Point Lepreau Instrument and Equipment Survivability Assessment during Severe Accident Conditions

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Abstract

Instrument and equipment survivability during severe accidents has always been recognized as an important consideration in assessing response capability. However, events during the 2011 Fukushima Dai'ichi accident have placed renewed focus on ensuring critical instrument and equipment is capable of performing its function during a severe accident. NB Power has performed a survivability assessment following the COG JP-4426 methodology to evaluate the capability of equipment and instrumentation used during a severe accident to achieve a controlled, stable state after core damage under the consequential unique and harsh containment environment. This paper describes the evaluation, its results and planned next steps.

1. Introduction

Instrument and equipment survivability during severe accidents has always been recognized as an important consideration in assessing response capability. However, events during the 2011 Fukushima Dai'ichi accident have placed renewed focus on ensuring critical instrument and equipment is capable of performing its function during a severe accident. Subsequently, the CNSC Fukushima Action Plan assigned the following Fukushima Action Item (FAI) 1.8 to utilities:

> *"Licensees should provide a reasonable level of confidence that the means (e.g., equipment and instrumentation) necessary for SAM and essential to the execution of Severe Accident Management Guidelines (SAMGs) will perform its function in the severe accident environment for the duration for which it is needed. This assessment should consider elements of Human and Organizational Factors under accident conditions."*

While CANDU utilities have considered this issue, additional work is needed to provide the required level of assurance that instrument and equipment essential to the execution of Severe Accident Management Guidelines (SAMG) would be capable of performing its function in a severe accident environment for the duration for which it is needed.

COG Joint Project JP4426 was initiated to systematically and jointly conduct the required work to support the utilities in closing specific FAIs and undertaking additional supporting work. In terms of instrument and equipment survivability, an assessment methodology was developed and issued [1] to ensure industry alignment in approach.

Instrument and equipment survivability during severe accidents has always been recognized as an important consideration in assessing response capability. Many modifications have already been implemented at Point Lepreau G.S. to provide a high degree of assurance that severe accidents can be mitigated and that applicable safety goals are met for such beyond design basis accidents. The procurement of portable emergency mitigating equipment provides even more defense-in-depth through a flexible response strategy to supply water and power to key equipment should existing engineered systems fail for any reason. The instrument and equipment survivability assessment is therefore a logical extension to the work that has already been done and implemented at Point Lepreau and is intended to give reasonable assurance that the existing design basis and design extension engineered systems will be available to perform their mitigating functions.

As highlighted above, the purpose of the survivability assessment is to provide reasonable assurance through a systematic review and evaluation of the availability of equipment and instrumentation used during a severe accident to achieve a controlled, stable state after core damage under the unique containment environments. Severe accident phenomena may create harsh, high temperature and pressure containment environments with a significant concentration of combustible gases and high radiation fields. Local or global burning of the gases may occur, presenting additional challenges to the equipment. Analyses should demonstrate that there is a reasonable level of confidence that essential equipment and instrumentation used to mitigate and monitor severe accident progression is available at the time it is called upon to perform, including ensuring measurements to assess core and heat sink conditions, and the state of containment barriers. This evaluation is based on a set of bounding environmental conditions and parameters which envelop the postulated conditions occurring in various stages of the severe accident progression.

2. Assessment

2.1 Methodology Overview

The methodology for performing the instrument and equipment survivability assessment is documented in COG-JP-4426-004-R0 [1], which has been developed to provide reasonable assurance that essential equipment needed for SAMG execution will be available to function as required. Reasonable assurance is a qualitative measure and would be provided by demonstrating survivability of the preferred line-ups, along with instrumentation sufficient to measure if the strategy lineup is being effective. Where survivability of a preferred lineup or instrumentation cannot be demonstrated, reasonable assurance can still be provided by demonstrating survivability of alternatives, or if it is determined that unavailability of the line up or instrumentation will not affect the overall defense in depth.

The key steps of the methodology include:

- Define basic phases for CANDU severe accidents
- Extract high level mitigating and control actions
- Compile list of instrument and equipment for the above actions
- Screen and align items with accident characteristics
- Assess survivability

2.2 Definition of Basic Phases for CANDU Severe Accidents

The purpose of this step is to provide quantitative information on boundary conditions during a severe accident, which includes five main tasks:

1. Identify the specific purpose of the instrument and equipment assessment being undertaken, so as to clearly define the scope
2. Review existing analyses that are relevant to the purposes of the assessment
3. Select site-specific Core Damage States (CDS)
4. Align accident phases with selected CDS
5. Collect bounding environmental conditions for each accident phase

In fulfillment of development of a full-scope Level 2 Probabilistic Safety Assessment (PSA) for PLGS, five representative severe accident reports were prepared:

- Station blackout scenarios [2]
- Small LOCA scenarios [3]
- Shutdown state scenarios [4]
- Feeder stagnation break scenarios [5]
- Steam generator tube rupture scenarios [6]

The timelines associated with core degradation and entry into various core damage states is highly dependent on the nature of the accident and availability of effective mitigating systems. Some accident scenarios are more likely (i.e. higher frequency of occurrence) but may not represent the bounding or worst case scenario in terms of in-containment environmental conditions against which instrument and equipment survivability should be assessed. As a result, the approach taken in this assessment is to utilize the most likely accident scenario to identify expected timing or accident phase duration, but applies the environmental conditions from the severe accident scenario that results in the greatest in-containment source term (or potential releases). Therefore, for this assessment, the station black-out scenario was selected or accident timing due to its postulated frequency of occurrence and the feeder stagnation break scenario to determine bounding environment conditions since it result in the highest source term within containment.

The timing associated with the station black-out case, assuming no operator intervention and a total loss of heat sinks (most representative of the accident at Fukushima Dai'ichi) is provided in Table 1. . Each accident sequence is divided into SAPs to facilitate alignment of bounding environmental conditions and to facilitate selection and analysis of instrumentation and equipment. The SAPs included here are only for the assessment of survivability of instrumentation and equipment and are not intended as input for the development of operational strategies and procedures. In general terms, SAPs align with severe accident core damage states (CDS) as shown in Table 2

Time (hrs.)	Time (s)	Event
0.0	0	AC power loss (Class IV and Class III)
0.0	0	Turbine stop valves closed (MAAP4-CANDU does not model them open)
0.0	0	Moderator cooling and circulation off, primary pumps off
0.0	0	Shield cooling system off
0.0	0	SG main and auxiliary feedwater pumps off
0.00	0	Reactor trip due to loss of power
0.4	1,603	Calandria vessel bleed valve opens
1.8	6.636	LRVs open for the first time, PHTS loops 1 & 2
1.9	6,688	SG secondary sides are dry, Loop 2
1.9	6,693	SG secondary sides are dry, Loop 1
2.0	7,178	Dousing system starts
2.2	7,840	Dousing system exhausted (dousing max flow rate is 2142 kg/s)
2.5	8,802	Pressurizer empty
N/A	N/A	Crash cooldown system start (unavailable in Case A)
3.9	14,084	At least one channel is dry Loop 2 (complete boil-off) - Channel 1
3.9	14,248	At least one channel is dry Loop 1 (complete boil-off) - Channel 1
3.9	14,288	Pressure and calandria tubes are ruptured Loop 2 – Channel 7
4.0	14,494	Moderator reaches saturation temperature
4.0	14,531	Calandria vessel rupture disk open, connecting vessel to containment volume
4.3	15,580	Calandria vessel rupture disk open, connecting vessel to containment volume
5.5	19,669	Beginning of core disassembly, Loop 2
5.5	19,681	Beginning of core disassembly, Loop 1
N/A	N/A	Massive core debris relocation (core dump) to calandria vessel bottom (does not occur in Case A)
N/A	N/A	Airlock seals failed (although postulated to occur in Reference 2, this is now practically precluded due to installation of the Emergency Filtered Containment Vent (EFCV) system.
11	39,005	Water is depleted inside calandria vessel
14	49,854	Water in the calandria vault reaches saturation temperature
N/A	N/A	Calandria vessel failed (although postulated to occur in Reference 2, this is now practically precluded due to effective implementation of In-Vessel Retention (IVR) strategy through installation of the Calandria Vault Make-up Line (CVML)
N/A	N/A	Although additional events are included in Reference 2 following calandria vessel failure, they are not included further here since calandria vessel failure is practically precluded as discussed above.

Table 1 Station Black-Out Accident Timing (No Operator Intervention)

Survivability Assessment		COG SAMG	
SAP	**SAP Description**	**Corresponding Core Damage State (CDS)**	**CDS Description**
SAP-1	**Initiate Event Response Phase** Recovery of core cooling prior to fuel damage via boiler make-up (including over an extended period) or via Emergency Core Cooling (ECC) injection and recovery. This phase is the transition to severe accident conditions only, and ends when the first pressure tube ruptures (high temperature creep).	N/A	No major fuel damage
SAP-2	**Extended Core Heat-up Phase** Leads to early In-Vessel Retention (IVR). Recovery of moderator make-up after onset of fuel damage but prior to core collapse or fuel channel rupture	CDS-1	Widespread fuel damage. Emergency Core Cooling (ECC) unavailable. Moderator and/or shield water heat sink remains available.
SAP-3	**Advanced In-Vessel Phase** Leads to late IVR. Recovery of moderator makeup / shield water after core collapse but prior to calandria vessel failure	CDS-2 and CDS-3	Upper core collapses onto lower pressure tubes (CDS-2) and finally core collapses to bottom of calandria (CDS-3). ECC, moderator and/or shield water heat sinks unavailable.
SAP-4	**Ex-Vessel Phase** No recovery prior to calandria vessel failure. Molten core debris relocates from calandria vessel to calandria vault or containment and eventually leads to CCI.	CDS-4 and CDS-5	Calandria fails and debris relocates to shield tank/calandria vault (late CDS-4). CCI may occur and debris may penetrate the vault concrete and relocate to the basement floor.
Note 1: During plant refurbishment, Point Lepreau G.S. installed a seismically robust and qualified Calandria Vault Make-up Line designed to operate during severe accident conditions as part of an IVR strategy to ensure that IVR is maintained. As a result, the methodology for instrument and equipment survivability assessment does not require survivability assessments for SAP-4.			

Table 2: Severe Accident Phase Definitions

Based on the applicable severe accident analyses without operator intervention, Table 3 provides the duration for each SAP. Table 3 confirms that the station blackout case for Point Lepreau G.S. has longer durations in each phase compared to the stagnation feeder break scenario.

		Station Blackout		**Stagnation Feeder Break**	
SAP	**Entry Condition**	**Timing (hours)**	**Duration in Phase (hours)**	**Timing (hours)**	**Duration in Phase (hours)**
SAP-1	Starts at time = 0	0 to SAP-2	3.9	0 to SAP-2	2.75
SAP-2	Starts at time of first pressure tube failure	3.9 to SAP-3	1.6	2.75 to SAP-3	0.27
SAP-3	Starts at time of core collapse (modified to start at beginning of core disassembly[1])	5.5 to SAP-4	40.5	3.02 to SAP-4	30
SAP-4	Starts at time of Calandria failure	46*	N/A	33.02*	N/A

Table 3: Severe Accident Phase Durations

* SAP-4 start times are provide only for information purposes to identify an appropriate duration for the SAP-3 phase. In reality, SAP-4 state is precluded through implementation of an effective In Vessel Retention (IVR) strategy at PLGS and, therefore, the duration in SAP-4 is shown as not applicable (N/A)

The methodology [1] identified that bounding environmental and process conditions should be collected for each phase of each accident scenario, which includes:

- Accident scenario
- Phase name (e.g., SAP-1, SAP-2, SAP-3, SAP-4)
- Phase duration (start and end times)
- Peak thermal hydraulic conditions in each room/location within the primary containment/confinement:
  - Pressure (i.e. containment pressure)
  - Gas temperature (assumed to be containment ambient temperature)
  - Relative humidity
  - Water level
- Flammability parameters in each room/location with the primary containment/confinement:
  - Combustible gas concentration
  - Oxygen concentration

[1] The severe accident analysis [2 to 5] uses the terminology "beginning of core disassembly" consistently but not "core collapse". Although disassembly starts earlier than core collapse, the former is used for timing in this report to permit accident case comparisons.

- Steam concentration
- Indication of combustion events in existing analyses during accident phase
- Radiological conditions in each room/location with the primary containment/confinement:
  - Airborne radioactivity concentration (gamma radiation only)
  - Deposited radioactivity concentration (gamma radiation only)

In general, concerns regarding the possible impacts of inert aerosols become negligible if mitigating actions are taken assuring IVR, thus precluding core material interaction with the concrete vault or containment basement floor. Aerosols generated during accident progression up to and including in-vessel retention are much smaller in quantity relative to those from CCI and do not represent a challenge to containment integrity outside of their radiological impact [10].

Table 4 summarizes the bounding environmental conditions used for the assessment.

Accident Phase	Parameter (General)	Containment Parameter (Specific)	Bounding Severe Accident Analysis Value	Design Basis [8]	Design Basis Notes
SAP-1 SAP-2 SAP-3	Thermal-hydraulic	Ambient Pressure	320 kPa(a) with pressure spikes to 340 kPa(a) [9]	425 kPa(a) maximum	340 kPa(a) + 25% margin
		Ambient Temperature	167ºC	200ºC	177ºC + margin
		Relative Humidity	Not analyzed	100%	Maximum possible humidity utilized in design basis for severe accident design requirements
		Water Level	2.75 m	Not included	
	Flammability	Combustible gas concentration	<5%	H2 <10%	
		Oxygen concentration	N/A	N/A	
		Steam concentration	N/A	Not included	
		Indication of combustible events	No events	N/A	
	Radiological	Airborne and deposited radioactivity concentration	N/A	2 MGy	

Table 4: Bounding Environmental Conditions

2.3 Extract High level Mitigation and Control Actions

The purpose of this step [1] is to extract the high level mitigating and control actions, and their station-specific strategies, in order to derive the necessary and essential instrumentation and equipment list in the next step.

This step involves two main tasks:

1. Extracting the high level actions from the generic COG SAMG [7]
2. Matching the station-specific strategies from the severe accident guides (SAGs) and severe challenge guides (SCGs)

Only the necessary instrument and equipment need to undergo the survivability assessment. The objective of this step is to define what strategies a station has to address the high level mitigating and control actions to determine the equipment involved. This is later used to develop the equipment list that is subject to assessment.

The high level SAMG strategies employed at PLGS include:

- Inject into Heat Transport System (SAG-1)
- Control Moderator Conditions (SAG-2)
- Control Calandria Vault/Shield Tank Conditions (SAG-3)
- Reduce Fission Product Releases (SAG-4, SCG-1)
- Reduce Containment Hydrogen (SAG-5, SCG-3)
- Control Containment Conditions (SAG-4, SAG-6, SCG-2)
- Inject into Containment (SAG-7)
- Control Containment Water Level (SCG-5)
- Control Containment Vacuum (SCG-4)

2.4 Compile Lists of Instrumentation & Equipment for Actions in Step 2

The purpose of this step [1] is the development of the complete list of essential instrument and equipment necessary to executing the high level actions, including equipment necessary for function.

This step involves two main tasks:

1. Identify the essential aspects for compilation.
2. Add Vital Support and Station Location Information to the Instrument List

Based on the Point Lepreau G.S. design, Table 5 provides a comparison of essential functions against the existing design. As can be seen, and in part as a result of the improvements made during plant refurbishment, only moderator level instrumentation requires further assessment to determine its capability to survive severe accident conditions.

Function	Equipment/ Instrumentation	Design Discussion [Reference]	Further assessment required?
Containment pressure indication	EFCV local pressure indication	The EFCV is located in the SCA tunnel and was specifically designed to function under severe accident conditions to vent a saturated steam atmosphere. It is located in the secondary control area (SCA) tunnel external to containment with the inlet located at elevation 51'-6" inside containment, well above predicted flood levels in severe accident analysis.	No
	SCA wide-range pressure indication	Pneumatic pressure gauges 63431-PI7N1, PI11P1 and PI3Q1, located in the SCA (S1-014) were replaced during plant refurbishment with high range gauges. These are not subject to harsh in-containment environmental conditions and are expected to remain available for pressure monitoring.	No
Moderator level indication	Original equipment	The moderator level instrumentation and equipment has not been specifically designed to cater to severe accidents	Yes
Calandria vault level indication	New modification per RDS #2700	The calandria vault level indication is being specifically designed to operate during severe accident conditions. The system can be operated from outside containment and the only equipment inside containment consists of tubing, support, and two normally open valves.	No
Containment basement water level indication	New modification per RDS #2498	Similar to calandria vault level indication, the containment basement water level indication is being designed to operate during severe accident conditions.	No
Make-up to moderator	New modification per RDS #2857	This consists of a piping connection to the moderator purification circuit outside containment and, therefore, is inherently robust against environmental hazards.	No
Calandria vault make-up	Emergency Calandria Vault make-Up (CVMUP) system	The portion of the system outside of containment has been designed to meet outdoor ambient conditions (snow, ice, etc.). Inside the system consists of a 3" pipe, whose capability not susceptible to harsh conditions. The design basis for severe accidents [8] was utilized to identify radiological conditions for safety requirements.	No
Vent containment	Emergency Filtered Containment System	The EFCV is specifically designed to function under severe accident conditions.	No

Table 5: Comparison of Essential Functions against Existing Design

2.5 Screen and Align Items with Accident Characteristics

The purpose of this step is to screen out instrument and equipment located in mild environments, and then aligns accident data and equipment mission times with the remaining instrument and equipment (those located in a harsh environment). This step involves two main tasks:

1. Screen instrument and equipment located in a mild environment;
2. Assignment of detailed accident profiles to the unscreened instrument and equipment.

Thus, the larger list of instruments and equipment compiled in Section 2.3 is reduced through the screening process such that only those items subject to harsh accident conditions will undergo the more detailed survivability assessment. A harsh environment will likely include all containment areas; but may also include non-containment areas, depending on the individual station design and the accident conditions assumed. A review of the potential for harsh environments outside containment was completed, with no additional instrumentation or equipment being identified for further assessment other than moderator level instrumentation.

2.6 Assess Survivability

The purpose of this step is to evaluate instrument and equipment survivability/suitability including acceptance criteria, with consideration of human and organizational factors. If instrumentation and equipment are determined not to survive, alternative solutions are examined and potential recommendations made. This step involves the following tasks:

- Develop process for evaluating instrument and equipment survivability (including suitability)
- Define success (or acceptance) criteria for the instrumentation and equipment
- Develop process to compare acceptance criteria with demonstrated survivability;
- Determine survivability (including suitability with consideration of human and organizational factors); and
- Develop process to identify alternative solutions for instrumentation and equipment that do not meet acceptance criteria.

To facilitate the assessment, there is an emphasis to use and, if necessary, extrapolate from existing Environmental Qualification data at the station. This is expected to be the most efficient approach, recognizing that severe accidents can be considered a more limiting extension of the environmental and process conditions experienced in design basis events.

The following assumptions are made for the purpose of the assessment:

- Component seals, gaskets, access covers, connection assemblies, etc. are properly installed and maintained to prevent moisture intrusion and other related forms of degradation.
- Component surveillance testing is up to date and components are in a state of good repair.
- Component installation, including pre-operational setup and testing, has been performed properly.
- Valves with actuators, especially motor operated valves, have been placed into their pre-accident positions by use of the associated control switch rather than manual operating devices.

- Components listed in the station EQ program fully meet the qualification requirements as stated in the associated documentation, and all significant aging mechanisms have been identified and addressed under the EQ program.
- Electromagnetic interference, including radiofrequency interference and power surge interference, is not sufficient to significantly impact survivability or suitability of a component.
- The instrumentation and equipment has survived the initiating event. It should be noted, however, that whereas the instrumentation and equipment may have survived the initiating event, consequential impacts of the initiating event (such as a loss of electrical power) may limit the effectiveness of some instrumentation and equipment unless suitable mitigating action is taken (i.e., providing backup electrical power).

The acceptance criteria are defined as;

1. The equipment or instrument loop is environmentally qualified with sufficient margin to meet the conditions of the severe accident.
2. The equipment is not submerged unless specifically designed for submergence

Severe Accident Phase	**Moderator Level Indication Loop**	**EQ**	**Acceptance**		
			Margin	**Submerged**	**Survival**
SAP-1 SAP-2 SAP-3	63210-L12	N	No	Yes	No
	63210-L13A/B/C	Y	No	No	No
	63432-L203K/L/M	N	No	Yes	No

Table 6: Evaluation of Survivability

From Table 6, it can be concluded that PLGS does not currently have an engineered direct moderator level monitoring capability that will survive the harsh environmental conditions of a severe accident that will support a long-term internal in-vessel retention strategy. However, the following alternative solution has been selected to implement in SAMG procedure to maintain the moderator full and avoid thermal stresses associated with possible boil-off-refill cyclical operation;

- If moderator level indication is lost and the level had been dropping or is unknown, initiate moderator make-up.
- In parallel, monitor calandria vault level. If calandria vault level is noted to be falling (i.e. indirectly indicating that calandria vessel is almost or completely dry);
  - Increase rate of make-up to the moderator to overfill and overflow the water onto the containment building floor. Indication of the floor level increasing may provide indication that the moderator could be full (provided that fuel channel bellows are intact).
  - Make up to the calandria vault as well to restore vault water level
- Reduce and throttle flow to the moderator to match boil-off rate (based on analysis) to maintain a nominal high water level in the calandria vessel.
- Monitor reactor building water level to ensure it is no longer rising, or is rising only very slowly as an indirect method, of providing reasonable assurance that the moderator is full.

3. Conclusion

An evaluation of instrument and equipment survivability has been performed for Point Lepreau G.S. The evaluation was performed by an individual with more than 26 years of experience at Point Lepreau ranging from reliability, system engineering, severe accident phenomenology and emergency preparedness. The study was then independently reviewed per CSA N286-05 by a consultant with extensive experience in reactor safety; severe accident management development and implementation; and emergency planning, and by other senior NB Power staff in the areas of reactor safety and instrumentation. The only weakness in the post-refurbished design is associated with moderator level monitoring, which has been assessed to not survive long-term in the harsh environment of a severe accident. The NB Power decision is to proceed with a permanent design modification with fixed instruments that will allow continuous moderator level monitoring throughout the harsh environmental conditions of a severe accident. In the interim until the design modification can be implemented, severe accident management documentation will be updated to indirectly infer coarse moderator level through other robust parameters.

4. References

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[3] Analysis Report, 87RF-03500-0016-001-AR-A-01, "Severe Accident Analysis of Small LOCA Scenarios", 87RF-03500-AR-016 Rev 1, AECL, 2009/08/13

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