depth, d	: H = 0.66 m, L = 0.15 m
water chamber side dimension, w	: H = 0.76 m, L = 0.38 m
entry velocity, v	: controlled roughly by the high and low drop heights of H = 2.7 m and L = 1.6 m.
water subcooling, SC	: H corresponds to cold water, L corresponds to a water as close to saturation temperature as can be achieved at the corresponding ambient pressure.
ambient pressure, P	: H = 11 bars, L = 0.83 bars
mass of water, M_c	: water depth and geometry dependent

FITS-D Test Series

Initial Parameters for the FITS-D Test Series

Test Name	Melt Mass Del. kg	Water Mass kg	Mass Ratio M_c/M_f	Water Temp. K	Water Subcool. K	Ambient Press. MPa	Water Side Dim. m	Water Depth m	Melt Drop Height m	Melt Entry Vel. m/s
FITS0D	17.8	182.9	10.3	359	9	0.085	0.610	0.508	1.79	5.92#
FITS2D[1]	18.0	95.7	5.3	289	168	1.103	0.381	0.660	2.69	7.26#
FITS5D	19.2	383.0	19.9	284	83	0.083	0.762	0.660	1.64	5.67#
FITS8D[1]	18.0	21.3	1.2	368	0	0.083	0.381	0.152	2.69	7.26#

- Entry was calculated by $[2 \times g \times h]^{(\frac{1}{2})}$

1 - Data for melt mass delivered and mass ratio are only rough estimates.

Melt composition: iron-alumina
Melt hold time: 1.5 seconds
Lid status(in/out): IN
All tests conducted in an inerted (Nitrogen) atmosphere.

FITS-D Test Series

Event Classifications and Characteristics for the FITS-D Test Series

Test Name	Event Type	Event Time After Melt Entry ms	Eruption Duration ms	Explosion Propagation Velocity m/s	Avg/Peak Particle Velocity m/s	Percent of Water Depth at Event
FITS0D	ER	N.A.	N.A.		N.A.	N.A.
FITS2D	No Events Were Observed					
FITS5D	SE	53		318.0	N.O.	29.7
FITS5D	SE	56		N.O.	N.O.	N.O.
FITS8D	ER	N.A.	N.A.		N.A.	N.A.

ER - Eruption TR - Nonpropagating trigger SE - Steam Explosion
N.A. - Not analyzed at publication. N.O. - Not Obtained.

FITS-D Test Series

Comments and Additional Results for the FITS-D Test Series

Test Name	Peak Gas Phase Press MPa	Peak Gas Phase Temp K	Melt Width at Entry m	Fraction of Iron Oxidized Fe_2O_3/FeO	Comments on Test
FITS0D	0.291	397	N.O.	0.19/0.29	Data very preliminary.
FITS2D	1.526	N.A.	N.A.	N.A.	Data very preliminary. Substantial amount of the delivered melt missed the water chamber. No explosive events seen on film data.
FITS5D	0.554	370	N.O.	0.16/0.24	Data very preliminary. Second explosion occurred 3 ms after first explosion. Substantial melt quenching prior to second explosion. First explosion drove melt into water at 150 m/s.
FITS8D	N.A.	N.A.	N.A.	N.A.	Data very preliminary. The films showed that the water was a boiling froth at main melt entry due to early entry by a small amount of pre-released melt.

N.O. - Not Obtained.
N.A. - Not analyzed at publication.

CORE MELT-COOLANT INTERACTIONS

PLAN FOR

RESOLUTION OF

TECHNICAL ISSUES

REACTOR SAFETY ISSUES AFFECTED BY FCIS

1. STEAM AND HYDROGEN GENERATION:

   WHAT ARE THE RATES AND TOTAL MAGNITUDES OF STEAM AND HYDROGEN WHICH CAN BE GENERATED DURING FCIs?

2. DEBRIS CHARACTERISTICS:

   WHAT ARE THE CHARACTERISTICS OF THE DEBRIS PRODUCED BY FCIS, INCLUDING PARTICLE SIZE DISTRIBUTION, POROSITY AND DEBRIS-BED STRATIFICATION?

3. ACCIDENT PROGRESSION AND SOURCE TERM:

   HOW DO FCIs INFLUENCE THE PROGRESSION OF THE ACCIDENT AND THE NATURE OF THE SOURCE TERM (INCLUDING FISSION PRODUCT CHEMISTRY, RELEASE RATE, PARTICLE SIZE AND MORPHOLOGY, AND FP DISPERSAL)? WHAT ARE THE CONSEQUENCES OF FUEL DEBRIS DISPERSAL IN- OR EX-VESSEL BY VIOLENT FCIs?

4. ACCIDENT TERMINATION AND SAFE SHUTDOWN:

   HOW DO FCIS AFFECT THE PROBABILITY OF SUCCESSFUL ACCIDENT TERMINATION BY THE ADDITION OF WATER TO THE MELT? WHAT OPERATOR ACTIONS WOULD INCREASE THE POSSIBILITY OF SAFE SHUTDOWN BY REDUCING THE RISK FROM DANGEROUS FCIS?

5. DIRECT FAILURE:

   WHAT ARE THE PROBABILITIES AND CONSEQUENCES OF DIRECT CONTAINMENT FAILURE BY A STEAM EXPLOSION (α - MODE)?

6. INDIRECT FAILURE:

   WHAT ARE THE PROBABILITIES AND CONSEQUENCES OF INDIRECT CONTAINMENT FAILURE BY FCIs (δ-, γ-, OR β- MODES)?

KEY QUESTIONS WHICH MUST BE ANSWERED

TO RESOLVE FCI ISSUES

1. WHAT ARE THE IMPORTANT INITIAL AND BOUNDARY CONDITIONS WHICH INFLUENCE FCI PHENOMENA?

   PAST RESEARCH HAS SHOWN THAT THESE ARE:

   FUEL MASS, COMPOSITION AND TEMPERATURE; FUEL/WATER MASS RATIO; WATER MASS, SUBCOOLING, DEPTH, CROSS-SECTIONAL AREA AND POSSIBLY COMPOSITION; TRIGGER STRENGTH; AMBIENT PRESSURE; CONTACT MODE; MELT/WATER POUR RATE AND ENTRY VELOCITY; WATER CHAMBER GEOMETRY, CONFINEMENT AND INTERNAL STRUCTURES.

2. FOR A GIVEN SET OF INITIAL CONDITIONS, WHAT ARE THE CHARACTERISTICS OF THE RESULTING FCI? THE ANSWERS TO THIS QUESTION WILL RESOLVE THE SAFETY ISSUES. SPECIFICALLY:

   A) WHAT ARE THE RATES AND QUANTITIES OF STEAM AND HYDROGEN THAT ARE GENERATED?
   B) CAN A LARGE-SCALE EXPLOSION OCCUR UNDER THESE CONDITIONS AND, IF SO, WHAT IS THE CONVERSION RATIO?
   C) CAN A MISSILE BE GENERATED? WHAT IS ITS ENERGY?
   D) WHAT ARE THE CHARACTERISTICS OF THE RESULTING DEBRIS?
   E) WHAT ARE THE EFFECTS OF THE FCI ON FP RELEASE AND DISPERSAL?

3. WITH A KNOWLEDGE OF THE FCI CHARACTERISTICS WHICH OCCUR, CALCULATE THE PROBABILITY AND CONSEQUENCES OF DIRECT AND INDIRECT CONTAINMENT FAILURE USING PHENOMENOLOGICAL, PROBABILISTIC OR INTEGRATED CONTAINMENT CODES, AS APPROPRIATE.

PLAN FOR RESOLUTION OF ISSUES

1. ASSESS CURRENT STATE OF KNOWLEDGE FOR ALL ISSUES.

2. BASED ON THIS KNOWLEDGE, DETERMINE MOST IMPORTANT EXPERIMENTAL AND MODELLING UNCERTAINTIES.

3. PLAN AND EXECUTE AN "EFFICIENT" TEST MATRIX.

4. INCORPORATE TEST RESULTS INTO NEW MODELS AND CODES.

5. ASSESS THE UNCERTAINTY IN MODEL PREDICTIONS. IF "SUFFICIENTLY" LOW, TERMINATE FURTHER EXPERIMENTAL AND ANALYTICAL FCI RESEARCH. MOVE TO RISK ASSESSMENT PHASE.

6. IF UNCERTAINTIES ARE STILL TOO HIGH AFTER STEPS 3, 4 AND 5, EXPAND TEST MATRIX AND REPEAT PROCESS.

TO RESOLVE THE FCI SAFETY ISSUES. SANDIA PROPOSES AN INTEGRATED RESEARCH PROGRAM CONTAINING THE FOLLOWING ELEMENTS:

1. LARGE-SCALE (≤ 2000 KG) FACILITY FOR OPEN-GEOMETRY EXPERIMENTS ON COARSE MIXING AND CONVERSION RATIO (EXO-FITS II USING THERMITE MELTS AT AMBIENT PRESSURE.

2. EXTENSION OF FITS CLOSED-GEOMETRY EXPERIMENTS TO 50 KG OF THERMITE MELTS.

3. SMALL-SCALE SINGLE-DROPLET EXPERIMENTS TO INVESTIGATE TRIGGERING AND CONVERSION RATIO AT HIGH AMBIENT PRESSURE (TO 170 BARS).

4. LARGE-SCALE (≤ 400 KG) FACILITY FOR CLOSED-GEOMETRY EXPERIMENTS USING INDUCTION-HEATED PROTOTYPIC OXIDIC AND METALLIC MELTS.

5. CONTINUATION OF FCI MODEL DEVELOPMENT AND APPLICATION.

*****

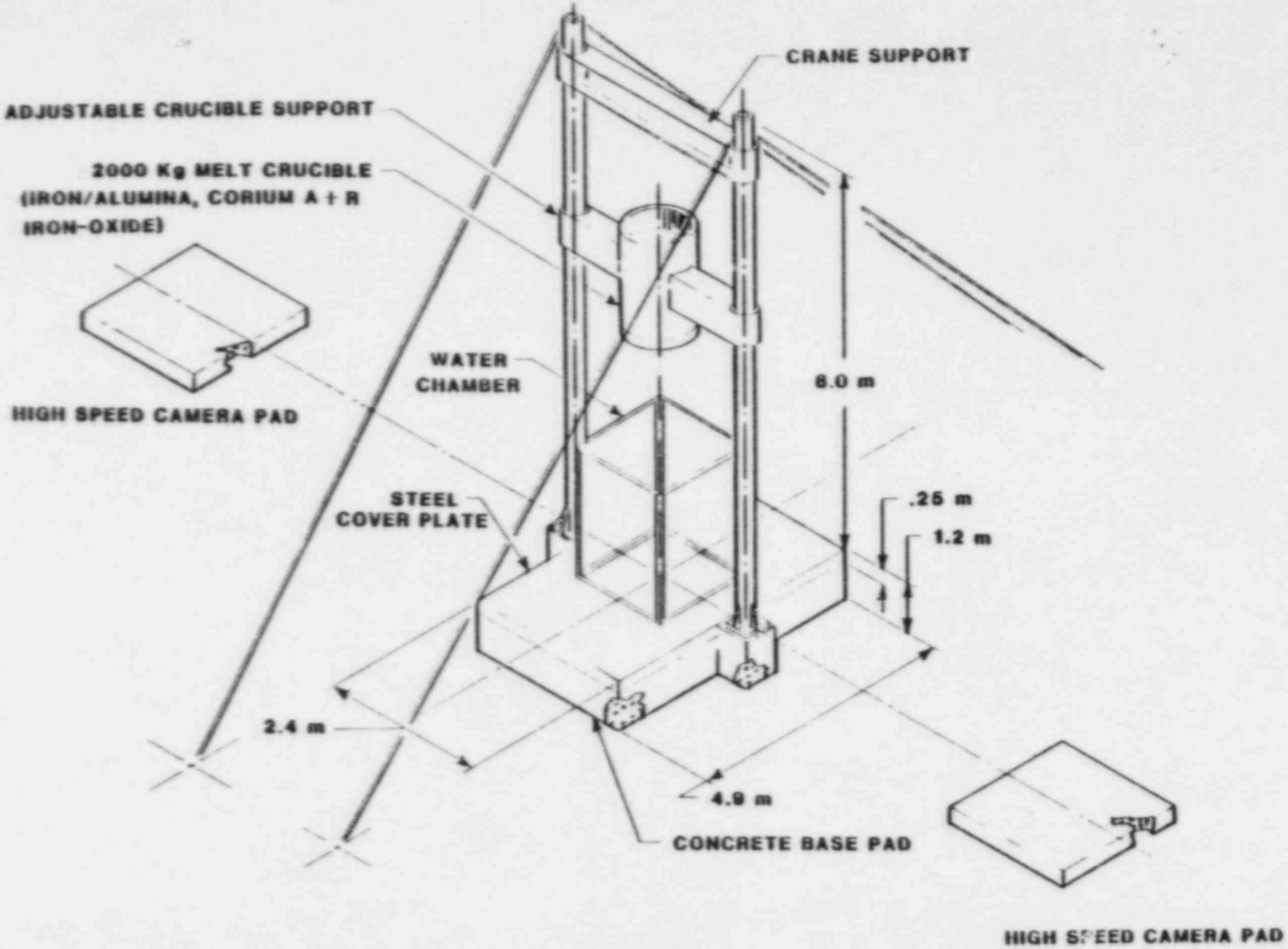
ABBREVIATION FOR PROGRAM ELEMENTS

1. EXO-FITS II
2. FITS EXTENDED
3. SHIP (SMALL-SCALE HIGH PRESSURE)
4. ELVIS (ENCLOSED LARGE VESSEL INTERACTION SYSTEM)
5. MODEL DEVELOPMENT

RATIONALE FOR EXPERIMENTAL PLAN

ELEMENT 1: EXO-FITS II

- THE PRIMARY OBJECTIVE OF THIS FACILITY IS TO DETERMINE WHETHER AN UPPER LIMIT EXISTS FOR COARSE MIXING, AND WHAT THIS LIMIT IS.
- THE FACILITY WOULD BE DESIGNED TO DETERMINE THIS LIMIT AS CHEAPLY AS POSSIBLE.
- IF A LIMIT WERE FOUND AT 2000 KG OR LESS, IT WOULD SIGNIFICANTLY AFFECT ALL SIX SAFETY ISSUES. FURTHERMORE, ISSUES 4 (ACCIDENT TERMINATION), 5 AND 6 (DIRECT AND INDIRECT FAILURE) WOULD BE COMPLETELY RESOLVED.
- THERE IS <u>NO OTHER WAY</u> TO INVESTIGATE THE EFFECTS OF LARGE MELT MASSES AT RELATIVELY LOW COSTS.
- BASIS FOR SELECTING 2000 KG OF FUEL:
  - -HIGH ENOUGH TO UNEQUIVOCALLY DISTINGUISH THE DIFFERENCE BETWEEN CURRENT COARSE MIXING MODELS;
  - -HIGH ENOUGH TO APPROACH THE RANGE OF MASSES WHICH MIGHT BEGIN TO THREATEN VESSEL AND CONTAINMENT INTEGRITY;
  - -LOW ENOUGH TO KEEP DOWN COSTS OF BUILDING AND OPERATING.



SCHEMATIC OF EXO-FITS II

EXO-FITS II: EXPERIMENTAL VARIABLES AND MEASUREMENTS

I. PRIMARY VARIABLES

FUEL MASS (UP TO 2000 KG)
WATER MASS
FUEL/WATER MASS RATIO
WATER TEMPERATURE (SUBCOOLING)
FUEL INJECTION RATE (DROP HEIGHT, POUR DIAMETER)
WATER DEPTH
WATER CHAMBER CONFINEMENT
TRIGGER STRENGTH.

II. SECONDARY VARIABLES

INTERNAL STRUCTURES IN WATER (LOWER PLENUM SIMULATION)
WATER COMPOSITION

III. FIXED PARAMETERS

FUEL COMPOSITION (IRON-ALUMINA THERMITE)
FUEL TEMPERATURE
AMBIENT PRESSURE
CONTACT MODE (FUEL INTO COOLANT)

IV. MEASUREMENTS

PHOTOGRAPHY (COARSE MIXING, CONVERSION RATIO)
WATER PHASE PRESSURE
BASE IMPULSE
POSSIBLY X-RAYS

RATIONALE FOR EXPERIMENTAL PLAN

ELEMENT 2: FITS EXTENDED

- THE PRIMARY OBJECTIVE OF THIS FACILITY IS TO PROVIDE QUANTITATIVE DATA FOR RESOLVING ISSUES 1 AND 2 (STEAM AND HYDROGEN GENERATION AND DEBRIS CHARACTERISTICS). IT WILL ALSO PROVIDE INFORMATION FOR RESOLVING ALL THE REMAINING ISSUES.
- QUANTITATIVE DATA GENERATED IN THIS FACILITY WOULD BE USED FOR MODEL DEVELOPMENT AND CODE ASSESSMENT.
- BECAUSE THE FACILITY IS CURRENTLY OPERATIONAL, EXPERIMENTS USING UP TO 50-100 KG OF THERMITE-GENERATED MELTS CAN BE INEXPENSIVELY CONDUCTED.
- THE MAJOR DRAWBACKS OF THIS FACILITY ARE LIMITED MELT COMPOSITION (ONLY VARIOUS THERMITES), LIMITED MELT MASS, AND NO CAPABILITY FOR HIGH PRESSURE INJECTION.

FITS-X (EXTENDED): EXPERIMENTAL VARIABLES AND MEASUREMENTS

I. PRIMARY VARIABLES

FUEL COMPOSITION (THERMITES: IRON-ALUMINA, CORIUM, IRON OXIDE)
FUEL MASS (20 - 100 KG)
WATER MASS
FUEL/WATER MASS RATIO
WATER TEMPERATURE (SUBCOOLING)
WATER DEPTH, CROSS-SECTION, CONFINEMENT
INTERNAL STRUCTURES (LOWER PLENUM SIMULATION)
FUEL INJECTION RATE (DROP HEIGHT, POUR DIAMETER)
AMBIENT PRESSURE (1 - 11 BARS)
CONTACT MODE (FUEL INTO COOLANT AND VICE VERSA)
ALTERNATE CONTACT MODE: FUEL DEPTH, WATER INJECTION RATE
TRIGGER STRENGTH

II. SECONDARY VARIABLES

WATER COMPOSITION
FISSION PRODUCT SIMULANTS IN MELT

III. FIXED PARAMETERS

FUEL TEMPERATURE FOR A GIVEN FUEL COMPOSITION
GRAVITY POURS ONLY: NO HIGH PRESSURE INJECTION

IV. MEASUREMENTS

PHOTOGRAPHY (FOR UNCONFINED TESTS WITH LUCITE CHAMBER)
X-RAYS (FOR COARSE MIXING)
BASE IMPULSE
WATER PHASE PRESSURE
GAS PHASE TEMPERATURE
GAS PHASE PRESSURE (FOR STEAM GENERATION RATES)
GAS SAMPLING (FOR HYDROGEN GENERATION RATES AND FISSION PRODUCTS)
DEBRIS CHARACTERISTICS
POSSIBLY FUEL TEMPERATURES

RATIONALE FOR EXPERIMENTAL PLAN

ELEMENT 3: SHIP (SMALL-SCALE HIGH PRESSURE TESTS)

- THE PRIMARY OBJECTIVE OF THIS FACILITY IS TO INVESTIGATE THE TRIGGERING OF STEAM EXPLOSIONS AT HIGH AMBIENT PRESSURE.
- THIS FACILITY REPRESENTS THE MOST INEXPENSIVE APPROACH TO RESOLVING THE QUESTION OF DIRECT FAILURE FOR ACCIDENTS AT HIGH AMBIENT PRESSURE.
- SINCE TRIGGERING IS THE FCI PHASE CURRENTLY BELIEVED TO BE MOST SENSITIVE TO PRESSURE, THIS FACILITY WOULD QUANTITATIVELY ADDRESS THAT PROCESS.
- SHIP WOULD PROVIDE SOME QUANTITATIVE DATA ON CONVERSION RATIO AT HIGH PRESSURE.
- SHIP COULD ALSO INEXPENSIVELY GENERATE DATA ON THE EFFECTS OF HIGH RADIATION LEVELS, WATER SUBCOOLING AND WATER COMPOSITION, ON EXPLOSION TRIGGERING AND CONVERSION RATIO.
- THIS FACILITY WOULD NOT ADDRESS LARGE-SCALE EFFECTS OF HIGH AMBIENT PRESSURE. SPECIFICALLY, IT COULD NOT ADDRESS CURRENT THEORETICAL PREDICTIONS THAT COARSE MIXING IS <u>ENHANCED</u> AT HIGH AMBIENT PRESSURE.

SHIP: EXPERIMENTAL VARIABLES AND MEASUREMENTS

I. PRIMARY VARIABLES

AMBIENT PRESSURE (1-170 BARS)
TRIGGER STRENGTH
FUEL COMPOSITION (OXIDES, METALS, MIXTURES)
WATER TEMPERATURE (SUBCOOLING)

II. SECONDARY VARIABLES

RADIATION ENVIRONMENT
WATER COMPOSITION

III. FIXED PARAMETERS

CONTACT MODE (FUEL INTO COOLANT)
INTERACTION CHAMBER

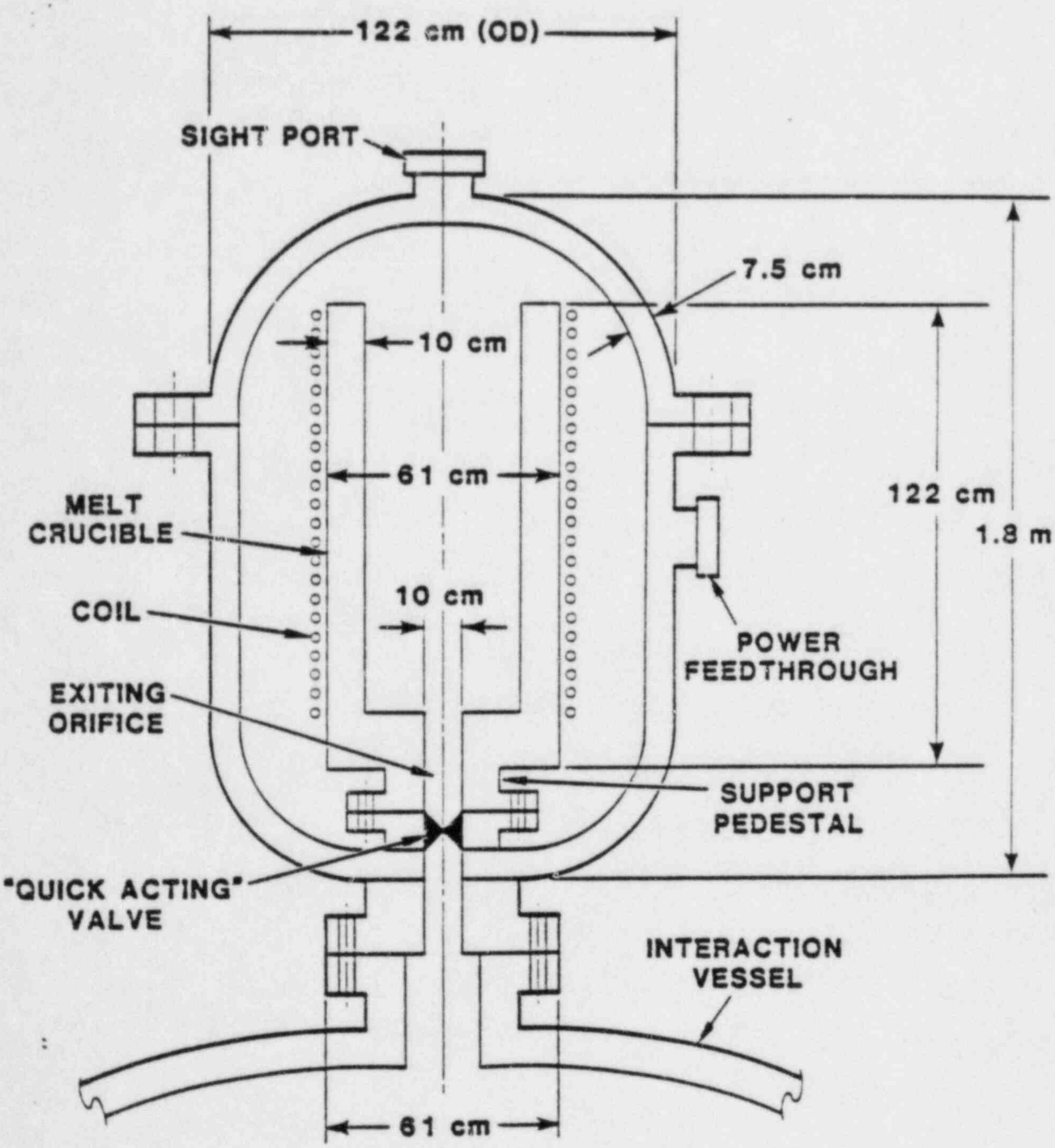
IV. MEASUREMENTS

PHOTOGRAPHY (CONVERSION RATIO)
WATER PHASE PRESSURE
DEBRIS CHARACTERISTICS
HYDROGEN GENERATION RATES

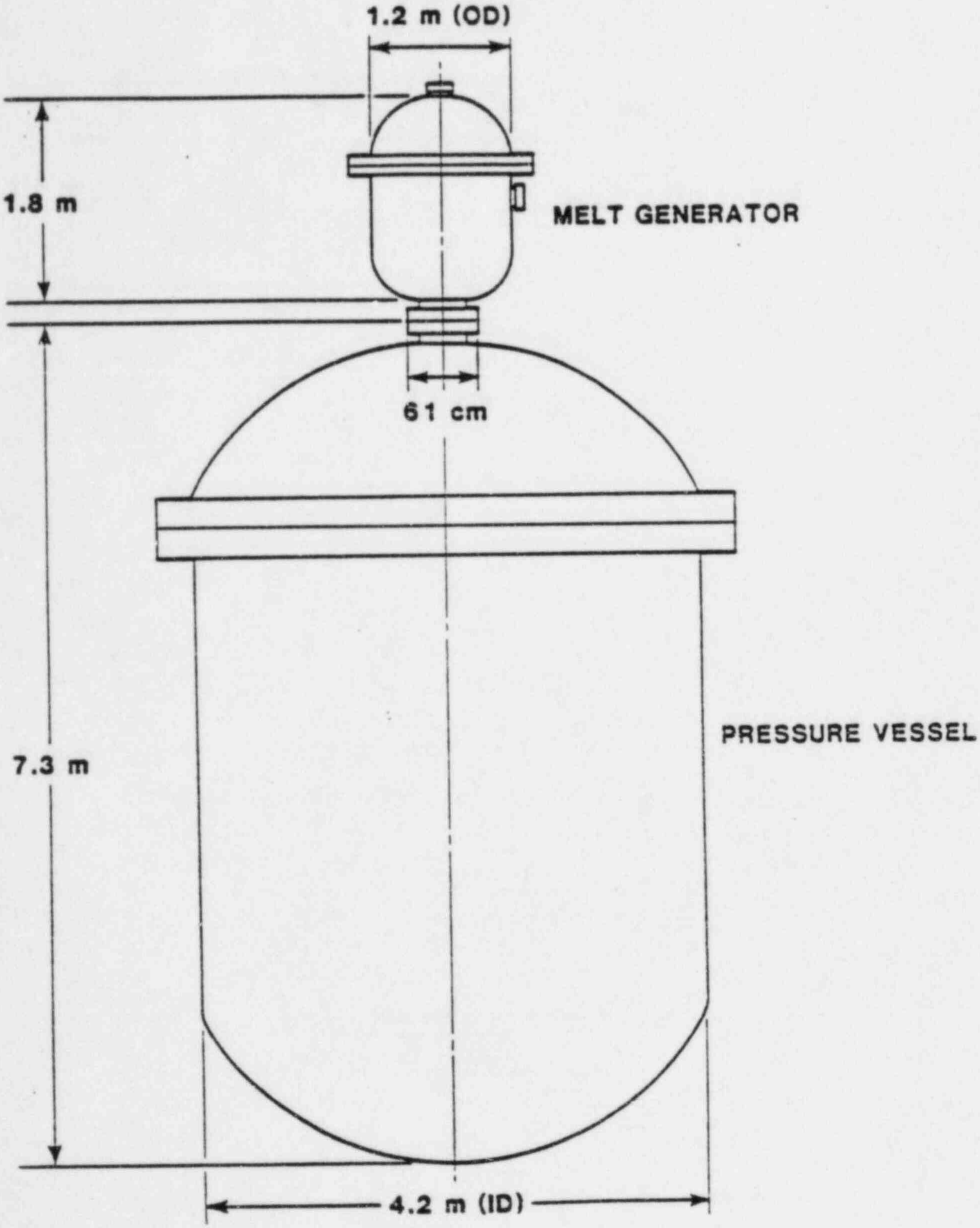
RATIONALE FOR EXPERIMENTAL PLAN

ELEMENT 4: ELVIS (400 KG ENCLOSED VESSEL)

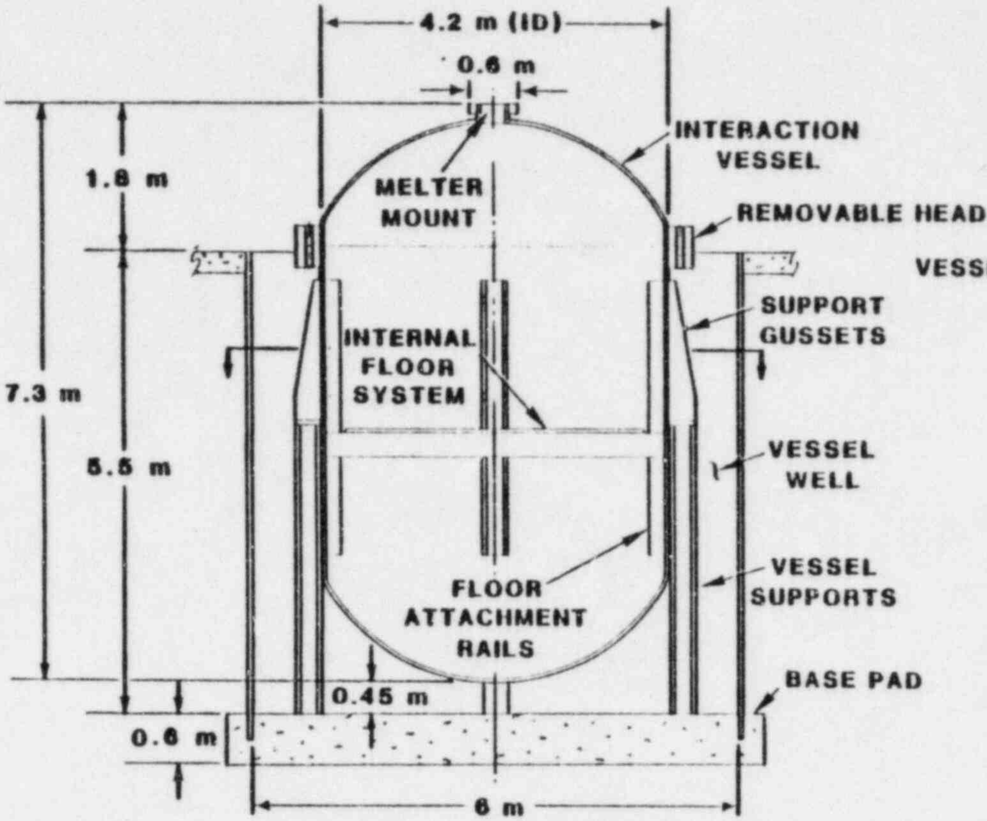
- THE PRIMARY OBJECTIVE OF THIS FACILITY IS TO ADDRESS ALL SAFETY ISSUES UP TO A SCALE OF 400 KG OF MELT, WITH OXIDIC, METALLIC AND MIXED FUEL MELTS INDUCTIVELY HEATED.
- THIS FACILITY WOULD GREATLY EXTEND THE AVAILABLE TEST MATRIX, COMPARED TO THE EXTENDED FITS FACILITY.
- ELVIS WOULD PROVIDE DATA FOR MODEL DEVELOPMENT AND CODE ASSESSMENT.
- THIS FACILITY WOULD BE ESSENTIAL IF THE EXO-FITS II FACILITY DID NOT DEMONSTRATE A LIMIT TO COARSE MIXING.
- ELVIS WOULD BE OPTIONAL IF A COARSE MIXING LIMIT WAS FOUND. DEPENDING ON THE EXTENT OF THE THREAT PREDICTED BY THE INTEGRATED CODES, THE FACILITY MIGHT NOT BE REQUIRED.
- SELECTION OF 400 KG IS CURRENTLY ARBITRARY, AND IS BEING USED FOR PRELIMINARY COST AND DESIGN STUDIES. ACTUAL MASS CAPABILITY WILL DEPEND ON RESULTS OF EXO-FITS II TESTS. IF THOSE TESTS DEMONSTRATE AN IMPORTANT LIMIT TO THE AMOUNT OF MASS MIXED, THEN AN UPGRADED FITS FACILITY MAY BE ADEQUATE, WITHOUT ELVIS.



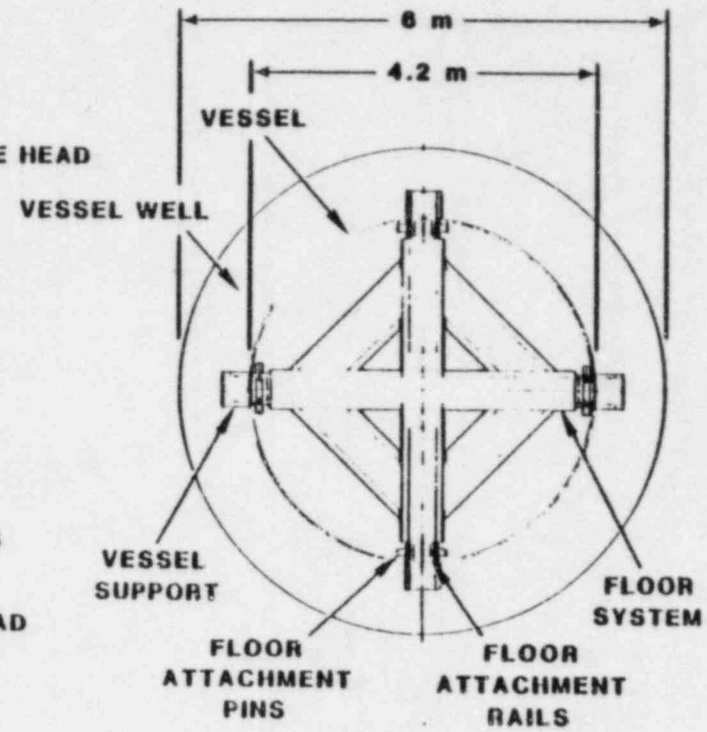
SCHEMATIC OF MELT GENERATOR



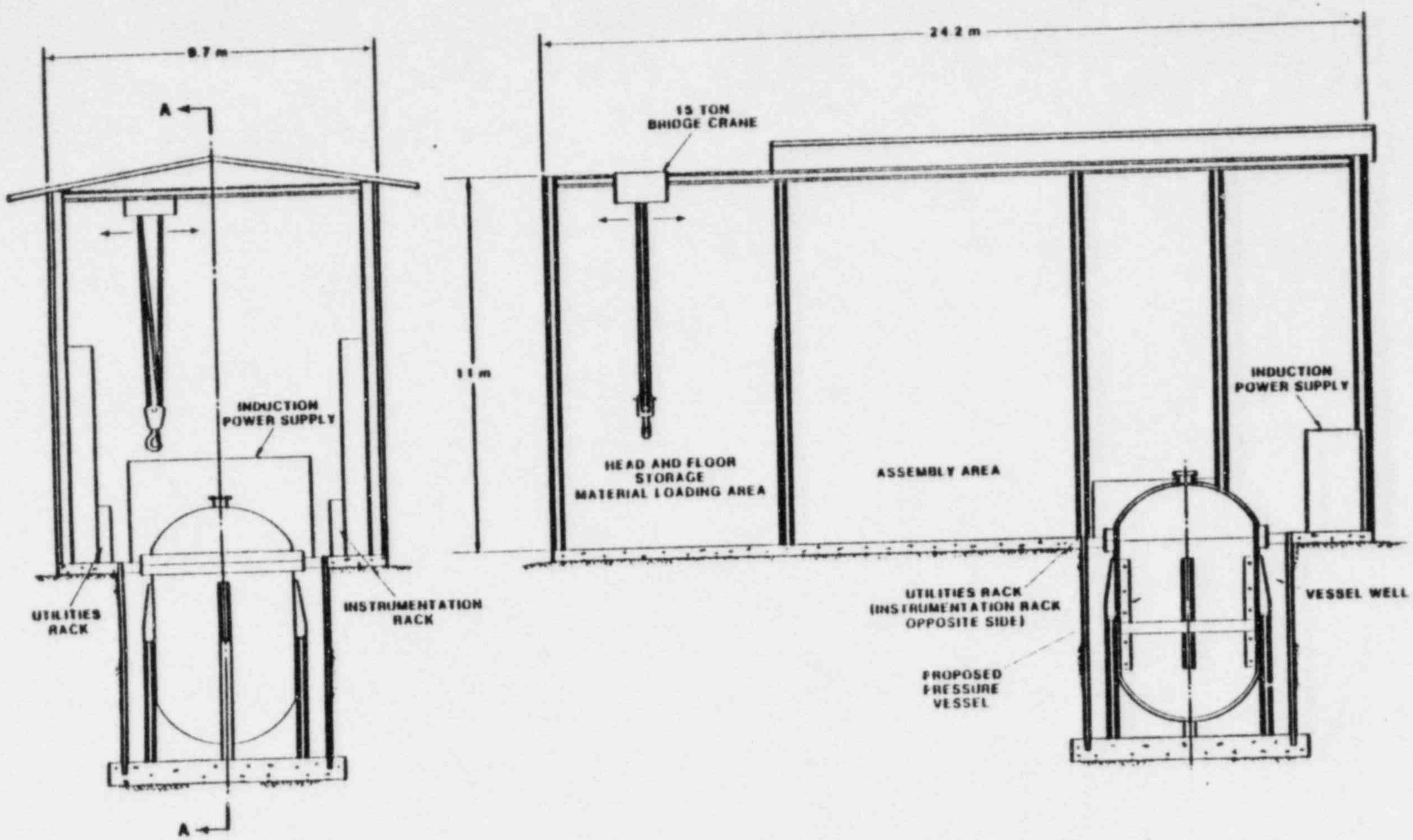
ASSEMBLED MELT GENERATOR AND PRESSURE VESSEL



VERTICAL SECTION VIEW OF PROPOSED PRESSURE VESSEL



HORIZONTAL SECTION VIEW OF PROPOSED PRESSURE VESSEL AND INTERNAL FLOOR SYSTEM



FRONT VIEW

SIDE VIEW (SECTION AA)

PROPOSED BUILDING AND MAJOR EQUIPMENT LAYOUT

ELVIS: EXPERIMENTAL VARIABLES AND MEASUREMENTS

I. PRIMARY VARIABLES: SAME AS FITS-X PLUS:

ADDITIONAL COMPOSITIONS INDUCTIVELY MELTED: PURE OXIDES, PURE METALS, MIXED METAL-OXIDES, VARIOUS CORIUMS
FUEL MASS: UP TO 400 KG
FUEL TEMPERATURE
HIGH PRESSURE INJECTION INTO WATER

II. SECONDARY VARIABLES

SIMULATION OF CONTAINMENT GEOMETRIES

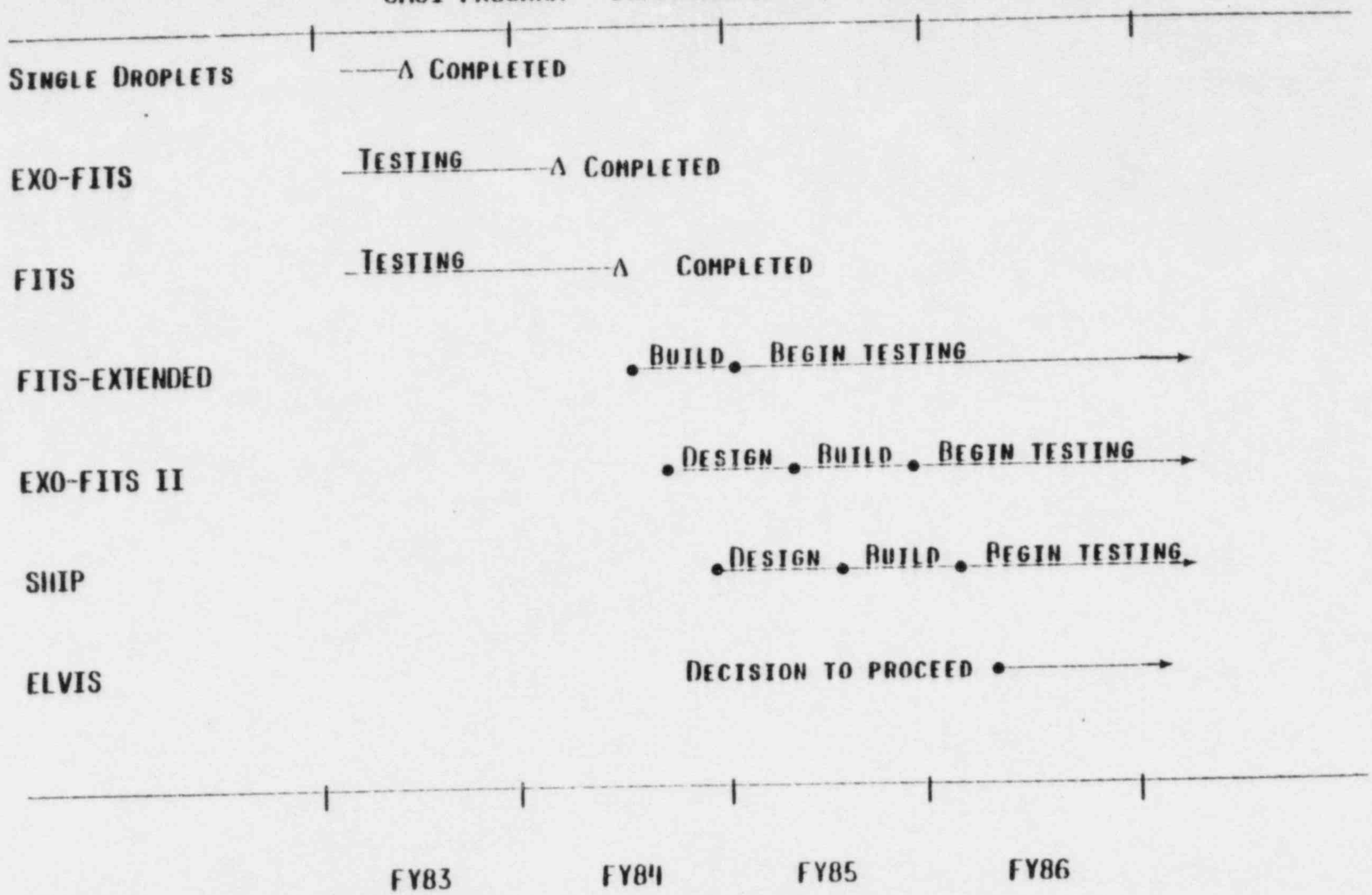
III. FIXED PARAMETERS

NONE

IV. MEASUREMENTS

SAME AS FITS-X

CMCI PROGRAM - EXPERIMENTAL FACILITIES



CORE MELT - COOLANT INTERACTIONS

MODEL DEVELOPMENT PLAN

	PHENOMENA	MODELS
1.	COARSE MIXING, FRAGMENTATION, H_2 AND STEAM GENERATION.	WISCI/TEXAS
2.	TRIGGERING AND FILM COLLAPSE.	SIMPLE-1D
3.	EXPLOSION PROPAGATION.	WONDY-1D/TEXAS
4.	EXPLOSION, EXPANSION, CONVERSION RATIO	CSQ-2D
5.	PROBABILITY OF DIRECT FAILURE BY STEAM EXPLOSION.	SIMPLE MONTE CARLO

RATIONALE FOR MODEL DEVELOPMENT

* THE CODES BEING DEVELOPED WOULD BE USED THREE WAYS:

  1. TO ANALYZE AND GUIDE EXPERIMENTS.
  2. TO DIRECTLY PREDICT THE CONSEQUENCES OF FCIs.
  3. TO PROVIDE MODELS DIRECTLY TO THE INTEGRATED ACCIDENT ANALYSIS CODES (MELPROG. CONTAIN. MELCOR).

* THE CODES BEING DEVELOPED WOULD MAXIMIZE THE EXISTING INVESTMENT IN THESE MODELS (REPRESENTED BY MEDICI. TEXAS. WONDY. AND CSQ).

* COSTS OF CODE DEVELOPMENT WOULD BE MINIMIZED. OVERLAP WITH OTHER NRC PROGRAMS WOULD BE MAXIMIZED (MELPROG. MEDICI. CONTAIN. MELCOR. SASA. ETC.).

PLAN FOR RESOLUTION OF ISSUES

ON AN ISSUE-BY-ISSUE BASIS

PLAN FOR RESOLUTION OF ISSUE 1:

STEAM AND HYDROGEN GENERATION RATES

STEP 1: DETERMINE THE MINIMUM SET OF TEST ELEMENTS NECESSARY TO QUANTITATIVELY RESOLVE THE ISSUE. DEFINE THE VARIABLES AND THEIR RANGES FOR AN "EFFICIENT" EXPERIMENTAL DESIGN. SUBMIT TEST PLAN TO NRC AND REACTOR SAFETY COMMUNITY FOR PEER REVIEW.

STEP 2: DETERMINE THE LOWEST COST FACILITY CONSISTENT WITH THE NECESSARY NUMBER AND RANGES OF THE VARIABLES.

STEP 3: IF AN EXTENDED FITS FACILITY IS TERMED ADEQUATE FOR THIS STUDY, MODIFY THE FACILITY AND CONDUCT THE TESTS.

STEP 4: IF A LARGER AND MORE SOPHISTICATED FACILITY (ELVIS) IS DEEMED NECESSARY AS A RESULT OF THE REVIEW IN STEP 1, THEN DESIGN AND BUILD THE FACILITY AND EXECUTE THE TEST PROGRAM.

STEP 5: USE THE EXPERIMENTAL DATA TO IMPROVE AND ASSESS THE APPROPRIATE CODES: WISCI, TEXAS, CSQ, ETC. PROVIDE DATA TO LASL FOR MULTI-DIMENSIONAL FCI CODE DEVELOPMENT.

STEP 6: PROVIDE CODES AND MODELS TO THE DEVELOPERS OF THE INTEGRATED CODES (MELCOR, MELPROG, MEDICI, CONTAIN).

NOTE: The resolution of this issue requires three program elements: FITS, ELVIS, and Model Development.

PLAN FOR RESOLUTION OF ISSUE 2:

DEBRIS CHARACTERISTICS

STEPS 1-6: SAME AS FOR ISSUE 1.

STEP 7: PROVIDE EXPERIMENTAL DATA. INCLUDING SAMPLES OF COLLECTED DEBRIS. TO PROGRAMS WHICH REQUIRE THEM FOR DEBRIS BED COOLABILITY STUDIES.

NOTE: The resolution of this issue is concurrent with issue 1, and only requires that the post-FCI debris be collected and analyzed.

PLAN FOR RESOLUTION OF ISSUE 3:

ACCIDENT PROGRESSION AND SOURCE TERM

STEP 1: DEFINE TEST OBJECTIVES: WHAT ARE THE KEY CHEMICAL PROCESSES TO BE INVESTIGATED? WHAT ARE THE IMPORTANT IN- AND EX-VESSEL GEOMETRIES TO BE STUDIED FOR DEBRIS DISPERSAL?

STEP 2: DETERMINE THE MINIMUM SET OF TEST ELEMENTS NECESSARY TO QUANTITATIVELY RESOLVE THE ISSUE. DEFINE THE VARIABLES AND RANGES FOR AN "EFFICIENT" EXPERIMENTAL DESIGN. SUBMIT TEST PLAN TO NRC AND REACTOR SAFETY COMMUNITY FOR PEER REVIEW.

NOTE: Although the resolution of this issue requires the same three program elements as issues 1 and 2, a new test matrix, additional hardware, and possibly new diagnostic systems, are required.

STEPS 3-6: SAME AS FOR ISSUE 1.

STEP 7: PROVIDE DATA TO SOURCE TERM ANALYSTS.

PLAN FOR RESOLUTION OF ISSUE 4:

ACCIDENT TERMINATION AND SAFE SHUTDOWN

STEPS 1-7: SAME AS PREVIOUS ISSUES

THE RESOLUTION OF THIS ISSUE WOULD NOT REQUIRE ANY ADDITIONAL EXPERIMENTATION OR MODEL DEVELOPMENT BEYOND THAT REQUIRED FOR RESOLVING THE OTHER ISSUES.

RESOLUTION OF THIS ISSUE SIMPLY REQUIRES A WRITTEN REPORT SUMMARIZING THE KNOWLEDGE GAINED BY THE PROGRAM. THIS KNOWLEDGE WOULD BE DISTILLED INTO SEVERE-ACCIDENT GUIDELINES FOR UTILITIES AND THE NRC TO USE IN EMERGENCIES.

PLAN FOR RESOLUTION OF ISSUE 5:

DIRECT FAILURE OF CONTAINMENT BY A STEAM EXPLOSION

THIS ISSUE CAN BE RESOLVED IN TWO DISTINCT WAYS:

EITHER:

PATH 1: Demonstrate that the probability of alpha-mode failure for high and low pressure accidents is negligible or zero by experimentally proving any one of the following:

a) An upper limit exists to the amount of molten fuel which can be coarsely mixed in reactor geometries and this limit is below the threshold necessary for containment failure for conservative estimates of conversion ratio.

b) For high pressure accidents, the probability of triggering an explosion is negligible or zero.

c) Conversion ratio decreases with increasing fuel mass, such that the yield of an explosion is below the threshold for containment failure for conservative estimates of the amount of fuel mixed.

d) The geometry and structures in the lower plenum of a BWR and/or a PWR prevent either large-scale coarse mixing or high conversion ratios.

OR:

PATH 2: Develop a comprehensive in-vessel steam explosion model, couple it to a statistical approach, and compute the probability of containment failure for a variety of accident scenarios.

RESOLUTION OF ISSUE 5: CONTINUED

PATH 1: A) THE EXO-FITS II FACILITY WILL PROVE OR DISPROVE THIS HYPOTHESIS FOR LOW-PRESSURE ACCIDENTS.

B) THE SHIP FACILITY WILL TEST THIS HYPOTHESIS.

C) SHIP, FITS, EXO-FITS II, AND ELVIS WILL PROVIDE DATA SUFFICIENT TO VERIFY THIS HYPOTHESIS.

D) FITS, EXO-FITS II AND ELVIS WILL TEST THIS HYPOTHESIS.

NOTE: If the experiments of Path 1 yield positive results, then the direct failure issue can be resolved. If the experimental results are inconclusive, then a determination of the non-zero probability for direct failure will require probabilistic model development, additional mechanistic models, or both.

PATH 2: REQUIRED IF PATH 1 EFFORTS ARE INCONCLUSIVE.

* WILL PROBABLY REQUIRE THE DEVELOPMENT OF A COMPLEX, MULTI-DIMENSIONAL MODEL OF ALL PHASES OF A STEAM EXPLOSION.

* MAY EMPLOY CURRENT CALCULATIONAL TOOLS (CSQ, SIMMER, MELPROG, ETC.), OR MAY INVOLVE FURTHER CODE DEVELOPMENT.

PLAN FOR RESOLUTION OF ISSUE 6:

INDIRECT FAILURE OF CONTAINMENT BY FCIs

STEPS 1-7: ALL DATA AND MODELS REQUIRED FOR RESOLVING THIS ISSUE WILL BE DEVELOPED CONCURRENTLY WITH THE RESOLUTION OF THE OTHER ISSUES.

STEP 8: PROVIDE DATA AND MODELS TO CONTAINMENT CODES. PERFORM CALCULATIONS FOR VARIOUS ACCIDENT SCENARIOS (AS WAS DONE IN CONTAINMENT LOADS WORKING GROUP).

STEP 9: PROVIDE DATA AND MODELS TO GROUPS INVESTIGATING EQUIPMENT SURVIVAL AND CONTAINMENT PENETRATION LEAKAGE.

FCI RESEARCH PRIORITIES

1. DETERMINE IF A LIMIT TO COARSE MIXING EXISTS, AND QUANTIFY AS A FUNCTION OF INITIAL CONDITIONS.

2. DETERMINE LIMITS TO THE OCCURRENCE AND ENERGETICS OF STEAM EXPLOSIONS AS A FUNCTION OF INITIAL CONDITIONS.

3. QUANTIFY RATES OF STEAM AND HYDROGEN PRODUCTION DUE TO FCIs, AND THE NATURE OF THE DEBRIS.

GENERAL DISCUSSION

- EXPERIMENTAL FACILITIES
- TEST MATRICES
- MODEL DEVELOPMENT
- RESEARCH PRIORITIES

NO CONSENSUS IS REQUIRED.

ALL OPINIONS AND SUGGESTIONS WILL
BE CAREFULLY CONSIDERED.

SCIENTIFIC TRUTHS ARE NOT DETERMINED
BY MAJORITY VOTE.

NRC/SANDIA

FUEL-COOLANT INTERACTIONS PROGRAM

INFORMATION EXCHANGE MEETING

JUNE 4, 1984

NEW ORLEANS, LOUISIANA

MARSHALL BERMAN
SANDIA NATIONAL LABORATORIES

MEETING OBJECTIVES

- FCI RESEARCH RATIONALE
- BRIEF PROGRAM UPDATE
- PLAN FOR RESOLUTION OF ISSUES
- GENERAL DISCUSSION:
  - -EXPERIMENTAL FACILITIES
  - -TEST MATRICES
  - -MODEL DEVELOPMENT
  - -RESEARCH PRIORITIES

FUEL-COOLANT INTERACTION PHENOMENA INCLUDE

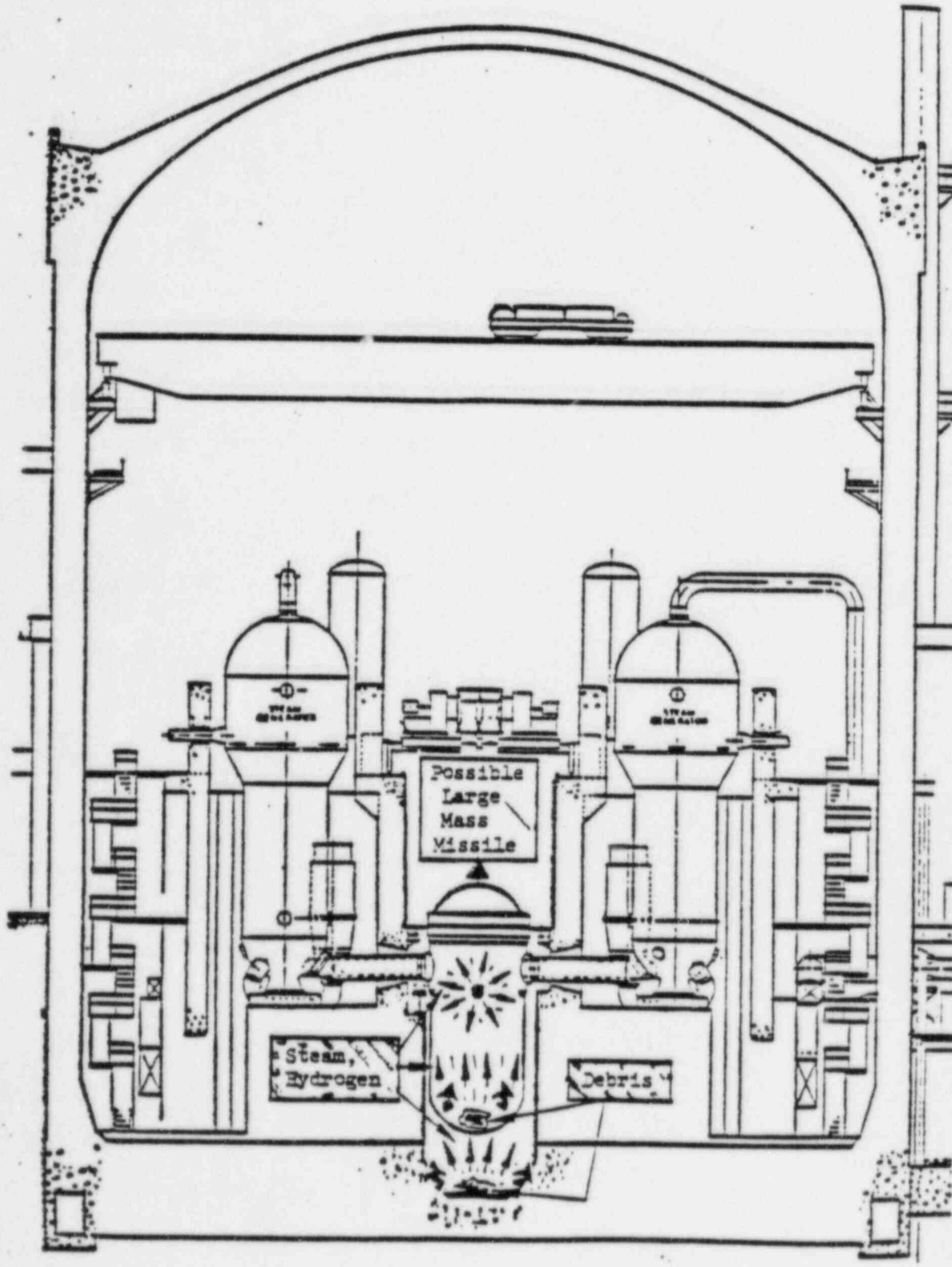
- STEAM EXPLOSION: RAPID HEAT TRANSFER AND VAPOR GENERATION ON A TIME SCALE OF MILLISECONDS.
- STEAM GENERATION: NON-EXPLOSIVE PRODUCTION OF STEAM, GENERALLY BY FILM BOILING.
- HYDROGEN GENERATION: PRODUCED BY THE INTERACTION OF MOLTEN METALS AND STEAM DURING THE FCI.
- DEBRIS BED FORMATION: THE DISTRIBUTION OF PARTICLE SIZES AND THE CHARACTERISTICS OF THE DEBRIS BED FORMED SUBSEQUENT TO THE FCI (POROSITY, STRATIFICATION).

FCI'S CAN OCCUR IN ANY ACCIDENT WHICH INVOLVES SOME MELTING OF THE CORE OR CLADDING MATERIALS.

WHY ARE FUEL-COOOLANT

INTERACTIONS IMPORTANT

FOR REACTOR SAFETY?



Possible
Large
Mass
Missile
Steam,
Hydrogen
Debris

FCI'S CAN OCCUR

- IN CORE BARREL
- IN LOWER PLENUM
- IN REACTOR CAVITY

WATER CAN BE SATURATED OR SUBCOOLED

PRESSURE CAN BE HIGH OR LOW

REACTOR SAFETY ISSUES AFFECTED BY FCIS

1. STEAM AND HYDROGEN GENERATION:

   WHAT ARE THE RATES AND TOTAL MAGNITUDES OF STEAM AND HYDROGEN WHICH CAN BE GENERATED DURING FCIS?

2. DEBRIS CHARACTERISTICS:

   WHAT ARE THE CHARACTERISTICS OF THE DEBRIS PRODUCED BY FCIS, INCLUDING PARTICLE SIZE DISTRIBUTION, POROSITY AND DEBRIS-BED STRATIFICATION?

3. ACCIDENT PROGRESSION AND SOURCE TERM:

   HOW DO FCIS INFLUENCE THE PROGRESSION OF THE ACCIDENT AND THE NATURE OF THE SOURCE TERM (INCLUDING FISSION PRODUCT CHEMISTRY, RELEASE RATE, PARTICLE SIZE AND MORPHOLOGY, AND FP DISPERSAL)? WHAT ARE THE CONSEQUENCES OF FUEL DEBRIS DISPERSAL IN- OR EX-VESSEL BY VIOLENT FCIs?

4. ACCIDENT TERMINATION AND SAFE SHUTDOWN:

   HOW DO FCIS AFFECT THE PROBABILITY OF SUCCESSFUL ACCIDENT TERMINATION BY THE ADDITION OF WATER TO THE MELT? WHAT OPERATOR ACTIONS WOULD INCREASE THE POSSIBILITY OF SAFE SHUTDOWN BY REDUCING THE RISK FROM DANGEROUS FCIS?

5. DIRECT FAILURE:

   WHAT ARE THE PROBABILITIES AND CONSEQUENCES OF DIRECT CONTAINMENT FAILURE BY A STEAM EXPLOSION (α - MODE)?

6. INDIRECT FAILURE:

   WHAT ARE THE PROBABILITIES AND CONSEQUENCES OF INDIRECT CONTAINMENT FAILURE BY FCIs (δ-, γ-, OR ϵ- MODES)?

THESE SAFETY ISSUES ARE ONLY IMPORTANT IF THEY AFFECT:

- THE PROBABILITY AND CONSEQUENCES OF TERMINATED ACCIDENTS
  - FISSION PRODUCT DISPERSAL
  - PRIMARY SYSTEM FAILURE
  - POST-ACCIDENT HYDROGEN REMOVAL
  - NEED FOR EMERGENCY EVACUATION
  - COSTS OF CLEANUP AND PLANT RECOVERY

- THE PROBABILITY AND CONSEQUENCES OF UNTERMINATED ACCIDENTS
  - TIME OF CONTAINMENT FAILURE:

    EARLY VS LATE
  - NATURE OF CONTAINMENT FAILURE:

    SMALL VS LARGE LEAK; OR CATASTROPHIC FAILURE
  - FISSION PRODUCT STATE AT FAILURE TIME:

    QUIESCENT, SETTLED, IN WATER SOLUTION, IN MELT, VS DISPERSED, AEROSOLIZED, VAPORIZED.

SOME NRC AND IDCOR POSITIONS ON FCI SAFETY ISSUES

ISSUE	IDCOR	NRC
MAXIMUM AMOUNT OF FUEL THAT CAN COARSELY MIX IN-VESSEL	100 KG	5000 KG OR MORE
MAXIMUM AMOUNT OF FUEL THAT CAN COARSELY MIX EX-VESSEL	7 KG	16000 KG OR MORE
MULTIPLE EXPLOSIONS AND HIGHLY TRANSIENT FCI PHENOMA	DO NOT OCCUR	NOT MODELED, MAY OCCUR
AMOUNT OF METAL-WATER REACTION THAT CAN OCCUR DURING AN FCI	NEGLIGIBLE	POSSIBLY 30% OR MORE
AMOUNT OF STEAM GENERATED DURING AN EXPLOSIVE OR NON-EXPLOSIVE FCI	NEGLIGIBLE	PRIMITIVE MODELS
COOLABILITY OF DEBRIS BED RESULTING FROM AN FCI	COOLABLE	MAY OR MAY NOT BE
IN-VESSEL FUEL DISPERSION DUE TO A STEAM EXPLOSION	DOESN'T OCCUR	NOT MODELED, MAY OCCUR
BWR GEOMETRY PRECLUDES SIGNIFICANT COARSE MIXING IN LOWER PLENUM	YES	MAYBE, BUT NO DATA
STEAM EXPLOSIONS DO NOT OCCUR AT HIGH AMBIENT PRESSURE	YES	MAYBE, BUT INSUFFICIENT DATA
LOWER PLENUM FAILURE DUE TO A STEAM EXPLOSION	DOESN'T OCCUR	NOT MODELED, MAY OCCUR
ENERGETIC STEAM EXPLOSION IN REFLOOD MODE	DOESN'T OCCUR	NOT MODELED, MAY OCCUR
ENERGETIC STEAM EXPLOSION IN STRATIFIED MODE (WATER ABOVE FUEL)	DOESN'T OCCUR	NOT MODELED, MAY OCCUR
CONTAINMENT FAILURE DUE TO STEAM EXPLOSION	DOESN'T OCCUR	NO MECHANISTIC MODEL
ALTERATION IN EX-VESSEL FISSION PRODUCT SOURCE TERM DUE TO FCIs	NOT IMPORTANT	NOT MODELED
FAILURE OF MARK II PEDESTAL WALL BY EX-VESSEL STEAM EXPLOSION	NOT CONSIDERED	POSSIBLE

FCI RESEARCH RATIONALE

- MANY ASPECTS OF SEVERE ACCIDENTS CAN BE STRONGLY INFLUENCED BY THE NATURE OF THE FCIs.
- UNCERTAINTIES CONCERNING MANY FCI PHENOMA ARE SO LARGE THAT ACCIDENT RISKS CANNOT BE ACCURATELY QUANTIFIED. NOR CAN ACCIDENT MANAGEMENT PROCEDURES BE ACCURATELY DEFINED.
- ADDITIONAL RESEARCH HAS A HIGH PROBABILITY OF REDUCING THESE UNCERTAINTIES.

CORE MELT-COOLANT INTERACTIONS

PROGRAM STATUS

AND

RECENT ACCOMPLISHMENTS

FRAGMENTATION AND MIXING

THE KEY QUESTION FOR FCIs IS:

TO WHAT DEGREE, AND AT WHAT RATE, DOES THE MOLTEN CORIUM FRAGMENT WHEN IT CONTACTS WATER?

POSSIBLE ANSWERS

1. NO FRAGMENTATION: STEAM AND HYDROGEN GENERATION RATES ARE SLOW AND BENIGN. EARLY CONTAINMENT FAILURE IS UNLIKELY OR IMPOSSIBLE.

2. COARSE FRAGMENTATION: (AKA "PREMIXING"); TIME SCALE OF ORDER OF SECONDS; SIGNIFICANT INCREASE IN STEAM AND HYDROGEN GENERATION RATES AND MAGNITUDES. INCREASED POSSIBILITY OF δ-, γ-, AND ϵ- FAILURE MODES.

3. FINE FRAGMENTATION: (AKA "STEAM EXPLOSION"); TIME SCALE OF ORDER OF MILLISECONDS; STEAM AND HYDROGEN GENERATION RATES AND MAGNITUDES CAN BE VERY HIGH. SHOCK WAVES AND MISSILES MAY BE GENERATED. INCREASED POSSIBILITY OF ALL FAILURE MODES, INCLUDING DIRECT FAILURE (α-MODE).

DEGREE AND RATE OF FRAGMENTATION IS A FUNCTION OF MANY VARIABLES SPECIFYING INITIAL AND BOUNDARY CONDITIONS:

1. FUEL PROPERTIES: COMPOSITION, TEMPERATURE, MASS

2. COOLANT PROPERTIES: COMPOSITION, TEMPERATURE, MASS

3. CONTACT MODE BETWEEN FUEL AND COOLANT:
   FUEL INTO COOLANT OR VICE VERSA
   INJECTION GEOMETRY AND RATE

4. NATURE AND STRENGTH OF SPONTANEOUS TRIGGERS

5. INTERACTION CHAMBER: GEOMETRY, SIZE, DEGREE OF CONFINEMENT, INTERNAL STRUCTURES

6. AMBIENT ATMOSPHERE: PRESSURE, RADIATION

FCI PROGRAM TASKS

1. BASED ON CURRENT STATE OF KNOWLEDGE, DEFINE MOST IMPORTANT VARIABLES AND THEIR RANGES.

2. CONDUCT EXPERIMENTS ON THESE VARIABLES, CONSISTENT WITH PROGRAM FUNDING.

3. DEVELOP MODELS TO EXPLAIN AND INTERPRET EXPERIMENTAL RESULTS, AND TO EXTRAPOLATE THOSE RESULTS TO REACTOR SCALES.

CMCI PROGRAM ELEMENTS

1. MECHANISTIC MODEL DEVELOPMENT AND APPLICATIONS.
2. PROBABILISTIC MODEL DEVELOPMENT AND APPLICATIONS.
3. SMALL-SCALE (SINGLE DROPLET) EXPERIMENTS.
4. INTERMEDIATE-SCALE OPEN-GEOMETRY EXPERIMENTS (EXO-FITS).
5. INTERMEDIATE-SCALE CLOSED-GEOMETRY EXPERIMENTS (FITS).

FCI EXPERIMENTAL PROGRAMS

INFORMATION GENERATED

SMALL-SCALE EXPERIMENTS:

- STEAM EXPLOSION TRIGGERABILITY.
- DROPLET FRAGMENTATION.
- CONVERSION RATIO.
- DEBRIS SIZE DISTRIBUTION, CHARACTERISTICS
- HYDROGEN GENERATION RATES.

INTERMEDIATE-SCALE EXPERIMENTS:

- PROBABILITY AND CONSEQUENCES OF STEAM EXPLOSIONS (TRIGGERING, PROPAGATION, EXPANSION, CONVERSION RATIO, SLUG FORMATION AND BREAKUP).
- NON-EXPLOSIVE STEAM GENERATION.
- DEBRIS SIZE DISTRIBUTION, CHARACTERISTICS.
- HYDROGEN GENERATION RATES AND MAGNITUDES.

INTERMEDIATE-SCALE FITS TESTS

EXPER. SERIES	NUMBER OF TESTS	MELT MASS	FUEL/COOLANT MASS RATIO	AMBIENT PRESSURE	FUEL COMPOSITION	MELT ENTRY	CHAMBER GEOMETRY	WATER TEMPERATURE	OTHER (LID, HOLD TIME, ETC.)	CONTACT MODE	FUEL TEMPERATURE	COARSE MIXING	GAS PHASE PRESSURE	WATER PHASE PRESSURE	HYDROGEN GENERATION	STEAM GENERATION	CONVERSION RATIO	DEBRIS CHARACTERISTICS
		INDEPENDENT VARIABLES										MEASUREMENTS						
MD	19	●				○	○					○		○			○	
FITSA	5			●								○	○	○		○	●	●
FITSG	2							●				○				●		●
MDC	7				●						○	○						
FITSB	9		●				○	○				○	○	○			●	●
FITSC	5			○	○			●				○	○	○	●	●	○	○
CM	12	○	○		?	○	○	●	●		?	○						
OM	4*				●			●	○			●	●+	●		●+	●+	●+
RC	2*						●							●			●+	●+
ACM	2*									●			●+		●+	●+	●+	●+

● PRIMARY VARIABLE

○ SECONDARY VARIABLE

* PRELIMINARY SCOPING TESTS

+ NOT YET MEASURED

FITS-C Test Series

Test Name	Melt Composition	Melt Mass Del. kg	Water Mass kg	Mass Ratio M_c/M_f	Water Temp. K	Water Subcool. K	Ambient Press. MPa	Water Side Dim. m	Water Depth m	Melt Drop Height m	Melt Entry Vel. m/s	Melt Hold Time s
FITS1C	$Fe+Al_2O_3$	17.[illegible]	112.9	6.6	298	69	0.088	0.610	0.305	1.82	5.59	1.52
FITS2C	Corium A+R	16.0	226.1	13.4	295	72	0.082	0.610	0.610	2.37	6.60	1.43
FITS3C	Corium A+R	11.5	108.1	9.4	297	70	0.081	0.533	0.381	1.82	5.97#	1.52
FITS4C	$Fe+Al_2O_3$	19.0	110.2	5.8	353	74	0.531	0.610	0.305	1.82	5.97#	1.50
FITS5C	$Fe+Al_2O_3$	19.6	110.4	5.6	351	75	0.510	0.610	0.305	1.82	5.97#	1.50

Table: Initial Parameters for the FITS-C Test Series

- Indicates that the entry was calculated by $[2 \times g \times h]^{(\frac{1}{2})}$

Lid status (in/out): IN

All tests conducted in an inerted (Nitrogen) atmosphere.

FITS-C Test Series

Event Classification and Characteristics for the FITS-C Test Series

Test Name	Event Type	Event Time after Melt Entry ms	Explosion Propagation Velocity m/s	Avg/Peak Particle Velocity m/s	Percent of Water Depth at Event
FITS1C	SE	78	415.0	280./379.	100.0
FITS2C	SE	10	N.O.	22.5/29.3	26.4
FITS2C	TR	169			100.0
FITS3C	No events observed				
FITS4C	No events observed				
FITS5C	No events observed				

TR - Nonpropagating trigger SE - Steam Explosion

N.O. - Not obtained.

FITS-C Test Series

Comments and Additional Results for the FITS-C Test Series

Test Name	Melt Width at Entry m	Comments on Test
FITS1C	0.07	Repeat of FITS2B. Some early melt leak. Lost mass was not used in particle diameter calculations.
FITS2C	0.23	Lid trails melt entry by 50 ms. Lid contacts bottom first after passing through melt. Possible partial melt crust formation prior to water contact. Lid/bottom contact may have caused last trigger. Lost mass was not used in diameter calculations.
FITS3C	N.O.	Melt delivery failure. Melt fell in a shower of approximately 500 ms in duration. Lid entered at tail end of melt shower. No events observed from film data.
FITS4C	N.O.	Gas samples lost. No films. Dispersed melt probably caused melt sensor not to respond. Detonator did not fire. Poor melt delivery.
FITS5C	N.O.	No film data. Apparently no explosion. Detonator fired at approximately 200 ms after entry. Probable dispersed melt delivery. Repeat of FITS4C/FITS2B tank/drop geometry.

N.O. - Not Obtained.

FITS-C Test Series

Debris Analysis and Fraction of Metal Oxidized

Test Name	Part. Mass Mean Dia. micrometer	Sauter Diameter micrometer	Total Mass Recovered kg	Lost Mass kg	Fraction of Metal Oxidized Fe_2O_3/ FeO
FITS1C	393.0	231.0	15.89	1.16	0.22/0.33
FITS2C	927.7	549.0	15.68	1.25	0.18/0.26
FITS3C	N.A.	N.A.	11.00	0.50	0.04/0.06
FITS4C	N.A.	N.A.	N.O.	N.O.	N.O.
FITS5C	N.A.	N.A.	19.49	0.07	0.05/0.08

N.O. - Not Obtained. N.A. - Not analyzed at publication.

RECENT EXO-FITS EXPERIMENTS

FY83 - 84

CM:	COARSE MIXING, 12 TESTS
OM:	OXIDE MELTS, 4 TESTS
ACM:	ALTERNATE CONTACT MODE, 2 TESTS
RC:	RIGID CONTAINER, 2 TESTS
FITSD:	IN-VESSEL, 4 TESTS

CM SERIES - COARSE MIXING

I. OBJECTIVE:

INVESTIGATE COARSE MIXING BEHAVIOR TO DISTINGUISH BETWEEN EXISTING MODELS.

II. SERIES DESCRIPTION:

USE MOLTEN IRON-ALUMINA MELTS (~ 20 KG) AND SATURATED WATER. VARY OTHER PARAMETERS TO QUANTIFY THE DEPENDENCE OF MIXING ON SCALE, GEOMETRY, AND THERMODYNAMIC PARAMETERS. ALSO DETERMINE EXPLOSIBILITY OF FUEL/COOLANT SYSTEM AND MEASURE WATER-PHASE PRESSURES AND CONVERSION RATIO, IF POSSIBLE.

III. STATUS:

SERIES COMPLETED: 12 TESTS.

MELT PENETRATION AND EVENT INITIATION

CRUCIBLE BOTTOM LID

WATER CHAMBER

NEAR-SURFACE EVENTS:

TIME ~20-50ms
AFTER MELT-WATER
CONTACT (t=0)

DEPTH OF PENETRATION
AT INITIATION
~5-10 cm

CM SERIES - COARSE MIXING

IV. RESULTS:

- SURFACE EVENTS OF SUFFICIENT VIOLENCE TO EXPEL MELT FROM THE WATER, AS WELL AS PREVENT SOME MELT FROM ENTERING, OCCURRED IN EVERY TEST.

- RESIDUAL MELT MASSES OF ~ 4 KG WERE NOT EXPELLED, AND FROZE ON THE CHAMBER BOTTOM FOR MOST HOT WATER TESTS.

- THE LATEST DELAY TO AN EXPLOSION EVER OBSERVED OCCURRED FOR THE COLD WATER TEST CM-7 (550 MS AFTER MELT ENTRY). EXPLOSION SEEMED TO OCCUR IN A VERY WATER-LEAN ENVIRONMENT.

- THE PRESENCE OF THE LID SEEMS TO DELAY THE SURFACE INTERACTION.

- LONGER HOLD TIMES SEEM TO CORRELATE WITH GREATER DELAYS IN MELT EXPULSION.

Coarse Mixing Test Series

Initial Parameters for the Coarse Mixing Test Series

Test Name	Melt Mass Del. kg	Water Mass kg	Mass Ratio M_c/M_f	Water Temp. K	Water Subcool. K	Water Side Dim. m	Water Depth m	Melt Drop Height m	Melt Entry Vel. m/s	Melt Hold Time s	Lid in/out
CM 1	18.5	109.7	5.9	358	9	0.305	1.220	0.305	2.44#	1.00	OUT
CM 2	18.0	109.3	6.1	363	4	0.305	1.220	0.305	2.44#	4.00	OUT
CM 3	18.0	437.0	24.3	364	3	0.610	1.220	0.483	3.11	0.68	OUT
CM 4	18.9	218.5	11.6	364	3	0.610	0.610	1.120	4.60	0.68	OUT
CM 5	7.6	218.7	28.7	363	4	0.610	0.610	1.120	4.78	0.75	OUT
CM 6	4.0	218.5	54.6	364	3	0.610	0.610	1.220	4.99	0.81	OUT
CM 7	18.5	169.6	9.2	294	73	0.610	0.457	1.120	4.77	0.65	OUT
CM 8	18.6	218.4	11.7	365	2	0.610	0.610	0.444	3.08	0.66	IN
CM 9	18.6	218.6	11.8	364	3	0.610	0.610	0.444	3.06	0.66	IN
CM 10	18.4	109.3	5.9	366	1	0.610	0.305	1.143	4.60	7.00	OUT
CM 11	18.7	218.6	11.7	366	1	0.610	0.610	1.120	4.68	5.00	OUT
CM 12	18.5	112.9	6.1	298	69	0.610	0.305	1.820	5.89	1.50	IN

- Indicates that the entry was calculated by $[2 \times g \times h]^{(1/2)}$

Melt composition: iron-alumina

Coarse Mixing Test Series

Event Classification and Characteristics for the Coarse Mixing Test Series

Test Name	Event Type	Event Time after Melt Entry ms	Eruption Duration ms	Explosion Propagation Velocity m/s	Avg/Peak Particle Velocity m/s	Percent of Water Depth at Event
CM 1	ER	30				
CM 2	ER	73				
CM 3	ER	43	41		47/88	7.5
CM 3	TR	56				
CM 4	ER	18	62			12.2
CM 4	TR	59,68,75,89				
CM 4	BC	197				100.0
CM 5	ER	27	119		33/43	13.0
CM 5	BC	252				100.0
CM 6	ER	22	163		20/26	11.0
CM 6	TR	66,88,108,132,159				
CM 6	BC	194				100.0
CM 6	TR	203				
CM 7	ER	43			62/73	49.0
CM 7	SE	69		301	197/—	71.8
CM 7	BC	113				100.0
CM 7	SE	503				100.0
CM 8	ER	37	179			11.8
CM 8	ER	117			41/96	24.6
CM 8	TR	195,202				
CM 8	SE	216				67.2
CM 9	ER	65	40			21.3
CM 9	SE	105			105/350	38.9
CM 10	ER	43	69		18/24	
CM 10	SE	112			37/78	100.0
CM 10	SE	311				
CM 11	ER	52	88		32/—	25.9
CM 11	BC					100.0
CM 12	ER	37				15.8
CM 12	SE	69			103/110	65.6
CM 12	BC	111				100.0
CM 12	SE	125				100.0

ER - Eruption TR - Nonpropagating Trigger SE - Steam Explosion
BC - Melt Contact with Bottom

Coarse Mixing Test Series

Comments and Additional Results for the Coarse Mixing Test Series

Test Name	Residual Mass in Chamber kg	Melt Width at Entry m	Comments on Test
CM 1	N.O.	N.O.	Lid skimmed water surface. High-speed cameras didn't work. Possible weak surface explosion can be seen from low-speed camera.
CM 2	3.80	N.O.	Lid skimmed water surface. Lid stuck in crucible for 1.5 to 2.0 s making hold time 3.5 to 4.0 s. No high-speed films. Water chamber remained intact.
CM 3	4.28	0.33	One nonpropagating trigger occurred at 56 ms after melt entry. The top 1/3 of water chamber fractured.
CM 4	3.50	0.53	Strong 25-30 mph crosswind at test time. Stripped some melt from the falling melt mass. Water chamber destroyed by nonpropagating triggers.
CM 5	3.40	0.28	Eruption velocity seemed to increase approx. 42 ms after eruption began. No triggers observed. A large amount of fine dust-size debris remained in chamber.
CM 6	1.94	0.18	Eruption appeared to be composed of multiple events. Water chamber remained undamaged.
CM 7	N.O.	N.O.	Melt shape was not uniform with a thin arm preceding main melt mass by 13 cm. Second explosion deformed water chamber support stand.
CM 8	N.O.	0.23	Lid entered water perpendicularly. The lid quickly separated from melt and slid off to side. Main center eruption was preceded by steaming. Weak explosion.
CM 9	N.O.	0.26	Lid entered water parallel to surface. Weak explosion.
CM 10	N.O.	0.19	Severe crucible melt leak prior to release at 5 s hold time. Fragments of lid entered with rest of melt. Water was a boiling froth at melt entry.
CM 11	5.80	0.20	No triggers observed. The chamber remained intact.
CM 12	N.O.	0.20	Large water swell due to eruption. Weak first explosion ruptured chamber. Strong second explosion did some mech. damage to stand and test tower. Second explosion began on bottom.

N.O. - Not Obtained.

OM SERIES - OXIDE MELTS

I. OBJECTIVE:

UNDERSTAND CMCIs WITH OXIDIC MELTS.

II. SERIES DESCRIPTION:

USE OXIDIC MELTS (FeO_x, UO_2, ETC.). VARY MELT MASS, WATER VOLUME AND TEMPERATURE, AMBIENT PRESSURE, AND OTHER PARAMETERS. DETERMINE EXPLOSIBILITY OF THIS FUEL/COOLANT SYSTEM. MEASURE PRESSURES, DEBRIS CHARACTERISTICS, CONVERSION RATIO AND COARSE MIXING CHARACTERISTICS.

III. STATUS:

4 TESTS COMPLETED: SATURATED AND SUBCOOLED WATER.

OM SERIES - OXIDE MELTS

IV. PRELIMINARY RESULTS:

- STEAM EXPLOSIONS OCCURRED FOR ALL FOUR TESTS (THREE IN COLD WATER, ONE IN HOT).

- PRESENCE OF LID IN OM-3 DELAYED EXPLOSION (100 MS AT 25 CM PENETRATION FOR OM-3 VS ~ 35 MS AND < 10 CM FOR OTHER THREE TESTS).

- MULTIPLE EXPLOSIONS OCCURRED FOR HOT WATER TEST OM-4: LAST EXPLOSION WAS ~ 490 MS AFTER MELT ENTRY.

- NO NON-EXPLOSIVE SURFACE EVENTS OCCURRED, IN CONTRAST TO CM SERIES.

→ IRON OXIDE MELTS ARE EASILY TRIGGERED AND EXPLODE READILY IN HOT AND COLD WATER.

Oxide Melt Test Series

Initial Parameters for the Oxide Melt Test Series

Test Name	Melt Mass Del. kg	Water Mass kg	Mass Ratio M_c/M_f	Water Temp. K	Water Subcool. K	Water Side Dim. m	Water Depth m	Melt Drop Height m	Melt Entry Vel. m/s	Melt Hold Time s	Lid in/out	Melt Width at Entry m
OM 1	N.O.	66.1	N.O.	298	69	0.43	0.36	0.635	3.53#	3.8	OUT	N.O.
OM 2	9.	100.9	11.2	298	69	0.53	0.36	0.635	3.83	3.8	OUT	0.24
OM 3	10.	131.7	13.2	298	69	0.61	0.36	0.635	3.34	3.8	IN	0.34
OM 4	9.	218.6	24.3	363	4	0.61	0.61	0.787	3.56	5.0	OUT	0.25

- Indicates that the entry was calculated by $[2 \times g \times h]^{1/2}$
N.O. - Not obtained.

Event Classification and Characteristics, and Comments for the Oxide Melt Test Series

Test Name	Event Type	Event Time after Melt Entry ms	Avg/Peak Particle Velocity m/s	Percent of Water Depth at Event	Comments on Test
OM 1	SE	N.O.	N.O.	N.O.	Some melt ejected through crucible vent holes, fell into chamber, and exploded. Chamber destroyed. Rest of melt released at 3.8 s and fell into empty chamber base.
OM 2	SE	47	193/272	29.2	Poor film visibility due to smoke from thermite burn. Chamber destroyed by surface explosion. Possibility of incomplete thermite reaction.
OM 3	SE	141	785/——	N.O.	Substantial melt leak from bottom of crucible prior to melt release. Poor film visibility. Only one high-speed camera and no low-speed camera.
OM 4	SE	19	332/427	N.O.	Chamber destroyed by surface explosion. Explosions at 198 and 247 ms were local explosions near west wall and did not propagate to entire melt.
OM 4	SE	198	N.O.	N.O.	
OM 4	SE	247	N.O.	N.O.	
OM 4	SE	360	132/184	100.0	

ER - Eruption TR - Nonpropagating Trigger SE - Steam Explosion
N.O. - Not obtained

ACM SERIES - ALTERNATE CONTACT MODE

I. OBJECTIVE:

UNDERSTAND THE PROBABILITY AND CONSEQUENCES OF CMCIs FOR DIFFERENT CONTACT MODES.

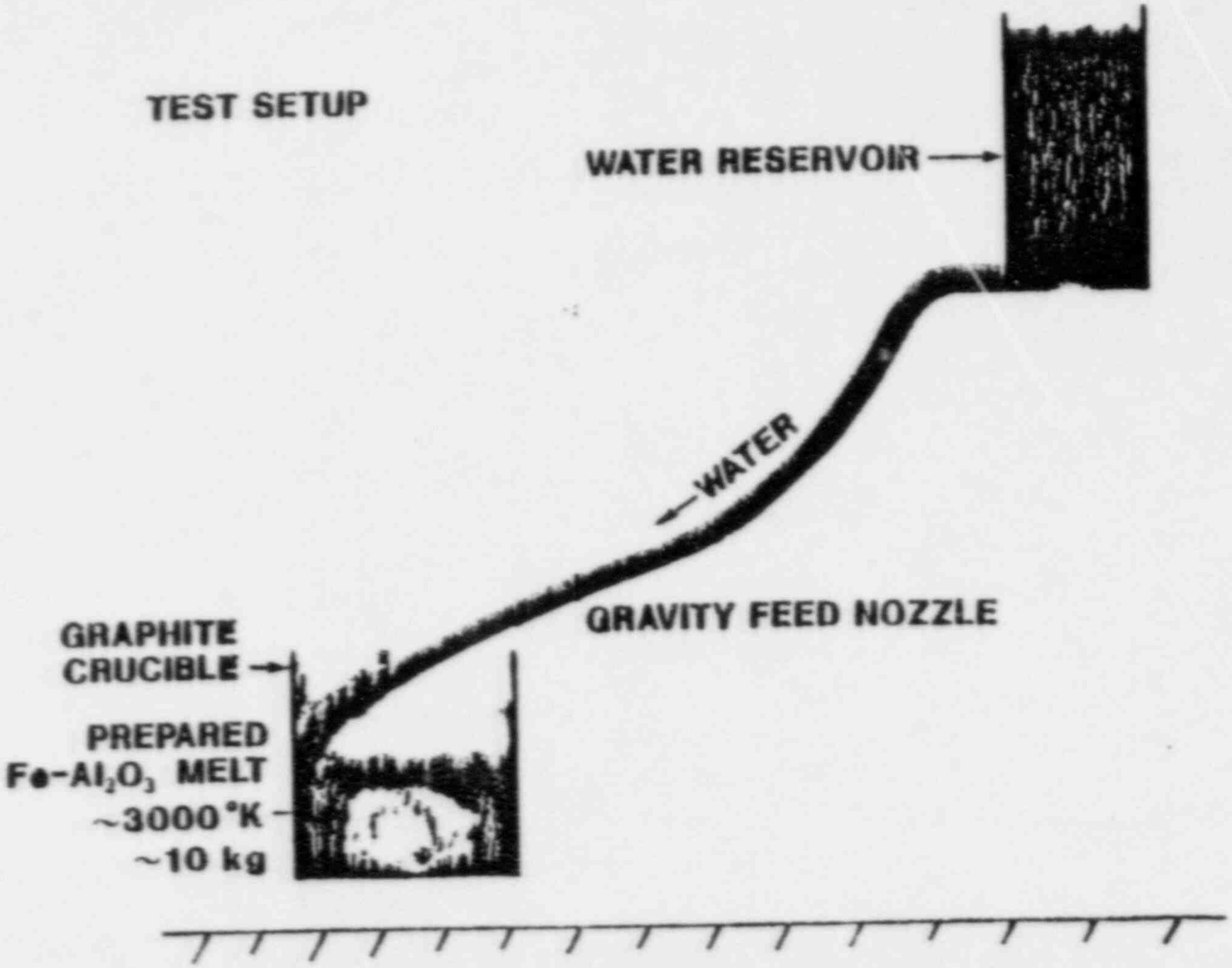
II. SERIES DESCRIPTION:

USING VARIOUS FUEL/COOLANT SIMULANT PAIRS, INVESTIGATE EXPLOSIBILITY AND STEAM AND HYDROGEN GENERATION RATES IN FLOODING AND WATER-INJECTION CONTACT MODES.

III. STATUS:

2 PRELIMINARY SCOPING TESTS COMPLETED.

TEST SETUP



WATER RESERVOIR
WATER
GRAVITY FEED NOZZLE
GRAPHITE CRUCIBLE
PREPARED
Fe-Al2O3 MELT
~3000°K
~10 kg

ACM SERIES - ALTERNATE CONTACT MODE

IV. PRELIMINARY RESULTS:

- ACM - 1: WATER INJECTED 1 s AFTER COMPLETION OF BURN. VIOLENT EXPLOSION AFTER AN ADDITIONAL 3 s.

- ACM - 2: WATER INJECTED 4.5 s AFTER BURN. NO EXPLOSION. PROBABLE CRUST FORMATION PRIOR TO WATER ENTRY.

- EXPLOSIONS IN REFLOOD MODE ARE POSSIBLE. ENERGETICS ARE UNKNOWN, BUT WILL PROBABLY DEPEND STRONGLY ON INITIAL AND BOUNDARY CONDITIONS.

Alternate Contact Mode Test Series

Initial Parameters for the Alternate Contact Mode Test Series

Test Name	Melt Mass kg	Water Mass kg	Water Temp. K	Water Subcooling K	Ambient Press. MPa	Water Hold Time s
ACM 1	10.0	0.6	298	69	0.083	1.0
ACM 2	18.5	3.8	298	69	0.083	4.5

Melt composition: iron-alumina

Event Classification and Characteristics; and Comments for the Alternate Contact Mode Test Series

Test Name	Event Type	Time after Melt Entry s	Comments on Test
ACM 1	Explosion	3	Delay between end of thermite burn and water-melt contact was 1 s. Explosion occurred at 3 s after water-melt contact. Several minor eruptions before explosion.
ACM 2	No Explosion		Delay between end of thermite burn and water-melt contact was 4.5 s. No explosion observed. Apparent crusting of melt prior to melt-water contact.

RC SERIES - RIGID CONTAINER

I. OBJECTIVE:

UNDERSTAND EFFECTS OF EXPLOSION CONFINEMENT.

II. SERIES DESCRIPTION:

USING VARIOUS FUEL/COOLANT SIMULANT PAIRS, INVESTIGATE THE CHANGE IN EXPLOSION CONVERSION RATIO DUE TO INCREASED CONFINEMENT.

III. STATUS:

2 TESTS COMPLETED. EXO-FITS FACILITY DESTROYED.

RC SERIES - RIGID CONTAINER

IV. PRELIMINARY RESULTS:

RC - 1: IRON-ALUMINA/COLD WATER, HOLD TIME = 4 S; VIOLENT EXPULSION, NO EXPLOSION.

RC - 2: IDENTICAL TO RC - 1 EXCEPT MELT WAS HELD FOR ONLY 1.5 S AFTER THERMITE BURN. STRONG EXPLOSION DESTROYED EXO-FITS CONCRETE PAD AND SUPERSTRUCTURE. WATER PHASE PRESSURE > 700 B.

Rigid Container Test Series

Initial Parameters for the Rigid Container Test Series

Test Name	Melt Mass Delivered kg	Water Mass kg	Mass Ratio M_c/M_f	Water Temp. K	Water Subcool. K	Chamber Diameter m	Water Depth m	Drop Height m	Melt Entry Velocity m/s	Melt Hold Time s
RC 1	19.0	111.7	5.9	298	69	0.56	0.46	1.78	5.77	4.0
RC 2	18.5	111.6	6.0	303	64	0.56	0.46	1.78	5.85	1.5

Melt composition: iron-alumina
Lid status(in/out): IN

Event Classification and Characteristics, and Comments for the Rigid Container Test Series

Test Name	Event Type	Event Time after Melt Entry ms	Eruption Duration ms	Avg/Peak Particle Velocity m/s	Comments on Test
RC 1	ER	86	232	N.O.	Rigid vessel was 94 cm long, 55.9 cm I.D. pipe with 2.5 cm thick walls and a plexiglass bottom. Entry velocity and time estimated using pipe inlet velocity and gravity.
RC 2	ER	56		N.O.	Same vessel as RC 1. Explosion lifted vessel 2 m off ground. Destroyed EXO-FITS test stand and concrete pad. Substantial ground and air shock felt.
RC 2	SE	180		853/1122	

ER - Eruption TR - Nonpropagating Trigger SE - Steam Explosion

N.O. - Not obtained

FITS-D Test Matrix

(Two experimental level, 1/8 rep fractional factorial experiment design)

Test	M_f	d	w	v	SC	P	Water mass-kg M_c	Water/Melt mass ratio M_c/M_f
FITS1D	H	L	H	H	H	H	87	1.7
FITS2D	L	H	L	H	H	H	95	4.8
FITS3D	L	L	H	L	L	H	87	4.4
FITS4D	H	H	L	L	L	H	95	1.9
FITS5D	L	H	H	L	H	L	381	19.0
FITS6D	H	L	L	L	H	L	22	0.44
FITS7D	H	H	H	H	L	L	381	7.6
FITS8D	L	L	L	H	L	L	22	1.1

The following parameters will be held constant during this series:

melt composition : iron-alumina thermite
melt pour rate : default
contact mode : melt into water
chamber confinement: unconfined, lucite walls
triggering : spontaneous or absent
melt hold time : 1.5 sec

Ranges of variable parameters corresponding to H and L values above:

melt mass, M_f : H = 50 kg, L = 20 kg, actual delivered mass will be less.
water depth, d : H = 0.66 m, L = 0.15 m
water chamber side dimension, w : H = 0.76 m, L = 0.38 m
entry velocity, v : controlled roughly by the high and low drop heights of H = 2.7 m and L = 1.6 m.
water subcooling, SC : H corresponds to cold water, L corresponds to a water as close to saturation temperature as can be achieved at the corresponding ambient pressure.
ambient pressure, P : H = 11 bars, L = 0.83 bars
mass of water, M_c : water depth and geometry dependent

FITS-D Test Series

Initial Parameters for the FITS-D Test Series

Test Name	Melt Mass Del. kg	Water Mass kg	Mass Ratio M_c/M_f	Water Temp. K	Water Subcool. K	Ambient Press. MPa	Water Side Dim. m	Water Depth m	Melt Drop Height m	Melt Entry Vel. m/s
FITS0D	17.8	182.9	10.3	359	9	0.085	0.610	0.508	1.79	5.92[#]
FITS2D[1]	18.0	95.7	5.3	289	168	1.103	0.381	0.660	2.69	7.26[#]
FITS5D	19.2	383.0	19.9	284	83	0.083	0.762	0.660	1.64	5.67[#]
FITS8D[1]	18.0	21.3	1.2	368	0	0.083	0.381	0.152	2.69	7.26[#]

\# - Entry was calculated by $[2 \times g \times h]^{(\frac{1}{2})}$

1 - Data for melt mass delivered and mass ratio are only rough estimates.

Melt composition: iron-alumina
Melt hold time: 1.5 seconds
Lid status(in/out): IN
All tests conducted in an inerted (Nitrogen) atmosphere.

FITS-D Test Series

Event Classifications and Characteristics for the FITS-D Test Series

Test Name	Event Type	Event Time After Melt Entry ms	Eruption Duration ms	Explosion Propagation Velocity m/s	Avg/Peak Particle Velocity m/s	Percent of Water Depth at Event
FITS0D	ER	N.A.	N.A.		N.A.	N.A.
FITS2D	No Events Were Observed					
FITS5D	SE	53		318.0	N.O.	29.7
FITS5D	SE	56		N.O.	N.O.	N.O.
FITS8D	ER	N.A.	N.A.		N.A.	N.A.

ER - Eruption TR - Nonpropagating trigger SE - Steam Explosion
N.A. - Not analyzed at publication. N.O. - Not Obtained.

FITS-D Test Series

Comments and Additional Results for the FITS-D Test Series

Test Name	Peak Gas Phase Press MPa	Peak Gas Phase Temp K	Melt Width at Entry m	Fraction of Iron Oxidized Fe_2O_3/FeO	Comments on Test
FITS0D	0.291	397	N.O.	0.19/0.29	Data very preliminary.
FITS2D	1.526	N.A.	N.A.	N.A.	Data very preliminary. Substantial amount of the delivered melt missed the water chamber. No explosive events seen on film data.
FITS5D	0.554	370	N.O.	0.16/0.24	Data very preliminary. Second explosion occurred 3 ms after first explosion. Substantial melt quenching prior to second explosion. First explosion drove melt into water at 150 m/s.
FITS8D	N.A.	N.A.	N.A.	N.A.	Data very preliminary. The films showed that the water was a boiling froth at main melt entry due to early entry by a small amount of pre-released melt.

N.O. - Not Obtained.
N.A. - Not analyzed at publication.

CORE MELT-COOLANT INTERACTIONS

PLAN FOR

RESOLUTION OF

TECHNICAL ISSUES

REACTOR SAFETY ISSUES AFFECTED BY FCIS

1. STEAM AND HYDROGEN GENERATION:

   WHAT ARE THE RATES AND TOTAL MAGNITUDES OF STEAM AND HYDROGEN WHICH CAN BE GENERATED DURING FCIs?

2. DEBRIS CHARACTERISTICS:

   WHAT ARE THE CHARACTERISTICS OF THE DEBRIS PRODUCED BY FCIS, INCLUDING PARTICLE SIZE DISTRIBUTION, POROSITY AND DEBRIS-BED STRATIFICATION?

3. ACCIDENT PROGRESSION AND SOURCE TERM:

   HOW DO FCIS INFLUENCE THE PROGRESSION OF THE ACCIDENT AND THE NATURE OF THE SOURCE TERM (INCLUDING FISSION PRODUCT CHEMISTRY, RELEASE RATE, PARTICLE SIZE AND MORPHOLOGY, AND FP DISPERSAL)? WHAT ARE THE CONSEQUENCES OF FUEL DEBRIS DISPERSAL IN- OR EX-VESSEL BY VIOLENT FCIS?

4. ACCIDENT TERMINATION AND SAFE SHUTDOWN:

   HOW DO FCIS AFFECT THE PROBABILITY OF SUCCESSFUL ACCIDENT TERMINATION BY THE ADDITION OF WATER TO THE MELT? WHAT OPERATOR ACTIONS WOULD INCREASE THE POSSIBILITY OF SAFE SHUTDOWN BY REDUCING THE RISK FROM DANGEROUS FCIS?

5. DIRECT FAILURE:

   WHAT ARE THE PROBABILITIES AND CONSEQUENCES OF DIRECT CONTAINMENT FAILURE BY A STEAM EXPLOSION (α - MODE)?

6. INDIRECT FAILURE:

   WHAT ARE THE PROBABILITIES AND CONSEQUENCES OF INDIRECT CONTAINMENT FAILURE BY FCIS (δ-, γ-, OR [illegible]- MODES)?

KEY QUESTIONS WHICH MUST BE ANSWERED

TO RESOLVE FCI ISSUES

1. WHAT ARE THE IMPORTANT INITIAL AND BOUNDARY CONDITIONS WHICH INFLUENCE FCI PHENOMENA?

   PAST RESEARCH HAS SHOWN THAT THESE ARE:

   FUEL MASS, COMPOSITION AND TEMPERATURE; FUEL/WATER MASS RATIO; WATER MASS, SUBCOOLING, DEPTH, CROSS-SECTIONAL AREA AND POSSIBLY COMPOSITION; TRIGGER STRENGTH; AMBIENT PRESSURE; CONTACT MODE; MELT/WATER POUR RATE AND ENTRY VELOCITY; WATER CHAMBER GEOMETRY, CONFINEMENT AND INTERNAL STRUCTURES.

2. FOR A GIVEN SET OF INITIAL CONDITIONS, WHAT ARE THE CHARACTERISTICS OF THE RESULTING FCI? THE ANSWERS TO THIS QUESTION WILL RESOLVE THE SAFETY ISSUES. SPECIFICALLY:

   A) WHAT ARE THE RATES AND QUANTITIES OF STEAM AND HYDROGEN THAT ARE GENERATED?
   B) CAN A LARGE-SCALE EXPLOSION OCCUR UNDER THESE CONDITIONS AND, IF SO, WHAT IS THE CONVERSION RATIO?
   C) CAN A MISSILE BE GENERATED? WHAT IS ITS ENERGY?
   D) WHAT ARE THE CHARACTERISTICS OF THE RESULTING DEBRIS?
   E) WHAT ARE THE EFFECTS OF THE FCI ON FP RELEASE AND DISPERSAL?

3. WITH A KNOWLEDGE OF THE FCI CHARACTERISTICS WHICH OCCUR, CALCULATE THE PROBABILITY AND CONSEQUENCES OF DIRECT AND INDIRECT CONTAINMENT FAILURE USING PHENOMENOLOGICAL, PROBABILISTIC OR INTEGRATED CONTAINMENT CODES, AS APPROPRIATE.

PLAN FOR RESOLUTION OF ISSUES

1. ASSESS CURRENT STATE OF KNOWLEDGE FOR ALL ISSUES.

2. BASED ON THIS KNOWLEDGE, DETERMINE MOST IMPORTANT EXPERIMENTAL AND MODELLING UNCERTAINTIES.

3. PLAN AND EXECUTE AN "EFFICIENT" TEST MATRIX.

4. INCORPORATE TEST RESULTS INTO NEW MODELS AND CODES.

5. ASSESS THE UNCERTAINTY IN MODEL PREDICTIONS. IF "SUFFICIENTLY" LOW, TERMINATE FURTHER EXPERIMENTAL AND ANALYTICAL FCI RESEARCH. MOVE TO RISK ASSESSMENT PHASE.

6. IF UNCERTAINTIES ARE STILL TOO HIGH AFTER STEPS 3, 4 AND 5, EXPAND TEST MATRIX AND REPEAT PROCESS.

TO RESOLVE THE FCI SAFETY ISSUES. SANDIA PROPOSES AN INTEGRATED RESEARCH PROGRAM CONTAINING THE FOLLOWING ELEMENTS:

1. LARGE-SCALE ($\leq$ 2000 KG) FACILITY FOR OPEN-GEOMETRY EXPERIMENTS ON COARSE MIXING AND CONVERSION RATIO (EXO-FITS II USING THERMITE MELTS AT AMBIENT PRESSURE.

2. EXTENSION OF FITS CLOSED-GEOMETRY EXPERIMENTS TO 50 KG OF THERMITE MELTS.

3. SMALL-SCALE SINGLE-DROPLET EXPERIMENTS TO INVESTIGATE TRIGGERING AND CONVERSION RATIO AT HIGH AMBIENT PRESSURE (TO 170 BARS).

4. LARGE-SCALE ($\leq$ 400 KG) FACILITY FOR CLOSED-GEOMETRY EXPERIMENTS USING INDUCTION-HEATED PROTOTYPIC OXIDIC AND METALLIC MELTS.

5. CONTINUATION OF FCI MODEL DEVELOPMENT AND APPLICATION.

*****

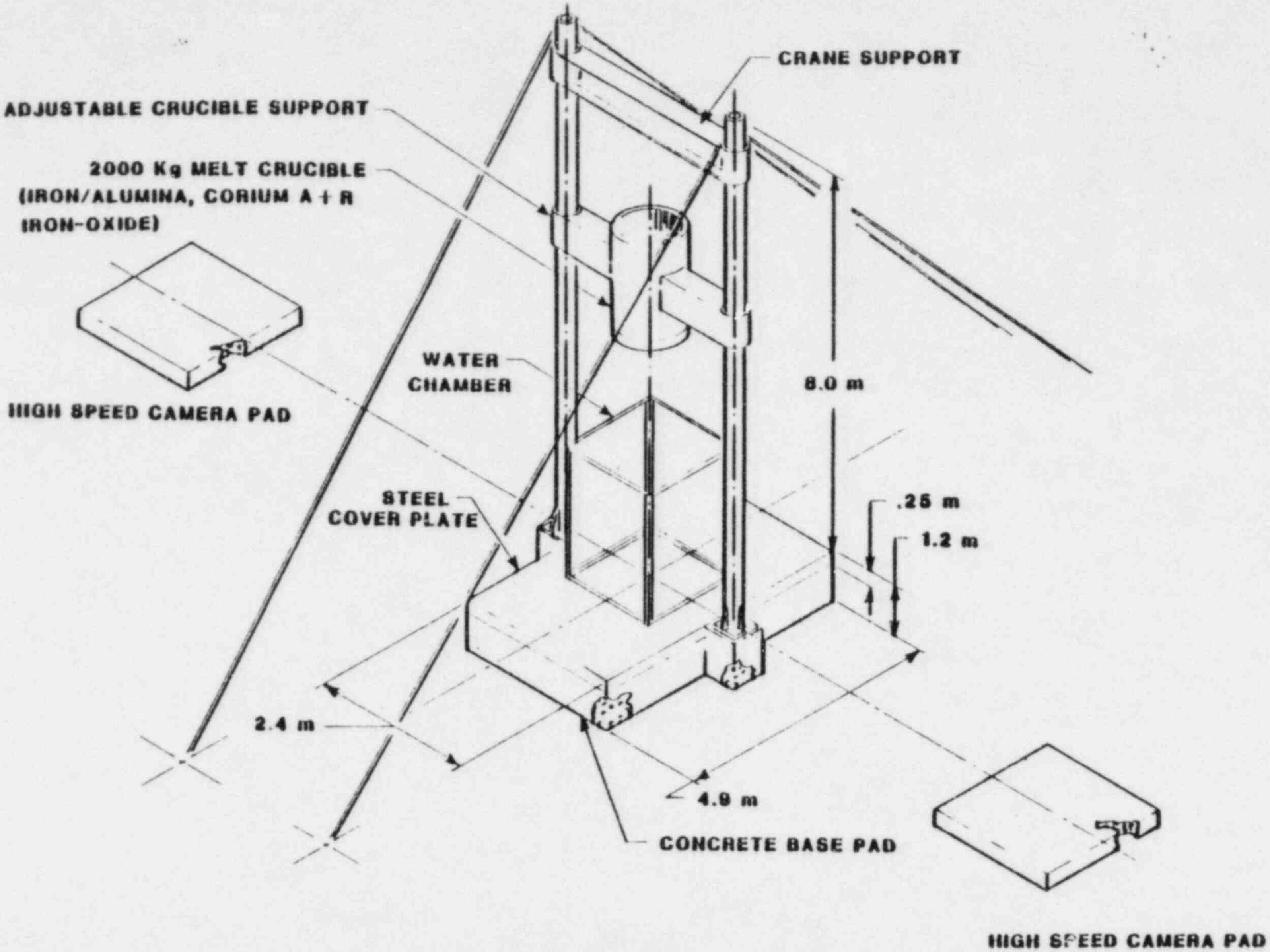
ABBREVIATION FOR PROGRAM ELEMENTS

1. EXO-FITS II
2. FITS EXTENDED
3. SHIP (SMALL-SCALE HIGH PRESSURE)
4. ELVIS (ENCLOSED LARGE VESSEL INTERACTION SYSTEM)
5. MODEL DEVELOPMENT

RATIONALE FOR EXPERIMENTAL PLAN

ELEMENT 1: EXO-FITS II

- THE PRIMARY OBJECTIVE OF THIS FACILITY IS TO DETERMINE WHETHER AN UPPER LIMIT EXISTS FOR COARSE MIXING, AND WHAT THIS LIMIT IS.
- THE FACILITY WOULD BE DESIGNED TO DETERMINE THIS LIMIT AS CHEAPLY AS POSSIBLE.
- IF A LIMIT WERE FOUND AT 2000 KG OR LESS, IT WOULD SIGNIFICANTLY AFFECT ALL SIX SAFETY ISSUES. FURTHERMORE, ISSUES 4 (ACCIDENT TERMINATION), 5 AND 6 (DIRECT AND INDIRECT FAILURE) WOULD BE COMPLETELY RESOLVED.
- THERE IS NO OTHER WAY TO INVESTIGATE THE EFFECTS OF LARGE MELT MASSES AT RELATIVELY LOW COSTS.
- BASIS FOR SELECTING 2000 KG OF FUEL:
  - -HIGH ENOUGH TO UNEQUIVOCALLY DISTINGUISH THE DIFFERENCE BETWEEN CURRENT COARSE MIXING MODELS;
  - -HIGH ENOUGH TO APPROACH THE RANGE OF MASSES WHICH MIGHT BEGIN TO THREATEN VESSEL AND CONTAINMENT INTEGRITY;
  - -LOW ENOUGH TO KEEP DOWN COSTS OF BUILDING AND OPERATING.



SCHEMATIC OF EXO-FITS II

EXO-FITS II: EXPERIMENTAL VARIABLES AND MEASUREMENTS

I. PRIMARY VARIABLES

FUEL MASS (UP TO 2000 KG)
WATER MASS
FUEL/WATER MASS RATIO
WATER TEMPERATURE (SUBCOOLING)
FUEL INJECTION RATE (DROP HEIGHT, POUR DIAMETER)
WATER DEPTH
WATER CHAMBER CONFINEMENT
TRIGGER STRENGTH

II. SECONDARY VARIABLES

INTERNAL STRUCTURES IN WATER (LOWER PLENUM SIMULATION)
WATER COMPOSITION

III. FIXED PARAMETERS

FUEL COMPOSITION (IRON-ALUMINA THERMITE)
FUEL TEMPERATURE
AMBIENT PRESSURE
CONTACT MODE (FUEL INTO COOLANT)

IV. MEASUREMENTS

PHOTOGRAPHY (COARSE MIXING, CONVERSION RATIO)
WATER PHASE PRESSURE
BASE IMPULSE
POSSIBLY X-RAYS

RATIONALE FOR EXPERIMENTAL PLAN

ELEMENT 2: FITS EXTENDED

- THE PRIMARY OBJECTIVE OF THIS FACILITY IS TO PROVIDE QUANTITATIVE DATA FOR RESOLVING ISSUES 1 AND 2 (STEAM AND HYDROGEN GENERATION AND DEBRIS CHARACTERISTICS). IT WILL ALSO PROVIDE INFORMATION FOR RESOLVING ALL THE REMAINING ISSUES.
- QUANTITATIVE DATA GENERATED IN THIS FACILITY WOULD BE USED FOR MODEL DEVELOPMENT AND CODE ASSESSMENT.
- BECAUSE THE FACILITY IS CURRENTLY OPERATIONAL, EXPERIMENTS USING UP TO 50-100 KG OF THERMITE-GENERATED MELTS CAN BE INEXPENSIVELY CONDUCTED.
- THE MAJOR DRAWBACKS OF THIS FACILITY ARE LIMITED MELT COMPOSITION (ONLY VARIOUS THERMITES), LIMITED MELT MASS, AND NO CAPABILITY FOR HIGH PRESSURE INJECTION.

FITS-X (EXTENDED): EXPERIMENTAL VARIABLES AND MEASUREMENTS

I. PRIMARY VARIABLES

FUEL COMPOSITION (THERMITES: IRON-ALUMINA, CORIUM, IRON OXIDE)
FUEL MASS (20 - 100 KG)
WATER MASS
FUEL/WATER MASS RATIO
WATER TEMPERATURE (SUBCOOLING)
WATER DEPTH, CROSS-SECTION, CONFINEMENT
INTERNAL STRUCTURES (LOWER PLENUM SIMULATION)
FUEL INJECTION RATE (DROP HEIGHT, POUR DIAMETER)
AMBIENT PRESSURE (1 - 11 BARS)
CONTACT MODE (FUEL INTO COOLANT AND VICE VERSA)
ALTERNATE CONTACT MODE: FUEL DEPTH, WATER INJECTION RATE
TRIGGER STRENGTH

II. SECONDARY VARIABLES

WATER COMPOSITION
FISSION PRODUCT SIMULANTS IN MELT

III. FIXED PARAMETERS

FUEL TEMPERATURE FOR A GIVEN FUEL COMPOSITION
GRAVITY POURS ONLY: NO HIGH PRESSURE INJECTION

IV. MEASUREMENTS

PHOTOGRAPHY (FOR UNCONFINED TESTS WITH LUCITE CHAMBER)
X-RAYS (FOR COARSE MIXING)
BASE IMPULSE
WATER PHASE PRESSURE
GAS PHASE TEMPERATURE
GAS PHASE PRESSURE (FOR STEAM GENERATION RATES)
GAS SAMPLING (FOR HYDROGEN GENERATION RATES AND FISSION PRODUCTS)
DEBRIS CHARACTERISTICS
POSSIBLY FUEL TEMPERATURES

RATIONALE FOR EXPERIMENTAL PLAN

ELEMENT 3: SHIP (SMALL-SCALE HIGH PRESSURE TESTS)

- THE PRIMARY OBJECTIVE OF THIS FACILITY IS TO INVESTIGATE THE TRIGGERING OF STEAM EXPLOSIONS AT HIGH AMBIENT PRESSURE.

- THIS FACILITY REPRESENTS THE MOST INEXPENSIVE APPROACH TO RESOLVING THE QUESTION OF DIRECT FAILURE FOR ACCIDENTS AT HIGH AMBIENT PRESSURE.

- SINCE TRIGGERING IS THE FCI PHASE CURRENTLY BELIEVED TO BE MOST SENSITIVE TO PRESSURE, THIS FACILITY WOULD QUANTITATIVELY ADDRESS THAT PROCESS.

- SHIP WOULD PROVIDE SOME QUANTITATIVE DATA ON CONVERSION RATIO AT HIGH PRESSURE.

- SHIP COULD ALSO INEXPENSIVELY GENERATE DATA ON THE EFFECTS OF HIGH RADIATION LEVELS, WATER SUBCOOLING AND WATER COMPOSITION, ON EXPLOSION TRIGGERING AND CONVERSION RATIO.

- THIS FACILITY WOULD NOT ADDRESS LARGE-SCALE EFFECTS OF HIGH AMBIENT PRESSURE. SPECIFICALLY, IT COULD NOT ADDRESS CURRENT THEORETICAL PREDICTIONS THAT COARSE MIXING IS <u>ENHANCED</u> AT HIGH AMBIENT PRESSURE.

SHIP: EXPERIMENTAL VARIABLES AND MEASUREMENTS

I. PRIMARY VARIABLES

AMBIENT PRESSURE (1-170 BARS)
TRIGGER STRENGTH
FUEL COMPOSITION (OXIDES, METALS, MIXTURES)
WATER TEMPERATURE (SUBCOOLING)

II. SECONDARY VARIABLES

RADIATION ENVIRONMENT
WATER COMPOSITION

III. FIXED PARAMETERS

CONTACT MODE (FUEL INTO COOLANT)
INTERACTION CHAMBER

IV. MEASUREMENTS

PHOTOGRAPHY (CONVERSION RATIO)
WATER PHASE PRESSURE
DEBRIS CHARACTERISTICS
HYDROGEN GENERATION RATES

RATIONALE FOR EXPERIMENTAL PLAN

ELEMENT 4: ELVIS (400 KG ENCLOSED VESSEL)

- THE PRIMARY OBJECTIVE OF THIS FACILITY IS TO ADDRESS ALL SAFETY ISSUES UP TO A SCALE OF 400 KG OF MELT, WITH OXIDIC, METALLIC AND MIXED FUEL MELTS INDUCTIVELY HEATED.

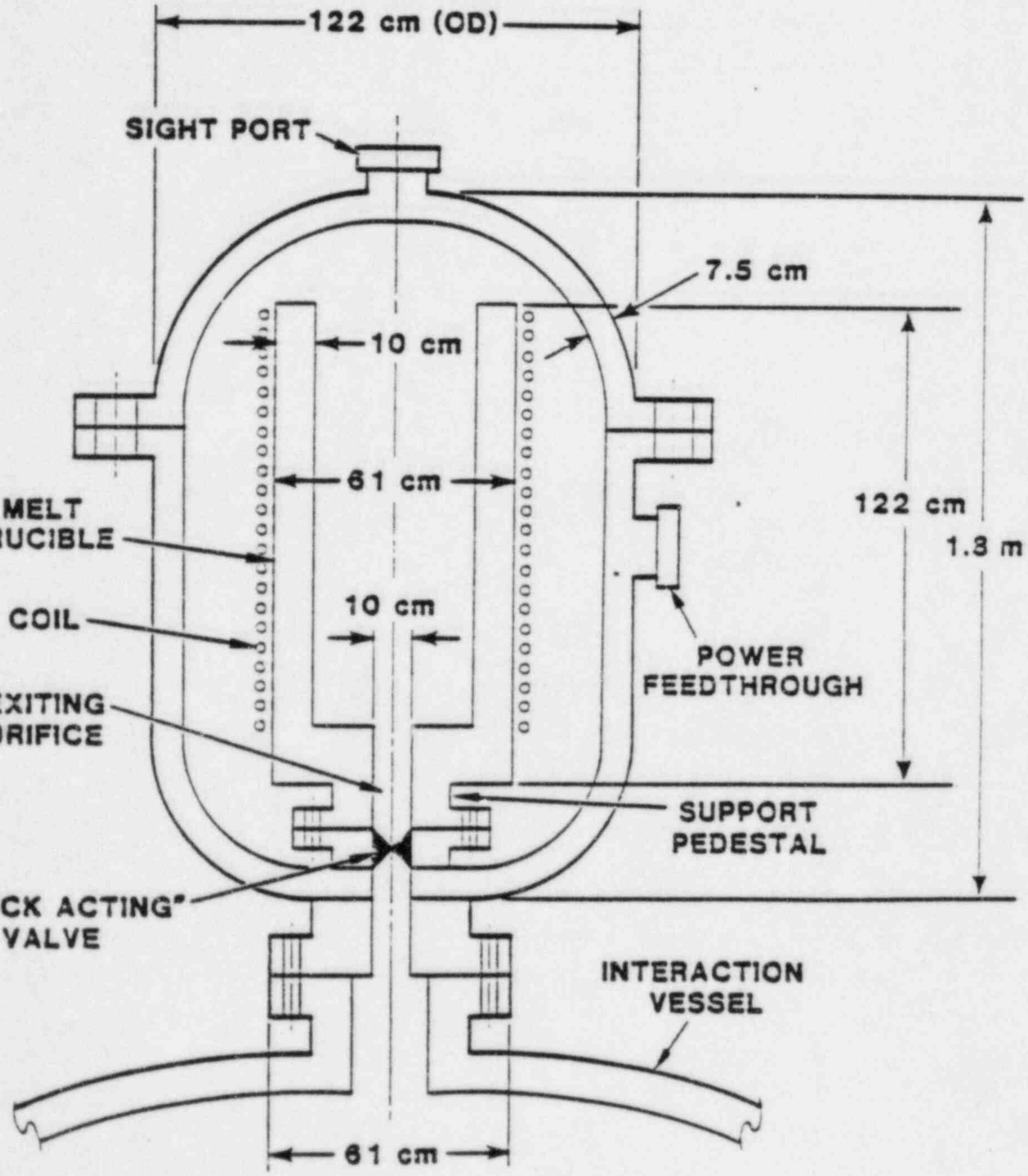
- THIS FACILITY WOULD GREATLY EXTEND THE AVAILABLE TEST MATRIX, COMPARED TO THE EXTENDED FITS FACILITY.

- ELVIS WOULD PROVIDE DATA FOR MODEL DEVELOPMENT AND CODE ASSESSMENT.

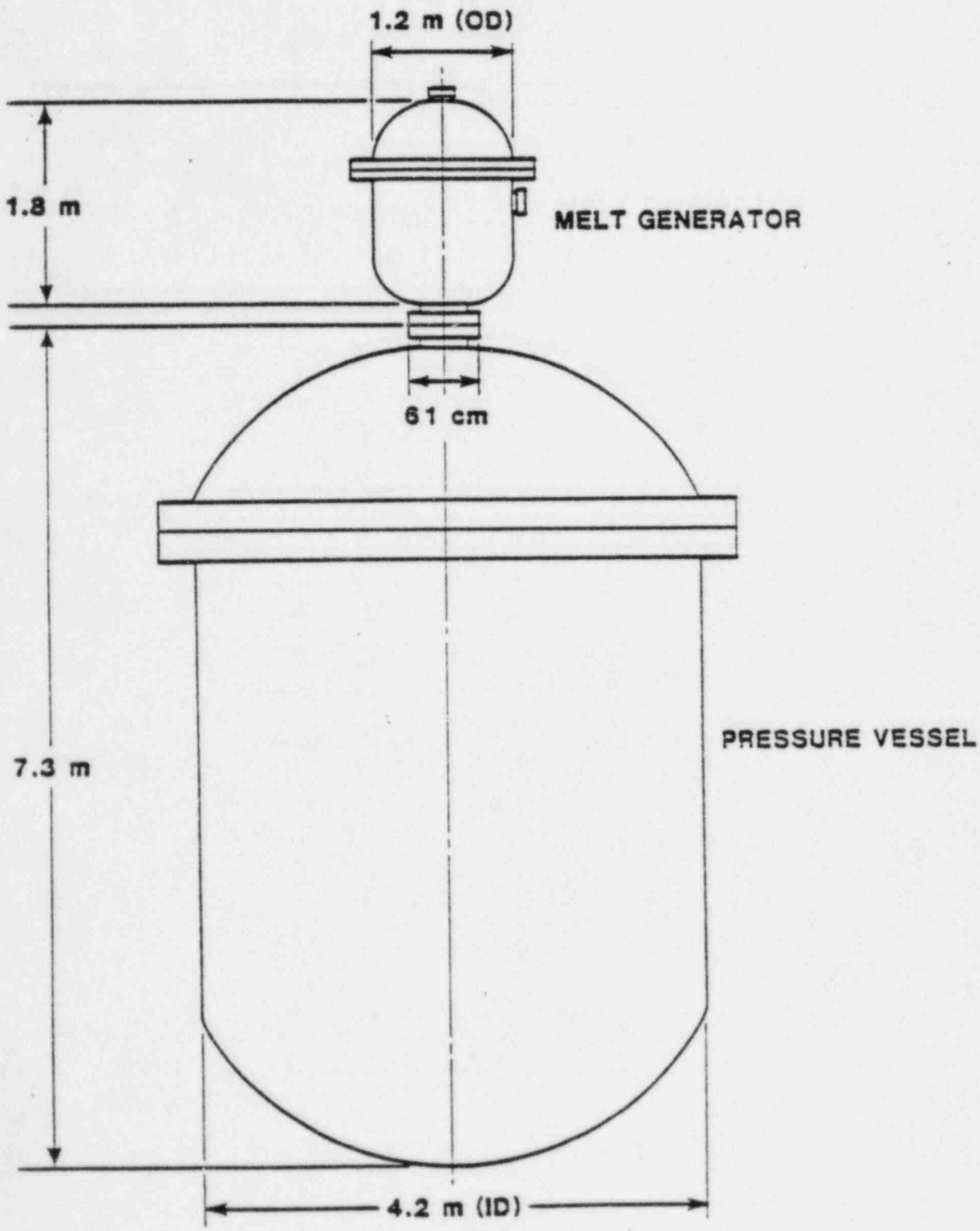
- THIS FACILITY WOULD BE ESSENTIAL IF THE EXO-FITS II FACILITY DID NOT DEMONSTRATE A LIMIT TO COARSE MIXING.

- ELVIS WOULD BE OPTIONAL IF A COARSE MIXING LIMIT WAS FOUND. DEPENDING ON THE EXTENT OF THE THREAT PREDICTED BY THE INTEGRATED CODES, THE FACILITY MIGHT NOT BE REQUIRED.

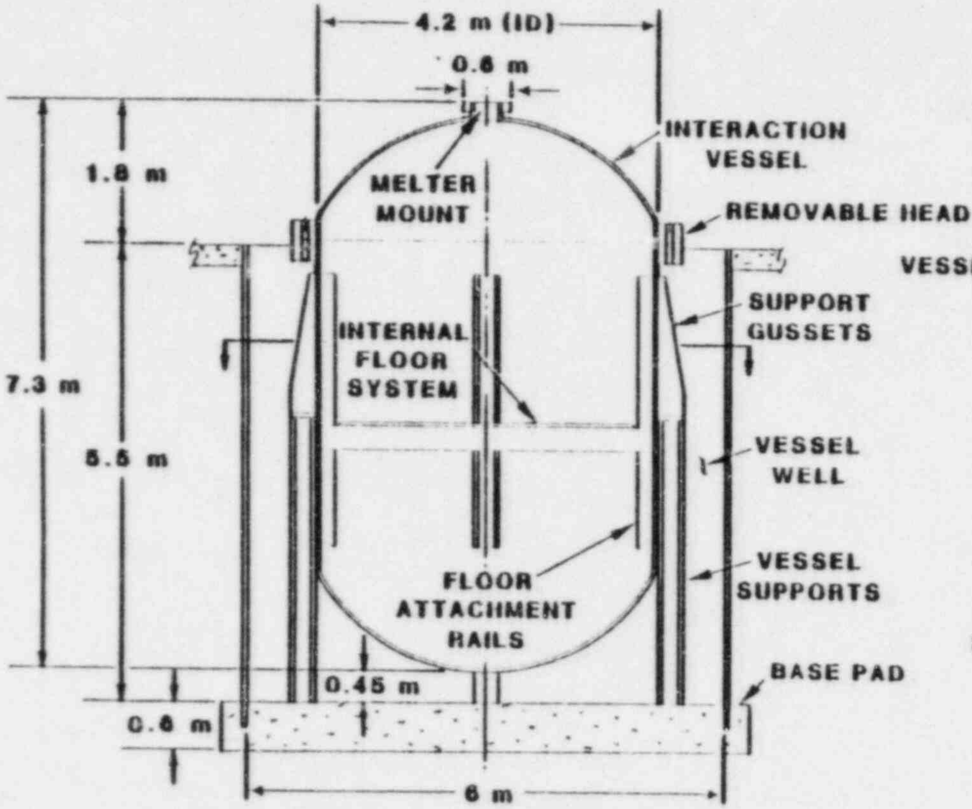
- SELECTION OF 400 KG IS CURRENTLY ARBITRARY, AND IS BEING USED FOR PRELIMINARY COST AND DESIGN STUDIES. ACTUAL MASS CAPABILITY WILL DEPEND ON RESULTS OF EXO-FITS II TESTS. IF THOSE TESTS DEMONSTRATE AN IMPORTANT LIMIT TO THE AMOUNT OF MASS MIXED, THEN AN UPGRADED FITS FACILITY MAY BE ADEQUATE, WITHOUT ELVIS.



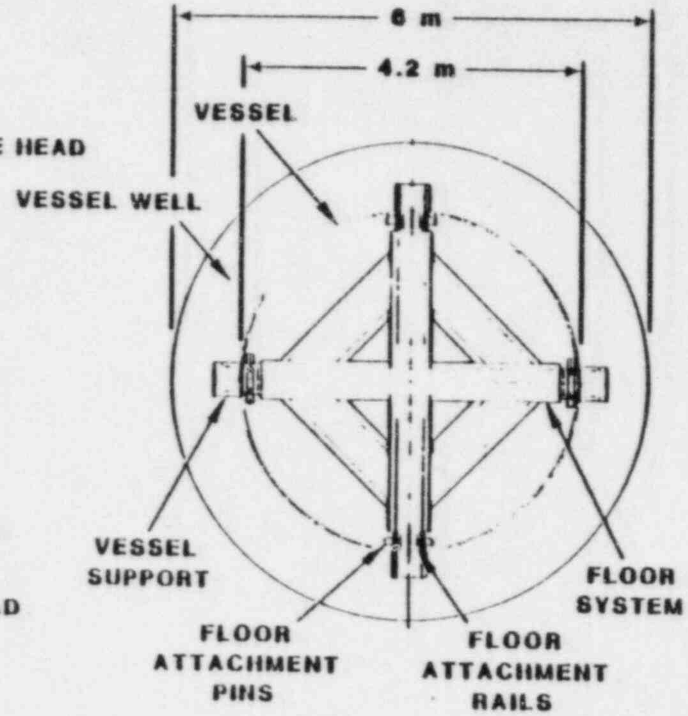
SCHEMATIC OF MELT GENERATOR



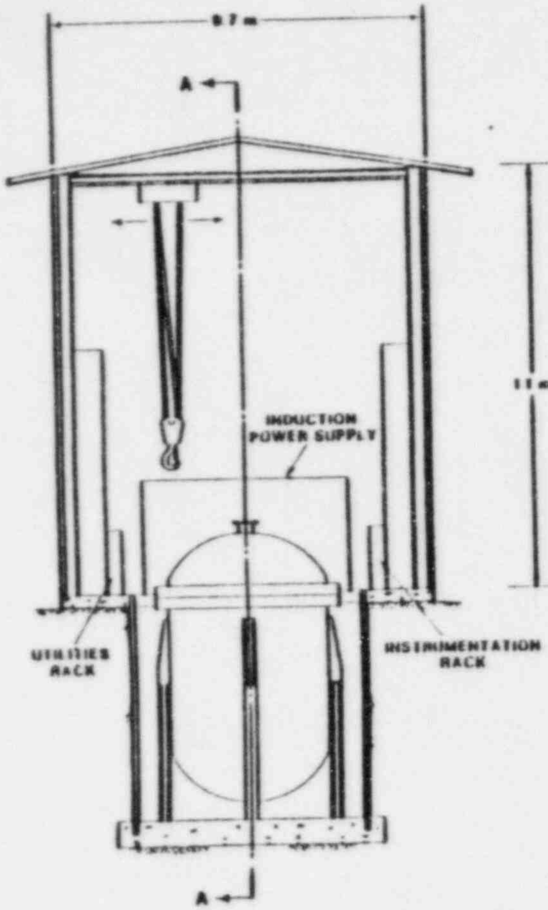
ASSEMBLED MELT GENERATOR AND PRESSURE VESSEL



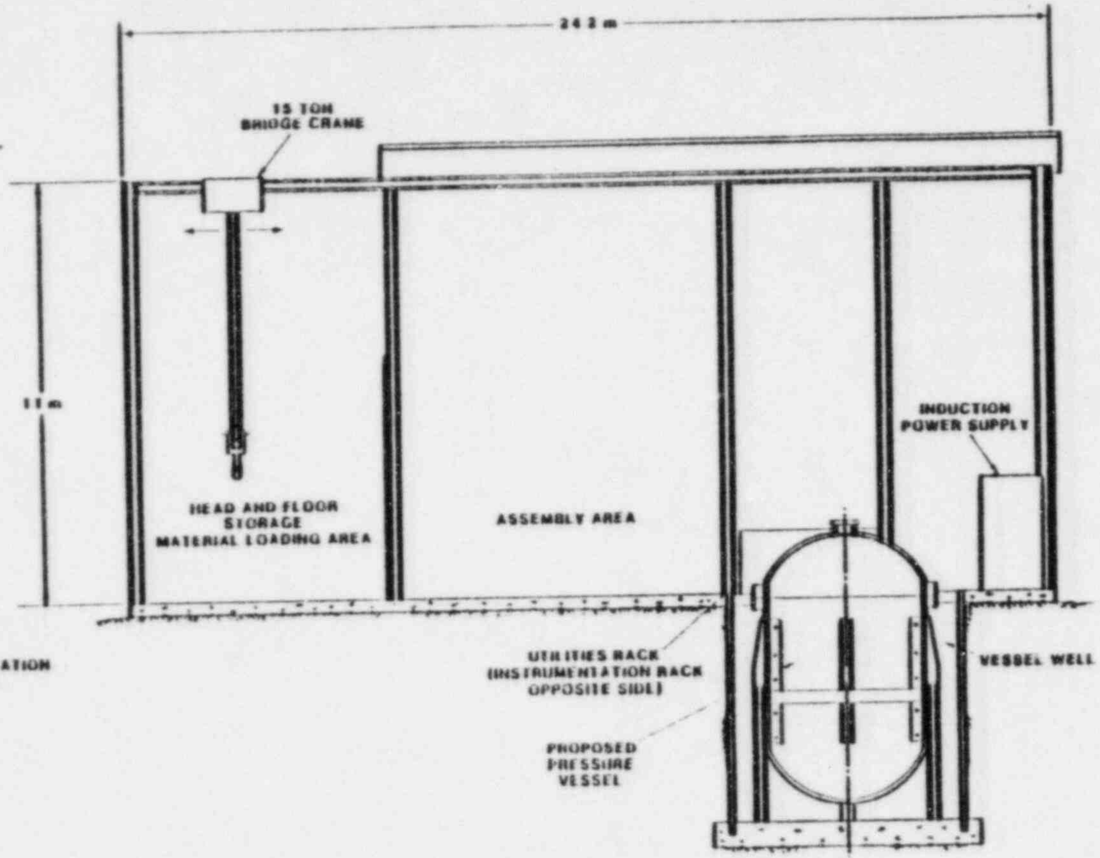
VERTICAL SECTION VIEW OF PROPOSED PRESSURE VESSEL



HORIZONTAL SECTION VIEW OF PROPOSED PRESSURE VESSEL AND INTERNAL FLOOR SYSTEM



FRONT VIEW



SIDE VIEW (SECTION AA)

PROPOSED BUILDING AND MAJOR EQUIPMENT LAYOUT

ELVIS: EXPERIMENTAL VARIABLES AND MEASUREMENTS

I. PRIMARY VARIABLES: SAME AS FITS-X PLUS:

ADDITIONAL COMPOSITIONS INDUCTIVELY MELTED: PURE OXIDES, PURE METALS, MIXED METAL-OXIDES, VARIOUS CORIUMS
FUEL MASS: UP TO 400 KG
FUEL TEMPERATURE
HIGH PRESSURE INJECTION INTO WATER

II. SECONDARY VARIABLES

SIMULATION OF CONTAINMENT GEOMETRIES

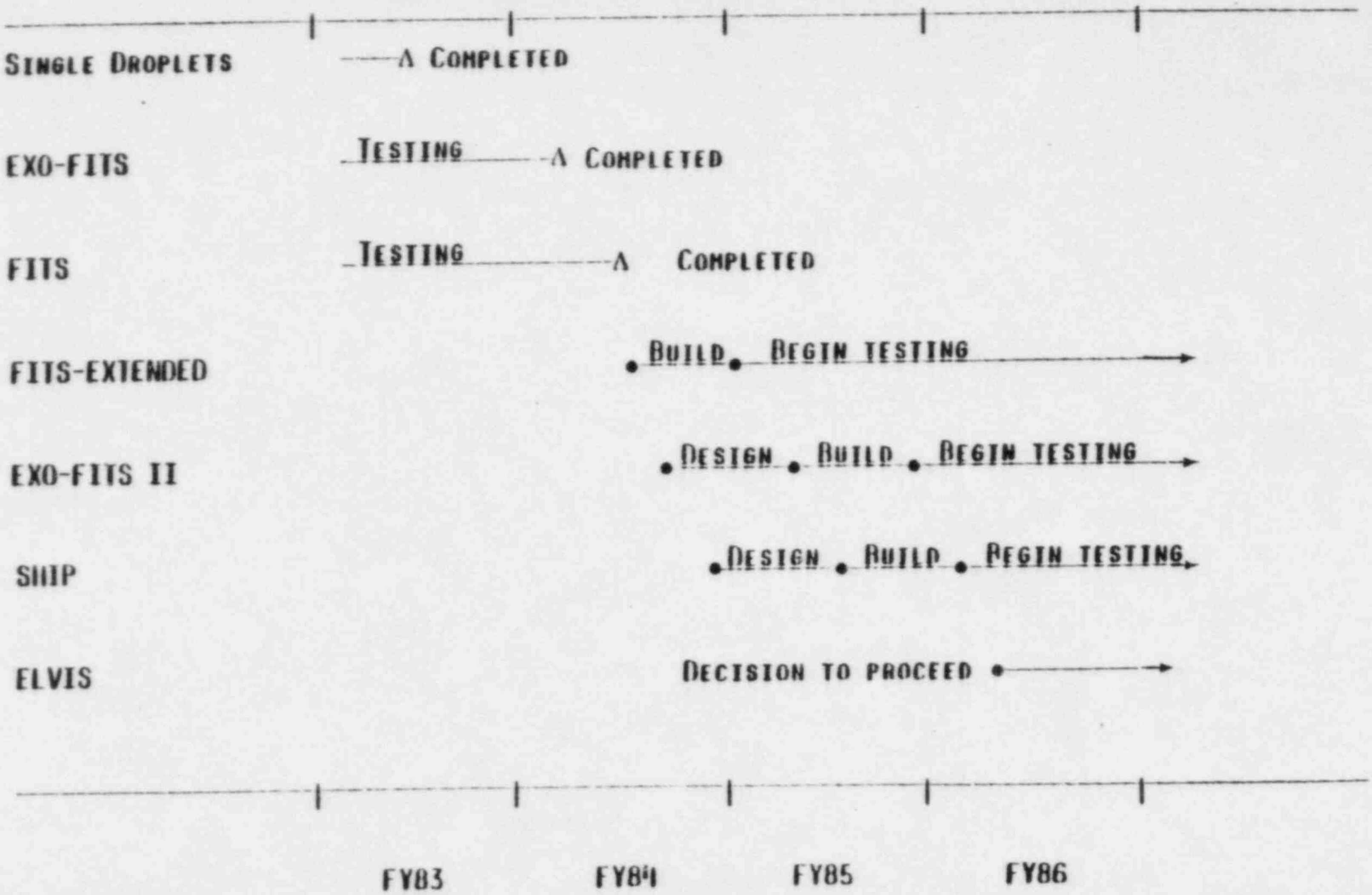
III. FIXED PARAMETERS

NONE

IV. MEASUREMENTS

SAME AS FITS-X

CMCI PROGRAM - EXPERIMENTAL FACILITIES



CORE MELT - COOLANT INTERACTIONS

MODEL DEVELOPMENT PLAN

PHENOMENA	MODELS
1. COARSE MIXING, FRAGMENTATION, H_2 AND STEAM GENERATION.	WISCI/TEXAS
2. TRIGGERING AND FILM COLLAPSE.	SIMPLE-1D
3. EXPLOSION PROPAGATION.	WONDY-1D/TEXAS
4. EXPLOSION, EXPANSION, CONVERSION RATIO	CSQ-2D
5. PROBABILITY OF DIRECT FAILURE BY STEAM EXPLOSION.	SIMPLE MONTE CARLO

RATIONALE FOR MODEL DEVELOPMENT

* THE CODES BEING DEVELOPED WOULD BE USED THREE WAYS:

  1. TO ANALYZE AND GUIDE EXPERIMENTS.
  2. TO DIRECTLY PREDICT THE CONSEQUENCES OF FCIs.
  3. TO PROVIDE MODELS DIRECTLY TO THE INTEGRATED ACCIDENT ANALYSIS CODES (MELPROG, CONTAIN, MELCOR).

* THE CODES BEING DEVELOPED WOULD MAXIMIZE THE EXISTING INVESTMENT IN THESE MODELS (REPRESENTED BY MEDICI, TEXAS, WONDY, AND CSQ).

* COSTS OF CODE DEVELOPMENT WOULD BE MINIMIZED. OVERLAP WITH OTHER NRC PROGRAMS WOULD BE MAXIMIZED (MELPROG, MEDICI, CONTAIN, MELCOR, SASA, ETC.).

PLAN FOR RESOLUTION OF ISSUES

ON AN ISSUE-BY-ISSUE BASIS

PLAN FOR RESOLUTION OF ISSUE 1:

STEAM AND HYDROGEN GENERATION RATES

STEP 1: DETERMINE THE MINIMUM SET OF TEST ELEMENTS NECESSARY TO QUANTITATIVELY RESOLVE THE ISSUE. DEFINE THE VARIABLES AND THEIR RANGES FOR AN "EFFICIENT" EXPERIMENTAL DESIGN. SUBMIT TEST PLAN TO NRC AND REACTOR SAFETY COMMUNITY FOR PEER REVIEW.

STEP 2: DETERMINE THE LOWEST COST FACILITY CONSISTENT WITH THE NECESSARY NUMBER AND RANGES OF THE VARIABLES.

STEP 3: IF AN EXTENDED FITS FACILITY IS TERMED ADEQUATE FOR THIS STUDY, MODIFY THE FACILITY AND CONDUCT THE TESTS.

STEP 4: IF A LARGER AND MORE SOPHISTICATED FACILITY (ELVIS) IS DEEMED NECESSARY AS A RESULT OF THE REVIEW IN STEP 1, THEN DESIGN AND BUILD THE FACILITY AND EXECUTE THE TEST PROGRAM.

STEP 5: USE THE EXPERIMENTAL DATA TO IMPROVE AND ASSESS THE APPROPRIATE CODES: WISCI, TEXAS, CSQ, ETC. PROVIDE DATA TO LASL FOR MULTI-DIMENSIONAL FCI CODE DEVELOPMENT.

STEP 6: PROVIDE CODES AND MODELS TO THE DEVELOPERS OF THE INTEGRATED CODES (MELCOR, MELPROG, MEDICI, CONTAIN).

NOTE: The resolution of this issue requires three program elements: FITS, ELVIS, and Model Development.

PLAN FOR RESOLUTION OF ISSUE 2:

DEBRIS CHARACTERISTICS

STEPS 1-6: SAME AS FOR ISSUE 1.

STEP 7: PROVIDE EXPERIMENTAL DATA, INCLUDING SAMPLES OF COLLECTED DEBRIS, TO PROGRAMS WHICH REQUIRE THEM FOR DEBRIS BED COOLABILITY STUDIES.

NOTE: The resolution of this issue is concurrent with issue 1, and only requires that the post-FCI debris be collected and analyzed.

PLAN FOR RESOLUTION OF ISSUE 3:

ACCIDENT PROGRESSION AND SOURCE TERM

STEP 1: DEFINE TEST OBJECTIVES: WHAT ARE THE KEY CHEMICAL PROCESSES TO BE INVESTIGATED? WHAT ARE THE IMPORTANT IN- AND EX-VESSEL GEOMETRIES TO BE STUDIED FOR DEBRIS DISPERSAL?

STEP 2: DETERMINE THE MINIMUM SET OF TEST ELEMENTS NECESSARY TO QUANTITATIVELY RESOLVE THE ISSUE. DEFINE THE VARIABLES AND RANGES FOR AN "EFFICIENT" EXPERIMENTAL DESIGN. SUBMIT TEST PLAN TO NRC AND REACTOR SAFETY COMMUNITY FOR PEER REVIEW.

NOTE: Although the resolution of this issue requires the same three program elements as issues 1 and 2, a new test matrix, additional hardware, and possibly new diagnostic systems, are required.

STEPS 3-6: SAME AS FOR ISSUE 1.

STEP 7: PROVIDE DATA TO SOURCE TERM ANALYSTS.

PLAN FOR RESOLUTION OF ISSUE 4:

ACCIDENT TERMINATION AND SAFE SHUTDOWN

STEPS 1-7: SAME AS PREVIOUS ISSUES

THE RESOLUTION OF THIS ISSUE WOULD NOT REQUIRE ANY ADDITIONAL EXPERIMENTATION OR MODEL DEVELOPMENT BEYOND THAT REQUIRED FOR RESOLVING THE OTHER ISSUES.

RESOLUTION OF THIS ISSUE SIMPLY REQUIRES A WRITTEN REPORT SUMMARIZING THE KNOWLEDGE GAINED BY THE PROGRAM. THIS KNOWLEDGE WOULD BE DISTILLED INTO SEVERE-ACCIDENT GUIDELINES FOR UTILITIES AND THE NRC TO USE IN EMERGENCIES.

PLAN FOR RESOLUTION OF ISSUE 5:

DIRECT FAILURE OF CONTAINMENT BY A STEAM EXPLOSION

THIS ISSUE CAN BE RESOLVED IN TWO DISTINCT WAYS:

EITHER:

PATH 1: Demonstrate that the probability of alpha-mode failure for high and low pressure accidents is negligible or zero by experimentally proving any one of the following:

a) An upper limit exists to the amount of molten fuel which can be coarsely mixed in reactor geometries and this limit is below the threshold necessary for containment failure for conservative estimates of conversion ratio.

b) For high pressure accidents, the probability of triggering an explosion is negligible or zero.

c) Conversion ratio decreases with increasing fuel mass, such that the yield of an explosion is below the threshold for containment failure for conservative estimates of the amount of fuel mixed.

d) The geometry and structures in the lower plenum of a BWR and/or a PWR prevent either large-scale coarse mixing or high conversion ratios.

OR:

PATH 2: Develop a comprehensive in-vessel steam explosion model, couple it to a statistical approach, and compute the probability of containment failure for a variety of accident scenarios.

RESOLUTION OF ISSUE 5: CONTINUED

PATH 1: A) THE EXO-FITS II FACILITY WILL PROVE OR DISPROVE THIS HYPOTHESIS FOR LOW-PRESSURE ACCIDENTS.

B) THE SHIP FACILITY WILL TEST THIS HYPOTHESIS.

C) SHIP, FITS, EXO-FITS II, AND ELVIS WILL PROVIDE DATA SUFFICIENT TO VERIFY THIS HYPOTHESIS.

D) FITS, EXO-FITS II AND ELVIS WILL TEST THIS HYPOTHESIS.

NOTE: If the experiments of Path 1 yield positive results, then the direct failure issue can be resolved. If the experimental results are inconclusive, then a determination of the non-zero probability for direct failure will require probabilistic model development, additional mechanistic models, or both.

PATH 2: REQUIRED IF PATH 1 EFFORTS ARE INCONCLUSIVE.

* WILL PROBABLY REQUIRE THE DEVELOPMENT OF A COMPLEX, MULTI-DIMENSIONAL MODEL OF ALL PHASES OF A STEAM EXPLOSION.

* MAY EMPLOY CURRENT CALCULATIONAL TOOLS (CSQ, SIMMER, MELPROG, ETC.), OR MAY INVOLVE FURTHER CODE DEVELOPMENT.

PLAN FOR RESOLUTION OF ISSUE 6:

INDIRECT FAILURE OF CONTAINMENT BY FCIs

STEPS 1-7: ALL DATA AND MODELS REQUIRED FOR RESOLVING THIS ISSUE WILL BE DEVELOPED CONCURRENTLY WITH THE RESOLUTION OF THE OTHER ISSUES.

STEP 8: PROVIDE DATA AND MODELS TO CONTAINMENT CODES. PERFORM CALCULATIONS FOR VARIOUS ACCIDENT SCENARIOS (AS WAS DONE IN CONTAINMENT LOADS WORKING GROUP).

STEP 9: PROVIDE DATA AND MODELS TO GROUPS INVESTIGATING EQUIPMENT SURVIVAL AND CONTAINMENT PENETRATION LEAKAGE.

FCI RESEARCH PRIORITIES

1. DETERMINE IF A LIMIT TO COARSE MIXING EXISTS, AND QUANTIFY AS A FUNCTION OF INITIAL CONDITIONS.

2. DETERMINE LIMITS TO THE OCCURRENCE AND ENERGETICS OF STEAM EXPLOSIONS AS A FUNCTION OF INITIAL CONDITIONS.

3. QUANTIFY RATES OF STEAM AND HYDROGEN PRODUCTION DUE TO FCIS, AND THE NATURE OF THE DEBRIS.

GENERAL DISCUSSION

- EXPERIMENTAL FACILITIES
- TEST MATRICES
- MODEL DEVELOPMENT
- RESEARCH PRIORITIES

NO CONSENSUS IS REQUIRED.

ALL OPINIONS AND SUGGESTIONS WILL
BE CAREFULLY CONSIDERED.

SCIENTIFIC TRUTHS ARE NOT DETERMINED
BY MAJORITY VOTE.