MULTIPHASE FLOW IN EX-VESSEL COOLABILITY: DEVELOPMENT OF AN INNOVATIVE CONCEPT

MICHAEL L. CORRADINI
University of Wisconsin, Madison, WI, USA 53706
E-mail : corradin@cae.wisc.edu

Received February 5, 2006

The interaction and mixing of high-temperature melt and water is the important technical issue in the safety assessment of water-cooled reactors to achieve ultimate core coolability. For specific advanced light water reactor (ALWR) designs, deliberate mixing of the core-melt and water is being considered as a mitigative measure, to assure ex-vessel core coolability. The paper provides the background of past experiments as well as key fundamentals that are needed for melt-water interfacial transport phenomena, thus enabling the development of innovative safety technologies for advanced LWRs that will assure ex-vessel core coolability.

KEYWORDS : Debris Coolability, Melt Quenching

1. BACKGROUND

In the design of the next-generation of nuclear reactors and in the safety assessment of currently operating nuclear power plants, it is necessary to evaluate the risk from a severe accident and to identify the key strategies to follow in order to mitigate possible consequences. In the unlikely event of a severe accident involving core melt, it is important to identify the processes that would allow the molten core material to cool down and resolidify, to reliably remove core decay heat, and to bring core debris to a safe and stable state – thereby achieving so-called "core coolability". For current nuclear plants, the safety approach taken by plant operators and the US Nuclear Regulatory Commission (USNRC) is to:

- Provide alternative sources of water to arrest progression of the degraded core accident;
- Develop accident management procedures to maximize reactor pressure vessel integrity;
- Provide long-term ultimate heat sink paths to remove decay heat from the containment;
- Delay any potential containment failure beyond 24 hours for off-site emergency actions.

For next-generation plants seeking final design certification from the USNRC (e.g., AP1000–NRC03-202, [1.2]), the approach has been to improve the reliability of each of these actions to reduce the probability of progressing further into a severe accident with required off-site emergency preparedness actions. Nevertheless, safety analyses of next-generation plants indicate that all four types of actions will be necessary to minimize off-site radiological dose; e.g., NRC03-202 indicates that in-vessel retention may not be assured, thereby eventually causing containment basemat melt-through and requiring a range of emergency actions to minimize off-site radiological impact; i.e., evacuation.

In contrast to this safety approach, next-generation nuclear plant safety in other countries (e.g., EPR in Europe [3,4,5,7,8] VVER in Russia [9]) have taken a more proactive posture and have a goal to eliminate off-site radiological consequences and the need for off-site emergency actions. For example, the planned nuclear plant for Finland, a Framatome EPR, will incorporate an ex-vessel coolability system with the objective to preclude containment failure and substantial off-site emergency action plans.

If the next-generation nuclear plants developed by US nuclear vendors (i.e., AP1000 or ESBWR) are to be competitive worldwide, the ability to preclude containment failure and off-site emergency actions will need to be incorporated into their future reactor designs. The OECD in collaboration with its members (e.g., USNRC) worldwide is planning a continuing research program [10,11]. One potential objective being considered is to develop a technical basis for ex-vessel coolability concepts independent of any specific reactor design for advanced Light Water Reactors (ALWR).

We propose that a key objective of the OECD program be to develop a technical basis for ex-vessel coolability concepts independent of specific reactor designs for advanced

LWR's. In this paper we discuss some key elements needed to achieve such an objective.

2. TECHNICAL BASIS

In a severe accident, core-melt material has the potential to be discharged from the core region and eventually fail the reactor pressure vessel lower plenum wall. USNRC analyses of AP1000 in NRC03-202 indicated the likelihood of reactor vessel failure given a core-melt relocating to the lower plenum was over 1-in-3. Given this scenario, the molten core material pours from the reactor pressure vessel, and accumulates as a molten pool in the reactor cavity below. This molten material, usually called corium, is composed of mainly uranium-dioxide and zirconium-dioxide, as well as some limited quantities of zirconium and stainless steel from the melting of the reactor core internals and lower plenum. The molten corium can thermally attack the concrete underneath and decompose it, producing gases, which agitate the pool, enhancing heat release to the boundaries as fission product decay heat and chemical reactions continue to add mass and energy to containment. The production of the gases can pressurize the containment while the attendant erosion can melt-through the containment basemat.

To achieve "core coolability" in the reactor containment cavity and eliminate any threats to containment integrity by over-pressurization or melt-through, a number of approaches have been proposed; i.e., water flooding from above or injection of water from below. The effectiveness of these techniques to achieve ultimate coolability involves the mixing of high-temperature melt with water, via boiling processes and/or injection. Because this process occurs at large scales and with materials whose physical properties are not well determined, the phenomenology involved is not completely understood. In addition, many of the current, most widely used models were not specifically developed to simulate this phenomenology and do not always predict the experimental observations. Various attempts have been made to reproduce the problem experimentally by using either prototypic or simulant materials. Some of these are integral experiments that try to reproduce the entire scenario to pinpoint all the processes involved (e.g., EPRI/DoE/NRC supported MACE tests, [12,13]), while others are separate effect studies [8,14,15,16] focused on the more detailed analysis of very specific phenomena (e.g., the current OECD supported MCCI program to examine water-flooding phenomena).

A concept of core-melt quenching and long-term coolability by the bottom injection of water into the melt was originally proposed for application to the European Pressurized Water Reactor (EPR). A number of tests employing simulant melts (COMET) were conducted to demonstrate the viability of this concept. The concept appears promising for the development of innovative safety technologies for next-generation LWRs. However, fundamental data on the transport phenomena involved with prototypic materials are needed for further refinement of the concept and potentially for regulatory acceptance and industry implementation. Recently, an INERI project was completed that provided fundamental data on the COMET concept [17,18,19].

3. FUNCTIONAL REQUIREMENTS

The ex-vessel coolability system must have some attributes:

- Heat removal capabilities in excess of decay-heat generation (e.g., > 2x decay heat),
- Continuous and appropriate amounts of coolant injection with no active actions,
- Minimize the probability of damaging fuel-coolant interactions.

4. EX-VESSEL REACTOR CAVITY FLOODING CONCEPTS

In the absence of a dedicated device for core-melt retention and heat removal (i.e., core catcher) the only option for achieving ex-vessel coolability is to add water to the reactor cavity so as to remove the decay heat and enthalpy of the corium by vaporizing the water mixed with the corium melt. Three different concepts for water addition have been proposed and experimentally tested:

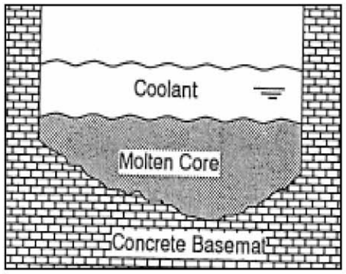
1. Core molten material falling into a flooded cavity and quenching (FARO tests),
2. Pouring of water onto the top of core molten materials and quench (MACE tests),
3. Injection of water into the bottom of molten pool and quench (COMET tests).

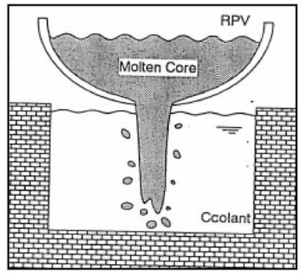
These different cavity flooding contact modes have been investigated in past experiments and analytical models have been developed (see figure below). Based on experimental results and evaluation to date, the COMET concept (i.e., bottom injection of water) appears to be the most effective approach. A short summary follows.

4.1 MACE Experiments

The Melt Attack and Coolability Experiment (MACE) program is focused on collecting the corium in the reactor cavity and flooding it with water (top flooding). Four major experiments have been performed. A variety of phenomena have been identified through experiments that may contribute to long-term coolability. When water is introduced on top of corium, several possible sequences of events may result depending on the initial conditions. In the short term following water addition, the question of whether or not a

Contact Mode	Top Flooding	Melt Pouring into Water	Bottom Injection
Experiment	MACE	FARO	COMET, Decobi





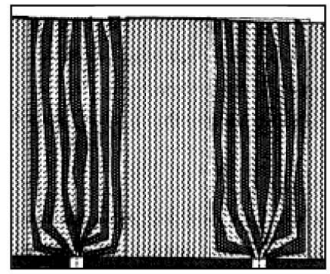


Fig. 1. Ex-vessel Contact Modes [6,11,20]

significant amount of the melt thermal energy is removed may depend upon whether or not a stable crust forms between the cooling water and molten core. If this occurs it would inhibit heat transfer from the corium to the water layer. For a sufficiently high sparging rate (gas generation due to concrete ablation), stable crust formation at the melt /water interface may be precluded. In this regime, film boiling is expected to be the dominant heat transfer mode, due to periodic introduction of high temperature melt at the interface, as the crust segments are broken up. Efficient melt/water heat transfer will thus be encountered due to conduction and, predominantly, radiation across the agitated (i.e., area enhanced) melt/water interface, in addition to the possible entrainment of melt droplets into the overlying water. An illustration of this process is provided in Figure 2. In a purely bulk freezing heat transfer mode, frozen material formed at the interface is mixed back into the melt causing an overall decline in the bulk melt temperature, eventually leading to the development of a slurry mixture of solid chunks and liquid.

As bulk cooling continues, the melt temperature will gradually decrease. If the downward heat transfer rate, which drives concrete ablation with co-current non-condensable gas release, is proportional to the melt temperature, then the melt sparging rate will also decrease. Thus, a point will eventually be reached at which a stable crust is able to form in the presence of the sparging gases. The physical configuration at this point would consist of a corium pool at reduced temperature with a crust on top of the melt. The crust will be characterized by some degree of porosity, or cracks, due to venting the concrete decomposition gases.

After the crust is formed, completion of the quench process can only be achieved if one of two conditions is met. The first condition is that the melt depth is less than the minimum depth at which decay heat can be removed via conduction heat transfer alone (estimated to be 10 cm, [12]). The second condition is that water is able to penetrate into the debris by some mechanism to provide a sufficient heat sink to remove the decay heat via evaporation. Three potential mechanisms have been identified through experiments, which provide pathways for water to penetrate the debris. The first mechanism, depicted in the figure above, is water ingression through interconnected porosity or cracks.

For this mechanism to exist, sustained contact between the crust and the underlying molten phase is required. This process relies on crack propagation through the material and, as such, is highly dependent upon the mechanical properties, since thermal stress is a key factor. The second potential mechanism, which would yield interconnected porosity 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 entrained droplets then solidify in the overlying coolant and accumulate as a porous particle bed atop the crust. This cooling process is shown in the figure above.

Another mechanism that may contribute to long-term debris coolability is mechanical breach of a suspended crust. Sustained separation of the crust from the underlying melt due to mechanical bonding of the crust to the reactor cavity walls is not expected in a plant accident, owing to the large lateral span of the drywell/pedestal regions of these structures. However, the thick crust (~10 cm) that develops may have sufficient mechanical strength to bond to the pedestal walls and temporarily separate from the ongoing MCCI. This

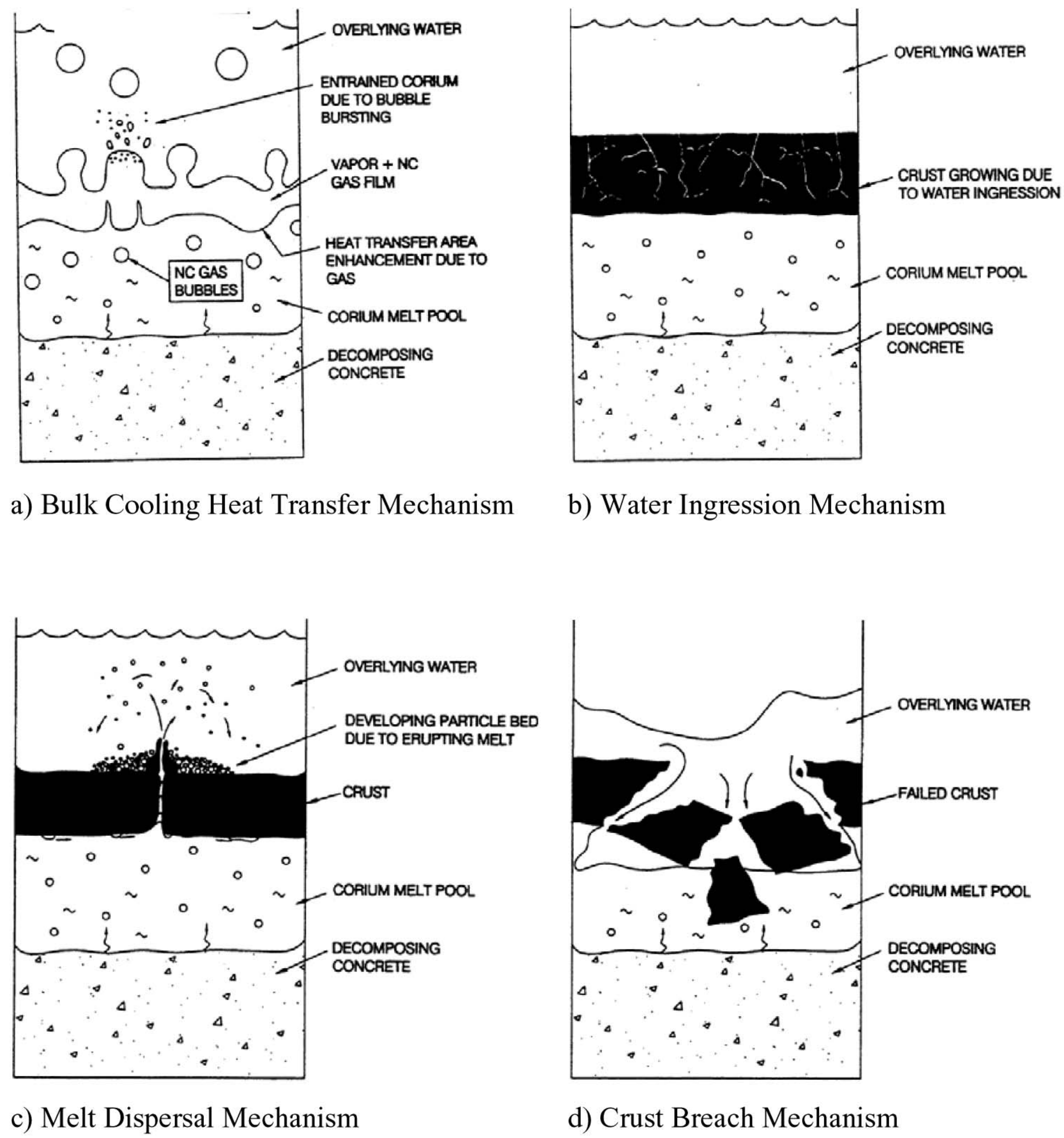


Fig. 2. Heat Transfer Mechanisms for MACE Experiments [11]

configuration is, however, not expected to be stable due to the shear weight of the crust, in addition to the dead weight imposed by accumulating, dispersed material atop the crust and water. Eventually the suspended crust will fail, leading to rapid ingression of water beneath the crust. This sudden introduction of water will provide a pathway for renewed debris cooling by bulk cooling, water ingression, and melt eruption-cooling modes. This transient cooling process is illustrated in the figure above. An excellent description of the above shown mechanisms with examples from the experiments and reference to analytical models is given by [11].

4.2 FARO Experiments

A different type of contact mode occurs if the molten corium pours into water. This scenario would occur if the corium were still in the reactor pressure vessel when the reactor cavity is flooded with water. When the pressure vessel melts through, a jet of molten corium falls into the water where it, ideally, fragments and solidifies. In the Fuel Melt and Release Oven (FARO) facility, up to 200 kg of oxide fuel type melts (up to 3000 °C) can be produced, possibly mixed with metallic components, and delivered to a test section containing a water pool at initial pressures of up to 50.bar. The FARO experiments were conducted over ten years beginning in 1991. Experiments are focused on the investigation of basic phenomena relevant to the fragmentation and quenching of molten material in the water coolant at different initial pressures and water subcooling. Twelve experiments have been performed: Five at 50 bar initial pressure, one at 20 bar and six tests at ambient pressures lower than 5 bar. The experimental data indicated that only partial quench of the molten core materials was possible.

4.3 COMET-Experiments

Similar to the MACE experiments, the corium is collected in the reactor cavity in the COolability of MElT (COMET) experiments. At the bottom of the reactor cavity, called the core catcher, a sacrificial layer of concrete with integrated nozzles is installed. Erosion of the sacrificial concrete layer agitates the melt by gas production and lowers the melt temperature. Mixing of concrete components and corium will also lower the solidus temperature of the mixture significantly. As the erosion of the sacrificial layer reaches the nozzle and ignites the burnable cap, coolant water starts to enter the melt from below. At first, the inflowing water is evaporated immediately and completely due to the high temperature difference between coolant and melt. The production of steam creates pressure inside the melt and fragments the melt. As long as the melt is in the liquid state, flow channels form. However, they are not stable, but permanently redeveloped in the turbulent melt flow. The direct water contact and its evaporation lead to a rapid cooling of the melt, which then starts to solidify in a solid - liquid mixture. The possibility of long term cooling of the solidified and decay heated debris will depend on the structure of the debris and the distance between the nozzles. If a porous structure is formed as a consequence of the solidification process and if the distance between the nozzles is properly designed, the continuous water inflow will ensure long-term coolability.

Up until now, three major series of COMET experiments have been performed [4]. The main focus of these transient tests was qualitative study of the fragmentation of the melt, safe design flooding water pressure, as well as quantitative study of the melt quench process via rapid and complete solidification, different melt compositions, inhomogeneous erosion, presence of zircaloy, steam explosions, hydrogen release during the interaction, aerosol release and long term coolability. In addition to these experiments, enhanced designs were under investigation. A schematic of the different cooling stages during the COMET experiments is shown in Figure 3.

4.4 Fuel Coolant Interactions (FCI)

The FCI phenomenon, known as vapor explosion, is a rapid evaporation of the injected coolant that can initiate shock waves, finer melt fragmentation, and possible mechanical damage to the reactor cavity. Similar to COMET-T Experiment 2.1 and 2.3 also in COMET-T 8.1, about 2-10 seconds after onset of water injection, FCI's were observed. In the water injection lines, pressure peaks up to 2 bar were measured. The table below gives three strong measured pressure peaks, the resulting impulses and the kinetic energies. The highest pressure peak occurred at onset of water injection. The calculated impulse is about 118.N◊s. About 70 kg of the melt participated in this interaction, nearly the total melt mass, resulting in a low kinetic energy of the melt mass of 0.1 kJ. Seven seconds after onset of water injection, the pressure increased again and 5 kg of melt were ejected from the test section. These energetic events need to be minimized in any successful external cavity-cooling concept.

5. EXTERNAL CAVITY COOLING REACTOR CONCEPTS

5.1 AP1000 Reactor Design

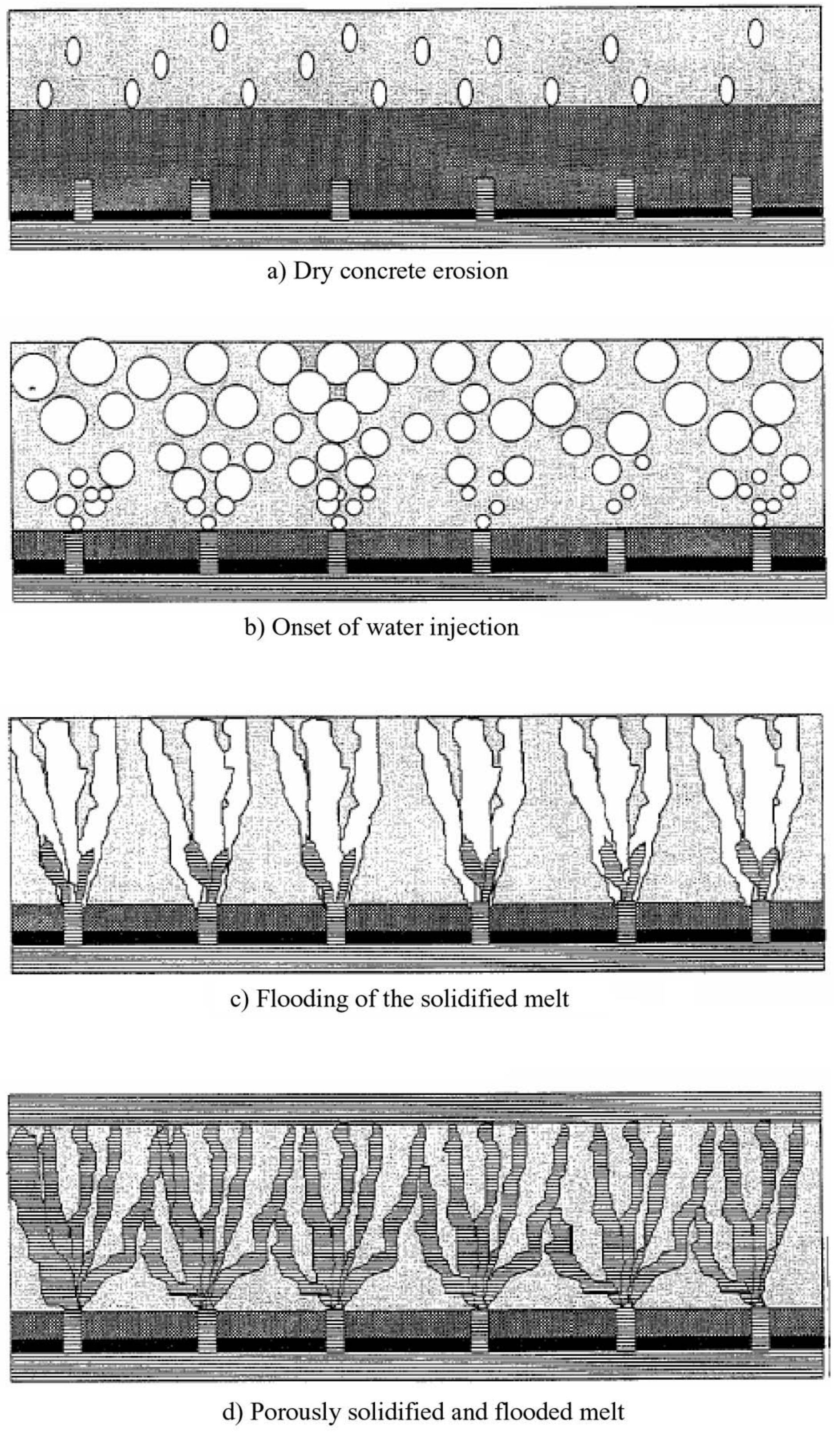
The current design for the AP1000 does not explicitly have an external cavity-cooling concept as noted previously. Rather, the IVR concept is used exclusively as the mechanism to provide debris coolability within the reactor pressure vessel after a core melt accident has progressed to the point where core material relocates beyond the core region. If the IVR concept is defeated and molten core materials released to the cavity, the range of phenomena and emergency actions need to be considered.

5.2 ESBWR Reactor Design

The conceptual design for the ESBWR is now being formulated for submission to the NRC for design certification. Thus, many of the details of containment systems that would be employed to handle severe accident phenomena are still not precisely specified. However, it is seems clear that, at this time, the ESBWR will need to explicitly consider an external cavity-cooling concept incorporated in its design.

5.3 EPR Reactor Design

The current EPR design has an external cavity-cooling concept that utilizes the approach in which the region



a) Dry concrete erosion

b) Onset of water injection

c) Flooding of the solidified melt

d) Porously solidified and flooded melt

Fig. 3. Phenomena During Melt Quenching Process [6]

Table 1. Measured Forces During COMET-T 8.1 [6]

Time [s]	Force [kN]	Impulse [N-s]	Time Dt [s]	Mass [kg]	Kin Energy [J]
0	7.7	118	33	70	100
7	3.7	95	64	5	880
8	3.2	69	45	5	480

below the reactor pressure vessel is kept dry. The current conceptual design would achieve coolability by allowing the corium melt to deposit on that cavity floor flow into an adjoining compartment (so-called spreading room) lined with a sacrificial material. In this room the corium would spread over this large sacrificial surface area as it erodes material, dilutes, radiates and transfers heat to the dry cavity region. This design has the option that after a few centimeters of erosion water channels could open up allowing water to be injected into the corium from below. The basic concept of this combined approach is to forcibly quench the core debris by limited fuel/coolant interactions atop the sacrificial layer and steel liner. Eventually the core would cool and solidify as debris, such that it would achieve long-term coolability.

6. PROPOSED CONCEPT FOR FURTHER STUDY

A new concept is proposed for achieving ex-vessel core debris coolability and long-term stabilization [21]. This concept is developed to accomplish the following objectives :

1. Totally passive safety measures;
2. Minimal sensitivity to the melt release condition at the time of RPV failure;
3. No energetic fuel-coolant interactions (FCI's);
4. Sufficient debris coolability margin (i.e., the volumetric heat removal rate should be significantly larger than the decay heat with high confidence).

The proposed concept is a combination of the two existing concepts discussed earlier, i.e., the bottom-flooded reactor cavity and the externally cooled core catcher. The reactor cavity would have provisions for sidewall cooling and bottom-injection of water (Figure 4). It would also contain internal structures that would minimize the FCI risk.

To provide the sidewall cooling, a steel cylinder is placed in the reactor cavity. The inner diameter of the metallic cylinder would be larger than the outer diameter of the RPV, so the melt released at RPV failure would be 100% collected in the region within the metallic cylinder. The inner wall of the cylinder could be lined with a thin layer of refractory material (e.g., zirconia or magnesia) in order to protect it from any direct melt contact caused by either jet impingement or melt-coolant mixing as the melt is discharged from RPV failure. The annular gap between the reactor cavity wall and the outer wall of the cylinder would be filled with water supplied by gravity from an in-containment water reservoir (or overflow from the inner cylinder given water presence from any IVR accident management strategies). This water would be available for providing sidewall cooling to the cylindrical wall as well as a backup for bottom-flooding into the inner cylinder where the debris is located. The thickness of the annular gap as well as the wall thickness (metal plus refractory material) would have to be determined from detailed design structural and fluid analyses but are expected to be 30-50cm for the annular gap and an order of magnitude smaller for the wall respectively.

The bottom of the reactor cavity would be provided with a liner made of sacrificial material, which contains nozzles for the injection of water from below. This water flow would be supplied by another in-containment reservoir specifically dedicated to bottom injection of water. Note that one could also consider for redundancy an alternative water supply by gravity flow from the outer annular space. The inner cylindrical area would be provided with an internal structure made of sacrificial material, which could be an array of tubes or honeycomb-shaped structure supported at the bottom of the reactor cavity. The primary purpose of the internal structure is to minimize the steam explosion risk if the reactor cavity is pre-flooded with water, as would be the case if the in-vessel retention (IVR) strategy were adopted. In addition, the sacrificial material, when mixed with the core melt, would have a dilution effect reducing the effective volumetric heat generation.

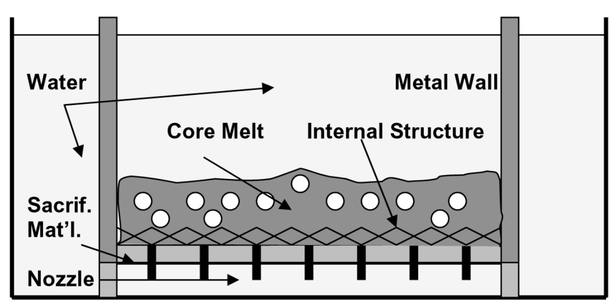


Fig. 4. Conceptual Picture of Proposed Ex-Vessel Coolability Scheme

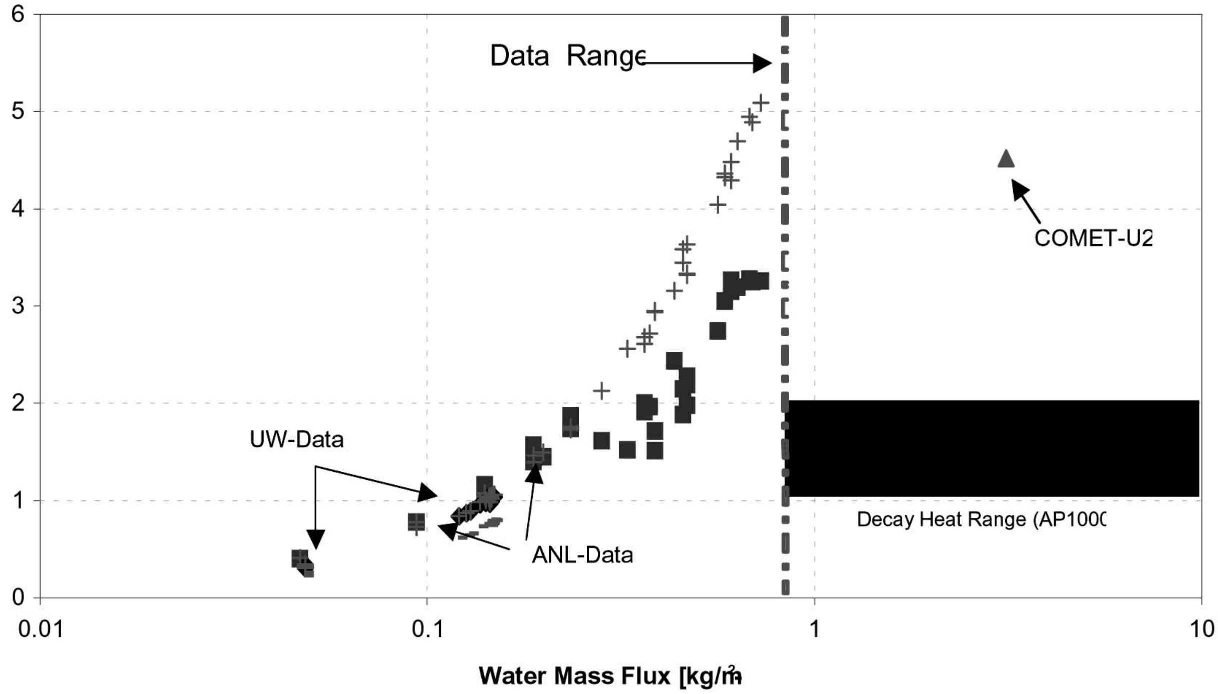


Fig. 5. Comparison of ANL and UW Data as Volumetric Heat Removal Rates

Let us discuss how the proposed concept might meet the specific objectives set forth.

6.1 Passive Safety

The measures used in the proposed concept are 100% passive, since the cooling water is supplied by a gravity feed either from a dedicated system or the outer cavity annulus.

6.2 Minimize Sensitivity to Melt Release

First consider the case where the inner metallic cylinder is dry; i.e., absence of any substantial pre-existing water pool. If the melt release at RPV failure is rapid as well as massive, a deep pool of melt would form in the cylinder before the injection of water from below begins. However, the annulus gap between the reactor cavity and the steel cylinder walls would be pre-filled with water prior to the melt release as in the IVR strategy, so the steel wall would be at this water temperature and the sidewall cooling would be immediate with a significant time delay. The subsequent erosion of the bottom sacrificial layer and the injection of water from below would provide significant additional cooling, the extent of which would depend on the water injection rate. Also, the water injection process would bring about good mixing of the melt pool and the melt pool temperature would likely be relatively uniform. Thus, some of the key uncertainties associated with the IVR strategy for the sidewall cooling (e.g., melt pool heat flux distributions including the so-called focusing effect) would all be eliminated.

If, however, the melt release is gradual (e.g., in the form of small melt streams), the melt pool formed by the time of water injection would be likely shallow. In this case, depending on the water injection rate, the injected water may not vaporize 100% in the melt, resulting in a pass-through of some of the coolant injection. The situation, then, would become similar to that of a pre-flooded reactor cavity as additional melt continues to pour into this reactor cavity region filled with water.

In the case of a pre-flooded cavity such as is being considered for the IVR strategy, both the inner cylinder and the annular region between the cavity wall and this cylinder would be filled with water prior to melt release from the RPV. The melt would be falling into a pool of water within the inner cylinder region. The timing of water injection, from the nozzles below the pool, would depend on the interaction of the melt and the debris with the underlying sacrificial material at the bottom of the cavity. Once the water injection starts from below, however, the injected water would remove heat from the melt in a similar manner, whether the cavity is pre-flooded or not. One exception may be that in the case of a pre-flooded cavity, an overlying layer of water would likely exist on the top of the melt. This overlying water layer would not impact the effectiveness of the injected water in the heat removal.

6.3 No Energetic FCIs

For the case when the inner cylinder is dry, the water injected from the bottom would be the only source of water mixed with the melt. Experimental studies conducted to date (e.g., COMET and ANL/UW experiments) seem to indicate that no energetic and damaging FCI would occur from the bottom injection of water. As a matter of fact, the water injection rate could be controlled and would be kept to a minimum necessary for melt quenching. A simple analysis would show that the amount of injected water mixed with the melt at any time would indeed be very small, minimizing any potential energetics. The water-to-melt mass ratio would so small that if the water were to interact with the melt in a 100% efficient manner, the resulting work would not be damaging to the reactor cavity or any other containment structures.

A major FCI concern may arise in the case of a pre-flooded cavity. In this case, an optimum mixing condition for melt and water, which would produce an energetic and damaging FCI is a theoretical possibility. This possibility would be minimized by adding an internal structure within the steel cylinder. If FCI's were to occur, the internal structure would be expected to render these events incoherent and benign. The FCI issue is an important consideration for the viability of the proposed concept, especially for the case of a pre-flooded cavity. The effectiveness of this internal structure in reducing the FCI risk deserves careful evaluation.

6.4 Sufficient Margin for Debris Coolability

Both COMET and ANL/UW studies have shown that the bottom injection of water alone would be capable of removing the decay heat with sufficient margin (Figure 5). In the proposed concept, a major fraction of the decay heat, could be removed by the side-wall cooling, where no FCI concerns exist. The bottom injection of water would be initially employed to quench the pool and ultimately to significantly enhance the margin of long-term coolability to such a level that no uncertainty analysis would be needed. The water injection rate would be optimized as necessary for this purpose. The optimum split of heat removal capabilities between the side-wall cooling and the bottom injection of water would be one of the prime subjects of future study.

REFERENCES

[1] Esmaili, H., Khatib-Rahbar, M., 2003, "Analysis of In-Vessel Retention and Ex-Vessel Fuel Coolant Interaction for AP1000", *ERI/NRC 03/202* (Revised November 2003).

[2] Esmaili, H., Khatib-Rahbar, M., 2004, "Analysis of In-Vessel Retention and Likelihood of Lower Head Failure", Proceedings of *International Congress on Advances in Nuclear Power Plants*, Pittsburgh, PA, June 13-17.

[3] Alsmeyer, H., Tromm, W., 1991, "A Core Catcher Concept and Basic Experimental Results", *International Topical Meeting on Safety of Thermal Reactors*, Portland, Oregon, USA.

[4] Alsmeyer, H., Tromm, W., 1999, "The COMET Concept for Cooling Core Melts: Evaluation of the Experimental Studies and Use in the EPR", *FZKA 6186, EXV-CSC(99)-D036*, Forschungszentrum Karlsruhe, Karlsruhe, Germany.

[5] Alsmeyer, H., Cron, T., Messemer, G., Häfner, W., 2004, "ECOKATS-2: A Large Scale Experiment on Melt Spreading and Subsequent Cooling by Top Flooding", *Proceedings of International Congress on Advances in Nuclear Power Plants*, Pittsburgh, PA, USA.

[6] Tromm, W., 1998, "Experimentelle Untersuchungen zum Nachweis der langfristigen Kühlbarkeit von Kernschmelzen", *FZKA 6187, Dissertation*, Forschungszentrum Karlsruhe, Karlsruhe, Germany.

[7] Tromm, W., Alsmeyer, H., Cron, T., Schmidt-Stiefel, S., Wenz, T., Adleheim, C., Grehl, C., Merkel, G., 2002, "Experiment on cooling of nuclear reactors under melt-down conditions, using bottom-up water flooding", *Annual Meeting on Nuclear Technology*, Stuttgart, Germany.

[8] Büerger, M., Widmann, W., Schmidt, W., Buck, M., Pohlner, G., 2001, "Theoretical investigations for the COMET concept – Overview of work at IKE", *EUROCORE, Contract FIKS – CT1999–20003*, Institut für Kernenergetik und Energiesysteme, Universität Stuttgart, Germany.

[9] Bechta, V.S. et al, "Crucible-type Core Catcher for VVER -1000 Reactor," *Proceedings of ICAPP 2005*, Seoul, South Korea (May 2005).

[10] Farmer, M.T., Spencer, B.W., Kilsdonk, D.J., Aeschlimann, R.W., 1998, "Quick Look Data Report for COMET Test U2", *ANL/RE-98-1*, Argonne National Laboratory, Argonne, IL, USA.

[11] Farmer, M.T., Spencer, B.W., 2000, "A Review of the Database Pertaining to Ex-Vessel Debris Coolability", *ACEX-TR-C34*, Argonne National Laboratory, Argonne, IL, USA.

[12] Fisher, M., Farmer, M., 1991, "MACE MCCI Pretest M0 Test Data Report", *MACE-TR-C01*, Argonne National Laboratory, Argonne, IL, USA.

[13] Fink, J.K., Thompson, D.H., Armstrong, D.R., Spencer, B.W., Sehgal, B.R., 1995, "Aerosol and Melt Chemistry in the ACE Molten Core-Concrete Interactions Experiment", *High Temperature and Material Science*, Vol. 33, p. 51-75.

[14] Paladino, D., 2000, "Investigation of Mechanisms for Melt Coolability with Bottom Coolant Injection", *Licentiate Thesis*, Department of Energy Technolgy, Division of Nuclear Power Safety, Royal Institute of Technology, Stockholm, Sweden.

[15] Paladino, D., Theerthan, S.A., Sehgal, B.R., 2002, "DECOBI: Investigation of Melt Coolability with Bottom Coolant Injection", *Progress in Nuclear Energy*, Vol. 40, 2, p. 161-206.

[16] Widmann, W., Bürger, M., Lohnert, G., 2002, "COMET Concept: Effects of Non-Porous Regions and Resulting Design Options", *Annual Meeting on Nuclear Technology*, Stuttgart, Germany.

[17] Abdulla, S.H., 2003, "Liquid-Metal/Water Direct Contact Heat Exchange", *Ph.D. Thesis*, University of Wisconsin –

Madison, Department of Mechanical Engineering, Madison, Wisconsin.
[18] Liu, X., 2003, "Flow Visualization and Void Fraction Measurement in Liquid-Metal/Water Direct Contact Heat Exchange by X-ray Attenuation Technique", *Ph.D. Thesis*, University of Wisconsin – Madison, Department of Engineering Physics, Madison, Wisconsin.
[19] Klockow, K., 2004, "Molten Pool Quenching Phenomena: Stability and Heat Transfer with Multiphase Injection", *Ph.D. Thesis*, University of Wisconsin – Madison, Department of Mechanical Engineering, Madison, Wisconsin.
[20] Annunziato, A., Leva, G., 1994, "FARO TEST DATA PACKAGE – TEST L-14", *Commission of the European Communities, Join Research Centre, Safety Technology Institute, Thermodynamics and Radiation Physics Unit*.
[21] Cho, D., 2004, Nuclear Engineering Research Initiative, "Interfacial Transport Phenomena and Stability in Liquid-Metal/Water Systems", *Final Report*, DOE-DE-FG03-99SF21928.