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Status and Future Direction of the Melt Attack and Coolability Experiments (MACE) Program at Argonne National Laboratory

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ABSTRACT

The Melt Attack and Coolability Experiments (MACE) program has been underway at Argonne National Laboratory addressing the ability of water to quench and thermally stabilize a molten core concrete interaction (MCCI) when the interaction is flooded from above. In this program, which has been sponsored by the EPRI-headed Advanced Containment Experiments (ACE) international consortium, large scale reactor material integral effects experiments have been conducted, in parallel with related modeling efforts. Plans are currently being developed for continued utilization of the MACE facility under the sponsorship of the Nuclear Energy Agency (NEA) to achieve the following objectives: i) resolution of the ex-vessel debris coolability issue through a redirected program which focuses on providing both confirmatory evidence and test data for the coolability mechanisms identified in MACE integral effects tests; and ii) address remaining uncertainties related to long-term two-dimensional MCCI under dry cavity conditions. In terms of the ex-vessel debris coolability issue, separate effects tests are planned to provide data on key melt coolability mechanisms identified in MACE integral effects tests. The results of these tests will provide both confirmatory evidence and test data to support development of validated models for extrapolation to plant conditions. In terms of dry cavity conditions, reactor material tests are planned to address remaining uncertainties related to long-term 2-D MCCI; in particular, lateral vs. axial power split. This paper describes the essential elements of the program to address these two remaining important LWR safety issues.

1.0 INTRODUCTION

Although extensive research has been conducted over the last several years in the areas of Molten Corium-Concrete Interactions (MCCI) and debris coolability, two important issues warrant further investigation. The first issue concerns the effectiveness of water in terminating an MCCI by flooding the interacting masses from above, thereby effecting a quench of the molten core debris and rendering it permanently coolable. This safety issue has been under investigation for some time as part of EPRI-headed Melt Attack and Coolability Experiments (MACE) program underway at ANL (Spencer and Sehgal, 1992; and Farmer et al., 2000). In this program, the approach has been to conduct large scale, integral-type reactor material experiments with core melt masses ranging up to 2000 kg. These experiments have provided unique, and for the most part repeatable, indications of viable heat transfer mechanism(s) for achieving long term coolability. However, the results of these tests have not been definitive insofar as demonstrating complete quench due to the fact that crust anchoring with subsequent melt/crust separation has occurred in all tests, even at the largest test section lateral span of 1.20 m. This decoupling is not expected in the typical 5-6 meter span of a NPP reactor cavity. In light of these results, it is clear that the technical approach of the MACE program needs to be redirected. In particular, separate effects experiments are needed to provide data on viable melt coolability mechanisms under well-controlled experiment conditions. The results of these tests will provide both confirmatory evidence and test data to support development of validated models for extrapolation to plant conditions.

For the case in which the cavity remains dry, the second issue concerns long-term two-dimensional ablation by a prototypic core oxide melt. As discussed by Foit (1999), the existing reactor material MCCI database is solely one-dimensional. As a result, there is significant uncertainty insofar as evaluating the lateral vs. axial power split. Accurate knowledge of this power split is essential in the evaluation of the consequences of an ex-vessel severe accident. In particular, for the case of a dry containment, lateral erosion is important to understand owing to the possibility of undermining containment structures. As a result of this uncertainty, substantial differences still exist between codes insofar as predicting 2-D cavity erosion behavior. Thus, reactor material experiments are needed to provide data in order to reduce the uncertainty associated with the evaluation of long-term 2-D erosion by a core oxide melt.

During the course of the MACE program, unique expertise and infrastructure has been developed at Argonne insofar as conducting large scale, high temperature reactor materials experiments. The purpose of the program described below is to continue to utilize the MACE facility, under the sponsorship of the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (NEA-OECD), to achieve the following technical objectives:

1. resolution of the ex-vessel debris coolability issue through a redirected program which focuses on providing both confirmatory evidence and test data for the coolability mechanisms identified in MACE integral effects tests, and

2. address remaining uncertainties related to long-term two-dimensional MCCI under dry cavity conditions.

Achievement of these objectives will lead to improved severe accident management guidelines for existing plants, and also better containment designs for future plants.

3.0 PROGRAM TECHNICAL OBJECTIVES

The overall objective of the program is to provide the necessary data to resolve the two LWR safety issues which were described above. As shown in Table 1, three types of experiments are proposed to accomplish this task.

In terms of the ex-vessel debris coolability issue, two types of separate effects tests are proposed to provide data on key melt coolability mechanisms identified in MACE integral effects tests; these cooling mechanisms are summarized in Table 2. The results of these tests will provide both confirmatory evidence and test data to support development of validated models for extrapolation to plant conditions. In particular, the proposed melt eruption experiments would provide data on the melt entrainment coefficient under well-controlled experiment conditions; this is the most important parameter in determining the entrainment rate. This data can be used directly in existing models (Bonnet and Seiler, 1992) for evaluating the effect of melt ejection on mitigation of ex-vessel accident sequences.

The proposed water ingression and crust strength experiments would provide data on the ability of water to ingress into core material, thereby augmenting the otherwise conduction-limited heat transfer rate. Dryout heat flux data obtained from these experiments can be used directly in existing models for evaluating the effect of water ingression on mitigation of ex-vessel accident sequences involving MCCI (Farmer and Spencer, 1999; and Farmer, 2001). The crust strength data obtained as part of this work would provide the basis for validating the concept of sustained melt/crust contact due to crust instability in the typical 5-6 m cavity span of most power plants.

In terms of dry cavity conditions, there is significant uncertainty insofar as evaluating the lateral vs. axial power split during MCCI due to a lack of experiment data (Foit, 1999). As a result, substantial differences still exist between MCCI codes (e.g., WESCHL, CORCON, and COSACO) insofar as predicting 2-D cavity erosion behavior[1]. This is principally due to a lack of experiment data to adequately qualify the computer codes insofar as long-term behavior is concerned. The specific objective of the proposed MCCI experiments is to provide this data.

4.0 EXERIMENTAL APRAOCH

Experimental approaches for achieving the two program objectives are outlined in Table 1. Essential elements of each experiment are provided below.

Ex-Vessel Debris Coolability

With respect to the ex-vessel debris coolability issue, separate effects experiments are planned to provide both confirmatory evidence and test data on the melt eruption and water ingression cooling mechanisms. The proposed melt eruption tests utilize an inert basemat and gas sparging to mock-up concrete decomposition gases. The corium mixture is initially generated in-situ using an exothermic chemical reaction over a timescale of ~ 1 minute. The mixture consists of core and concrete oxides in various ratios reflecting different depths of concrete ablation. Direct Electrical Heating (DEH) is utilized to maintain melt temperature. The overall system design for this test is shown in Fig. 1, while details of the lower test section design are provided in Fig. 2. The system for controlling the basemat gas sparging rate is depicted in Fig. 3. The use of an inert basemat for this test eliminates the tendency for the melt to separate from the crust by the mechanism of basemat densification upon melting. The use of an externally supplied gas source to mock-up the concrete decomposition gases provides control over the principal parameter influencing the melt entrainment rate. Moreover, the gas flowrate (as opposed to the input power) can be used to reestablish melt/crust contact if separation occurs by increasing the melt pool void fraction. These two steps circumvent shortcomings which were identified in the MACE integral effects tests insofar as maintaining melt/crust contact. Basic data to be obtained from the gas sparging test consists of the melt entrainment rate as a function of the gas sparging rate. The slope of the line fit to the entrainment rate data then determines the melt entrainment coefficient, which is the key piece of information needed for model development.

A total of three gas sparging tests are planned, which will parameterize on the melt composition. Aside from the gas sparging rate, the melt composition has been identified as a key parameter which may influence the entrainment rate (Bonnet and Seiler 1992). The test matrix will consider not only the type of concrete, but also the amount present in the corium composition.

To examine the water ingression cooling mechanism and also to provide data on the overall crust strength, two types of tests are planned:

i) small scale tests to provide pseudo-quantitative crust dryout heat flux data, and also crust macroscopic strength data, over a wide range of compositions, and

ii) dedicated, intermediate scale, well instrumented experiments focused on quantitative measurement of the dryout heat flux for a few selected compositions.

The test apparatus for the small scale tests is shown in Fig. 4. As for the gas sparging tests, the corium melts are generated in-situ through an exothermic chemical reaction. Several tests will be conducted with an inert basemat and no gas sparging; the water ingression rate (or dryout heat flux) can then be readily determined by comparing the actual corium cooling rate with well known analytical solutions for the case of conduction-limited cooling of liquids. Several tests will also be carried out with a thin concrete basemat to examine the effect of concrete decomposition on the crust formation and quenching process. For these tests, posttest measurements of the quenched crust specimens consist of: i) water percolation rate, ii) axial composition/phase distribution, and iii) crust strength measurements made on the entire crust sample. The test stand for carrying out the strength measurements is shown in Figure 5. The macroscopic crust

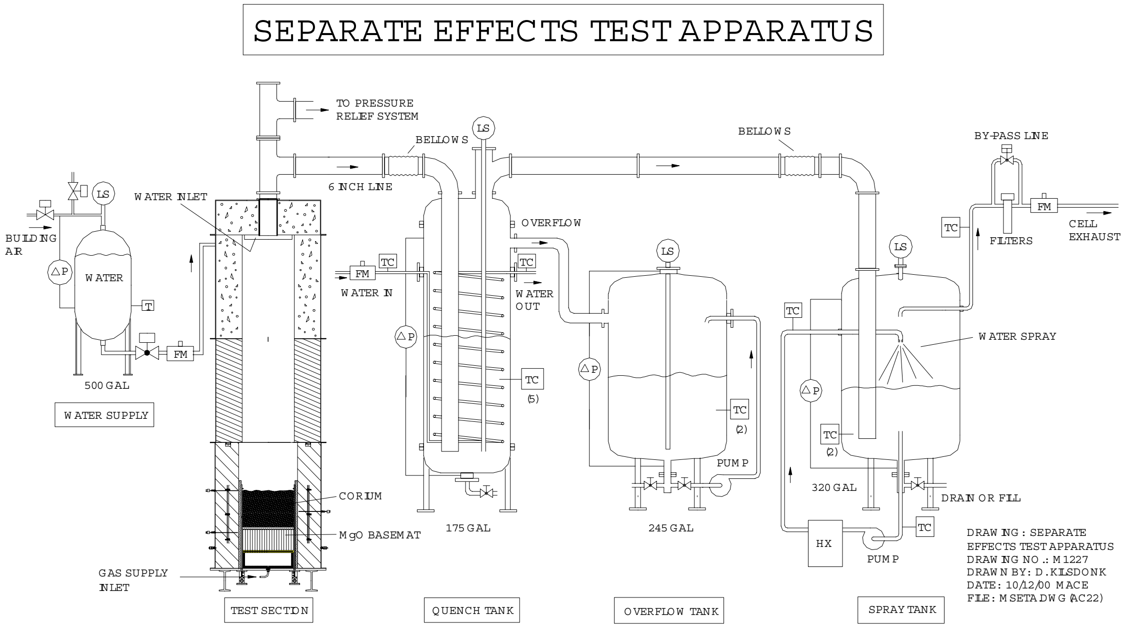


Figure 1. Overall System Design for Melt Eruption Separate Effects Tests.

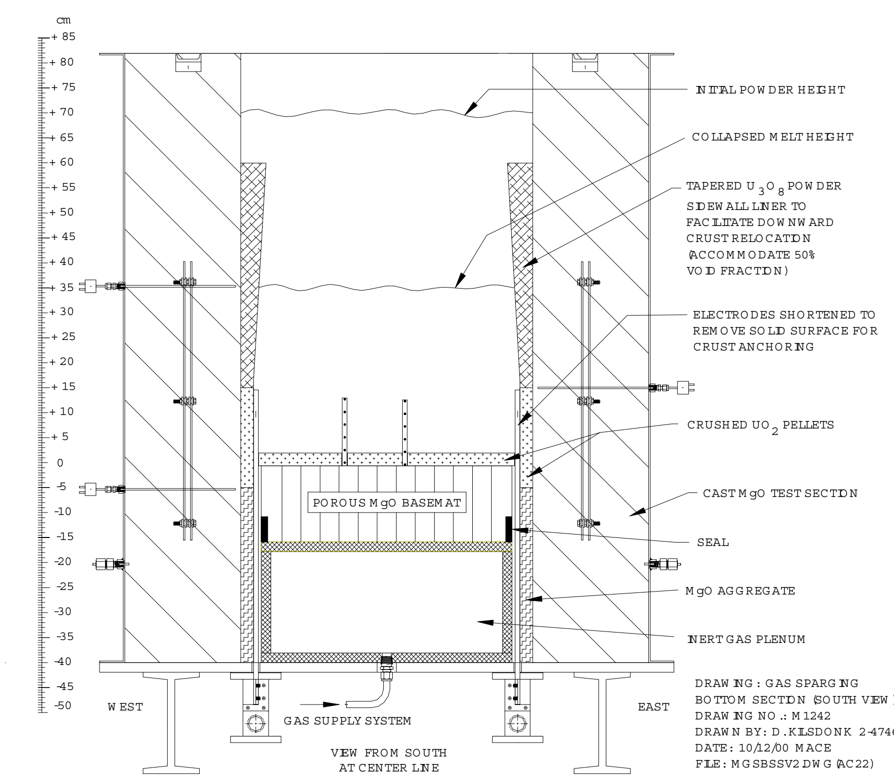
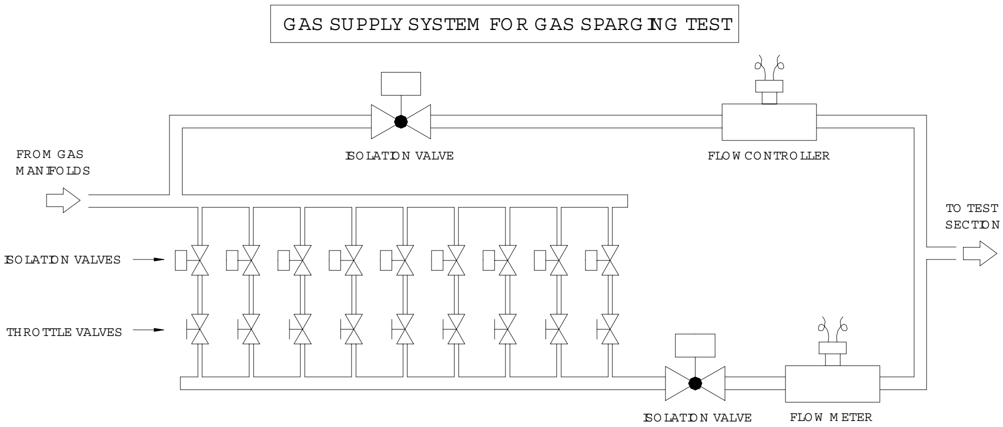


Figure 2. Details of Lower Test Section Design for Melt Eruption Separate Effects Tests.



VALVE NUMBER	1	2	3	4	5	6	7	8	9
FLOW RATE (SLPM/VALVE)	25	25	25	25	50	50	50	50	50
TOTAL FLOW RATE (SLPM)	25	50	75	100	150	200	250	300	350
CORRESPONDING MELT SPARGING RATE AT 2000K (50 cm X 50 cm)	1.1	2.2	3.4	4.5	6.7	9.0	11.2	13.4	15.7

DRAWING: GAS SUPPLY SYSTEM FOR GAS SPARGING TEST
DRAWING NO.: M1228
DRAWN BY: D.KILSDONK
DATE: 10/12/00 MACE
FILE: MGSS.DWG (AC22)

Figure 3. Basemat Gas Supply System for Melt Eruption Separate Effects Tests.

strength data obtained from these measurements would be used to validate the concept that the crust will be mechanically unstable at plant scale.

A total of six tests are planned with the small scale water ingression test apparatus. A key parameter in the matrix is melt composition, since composition is felt to be one of the most important variables influencing cracking behavior. Both in-vessel and ex-vessel compositions will be addressed. The test matrix will also parameterize on the amount of concrete present in the corium composition, which will provide information on the effect of concrete decomposition on the crust formation and quenching behavior.

If the results of the small scale tests indicate that water ingression is a viable heat transfer mechanism insofar as achieving long-term debris coolability, then two fully instrumented intermediate scale tests are planned. The apparatus is shown in Fig. 6. This test is conducted in a larger diameter test vessel to reduce edge effects (i.e., 30 cm vs. 20 cm), and also with a much deeper melt pool (40 cm vs. 5 cm). The deeper pool will provide high resolution dryout heat flux data by comparing the measured melt/water heat flux and crust growth rate with well known analytical solutions for conduction-limited cooling of melt pools. These tests would be conducted using two compositions considered in the small scale water ingression tests. If the results from the small scale tests indicate that concrete decomposition is an important parameter influencing the water ingression rate, then a thin concrete layer could be incorporated into the fully instrumented test design to include this effect.

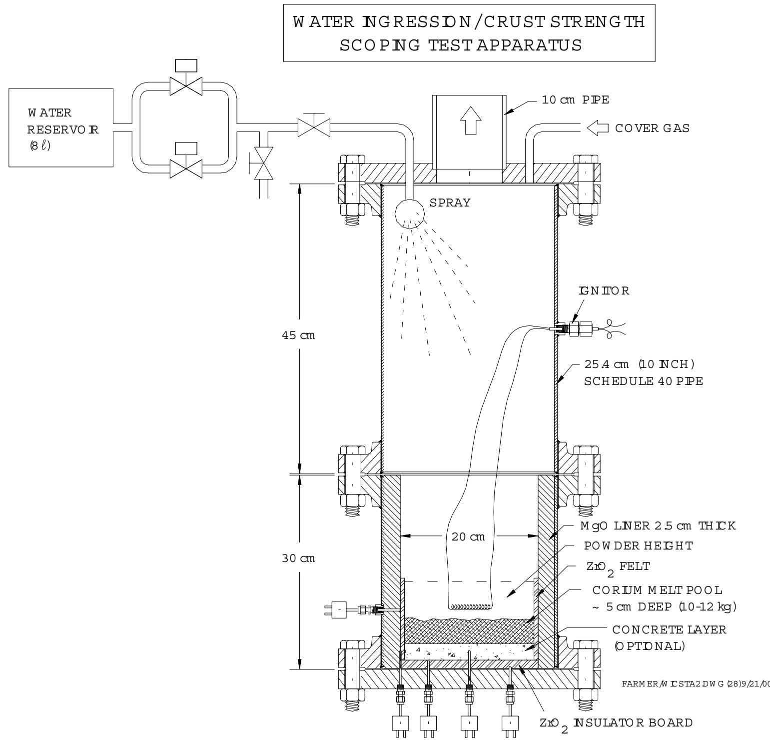


Figure 4. Apparatus for Small Scale Water Ingression and Crust Strength Tests.

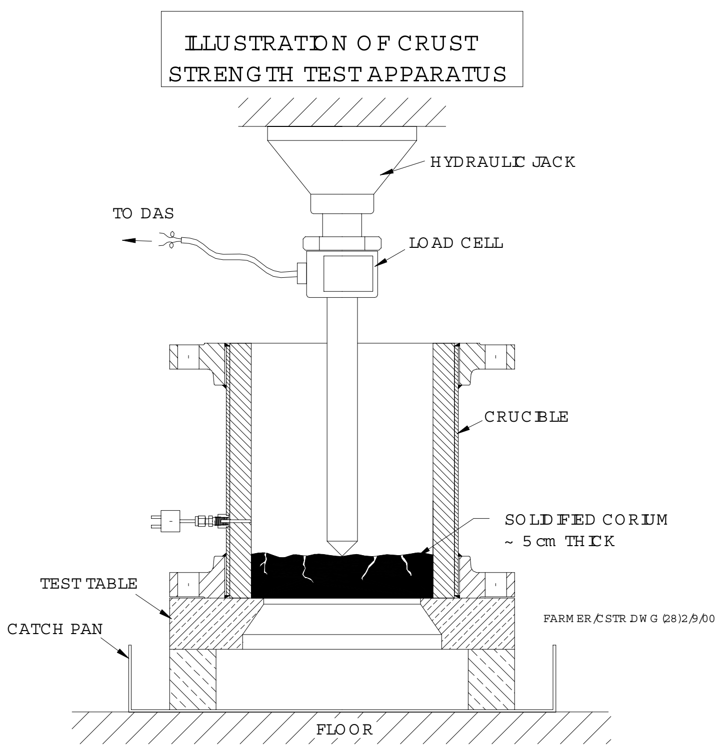


Figure 5. Test Stand for Macroscopic Crust Strength Measurements.

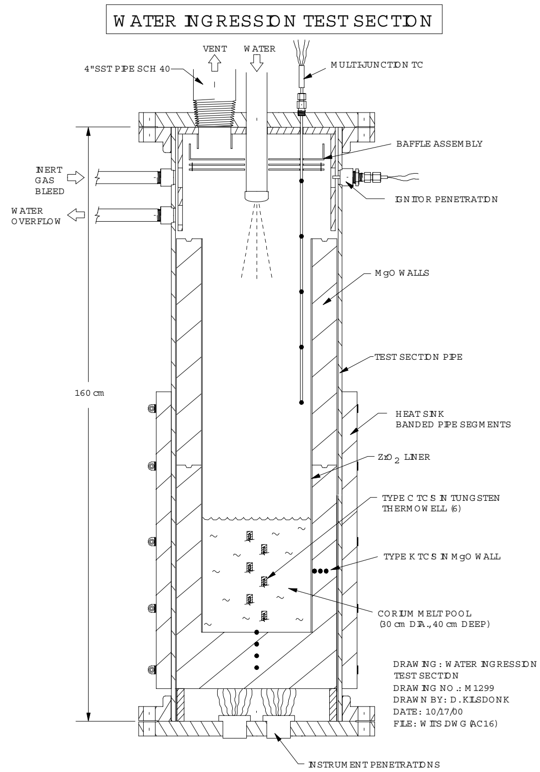


Figure 6. Proposed Apparatus for Intermediate Scale Water Ingression Tests.

Long-Term 2-D MCCI Under Dry Conditions

The 2-D MCCI test will utilize existing MACE technology for conducting long term MCCI experiments with sustained internal heating. An illustration of the facility is shown in Fig. 7. The test section incorporates concrete sidewalls as well as basemat. This approach allows for 2-D MCCI, as was done in the MACE Scoping Test (Farmer et al., 2000). Melt generation for this test is also achieved using an exothermic chemical reaction over a timescale of ~ 1 minute. This technique ensures well-defined initial and boundary conditions at the start of the experiments, which is essential for code validation purposes. As shown in Fig. 7, both the basemat and sidewalls of the test section are heavily instrumented with thermocouples to determine the melt temperature and 2-D ablation profile as a function of time. For this test, the DEH input power is adjusted to reflect the decay heat curve associated with a predetermined reactor configuration. Three tests are proposed for this facility. The concrete composition and initial melt composition are parameters addressed in the test matrix. These experiments will operate over the course of a day (or possibly longer) to provide definitive long term 2-D reactor material MCCI data for code benchmarking and validation, since there is currently a lack of such information (Foit, 1999). At the end of the planned ablation sequence, the cavity will be flooded for each test to provide data on corium quench behavior following long term MCCI.

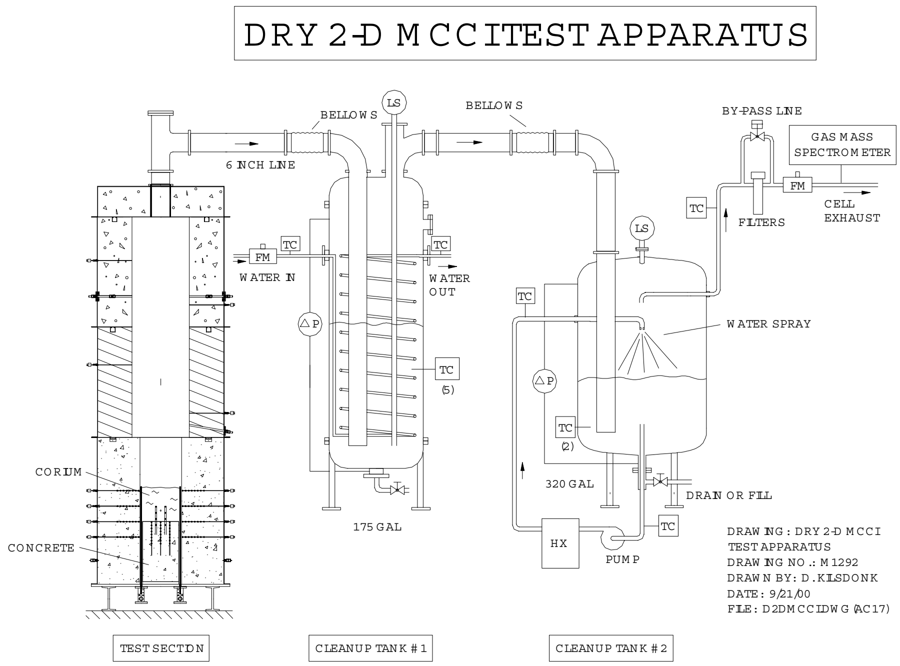


Figure 7. Apparatus for Proposed Long-Term 2-D MCCI Tests.

5.0 PROGRAM SCHEDULE

The program is targeted to begin the second half of 2001. The schedule for carrying out the nature and scope of testing described in this paper is approximately four years.

6.0 SUMMARY AND CONCLUSIONS

This paper has summarized plans which are currently under development for continued utilization of the MACE facility under the sponsorship of the Nuclear Energy Agency (NEA) to achieve the following objectives: i) resolution of the ex-vessel debris coolability issue through a redirected program which focuses on providing both confirmatory evidence and test data for the coolability mechanisms identified in MACE integral effects tests; and ii) address remaining uncertainties related to long-term two-dimensional MCCI under dry cavity conditions. In terms of the ex-vessel debris coolability issue, separate effects tests are planned to provide data on key melt coolability mechanisms identified in MACE integral effects tests. The results of these tests will provide both confirmatory evidence and test data to support development of validated models for extrapolation to plant conditions. In terms of dry cavity conditions, reactor material tests are planned to address remaining uncertainties related to long-term 2-D MCCI; in particular, lateral vs. axial power split. Achievement of the two program objectives will lead to improved severe accident management guidelines for existing plants, and also better containment designs for future plants.

7.0 REFERENCES

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Table 1. Planned Experiments to Address LWR Safety Issues in the MACE Facility.

Stage	Issue	Experiment Type	Experiment Approach	Benefits of Proposed Research
1	Debris Coolability	Melt Entrainment & Eruptions	Conduct dedicated reactor material separate effects tests with an inert basemat and remotely controlled gas sparging. For a given test, vary the melt sparging rate and measure the corresponding melt entrainment rate. Parameterize on melt composition and temperature, since these variables influence the entrainment rate.	• The results will provide direct measurements of the melt entrainment coefficient under well controlled experiment conditions; this is the most important parameter in determining the melt entrainment rate. • The entrainment rate data can be used directly in existing models for evaluating the effect of ejections on mitigation of ex-vessel accident sequences.
		Water Ingression & Crust Strength	Perform dedicated reactor material water ingression experiments with no gas sparging; parameterize on melt composition since this is the most important variable influencing corium cracking; also examine the effect of concrete decomposition on the water ingression rate; address both in-vessel and ex-vessel melt compositions. Perform posttest crust strength measurements to determine the macroscopic failure stress of the crust after quench by water.	• The experiments will provide data on the ability of water to ingress through cracks and/or fissures in corium to augment the otherwise conduction-limited heat transfer; the crust strength measurements will provide data to validate the concept of sustained melt/crust contact anticipated at plant scale. • The results of the research will be applicable to both in-vessel and ex-vessel accident sequences; information obtained with in-vessel compositions will compliment the MASCA program. • For ex-vessel compositions, the dryout heat flux data can be used directly in existing models for evaluating the effect of water ingression on mitigation of ex-vessel accident sequences[4]
2	Long Term 2-D MCCI	2-D MCCI	Utilize MACE technology to conduct long-term 2-D MCCI tests, since plant calculations still require extrapolation well beyond the existing database; in particular, the treatment of long term radial and axial ablation by a prototypic core oxide melt[1].	• Reduction in the uncertainty in evaluating the long-term lateral/axial power split during MCCI by providing prototypic experiment data. • Resolve differences between CORCON and WESCHL in the prediction of 2-D MCCI cavity erosion behavior.[1]

Table 2. Summary of Coolability Mechanisms Observed in MACE Integral Effects Tests.

Mechanism	Description	Experimental Evidence
Bulk Cooling	The melt sparging rate is initially high enough to preclude stable crust formation at the melt/water interface. As a result, high heat transfer rates occur due to conduction and, predominately, radiation across the agitated (i.e., area enhanced) interface. This cooling phase is terminated when a stable interfacial crust forms.	High heat transfer rates measured during initial interaction; video of melt surface illustrate the intensity of the interaction; physically based models have been developed and validated against the test data.
Melt Eruptions	Melt dispersal occurs by the mechanism of melt entrainment by the concrete decomposition gases, which carries melt through defects in the crust into the overlying coolant. The dispersed material is rendered coolable in the form of porous particle beds and high surface area volcanic formations.	Eruptions have been observed in all MACE tests conducted with limestone-common sand concrete basemats after incipient crust formation. The particle beds are characterized by high porosity and large particle size.
Water Ingression	During crust formation, corium shrinkage from an initially molten to a fully quenched state amounts to ~ 18 vol%. This causes voids/defects to appear in the frozen material. Water percolates down through the interstitial voids/defects, augmenting the otherwise conduction-limited heat transfer process.	Melt/water heat flux far exceeds that which could by transferred by conduction across the (up to 10 cm) thick crusts formed during the tests. Posttest measurements indicate that crusts are permeable to both gas and water flows.
Crust Breach	Due to water ingression, thick crusts will form which may bond to the reactor cavity sidewalls. These crusts will not be stable in the typical ~ 6 m span of most plants. As a result, they will periodically fail, leading to renewed debris cooling by the above three mechanisms.	Partial crust failure and relocation events observed in tests M3b and M4. Various structural/mechanical analyses have shown that crusts will not be stable at reactor scale.