Design Features of ACR in Severe Accident Mitigation

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Abstract – New reactor designs require the evaluation of design alternatives to reduce the radiological risk by preventing severe accidents or by limiting releases from the plant in the event of such accidents. The Advanced CANDU Reactor™ (ACR™)[*] design has provisions to prevent and mitigate severe accidents. This paper describes key ACR design features for severe accident mitigation.

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[*] ACR™ (Advanced CANDU Reactor™) is a trademark of Atomic Energy of Canada Limited (AECL).

I. Introduction

Historically, the effort by the Canadian nuclear industry was aimed at the prevention of severe accidents by developing robust reactor designs and ensuring a high reliability of vital reactor systems. For new reactor designs, domestic and international regulatory bodies require the evaluation of design alternatives to reduce the radiological risk in the unlikely event of severe core damage. The purpose of this evaluation is to establish whether any cost-effective Severe Accident Mitigation Design Alternatives (SAMDAs[1]) should be added to the ACR design.

Relevant reactor design features are those provided to facilitate Severe Accident Management (SAM). The international definition of SAM is as follows (Reference [1])[2]:

Severe accident management consists of those actions that are taken by the plant staff during the course of an accident to ***prevent core damage****,* ***terminate progress of core damage*** *and* ***retain the core within the vessel****,* ***maintain containment integrity****, and* ***minimize offsite releases****. Severe accident management also involves pre-planning and preparatory measures for SAM guidance and procedures, equipment modifications to facilitate procedure implementation, and severe accident training.*

This paper overviews the SAM-related design features of the ACR according to topics highlighted in bold in the preceding definition. It should be noted that the SAMDA assessment is ongoing. Some of the SAMDAs remain under consideration pending completion of the Probabilistic Safety Assessment (PSA)[3], which provides quantitative information of the effect of a design alternative on the radiological risk.

II. ACR core damage

CANDU reactors have different characteristics of core damage relative to pressure vessel reactors. Since ‘core damage’ comprises the first three topics in the above SAM definition, this section briefly summarizes the ACR reactor design and explains its core damage states.

II.A. ACR design

The ACR design is based on horizontal fuel channels surrounded by a heavy water moderator, the same as with all CANDU reactors (Figure 1). The major innovation in ACR is the use of slightly enriched uranium fuel and light water as the coolant. The equilibrium core has a negative power coefficient. The coolant void reactivity is small and negative under nominal design conditions. . The safety systems provided in the ACR are (Reference [3]):

- Two fast-acting, fully capable, diverse, and separate shutdown systems, which are physically and functionally independent of each other and from the reactor regulating system;
- Emergency Core Cooling (ECC) System consisting of the Emergency Coolant Injection (ECI) System and the Long-Term Cooling (LTC) System; and

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[1] The acronym SAMDA is commonly used in the USA.

[2] There are variations of the SAM definition (e.g., Reference [2), but the substance is the same in all definitions

[3] PSA is synonymous to the term “Probabilistic Risk Assessment” used in the USA.

- Containment System (strong containment structures (steel lined and low leakage), with containment isolation system, containment heat removal system, etc.)

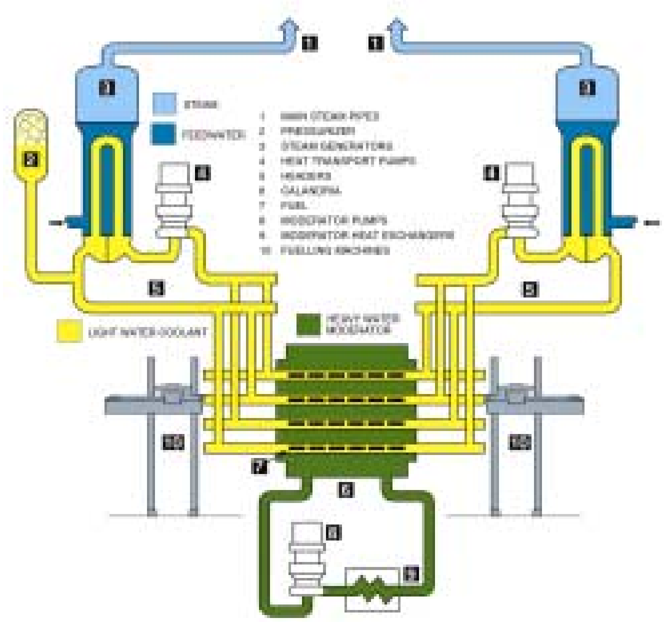

Figure 1 Schematic of ACR Nuclear Systems

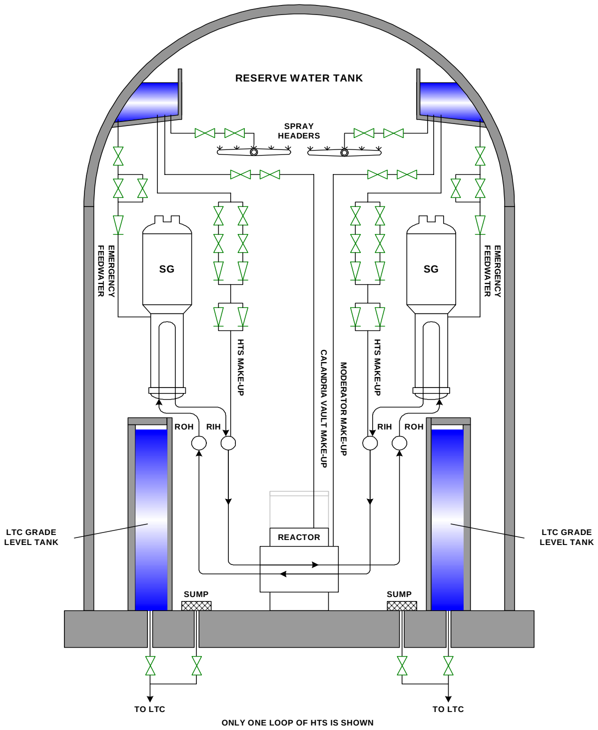

Figure 2 Schematic of Reserve Water System

Systems that provide reliable support services are referred to as safety support systems, which include:

- Reserve Water System (RWS, Figure 2), which provides an emergency source of water by gravity to steam generators, moderator system, shield cooling system, and heat transport system if required.
- Emergency Feedwater System (EFW) with two EFW pumps.
- Electrical Power Systems supply. The safety-related portions of the systems are seismically qualified and consist of redundant divisions of standby generators, batteries, and distribution to the safety-related loads.
- Recirculated Cooling Water (RCW) System circulates demineralized cooling water to different loads in the plant. The safety portions of the RCW are seismically qualified and comprised of redundant, closed-loop divisions. One division is sufficient to cool the plant in a shutdown state.
- Raw Service Water System disposes of the heat from the RCW to the ultimate heat sink. The safety-related portions of the system are seismically qualified and comprised of redundant, open-loop divisions.
- Compressed Air System provides instrument air and breathing air to different systems in the plant.
- The Chilled Water System supplies water to air conditioning and miscellaneous equipment.
- Secondary Control Area contains monitoring and control capability to shut down the reactor and to maintain the plant in a safe shutdown condition following events that may render the main control room unavailable.

The safety enhancements made in the ACR encompass safety margins, performance, and reliability of safety-related systems.

II.B. ACR core damage states

The core damage states (CDSs) pertinent to SAMDAs are schematically illustrated in Figure 3. All these core damage states pertain to a shutdown reactor[4] and they all involve a loss of multiple heat sinks.

The first category of core damage states, Limited Core Damage (LCD), is CANDU-specific. A common characteristic of this category is that the accident progression is arrested within multiple, distributed "vessels" (i.e., within the fuel channels). These vessels (fuel channels) may be cooled either externally, by water (moderator) surrounding the channels or internally, by water within the channels (SAM action). The alternate moderator heat sink, one of the CANDU hallmarks, can maintain any of the states illustrated in Figure 3 indefinitely.

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[4] Loss of shutdown is not credible, see multiple shutdown provisions in Section II.A.

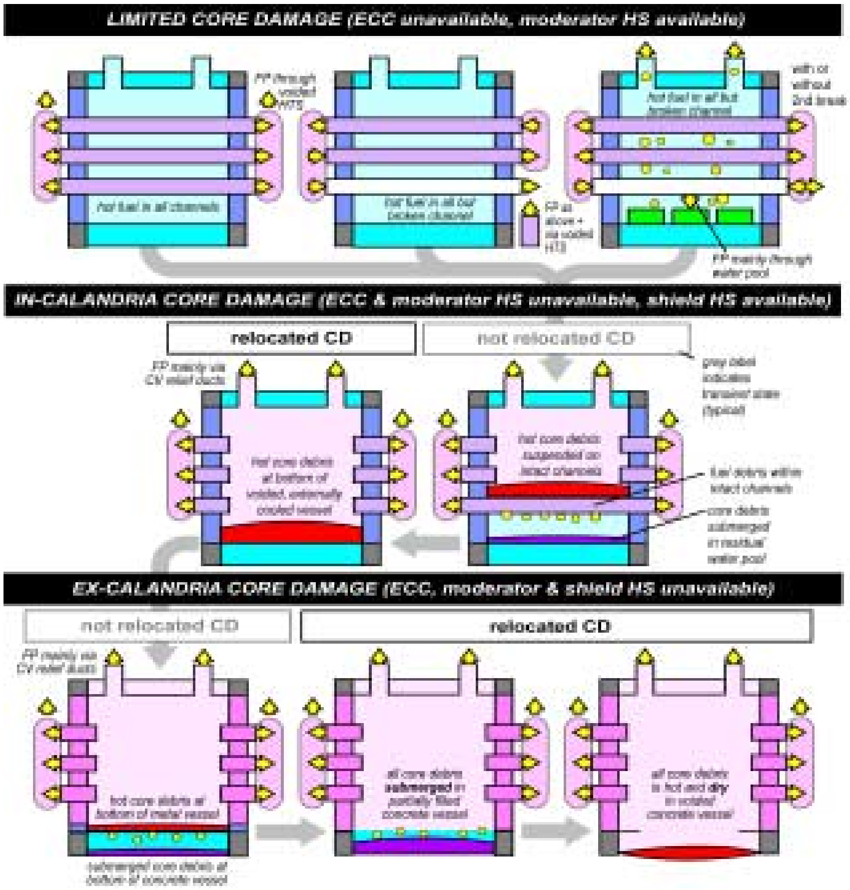

Figure 3 ACR Core Damage States

Extensive experimental and analytical databases exist for these CDSs. Fuel debris remains solid and is readily coolable (Figure 4). Fission products are released from the fuel and hydrogen is produced, but only in modest quantities.

The second category in Figure 3, In-Calandria Core Damage (ICCD), is analogous to the in-vessel core damage state of the Advanced Light Water Reactors (ALWRs) in terms of final configuration (i.e., hot core debris at the bottom of an externally cooled metal vessel). However, the transient ACR core relocation phenomena are considerably different from those in ALWRs, resulting in different challenges caused by severe accident phenomena. Notable differences are that the core break-up and relocation (Figure 5) proceed only at low system pressures in the ACR and that melting of core materials is typically avoided until after the debris has relocated to the bottom of the calandria vessel. The fuel channels act as ‘pressure fuses’ should the accident evolve to produce a sustained power-cooling mismatch in a pressurized Heat Transport System (HTS). When the HTS voids at high pressures, a lead channel (or, at most, a couple of channels) fails at modest temperatures (fuel at 1000°C or less) to depressurize the system. This would normally activate the ECC, preventing a significant fission product release from the fuel. If the ECC were unavailable, the LCD configuration in the top, right-hand corner of Figure 3 arises, which is stable as long as a liquid pool is available in the calandria vessel (i.e., a small amount of fuel is ejected into the vessel, with the bulk of fuel in configuration on the left-hand side of Figure 4). The core break-up and relocation illustrated in

Figure 5 only come into play if fuel channels are voided on the inside and not submerged in liquid on the outside.

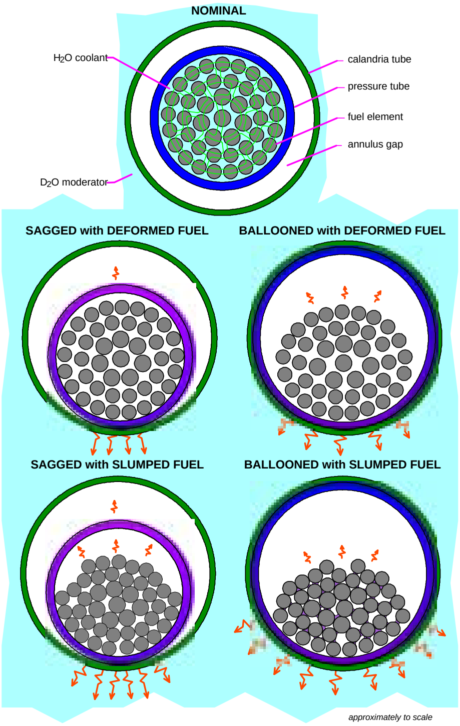

Figure 4 Conditions of Limited Core Damage State

Uncovered, depressurized channels deform and break up into coarse core debris, which is largely trapped on the rows of channels at lower elevations. The low-elevation channels would typically be located within a residual liquid pool of calandria vessel and are thus structurally stable.

The weight load imposed by the accumulating core debris (‘suspended debris’ in Figure 5) eventually exceeds the load-bearing capacity of low-elevation channels, and the whole core collapses (relocates) into the residual water pool in the calandria vessel.

Extensive experimental and analytical databases exist for the “pressure-fuse” aspect of the ICCD state. Core break-up and relocation aspects are determined by analyses, with limited experimental demonstration of integral (multi-channel) core relocation kinetics. Hence, there is considerable uncertainty in terms of fission product and hydrogen release during the transient core relocation. This uncertainty is being enumerated by deterministic analyses of ACR severe accident progression, which are in progress. The best estimate shows a “core-collapse” (relocation to the bottom of vessel) while the fuel is solid; much of the Zircaloy is unoxidized, and the bulk of fission products retained in the fuel matrix. Therefore, severe accident phenomena such as core-coolant and core-structure interactions are qualitatively and quantitatively different from those in ALWRs. A pressurized melt ejection from the ACR is physically impossible.

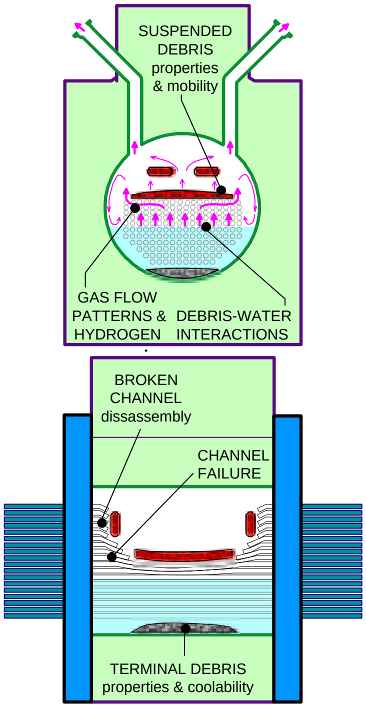

Figure 5 Transient Conditions of In-Calandria CDS

The relocated solid fuel debris eventually dries out, compacts, and partially liquefies. This "dry debris compaction" process is not amenable to the escape of residual fission products from debris. The calandria vessel geometry (cylinder) provides conditions well-suited to in-vessel debris cooling by external water (Figure 6).

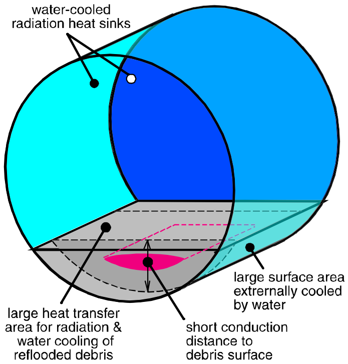

Figure 6 Debris Coolability in Calandria Vessel

The heat fluxes are low and the "terminal debris" bed is largely solid as long as a water pool is available on the outside. An extensive database is available internationally on debris coolability within metal vessels, which is applicable to the ACR. The relocated ICCD state can be maintained indefinitely by external vessel cooling. After the transient core relocation stage, there are no particularly strong challenges to containment integrity posed by severe accident phenomena other than external water pool steaming, if applicable (i.e., if external pool is not actively cooled).

The third category in Figure 3, Ex-Calandria Core Damage (ECCD), is generic to all reactor designs. This category needs to be avoided in order to avoid severe accident phenomena related to core-concrete interactions that invariably challenge the containment integrity. Any reactor design needs to provide sufficient floor space for debris spread and a means to keep the debris on the floor submerged in water.

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III. Core retention within vessel

The core retention is an intermediate state of accident progression during which the core materials are hot but immobile. The 'vessels' within which the core materials can be retained are the fuel channels (which are a part of the HTS) and the calandria vessel, which normally contains the heavy water moderator at low pressure.

III.A. Retention in HTS

The fuel channels are invariably depressurized by the time the fuel heats up to highly elevated temperatures (Section II.B). Heat rejection paths to the water volume in the calandria are established by fuel and pressure tube deformations (Figure 4). The only prerequisite for retaining the hot, solid fuel debris within the fuel channels is to maintain all the channels submerged in water on the outside.

The main moderator system has ample heat removal capacity when available. The passive heat sink is provided as follows:

- Two steam relief paths from the calandria are provided (through bleed valves of the cover gas system and through rupture disks on the calandria vessel).
- Water make-up (by gravity) from the RWS (Figure 2) has sufficient flow capacity to compensate for steaming at decay power levels.
- Instrumentation is provided to measure levels in the calandria vessel and reserve water tank of the RWS.
- Means to control the calandria make-up under SAM conditions are provided. (The motorized valves are powered by the uninterruptible Class II supply; the valves will be assessed for their operability under severe accident conditions; the status indications and remote controls are provided for all relevant valves.)

The SAMDA under consideration involves a fine-tuning of the calandria vessel design to permit passive rejection of decay heat from moderator to shield water as an alternative to gravity make-up from the RWS (additional heat sink).

III.B. Retention in calandria vessel

Broad requisites for retaining the hot core materials within the calandria vessel are:

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[5] It should be noted that stringent separation requirements are in place for all safety-grade systems to enhance protection against common cause events. The ACR cross-connections are designed according to these requirements.

- The calandria vessel is strong enough and its relief is large enough such that it is not destroyed by transient pressure excursions during the core break-up (see challenges in Figure 5).
- The walls of the calandria vessel remain sufficiently cool such that the wall does not fail under the combined thermal and weight loads. This is satisfied when the outer wall surface is in contact with water, and heat fluxes through the vessel wall are sufficiently low so that a departure from nucleate boiling is avoided (Figure 6).

The ACR design is inherently well-suited for debris retention in the calandria vessel as explained below.

- The calandria overpressure protection provisions accommodate the steam surges due to the reactor core collapse into the residual water pool.
- An active heat sink with sufficient capacity is provided for the shield water in the interconnected calandria vault and the two end-shields.
- A passive heat sink (steaming and liquid make-up) is provided by RWS (Figure 2). For the passive heat sink:
    - a steam relief path is available from each of the three volumes surrounding the calandria vessel, which does not interfere with each other or with liquid make-up; and
    - water make-up paths into each of the three volumes are available with sufficient flow capacities; and
    - means are available for the operator to monitor that the water level in each of the three volumes is well above the corium elevation; and
    - means are available for the operator to monitor the status of make-up water source; and
    - means are available for the operator to remotely control the supply of water into each of the three volumes.

The calandria vessel design minimizes penetrations at the bottom periphery and accommodates thermal and weight loads of core debris.

IV. Core damage termination

A subtle difference between retaining the core within a vessel and terminating the progress of core damage is the temperature of core materials. The retained materials can be hot and chemically reactive. The core damage is terminated when the materials are sufficiently cool to be non-reactive. This is when there is no temperature-driven release of fission products from the debris; no thermal-chemical reactions between debris and water or steam are possible; and the cooled-down condition of debris can be maintained into the long term.

In practice, terminating the core damage means flooding the core materials with water and keeping them flooded thereafter. For shallow debris beds (Figure 5 and Figure 6), providing an external water jacket should not be essential after the debris is flooded, but providing this jacket is desirable during the flooding process and a sound engineering principle.

IV.A. Termination in fuel channels

Water can be manually supplied to the HTS:

- from the containment sumps by the LTC pumps (after an earlier LTC failure is restored by SAM actions. and
- by gravity from the RWS (Figure 2).

The calandria vessel can be maintained full of water during the flooding process. The combined make-up capacity (i.e., HTS plus calandria vessel) is well in excess of minimum SAM requirements. In order to maintain the core materials flooded into the long term, the restored LTC function (one division) is required. The inventory of the reserve water tank can be replenished by an external water supply (SAM cross-connection, which extends the RWS mission time). A SAMDA is under consideration to recirculate the sump water through the RWS tank.

IV.B. Termination in calandria vessel

The fuel channels are broken when the damage is terminated in the calandria vessel; therefore, the provisions in Section IV.A apply. In addition, water from the RWS can be supplied directly into the calandria while maintaining the shield water cooling jacket (Figure 2). The calandria pressure relief is not at issue for the flooding of debris because the steaming rate is governed by the rate of water addition and lower than that during transient core break-up (Figure 5).

IV.C. Termination in calandria vault (containment)

At issue are the corium-concrete thermal and chemical interactions. A criterion developed by Electric Power Research Institute is that the floor space for corium debris spreading should be $\geq 0.02\ m^2\ MWth^{-1}$ of full power in order to avoid these interactions when the floor is flooded with water. The ACR layout meets this criterion.

V. Containment integrity maintenance

The containment is a combination of structures, isolation devices, and metallic extensions of the containment envelope (Figure 7). The containment is designed to withstand external events such as earthquakes, tornados, and floods. For internal challenges, design features for energy suppression (spray system and local air coolers (LACs)) and atmospheric control (hydrogen control system) are provided (Figures 8 and 9).

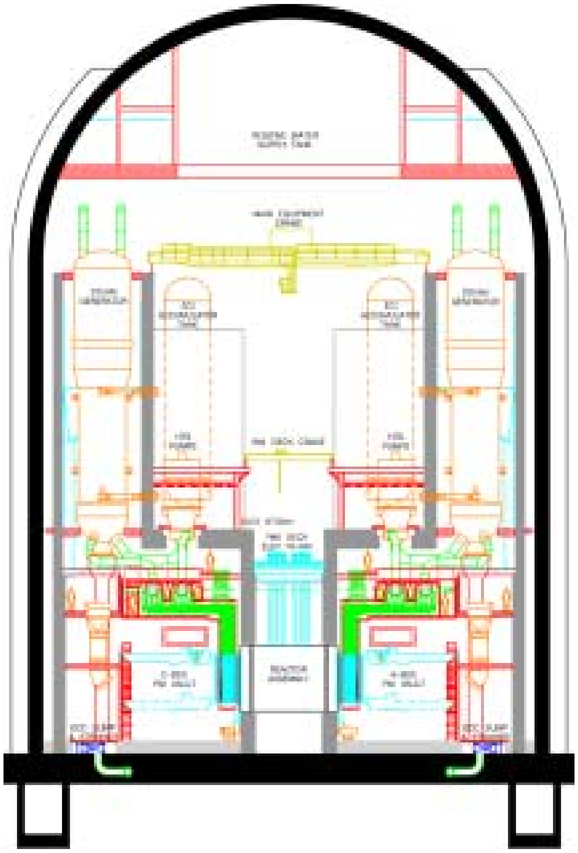

Figure 7 ACR Containment

Following an accident, the containment is sealed (isolated). Decay heat and any other post-accident heat sources are dissipated to the outside by the process systems. Should the energy dissipation systems be unavailable, the energy is stored in the containment as sensible heat in various fluids and structures until the energy dissipation to the outside is re-established by SAM.

The containment pressure rises when the heat generation rate exceeds the heat dissipation rate in the sealed volume. Non-condensable gases can also be generated by thermal-chemical interactions of hot core materials and contribute to the containment pressurization. The pressurization poses a challenge to the containment integrity. Features to control containment pressure are described in Section V.A.

Some of the non-condensable gases generated in severe accidents are flammable. Should these gases ignite, large amounts of chemical energy are rapidly released, causing pressure spikes or, in an extreme, shock waves. The accumulation of the non-condensable gases and the attendant deflagration hazard is a threat to the containment integrity. ACR features to control hydrogen are described in Section V.B.

A high-pressure core-melt ejection into the containment, which could threaten the containment integrity by the so-called direct containment heating, is not possible in the ACR (Section II.B).

Thermal-chemical interactions between corium and concrete are a direct threat to containment integrity as well as major sources of non-condensable gases. As described in preceding sections, this hazard is minimized in the ACR.

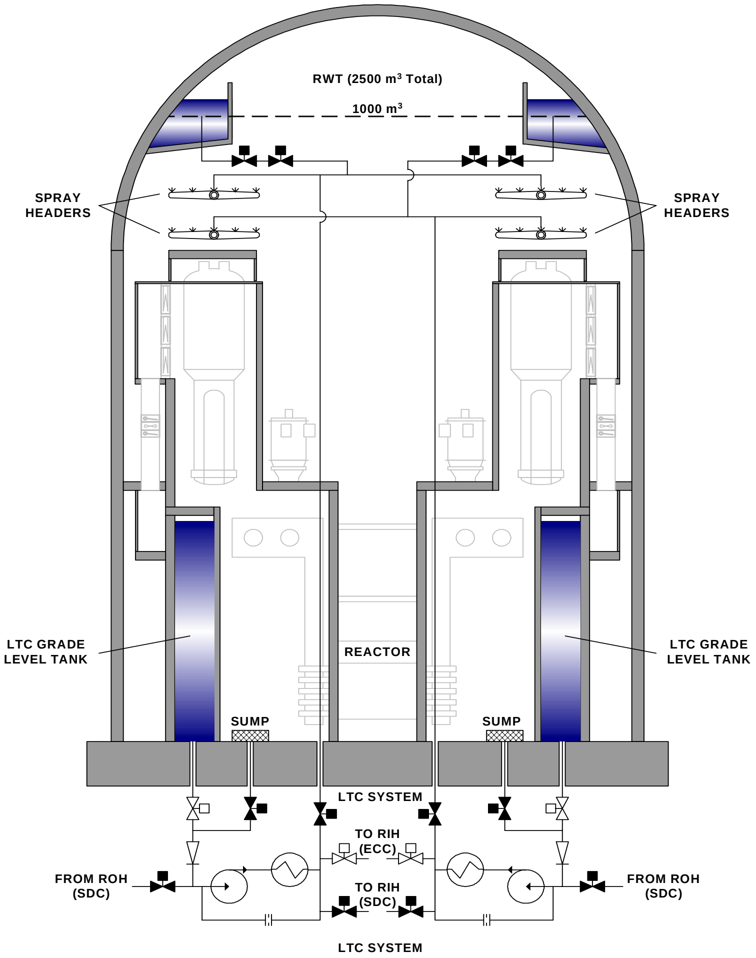

Figure 8 Containment Sprays

V.A. Containment pressurization

Design features to prevent containment failure due to pressurization include:

- Strong containment — the ACR is at the upper end of modern ALWR containment strength.
- Features to control containment pressure are design provisions to condense steam in the containment atmosphere:
    - A containment spray system supplied from the RWT performs post-accident pressure suppression. Connections to the spray are provided from both the LTC system, and the firewater system for long term pressure suppression and containment heat removal. Sprays may also be used for airborne radioactivity control.

  - Non-safety related LACs used for heat removal during normal operation, are robust in design and assessed for operability under severe accident conditions. The LACs receive cooling water supply from a non-safety service water system, that is separate from the safety-related service water system supplying the LTC system heat exchangers.

- Provisions to avoid steaming into the containment — highly reliable, active, post-accident heat sinks are provided for the HTS, the calandria vessel, and the shield water, which would stop the steaming into the containment atmosphere when available.

- SAMDAs under active consideration include manual containment venting (for pressure relief prior to failure).

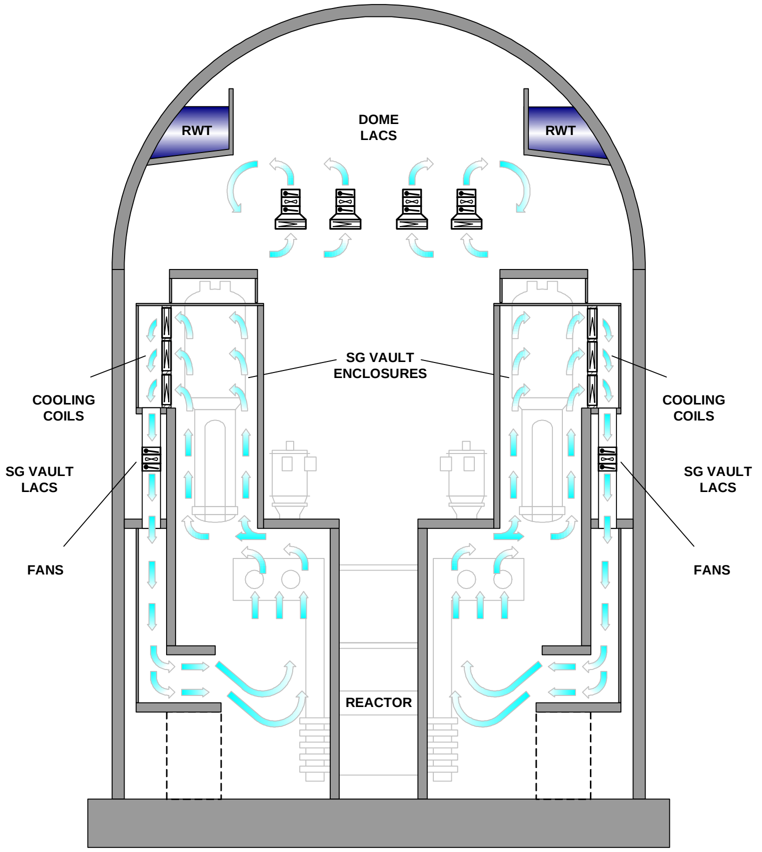

Figure 9 Containment Cooling System Major Local Air Coolers

V.B. Flammable gas control

Hydrogen is generated slowly (by radiolysis) in most accidents. Severe accidents also have hydrogen generated by chemical reactions between metals (mainly Zr) and steam at high temperatures. The generation rates in severe accidents can be fast and the amounts produced can be large.

Hydrogen accumulates in the atmosphere of the sealed containment. If and when elevated concentrations build up, the atmosphere becomes flammable. The flammability is suppressed by a presence of steam in the containment atmosphere. The worst severe accident condition in terms of burn/detonation potential is during the transient core break-up (Figure 5) when large amounts of hydrogen can be generated rapidly and when the spray and/or LACs are available to condense steam in the containment atmosphere.

Numerous combinations and permutations of severe accident progression can be postulated that produce hazardous gas mixtures in the containment atmosphere. Broad requisites on post-accident hydrogen control can be stated as follows:

- As far as practical, remove H_2 from the containment atmosphere.
- Prevent H_2 detonation. This is a broadly accepted requirement, expressed by various regulatory criteria such as the maximum hydrogen concentration in Reference [4].

Hydrogen concentration in containment will be controlled via igniters and passive catalytic recombiners.

The containment structure (Figure 7) is designed to provide a thorough mixing of containment atmosphere, both in forced and natural circulation modes. This minimizes any flammable gas pockets. The layout also minimizes a possibility of any standing flame thermally interacting with the containment boundary.

V.C. Core concrete interaction

The ACR containment envelope cannot come in contact with hot core debris at any location other than the base of the calandria vault. The provisions to avoid these interactions in the vault are described in Section IV.C.

VI. Offsite release minimization

The isolated ACR containment is leak-tight (the design target is ≤ 0.2% per day at design pressure). The emergency operating procedures, which precede the SAM, invariably call on the operator to (a) confirm that the containment is isolated, (b) manually close any open penetration, and (c) monitor radioactivity levels in the plant to identify any leaks in the containment envelope. The ACR provides a highly reliable containment isolation system designed to fail safe (i.e., to isolate) in the event of support service failures.

The ACR containment structure is of robust design with large margin (more than twice the design pressure) Reference [5]. Design features to minimize the offsite releases are containment sprays and containment venting.

VII. Conclusions

The review of the ACR design provisions for severe accident management is ongoing from the early stages of design. This paper provides a high-level overview of the findings to date. Several design provisions have not yet been finalized or decided, but the designers are keenly aware of the SAM concepts and their requirements.

The active heat sinks for ‘vessels’ (i.e., the fuel channels, the calandria vessel, the calandria end-shields and the calandria vault) are all amply capable of dissipating the severe accident heat loads. These heat sinks are designed to be operable under severe accident environmental conditions; however, their operability is yet to be confirmed by assessments.

The active heat sinks for the various process vessels are ‘backed up’ by passive heat sinks (i.e., steaming plus water make-up from the RWS). The supply side of passive heat sinks is simple, rugged, and not vulnerable to failures of plant systems. The importance of the steam relief side is recognized, and the adequate relief capacity will be provided. The passive heat sinks will give the SAM more than 1 day (likely several days) to diagnose the accident and to establish the ultimate heat sinks.

The spray system for containment pressure suppression is designed for high reliability and has ample capacity to ensure low containment leakage without external intervention, after which time alternative supply to the sprays can be brought on line manually. The sprays are backed up by the LACs which are assessed for operability following a severe accident. The strong ACR containment will provide a long time of completely passive protection for any severe accident at decay power. Its characteristics are not prone to catastrophic failures. The failed structure would retain some capability to reduce radioactivity release into the environment. SAMDAs that enhance the capabilities for minimizing the offsite releases (venting) are being actively examined further.

State-of-the art hydrogen control of igniters and passive, auto-catalytic recombiners are provided.

The ACR design is not prone to core-concrete interactions by virtue of multiple, externally cooled barriers between the fuel and the containment floor as well as due to characteristics of the compartment into which the core materials would eventually penetrate (i.e., a large area for debris spread and multiple means of keeping the debris submerged in water).

The instrumentation that provides reliable data to the severe accident management team is critical to successful accident mitigation. The ACR instruments provide the necessary coverage of all critical plant parameters in two locations (main control room and secondary control area). As far as practical, these instruments will be hardened to withstand the severe accident conditions. All critical instruments will be assessed for survivability under severe accident conditions.

Acknowledgments

Contributions of A. White and B. Sanderson, AECL Chalk River Laboratories, on severe accident phenomenology are gratefully acknowledged.

Nomenclature

ACR	Advanced CANDU Reactor
ALWR	Advanced Light Water Reactor
CDS	Core Damage State
ECCD	Ex-Calandria Core Damage
ECC	Emergency Core Cooling
ECI	Emergency Coolant Injection
HTS	Heat Transport System (same as Reactor Cooling System)
ICCD	In-Calandria Core Damage
LAC	Local Air Cooler (containment)
LCD	Limited Core Damage
LTC	Long-Term Cooling

PSA	Probabilistic Safety Assessment (same as Probabilistic Risk Assessment)
RCW	Recirculated Cooling Water
RWS	Reserve Water System
SAM	Severe Accident Management
SAMDA	Severe Accident Mitigation Design Alternative

References

[1] Senior Group of Experts on Severe Accident Management, *Implementing Severe Accident Management in Nuclear Power Plants,* OECD (1996).

[2] *Severe Accident Issue Closure Guidelines*, Nuclear Energy Institute, report NEI 91-04, Rev. 1 (1994).

[3] M. Bonechi et al., *Safety Basis of the Advanced CANDU Reactor*, Proceedings of the 2004 Annual Conference of the Canadian Nuclear Society, Toronto, Ontario, June 6-9 (2004)

[4] *Policy, Technical, and Licensing Issues Pertaining to Evolutionary and Advanced Light-Water Reactor ALWR Designs*, US Nuclear Regulatory Commission SECY-93-087, April 2 (1993).

[5] A.M. Saudy et al., *Ultimate Pressure Capacity of the ACR Containment Structure*, SMiRT-18 Conference, Beijing, China, August 7-12, (2005).