MITIGATION STRATEGIES OF BEYOND DESIGN BASIS ACCIDENTS (BDBA) IN A CANDU NUCLEAR POWER PLANT

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Abstract

The Fukushima nuclear accident of March 2011 has changed the nuclear industry worldwide. Nuclear power plants around the world are working to prevent Beyond Design Basis Accidents (BDBAs) like the Fukushima accident and to mitigate the damage when they do occur. One multi-unit Canadian utility has taken a multi-pronged approach, which promotes physical and philosophical diversity for preventing and/or minimizing the progression of a BDBA. The phased approach provides new system connections for delivering emergency makeup water to the primary reactor heat sink via independent and external Emergency Mitigation Equipment pumps. This paper presents the strategies of a CANDU nuclear power to prepare for nuclear power plant BDBA like the Fukushima accident.

1. Introduction

The events that occurred on March 11, 2011 at the Fukushima Daiichi Nuclear facility in Japan prompted a worldwide nuclear regulatory inquiry. Nuclear Reactor Operators were tasked to review their ability to mitigate challenges brought on by external hazards and extreme weather events, and manage the challenges caused by those events. In response to the events, the Canadian Nuclear Safety Commission (CNSC) requested that all Canadian utilities review the lessons learned and implement measures to address Beyond Design Basis Accidents (BDBA). The postulated BDBA is a Station Blackout (SBO), or site wide loss of AC power, leading to a total loss of heat sink. This paper presents the mitigation strategies in a CANDU nuclear power plant, for supplying the make-up water as a heat sink for the reactor decay heat after a Station Blackout.

2. SBO Accident Progression

Before discussing the strategies to mitigate the postulated BDBA – Station Blackout, let's review the estimated timeline of the accident progression in a CANDU Nuclear Power Plant plan.

1) Boiler dry-out occurs 2 hrs after total loss of station power
2) Heat transport system inventory depleted after 4 hrs
3) Moderator system inventory depleted after 8 hrs
4) Shield tank system starts to deplete after 12 hrs

In order to mitigate BDBA progression, the emergency make-up water will be supplied to each system as required. Based on the above timeline, the maximum time to deploy and activate each mitigation strategy is provided in Table 1. The mitigation activation time is superimposed onto a modified version of the reactor decay heat curve. The flow requirement based on decay heat for each system is determined and shown in Figure 1.

Table 1 Emergency Water Make-up Activation Time

Mitigation Strategy		Max. Activation Time
Emergency Boiler Makeup	(EBM)	2 hrs
Emergency Coolant Makeup	(ECM)	4 hrs
Emergency Moderator Makeup	(EMM)	8 hrs
Emergency Shield Tank Makeup	(ESTM)	12 hrs

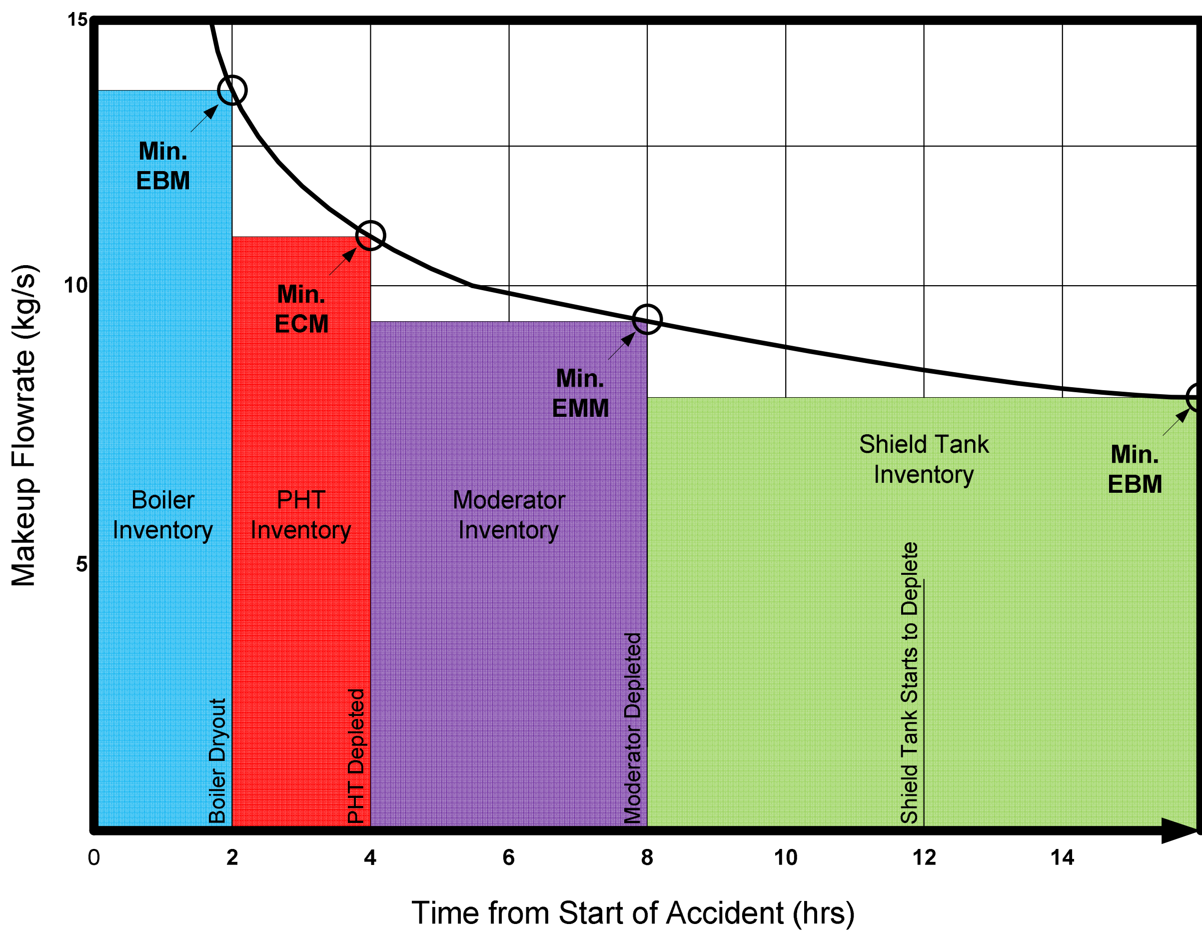

Figure 1 Determination of Makeup Flowrates Based on Decay Heat Removal

3. Emergency Water Make-up Strategies

As mentioned in the above section, the mitigation strategies for a postulated BABA – SBO in a CANDU nuclear power plant is to provide diverse and redundant emergency water make-up provisions to various systems.

Water is provided using two approaches, Emergency Mitigation Equipment (EME), and Severe Accident Management (SAM). EME and the connection points into the boilers are primarily intended to prevent a severe accident from occurring and are implemented through the use of EME Guides (EMEGs). Additional EME modifications to add water into the Primary Heat Transport system (PHT) and Moderator system have a dual role in that they can be used to both prevent a severe accident from occurring (using EMEGs) and also to mitigate a severe accident using SAM Guides (SAMGs) if core damage has already occurred.

Figure 2 summarizes the emergency water make-up strategies in the schematic format. The details are provided in the following sections.

3.1 Emergency Boiler Makeup (EBM)

Following a SBO, EBM is capable of providing a heat sink for the reactor decay heat via heat exchange with the Primary Heat Transport (PHT) water. Timely implementation of the strategy is predicted to allow the fuel, core, and PHT system to remain intact.

All sources of low pressure boiler make-up require a boiler depressurization path via the Boiler Safety Relief Valves (BSRVs). Provisions were installed to allow local opening and latching of BSRVs using existing air receivers after loss of DC battery power. The modification is seismically qualified.

Strategy 1 Allows EBM into the Boiler Feed system via the Inter Unit Feedwater Tie (IUFT), to all reactor units simultaneously from 1 single connection. This is the simplest strategy from a deployment point of view as there is only 1 connection to make. The design of the connection is such that it will provide natural flow balance between all units. Additionally, the high design pressure of the IUFT means that there is no need to adjust and monitor pump output pressure.

Strategy 2 Allows EBM into the Boiler Feed system of each unit, via individual connections to each unit's Emergency Boiler Cooling (EBC) system. This strategy is more difficult to deploy, but offers independence which would prevent the failure of one unit from propagating to adjacent units. This connection provides a seismically qualified EBM.

3.2 Emergency Coolant Makeup (ECM)

ECM allows injection of makeup water to the PHT system in support of Strategy 1 and 2 above. By compensating for normal inventory losses from PHT (e.g., through shrinkage, bleed condenser relief valve, etc.), PHT is capable of removing decay heat from the fuel and transferring the heat to the boilers. PHT can only act as an effective heat removal mechanism (through natural circulation or Intermittent Buoyancy Induced Flow (IBIF)) as long as the headers remain full.

Strategy 3 ECM allows pumping cooling water through the reactor core, via the PHT system of each unit, via individual connections to each unit's Emergency Coolant Injection (ECI) system. This connection provides a seismically qualified ECM. Timely implementation of the strategy is predicted to allow damaged fuel to be contained in the PHT system and an intact reactor core.

3.3 Emergency Moderator Makeup (EMM)

If the boilers dry out, the PHT will subsequently dry out, and the moderator will then begin to act as a heat sink by steaming into containment. Pressure tube heat up will occur causing the pressure tubes to balloon or sag into contact with their respective calandria tubes. As the moderator boils off, the calandria level will drop causing calandria tubes to become exposed, resulting in pressure tube/calandria tube failure into the calandria vessel.

A generic industry review of the efficacy of In Vessel Retention (IVR) in CANDU reactors was undertaken under an industry joint project [5] [6]. It concluded that flooding of the interior of the calandria with water prior to core collapse and melting/compaction is an effective method of IVR. Late flooding can become ineffective if core debris relocates to the bottom of the calandria to form a geometry that is not coolable by submersion in water.

Strategy 4 Allows EMM into the reactor core via the Moderator system of each unit, via individual connections to each unit's Moderator Purification system. This connection provides a seismically qualified EMM. Timely implementation of the strategy is predicted to allow damaged fuel to be contained in the PHT system and an intact reactor core.

3.4 Emergency Shield Tank Makeup (ESTM)

References [5] and [6] also concluded that cooling the calandria by liquid water applied to the outside surfaces of the calandria (e.g., by the shield tank) is an effective method of IVR. However, this IVR strategy works primarily only after the core is fully degraded and molten.

Shield Tank Overpressure Protection (STOP) is required for the postulated severe accident scenarios which have progressed to the point where all other methods of core cooling have failed and the moderator can no longer act as an effective heat sink. In this scenario, most of the decay heat is transferred through the calandria shell into the shield tank. The shield tank will heat up, pressurize and, in the absence of sufficient overpressure protection, will rupture. The overpressure transient resulting from shield tank failure will lead to gross failure of the containment envelope. STOP will prevent overpressure failure of the shield tank. It will also facilitate ESTM by providing a flow path for liquid and steam to exit the shield tank.

Strategy 5 Allows ESTM into the reactor core via individual connections to each unit's Shield Tank and End Shield Cooling (ESC) system. Timely implementation of the strategy is predicted to allow IVR of the corium.

It is worth mentioning that in order to ensure adequate cooling of the used fuel, as part of the mitigation strategies, hard pipes are installed inside the Primary and Secondary Irradiated Fuel Bay to allow connection of the portable pump discharge hoses from the outside of the bays.

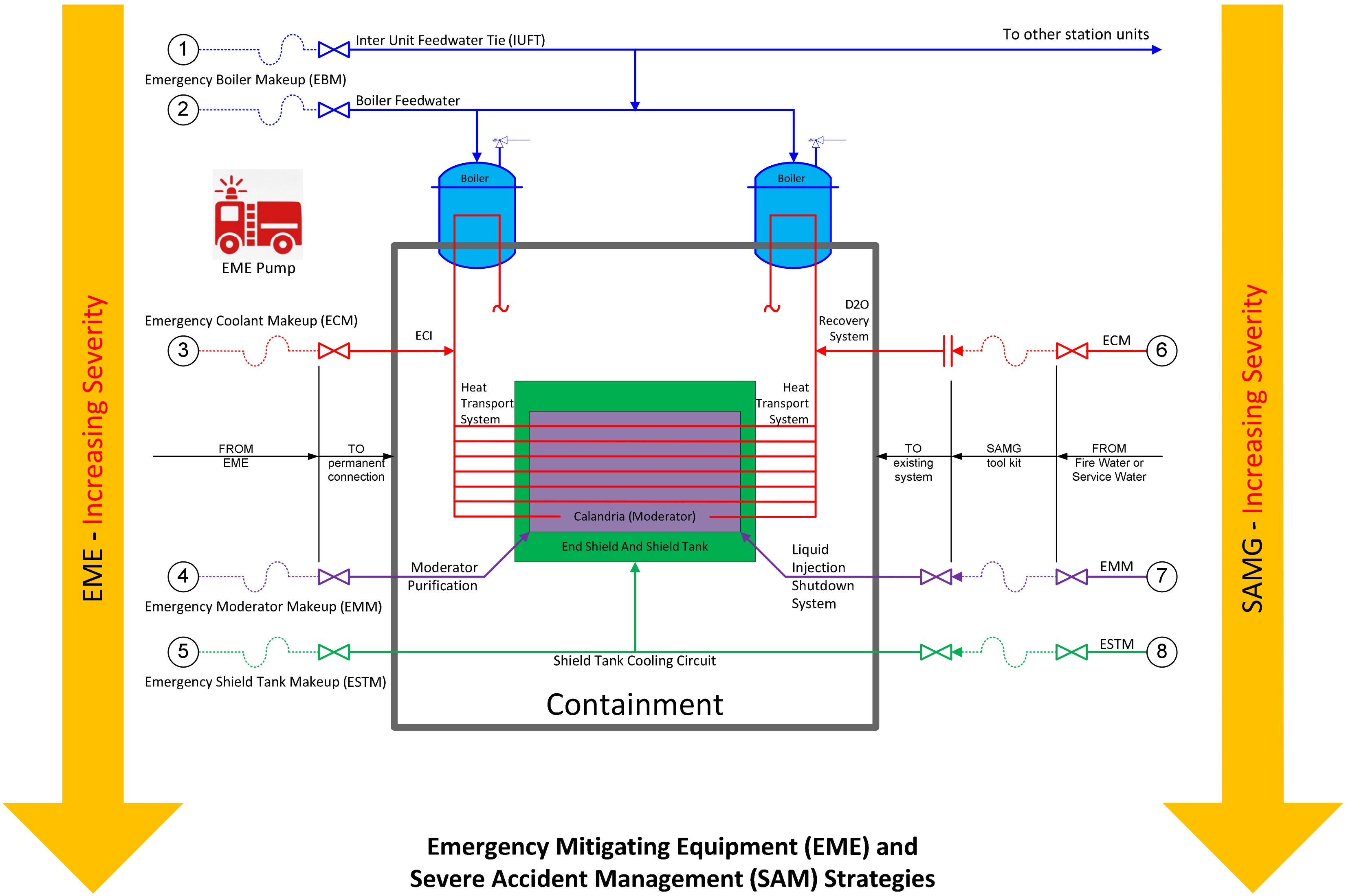

Figure 2 Water Makeup Strategies

4. Impact on the Existing Station Systems, Structures, or Components (SSCs)

In order to allow fast and efficient deployment and connection, the majority of the EME strategies are provided with permanent connections to existing systems. The connections are designed to incorporate the minimum equipment and components, for reliability and for safe operation. The permanent connections incorporate manual valves for isolation during normal station operation. Reverse flow of contaminated water must be prevented from reaching the outside environment. Therefore, the connections incorporate check valves in the event the receiving system is re-energized and/or the temporary hose fails.

The modifications to the existing systems are designed in such ways that they do not adversely impact the function, safety, qualification (seismic or environmental), reliability, code compliance, or operability of the existing SSCs. The impact on the Design Basis of the existing SSCs is confirmed to be acceptable via stress analysis. Stress analysis is also performed to ensure the connections can withstand BDBA loadings where prescribed (water hammer, hose loads, etc.). Additionally, one of the primary or secondary makeup water supply paths for EBM, ECM, and EMM is designed to be seismically qualified. ESTM is not seismically qualified.

Hydraulic analysis is also performed to confirm that the EME and SAM strategies are capable of supplying the required flows, with sufficient pressure to overcome residual equipment pressure, containment pressure, and system resistance.

5. Implementation of Emergency Water Make-up Strategies

5.1 Emergency Water Dry Hydrants

The site layout poses a pumping challenge due to the elevation difference between the lake level and station grade. In order to overcome the great suction lift and to provide the required flow, multiple dry hydrants are installed for each EME pump (See Figure 3) which will draw water from the cooling water outfall when the emergency water make-up strategies are implemented for a BDBA.

Figure 3 Installed Emergency Water Dry Hydrants

5.2 Standardization of Equipment

In order to minimize the risk of human error and to allow interchangeability, it is decided to use standard connections throughout. The design and operation of the pumping equipment, and the connections used are consistent and interchangeable between the stations and units.

The portable equipment consists of fire trucks and pumpers (EME pumps) which are capable of being refueled while in operation and of operating continuously for at least 72 hours. The pumps discharge to industrial fire hose, with standard fire hose couplings. Storz quick connect couplings are used on 6" hose and CSA couplings (municipal and residential fire service throughout the province of Ontario) are used on 2.5" hose.

5.3 Division of Responsibility

The deployment of Emergency Mitigation Equipment (EME) is undertaken by Emergency and Protective Services (EPS) using Standard Operating Guidelines (SOGs). The SOGs have been developed specifically for the purpose of transporting the EME to the impacted station/units and for operating the EME once in service. The portable EME is stored on-site or at a nearby area, provided with reasonable protection from severe natural phenomena, and is capable of being brought into place in the required time frame. This makes it less likely that equipment will be damaged during an external event which simultaneously impacts the station.

During a BDBA, it is a requirement that the equipment be capable of being deployed and connected to the tie-ins with the existing minimum shift complement. Division of responsibility is flexible and can be re-structured to suit the actual accident conditions, staff availability, and mitigation strategies. In general, the following guidelines will allow the above to be achieved:

1) Operations and/or Maintenance install the tool kits onto the permanent connection.
2) EPS deploys the hoses and makes the fire hose connection.
3) Operations operate the valve.

5.4 Physical Diversity and Separation

The deployment routes and connection locations are physically diverse to ensure that one event does not impact the inaccessibility of all makeup strategies. The connections are illustrated in Figure 4.

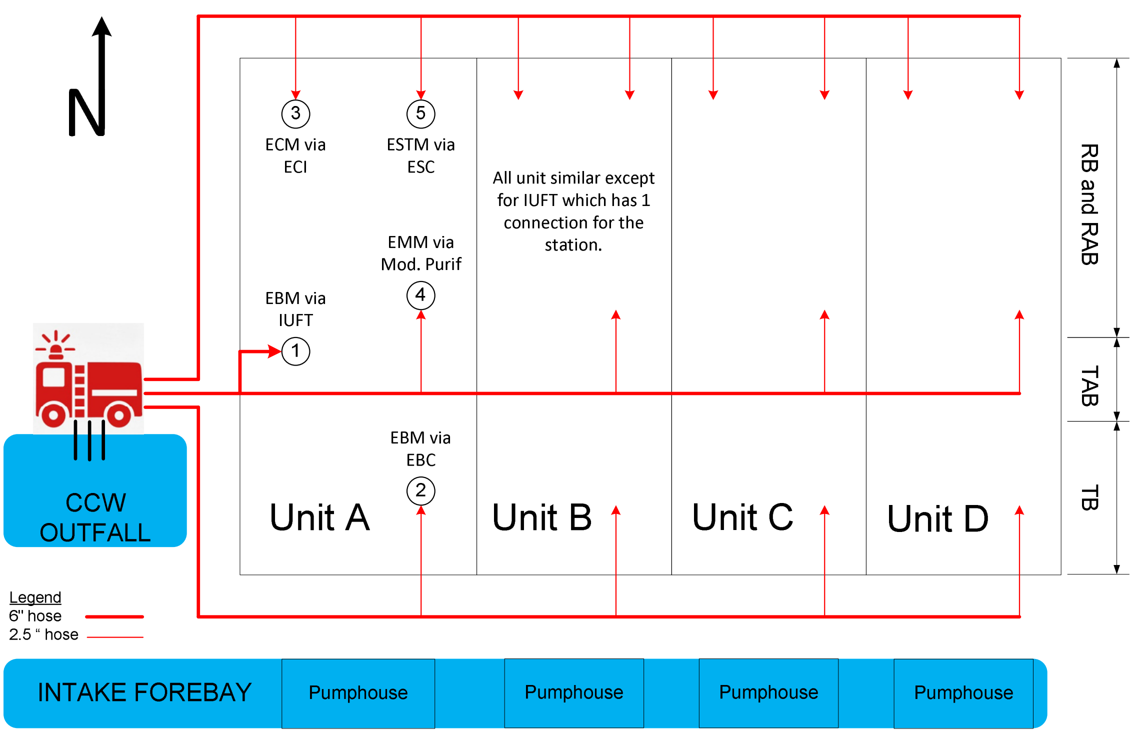

Figure 4 – Physical Diversity and Separation of Connections

6. Conclusions

This paper presents strategies of a CANDU nuclear power plant, for mitigating a Beyond Design Basis Accident (BDBA) similar to the Fukushima Daiichi Nuclear facility accident. The multi-phased approach is to provide the new system connections for delivering emergency make-up water to the primary reactor heat sink via independent and external Emergency Mitigation Equipment (EME) pumps. The impact of the new permanent connections on the existing systems and components is discussed. The implementation strategies for providing emergency water make-up during a BDBA are also presented. This paper demonstrates independent and comprehensive initiatives taken by the CANDU nuclear power plant to address the Canadian Nuclear Safety Commission (CNSC) requirements for mitigating BDBA events.

7. Acknowledgement

References [1] to [4] are used extensively throughout this paper. The authors would like to thank Lovell Gilbert and Gabe Balog for their contributions to this paper.

8. References

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