Severe Core Damage Accident Progression within a CANDU 6 Calandria Vessel

P. Mani Mathew, T. Nitheanandan and S.J. Bushby
AECL Chalk River Laboratories
Reactor Safety Division
Chalk River, Ontario, Canada, K0J 1J0

Introduction

This paper focuses on the current understanding of the progression of a severe core damage accident within a CANDU 6 calandria vessel and the supporting experimental research and analysis conducted at AECL. In general, the progression of a severe core damage accident in a CANDU reactor is slow because the fuel is surrounded by a large quantity of light and heavy water, which acts as a heat sink to remove the decay heat and the conditions leading to a severe accident and the disassembly of the core are slow processes. A short general description of the design of a CANDU 6 core is given at the beginning of this paper for a better understanding of the processes, which occur during the progression of a severe core damage accident.

General CANDU 6 Design Features

A CANDU 6 fuel bundle consists of 37 elements, which are arranged in circular rings, and each element consists of sintered natural uranium dioxide cylindrical pellets, which are contained in a Zircaloy-4 sheath closed at each end by an end cap. The fuel elements in a bundle are held together by end plates at each end with spacers providing the necessary separation between the elements. Bearing pads on the outer elements of the fuel bundle provide the necessary separation between the outer elements and a pressure tube. A pressure tube (PT) in a CANDU 6 contains 12 fuel bundles each and contains heavy water coolant, which is thermally insulated from a low-pressure cool moderator by a gas annulus formed between the pressure tube and the calandria tube (CT) surrounding it. Two end-fittings at each end of the fuel channel incorporate a feeder connection through which pressurized heavy water coolant enters and leaves the fuel channel. The feeders are connected to the reactor inlet and outlet headers. A CANDU 6 has two independent loops, containing 190 fuel channels in each loop and four steam generators with two in each of the loops. The fission heat produced in the fuel is transferred to the light water in the secondary side of the steam generators to produce steam, which drives the turbine generators to produce electricity.

The 380 fuel channels, each about 6 m long, are located in horizontal position, inside a horizontal cylindrical calandria vessel made of stainless steel and is surrounded by a low pressure heavy water moderator. Vertical and horizontal flux assemblies to provide accurate flux measurements and reactivity control devices are located between the rows and columns of the fuel channels. Fuelling machines connect to each fuel channel as necessary to allow on-power refuelling, which eliminates the need for refuelling outages. The calandria vessel is equipped with rupture discs, which open and relieve the pressure in case of unlikely accidents, which lead to a pressure increase in the calandria vessel. The calandria vessel is closed at each end by end-shields, which support the fuel channels and provide radiation shielding. The calandria vessel is housed in and supported by a light water-filled steel-lined concrete vault, called reactor vault or calandria vault, which provides thermal shielding.

Figure 1 shows a schematic of the CANDU 6 reactor. The figure shows the approximate inventory of heavy and light water, which surrounds the fuel and calandria vessel respectively. The significant quantity of heavy water surrounding the fuel acts as a heat sink to remove the decay heat after reactor shutdown.

Severe Core Damage Accident Progression

A severe core damage accident is an accident in which substantial damage is done to the reactor core, whether or not there are serious off-site consequences. These accidents have a very low probability and result in the loss of the geometry of the core. A number of safety systems prevent the reactor from reaching the conditions leading to a severe core damage accident.

There are two independent, diverse and fast acting reactor shutdown systems, in addition to the reactor regulating system, each capable of rapidly shutting down the reactor in any postulated accident scenario. The decay heat following shutdown is removed by the steam generator heat sink or a dedicated shut down cooling system. For loss-of-coolant accidents, the decay heat is removed by the Emergency Core Cooling System. Even in the unlikely failure of the decay heat removal systems, the moderator cooling system will prevent gross damage to the fuel and maintain fuel channel integrity [1]. In the unlikely event that the moderator cooling also fails, as in a severe core damage accident, the fuel channels would sag and collapse as the moderator boils off; but the core debris would still be contained within the calandria vessel as long as it remains cooled on the outside by the reactor vault water [2].

The various phenomena, which occur during the progression of a severe core damage accident in a CANDU 6, are described below.

Phenomena During Severe Core Damage Accident Progression

The various phenomena during a severe core damage accident are explained here by selecting a station blackout (SBO) accident sequence with the loss of class IV and all back up power including loss of all on-site standby and emergency electric power supplies. If the high pressure, medium pressure and the low pressure emergency core cooling, crash-cooling function, shut-down cooling and shield cooling systems are not available; the loops not isolated from each other, the local air coolers and operator intervention are assumed unavailable, the SBO the accident sequence can progress to a severe core damage accident [3]. The progression of such an unlikely accident is described here.

Primary Heat Transport System Behaviour

Following this postulated SBO scenario, the reactor is promptly shutdown by the shutdown systems. Since the primary heat transport system (PHTS) pumps are not available due to loss of power, the fuel heats up and the decay heat is transferred to the heavy water coolant. A temperature gradient develops between the coolant in the core and the steam generator region, which promotes natural circulation between the two regions. The decay heat is transferred to the secondary side of the steam generators, which results in a decrease in the PHTS pressure. The secondary side inventory of the steam generators boils off and with the deteriorating natural circulation, the PHTS pressure in the fuel channels increases and reaches the set point of the liquid relief valves (LRV), when the LRVs open and close to release the PHTS pressure. The PHTS inventory is lost through the LRVs and the fuel bundles begin to uncover within the pressure tubes.

The PHTS inventory is gradually lost through the LRVs resulting in fuel channel dryout. In parallel, the moderator heats up and the water level in the calandria vessel decreases gradually since moderator cooling is not assumed available. With the loss of moderator as a heat sink, a lead channel with the highest decay power and the smallest inventory in each loop, which is situated at a high elevation in the calandria vessel, reaches high pressures and temperatures such that the lead channel will not be able to sustain the pressures. As a result, a lead channel ruptures. With the rupture of the lead channel, the PHTS pressure drops rapidly and the loop inventory is blown down into the calandria vessel. With the rapid blow down of the PHTS inventory into the calandria vessel, the pressure inside the calandria vessel reaches the set point of the rupture disc and the calandria vessel rupture discs burst.

Moderator Behaviour

A significant quantity of the moderator inventory is discharged into the containment when the fuel channels rupture pressurizes the calandria vessel. This phenomenon occurs at approximately 4 to 5 hours into the accident. Several top fuel channel rows are uncovered during this process. After the initial rapid moderator expulsion, the moderator continues to discharge gradually into the containment as a result of the continued moderator boil off due to the heat transfer from the core. Figure 2 shows a schematic of the condition of a CANDU 6 core at this point in time.

Core Disassembly and Suspended Debris Bed Behaviour

With the loss of the moderator inventory surrounding the fuel channels and as a result of the exothermic zirconium-steam reaction, which generates hydrogen, the fuel channel temperature increases. The fuel channels on the top rows heat up and sag under gravity. The top row of channels sags and contacts the next row of the lower uncovered channel and transfers the load and heat. During the sagging process the longitudinal total strain of the fuel channel increases. The total strain will concentrate between the fuel bundle junctions as the sagging increases and lead to wall-thinning at the junction region between the fuel bundles [4,5]. The calandria tube will perforate as a result, which will allow steam to enter the gap between the pressure tube and the calandria tube. The fresh Zircaloy surfaces in the gap between the pressure tube and the calandria tubes are exposed to steam and as a result the fuel channel temperatures will rapidly increase from the Zircaloy-steam exothermic reaction and produce hydrogen. Figure 3 shows a schematic of the sagging process leading to core disassembly and the build up of debris inside the calandria vessel. Some of the low-power peripheral channels may still remain cool and may not form debris until later in the transient. A number of vertical in-core devices, such as guide tubes, adjuster rods etc., which are positioned between the fuel channels, would help the fuel channel debris to line up in the vertical gap between them during the debris mass build up.

The broken channels accumulate to form a porous "suspended debris bed" on the stronger and colder channels underneath, which are immersed in the moderator. The suspended debris mass builds up with time and as the calandria vessel inventory decreases the debris will continue to produce hydrogen and release fission products since they are exposed to steam. As the debris mass increases steam access to the interior of the debris mass becomes more difficult and hydrogen and fission products are released into the containment through the calandria vessel rupture discs. Since the calandria vessel is immersed in the reactor vault water the radiative heat from the suspended debris bed is absorbed by the colder calandria vessel wall. However, some molten material is expected to be formed from the UO_2-Zr eutectic reactions within the suspended debris bed, which will gradually relocate into the moderator below. During this quenching process the molten corium interacts with the water (Molten Corium Interaction (MCI)) and small-size particulate debris will be formed, which will relocate to the bottom of the calandria vessel to become part of the terminal debris bed and coat the vessel wall to subsequently become part of the crust. Solid debris can also relocate from higher elevations of the core region to lower elevations within the suspended debris bed, when space is available to accommodate them. Figure 4 shows the various phenomena, which occur inside the calandria vessel during the transient process. The end-stubs shown in figure 4 are remains of the fuel channel ends, which are still attached to the calandria tube sheets at two ends of the calandria vessel, since fuel channel perforation and break up of the debris from the original channel occurs at those locations. The small-scale core disassembly experiments, which are described in this paper discusses in more detail the test performed to address the channel perforation phenomena.

Core Collapse

As the accident progresses and the calandria vessel inventory decreases, more and more debris accumulate on the colder supporting fuel channels immersed in the remaining water. The supporting channels have a limited load-bearing capacity to support the debris load. When the load on the supporting channels exceeds a critical value the supporting channels will fail at the calandria tube/tube sheet rolled joint. The suspended debris bed including the supporting channels and the channels below in the remaining moderator will collapse and fall into the moderator, where the debris will be quenched. The phenomenon of rapid debris relocation into the calandria vessel bottom by this process is called "Core Collapse". The core collapse occurs at about 8 h in a CANDU 6. The core collapse is associated with rapid steam formation and a pressure rise in the containment. The reactor vault water would still be below the saturation temperature and continue to keep the calandria vessel wall cool. Figure 5 shows a schematic of the core collapse phenomenon and the resulting formation of a porous terminal debris bed at the bottom of the calandria vessel. The resulting terminal debris bed will be initially porous and will be covered with the residual water in the calandria vessel. The terminal debris bed at the bottom will contain fuel channel debris containing oxidized segments of PT, CT, UO_2 and a small quantity of fragmented Zr-U-O material, which relocated from the suspended debris as molten material from UO_2-Zr interaction.

Calandria Vessel Behaviour

Following core collapse, the remaining water in the calandria vessel eventually boils off releasing hydrogen and fission products if the water is not replenished; the debris will form a compacted terminal bed. When all of the steam in the calandria vessel is used up by the Zircaloy/steam reaction the hydrogen generation will cease. The compacted terminal debris bed inside the calandria vessel is still surrounded by the water in the reactor vault, which will keep the outer layers of the terminal debris bed facing the reactor vault cool. With the absence of in-vessel cooling assumed here, the core debris will begin to melt near the top of the terminal debris bed as shown schematically in Figure 6. The top layers of the compacting debris bed will radiate heat to the colder top calandria vessel walls and will form a crust on the top surface. The melting process will generate a U/Z/O alloy, called corium, which will gradually spread from the center region of the terminal debris bed outwards and penetrate the solid debris surrounding the molten corium. The molten material will solidify eventually due to high heat transfer from the calandria vessel wall to the reactor vault water. Figure 7 shows a schematic of the transient scenario when a crust is formed on the top and side walls of the terminal debris bed. The molten corium pool is surrounded on all sides by the crust. As long as the critical heat flux at the calandria vessel wall/reactor vault interface is not exceeded, the solid crust, insulating like a crucible, will be in place and will contain the molten corium inside the calandria vessel. Analytical studies indicate that the critical heat flux will not be exceeded. By replenishing the water in the reactor vault, the calandria vessel wall can be maintained cool, which will enhance heat transfer from the corium top and bottom surfaces to the calandria walls. Natural convection currents will develop within molten corium and will enhance the removal of decay heat to the crust layer. The corium will be maintained inside the calandria vessel by this in-vessel retention strategy [2].

Small-scale Core Disassembly Tests

A number of experiments were conducted by the LWR community to study the behaviour of a reactor core under severe accident conditions. Since the behaviour of the CANDU core is different compared to LWRs, as explained above, a number of small-scale tests of one-fifth scale were conducted to study the fuel channel sagging and break up phenomenon [4,5]. The focus of these core disassembly tests is to understand the CANDU core disassembly behaviour during a severe core damage accident. As described above under phenomena description, the fuel channel break-up is preceded by fuel channel sagging leading to localized strain between the fuel bundle junctions and perforation of the channel.

Core Disassembly Tests

Single and multi-tube tests were conducted in an inert and in an oxidizing atmosphere with heaters inside the Zr-2.5 Nb tubes, which simulated the fuel channels. Results of those tests showed that significant sagging of the channel occurred when the channel temperature exceeded 850°C. In the single tube tests significant strain localization was observed at the junctions between the heaters along the bottom side of the tube, which suggested that fuel channel perforation would occur at junctions between the fuel bundles. Perforation of the fuel channel would allow steam to enter into the gap between the calandria tube and the pressure tube and drive up the channel temperatures, which would lead to debris formation. The multi-channel tests showed that the wall thinning and tube perforation were concentrated more in the regions away from the tube mid-point near the ends. The centre region of the sagging channel was supported by the colder lower channels below such that strain localization was more pronounced at regions near the channel ends. It was concluded that the debris formed by this process would be long and coarse. Figure 8 shows a photograph of the test assembly following a three-tube test in an inert atmosphere. The figure shows the support provided by the lower tubes and tube perforation at the lower half of the top tube in the unsupported region.

Core Disassembly Model Development

To explain the test findings of the core disassembly tests, an ABAQUS beam element model was developed, which included a stress concentration factor in the longitudinal creep equation for Zr-2.5 Nb, which is the pressure tube material used to perform the core disassembly tests. The stress concentration factor accounted for the localized strain, which developed in the test channel between the heaters in the gap region [5]. Figure 9 shows a comparison of the sag measured at the centre of a single channel undergoing sagging with the modeling results for a single channel test in an inert atmosphere. In this test the maximum temperature reached at the centre of the test channel was 1390°C and the measured maximum transient sag was 132 mm. Figure 9 shows that the ABAQUS model, which included localized strain, compared well with the measured sag. The model without localized strain under-predicted the measured sag.

Results of small-scale core disassembly tests conducted in an oxidizing atmosphere containing argon and oxygen showed an additional mechanism for the break up of a sagging channel. Micrographs of test wall from sections taken from the lower wall of the sagged tube showed cracking of the oxide layer formed on the channel surface, which allowed ingress of oxygen to localized regions under the oxide layer. Progressive localized oxidation at those regions assisted with the sagging of the tube would be another mechanism for debris formation.

MAAP4-CANDU Analysis Results for a Generic CANDU 6 Reactor

Various phenomena discussed above are modeled in MAAP4-CANDU code, which is used to calculate the progression of a severe core damage accident in a CANDU reactor.

Results from the core disassembly tests described above showed that fuel channel segments separate near the bundle junctions as a result of high temperature sag. As discussed under the phenomena section, a suspended debris bed will then be formed inside the calandria vessel, which will be supported on submerged channels until the loading on the submerged channels increases with the accumulation of debris from top channels. This process will lead to progressive failure of the lower channels and ultimately resulting in the collapse of the core into the moderator pool at the bottom of the calandria vessel.

The core debris behaviour within the calandria vessel was analysed with the MAAP4-CANDU code (version 4.0.4A+) for a generic CANDU 6 SBO accident scenario with the loss of off-site AC (Class IV) power and subsequent loss of all on-site standby and emergency electric power supplies with no operator actions. For reference, the CANDU 6 calandria vessel has an I.D. of ~7600 mm and a wall thickness of ~29 mm. The CANDU 6 core has an inventory of ~98.8 Mg uranium dioxide and ~38.7 Mg Zircaloy. Details of the accident progression following a SBO accident sequence is described elsewhere [8]. No inventory make-up to the moderator and reactor vault inventory was credited in those calculations.

In the SBO accident scenario analyzed [8], the reactor is shut down and the core decay heat is transferred to the steam generators by natural convection. As a result, the steam generator secondary side boils off discharging steam from the secondary side to outside of the containment through the main steam safety valves. The steam generators dry off at ~2.5 h and the PHTS pressure increases until it reaches the liquid relief valve set point and oscillates at the relief valve set point, which finally results in fuel channel dryout. Subsequent heat up of the pressure and calandria tubes at ~10 MPa HTS pressure results in ballooning and rupture of a lead channel causing rapid blowdown of the HTS coolant into the calandria vessel at ~4.4 h. Since no moderator cooling and make-up is credited, the moderator level in the calandria vessel further decreases as a result of moderator boiloff and causes the uncovery of the top fuel channels.

As fuel channel axial segments heat up and sag, they break up and form debris. In the MAAP4-CANDU model, the fuel channel fragments relocate to “holding bins”, where they are held temporarily as a “suspended debris bed”. The suspended debris bed heats up further from the decay heat and from the Zr/steam exothermic reaction resulting in partial melting. Some of the molten material relocates from the suspended debris bed to the bottom of the calandria vessel, where it is quenched. When the suspended debris bed cannot be supported by the intact channels covered by water, the suspended debris bed and the intact channels below relocate to the bottom of the calandria vessel by core collapse, which was calculated to occur at ~8.3 h.

Following core collapse, the moderator in the calandria vessel is depleted at ~8.9 h. The water in the reactor vault cools the outer calandria vessel wall. Steam generated in the reactor vault is released into the containment. Since no reactor vault inventory make-up is credited in this analysis, the reactor vault water reaches saturation temperature at ~14.5 h. Since no local air-cooler is credited in the analysis, the containment pressure increases gradually and reaches the containment failure pressure of 500 kPa(a) at ~27.1 h. By providing make-up to the reactor vault water and by assuring that the heat flux at the calandria vessel/reactor vault water boundary does not exceed the critical heat flux the corium can be maintained in the calandria vessel.

Figure 10 shows the terminal debris mass in the calandria vessel for the SBO scenario from the MAAP4-CANDU analysis. The figure shows (a) the total corium mass including particulates (solid debris), corium crust, and molten corium, (b) the mass of the corium crusts (bottom, side and top surfaces) and (c) the mass of particulates in the calandria vessel. After the water in the calandria vessel is depleted, the core debris in the calandria vessel begins to heat up and eventually the solid debris melt to join the molten debris pool at ~14 h. The thickness of the crust formed on the calandria vessel wall is in the range 5 to 10 cm. Similar corium crust thickness (7 to 8 cm) was predicted for similar conditions in independent studies [6,7]. The molten debris pool is surrounded by a solid crust, which grows with time.

Since no reactor vault make-up was credited in the analysis, the reactor vault water level decreases to ~2.5 m at ~42.4 h, the calandria vessel bottom heats up rapidly and fails due to creep at ~42.4 h, when the debris relocate into the reactor vault, where it is cooled by the calandria vault water. If reactor vault make-up is credited and critical heat flux at the calandria vessel wall/reactor vault water interface is not exceeded, the corium crust thickness would grow and contain the corium inside the calandria vessel.

Summary

This paper discusses some of the design details of a generic CANDU 6 reactor, which are required to understand the phenomena that occur during a postulated sever accident in a CANDU 6 reactor. The various severe accident phenomena are explained in detail with the assumption that the generic CANDU 6 would undergo a postulated station blackout sequence. The core disassembly phenomenon, which is specific to a CANDU reactor, is explained in detail along with supporting experiments and model development to support the test findings. The discussion on severe accident phenomena explains the development of a corium crust, which will surround the molten corium and contain the corium inside the calandria vessel if make-up to the reactor vault water is credited and the critical heat flux at the calandria vessel wall/reactor vault water interface is not exceeded. Analytical studies performed show that critical heat flux on the calandria vessel outside wall will not be exceeded.

The results of SBO analysis performed with the MAAP4-CANDU code, which is the severe accident consequence analysis code used for CANDU reactors, are also discussed in this paper. The results demonstrate that significant time is available for operator intervention to arrest the progression of such a severe accident.

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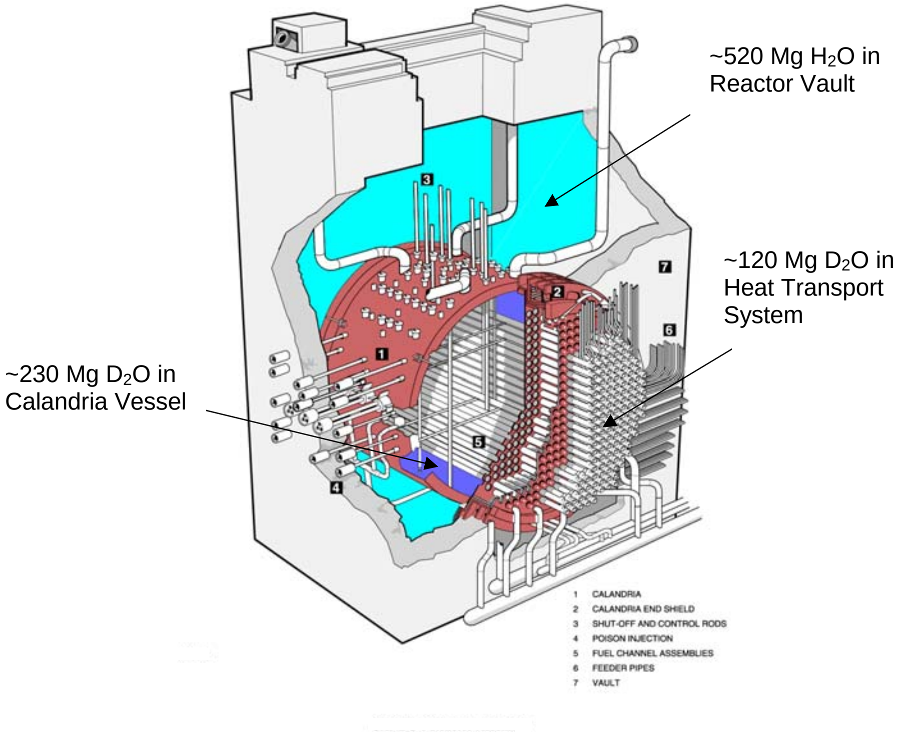

Figure 1 Schematic of a CANDU 6 Reactor Core

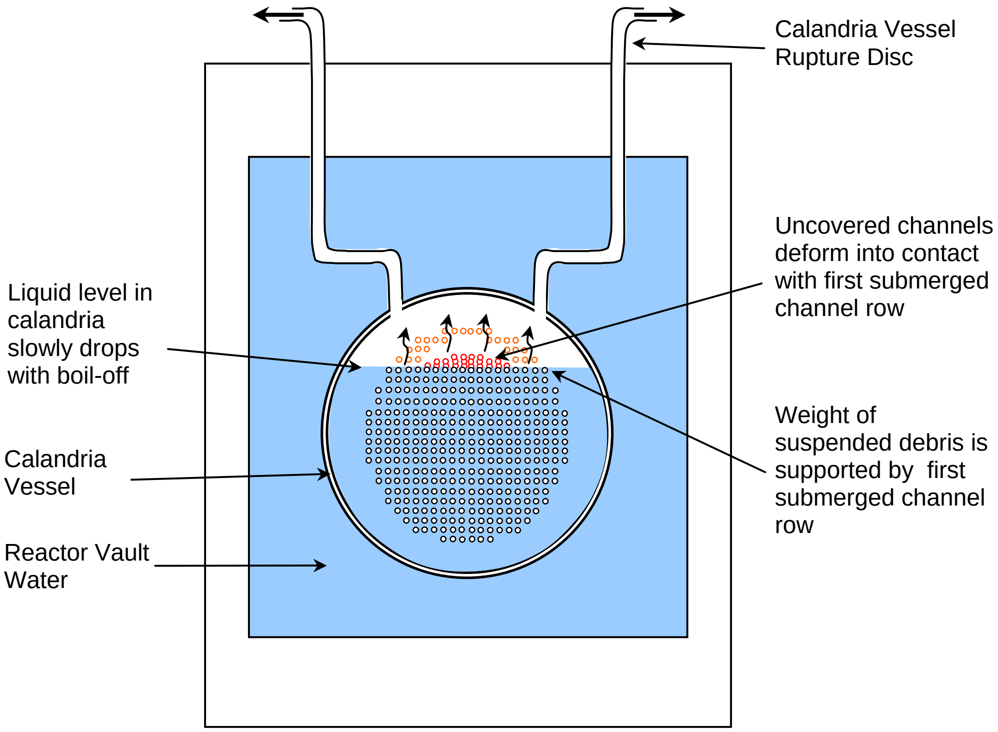

Figure 2 A schematic showing the uncovery of top fuel channels following moderator expulsion

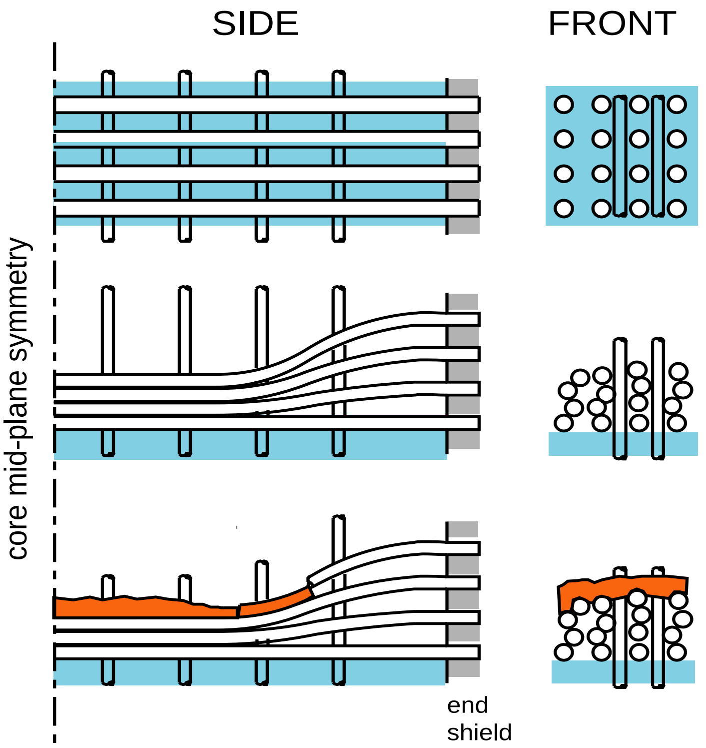

Figure 3 A schematic of the different views of a section of the CANDU core during sagging and disassembly

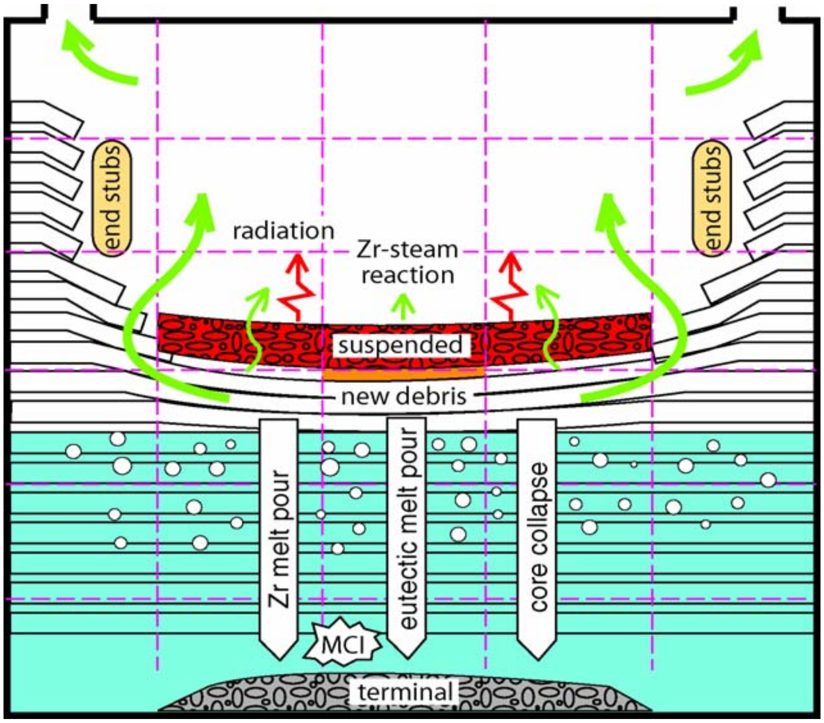

Figure 4 A schematic showing the various phenomena inside the calandria vessel during the transient

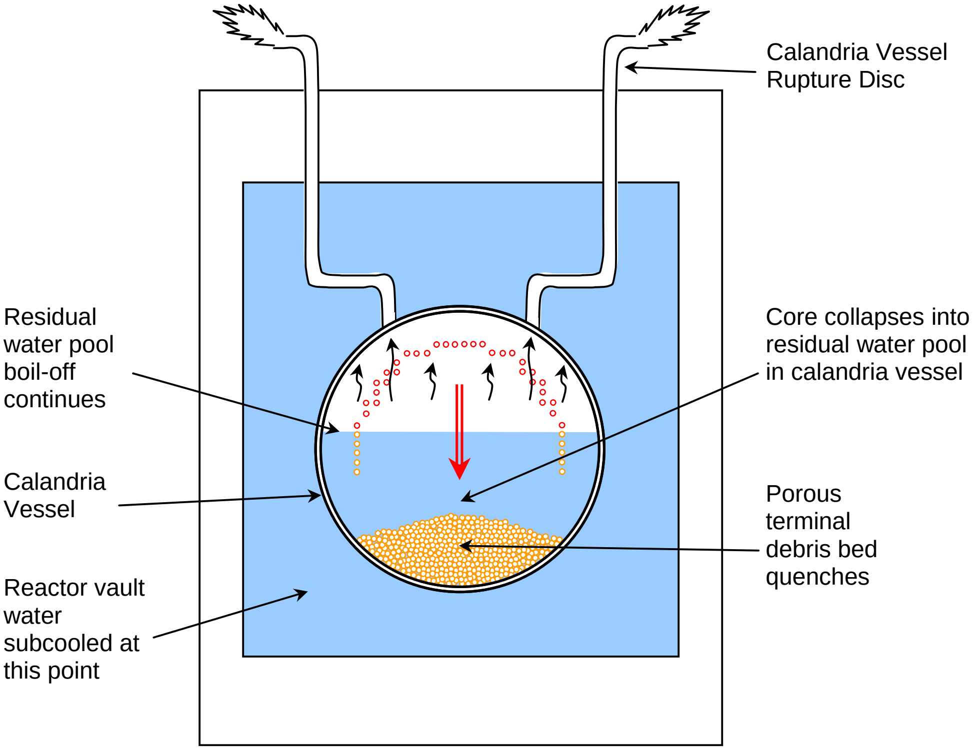

Figure 5 A schematic showing the collapse of the core into the residual water below

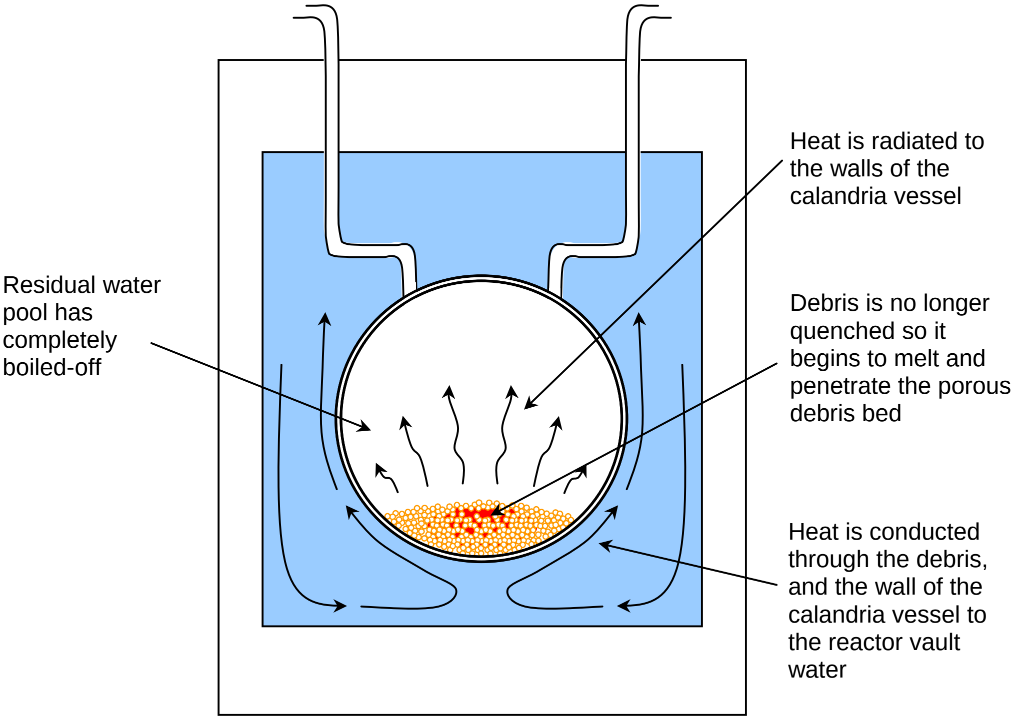

Figure 6 This Figure shows the consolidated terminal debris bed, the beginnings of molten corium formation near the top surface and the evolution of natural circulation in the reactor vault water

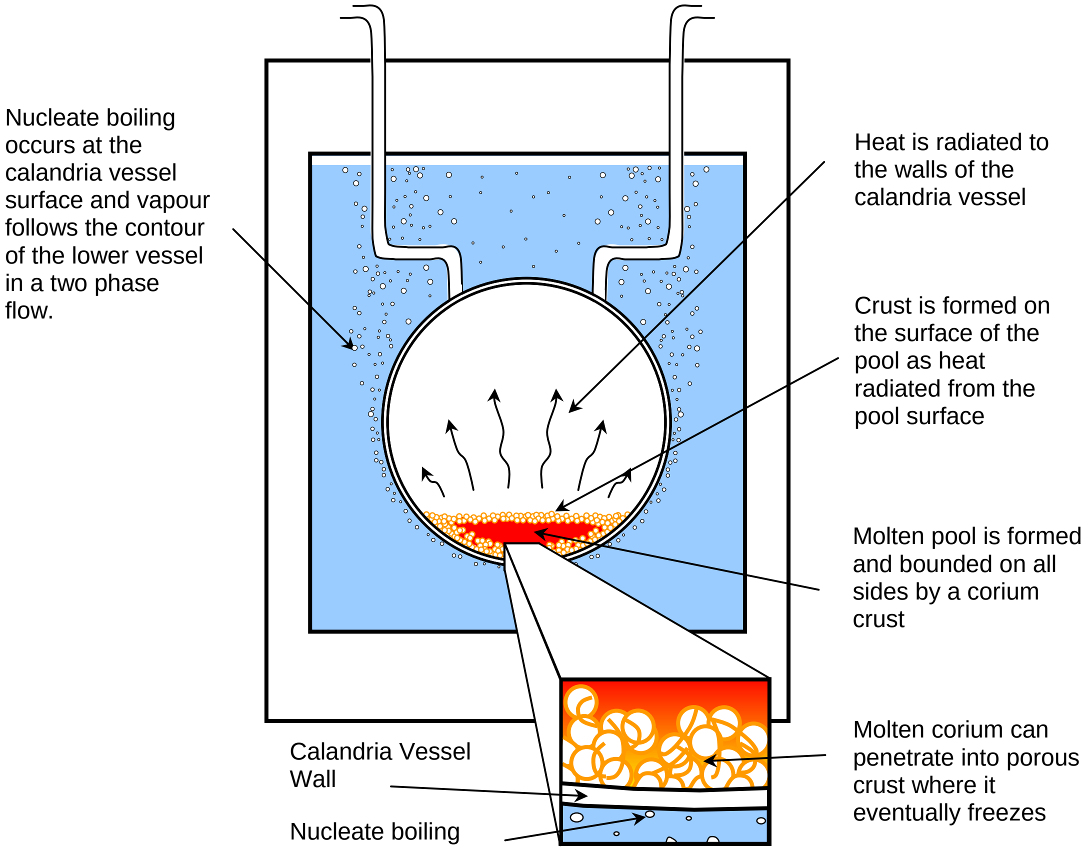

Figure 7 Shows the formation of solid crust, which will surround the molten corium on the cooler surfaces of the calandria vessel

Figure 8 A View of the channel assembly after a three-channel test

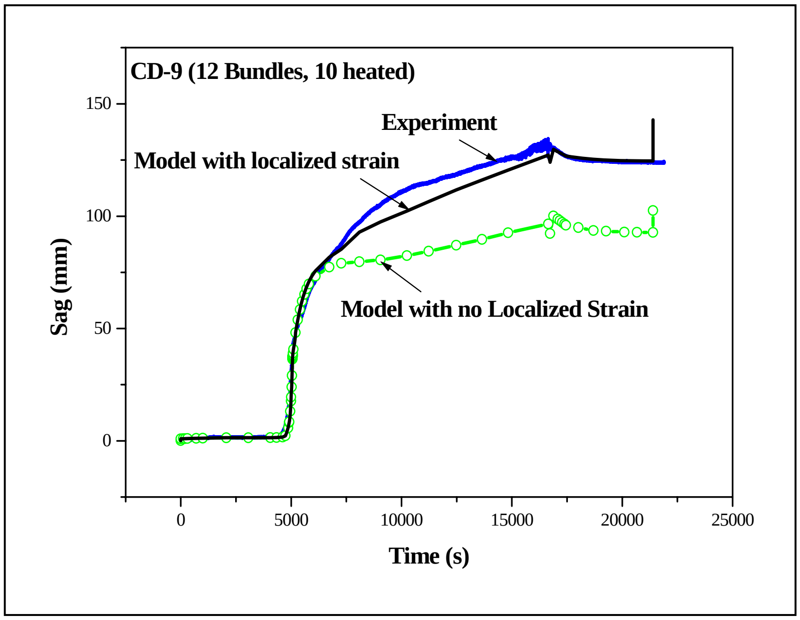

Figure 9 A comparison of calculated sag of a single channel in an inert atmosphere using ABAQUS with and without localized strain

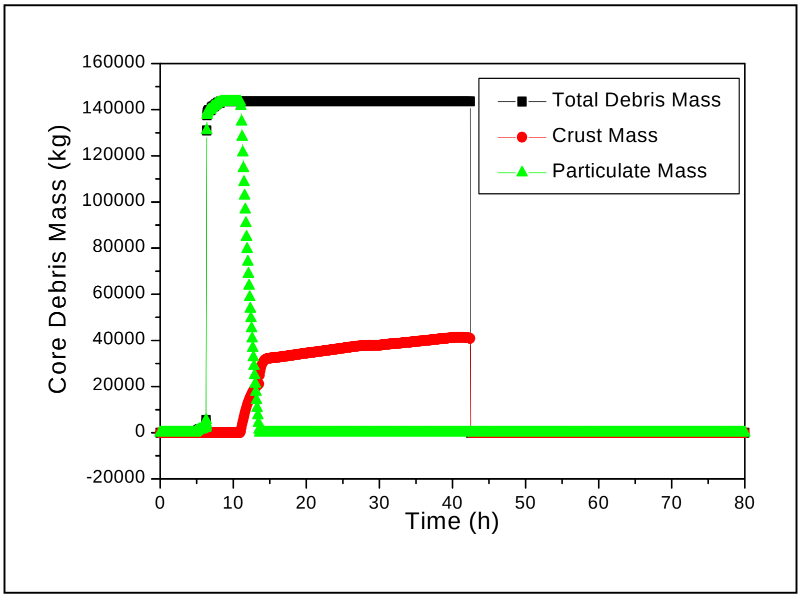

Figure 10 Corium mass in terminal debris bed in calandria vessel