Study on Protective Layer for Severe Accident Conditions for EC6 Reactor Vault Structure

H. H. Abrishami [1], R. Ricciuti [1] and A. Khan [1] and R. Singh [1]
[1] Candu Energy Inc., Mississauga, Ontario, Canada
(homayoun.abrishami@candu.com)

Abstract

The Enhanced CANDU 6® (EC6®[1]) is designed both for the prevention and mitigation of Design Basis Accidents (DBAs) as well as Beyond Design Basis Accidents (BDBAs). The foremost objective, in accordance with the safety goals specified in the CNSC Regulatory Document (RD-337) [1], is to prevent the occurrence of any accident that could jeopardize nuclear safety, and, if an accident should occur, to limit the radiological releases resulting from the accident and minimize the impact on nearby communities.

During a postulated severe core accident, Molten Core-Concrete Interaction (MCCI) may occur when molten core debris breaches the calandria vessel and contacts concrete surfaces, whereby the thermal and chemical properties of the melt contribute to the potential degradation of the concrete. The earliest phase of MCCI is characterized by very-high-temperature molten metal and oxide pouring from the calandria vessel and settling as a pool on the concrete surfaces of the vault floor. The molten material can result in spalling or fragmentation of the concrete near where the corium first contacts the concrete. As the corium settles on the concrete surface, the melt begins to react chemically with the concrete through the penetrating cracks and fragments produced on the initial contact, generating various gases including carbon monoxide and combustible hydrogen.

In order to control and mitigate MCCI, a protective layer (refractory material) with suitable material properties and sufficient thickness was proposed to protect the reactor vault concrete floor. To further enhance vault floor protection and mitigate the conditions under severe accidents a special concrete composition in the upper layer of the vault floor concrete is to be provided in case the refractory material is breached. This special concrete should minimize the generation of various gases including combustible hydrogen and carbon monoxide during MCCI.

As a part of research and development program an experimental study has been proposed to qualify refractory material to meet the CNSC requirements. This paper presents the outcome of this research study.

1. Introduction

During a postulated severe core accident, Molten Core-Concrete Interaction (MCCI) may occur when molten core debris breaches the calandria vessel and contacts steel liner andconcrete surfaces, whereby the thermal and chemical properties of the melt contribute to the potential degradation of the concrete. The earliest phase of MCCI is characterized by very-high-temperature molten metal and oxide pouring from the calandria vessel and settling as a pool on the concrete surfaces of the vault floor. The molten material can result in spalling or fragmentation of the concrete near where the corium first contacts the

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concrete. As the corium settles on the concrete surface, the melt begins to react chemically with the concrete through the penetrating cracks and fragments produced on the initial contact, generating various gases including carbon monoxide and combustible hydrogen. The phenomena described apply to the reference design.

Obviously, the ideal objective of using refractory material is to protect concrete, however, in reality the refractory material will slow the rate of molten core penetration to concrete. This is an additional design feature in our severe accident management strategy in accordance with the defense in depth philosophy.

The Enhanced CANDU 6 (EC6®) is designed both for the prevention and mitigation of Design Basis Accidents (DBAs) as well as Beyond Design Basis Accidents (BDBAs). The foremost objective, in accordance with the safety goals specified in the CNSC Regulatory Document (RD-337) [1], is to prevent the occurrence of any accident that could jeopardize nuclear safety, and, if an accident should occur, to limit the radiological releases resulting from the accident and minimize the impact on nearby communities.

2. CNSC Requirements and Expectations

CNSC Regulatory Document RD-337 [1] contains numerous requirements related to prevention and mitigation of severe accidents. The highest level requirements, against which the adequacy of the design is measured, are the Safety Goals (4.2.4), the requirements for Accident Mitigation and Management (4.2.4), and the containment performance requirement (7.3.4). Safety goals have been established by the CNSC in RD-337.

As per RD-337 [1] the containment is an integral part of the defence in depth concept associated with its severe core damage prevention and mitigation philosophy. Clause 7.3.4 defines the following requirement for containment performance:

> *"Containment maintains its role as a leak-tight barrier for a period that allows sufficient time for the implementation of off-site emergency procedures following the onset of core damage. Containment also prevents uncontrolled releases of radioactivity after this period."*

The containment performance requirement is intended to ensure that the containment structure can withstand the loads associated with severe accident challenges, and that the potential for radioactive releases from the containment is minimized.

3. EC6 Strategy for MCCI

The Enhanced CANDU 6® (EC6) design consists of an appropriate combination of preventative and mitigative features which prevent uncontrolled radioactive releases during a severe accident, including a severe core damage (SCD) accident. A severe core damage accident results from an initiating event (or combination of events) followed by a series of failures of mitigating actions (including operator actions), resulting in extensive physical damage to the core such that the fuel bundles and channels would be disabled either by mechanical fracture or by melting. As a result, core coolability is compromised. For EC6, a severe accident is defined as having more than one fuel channel fail under accident conditions.

The EC6 includes a number of complementary design features for defence in depth against unlikely severe accidents involving failure of the calandria vessel including protective layer (refractory material). The primary defense is In-Vessel Retention (IVR) and this phenomenon occurs if IVR fails. The protective layer slows the rate at which the corium penetrates through the floor and delays generation of non-condensable gases that would be generated due to MCCI, which would also contribute to containment pressurization. A protective layer on the floor of the calandria vault resists the extremely high temperatures of the corium discharged into the calandria vault, minimizing generation of non-condensable gasses due to concrete-corium interaction (CCI), and prolongs the available time between onset of the event and challenge to the containment structure due to overpressure or a potential melt-through breech.

4. Experiences from Other Nuclear Power Plant Design Features

This section provides the design features of NPP vendors to control/mitigate MCCI during severe accidents. The design philosophy with respect to severe accident given by GE-Hitachi Nuclear Energy for ESBWR [2], Westinghouse Electric Company LLC for AP 1000 [3], and AREVA NP Inc. for US EPR [4] are described below. Among the above design features, only US EPR used protective layer and sacrificial concrete in its design to provide a stage of temporary melt retention.

4.1 ESBWR Design Philosophy

The ESBWR is designed to minimize the effects of direct containment heat, ex-vessel steam explosions, and core-concrete interaction. The ESBWR containment is designed to a higher ultimate pressure than conventional BWRs. The Basemat internal Melt Arrest Coolability (BiMAC) device is designed to prevent core-concrete interactions (see Fig.1). During the severe accident, BiMAC device is intended to provide coolability and eliminates the uncertainty of ex-vessel debris coolability and core-concrete interaction gas generation. The lower drywell floor is designed with sufficient floor space to enhance debris spreading, and also contains the BiMAC device to protect the containment liner and basemat. The debris bed cooling limits basemat penetration, radiated heat and non-condensable (not easily condensed by cooling) gas generation due to core-concrete interaction. The core debris coolability analysis shows that BiMAC device is effective in containing the potential core melt releases from the Reactor Pressure Vessel (RPV) in a manner that assures long-term coolability and stabilization of the resulting debris. Therefore, the possibility of corium-concrete interaction is negligible.

The BiMAC device provides an engineered method to assure heat transfer between a core debris bed and cooling water in the lower drywell during some severe accident scenarios. Waiting to flood the lower drywell until after the introduction of core material minimizes the potential for energetic fuel-coolant interaction. Covering core debris with water provides scrubbing of fission products released from the debris and cools the corium, thus limiting off-site dose and potential core-concrete interaction.

The BiMAC device provides additional assurance of debris bed cooling by providing engineered pathways for water flow through the debris bed. BiMAC failure could occur if no water is supplied. The BiMAC device is not safety-related.

The BiMAC function has been developed to a conceptual level, with several design details that are not yet finalized. These details are needed to justify the target failure probability of less than 1.0 x 10^{-3}. BiMAC plays an important role in mitigating core melt scenarios.

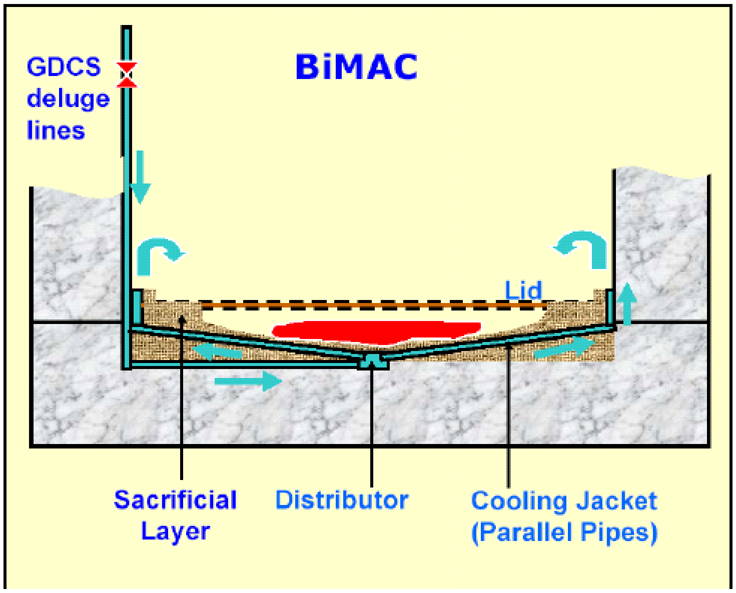

Figure 1 BiMAC System in ESBWR

4.2 AP 1000 Design Philosophy

The AP1000 design incorporates ERVC (External Reactor Vessel Cooling) as a strategy for retaining molten core debris in-vessel in severe accidents. The objective of ERVC is to remove sufficient heat from the vessel exterior surface so that the thermal and structural loads on the vessel (from the core debris which has relocated to the lower head) does not lead to failure of the vessel. By maintaining RPV (Reactor Pressure Vessel) integrity, the potential for large releases due to ex-vessel severe accident phenomena (i.e., ex-vessel Fuel-Coolant Interactions (FCIs), and Core-Concrete Interactions (CCIs)) is eliminated.

The AP1000 reactor cavity design incorporates features generally consistent with the Electric Power Research Institute's (EPRI) Utility Requirements Document (URD) guidance, including the following:

- a cavity floor area and sump curb that provides for debris spreading without debris ingression into the reactor cavity sump
- a manually actuated reactor cavity flood system that would cover the core debris with water and maintain long-term debris coolability
- a minimum 0.85-m (2.8-ft) layer of concrete to protect the embedded containment shell, with an additional 1.8 m (6 ft) of concrete below the liner elevation

The enhanced capability to retain a molten core in-vessel, in conjunction with these design features, results in a low expected frequency of basemat melt-through in the AP1000.

Compared to other advanced light-water reactors (ALWRs), the AP1000 ex-vessel debris bed is deeper and the concrete basemat is thinner. The AP1000 design does not impose any restrictions on the type of concrete that can be used for the containment basemat and the reactor cavity walls. Although these factors tend to increase the severity of basemat erosion, analyses using the MELTSPREAD and Modular Accident Analysis Program (MAAP) codes indicate that in the event of unabated CCI, containment basemat penetration or containment overpressurization will not occur until after 2 days, regardless of concrete composition. For a limestone basemat, which maximizes noncondensable gas generation and minimizes concrete ablation, basemat penetration would occur after about 3 days following the onset of core damage. Containment pressure will not reach the applicant’s Service Level C estimate (728.8 kPa (91 psig)) until even later. Use of basaltic concrete, which maximizes concrete ablation and minimizes noncondensable gas generation, would reduce the time of basemat melt-through to about 2 days, but containment pressure would not reach Service Level C until much later. Thus, in the event that core debris is not retained in vessel, the AP1000 design provides adequate protection against early containment failure and large releases resulting from CCIs.

4.3 AREVA US EPR Design Philosophy

A depiction of the U.S. EPR Reactor Building is provided in Figure 2. The reactor cavity utilizes a combination of sacrificial concrete and a protective layer of refractory material to provide a stage of temporary melt retention. The melt plug and gate are located in the reactor cavity and support the melt retention concept by providing a pre-defined failure location. The melt discharge channel utilizes a steel duct lined with refractory material to direct the conditioned melt from the reactor cavity to the lateral spreading compartment. The spreading area consists of a dedicated cooling structure lined with sacrificial concrete to promote stabilization of molten core debris.

Although the limestone common sand (LCS) and siliceous concrete would be able to meet the objective of sufficient stability and mechanical properties, in comparison to siliceous concrete, LCS concrete has the drawback of releasing significantly more non-condensable gas, particularly CO_2, which would result in an increased pressure in the containment. Therefore, in view of the low gas content objective, LCS concrete was rejected and siliceous concrete selected as the base material. The sacrificial layer consists of a 19.7 in (500 mm) layer of siliceous concrete with high iron-oxide content. In view of low gas content, Iron-oxide contributes favourably to oxidizing Zr and U.

The melt discharge channel consists of a steel structure that is embedded within the structural concrete of the containment. The bottom, side walls and top of this structure are layered with refractory material. This protective layer consists of zirconia bricks which have a low thermal conductivity and greater mechanical strength than concrete.

The spreading area consists of an approximately 1872 ft^2 (170 m^2) horizontal concrete surface over which the molten core debris can be dispersed. Spreading increases the surface-to-volume ratio of the molten core debris to ensure fast and effective stabilization via subsequent cooling.

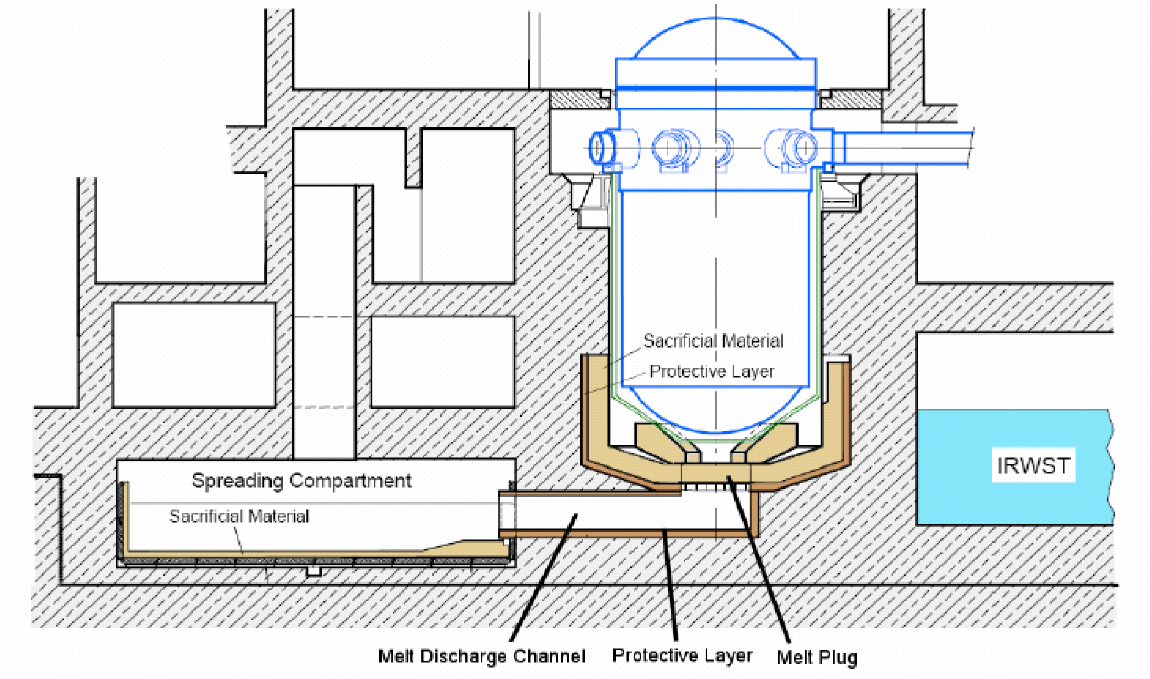

Figure 2: Core Melt Stabilization System (U.S. EPR)

5. Proposed Refractory Material for EC6 Reactor Vault

A 300 mm thickness of refractory material is proposed to be placed on the top of the calandria vault steel liner. Refractory material selected for the protective layer is expected to maintain integrity (thermal stability) and have low thermal conductivity, high specific heat and density in order to minimize heat transfer to the reactor vault concrete floor.

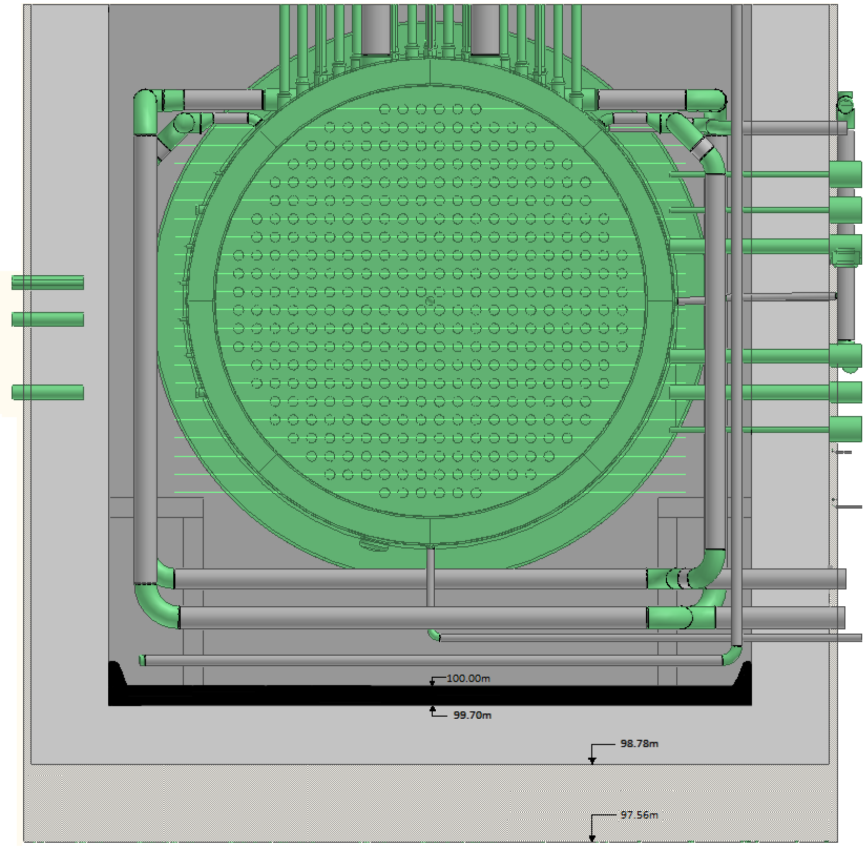

Figure 3 Design layout for refractory material

6.1 Characteristics of the Refractory Material

The term refractory refers to the quality of a material to retain its strength at high temperatures. ASTM C71 defines refractories as "non-metallic” materials having those chemical and physical properties that made them applicable for structures, or as components of systems, that are exposed to environments above 1000 °F (538 °C). Refractory materials are used in linings for furnaces, kilns, incinerators and reactors. They are also used to make crucibles. Refractory materials are used extensively in the metal industries, along with glass melting and other heat treatment operations.

Refractory materials must be chemically and physically stable at high temperatures. Depending on the operating environment, they need to be resistant to thermal shock, be chemically inert, and/or have specific values of thermal conductivity and of the coefficient of thermal expansion.

Obviously refractory material may lose the strength during MCCI. However, the refractory material is not load bearing and that the special concrete below it can handle all the loads at high temperature. The refractory material is not a load bearing material and pipe supports cannot penetrate through the refractory to the concrete surface. Thus pipe supports cannot be supported from the floor of the Calandria vault with a refractory cover.

The oxides of aluminum (alumina), silicon (silica) and magnesium (magnesia) are the most important materials used in the manufacturing of refractories. Another oxide usually found in refractories is the oxide of calcium (lime). Fireclays are also widely used in the manufacture of refractories.

The refractory material must be capable of being cast in the field for the depth and extent required without cracking or otherwise losing its effectiveness in workability, curing and finishing.

6.2 Acceptance Criteria for Selecting Refractory Materials

As a basic criterion there are three major parameters with respect to the selecting refractory materials. The selected refractory material shall meet the following criteria:

- Maximize melting temperature of refractory material with sufficient margin of safety for corium temperature > 2400 ^{o}C;
- Minimize heat transfer to the reactor vault concrete floor and therefore appropriate thermophysical properties such as thermal conductivity, specific heat and density; and
- Minimize chemical reaction of refractory material with molten core.

Refractory materials for use a protective layer in the calandria vault floor must be chemically and physically stable at high temperatures and resistant to degradation from radiation exposure. In addition, the refractory material should not have negative impact on the containment response in the long term.

In order to meet the above acceptance criteria, several refractory material candidates were studied and investigated. Among the material candidates, the ones with higher ranking evaluation were selected for experimental R&D program.

7. R&D Program

An R&D program is being undertaken to select a suitable refractory material that can meet the acceptance criteria specified above. The program involves experimental tests to select a suitable refractory material layer which protects the reactor vault concrete floor in the event of severe accident. This research program is near completion. Three promising refractory material candidates, Thoria, Urania, and Zirconia (see Figure 4), are being tested. Successful completion of the program will enable designers to select a qualified refractory material to meet the design requirements.

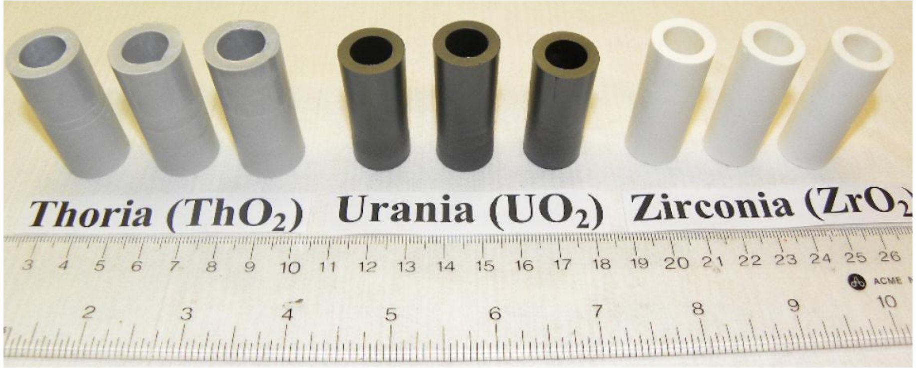

Figure 4 EC6 Refractory material candidates for R&D experiments

8. Summary and Conclusions

The Enhanced CANDU 6® (EC6) design consists of an appropriate combination of preventative and mitigative features which prevent uncontrolled radioactive releases during a severe accident, including a severe core damage (SCD) accident.

In addition to a number of complementary features, in order to control and mitigate MCCI, a protective layer (refractory material) with suitable material properties and sufficient thickness was proposed to protect the reactor vault concrete floor. To further enhance vault floor protection and improve containment performance under severe accidents a special concrete composition in the upper layer of the vault floor concrete is to be provided in case the refractory material is breached. This special concrete should minimize the generation of various gases including combustible hydrogen and carbon monoxide during MCCI.

Refractory material selected for the protective layer is expected to maintain integrity (thermal stability) and have low thermal conductivity, high specific heat and density in order to minimize heat transfer to the reactor vault concrete floor. Refractory materials for use as protective layer in the calandria vault floor must be chemically and physically stable at high temperatures and resistant to degradation from radiation exposure. In addition, the refractory material should not have negative impact on the containment response in the long term.

An R&D program is being undertaken to test three refractory material candidates leading to the selection of a suitable material for incorporating in the EC6 design. Successful completion of the program will enable designers to select a qualified refractory material to meet the design requirements.

9. References

[1] CNSC Regulatory Document RD-337 "Design of New Nuclear Power Plants", CNSC, November 2008.

[2] ESBWR Design Control Document, Tier 2, Chapter 19, Probabilistic Risk Assessment and Severe Accidents, GE-Hitachi Nuclear Energy, 26A6642BY, Revision 4, September 2007

[3] Chapter 19, Severe Accident, AP 1000 Design Control Document (DCD), Revision 14, Westinghouse Electric Company LLC, 2004.

[4] U.S. EPR Severe Accident Evaluation, Topical Report**,** ANP-10268NP, Revision 0, October 2006