

Station Blackout Scenario Analysis for the Enhanced CANDU 6[®] (EC6)¹ Reactor Design

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ABSTRACT

After the Fukushima accident in Japan in 2011, a thorough safety review of nuclear power plants (both current and new build designs) has been performed to confirm their plant provisions to deal with the Station Blackout (SBO) event. The SBO event involves loss of alternating current (AC) electrical power sources and potential loss of the ultimate heat sink. The safety reviews by the nuclear operators, regulators and nuclear power plant designers have confirmed the robustness of the current CANDU reactor designs and have identified improvements to plant features to further reduce the risk of radioactive releases to the environment.

This paper illustrates the robustness of the Enhanced CANDU 6 (EC6[®]) reactor design in preventing the onset of severe core damage and mitigating the consequences for typical SBO scenarios. The EC6 reactor design has been enhanced over the current CANDU 6 reactor designs by including specific complementary design features, e.g., severe accident recovery and heat removal system (SARHRS), and more a robust containment design, to meet modern regulatory expectations (such as those described in the Canadian Nuclear Safety Committee (CNSC) regulatory document, RD-337). The severe accident progression and consequence analyses for the SBO event using MAAP4-CANDU [1] is presented to illustrate the failure of multiple barriers that would have to occur (e.g., loss of emergency core cooling, loss of moderator cooling, loss of shield cooling) and the time available for actions to arrest the accident progression and mitigate the consequences. The concurrent and/or consequential failure of these multiple barriers has a very low probability of occurrence for the EC6 design.

1. INTRODUCTION

The EC6 reactor [2] is an evolution of the proven CANDU 6² design most recently built at Qinshan site in China. It retains the fundamental core design of the CANDU 6 reactor, a heavy-water- moderated, heavy-water-cooled horizontal pressure tube reactor using natural uranium fuel. While retaining the basic features of the CANDU 6 reactor design, the EC6 reactor incorporates innovative features and state-of-the-art technologies that enhance safety, operation and performance.

After the Fukushima event, nuclear operators, regulators and nuclear power plant designers performed systematic reviews of nuclear power plant designs to confirm the plant robustness to cope with an SBO event, and to identify improvements to further reduce the risk of radioactive releases to the environment. This paper presents a summary of the systematic review of the EC6 reactor design, to confirm the robustness for an SBO event. This paper describes:

- 1) The design features of the EC6 reactor design to address the SBO event,
- 2) Assesses the loss of normal on-site and off-site power, on-site backup power sources and loss of heat sinks to indicate how long the reactor can withstand the situation before damage to the fuel becomes unavoidable and

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- 3) The severe accident progression for severe core damage when assumptions are made that prevention of severe core damage is not effective. The severe accident progression and consequence analysis for the SBO event uses MAAP4-CANDU Version 4.0.7 [1].

2. DESIGN FEATURES OF THE EC6 REACTOR

Each unit of the EC6 reactor design has the following electrical power sources:

- The normal Class IV power from on-site and offsite power sources of the turbine generator and the electrical grid (Level 1 defence-in-depth);
- Backup to the Class IV power from two redundant Class III standby diesel generators with 10 hours of fuel supply from day tanks and in-door tanks (Level 2 defence-in-depth); Fuel reserve of 7 days supply from out-door fuel tanks to support each standby diesel generator (Level 3 and 4 defence-in-depth);
- An emergency power supply (EPS) from two redundant, seismically qualified emergency diesel generators with four hours of fuel supply from fuel day tanks (Level 3 defence-in-depth); Fuel reserve of 7 days supply from main fuel tanks to support each EPS diesel (Level 3 and 4 defence-in-depth);
- Seismically qualified batteries and uninterruptible power supplies (Class II and Class I power) with capacity for at least 24 hours (before needing to be recharged) (Level 3 defence-in-depth);
- A dedicated diesel generator for the severe accident recovery and heat removal system with 7 days fuel supply (SARHRS) (Level 4 defence-in-depth);
- Engineered electrical connections to facilitate connection of portable power sources to recharge the batteries and uninterruptible power supplies after 24 hours; (Level 4 defence-in-depth);
- Engineered electrical connections to facilitate connection of portable power sources to provide AC power to replace the permanent emergency power generators (Level 5 defence-in-depth), and
- Engineered electrical connection to facilitate connection of a portable power source to provide AC power to replace dedicated diesel generator for SARHRS (Level 5 defence-in-depth).

The primary Ultimate Heat Sink (UHS) is based on decay power heat removal using forced circulation in the Primary Heat Transport System (PHTS). The preferred way to remove the decay power is using the shutdown cooling system (SDCS). SDCS transfers the heat to the closed loop Recirculated Cooling Water (RCW) system through its heat exchangers. The RCW system transfers the heat to the Raw Service Water (RSW) system through its heat exchangers, and the heat is dissipated into a local body of water. After reactor shutdown, the SDCS represents the main system of the primary UHS. The system is interconnected with the PHTS by opening isolation motorized valves

Each unit of the EC6 reactor design has the following alternate ultimate heat sinks relevant to the loss of AC power and loss of forced circulation decay power heat removal:

- Main Feedwater System, operating on Class IV power, to remove decay heat from the primary heat transport system through the steam generators via natural circulation or thermosyphoning (Level 1 and 2 defence-in-depth);

- Auxiliary Feedwater System, operating on Class IV and III power, to remove decay heat from the primary heat transport system through the steam generators via natural circulation (Level 2 and 3 defence-in-depth);
- Atmosphere Steam Discharge Valves (ASDVs)/ Condensate Steam Discharge Valves (CSDVs), operating on Class II power, automatically open to relieve steam from the SG secondary side (Level 1 and Level 2 defence-in-depth);
- Main Steam Safety Valves (MSSVs) crash cool-down mode, operating on Class II power, automatically open to relieve steam from the steam generator's (SG) secondary side (Level 3 defence-in-depth);
- Reserve Water Tank (RWT) has 7 days capacity to supply water to the steam generators via the Emergency Heat Removal System (EHRS) piping, by manually opening isolation valves that operate on Class II power (Level 3 defence-in-depth);
- EHRS, operating on the EPS, can provide make up water after the RWT is exhausted (Level 3 defence-in-depth);
- SARHRS, operating on its dedicated diesel generator, to refill the RWT and extend the availability of water to the steam generators for additional 7 days to allow the operators sufficient time to re-establish power to the normal systems. SARHRS can also provide water makeup to the calandria vessel and calandria vault, if necessary, and heat removal from containment through its containment heat removal pump. (Level 4 defence-in-depth); and
- Engineered water connections to facilitate connection of portable water sources to provide makeup water in place of the SARHRS (Level 5 defence-in-depth).

3. SBO PLUS LOSS OF PRIMARY ULTIMATE HEAT SINK EVENT

The postulated SBO event involves the loss of the following AC power sources:

1. Class IV power (off-site and on-site sources)
2. Class III power from both standby diesel generators and
3. Emergency power supply from both seismically qualified emergency diesel generators.

As a consequence of the SBO event, the primary UHS is lost:

- Forced circulation in the PHTS stops, and only thermosyphoning is available; and
- Heat removal via the SDGS to the RCW/RSW systems is not available.

Thermosyphoning in the PHTS is maintained by:

- Automatic opening of the MSSVs, which operates on the available Class II power source, to relieve steam from the secondary side of the steam generators; and
- Automatic water make-up to the secondary side of the steam generators from the RWT when the isolation valves, which operate on the available Class II power source, open on the EHRS piping. After the RWT water inventory is exhausted, water make-up can be supplied from the EHRS, if power is available to the EHRS pumps, or from the SARHRS. The SARHRS is credited to be available because it has a separate dedicated diesel generator.

The typical initial plant conditions are provided in Table 1 for consequence analyses when it is assumed that severe core damage cannot be prevented. The main assumptions used in the MAAP4-CANDU analyses are:

- After channel rupture, it is assumed that there is no coolant drainage from failed bellows to the containment due to the pressure tube/calandria tube rupture.
- The degasser condenser is not simulated directly. The degasser condenser relief valves (DCRVs) in the pressure and inventory control system are simulated to connect between the PHTS and the containment directly.
- When the suspended debris bed mass (variable MLOAD) for a loop exceeds 12,000 kg, the channels in that loop are assumed to relocate to the bottom of the calandria vessel (triggering a massive core collapse).
- When the water level in the calandria vault decreases below the elevation of the top of the corium, the calandria vessel is conservatively assumed to fail.
- For all cases, the following systems are not credited: Class IV power, Class III power, EPS, Emergency Heat Removal System, moderator cooling, Medium Pressure Emergency Core Cooling (MPECC), Low Pressure Emergency Core Cooling, recirculated cooling water, raw service water, shield cooling system, Local Air Coolers cooling coils and fans, Containment Spray, hydrogen control system.
- For all cases, the following systems are credited: reactor shutdown, loop isolation, Main Steam Safety Valve (MSSV) over-pressurization-protection-mode.
- In this analysis, the containment is assumed to fail when the pressure exceeds 2.5 times the design pressure.

A summary of the main assumptions for the selected MAAP4-CANDU simulations is given in Table 2.

4. ANALYSIS RESULTS

4.1 Reference Case

At the onset of the SBO, all equipment that contributes to the functioning of the primary UHS is lost (i.e., SDCS), because all AC power from the Class IV, Class III, and EPS system are assumed to be lost. Furthermore, the loss of AC power causes the main and auxiliary feedwater pumps to be unavailable. In this scenario, the MSSVs open to depressurize the SG secondary side. The immediate source of water to the steam generator's secondary side is provided by gravity-driven flow from the RWT to maintain the SG as an effective heat sink.

This case is referred to as a reference case, which is summarized in Table 2. The major event sequence for this case is provided in Table 3.

In this scenario (the reference case), the nuclear safety functions are ensured as follows:

Shutting down the reactor and maintaining in a safe shutdown condition: On loss of Class IV power, the reactor is automatically shut down and maintained sub-critical by the actuation of Shutdown Systems 1 and 2 (SDS1 and SDS2). Monitoring of the status of SDS1 and SDS2 continues to be available because they are supplied from Class I and II electrical power.

Containment integrity: Heat is removed from containment by one of the following:

- Containment spray using SARHRS, absorbing steam heat inside the containment, or
- Heat exchanger using SARHRS, which has a containment heat removal pump powered by its dedicated diesel generator.

The containment will remain in a leak-tight condition with the following features:

- The containment stresses do not exceed Factor Load Category limits for concrete containment for a period following the onset of core damage that is sufficient to allow implementation of off-site emergency measures.
- Emergency filtered containment venting to protect containment integrity and avoid uncontrolled radioactive releases to the environment.

Core cooling function: Figure 1 illustrates the coolant inventory transient history for the progression towards severe core damage during the SBO. From this transient history, the key times for taking actions are identified. The following is a description of key points in the accident progression for the core cooling function:

- **Early transient:** The decrease in power when SDS1 and SDS2 actuation causes the PHTS pressure to decrease and the coolant volume to shrink.
- **After 20 minutes:** The SG low level signal is triggered due to the decrease in the water level in the SGs as a result of boil-off. After 20 minutes, the crash cooldown is predicted by opening the MSSVs to depressurize the SG secondary side. Only one of the MSSVs in each SG is needed to successfully depressurize the SG secondary side.
- **Make-up to SGs from RWT:** Gravity-driven water makeup is provided from the RWT to the SGs when the isolation valves on both the large and small pipes from the RWT to the SGs are opened due to the SG pressure dropping below the hydrostatic head of the RWT. The pressure in the SGs decreases because the SG water inventory is continuously lost via the open MSSVs. The power required to operate these valves is supplied from the available Class II power, which has a capacity of 24 hours.
- **RWT inventory depleted:** After 24 hours, it is assumed that Class II power is no longer available to keep the large pipe valve from the RWT to the SGs open. However, makeup from the RWT to the SGs keeps flowing via the small pipe until the allocated water in the RWT is used up; this occurs at 85.1 hours.
- **PHTS inventory:** Due to the SG crash cooldown, the PHTS pressure decreases to below the pressure for initiation of high pressure ECC injection into the PHTS from the ECC accumulator tanks. The high pressure injection of passively cool water begins at 0.5 hours and ends at ~ 8.9 hours, during which time the PHTS remains full of water.
- **SGs Heat sink:** As a result of the coolant inventory loss through the DCRVs, coolant phase separation occurs in both PHTS loops at ~39.6 hours. While thermosyphoning in the PHTS has broken down due to phase separation, heat transfer from the PHTS coolant to the secondary side continues via reflux condensation through the cold SG U-tubes.
- **RWT refilling by SARHRS:** After the initial RWT inventory is exhausted, the SARHRS containment heat removal pump, driven by the SARHRS dedicated diesel generator, would be manually initiated to refill the RWT from the forebay to the RWT for continued fuel cooling and preventing continued progression of core damage. There is adequate

time (up to 85 hours) to manually start up the SARHRS to ensure that the RWT can provide continuous make-up to the SGs to remove the decay heat. Up to 7 days fuel supply on-site is available for the SARHRS operation.

- **RWT refilling by portable sources:** If the SARHRS diesel generator fails, engineered electrical connections to facilitate connection of portable power sources are available to provide AC power to replace the SARHRS diesel generator. As shown by the time history, there is sufficient time for connecting on-site portable power sources and/or off-site portable power sources for the long-term operation to remove the core decay heat, if the off-site Class IV power has not been restored.
- After the RWT inventory allocated for the SGs is depleted, in the absence of any further water make-up to the SG secondary side, the remaining water inventory in the SGs heats up and boils off. The SGs as an effective heat sink to the PHTS coolant are compromised. As the PHTS coolant temperature increases, the PHTS pressure increases until the PHTS reaches the liquid relief valve setpoint. The pressure in the PHTS then oscillates at the relief valve setpoint, and the coolant inventory in the PHTS is slowly lost. After the RWT is depleted, it is predicted to take 7.8 hours to have the first channel become dry. The core channel disassembly starts at ~ 111.4 hours, followed by the core collapse 5.3 hours later.
- **Monitoring of the critical safety parameters** remains available from the main control room, as long as the batteries are available, i.e., for about 24 hours. After the EPS bus power is re-energized (e.g., by connecting mobile diesel generators to recharge the batteries), plant monitoring is performed from secondary control area.

This scenario has identified the following cliff edge effects:

- Loss of batteries after 24 hours. Recharging the batteries requires use of a portable power source or recovery of the EPS emergency power generators. Recovering the Class II power within 24 hours would enable the RWT provide makeup water to the SGs to remove decay heat and avoid severe fuel damage for more than 7 days.
- Loss of SG secondary side as a heat sink after ~85 hours. To avoid loss of the SG secondary side as a heat sink to the PHTS, water makeup from the SARHRS or from a portable water source is needed.
- Loss of PHTS inventory after ~92.9 hours. To avoid internal dry out to the fuel, water make-up to the PHTS is from the EHRS or from a portable water source is needed.

4.2 Sensitivity Cases

The following summary of analysis results for few sensitivity cases is also presented to illustrate the severe progression.

Fewest Systems Available for Mitigation (Sensitivity Case A)

Case A has the fewest systems available for slowing or mitigating the severe core damage accident consequences. The major event sequence is provided in Table 3.

The early transient includes the PHTS pressure decreases and coolant shrinks due to reactor shutdown. The SG pressure increases gradually until the pressure oscillates at the MSSV

setpoint; the water level in the SGs decreases as a result of the SG water boil-off. As the auto-depressurization of the SGs is not available, the make-up from the reserve water tank (RWT) to the SGs cannot be credited. The SGs become dry at ~3.1 h. Consequently, the PHTS pressure goes up and oscillates at the degasser condenser relief valve (DCRV) set-point, leading to PHTS coolant inventory reduction and increase of the containment pressure (Figure 2).

After the first channel dries at 4.9 h, the core starts to heat up. The zirconium-steam exothermic reaction contributes to the heat-up once the fuel and fuel channel are sufficiently hot, and in the presence of steam. Bundle deformation occurs and fuel relocates to lower element locations. Then, non-uniform heating of the pressure tubes at high internal pressure results in localized high stresses and strains, causing a PT and its CT to rupture in each loop. Such ruptures likely occur in a high bundle power location of a high power channel in both loops, since the loops are now isolated from each other. At this time, the pressure in the PHTS drops quickly and the remaining PHTS coolant inventory is discharged into the moderator.

At 5.0 h, the calandria vessel rupture disc opens due to channel ruptures to protect the calandria vessel. About 70 tonnes of moderator is expelled to the containment via the rupture disc (Figure 3), causing further increases of the containment pressure.

At 5.9 h, many channels in the broken loop start to disassemble and the fuel bundles and channels are assumed to turn into debris. At ~7.2 h, massive core collapse is predicted and the entire suspended debris bed and most of the intact channels relocate to the bottom of the calandria vessel (Figure 4), where they are quenched by the remaining water in the calandria vessel. After core collapse, Zr-steam reaction continues for the stubs of channels and low-power channels that remain intact. The total amount of hydrogen produced during the core heat-up and disassembly is ~ 170 kg from both loops.

At ~15.4 h the calandria vault starts to boil. At ~33 h the water level in the calandria vault reaches the top of the calandria vessel. At this time most of the decay heat is contained in the debris bed and results in the formation of a molten pool at the centre of the bed. At ~41.3 h the calandria vessel is assumed conservatively to fail when the calandria vault water level is below the top of the debris bed. All of the core debris is relocated out of the calandria vessel and onto the calandria vault floor. The relocation of the corium causes a sharp pressure spike (due to steam surge) in the containment since the 24-inch calandria vault rupture disc opens.

After corium is relocated into the calandria vault, the remaining water boils off and the calandria vault is dry at ~46.4 h. As the major decay heat of the corium transfers to the concrete floor of the calandria vault, the concrete floor temperature increases. At 49.6 h, molten corium concrete interaction (MCCI) occurs. After MCCI begins, a large amount of hydrogen is produced. Without any mitigation, the calandria vault floor is melted through ~112.4 h and all corium relocates into the reactor building basement. This corium relocation causes another pressure spike in containment (Figure 2) as the corium is quenched by water accumulated in the basement throughout the accident. The containment catastrophic failure is predicted at 113.2 h.

Impact of Make-up to the Calandria Vessel during Transient (Sensitivity Case B)

Case B has make-up to the calandria vessel from SARHRS available, compared with Case A. Before SARHRS is activated, the calandria vessel water temperature (Figure 5) rises up to nearly 100 °C due to the massive core heat load to the moderator water. An alarm to trigger the SARHRS is activated at 2.4 h. After half an hour, the operator can open the isolation valves and

initiate the water flow from the RWT to the calandria vessel at a rate of ~50 L/s. After channel rupture, the calandria vessel rupture discs open, about 70 tonnes of moderator is expelled. Consequently the calandria vessel water temperature increases to near saturation.

At ~10 h the water in the RWT available for injection into the calandria vessel is exhausted and SARHRS is switched to pump water from the lake into the calandria vessel at a rate of 200 L/s. As the injection flow rate is much higher for the pumped flow, the water temperature in the calandria vessel drops at a much faster rate.

The operator will switch the operation of SARHRS to the recirculation mode to avoid the flooding of the containment building. This operation mode provides a means of decay heat removal for up to 7 days, which provides sufficient time to return the off-site power or EPS back to service in order that the plant can be brought into a controlled, stable state for the long term.

Impact of Make-up to the Calandria Vault during Transient (Sensitivity Case C)

Case C credited water make-up to the calandria vault. The concern in this case is the integrity of the tube-sheets to support the in-vessel retention (IRV) strategy.

At 11.6 h, the water in the end shields reaches the saturation; more water loss is expected in the end shield. However, the faster water level decrease will add more driving force and put more water into the end shield from the calandria vault. Therefore, the water loss in the end shield goes slowly. At 16.9 h, the water level in the reactor vault is low enough to trigger the operator action to provide make-up from the RWT to the reactor vault.

The flow to the end shields, which is driven by the elevation difference of water levels between the calandria vault and the end shields, can mainly compensate for the inventory loss due to boil-off inside the end shields. It is preliminarily concluded that the IVR strategy works if the make-up to the calandria vault is available during the transient.

5. CONCLUDING REMARKS

In this paper, the EC6 reactor design features are described to address the SBO event. Assessment of cases with the loss of off-site power, on-site backup power sources and loss of heat sinks indicates that the multiple defence-in-depth provisions provide sufficient time to take mitigative actions before fuel damage occurs for a SBO event. Finally, the severe accident progression and consequence analysis are made for severe core damage scenarios when assumptions are made that prevention of severe core damage is not effective. The concurrent and/or consequential failure of these multiple barriers has a very low probability of occurrence for the EC6 design. The EC6 design has been demonstrated to be robust in terms of providing multiple sources of power and water and ample time for manual actions to restore core cooling functions, should a SBO occur.

6. REFERENCE

- [1] P.M. Mathew, S.M. Petoukhov and M.J. Brown, "An Overview of MAAP4-CANDU Code", 28th Canadian Nuclear Society Conference, Saint John, NB, June 3-6, 2007.
- [2] S. Yu, "EC6 Safety Enhancement – Including Impact of Fukushima Lessons Learned", 33th Canadian Nuclear Society Conference, Saskatoon, June 4-7, 2012.

Table 1 Example of Key Parameters of the EC6 Plant

Key Input Parameter Name	Units	Value
Total core power, including fission power and PHTS pump power	MW	2182
UO ₂ mass in the core	tonnes	99.3
Zircaloy mass in the core (including PTs and CTs)	tonnes	46.4
Coolant inventory in PHTS (with pressurizer)	tonnes	112
Water inventory in ECC accumulator tanks	tonnes	180
Water inventory in RWT	tonnes	2025
Water inventory (simulating an equivalent volume of D ₂ O) in calandria vessel	tonnes	219
Water inventory in calandria vault	tonnes	514
Water inventory in each SG secondary side	tonnes	39
Pressure to open calandria vault rupture discs	kPa (g)	69
Pressure to open calandria vessel rupture discs	kPa (g)	138
Containment free volume	m ³	48,000

Table 2 Summary of Selected Cases

System / Process	Reference Case	Sensitivity Case		
		Case A	Case B	Case C
MSSV opening for crash-cooldown	✓	N/C	N/C	N/C
Make-up from RWT to SGs	✓	N/C	N/C	N/C
ECC High Pressure	✓	N/C	N/C	N/C
Make-up to calandria vessel by SARHRS	N/C	N/C	✓	N/C
Make-up to Calandria vault by SARHRS	N/C	N/C	N/C	✓

Note: Check-mark “✓” means the system is credited; “Not Credited” (N/C) means that the system is not credited.

Table 3 Summary of Event Sequences for Selected Cases

Events	Reference Case	Sensitivity Case		
		Case A	Case B	Case C
SG dryout (h)	Not occur	3.1	3.1	3.1
First characteristic channel in Loop 1 dry (h)	92.9	4.9	5.0	4.9
Channel rupture starts (h)	N/A	4.9	5.0	4.95
Onset of severe core damage (h)	111.4	5.9	Not occur	5.9
Core collapse starts (h)	116.8	7.2	Not occur	7.2
Failure of calandria vessel occurs (h)	138.9	41.3	Not occur	N/A
MCCI starts (h)	Not occur	49.6	Not occur	N/A
Containment catastrophic failure occurs (h)	Not occur	113.2	Not occur	N/A

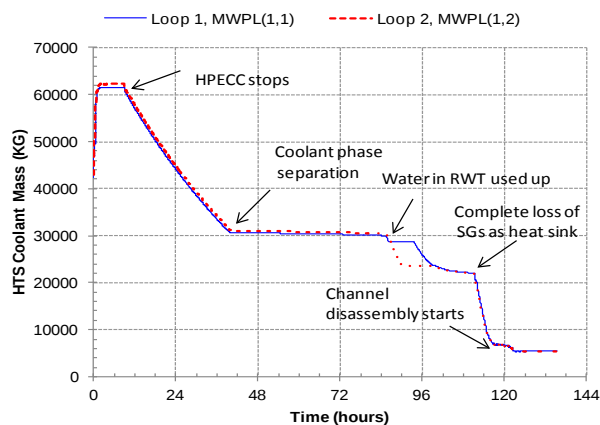


Figure 1 Reference Case: PHTS Water Inventory during an SBO

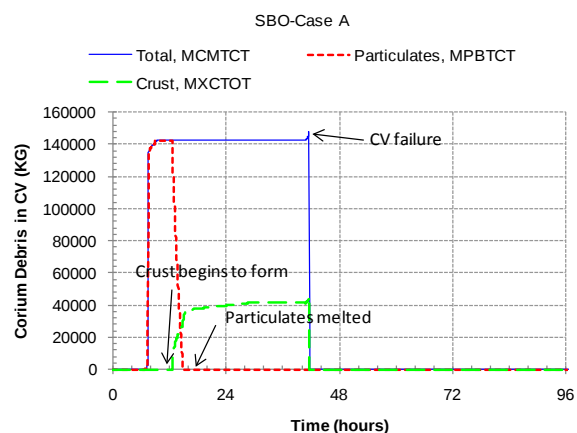


Figure 4 Sensitivity Case A: Mass of Corium Debris in the Calandria Vessel

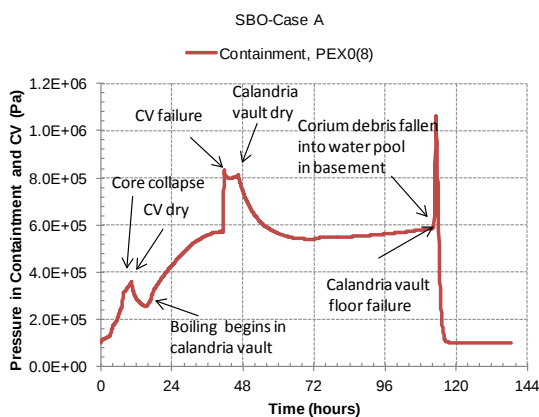


Figure 2 Sensitivity Case A: Calandria Vessel and Containment Pressures

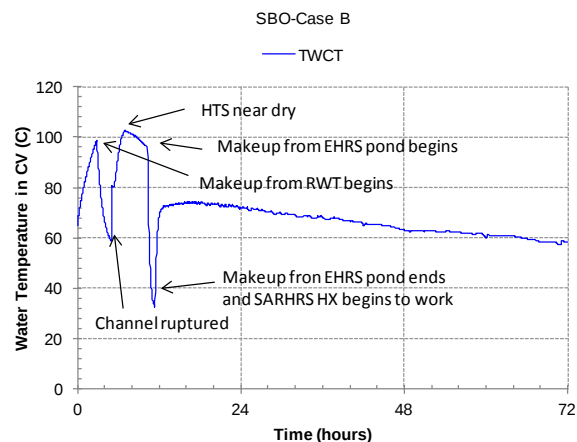


Figure 5 Sensitivity Case B: Water Temperature in Calandria Vessel

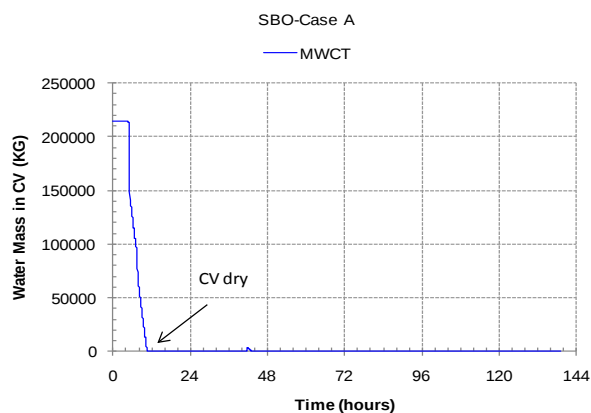


Figure 3 Sensitivity Case A: Calandria Vessel Water Mass