Significance of the OECD-MCCI Program
in Relation to Severe Accident Uncertainties Evaluation

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Abstract

Over the past two decades, a substantial amount of research has been conducted — in the United States during the early days and later in other countries as well — to improve the understanding of severe accident phenomena for more realistic assessment of the associated risk and to address epistemic uncertainties. This research has resulted in resolution of issues from a risk perspective (e.g., containment failure attributable to an energetic fuel-coolant interaction or the so-called alpha-mode failure, direct containment heating from high-pressure melt ejection, etc.), implementation of severe accident management strategies (e.g., flooding drywell in a Mark-I containment to prevent liner failure), and improved assessment of the source term and uncertainties associated with hydrogen production (both in- and ex-vessel). An unresolved issue that has received increased attention in recent years relates to melt coolability (in particular, ex-vessel coolability) and consequent containment integrity and fission product release into the environment. The Organization for Economic Cooperation and Development Melt Coolability and Concrete Interaction (OECD-MCCI) program is experimentally investigating the effectiveness of cooling ex-vessel core debris using an overlying water pool. This paper discusses the significance of the OECD-MCCI program in relation to severe accident uncertainties. Specifically, this paper discusses the important findings of the experimental program with regard to an assessment of epistemic uncertainties in coolability and core-concrete interaction (CCI) models that are used to extrapolate the results to plant conditions.

1. Introduction

In a postulated core melt accident, if the molten core is not retained in-vessel despite taking severe accident mitigation actions, the core debris will relocate in the reactor cavity region. There, it will interact with structural concrete and could potentially result in basemat failure (through erosion or overpressurization) and consequent fission product release to the environment. Although this is a late release event, the potential radiological consequences (in terms of land and groundwater contamination, as well as latent cancer risk), could be substantial and warrant effective strategies to prevent or mitigate such a release. As one of several strategies, the severe accident management guidance for many operating light-water reactor plants includes flooding the reactor cavity in the event of an ex-vessel core melt release. The effectiveness of cavity flooding to cool ex-vessel core debris and mitigate CCI depends, among other factors, on the mode and timing of water addition, as well as the heat transfer characteristics of the melt-water interface.

Cooling of ex-vessel core debris using an overlying water pool was previously investigated in the Melt Attack and Coolability Experiments (MACE) program[1] at Argonne National Laboratory (ANL), under the sponsorship of the Electric Power Research Institute. Large-scale integral experiments (with a test section lateral span up to 1.20 m) were conducted with melt masses of reactor prototypic materials ranging up to 2 metric tons. These experiments suggested various heat transfer mechanisms that could provide long-term debris cooling. However, the integral results did not definitively demonstrate that the core debris would be completely quenched, because the crust anchored to the test section sidewalls in every test, thereby leading to melt/crust separation and loss of efficient heat transfer from the melt to an overlying water pool.

More recently, ANL launched the OECD-MCCI program (under the auspices of OECD) to address two specific issues. The first issue relates to several debris cooling mechanisms identified in the MACE program (specifically, the relative roles of these mechanisms to achieve overall coolability), while the second issue relates to long-term, two-dimensional concrete ablation by ex-vessel core debris under both dry and flooded cavity conditions. The program addressed the first issue through a series of eight separate effect tests designed to investigate cooling by water ingression, melt eruption, and crust breach mechanisms. By contrast, the program addressed the second issue through a series of three large-scale CCI tests, which were specifically designed to provide data on (1) the lateral vs. axial power split during dry CCI, (2) integral debris coolability following late phase flooding, and (3) the nature and extent of the cooling transient following a breach of the crust formed at the melt-water interface.

This paper discusses the program's important findings and their significance to severe accident uncertainties involving CCI and debris coolability. Specifically, the phenomenological uncertainties addressed in this program relate to heat transfer at the melt-water interface (which influences debris cooling) and at the melt-concrete interface (which influences concrete ablation). Note that phenomenological uncertainties also exist in other areas (notably, lower head failure size, location, and timing, which influence the ex-vessel debris characteristics); however, these uncertainties were addressed in the recently completed OECD Lower Head Failure (OLHF) program[2], the earlier NRC Lower Head Failure program[3], and the Swedish FOREVER program[4]. The data generated in the OECD-MCCI program are useful in reducing relevant uncertainties and developing models for severe accident codes.

2. Debris Coolability Experiments

The OECD-MCCI program addressed the ex-vessel debris coolability issue through a series of separate effects experiments, which provided both confirmatory evidence and test data on water ingression, melt eruption, and crust breach cooling mechanisms. In particular, a series of seven Small-Scale Water Ingression and Crust Strength (SSWICS) tests[5,6] provided data to answer the following questions:

(1) To what extent does water ingress into cracks/fissures in the solidifying core material to augment what would otherwise be an inefficient, conduction-limited cooling process?

(2) What is the mechanical strength of the crust, and would it be mechanically stable if attached to the reactor cavity walls during the quench process and suspended along the span of the cavity?

Table 1 summarizes the key parameters for the seven SSWICS tests. The water ingression phenomenon was studied by measuring the cooling rate of a melt pool in an inert crucible (~30 cm ID) with no internal heating. Under these conditions, the water ingression rate can be determined by comparing the actual debris cooling rate with well-known analytical solutions for the conduction-limited cooling of solids. A plateau in the cooling rate is expected to occur above the conduction-limited solution (the so-called "dryout heat flux") when equilibrium is achieved in the percolation of water down to the quench front and the return flow of steam through the network of cracks within the crust.

Table 1. Key parameters for SSWICS tests

Parameter	**SSWICS-1**	**SSWICS-2**	**SSWICS-3**	**SSWICS-4**	**SSWICS-5**	**SSWICS-6**	**SSWICS-7**
Melt composition (UO_2/ZrO_2/Cr/conc)	61/25/6/8	61/25/6/8	61/25/6/8	48/20/9/23	56/23/7/14	56/23/7/14	64/26/6/4
Concrete type	LCS[a]	SIL[b]	LCS	LCS	LCS	SIL	LCS
Melt mass (kg)	75	75	75	60	68	68	80
Init. melt T (°K)	~2300	~2100	~2100	~2100	~2100	~1950	~2100
Syst. press. (MPa)	0.1	0.1	0.4	0.4	0.4	0.1	0.4
Water inject. (lpm)	4.0	4.0	12.0	13.0	6.0	14.0	13.0

a. limestone common sand concrete; b. siliceous concrete

Figure 1 presents the heat flux data from all seven tests, and depicts the conduction-limited curve for comparison with the test data. Fluctuations in the data during the first ~1,000 seconds are attributable to structure heat sink and inlet water subcooling effects. After this time, the data are indicative of the heat fluxes from the debris/water interface. Figure 1 also shows that the cooling rate in all tests exceeds the conduction limit, indicating that water ingression provides additional cooling of debris. Further, the cooling rate decreases as concrete in the melt increases (due to concrete ablation); however, for a given amount of concrete, the cooling rates are similar for limestone common sand and siliceous concrete.

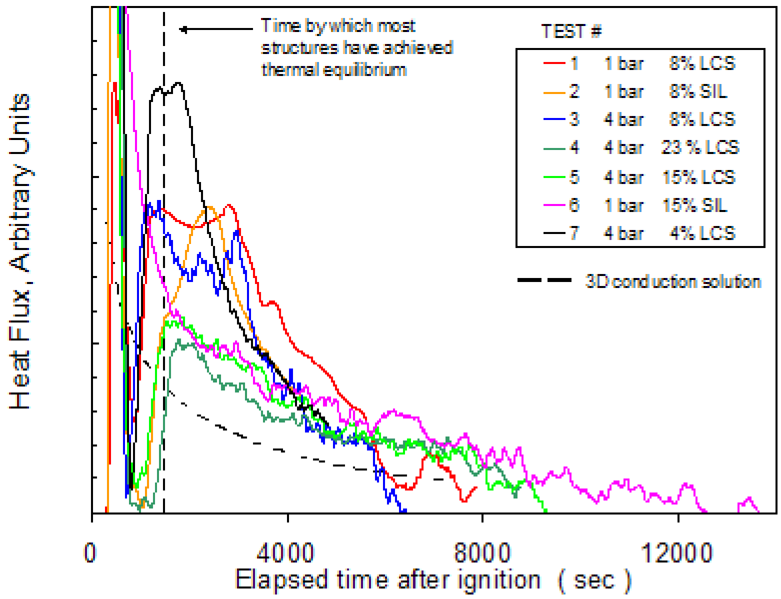

Figure 1. Melt-water interface heat flux data from the SSWICS tests

Dryout heat flux data obtained from these experiments can be used to develop models for use in evaluating the effect of water ingression on debris coolability and CCI.[7] Currently, the severe accident codes primarily include parametric treatment of heat flux partitioning at the melt-water interface for assessing coolability by an overlying water pool. As a result, there is considerable uncertainty in the amount of heat transferred from the melt to the concrete basemat and the consequent ablation of concrete. Likewise, there is considerable uncertainty in the amount of heat transferred from the melt to an overlying water pool. The data generated in the OECD-MCCI program can be used to reduce uncertainties in these areas.

The Melt Eruption Tests (MET) were designed to provide data on the melt entrainment coefficient under well-controlled experimental conditions. These experiments featured an inert basemat with remotely controlled gas sparging rate, because this is the most important parameter in determining the entrainment rate. Entrainment rate data obtained from these tests can be used directly in existing models[8] for evaluating the effect of melt ejection on mitigation of ex-vessel accident sequences. One melt eruption test involving siliceous concrete was conducted under the OECD-MCCI program. However, this test had to be terminated prematurely because the test section failed to contain the melt. As such, melt eruption data for siliceous concrete are not available from the program. Nonetheless, it is interesting to note that in the previously mentioned MACE experiments[1] and CCI tests (discussed later in this paper), melt eruptions were not observed in experiments involving siliceous concrete. In contrast, melt eruptions were consistently observed in experiments involving limestone common sand concrete. Thus, these latter tests provide an adequate database for melt eruption modeling for the case of limestone common sand concrete. The data and associated model(s) can be used to determine whether the melt entrainment rate is in the range that can contribute to long-term debris cooling under plant conditions.

Debris cooling can be substantially enhanced by a large-scale breach of crust that is formed at the melt-water interface. It is stipulated that an anchored crust (i.e., a crust formed at the melt-water interface that is attached to the sidewall and otherwise suspended along the span) is likely to fail at the plant scale because of its low structural strength. Once the crust fails, it will provide pathways for significant water ingression through macroscopic breaches and, as a result, will provide additional cooling. To verify this hypothesis, the crust structural strength was measured as part of the post-test analysis of the SSWICS debris. The measurements indicate that core debris that has been quenched by water has very low strength. The presence of extensive cracks in the crust (see Figure 2 as an example) contributes, in large part, to such low strength. Such a crust is expected to fail under the applied load (namely, the combined weight of the crust, overlying particle bed, and water pool) at the plant scale, and provide an opportunity for sustained melt/crust contact and consequently, sustained cooling. As discussed in the next section, the CCI tests investigated enhanced cooling by large-scale crust breach and consequent large-scale water ingression.

Figure 2. Extensive crack structure in the midplane sample of the SSWICS-3 crust

3. Core-Concrete Interaction Experiments

The existing database for CCI under dry cavity conditions is primarily one-dimensional[9-10]. Although the MACE scoping test[11] was carried out with a two-dimensional concrete cavity, the test section was flooded shortly after the initiation of interaction in order to investigate debris coolability. Moreover, given the nature of this test, the apparatus was minimally instrumented and, therefore, did not produce the required data for model development and code validation. The BETA[12] test series provided valuable data on two-dimensional CCI under dry cavity conditions, but these tests focused on the interaction of the metallic (steel) phase with concrete. Aside from the MACE and BETA programs, the COTELS[13] test series investigated two-dimensional CCI under flooded cavity conditions; however, the input power density in the COTELS tests was quite high relative to the prototypic case and, thus, the limited database points to significant remaining uncertainty in the partition of energy dissipated for the ablation of concrete in the lateral and axial directions under dry cavity conditions[14]. Owing to this uncertainty, there are still substantial differences in the predicted two-dimensional cavity erosion profiles as computed by various severe accident codes. Improved knowledge of the power split or heat flux partitioning is important in reducing these differences and in evaluating the consequences of an ex-vessel severe accident. (Note that excessive radial erosion can undermine containment integrity, while excessive axial erosion can fail the basemat, leading to ground contamination and release of radiological source terms in the environment.)

The two-dimensional CCI experiments conducted under the OECD-MCCI program attempted to bridge the database gap identified above. Table 2 shows the key parameters for these tests, and References 15

Table 2. Key parameters for CCI tests

Parameter	Specification
Corium	100% oxidized PWR with 8 wt % concrete
Concrete type	CCI-1: siliceous; CCI-2: limestone common sand; CCI-3: European hybrid of siliceous and limestone
Initial basemat dimension	50 cm x 50 cm
Initial melt mass (depth)	400 kg (25 cm)
Test section sidewall construction	Nonelectrode walls: concrete Electrode walls: MgO with UO_2 pellet layer
Radial ablation limit	35 cm
Axial ablation limit	35 cm
System operating pressure	Atmospheric
Melt formation technique	Chemical reaction (~30 s)
Initial target melt temperature	2100 °C
Melt heating technique	Direct electrical
Power supply operation prior to water addition	CCI-1: constant power at 150 kW CCI-2: constant power at 120 kW CCI-3: constant power at 120 kW
Criteria for water addition	(1) 5.5 hours of operation with DEH input, or (2) radial or axial ablation reaches 30 cm
Inlet water temperature	20 °C
Inlet water flow rate	2 l/s
Water level over melt	50 5 cm
Power supply operation after water addition	Constant voltage
Test termination criteria	(1) Melt T < concrete solidus, (2) basemat ablation arrested, or (3) max. radial/axial ablation of 35 cm.

and 16 previously reported provide detailed descriptions of the CCI tests conducted to date, as well as the results of the CCI-1 and the CCI-2 tests. These tests investigated the two-dimensional interaction of a nominally 400-kg mass of pressurized-water reactor (PWR) core melt with concrete in a rectangular test section with two opposing sides and the basemat made of concrete (siliceous, limestone common sand, or other) and two other opposing sides made of non-ablative material (MgO). The initial phase of the tests was conducted under dry conditions; however, after a predefined ablation depth was achieved, the cavity was flooded to obtain data on coolability of core debris by an overlying water pool after CCI has progressed for some time. This flooding initially resulted in an increase in upward heat flux, indicating efficient cooling. Shortly afterward, however, a crust formed at the melt-water interface. The test operating procedure called for insertion of a lance probe to breach the crust at this time to obtain data on the nature and extent of debris cooling that occurs following a transient crust breach. This cooling mechanism is likely to be effective at plant scale, given the mechanical instability of crusts that would form at the melt-water interface.

The CCI tests yielded valuable information on the two-dimensional behavior of CCI. Of particular interest is melt-water heat flux data and concrete ablation data, as shown in Figures 3 and 4, respectively, for the CCI-2 test.

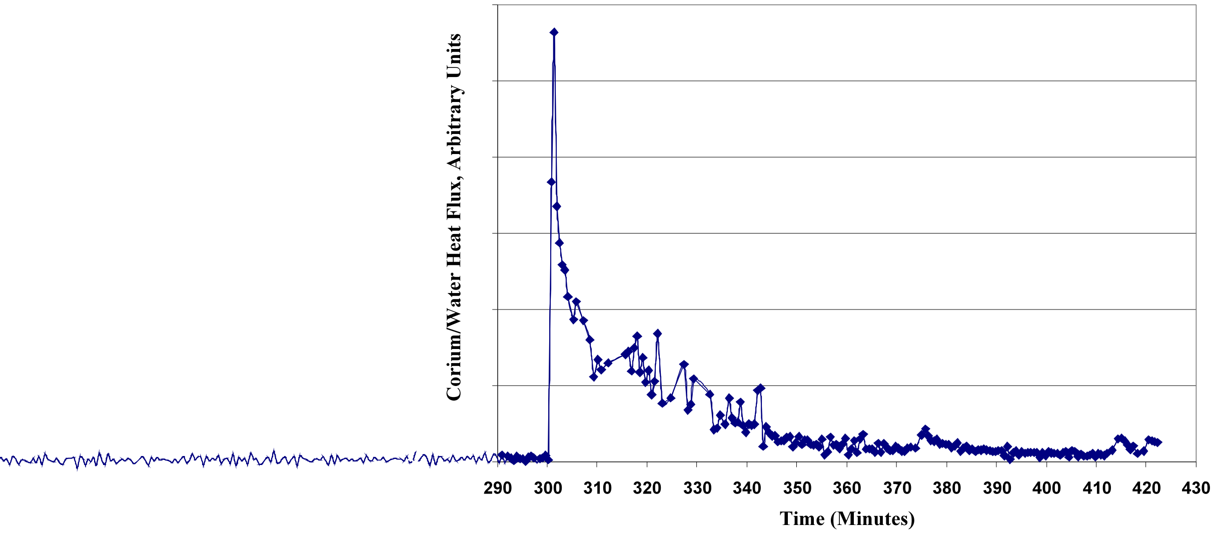

Figure 3. Melt-water heat flux data from the CCI-2 test

4. Significance of Data to Uncertainties Evaluation

The OECD-sponsored MCCI program has yielded valuable data that have direct bearing on reducing uncertainties related to CCI and ex-vessel coolability. Specifically, with regard to coolability, the program has provided confirmatory evidence and test data for different coolability mechanisms originally identified during the MACE program. This database is useful for developing and validating coolability models for incorporation into severe accident codes ,so that the codes can be used more reliably for plant accident analyses. In general, the modeling approach focuses on developing standalone models and correlations for individual cooling mechanisms, and then deploying those models and correlations within integral system-level codes that can simulate the interrelated phenomenological effects to predict the course of accident progression under plant conditions. Toward this end, the SSWICS database was first compared with a number of conduction-limited coolability models to qualitatively assess the enhancement of cooling by water ingression. The comparison was also to intended identify deficiencies in the existing coolability

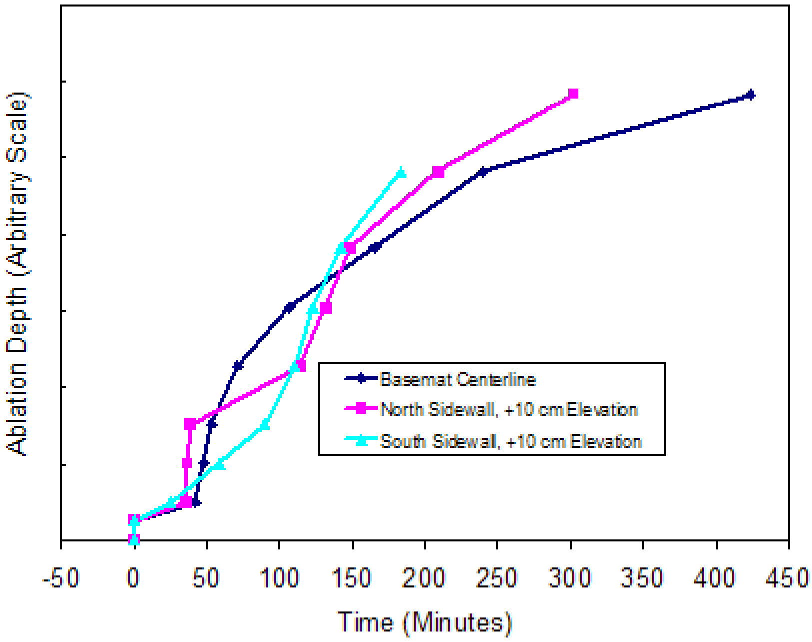

Figure 4. Concrete ablation rate at selection locations in the CCI-2 test

models, so that improved models can be developed to quantify the effect of water ingression. Figure 5 illustrates the comparison.

Analysis of the SSWICS test data indicates that water ingression contributed to enhanced coolability, significantly in some tests and moderately in others. The occurrence of water ingression is evidenced by a plateau in the debris cooling rate at a heat flux corresponding to the crust dryout limit. The data also indicate that the water ingression rate decreases with overall concrete content in the melt; however, for a given concrete content in the melt, the water ingression rate is insensitive to concrete type. Finally, the data indicate that the water ingression rate is not significantly influenced by system pressure. Thus, from the viewpoint of accident management, this collection of information indicates that the reactor cavity should be flooded as soon as possible after vessel breach to optimize the extent of debris cooling achieved by the water ingression cooling mechanism.

The three conduction-limited cooling models in the above figure are based on a simple approach in which convective heat transfer in the pool is either not accounted for or assumed to be negligible compared to the heat conduction across the crust. The fourth model, which is in MELCOR 1.8.5,[17] has a relatively simple quasi-steady-state model for the growth of an impervious crust. That model calculates crust thickness at the melt/water interface on the basis of the interface temperature between the melt pool and the overlying water pool falling below the melt freezing temperature. The model appears to overpredict the dryout heat flux, as shown in the above figure. As a result, considerable uncertainties remain in the heat flux partitioning and consequent debris cooling behavior.

The basic premise underlying the water ingression phenomenon is that after the incipient crust formation occurs at the melt/water interface, crust growth will continue with the potential for water to ingress into the solidifying core material depending upon the time-dependent thermal-hydraulic conditions at the crust/water interface. Water will not be able to penetrate into the crust when the heat flux from the upper surface of the crust exceeds the dryout limit. However, when the heat flux falls below that limit, water will begin to penetrate down into the crust, thereby augmenting the otherwise conduction-limited cooling rate.

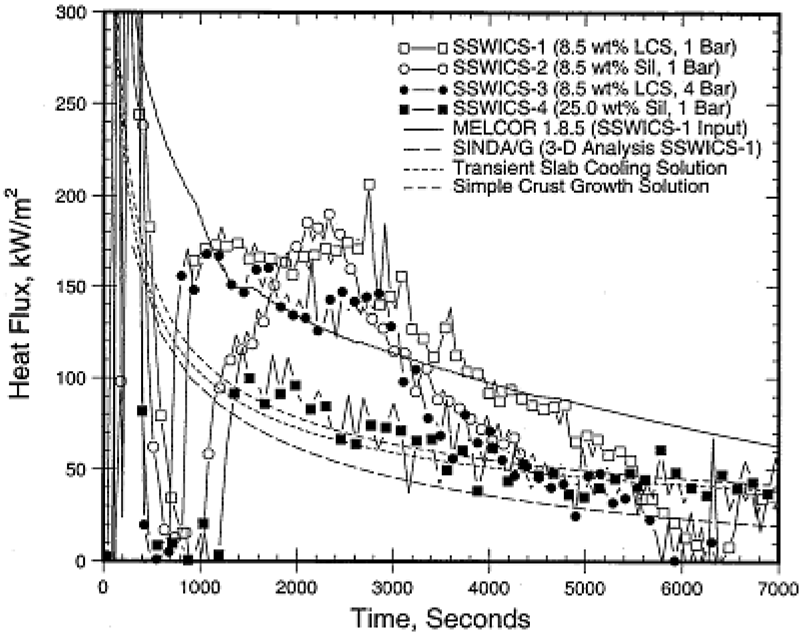

Figure 5. Comparison of conduction-limited coolability models with the SSWICS database

During long-term augmentation of the debris cooling rate by water ingression, crust growth will proceed until ongoing concrete erosion reduces the dryout limit of the material in the melt zone below a critical value that can support additional crust growth. Thereafter, the crust will act as an interstitial heat transfer medium, with the upper portion of the material quenched and stabilized. A thin thermal boundary layer at the crust/melt interface will control the heat transfer from the melt zone to the overlying water pool. The particular form of the boundary condition at the upper surface of the crust depends upon whether an overlying particle bed develops as a result of melt eruptions.

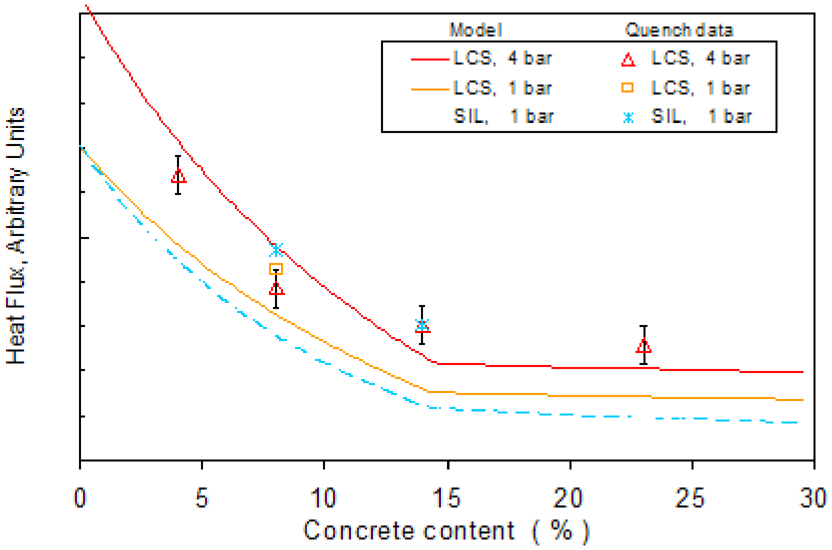

Figure 6. Dryout heat flux correlations compared with the SSWICS database

Following the modeling approach of Lister[18] and Epstein,[19] a simplified dryout heat flux correlation was developed based on the SSWICS test data. The correlation, plotted in Figure 6, is an example of how the SSWICS data can be effectively used to reduce uncertainties in modeling ex-vessel coolability.

The CCI tests addressed uncertainties related to long-term two-dimensional molten core-concrete interactions under both wet and dry cavity conditions. Specifically, the CCI tests provided information in several areas, including (1) lateral vs. axial power split during dry CCI, (2) extent of the cooling transient following a breach of the crust formed at the melt-water interface, and (3) debris coolability limit following late-phase flooding. The data indicate that radial ablation is an important element of the overall cavity erosion process, and provide information to model two-dimensional concrete ablation behavior more precisely in the severe accident codes. Spindler[20] noted considerable differences in concrete ablation behavior predicted by various severe accident codes (see Figure 7 below). Note that an improved knowledge of CCI phenomena reduces uncertainties in the assessment of containment integrity and consequent fission product release into the environment. Lacking this knowledge, a statistical or probabilistic approach is often employed to address uncertainties.[21,22]

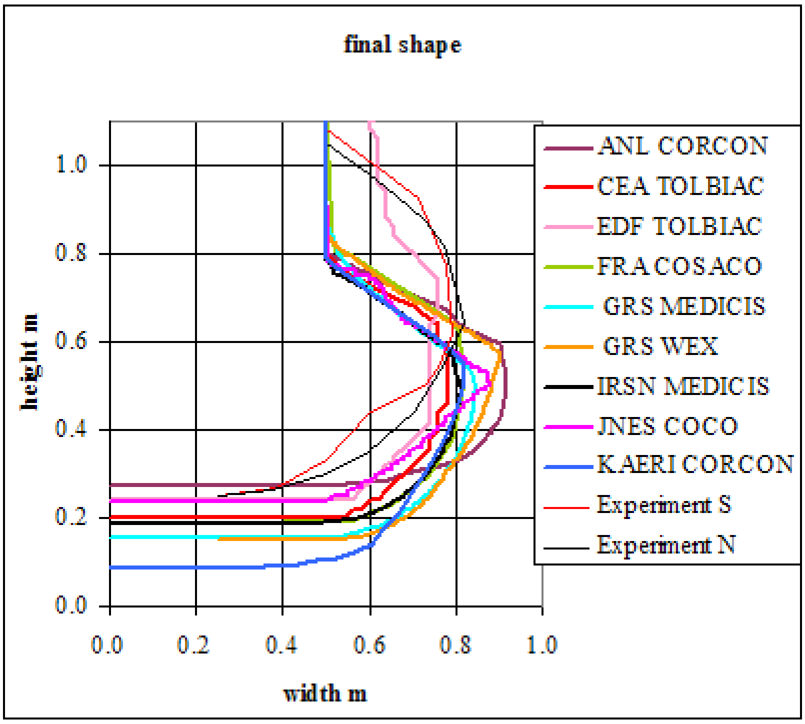

Figure 7. Comparison of two-dimensional concrete ablation between codes and experiments

5. Concluding Remarks

This paper provides a brief account of the OECD-MCCI program and its significance for reducing uncertainties in severe accident phenomena involving ex-vessel debris coolability and CCI. In general, the test results indicate that the various debris cooling mechanisms will indeed contribute to achieving long-term debris coolability during ex-vessel severe accidents. Analysis of the SSWICS test data indicates that early flooding of the cavity enhances debris coolability through water ingression mechanism, although the effectiveness decreases with an increase of concrete content in the melt. From the viewpoint of accident management, this information suggests that the reactor cavity should be flooded as soon as possible after a vessel breach to optimize the extent of debris cooling achieved by water ingression. The

CCI test data indicate that late flooding likewise enhances debris coolability through melt eruption and large-scale crust breach mechanisms. Overall, however, the results also indicate that these mechanisms may not be sufficiently robust to fully quench and stabilize the full range of melt depths calculated for all accident sequences. Thus, additional work would be beneficial to investigate engineering features that can ensure that the full range of melt depths can be quenched and thermally stabilized under all accident conditions.

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