CANDU RESPONSE TO LOSS OF ALL HEAT SINKS

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ABSTRACT

The paper examines processes and phenomena which control the progression of severe accidents in a multi-unit CANDU station. Theoretical models and relevant experimental data are reviewed. It is shown that modern CANDU reactors are inherently tolerant of a prolonged loss of engineered heat sinks at decay power levels. Most severe accident phenomena discussed in this paper are quantitatively understood, supported by results of domestic and international research. Where quantitative information is sparse or lacking, parametric analyses are available using MAAP-CANDU computer code to explore the range of uncertainty.

I. INTRODUCTION

This paper explores severe accident phenomena relevant to large CANDU reactors. A loss of all engineered heat sinks due to a loss of all electrical power is used to illustrate these phenomena The multi-unit (4 x 850 MWe) Darlington Nuclear Generation Station[1,2] (DNGS) in Ontario, Canada is analyzed assuming that the power is lost to one of its units during a transfer to local power supplies following a damage to the main switch-yard. It is further assumed that the emergency power generators are unavailable and that the operators do not undertake effective recovery actions, although ample time is available and appropriate emergency procedures are in place (both event based as well as symptoms based procedures) Simulations with MAAP-CANDU computer code[3] are employed to characterize the progression of this stylized accident with a focus on the underlying thermal-hydraulic, thermal-mechanical and chemical processes.

II. EARLY RESPONSE

The loss of all electrical power results in an immediate, automatic reactor shut-down, but engineered heat removal systems in the affected unit gradually degrade after the shut-down. The primary heat sink (steam generators) as well as alternate heat sinks (heavy water in the calandria vessel and light water in the shield tank) rely on their existing water inventories for heat dissipation due to a loss of feed and service water supplies. The emergency core cooling system requires electrical power for pumped delivery and is therefore not available. The instrument air becomes depleted due to a loss of compressors, disabling the atmospheric steam discharge valves and other pneumatically operated devices. Air coolers in the accident reactor vault cease to operate, although containment heat sinks are still available in the interconnected, non-accident units which successfully transferred to their internal power supplies. In longer term, when battery-backed power supplies become depleted, all instruments become unavailable.

A. Heat Transport System Response

Decay heat from the reactor is initially transported to steam generators (SG) and later relieved into the bleed condenser and containment. Coolant inventory and pressure in the heat transport system (HTS) are shown in Figure 1, indicating that the coolant relief commences at about 6 hours. This timing depends primarily on the initial SG water inventory (normal inventory is 340 Mg ± 10% in 4 SG's).

Forward flow through all 480 parallel fuel channels is maintained by single phase natural circulation which is assured by the liquid-

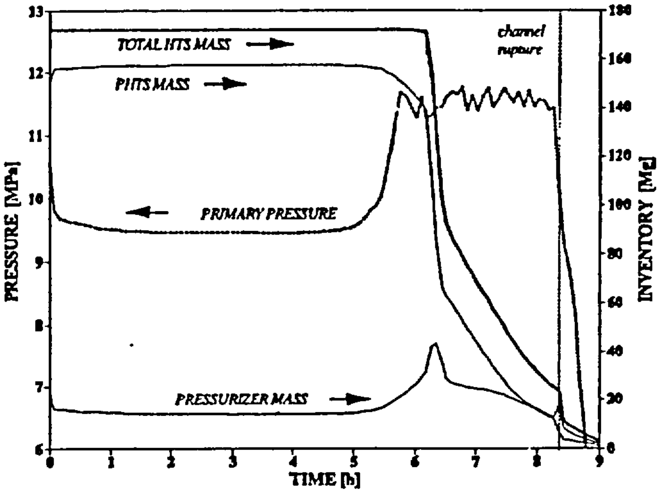

Figure 1 HTS pressure and inventory

filled HTS and the effective SG heat sink[4]. When the SG heat sink inventory is significantly depleted and a large fraction of the U-tube surface becomes uncovered, the natural circulation pattern can be altered by increasing negative pressure differentials between the reactor headers This can cause some fuel channels to experience flow reversals[5].

During the period in which the steam generator heat removal capability deteriorates and bi-directional flow patterns emerge (i e between 4½ and 6 hours, Figure 2), adequate convective cooling is maintained to limit temperature excursions in the fuel channels At prevailing HTS pressures (10 to 12 MPa, Figure 1), the pressure tube would start to strain radially (balloon) if heated to about 600°C[6]. However, such temperatures are not attainable even if a local voiding were to occur in the fuel channels[7].

Figure 2 shows contributions of available heat sinks to the dissipation of decay heat. Heat flows to the alternated heat sinks are limited in the early stages by small temperature gradients among the HTS coolant and the liquid pools in the Calandria Vessel (CV) and the Shield Tank (ST) The difference between the net heat generation and the total heat removal to the heat sinks is first stored in the HTS coolant and structures (< 6 hours) and then relieved into the bleed condenser and containment (> 6 hours) The relief of coolant alters the HTS flow patterns, but maintains the core temperatures close to saturation as long as the fuel channels remain flooded.

The reactor headers become voided around 6.5 hours when the HTS coolant inventory depletes to about 50 percent A global HTS phase separation is expected at this juncture, with liquid collecting below the headers and only steam relieved into the containment. Subsequently, the fuel channels gradually boil off their residual liquid inventory during which time stratified conditions develop in horizontal fuel strings. By the time the HTS liquid inventory drops to between 15 and 25 kg per channel, the steam is superheated and unable to keep the pressure tube temperatures low enough to prevent thermal-mechanical deformations. A fuel channel with stratified liquid and steam develops a large top-to-bottom temperature gradient (i e liquid filled bottom near saturation temperature, steam filled top superheated) This induces non-uniform straining of the pressure tube wall to failure[6] at 8 4 ± 1 hours The uncertainty stems from the precise timing of phase separation in the inlet headers and the duration of channel boil-off, which varies across the core according to local channel conditions (i e. volume and power) The thin calandria tube cannot withstand the discharge of superheated steam at high pressure (> 12 MPa)[8] and ruptures very shortly after the pressure tube failure.

The fuel channel rupture produces a relatively large discharge of HTS coolant into the calandria (about 150 kg/s) and temporarily enhances the convective cooling of remaining intact channels by flashing the liquid and forcing the flow towards the break. Since the pressure tube deformation temperature is very sensitive to pressure[6], the depressurization transient in conjunction with improved cooling prevent additional channel failures at this time. The HTS relief valves close and the core is cooled by the blowdown discharge of the remaining coolant until the HTS depressurizes.

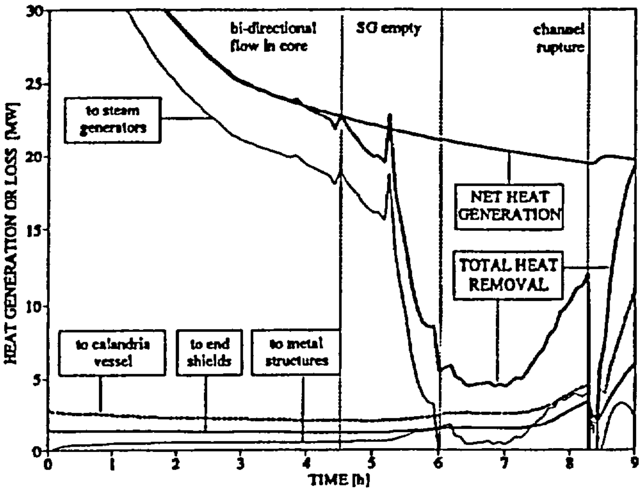

Figure 2 HTS heat balance

B. Moderator System Response

The liquid moderator (about 260 Mg in the CV) surrounding the fuel channels is initially sub-cooled at about 65°C. Boiling of this moderator fluid starts at around 7.5 hours due to heat rejection from the fuel channels. The net heat load to the calandria vessel is reduced by the heat transfer to some 800 Mg of light water in the shield tank as shown in Figure 2. When the moderator boils, the steam relief through spring loaded relief valves maintains the CV at about 165 kPa until the first fuel channel ruptures.

The discharge from the ruptured channel cannot be condensed in the boiling moderator and exceeds the capacity of relief valves. Consequently, one or more of the four large CV rupture disks burst to protect this vessel from excessive pressurization. Void-induced swell of the moderator level causes a two-phase discharge from the CV into the containment. When the coolant discharge from the HTS subsides, fuel channels at the top of the core are above the liquid level in the CV. Between 6 and 10 channel rows (out of 24 rows total) become uncovered, depending on the elevation and orientation of channel rupture which, in turn, determines the number of burst CV rupture disks[9].

III. REACTOR HEAT-UP AND DISASSEMBLY

Conditions at the onset of core heat-up are schematically illustrated in Figure 3. The HTS and CV are near atmospheric, since they are interconnected to the containment The containment vacuum pressure suppression system[2] readily copes with the mass and energy discharges that have occurred from the HTS and CV. The HTS is voided, containing some 150 kg of steam. The CV is partially voided, containing some 150 ± 10% of boiling heavy water. The ST is still liquid filled and sub-cooled at less than 80°C. The fuel in intact fuel channels is at ≤ 300 °C and generating ≤ 0.8 percent power

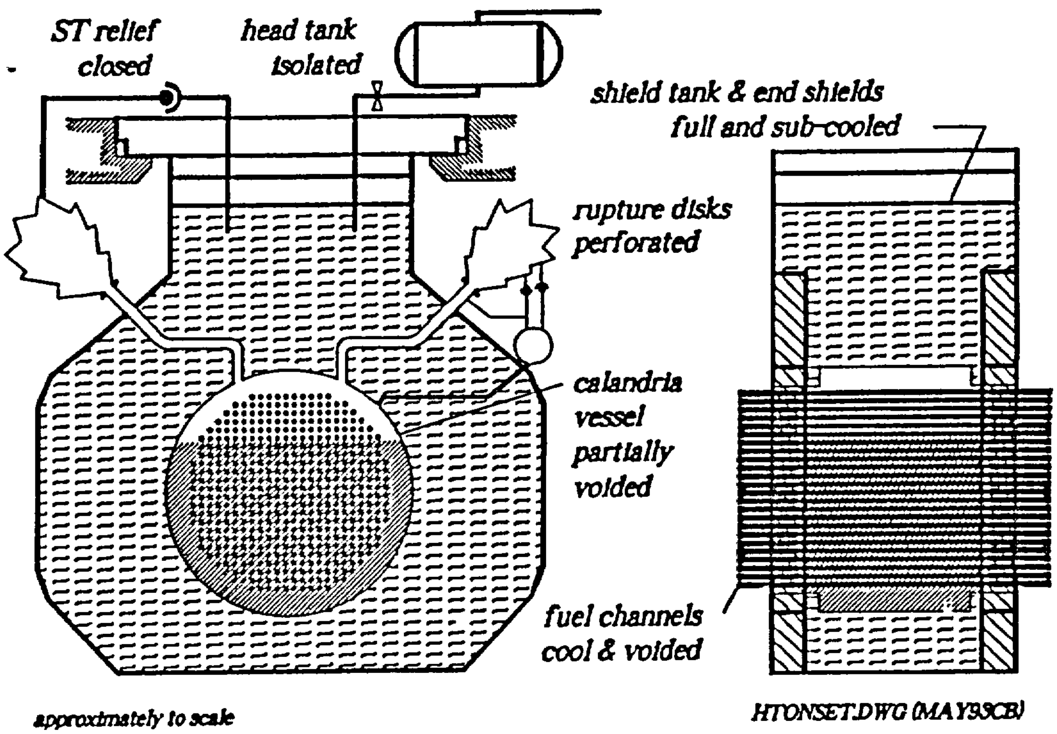

Figure 3 Onset of core heat-up

Fuel channels heat up at different rates, depending on their decay power level (pre-accident power ranges from < 4 to about 6.5 MW), axial power distribution (can vary by a factor of 15 along the fuel string) and fluid conditions surrounding the channel (uncovered or submerged). The chemical environment in the intact channels is initially oxidizing (i.e. steam), changing to reducing as the steam in the HTS is consumed to produce H_2 and then to oxidizing again when a number of channels disassemble and the steam ingress from the CV occurs.

Fuel temperature excursions in the submerged channels are arrested below about 1200°C by the radial rejection of decay heat into the moderator/coolant pool[10]. These channels then maintain their integrity as long as the alternate heat sink (i.e. water pool) is present on the outside surface of calandria tubes[11]. The uncovered channels continue their slow temperature excursion until rapid lateral deformations (i.e. sagging) commence when the calandria tube wall temperature reaches about 1000°C over an appreciable axial length. The temperature excursion is then accelerated by the exothermic reaction of Zr on the outside of channel with the steam in the CV.

A. Fuel Channel Disassembly

Disassembly of uncovered, deformed, horizontal fuel channel is very complex. It involves mechanical and chemical interactions with the surrounding horizontal channels, in-core devices and debris. Local chemical interactions with the CV environment also occur which are sensitive to details of geometry. Anticipated processes are schematically depicted in Figure 4. Channel segments will separate near the individual bundle junctions by a sag-induced local strain when a sufficient displacement distance is available (i.e. vertical span to the first submerged channel row > 1 m).

The coarse debris from disassembled upper channels tends to remain suspended on the lower, deformed channels, ultimately being supported by the first row of channels that is still submerged and thus adequately cooled. This debris contains large, hot, unoxidized Zr surfaces (i.e. gap between the pressure tube and calandria tube) which are suddenly exposed to steam. The reaction heat melts the metallic Zr a short time later (within about 15 minutes of channel segment separation). This melt (some 13 kg Zr per meter of channel length) tends to be non-wetting since the local heat-up is too rapid to appreciably raise its dissolved oxygen content. Hence, most of this melt flows into the water pool at the bottom of CV, chemically interacting with liquid water when it enters the pool. The extent of this latter reaction depends on the dispersion of molten metal stream into droplets, and it is typically less than 3 percent of Zr mass.

Timing of channel segment disassembly is illustrated by ticks on dashed horizontal bars in Figure 5 which represent time during which high, medium and low power channels at their respective elevations in the CV are identifiable entities (i.e. channel stubs with fuel remain attached to end faces of CV).

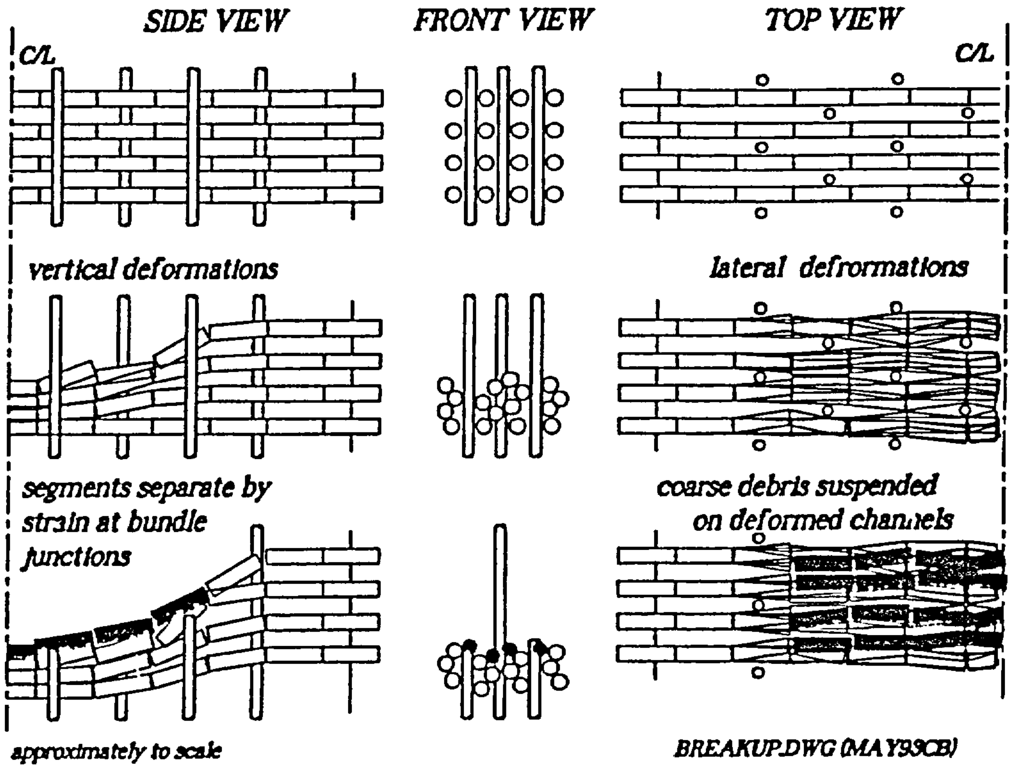

Figure 4 Fuel channel disassembly

B. Suspended Debris Response

Ceramic oxides and a small amount of metal remaining in the suspended debris compact by sintering, eventually limiting access of steam into the debris bed. A portion of this debris may liquefy if a sufficient time is available prior to the collapse of the bulk of the core (see below) However, any appreciable build-up of melt is precluded by the downward motion of the whole debris bed which follows the falling liquid level in the CV. This motion disrupts any crust containing the melt.

As the mass of suspended debris increases, the load on the first submerged channel row also increases. Each submerged channel can only support the weight equivalent to about 7 other channels, so a row of channels can hold 75 ± 25 Mg of debris. Excessive debris loading will shear the submerged channels near the vertical faces of CV, increasing the loading on the channels below. This leads to progressive shearing of all but some low power peripheral channels, causing a collapse of the reactor core into the liquid pool at the bottom of CV at approximately 11 hours (Figure 5) No appreciable amount of molten corium is present at the time of core collapse since, as shown in Figure 5, the suspended debris load builds up quite rapidly to the collapse threshold, limiting the time available to melt the materials.

The core collapse may be delayed by several hours if the debris does not accumulate on the submerged channels (i.e. if it falls to the bottom of CV after it is formed) However, the outcome is the same for all disassembly pathways: a solid debris bed located at the bottom of CV which dries out after about 14 hours (Figure 5). The various modes of suspended debris motion result in differences in fission product release and H_2 generation transients, but do not affect the terminal state of the debris.

C. Terminal Debris Response

The terminal debris bed at the bottom of CV transforms to a molten pool of U/Zr alloy surrounded by a relatively thin solid crust. It reaches a quasi-equilibrium state in which essentially all the decay heat is absorbed by the 800 Mg of light water in the ST[12]. The volumetric expansion of this water is relieved into the containment, but the relief capacity is insufficient when a bulk boiling of light water commences. The ST pressurizes to 880 kPa sometimes after 27 hours. At this pressure, a seam at the bottom of ST is predicted to fail, opening a long and narrow discharge path into the containment. Water drains relatively rapidly from the ST, thereby removing the heat sink for the corium pool. CV wall melt-through follows shortly after ST draining.

IV. LONG-TERM RESPONSE

It is likely that the core disassembly process will be arrested in the empty shield tank. The melt from the CV pours onto a layer of cool, steel shield balls (> 80 Mg) and freezes as it spreads on 68 m² of flat ST floor. The large steel mass at the

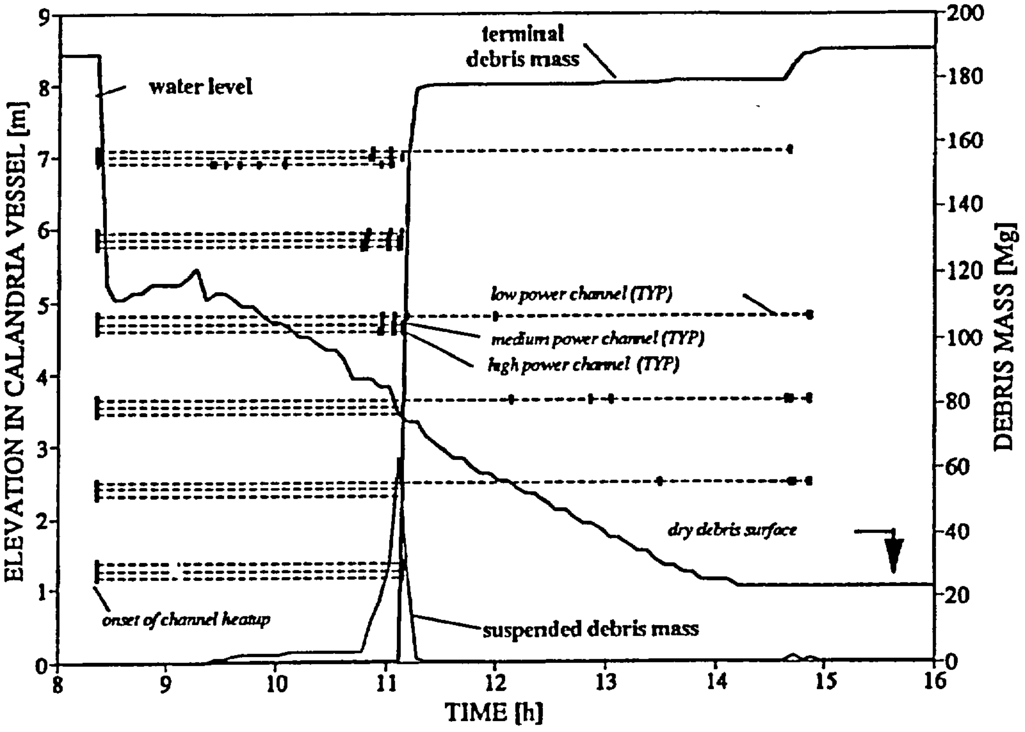

Figure 5 Core disassembly transient

bottom of ST (i e. steel balls and wall structures) is capable of absorbing the stored heat and then dissipating the decay heat to the containment atmosphere. The arrangement of the ST in the containment promotes natural convection cooling along the bottom of the tank (Figure 6) Another convection flow is established through the ruptured ST seam, the penetration in the bottom of CV and the CV relief ducts Deterministic analysis of the long term ST thermal-mechanical response is not attempted, since the consequences are not fundamentally different whether or not the debris is released into the containment.

If the debris remains in the ST and the CV, it will be gradually oxidized by a mixture of air and steam drawn into the damaged vessels by buoyancy. Some relocation of materials remaining in the CV (e g channel stubs) may occur due to embrittlement and/or localized heating by chemical heat. The oxidation may volatilize UO$_2$[13] and alter kinetics of fission product release[14] until a protective oxide builds up on exposed surfaces of debris Aerosol release into the containment will thus continue for some time. Hydrogen production will also continue, at least until steam in the containment atmosphere is condensed

If the hot floor of the shield tank cannot support the load of debris and fails by thermal creep, then a fraction of the solid debris will fall onto a floor of fuelling machine duct (FMD) covered by a thin layer of water (some 1200 Mg of H$_2$O spread over 3600 m^2 of FMD floor with several shallow sumps) This debris may cool down rapidly if dispersed by the impact, or gradually if it remains in a pile which spreads by liquefaction. The material remaining in the damaged reactor will again experience a convective cooling in an oxidizing environment.

In either case, thermal-chemical interactions of core materials with concrete are practically impossible, as are any steam explosions in the containment Non-condensible gas generation is limited to H$_2$ produced by the reaction of Zr with steam, and to the instrument air leakage in the non-accident units Hydrogen combustion is mitigated by a prolonged period of high moisture content in the containment atmosphere which allows for its dispersion throughout the large volume of multi-unit containment (> $2 \cdot 10^5$ m^3) Containment heat sinks in non-accident units tend to speed up the condensation, but also promote the inter-unit mixing of the atmosphere and the dilution of H$_2$.

V. DISCUSSION

The early response is governed by the heat rejection to the water inventory in the SG's, and latter by the relief of HTS coolant This is similar to any other reactor system. The delivery of heat to the generators through a network of parallel piping results in complex flow patterns and mild localized temperature excursions. A considerable experimental data base, and sophisticated models are available on these subjects, although these are typically focused on less severe accident conditions.

Liquid moderator delays the timing of channel rupture somewhat, but it cannot prevent this rupture with the HTS fully pressurized.

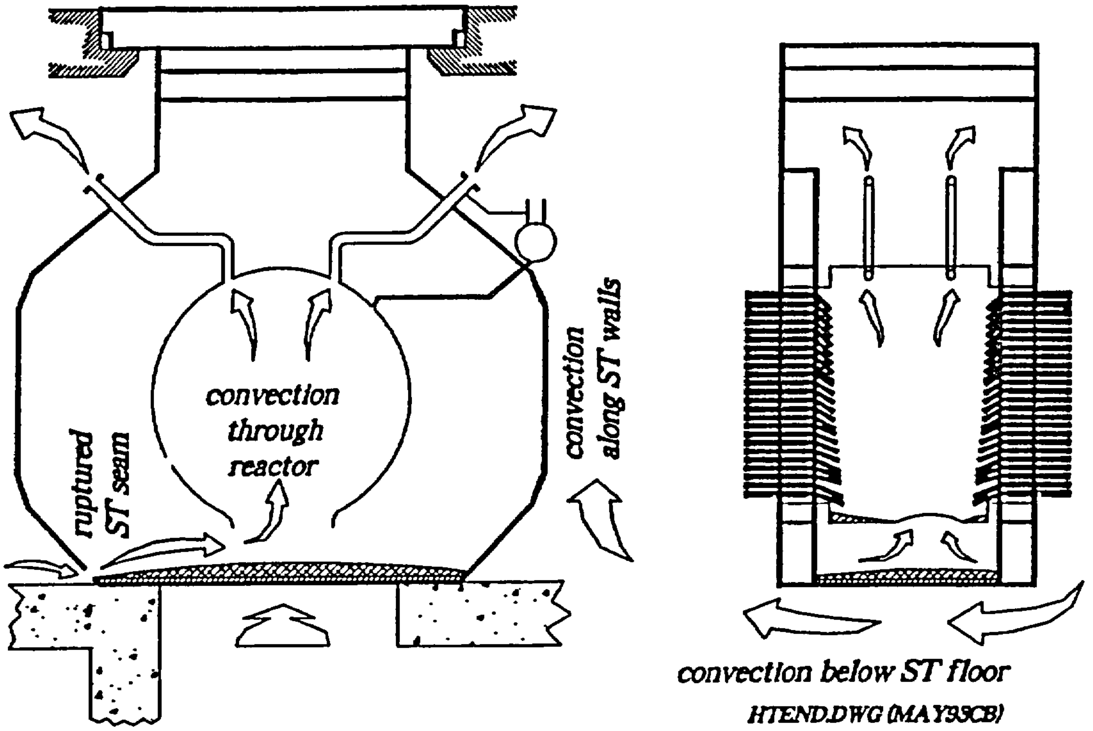

Figure 6 End of core heatup

A fuel channel must fail when the HTS becomes highly voided and steam temperatures climb locally beyond about 600°C. The criteria of channel rupture are well understood and experimentally verified. The CANDU fuel channel acts as a "fuse" which precludes any melting of core materials at high pressures.

Some of the liquid moderator is displaced into the containment following an in-core rupture. Analytical models supported by pilot-scale experiments are available to describe the response of the CV to the pressurized discharge from the HTS. The amount of water left in the CV can vary within ± 10 %, depending on the location and orientation of channel rupture.

Thermal-mechanical response of voided fuel channels is also well understood and experimentally verified. However, the disassembly of uncovered, horizontal channels can only be treated by parametric analyses because of the complex interactions involved. The MAAP-CANDU computer code is designed to facilitate these parametric analyses. It is found that, for the DNGS reactor, the dynamics of core disassembly are not crucial to the outcome All disassembly pathways lead to a bed of solid debris at the bottom of CV which melts when the alternate moderator heat sink diminishes by boiling

In the course of core disassembly, small amounts on molten materials may cascade into a boiling water pool in the CV at near atmospheric pressure. The geometry favours a quenching of this melt, but a potential for, and consequences of, highly energetic interactions are yet to be quantified.

Drying of large, coarse debris beds and subsequent heating to liquefaction is well understood, but only limited information is available about a release of fission products from such beds Indications are that the release may be severely curtailed by the absence of carrying gases to transport the fission products from the melting bed.

Behaviour of molten pools in water cooled, steel vessels is well known from industrial applications Properties of molten corium have been established by international research programmes.

Thermal-mechanical response of ST after CV failure has not been investigated in detail. Literature reports an order-of-magnitude variation in heat transfer coefficients for free convection along surfaces of large vessels. This range spans the condition under which the ST would survive or fail. Also, thermal-chemical interactions of hot, solid debris with air drawn into the failed vessels are difficult to describe because heterogenous chemical reactions are sensitive to details of geometry. Extensive data base of small scale experiments is available which indicates that UO_2 and certain fission products may be volatilized at moderate temperatures and high partial pressures of oxygen.

Considering the timing of CV failure (> 1 day) an improved understanding of the long-term phenomena is mainly of academic interest Any real accident sequence will involve numerous interventions by this time, and the outcome will be determined by the interventions.

VI. CONCLUSIONS

Modern CANDU reactors are inherently tolerant of a prolonged loss of engineered heat sinks at decay power levels. This is primarily because two large volumes of water (i e. moderator and shielding water) surround the reactor core and act as passive heat sinks in severe accidents. The effectiveness of these heat sinks depends on plant specific design features[15].

The pressure tube reactor design precludes any melting of core components at high internal pressures Small amounts of molten metal (mainly Zr) may drain into liquid pool in calandria vessel at near atmospheric pressure, but other interactions with water during the core disassembly involve coarse, solid debris.

The debris is contained in the calandria vessel for a long period (>1 day). If no recovery is successful during this time, the debris will penetrate into the shield tank and reject its decay heat into the containment atmosphere The multi-unit containment design facilitates a cooling of atmosphere in non-accident units.

The plant specific arrangement of the reactor in the containment avoids core-concrete interactions whether or not the debris eventually penetrates into the containment. Instead, at least a portion of the debris is slowly oxidized by the containment atmosphere in the long term. This oxidation releases aerosols into the containment, but does not produce large volumes of non-condensable gases.

Most severe accident phenomena discussed in this paper are quantitatively understood, supported by results of domestic and international research. Where quantitative information is sparse or lacking (e g. details of core disassembly dynamics, free convection cooling of large vessels), parametric analyses are available to explore the range of uncertainty. It is found that the lacking information is not crucial to understanding the progression of accident, nor to evaluating the ultimate consequences.

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