DEVELOPMENT AND IMPLEMENTATION OF A SEVERE ACCIDENT MANAGEMENT PROGRAM FOR NRU

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Abstract

The National Research Universal (NRU) reactor has been operating at Chalk River Laboratories (CRL) since 1957. An Integrated Safety Review was performed to support renewal of the site licence in 2011. The resultant improvement plan identified activities to develop and implement a Severe Accident Management Program (SAMP) for NRU.

The three main objectives of the SAMP are:

1. Termination of a Beyond Design Basis Accident (BDBA) event.
2. Maintaining vented confinement during the BDBA event.
3. Minimizing radioactivity release to the environment.

A diverse team from Canadian Nuclear Laboratories (CNL), Candesco, Westinghouse, Fauske and Associates and individual specialist consultants completed the SAMP initiative by:

- Establishing the technical basis for severe accident progression for NRU;
- Identifying and installing instrumentation to monitor critical safety parameters;
- Identifying and installing equipment to mitigate a severe accident;
- Preparation of SAMP documents;
- Establishing roles and conducting training, and
- Validating the program.

This paper describes the unique aspects of this project and provides an overview of the implemented SAM Program.

1. Introduction

The NRU reactor, one of the world's most versatile research reactors, has been operating at CRL since 1957. An Integrated Safety Review was performed to support renewal of the CRL site licence in 2011. The resultant improvement plan identified the requirement for Severe Accident Management Guidance (SAMG) and included activities to develop and implement a SAMP for NRU. The schedule for SAMP development and implementation was accelerated following the events at the Fukushima Dai-ichi plant in March 2011, which reinforced the need for effective severe accident management.

The scope of the project was directed at achieving 3 main objectives:

1. **Terminate a BDBA event(s).**
This involves an achievement of a stable and controlled state of the NRU reactor and a termination of core degradation.
2. **Maintain vented confinement during the event.**
This involves maintaining a negative pressure within the NRU confinement envelope relative to outside environment, and filtering airborne effluents from the NRU confinement envelope.
3. **Minimize radioactivity release to environment during and after the event.**
This involves measures to be taken only if and when the preceding SAM goal cannot be fully achieved; otherwise, releases to environment will have already been minimized by maintaining vented confinement.

The project wasimplemented in two phases:

Development activities, where the technical basis for a Severe Accident (SA) in NRU was updated and SAMG documentation was developed.The development phase of the NRU SAM project was completed in 2014 and focused on developing a suite of documents that would be used by NRU Operations and a new Technical Support Group (TSG) during a severe accident.

Implementation activities, where the SAMP documents, procedures and trainingprogram(s) were finalized and training was delivered to CNL personnel assigned to the SAMPorganization. The second phase of the project commenced in early 2015 and was focused on full implementation of the SAM Program and confirming that the individual component parts of the SAM Program work as intended. A limited scale drill and a validation exercise were conducted as part of the implementation activities to validate SAMP integration into the NRU emergency response plan.

Successful completion of the project required a large, multidimensional team of highly skilled individuals in the areas of severe accident assessment for NRU, SAMG framework, NRU Operations, emergency preparedness and training.

2. Technical Basis for Severe Accident Progression in NRU

The definition of a severe accident is universally applied to all water-cooled reactor types and involves significant fuel melting. For NRU, accidents leading to melting of a single fuel rod (a fuel rod assembly in a single flow tube) are part of the design basis and are covered by Emergency Operating Procedures (EOPs). Therefore, a severe accident is defined as melting of more than one fuel rod, and the severe accident analysis considers events that lead to melting of all fuel in the core.

There are several key features of the NRU reactor that influence how a severe accident progresses differently from a power reactor. Among the features that separate NRU from power reactors aremaximum power operation(130 MWth vs.~3000 MWth), NRU's low operating pressure, low temperature operating conditions, and the metallurgical composition of the fuel. The Uranium Silicide/Aluminum dispersion fuel is unique as it melts at a relatively low temperature (660 °C) and retains a relatively high proportion of fission products in the non-volatile form. The two-phase melt characteristicsof Aluminum based fuel and the inability to accumulate melt pools before interacting with alternate/passive heat sinks precludes melt superheating, which precludes steam explosions and hydrogen generation in NRU.

A simplified cross-section of the NRU reactor is shown inFigure 1, which indicates several of the key components that play a role in slowing SA progression in NRU. Although NRU has a relatively small power output compared to a power reactor, the physical structure of the NRU is large and the reactor is surrounded by massive passive heat sinks that can absorb heat in the event of a severe accident.If the fuel melts, the corium will relocate to the bottom of the reactor vessel and make contact with large steel structures (bottom shield and bottom header).These passive heat sinks are effective in slowing the progression of the accident by absorbing stored and decay heat from within the corium. This keeps the corium within the reactor vessel or connected piping for an extended period of time and allows time for alternative cooling mechanisms to be used to remove decay heat.

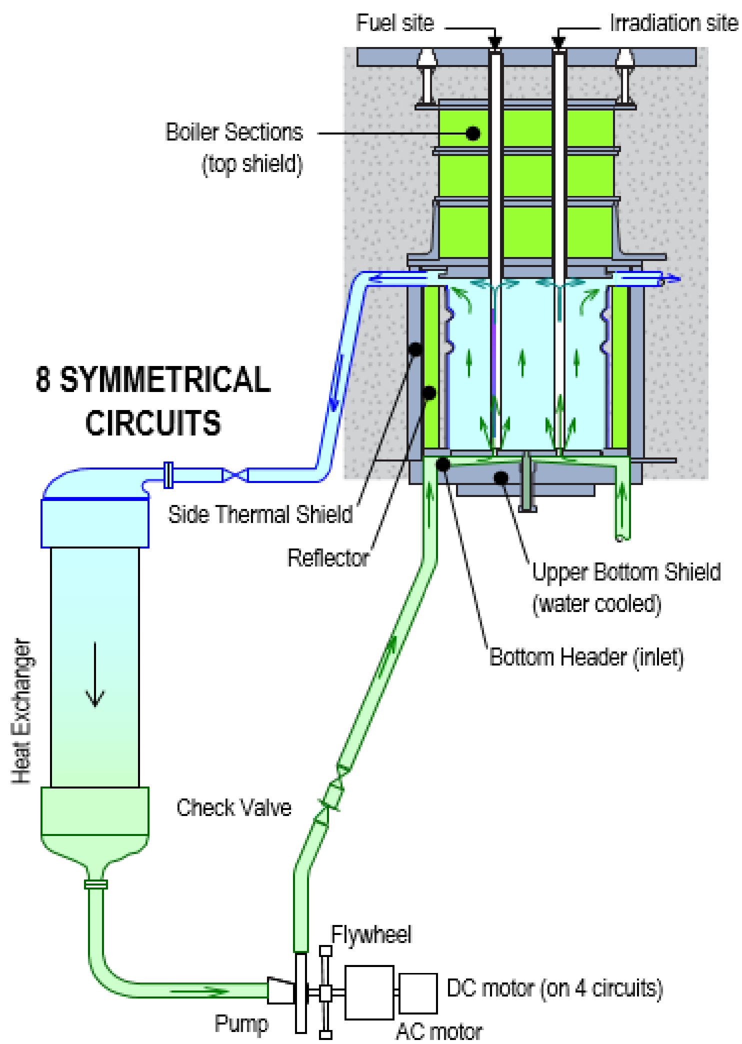

Figure 1: Simplified cross-section of NRU reactor

Fuel is widely distributed in the NRU core. This allows the fuel to melt and form a fairly evenly distributed mass of corium at the base of the reactor vessel.

Even in absence of cooling water flow, the relocation of molten fuel will initially be halted when it makes contact with the large passive heat sinks at the base of the reactor vessel. If cooling water flow is applied from either above or below as part of SAM actions, a stable long term condition can be achieved with decay heat being matched by the heat being removed by the cooling water flow. Adding the ability to inject emergency water to the reactor to cover the corium illustrated the added benefit of scrubbingfission products in the vessel.In the longer term, the Thermal Shield Cooling System (TSCS) is capable of indirectly removing all of the decay heat.

There is a large body of experimental data related to the interaction of steam with molten Aluminum including extensive datafrom the Aluminum smelting industry [1]. This data shows that the Melt-Coolant Interaction (MCI) at the melt temperatures that are applicable to an NRU severe accident result in very little oxidation and minimal hydrogen generation.There have been no specific MCI tests conducted on NRU fuel but all of the available information indicates that violent steam explosions are not possible at the temperatures that could be achieved in the fuelduring core meltdown.

The U-2 experimental loop includes two test sections in the reactor and is designed to simulate power reactor conditions and therefore operates at high pressure and temperature with fuel that is similar to power reactor fuel. Any accident that is confined to the U-2 loop is a design basis event. It is only when a severe accident causes fuel melting in both the NRU reactor and the U-2 loop that the consequences have to be a re-evaluated to determine if additional SAM mitigating strategies are required.The overall insights from performing the U-2 loop assessment arethat the baseline SAM guidance does not change and remains appropriate.

3. Severe Accident Critical Safety Parameters and Instrumentation for Monitoring

The Severe Accident Critical Safety Parameters delineate the threshold between event-based emergency procedures and symptom-based SAM guidance. At this threshold, the NRU emergency procedures are not able to terminate the accident and restore the NRU facility into a controlled, stable state.

A low value of reactor bottom header to cover gas differential pressure (the pressure differential between the bottom and top of the reactor) is an indicator of the onset of severe core damage, regardless of whether the vessel is intact or breached, and is the primary criterion for SAM entry. This parameteris the indicator of the driving force for coolingwater flowin the flow tubes of the NRU reactor. With insufficient water flow in the flow tubes, adequate fuel cooling cannot be maintained.

A backup parameter, vessel temperature, is designed to indicate when bulk fluid reaches saturation or there is superheated vapor at the top of the vessel. These conditions indicate that multiple flow tubes are experiencing degraded cooling. This parameter is a good indicator for boiloff scenarios, e.g., sustained loss of forced flow resulting from sustained loss of electrical power, as well as, draining scenarios, e.g., uncompensated loss of coolant.

An additional backup parameter for draining scenarios is very low pressure in the bottom header of the reactor. This is indicative of a loss of coolant that is not being mitigated by the emergency core cooling system. In such circumstances a severe accident is inevitable.

A severe accident in NRU will result in a significant release of radioactivity, although depending on the scenario much of this release could be retained in the vessel. Nevertheless, a severe accident is expected to result in multiple High Level Radiation Monitors in NRU reaching their alarm setpoints. If the primary and backup parameters are not available, a combination of high radiation alarms and other available indicators of inadequate core cooling can be used to identify severe accident conditions.

During the development phase of the project, it was determined that new instrumentation to monitor the differential pressure and bottom header pressurewould have to be installed to provide NRU Operations personnel with unambiguous indications that severe fuel damage had occurred (or was imminent). Temperature instrumentation already existed and was available for use.CNL expedited the design, procurement, and installation activities associated with these modifications, and the instrumentation was available for use in January 2016.

4. Severe Accident Management Guidance

The NRU SAMP framework follows international practice for mitigation of severe accidents in nuclear power reactors, with differences between NRU and power reactors taken into account. The Westinghouse SAM framework had been adopted by the Canadian nuclear industry, and was also adopted and modified for NRU.

An overview of the SAM guidelines is illustrated in Figure 2. The fact that entry criteria for SAM was met(severe accident has occurred) means that the operators were unable to regain control of the plant's critical safety parametersusing design basis emergency procedures and engineered safety systems. At this point the operators transition into the SAM domain and they rely upon control room guidelines until the TSG is assembled and communication with the facility is established. Upon establishing communication with the TSG, control room guidelines are set aside and guidance from the senior technical staff to cope with the situation begins. InFigure 2, the group providing the guidance is called the TSG. The TSG is located outsideNRU in a different building. This group is responsible for assessing the accident, evaluating the effectiveness of Control Room actions and recommendingstrategies to maintain or recover the safe condition of the plant.

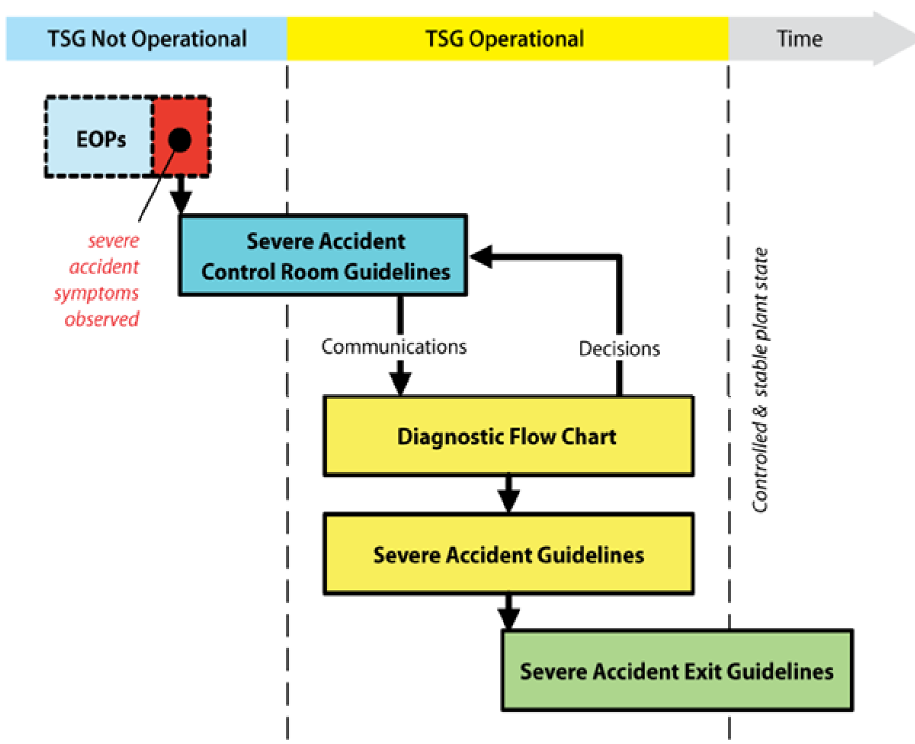

Figure 2: Overview of NRU SAM guidance documents

The TSG employs the SAM Guidelines, which function as decision-making tools. Due to the complex nature of a severe accident, it is not possible to define specific recovery actions a priori. Since the technical expertise required to cope with severe accidents is normally beyond that inherent in the plant operating staff, the TSG becomes the vehicle for selecting mitigation strategies. This group can bring to bear a wide range of expertise. The objective of the SAM Guidelines is to present the TSG with a range of predefined options, along with the supporting rationale and the technical information needed to select and recommend an optimum strategy for implementation that will address the symptoms of the severe accident.

The documents that constitute the NRU SAM Program document suite are outlined below. The format of the NRU SAM Guidelines, in particular, the Diagnostic Flow Chart (DFC), Severe Accident Guidelines (SAGs), Severe Accident Exit Guidelines (SAEGs), and Computational Aids (CAs), follows the accident management conceptused by Westinghouse and widely adopted by nuclear power utilities internationally.

SAM Entry EOP: The SAM Entry EOP is used by NRU Operations when design basis emergency procedures are not able to control the event. The SAM Entry EOP contains the list of parameters to be monitored and their values that indicate that a severe accident is imminent or underway.

Severe Accident Control Room Guidelines (SACRGs): Two SACRGs direct the actions taken by the Control Room staff (1) prior to the TSG assembling and becoming operational, and (2) actions to be taken following the activation of the TSG. The SACRGs also identify plant parameters and systems whose status is to be monitored during the severe accident and communicated periodically to the TSG.

Diagnostic Flow Chart (DFC): The DFC comprises a set of plant parameters to be monitored and a decision tree (flow chart) that helps the TSG determine which SAM strategies to focus on based on the values of critical plant parameters. The DFC provides an order for evaluating the need for the high-level SAM strategies and directs the TSG to the corresponding SAG based on whether the plant symptoms (i.e., measurable or observable parameters) indicate a need for the given SAG. The DFC also provides criteria for exiting the SAM realm, based on plant symptoms indicating that a stable, controlled plant state has been achieved.

Severe Accident Guidelines (SAGs): These guidelines are called from the DFC. Apart from the primary goal of the SAGs, reflected in the SAG titles, the SAGs provide specific strategies for achieving their objective, and tools for the evaluation of the benefits and potential negative impacts of the SAG strategies before they are implemented.

There are five SAGs listed in the DFC in the following order:

- SAG-1: Mitigate Activity Releases
- SAG-2: Inject Coolant into Reactor Vessel
- SAG-3: Protect Reactor Vessel Boundaries
- SAG-4: Remove Heat from Reactor Vessel
- SAG-5: Protect the Rod Storage Bay and Storage Block

Computational Aids: Computational Aids (CAs) are means for the TSG to use observable parameters, e.g., time, water level readings, water supply rates, etc., to derive values of parameters that can assist the TSG in making strategy recommendations. There are two CAs as follows:

CA-1, Long Term Decay Heat Removal: provides graphs that enable the TSG to estimate water injection flows required to remove decay heat, either by direct cooling waterinjection to the reactor core or through indirect vessel boundary cooling by providing cooling water flow to the J-Rod Annulus (a vertical annulus on the outside of the reactor vessel)or tothe Bottom Thermal Shield.

CA-2, Confinement Water Level and Volume: provides a correlation between the volume of water added to confinement and confinement water level so that the margin to the flood protection gates in confinement can be estimated, the goal being to avoid release of contaminated water outside confinement and to the environment through the flood gates.

Enabling Instructions: Enabling Instructions (EIs) may be consulted by the TSG when determining which strategy to recommend and are used by NRU Operations to execute specific steps within a mitigation strategy. EIs have been developed for SAM for circumstances where existing procedures do not cover the specific actions required.

Severe Accident Exit Guidelines (SAEGs): Two SAEGs are available to (1) monitor the long term concerns associated with the strategies contained in the SAGs and (2) provide information that is important to supplement the recovery actions after SAM guidance is no longer in effect.

The project team, including SAMG experts and ex-NRU Operations staff, prepared the SAMG documents during the development phase with input from current NRU Operations staff. To ensure the suite of documentation would be effective in supporting mitigation of a SA at NRU, training on the SAM program was deliveredto the key groups.

Development of the SAM Guidance documents identified cost-effective modifications that could be readily implemented that would significantly enhance severe accident mitigation. The primary modification was installation of a permanent connection to facilitate addition of water from an external source to the top of the reactor. This modification was designed and installed as part of the project. In addition, CNL had procured portable diesel generators, and their availability was factored into the SAM Guidelines as potential sources of electrical power to support SAM actions. Other equipment such as portable self-powered light standards, additional firefighting equipment, debris clearing equipment, etc., was in the process of being procured by CNL and would also contribute to effective SAM.

5. Severe Accident Management Roles and Training

Two critical components of a SAMP for any reactor, including NRU, are ensuring that roles are well established, and processes are in place to enable clear, effective communication. An overview of NRU SAM communication protocol is shown in Figure 4.

There are three groups that play specific roles in the event of a Severe Accident in NRU:NRU Operations, the Emergency Operations Centre (EOC),and the SAM TSG.

NRU Operations consists of certified reactor operators and field operators who monitor NRU conditions and implement mitigating strategies to support the SAM objectives.

NRU personnel positions include:

- NRU Liaison Officer who is designated to interact with the TSG Operations Specialist.
- The Senior Reactor Shift Engineer (SRSE) who is certified to operate NRU.
- The Facility Manager (or designate) is the Officer In Charge (OIC) of NRU for abnormal or emergency events. In the event of a Severe Accident at NRU, command and control for NRU stays within the NRU Control Room.

The Emergency Operations Centre consists of a wide range of Emergency Preparedness experts who deal with site-wide response, and external communications in support of the SAM objectives.

For the purpose of SAMP, the key personnel positions in the EOCinclude:

- EOC commander, who maintains command and control of the CRL site.
- Incident Authority, who in the case of an event at NRU, is an NRU Facility Authority (FA)

The Technical Support Group consists of technical experts who provide technical diagnostics and operational recommendations to the Incident Authority that will enable NRU Operations personnel to support the SAM objectives.

The TSG is comprised of the following positions:

- The Head of TSG is responsible to supervise the technical work and communicate TSG recommendations to the Incident Authority.
- The SAM Specialist is responsible to use plant data and the SAM DFC and guidelines
- The NRU Operations Specialist is responsible to communicate directly with the NRU regarding plant status.
- The Recorder is responsible to record plant status information and track action assignments to completion.

When a Severe Accident has been declared, notifications will be issued to the TSG members on call and the TSG members will be expected to report to the TSG room within 90 minutes.Oncethe TSG is operational, the TSG Head will advise the IA. The IA provides an initial brief of the event.The TSG Head will then declare the TSG operational and will advise NRU: that TSG is operational, transition into SACRG-2 (as shown in Figure 2) is to commence, and communication with the TSG is to be initiated.

Training and initial validation activities identified a need for increased collaborative communications among the three groups. Enhanced communication mechanisms such as Situational Update Briefings (SUBs) among the groups were introduced as a result of lessons learned during the implementation phase to facilitate a common understanding of the status of NRU and the site. Status of strategies in place or in progress are communicated at SUBs, however recommendations for implementation of specific strategies must follow the chain of command, as outlined in Figure 4.

The TSG receives plant status information from NRU and uses it with the SAM guidance documents to recommend mitigation strategies. The strategies are communicated by the Head of TSG to the Incident Authority (IA), who in turn discusses the recommended strategy with the OIC in NRU. With viability confirmed and approved, the IA will then present the TSG Recommendation to the EOC Commander who will confer with EOC members to confirm any impacts to the site or off-site are managed appropriately and provide any necessary resources to support the strategy. After the strategy is implemented in NRU, the TSG receives feedback on the effectiveness of each strategy from NRU through the IA.

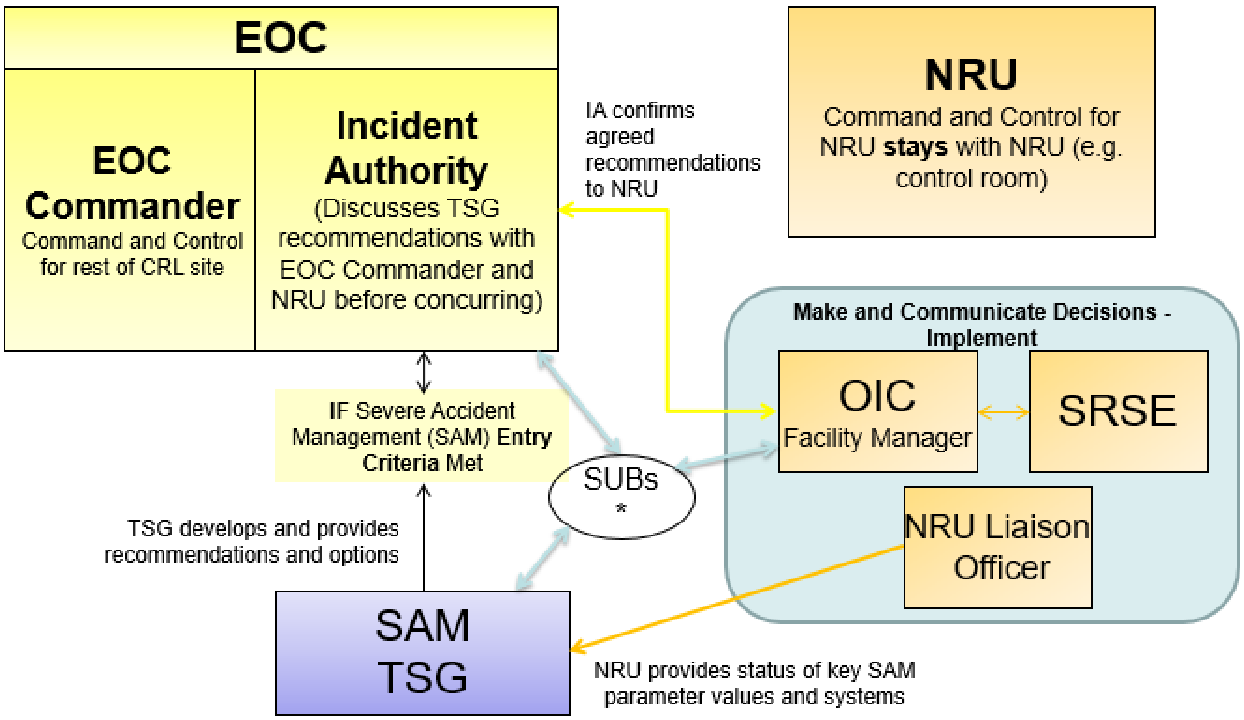

Figure 3: Overview of NRU SAM Program Communications

Extensive SAM training was provided to each of the three groups in addition to the highly specialized training that they would typically receive to support their daily job functions. The development and delivery of training material followed CNL's Systematic Approach to Training.

NRU Operations Training: The training material included an overview of the SAM program, a detailed review of the SAM documents that would be used by Operations, and application of the SAM documents to two severe accident scenarios.

Technical Support Group Training: Individuals selected for TSG positions and individuals designated as Incident Authority (NRU Facility Authority) were provided TSG training. The training provided an overview of the SAM program, background information on the technical basis for the program, a detailed review of the SAM documentation, and three separate severe accident training scenarios. During the training scenarios, the trainees assumed the roles they would occupy during a severe accident and systematically worked through the SAM processes.

Emergency Operation Centre Training: EOC qualification requires extensive emergency preparedness training prior to receiving this 3 hour training course that describes how a severe accident at NRU differs from any other emergency on the Chalk River site. The training focused on the chain of command during a severe accident and the increased challenges to EOC operation during such an event.

During each training session, the participants were encouraged to provide feedback on the SAM process and the supporting documentation. These suggested improvements were documented and reviewed by project team members and as a result numerous improvements were implemented in the SAMP documents. Refresher training was provided to NRU Operations and the TSG following these updates.

6. Severe Accident Management Validation Activities

Canadian Nuclear Safety Commission (CNSC) Regulatory Documents [1] [2] and the International Atomic Energy Agency (IAEA) Safety Guide on Accident Management [3] describe the need for a structured and documented approach to validation during implementation of a Severe Accident Management Program. The NRU SAM Program Validation Plan considered all of the activities in the project and their potential contribution to the validation process.

As the implementation phase of the project progressed during 2015, systematically planned validation activities such as document walkthroughs, training evaluation, equipment testing, a limited scale exercise and a large scale functional exercise were completed. The lessons learned from these activities were documented and used to improve the SAM Program in ways such as revising the SAM documentation, making physical improvements to the TSG room, enhancing the initial training material and delivering refresher training.The sequence of validation activities that followed from May 2015 through to the declaration of the SAM Program in service was as follows:

Human Factors Assessment: Reliable human and organizational performance is an essential part of severe accident management and CNSC regulatory requirements emphasize that HF assessment must be included as part of the validation process [4]. HF specialists were involved with the planning and assessment of the documentwalkthroughs, the limited scale exercise and the large scale functional exercise. For all of these activities, specific HF objectives were developed, performance was assessed against defined criteria, and recommendations were formulated. Human Factors assessment was integrated into each step in the process, that is, HF was not considered as a separate validation activity.

Tabletop Walkthroughs: Tabletop review of the SAM documents that were developed for the NRU control room and the Technical Support Group were conducted with teams of individuals who were representative of the NRU Ops and Technical Support Group members, respectively. For each of these tabletop walkthroughs, the teamsused the relevant SAM documents to walk through severe accident scenarios. The sessions were controlled and observed by SAM project team members.

The feedback obtained during simulated use of the SAM documents and from the interviews and questionnaires that followed was used to improve the SAM process, improve the quality of the documents and provided valuable insight into how best to structure SAM training.

Limited Scale Exercise: In August 2015, a limited scale exercise was conducted that included NRU Operations personnel, a fully staffed and qualified TSG, and the staff of the EOC. The four-hour exercise scenario was developed and executed in accordance with CNL Emergency Preparedness Governance and was observed by a CNSC staff member. Overall, this exercise confirmed that the SAM process was sound, the suite of SAM documents provided the necessary guidance, and the training had adequately prepared the participants. A number of opportunities for improvement were identified, most notably related to communications amongthe three groups.

Large Scale Functional Exercise: In October 2015, a large scale functional exercise was conducted that included NRU Operations control room personnel, activation of the EOC, activation of the TSG facility, and simulated field activities to implement SAM Enabling Instructions. Higher priority improvements arising from the August limited scale exercise were implemented prior to this larger exercise. Refresher training was delivered to TSG and Operations personnel to ensure they were familiar with these changes and the lessons learned from the August exercise.

The eight-hour exercise scenario was developed, executed and evaluated in accordance with CNL Emergency Preparedness Governance and was observed and evaluated by Human Factors subject matter experts. Several CNSC staff members observed the exercise. Once again, the exercise confirmed that the SAM process was sound and only minor improvements to the SAM documents and training were identified. The most notable areas for improvement were clearer definition of the chain of command, communications and situational awareness.

7. Summary

Successful completion of the project required a large, multidimensional team of highly skilled individuals in the areas of severe accident assessment for NRU, SAMG framework, NRU Operations, emergency preparedness and training. The SAMG documentation that was developed for NRU is based on the well-established Westinghouse framework that was also adopted by Canadian utilities, tailored appropriately for the NRU research reactor.

CNL expedited the design, procurement, and installation activities associated with the instrumentation to provide unambiguous declaration that a Severe Accident had occurred or was imminent, prior to declaring the SAM program operational. In addition, new equipment such as portable diesel generators and a permanent connection for water addition to the top of the reactor were implemented.

In a period of approximately 2.5 years, the integrated project team successfully developed and implemented a Severe Accident Management Program for the NRU reactor. The SAM program was formally declared operational in February, 2016.

8. Acknowledgement

The authors would like to thank all members of the NRU SAMP project. The Severe Accident Management Program for NRU was developed and implemented in just over two years, due largely to the expertise, commitment and teamwork from all involved.

Special thanks to Glenn Archinoff and Jamie Doyle for providing outstanding leadership throughout both phases of the project.

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10. Acronyms

BDBA	Beyond Design Basis Accident
CA	Computational Aid
CNL	Canadian Nuclear Laboratories
CNSC	Canadian Nuclear Safety Commission
CRL	Chalk River Laboratories
DFC	Diagnostic Flow Chart
EI	Enabling Instruction
EOC	Emergency Operations Centre
EOP	Emergency Operating Procedure
FA	Facility Authority
IA	Incident Authority
IAEA	International Atomic Energy Agency
MCI	Melt-Coolant Interaction
NRU	National Research Universal
OIC	Officer In Charge
SA	Severe Accident
SACRG	Severe Accident Control Room Guideline
SAEG	Severe Accident Exit Guideline
SAG	Severe Accident Guideline
SAMG	Severe Accident Management Guidance
SAMP	Severe Accident Management Program
SRSE	Senior Reactor Shift Engineer
SUB	Situational Update Briefings
TSCS	Thermal Shield Cooling System
TSG	Technical Support Group