

ACR-1000: ENHANCED RESPONSE TO SEVERE ACCIDENTS

Popov, N.K., Santamaura, P., Shapiro, H. and Snell, V.G
Atomic Energy of Canada Limited
2251 Speakman Drive, Mississauga, Ontario, Canada L5K 1B2

1. INTRODUCTION

New reactor designs require the evaluation of design alternatives to reduce the radiological risk by adequate prevention of severe accidents or by limiting releases from the plant in the event of such accidents. The Advanced CANDU Reactor™-1000 (ACR-1000) design includes features and provisions to prevent and mitigate severe accidents. These design provisions meet the Canadian regulatory requirements [1], and account for international practice and guidelines [2, 3] with respect to achieving cost-effective severe accident mitigation design. Also, as part of the defense-in-depth strategy, the ACR-1000 design includes a variety of passive features.

The ACR-1000 Core Damage States (CDSs) include two categories of Beyond Design Basis events (BDBAs) [4]: fuel damage events that are CANDU-specific, and Severe Core Damage events (SCDs). The Severe Core Damage events include In-Calandria Core Damage states (ICCDs), which are also CANDU-specific.

2. ACR-1000 DESIGN FEATURES

The ACR-1000 design has evolved from AECL's internationally recognized line of CANDU pressure tube reactors, based on in-depth knowledge and experience with CANDU systems, components and materials, as well as from the experience and feedback received from owners and operators of CANDU plants. The ACR design is based on the use of modular, horizontal fuel channels surrounded by a heavy water moderator, the same feature as in all CANDU^{®1} reactors. The major innovation in ACR is the use of low enriched uranium (LEU) fuel and light water as the coolant, which circulates through the fuel channels [5,6]. This results in a more compact reactor design and a reduction of heavy water inventory, both contributing to a significant decrease in cost compared to traditional CANDU reactors. Figure 1 shows a schematic of the ACR-1000 Heat Transport System (HTS).

As in previous CANDU designs, the ACR-1000 incorporates two fast-acting, fully capable, diverse, and separate shutdown systems (SDS1 and SDS2), which are physically and functionally independent of each other. Both shutdown systems perform their function in the low-pressure moderator contained in the calandria.

The Reserve Water System (RWS) (Figure 2) is comprised of a seismically qualified Reserve Water Tank (RWT), containing a large volume of water used by other systems to mitigate accidents. The RWT is located at a high elevation in the reactor building, and it provides a passive emergency source of water to the steam generators (back-up emergency feedwater), containment cooling system, moderator system, shield cooling system and heat transport system. Injection from the RWT to the Heat Transport System by gravity helps mitigating accidents for which Emergency Core Cooling (ECC) system is postulated to be impaired.

Following a severe accident, heat transfer to the moderator and shield cooling systems' inventory is important as it maintains fuel cooling and helps arresting progression of the accident. In a severe accident the operator has a choice of manually connecting the RWT to the moderator system and/or the shield cooling system.

The ACR-1000 Emergency Coolant Injection (ECI) system supplies light water coolant to the HTS and refills the fuel channels in the short term after a LOCA. The ECI system consists of two passive RIH accumulators connected to the heat transport system reactor inlet headers (RIH) of both loops on the corresponding reactor face, and four passive ROH accumulators (arranged in pairs) connected to the heat transport system reactor outlet headers (ROH) of both loops on the corresponding reactor face.

Core Make-up Tanks (CMTs) provide passive make-up to limit the extent and duration of HTS voiding for

¹ CANDU® (CANada Deuterium Uranium) is a registered trademark of Atomic Energy of Canada Limited (AECL).

secondary side depressurization events in the intact HTS loop during a LOCA event. CMTs also provide large make-up flows to the broken HTS loop in the short-term following a LOCA, and facilitate thermosyphoning and operation of the Long Term Cooling (LTC) pumps.

The Long Term Cooling System is a safety system incorporated into the ACR-1000 to circulate water through the reactor fuel channels to remove decay heat. The LTC system provides long-term decay heat removal following a reactor shutdown with Heat Transport System pressure boundary intact (shutdown cooling mode), or following a Loss of Coolant Accident (LOCA) to the broken HTS loop (post-LOCA recovery mode).

The LTC is comprised of four independent divisions each having a single pump and a heat exchanger, with separate divisions of electrical power and service water supply. Use of a four-division design provides complete separation between divisions of the LTC system and increases reliability by minimizing common-mode failures.

The containment system includes a steel-lined, prestressed concrete reactor building containment structure, access airlocks, sprays for pressure reduction, and a containment isolation system, consisting of valves in certain process lines and ventilation ducts that penetrate the containment structure. This containment design ensures a low leakage rate and, at the same time, provides a pressure-retaining boundary for LOCAs.

A safety-related containment cooling spray system, supplied from the Reserve Water System, is provided for steam condensation and post-accident pressure suppression. Back-up connections to the Long Term Cooling system are provided for long-term post accident containment heat removal. The ACR-1000 design has been adapted to utilize passive components of the system for short-term mitigation of harsh environmental conditions inside containment following a postulated accident. The containment cooling spray is actuated automatically for any event resulting in pressures or temperatures that challenge the environmental conditions for equipment qualification or the integrity of the containment structure.

Following a postulated severe accident (e.g. a LOCA co-incident with a total loss of service water), the gravity-driven sprays, utilizing only the allocated RWT inventory, will ensure containment leak tightness for at least 24 hours after the onset of core damage. After 24 hours, other intervention may be taken to establish a sustainable means of preventing containment failure.

The containment atmospheric hydrogen control is achieved by passive autocatalytic recombiners, and active igniters that limit the concentration of hydrogen in the Reactor Building (RB) atmosphere to below the threshold limit at which deflagration or detonation could occur. In the event of severe accidents, active igniters placed at strategic locations in the containment supplement the action of the passive recombiners.

The containment structure is designed to provide a thorough mixing of the containment atmosphere, to minimize occurrence of flammable gas pockets. The containment layout also minimizes the possibility of any standing flame thermally interacting with the containment boundary.

3. ACR-1000 CORE DAMAGE STATES

The Core Damage States (CDSs) pertinent to Severe Accident Mitigation Design Alternatives (SAMDA) are schematically illustrated in Figure 3. All these core damage states pertain to a shutdown reactor and they all involve a loss of multiple heat sinks and multiple barriers.

The first category of core damage states is local and widespread fuel damage states that are specific to a channel type reactor. A common characteristic of this category is that the accident progression is arrested within multiple, distributed “pressure vessels” (i.e., within the fuel channels). The fuel channels may be cooled either externally by heavy water (moderator) surrounding the channels, or internally, by light water within the channels. The moderator heavy water serves as an alternate heat sink that provides an indefinite heat removal function, which is one of the characteristics of the CANDU reactor designs that is utilized in the ACR-1000 design, as illustrated in Figure 3. Extensive experimental and analytical databases exist for the local and widespread fuel damage states, which demonstrate that fuel debris remains solid and is readily coolable.

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), and results in the same final configuration (i.e., hot core

debris at the bottom of an externally cooled metal vessel). However, the transient ACR-1000 core relocation phenomena are considerably different from those in ALWRs, resulting in different severe accident phenomena. Core break-up and relocation (Figure 4) is slow due to presence of residual water in the calandria and proceeds only at low system pressures in the ACR. Also, melting of core materials is typically avoided until after the debris has relocated to the bottom of the ACR-1000 calandria vessel.

In the event of an accident resulting in a sustained power-cooling mismatch in a pressurized Heat Transport System, the fuel channels act as ‘pressure fuses’. When the HTS voids at high pressures, one or a few channels fail 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 widespread fuel damage configuration as shown in Figure 3 would arise, 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 the configuration illustrated on the right-hand side of Figure 3). The core break-up and relocation illustrated in Figure 5 only comes into play if fuel channels are voided on the inside and not submerged in liquid on the outside.

In severe accidents, 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 inside the 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.

Experimental and analytical data support the “pressure-fuse” behaviour of the pressure tubes and aspect of the ICCD state. Core break-up and relocation aspects are determined by analyses, with some experimental demonstration of integral (multi-channel) core relocation kinetics. Uncertainty in terms of fission product and hydrogen release during the transient core relocation will be covered by deterministic ACR-1000 specific severe accident analysis. Generic best-estimate analysis has shown a “core-collapse” (relocation to the bottom of the 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-1000 core (calandria) is physically impossible.

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 provides conditions well suited to in-vessel debris cooling by external water. The calandria vessel assembly is situated in the reactor vault that is filled with shield water (Figure 5). Also, both ends of the calandria vessel cylinder are surrounded by end-shield water.

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-1000. The 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 if the external water pool is adequately cooled.

Uncovered and 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 in the calandria vessel and are thus structurally stable.

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. To address regulatory requirements with respect to this type of a severe accident, the ACR-1000 reactor design provides sufficient floor space for debris spread, and means to keep the debris on the floor submerged in water. Further details are provided in [7].

4. SEVERE ACCIDENT MITIGATION

Severe accident mitigation is defined internationally as [8]: *“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 section discusses briefly the ACR-1000 capabilities for severe accident mitigation for a postulated severe accident sequence for ACR-1000. A limiting severe accident is the loss of all AC Power Supplies (“Station Blackout”). The sequence of events for this severe accident is based on preliminary analyses of CANDU 6 and ACR-700. For this case, total loss of all AC power supplies is postulated. Power from the grid (off-site) and the turbine generator is lost (Class IV power), and the on-site Class III diesel generators are assumed to fail. In this scenario, the HTS pumps lose power and the reactor is promptly shut down by the two shutdown systems. There is no power available to the service water system, the LTC system, the emergency feedwater system, the moderator cooling system, the shield cooling system, and the containment cooling system LACs. The HTS remains full by the CMTs and circulation is maintained by thermosyphoning. The inventory in the SGs boils off providing heat removal. Initiation of gravity-fed make-up water to the SGs from the RWT extends heat removal. The remaining inventory in the SGs will boil off and the SGs will dry out when the RWT inventory is depleted (after several hours).

Under these conditions, one or two calandria tubes are postulated to fail resulting in a depressurization of the primary side. The CMTs and ECI are available to inject into the HTS. As the moderator heats up and boils off, water from the RWT is directed to the calandria and the reactor vault. This delays accident progression, allowing alternative (e.g. off-site) sources of make-up water to be provided to maintain containment integrity.

5. ACR-1000 HEAT SINK CAPABILITIES

Availability and sequencing of the ACR-1000 safety and safety related systems is important for fuel heat removal and containment cooling during postulated severe accidents. The viable heat sinks for fuel heat removal are predominantly dependent on whether or not the HTS is intact. Reference 6 summarizes the fuel heat removal capabilities of ACR-1000 for two key groups of events: LOCA events, in which the HTS is not intact, and non-LOCA events (e.g. station blackout or Main Steam Line Break), in which the primary pressure boundary is intact. The severe accident prevention and mitigation features of the ACR-1000 are shown in Table 1. These heat sinks will give the severe accident management more than 1 day (likely several days) of time to diagnose the accident and to establish the ultimate heat sinks.

For LOCA events, following reactor shutdown, crash cooldown (via opening of the main steam safety valves) is initiated automatically upon detection of the LOCA. This depressurizes the HTS and facilitates HTS refill by injection from the ECI accumulators, or make-up by gravity from the RWT. Crash cooldown also reduces the tendency of the secondary side to act as a heat source. Fuel integrity may be affected if ECI is unavailable and RWT is relied upon for core refill, but the fuel and fuel channels will still be maintained in a configuration that allows long-term heat removal. Once the HTS is sufficiently depressurized, the LTC system begins to take water from the RB sumps and/or the grade level tanks and injects recirculated cooled water into the HTS.

In the event of a small LOCA, heat removal via the secondary side (using Main Feedwater or Emergency Feedwater as the heat sink) would be the method of choice. In the event of a postulated failure of the LTC system, the fuel and fuel channels will heat up until the pressure tubes contact the calandria tubes, resulting in efficient heat transfer by direct conduction to the moderator. The moderator cooling system can then operate to remove decay heat. The above systems provide severe accident prevention.

If the moderator cooling system is also unavailable, heating, and eventually boiling of the moderator and reactor vault inventory will occur. The calandria and shield tank rupture discs will burst, and decay heat is removed from the core by discharge of steam to the Reactor Building. Further accident progression is delayed by initiation of make-up to the calandria and reactor vault from the RWS.

6. SUMMARY AND CONCLUSIONS

The severe accident design provisions of the ACR-1000 provide both accident prevention and mitigation. The heat sinks for the fuel channels, the calandria vessel, the calandria end-shields, and the reactor vault are all capable of dissipating the severe accident heat loads. These heat sinks are designed to be operable under severe accident environmental conditions.

The active heat sinks for the various process vessels are ‘backed up’ by passive heat sinks (e.g., steaming plus water make-up from the RWS). For any postulated accident, there is at least one group of systems available to mitigate the event that is comprised solely of passive systems and features. 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 is provided. The passive heat sinks will give the severe accident management more than 1 day (likely several days) to diagnose the accident and to establish the heat sinks.

The ACR-1000 design has achieved safety improvements by building on the CANDU traditional design features, by implementing further design enhancements for prevention and mitigation of severe accidents, and by improving reliability in support of key safety functions and heat sinks.

7. REFERENCES

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- [3] 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).
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Table 1: Severe Accident Prevention and Mitigation Features

SCD Prevention (no loss of core coolability)	SCD Mitigation (Many hours available for boiling water in the calandria and reactor vault)
Normal Heat Removal Systems	Passive thermal capacity of moderator
Emergency Feedwater System	Passive thermal capacity of reactor vault
Core Makeup Tanks	Passive makeup to calandria vessel from Reserve Water Tank
Emergency Core Cooling	Passive makeup to reactor vault from Reserve Water Tank
Backup moderator heat sink	Other Severe Accident Management features

NOMENCLATURE

ACR	Advanced CANDU Reactor
ALWR	Advanced Light Water Reactor
BDBA	Beyond design Basis Accident
CDS	Core Damage State
CMT	Core Makeup Tank
ECCD	Ex-Calandria Core Damage
ECC	Emergency Core Cooling
ECI	Emergency Coolant Injection
HTS	Heat Transport System
ICCD	In-Calandria Core Damage
LAC	Local Air Cooler (containment)
LTC	Long-Term Cooling
RCW	Recirculated Cooling Water
RWS	Reserve Water System
RWT	Reserve Water Tank
SAM	Severe Accident Management Design Alternative
SAMDA	Severe Accident Mitigation Design Alternative
SCD	Severe Core Damage
SG	Steam Generator
RIH	Reactor Inlet Header
ROH	Reactor Outlet Header

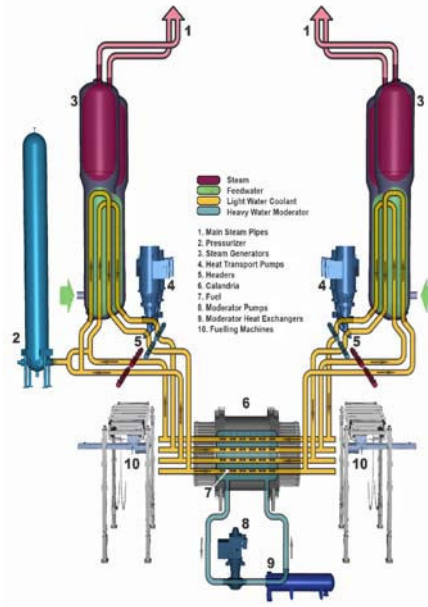


Figure 1: Schematic of ACR-1000 Reactor Heat Transport System

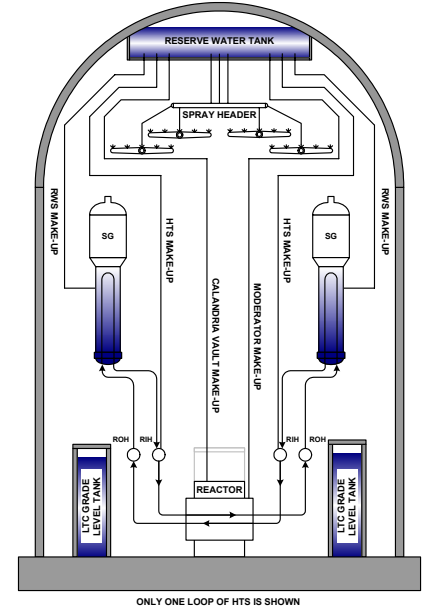


Figure 2: Reserve Water System

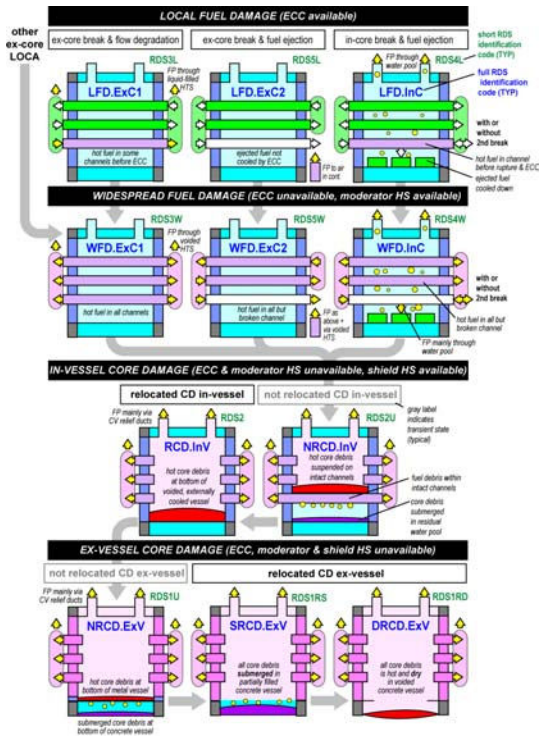


Figure 3: ACR-1000 Fuel and Core Damage States

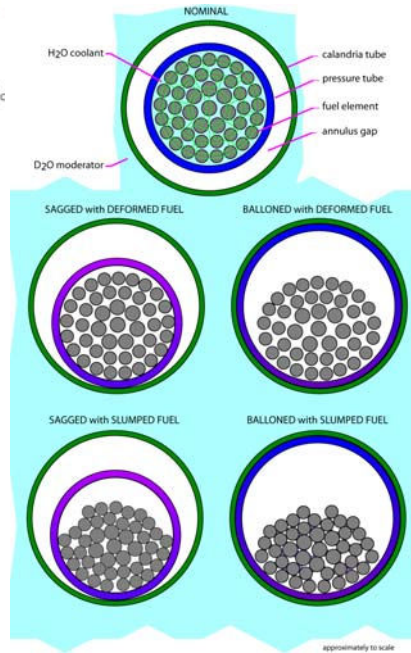


Figure 4: Conditions of Widespread Fuel Damage State

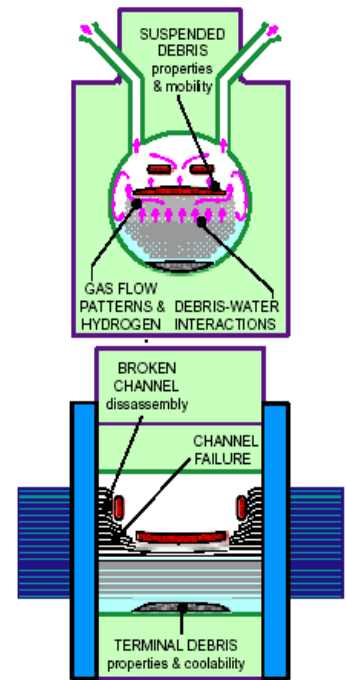


Figure 5: Severe Core Damage – Molten Debris on Reactor Floor