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The Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD) has, since 2002, sponsored Melt Coolability and Concrete Interactions (MCCI) co-operative project in two phases to investigate ex-vessel melt coolability and concrete interaction by means of separate-effects tests and large scale integral tests carried out at the Argonne National Laboratory (ANL). Key elements of this project included the conduct of experiments involving real reactor material and associated analyses with the objectives of resolving the ex-vessel debris[1] coolability issue and addressing remaining uncertainties related to long-term two-dimensional molten core-concrete interactions under both wet and dry cavity conditions. It was expected that the achievement of these two objectives would demonstrate the efficacy of severe accident management guidelines for existing plants and provide the technical basis for better containment designs for future plants.

Six months after the second phase of the experimental program was completed, the CSNI held a seminar in November 2010 where the major outcomes of the MCCI Project and other complementary experimental activities were presented and discussed. One of the recommendations from the seminar was, *"The preparation of a state-of-the-art report on melt coolability and core concrete interactions that captures the last thirty years of international research results"*. A working group was established in April 2012 within the frame of the Working Group on Accident Management and Analysis (WGAMA) to address this recommendation.

The state-of-the-art report (SOAR) provides a background discussion of safety issues relevant to core-concrete interactions and melt coolability and related containment failure modes, an overview of various experiment programs that have been carried in the areas of MCCI and debris coolability, a description and assessment of various analytical tools ("codes") that have been developed to analyze MCCI behavior and finally, a summary of plant analysis activities that have been carried out using these codes. These various activities, carried out over the last three decades, have significantly increased our level of understanding regarding MCCI behavior under both wet and dry cavity conditions. Depending upon containment design, regulatory requirements, and accident management considerations that are unique to each country and reactor type, the current level of understanding in this area is sufficient for conservative reactor safety assessments. However, a few areas have been identified (particularly based on lessons learned from Fukushima Daiichi) that may warrant further investigation to reduce residual uncertainties.

[1] The term "debris" refers to the corium melt in general and not only to the solid particles

While existing data and experiments indicate that debris coolabilty can be achieved within an envelope that is principally based on concrete type, melt depth, and timing of cavity flooding, this envelope does not encompass the full range of accident conditions that can be encountered in certain plant configurations. Neither does the envelope encompass various abstractions of melt progression in-vessel which give rise to different initial and boundary conditions for ex-vessel melt progression and also, wide variations in concrete constituents within the two major types investigated in the experimental program and consequent effects of such variations. Also, the report focuses on the progress made in the last two decades on the thermal-hydraulic aspects of MCCI and mentions in passing some early research programs dealing with fission products aspects of MCCI. Finally, the report discusses general aspects of severe accident management strategies aimed at achieving melt stabilization in both Gen II and Gen III reactors.

## LESSONS LEARNED FROM EXPERIMENTS

The general goals of the MCCI experiments under both dry cavity (i.e., without mitigation measures involving water addition) and wet cavity (i.e., with mitigation measures involving water addition) have been to: i) identify and characterize important phenomenological processes in order to facilitate model development, and ii) provide experimental data to support validation of models and codes that are used in reactor safety assessments. For dry cavity conditions, the research focused on evaluating the nature and extent of core-concrete interaction, basemat and sidewall erosion, and concurrent fission product release. For wet cavity conditions, the research focused on evaluating the effectiveness of water in terminating the MCCI by quenching the molten core material and rendering it permanently coolable, i.e. to achieve the melt stabilization condition.

The various accident sequences and the possibility of operator intervention result in a broad range of possible initial conditions at time of vessel failure. Following the accident at Three Mile Island and some studies of melt interactions with concrete, it was presumed that core degradation would be very heterogeneous with central regions of the core melting while peripheral regions were barely degraded. Additional core materials would cascade for protracted periods from the reactor vessel as core debris attacked concrete. A certain fraction of the cladding would not be oxidized at the time of core debris relocation to the lower head of the pressure vessel and upon vessel breach, there would be a chemical component to the heat generation in the core debris. Additionally, the state of knowledge about late in-vessel melt progression is incomplete (particularly for BWRs). Thus, there is considerable uncertainty regarding the MCCI initial conditions that includes the timing of RPV failure; the initial temperature, mass, and composition of the core debris; the possibility of segregation of metal and oxide melt phases; the pour rate of the melt from the RPV that is determined principally by the melting rate of residual core material, and to a lesser extent by the opening in the RPV lower head; and finally, the timing of water injection (if any).

Many of these parameters (e.g. power level in the ex-vessel core debris, which is indicative of the time of vessel failure, as well as melt mass and composition) have been addressed in various experimental programs that are described in the second chapter. It is important to recognize that as the understanding of core degradation evolved since the Three Mile Island accident and now continues to evolve since the Fukushima accident, modeling of in-vessel melt progression likewise will continue to evolve. As such, no attempt has been made in this report to encompass the full range of possible initial and boundary conditions (some of which are known at present) and to conclude that the current understanding of the MCCI phenomena is complete.

The various test series described in Chapter 2 investigated the effects of melt composition, concrete type, input power to melt, and in experiments with cavity flooding (wet cavity experiments), the timing of water addition on two-dimensional core-concrete interaction and melt coolability. Principal variables measured during the experiments included melt temperature and local concrete ablation rates. For flooded cavity experiments, the debris/water heat flux after cavity flooding was also estimated based on the rate of steam production from the interaction. Key observations from these tests are summarized below.

Under dry cavity conditions, all tests exhibit the overall trend of decreasing melt temperature as concrete ablation progresses and increasing heat transfer surface area as the melt expands into the concrete. This trend depends also on the decrease of the interface temperature between the melt and the upper crust as the melt becomes enriched with low melting concrete decomposition products. The results from several reactor material experiments indicate that the concrete ablation process for oxidic core melts is influenced by concrete types. For limestone-common sand concrete, the radial to axial erosion rate and ablation depth are approximately one to one whereas for siliceous concrete, it is approximately three to one. To investigate whether the relatively small melt pool aspect ratio (i.e., test section width/melt depth) used in the experiments has an influence on the radial/axial power split observed in the dry cavity experiments, a dedicated large scale experiment was carried out. The results indicate that an increase in aspect ratio from approximately 1 (typical of most reactor material tests) to about 3.2 has no noticeable effect on the ablation characteristics for siliceous concrete. This observation lends additional credibility to the measured erosion rates and ablation depths in various experiments. It is noted that the forensic examinations of Chernobyl Unit 4 are consistent with the experiment observations for siliceous concrete thus giving credibility to long term extrapolation of experimental data even if the ablation assymmetry is not yet understood from a mechanistic point of view.

Post-test examinations have shown that the nature of the core-concrete interface is noticeably different for limestone tests in comparison to siliceous tests. The differences in interface characteristics may influence the heat transfer at the interface, yielding different concrete ablation behavior for different concrete types. The overall trend in the ablation front progression that has been observed under experiment as well as Chernobyl Unit 4 examinations cannot, however, be explained fully on the basis of our current understanding of the ablation behavior and modelling of such behavior. Thus, extrapolation of the results to plant conditions remains somewhat uncertain due to the lack of a more robust phenomenological model that can rationalize the differences in the observed cavity erosion behavior of the two concrete types used in the experiments. It is worth mentioning that while variations of the two major concrete types (e.g., representative concrete type in French plants with variations of siliceous aggregates and "serpentine" concrete used in one of the ACE experiments) were used in some experiments, the database of such variations is somewhat limited.

Several experiments have provided evidence that initial corium crust formation on cold concrete surfaces can influence the early (tens of minutes to an hour) core-concrete interaction behavior. During this phase, basemat ablation is minimal and melt temperature remains high due to the insulating effect of the crusts. This effect has been observed in both transient as well as sustained heating reactor material tests. However, once crusts at concrete interface fail, concrete ablation proceeds vigorously and the melt temperature declines due to the above mentioned affects. Although the data are not conclusive, there is evidence that gas evolution from concrete decomposition can act to destabilize these interfacial crusts.

The effect of unoxidized Zr cladding on the thermal-hydraulics of the core-concrete interaction was investigated in several experiment programs. The oxidation reaction between Zr and sparging concrete decomposition gases ($CO_2$, $H_2O$) caused exothermic transients during which the melt temperatures increased over a period of tens of minutes in the experiments. This transient behavior was observed in both reactor material as well as simulant experimental tests. The data further indicate that, after the cladding is fully oxidized, melt temperature drops to a value consistent with fully oxidized melt conditions. Aside from cladding oxidation effects, a limited number of experiments have been conducted to examine the effect of significant structural steel[2] content in the melt on core-concrete interaction behavior. One outcome from these tests is the extensive amount of iron oxidation that occurs with limestone-common sand concrete. Steel oxidation also occurred in tests with siliceous concrete, but to a lesser extent in comparison to the limestone case. Concrete temperatures showed that axial and radial ablations were more pronounced in the areas where metal was found. This is consistent with other oxide-metal simulant tests that have shown enhanced heat transfer at the metal-concrete interface relative to the oxide-concrete interface. Notwithstanding these findings, the metal-oxide database is noted to be limited and there is no clear understanding of the phenomenological behavior for this case (i.e. mixed vs. stratified metal-oxide conditions, and/or bifurcation between these two states during the interaction). Therefore, extrapolation of experimental results obtained thus far to plant conditions is somewhat uncertain.

The fission product release during core/concrete interaction is only briefly mentioned in the report as it has not been the main focus of the MCCI experiments in the last two decades. The aerosols released during corium/concrete interaction contain mainly elements from the concrete. The release of uranium or low-volatile fission product is enhanced by the presence of metal in the melt and by the higher gas content of limestone common sand concrete but remains low. Interaction with silicon to form silicates tends to lower the release of fission products of main interest like barium and strontium.

Regarding debris coolability, the test series provided evidence of several heat transfer mechanisms that can contribute to long-term corium cooling. When the core debris is flooded from above, the question of whether or not a significant amount of the thermal energy will initially be removed depends upon whether a stable crust is able to form that inhibits heat transfer from the melt to the water layer. For a stable crust to form, two conditions must be met: (i) a thermal condition, viz., the melt/water interfacial temperature must fall below the corium freezing temperature, and (ii) a mechanical condition, viz., the incipient crust must be stable with respect to local mechanical loads imposed by the agitated melt. In this bulk cooling regime, efficient melt/water heat transfer occurs predominately by radiation heat transfer across the agitated (i.e., area enhanced) melt/water interface, in addition to entrainment of melt droplets into the overlying water and conduction.

As bulk cooling heat transfer continues, the melt temperature gradually declines. As the downward heat transfer rate decreases, then melt sparging arising from concrete decomposition also decreases. Thus, a point is eventually reached at which the thermal and mechanical thresholds for interfacial crust formation are both satisfied, and an insulating crust forms between the coherent melt zone and the water layer. This crust is characterized by some degree of porosity, or cracks, owing to the necessity of venting concrete decomposition gases.

After the crust forms, completion of the quench process can only be achieved if water is able to penetrate into the debris by some mechanism to provide sufficient augmentation to the otherwise conduction-limited heat transfer process to remove the decay heat. The tests have revealed three mechanisms that provide pathways for water to penetrate the debris. The first is water ingression through interconnected porosity or cracks. The second mechanism is particle bed formation through “volcanic” eruptions. In this case, concrete decomposition gases entrain melt droplets into the overlying coolant as they pass through the crust. The third mechanism is mechanical breach of a suspended crust. In particular, the thick crusts that form from water ingression could bond to the reactor cavity walls, eventually causing the melt to separate from the crust as the MCCI continues downwards. However, this “anchored” or suspended

[2] Steel comes from in-vessel structures or rebars embedded in the concrete for its reinforcement

configuration is not expected to be mechanically stable at reactor scale due to the low mechanical strength of the crust. The suspended crust situation is somewhat different from a supported crust situation as in many magma flow from volcanic eruptions. Eventually the suspended crust is expected to fail, leading to rapid and massive ingression of water beneath the crust. This sudden introduction of water provides a pathway for renewed debris cooling by the bulk cooling, water ingression, and melt eruption cooling mechanisms.

Several findings related to debris coolability are directly applicable to evaluating plant accident sequences. In terms of the water ingression mechanism, the test results indicate that the heat transfer correlation based on previous one-dimensional (SSWICS) tests is conservative insofar as calculating ingression-limited crust growth behavior. In particular, the correlation tends to under-predict the heat flux to overlying water during time intervals when water ingression is occurring. In terms of the melt eruption mechanism, significant eruptions have been observed in the case of limestone common sand concrete. Eruptions have also been observed under early cavity flooding conditions for siliceous concrete. For tests conducted in two dimensional cavity configurations, the eruptions appear to have occurred under a floating crust boundary condition, which is expected at plant scale. Finally, the crust breach data indicate that the crusts that form at the melt/water interface after cavity flooding have a low mechanical strength, and cannot be mechanically stable at plant scale. Rather, the crust is expected to fail and, thereby, maintain a floating crust boundary condition that will allow the melt eruption and water ingression cooling mechanisms to proceed.

It is noted the debris coolability experimental database consists almost exclusively of tests conducted with oxidic melts. When a significant metal fraction is present in melt, it may result in a stratified pool configuration. This type of pool structure has not been evaluated from a coolability standpoint. Thus, additional analysis and testing may be required with melts containing a significant metal fraction to further reduce phenomenological uncertainties related to debris coolability, as well as core-concrete interaction.

## CAPABILITIES AND SHORTCOMINGS IN CURRENT CODES AND MODELS

One goal of this SOAR was to summarize and assess capabilities of various simulation tools currently used in the world, focusing on models used to describe the corium concrete interaction phenomena and the coolability mechanisms induced by top flooding. Chapter 3 of this report provides a generic description of MELCOR MCCI module (i.e., CORCON), CORQUENCH, COSACO, ASTEC MCCI module MEDICIS, TOLBIAC-ICB, WECHSL, COCO, MAAP MCCI module, and the SOCRAT MCCI module. More detailed models descriptions are also provided as in the appendices.

All codes can currently analyse the case in which the corium is assumed to be instantaneously spread over the entire floor of the reactor pit under dry cavity conditions. This situation is most consistent with rapid high temperature melt pour scenarios in dry cavities, for which efficient spreading can be expected. However, not all the codes can adequately model the impact of top quenching. In addition, the ability to analyse situations in which concrete ablation is limited to a part of the reactor pit walls and/or floor due to localized corium accumulations, as well as scenarios involving multiple pours separated in time, cannot be currently treated in an easy and systematic way using available codes. Moreover, many current codes are not able to treat MCCI scenarios that involve spreading into additional cavities adjacent to the reactor pit. Finally, the effect of concrete type on concrete erosion pattern viz., the experimental results for siliceous or limestone common sand concrete cannot be explained satisfactorily by existing phenomenological models.

Another aspect documented in Chapter 4 of the SOAR relates to validation and discussion of modelling. Detailed and often different models of various phenomena are recommended for use in different codes, as a result of individual code validation work that is often based on separate effect experiments. However, MCCI is a complex interaction of several phenomena and it is important to validate the codes against integral MCCI experiments to gain an appreciation of the predictive capability of these tools. The validation status of individual codes is described from a general viewpoint, with additional details regarding higher-level phenomenological models provided in the appendices. Since all models require material property data, the validation status of property data and supporting correlations are also reported, along with an assessment of how the experiment data can be scaled to reactor conditions based on available models in the codes.

The validation work is commonly focused on comparing key calculated results (i.e., corium temperature and local or maximum ablation depths) with the experimental data. Transient effects often impact the course of individual experiments – principally at the start of the interaction between the newly generated melt contacting cold test section structures, resulting in the formation of melt crust at the interface with the concrete that prevents its ablation – for which the codes cannot be assessed and adequately validated since most codes do not have the necessary modelling capabilities. However, in the longer term, the experiments enter a quasi-steady regime in which code predictions of concrete ablation progression and temperature history are reasonably well understood. Good agreement with oxide melt experiments in terms of ablation and temperature history are noted when heat transfer coefficients on the order of 300 $W/(m^2K)$ and concrete decomposition temperature close to ~1600 K are selected as boundary conditions at the melt-concrete interface.

Among other relevant findings from code assessment activities, it is noted that anisotropic ablation observed for siliceous concretes can currently be captured in the codes only via empirical application of heat transfer coefficients based on observations from two-dimensional experiments. The assessment of top flooding conditions on the course of the MCCI is not yet clear since the crust anchoring effect, observed in many experiments but not expected at reactor scale, is difficult to take into account and is modelled in very few codes. Uncertainties were identified for melts consisting of both oxides and metals. In particular, in a stratified pool configuration the metal melt thermal material properties suggest elevated heat transfer at the metal/concrete interface, but the overall transfer of decay power (which is predominantly released in the oxide melt) to the concrete via the metal layer is governed by the heat transfer at the interface between the oxide and the metal layer. Direct model validation for this interlayer heat transfer is not yet possible due to lack of appropriate data from experiments under MCCI conditions. Additional uncertainty is introduced due to a lack of knowledge regarding stratification and mixing processes under MCCI conditions. For situations in which concrete reinforcement serves as a continuous source of metal, its impact on the concrete ablation mechanism is still not properly understood.

Based on these underlying experiment and code assessments, an additional high level goal of this SOAR is to review applications of MCCI phenomena, models, and data to safety analysis of nuclear power plants under severe accident conditions, particularly in the context of reactor safety requirements and containment designs to address such requirements. Safety requirements, promulgated by various international bodies, are discussed as well as containment designs for a number of Generation II and Generation III plants with particular emphasis placed on features relevant to the MCCI issue. Three idealized plant (containment) configurations for reference plant calculations are also discussed, and a few example plant calculations are presented. These examples illustrate the approach of plant idealization (simplification) that is quite common and reasonable in the field of safety analysis, noting the inherent uncertainties in severe accident phenomena. As with virtually all other severe accident phenomena, extrapolating the results of scaled experiments to MCCI in plant scale involves some idealization of plant geometry and configuration. For full-scale plant safety assessment, the approach appears to be pragmatic whereby MCCI phenomena are analyzed based on conservative assumptions with respect to the weaknesses of the containment design.

### REMAINING ISSUES IN THE AREAS OF MCCI AND DEBRIS COOLABILITY

Notwithstanding the progress made in the field of core-concrete interaction, the apparent simplicity of the treatment of thermal-hydraulics of a well-mixed corium pool in the presence of the concrete decomposition gases is contrasted by the complexity of the concrete ablation mechanism where the heated concrete, a highly heterogeneous material, is gradually incorporated into the melt through an evolving melt-concrete interface that is still difficult to observe experimentally and capture from a modelling point of view. Because many of the models are not mechanistic, several parameters are often empirically fit to reproduce as best as possible the scaled experimental results. Attempts to model MCCI by a multi-scale computational approach to eliminate these tuned parameters with more mechanistic models have been unsuccessful to date. This is mostly due to the difficulty of observing and measuring local phenomena needed to validate multi-scale modelling approaches.

Based on the foregoing results, this SOAR focused on identifying remaining issues and residual uncertainties in the areas of MCCI and debris coolability, and formulates some recommendations for addressing these questions in the near future in order to increase the reliability of reactor simulations. These issues are: (1) long-term core-concrete interaction behavior; (2) realistic plant simulations; and (3) coolability enhancement under top flooding conditions

## Long term core-concrete interaction behavior

The past MCCI experiments with prototypic materials were relatively short in duration, which is partially due to the fact that constraints did not allow significantly longer duration experiments. Admittedly, in many of these experiments the test duration was adequate to assure at least partial melt cooling and slowing down of basemat ablation to a level that could be considered acceptable for regulatory purposes (i.e., ablation limited to a specified amount by say 24 hours into the accident).

The Fukushima accidents suggest that a much longer transient is quite likely. A recent draft report (OECD/NEA, in preparation) on safety research post-Fukushima by an international group of experts noted that MCCI very likely occurred in one or more Fukushima Daiichi units for some time, but did not lead to a significant melt release outside the containment vessel to the reactor building. The analyses performed to date in the OECD BSAF project phase 1 have not provided a consensus view on the MCCI issue. In particular, the termination of the MCCI process was found to have been impacted significantly by differences in melt pour conditions predicted by different codes at reactor vessel failure. These findings put into question those analyses results which predict ongoing MCCI for a long time, especially in the presence of water. Hence, there is a need to obtain longer duration experimental data if the shorter duration experimental data cannot be extrapolated to the reactor situation with a high degree of confidence.

Longer duration experiments will provide data needed to: (1) confirm that intermittent phenomena like melt eruptions are reproducible; and (2) investigate if the crust formed by water ingression is stable. Long duration experiments will also provide data on long term behavior dealing with the final phase of the interaction, i.e. the time when the heat flux to concrete is low enough that it can be dissipated by conduction into concrete without further ablation, or the heat flux that is applied in a specific coolant circuit of a core catcher. Finally, long term behavior also refers to situations wherein the concrete fraction within the melt and the heat flux level are representative of the situation after many hours of interaction. The subject of long-term behavior vis-à-vis further research needs and recommendations is discussed further in the following paragraphs.

It is noted elsewhere that more rapid radial ablation (relative to axial) was observed for siliceous concrete, whereas limestone common sand concrete showed an isotropic (uniform axial and radial) ablation profile. Currently, there is no generally accepted phenomenological explanation for this behavior, and the question remains if it is reliable to extrapolate this result to reactor scale for a longer duration ablation process. This general scaling issue is equally important to concrete ablation in a wet cavity situation.

Another complex issue is associated with intermittent ablation bursts that are observed in experiments. It is not clear if this is a result of crust instability or rather a result of concrete spalling due to mechanical instability. Depending on the phenomena, the characteristic time period can be several hours; e.g., crust dissolution processes with siliceous concrete. In this case the test duration has to be long enough to observe at least two or three ablation bursts. Data from these long duration experiments will reduce uncertainties in current melt eruption models and will provide better confidence in extrapolating to reactor scale.

It is important to recognize that in every facility, the size of the test section, the heating technique, and/or the operating procedure always induces some transient system effects. These transient effects are not modeled in the codes and it is not required for most of plant applications. As a result when the transient effects are dominant, the codes cannot reproduce accurately the final cavity shape which is commonly used to estimate the ablation rate. It is recommended that an experiment objective should be to reduce the duration of the initial transient, and experiment techniques that can contribute to homogenous initial melting of the corium and limit initial crust formation should be encouraged. Furthermore, future tests should be designed to run under steady state conditions for a longer duration.

Under long test operating conditions involving top flooding, one systematic drawback of the experiments is the top crust anchoring phenomena. In tests performed with top flooding, the upper crust eventually anchored to the side walls. The anchoring phenomenon unrealistically reduces the efficiency of the melt ejection phenomena because a gap between the pool and the upper crust appears and then increases due to concrete densification upon melting as well as loss of liquid corium as eruptions occur. At the beginning of the process, crust anchoring could also create a pressure buildup effect below the crust that experimentally distorts the eruption process. Crust strength measurements made on crust samples obtained from experiments and supporting structural analyses indicate that a floating crust boundary condition is likely in a full-scale reactor geometry. In this spirit, experiment techniques that can promote a floating crust boundary condition in reduced scale experiments should be encouraged.

The final step of the MCCI process is characterized by a core-concrete heat exchange surface so large that the heat can be transferred by conduction to the remaining concrete without further ablation. This scenario would yield a very viscous melt with high concrete fraction. Under such conditions, the heat transfer models at the core-concrete interface may not be valid. Some codes utilize a quasi-steady modeling approach in which conduction into the concrete is not modeled. Thus, all heat transfer from the core debris is dissipated by concrete ablation, and as a consequence, the ablation never stops. Some of these deficiencies in analytical tools can be addressed with data from longer duration experiments.

## Realistic plant simulations

Improving the realism in plant simulations inherently introduces more complexity. As a result, the associated efforts have to be balanced with approaches that rely on invoking additional levels of conservatism to define a bounding set of hypotheses for safety-relevant issues. Three major topics of interest in this area are: (1) the presence of metal within the melt or within the concrete; (2) the initial conditions for MCCI based on melt pour conditions into the reactor pit; and (3) the presence of impurities in cooling water (e.g., seawater or brackish water).

The presence of metal within the melt or within the concrete influences the ablation profile as soon as stratification occurs. The stratification process is governed by the higher density ratio between metal and oxides as soon as the fuel oxides become diluted with concrete oxides. While several experiments have been performed with iron-alumina thermite simulant, only a few tests have been performed with a fully prototypic metal-oxide core melt composition. It was not possible to establish from the results clear evidence of stratification, but ablation was observed to be increased in front of the metallic masses. For prototypic metal-oxide core melt, the oxidation kinetics and the stratification thresholds are important as they influence the time window when the melt is stratified at reactor scale and as a result, the prediction of the basemat melt-through time.

The initial phase of the melt-concrete interaction involving unoxidized cladding (zirconium) in the melt has been investigated in a few reactor material experiments. This stage can lead to highly exothermic metal oxidation reactions. Zirconium-bearing concrete-metal inserts were used in some Argonne experiments in which a relatively small amount of Zr was incorporated into the melt just prior to melt contact with the concrete basemat. However, it is likely that a significant fraction of the Zr in the inserts was oxidized before the test initiation, thereby limiting the impact on the actual MCCI phase of the experiment. Another aspect not investigated in experiments is the presence of uranium within the metallic phase. During the in-vessel stage of the accident, uranium is found in the metal phase in scenarios that lead to a significant fraction of un-oxidized cladding in the lower head. Under these conditions it seems appropriate to implement an oxidation model for uranium in simulation tools and to perform sensitivity analyses.

Reinforcing bars in concrete play a double role as they are a continuous source of metal which is prone to oxidation during ablation and additionally, they change the ablation mechanism. In particular, some recent test results indicate that the presence of reinforcing bars in siliceous concrete leads to a homogeneous ablation profile, which contrasts the results from reactor material tests carried out with non-reinforced siliceous concrete in which anisotropic ablation was observed.

The presence of metallic inclusions in an otherwise oxidic crust could change the properties and thereby impact the water ingression cooling mechanism. Specifically, the presence of metal could influence the critical heat flux associated with cracks that form in the crust due to thermal contraction induced by top flooding. To address this issue, additional experiments could be performed with different metal contents in the melt and a representative gas release to promote good mixing conditions. For these tests, as well as large scale experiments with sustained heating, new thermite compositions need to be developed that would produce a melt with adequate metal fraction.

The effect of metallic inclusions in melt on the melt ejection cooling mechanism is different as it is occurs over a longer duration. It would be interesting to evaluate the entrainment rate of pure metal melts and check the morphology of the particles formed during the quenching process to assess their coolability as well as their influence on the coolability of the particulate debris bed in general. As soon as the specific technological challenges of metal-oxide experiments are resolved, tests with high metal fraction are recommended.

Thermal stresses on concrete structures brought on by core debris interactions with concrete have not been investigated in MCCI programs. These stresses are largely inconsequential for below grade reactor cavities but can be quite important for free standing cavities such as sub-atmospheric containments and especially for reactor pedestals in boiling water reactors. The core debris interactions place the inner region in compression where concrete is strong but the outer region in tension where concrete is weak and easily cracks. This has structural implications which again have not been investigated in MCCI programs.

## MCCI initial conditions following melt relocation into the reactor pit

It is often assumed that the MCCI phase starts as soon as the vessel fails and the corium mass in the lower head (which in bounding analyses includes the entire fuel and structural inventory in the reactor) is relocated into the reactor pit. This approach offers a degree of conservatism in terms of axial-melt-through delay if one assumes that the melt is spread instantly over the entire surface of a dry pit. However, when the reactor cavity is flooded, spreading may be limited leading to corium accumulation in one part of the reactor cavity. This scenario will result in higher heat fluxes to concrete and reduce the basemat melt through time if this accumulation is stable and does not eventually spread out uniformly. Among other things, local corium accumulation in the reactor cavity mainly depends on the corium temperature, corium pour rate, reactor pressure vessel failure location, amount of water present in the reactor cavity at reactor pressure vessel failure, and finally on the ability to provide water continuously on top of the corium accumulation.

Such configurations are quite complex to study because they involve the formation and spreading of corium accumulations under water as well as the possibility of boiling off the water inventory, drying out the core debris, re-melting, and onset of concrete ablation. An ancillary issue is that core debris in a reactor cavity, if not covered by water, exposes a great deal of concrete surface area to intense convective and radiative heat flux. The gas generation and concrete degradation from this exposed concrete cannot be neglected in the analysis of core concrete interactions and containment integrity.

Depending upon the melt pour conditions and with a relatively shallow water layer, melt jet fragmentation is expected to be minor. For this type of scenario, existing MCCI models that treat the corium as an initially intact melt pool interacting with concrete may be employed as a reasonable approximation. However, for deeper water pools melt jet fragmentation may be significant, leading to formation of a coherent particle bed, or a compact melt layer commonly referred to as a cake surrounded by particle bed. Depending upon the bed depth, decay heat level, particle size, and porosity, the configuration may be coolable. However, if the dry-out limit for the bed is too low then gradual reheating, dry-out, melting, and onset of concrete ablation will occur.

These particular configurations have not been extensively investigated as part of MCCI research, nor can existing MCCI models address all of these configurations. However, there has been a significant amount of research done in this area (both experiments and modeling) that generically addresses particle debris bed coolability for both in-vessel and ex-vessel applications. Conducting experiments that involve dry-out and melting of particle beds composed of reactor materials is a technical challenge given limitations with current core debris heating techniques. Thus, a possible first step to address this issue is to utilize existing models to evaluate coolability of particle bed formations predicted for plant applications. If these analyses indicate that the beds are not likely to be coolable, then effort should be devoted to developing appropriate experiment techniques to address this type of behavior.

Another related issue is that of multiple pours and how that affects the coolability of debris in the reactor pit. Again, in all experimental and analytical studies concerning MCCI, it is traditionally assumed that at reactor pressure vessel failure, the molten material (whether the entire reactor inventory or partial inventory) is poured all at once and instantly spreads on the whole reactor pit surface. It is likely that in some accident scenarios, the melt pour would be periodic which has two consequences: non-uniform melt accumulation and non-uniform spreading. Conducting experiments with this kind of melt configuration may be quite challenging, and an analytical extrapolation of experimental data for symmetric and uniform melt configuration may be more worthwhile based on simulant data.

### Presence of impurities in cooling water

The impact of impurities in cooling water on severe accident behavior resurfaced following the Fukushima accident. In particular, the use of sea water brought into question the impact of salt (sodium chloride) on coolability mechanisms, on fission products chemistry, and the performance (i.e. potential for clogging) of coolant loops. Generally speaking, any impurity in cooling water (whether it is salt in sea water or other forms of impurities in brackish inland fresh water) can impact one or more of these areas.

For the ex-vessel corium cooling mechanisms identified under top flooding conditions, the formation of precipitate in the cracks of the upper crust or in the overlying debris bed could reduce the dry-out limits for these formations. As the composition of water present in the sumps at the bottom of the reactor building is complex and may depend on the accident management strategy, it seems easier to address the issue in separate effect tests than in semi-integral experiments. Ongoing experiments in Japan are addressing some aspects of the water impurity issue. To parametrically investigate the effect of water impurities on melt coolability by water ingression, SSWICS-like tests could be run to evaluate the impact on the cracks formation and on the crust critical heat flux. If warranted, more complex experiments (i.e. with sustained heating) could be conducted to assess the behavior over the long term. For the melt ejection mechanism, the influence of impurities on debris bed coolability could be investigated in separate effects tests that utilize existing facilities for investigation of dry-out in debris beds for in vessel conditions.

The water at the bottom of the containment building will be highly contaminated with fission products. If this water is used to cool the melt, the chemistry of the fission products will likely be modified by gas bubbling and more generally by particulate entrained in the water. While the fission product behavior under such conditions is an ancillary issue related to the consequences of clogging, water samples could be collected quite easily at the end of MCCI experiments to perform chemical analysis in order to characterize the chemical composition. If some impurities in the water plays a role in trapping other species released during MCCI, it would be useful to carefully select the composition of the water before running these tests.

## Methods for improving melt coolability under top flooding conditions

This SOAR is focused on ex-vessel corium coolability under top flooding which is largely regarded as a generic accident management strategy for ex-vessel melt stabilization in existing plants. The improvement of melt coolability under top flooding conditions can also be viewed as a potential back-fitting strategy for operating reactors. Moreover, for new reactors, spreading and top flooding can be incorporated in the design phase as a generic approach.

In terms of improvement, it is noted that a larger initial corium spreading area will reduce the downward heat flux to the concrete and hence, reduce the likelihood of basemat melt-through. One approach for increasing melt spreading area for plants with limited floor space is to allow radial melt-through of a barrier with subsequent spreading of a portion of the melt into the reactor building. This situation is more likely for siliceous concrete but remains limited only to the level of corium above the breach elevation. This corium spreading strategy may be more effective in a dry cavity situation, one that also provides the benefit of eliminating the risk of steam explosion.

The coolability of debris can be more efficient if corium spreading is combined with flooding. Water ingression mechanism is most efficient at the early flooding stage with little concrete present in the melt, and that the melt eruption mechanism is also most effective in the early phase of the corium-concrete interaction due to the higher melt gas sparging rate. Ideally, it is desirable to have an initially dry pit to maximize spreading and to avoid the risk of a steam explosion, followed by early flooding. In this case, the time window to add water is narrow and a subsequent melt pour after top flooding cannot be excluded.

Another consideration is the composition of the concrete that is used for the reactor basemat at the plant. For new plants, a recommendation can be made to consider high carbonate and/or hydrate contents for the concrete used for reactor basemat. For existing plants with a potentially too thin siliceous concrete basemat, a possible back-fitting measure could be to consider pouring an additional (sacrificial) layer of high carbonate and/or hydrate concrete. In this case, since the thickness of this additional layer can be limited for a specific plant site, the key piece of information needed is the efficiency of the melt ejection mechanism so as to ensure that the liquid melt is transformed into a coolable particle debris bed before reaching the original siliceous concrete.

In the coming years the examination of the debris in the three damaged Fukushima reactors will likely provide additional insights that will enhance the understanding of MCCI phenomena at large scale and under fully prototypic conditions. The findings will undoubtedly provide opportunities to gain additional confidence in the application of simulation tools to existing plants. They will also provide data and information for optimizing severe accident management strategies for existing as well as future plants.

One of the top level recommendations in the OECD-SAREF report (in preparation) is to organize an MCCI workshop to discuss current state of MCCI knowledge, identify knowledge gaps, and identify data needs to bridge the gaps – the idea being that the Fukushima decommissioning effort can be informed by the outcome of such a workshop while at the same time, data collected during the decommissioning activities can be optimized to bridge the MCCI knowledge gaps. In two companion studies (one on severe accident knowledge gaps post-Fukushima and the other on Fukushima forensic data needs), MCCI knowledge and data gaps were identified as high priority topics. These findings confirm that in order to perform experiments and additional analysis to address more realistic situations, it is necessary to improve the capabilities of existing facilities and to perform needed experiments to bridge the knowledge gaps and reduce residual uncertainties. Since experimental MCCI research with prototypic reactor materials is an expensive undertaking, a collaborative effort among various nuclear safety research organizations in different countries is highly recommended.