Spent Fuel Response after a Postulated Loss of Spent Fuel Bay Cooling Accident

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Abstract

A study of the spent fuel behavior in a postulated severe accident is performed to understand the timings of actions and potential consequence associated with an unmitigated loss of cooling for an extended period of time. This study provides input to the "stress test" for Cernavoda CANDU® 6 plants, requested by WENRA/ENSREG. For extreme situations, in the light of the events which occurred at Fukushima in 2011, this work has assessed the spent fuel response after a postulated loss of spent fuel bay cooling accident, assuming that there is a prolonged loss of all electrical power and water make-up to the spent fuel bay. Assessment results indicate that hydrogen generation is insignificant as long as the spent fuel remains submerged. With a large amount of shield water in the CANDU spent fuel bay, as a passive inherent feature, it is estimated that the onset of spent fuel uncovering takes more than two weeks after loss of the spent fuel bay cooling for the spent fuel bay design with normal load. The potential consequence is also discussed after the water level drops below the first few layers of spent fuel bundles due to boil-off/evaporation. However, there is a significant amount of time to take corrective actions using a number of backup design provisions to prevent spent fuel bundle uncovering.

1. Introduction

Considering the accident at the Fukushima nuclear power plant in Japan in 2011, the Council of the European Union declared that the safety of all European Union nuclear plants should be reviewed, on the basis of a comprehensive and transparent risk assessment ("stress tests") [1][2]. The WENRA stress test is defined as a targeted reassessment of the safety margins of nuclear power plants in extreme natural events challenging the plant safety functions and leading to a severe accident. In these extreme situations, sequential loss of the lines of defence is assumed, in a deterministic approach, irrespective of the probability of this loss.

As a subtask of WENRA stress test for Cernavoda CANDU 6 plants, the spent fuel bay (SFB) is one of the reassessment targets. For extreme situations, in the light of the events which occurred at Fukushima in 2011, it is assumed that there is a prolonged loss of all electrical power and water make-up to the spent fuel bay. Hence, for this work, a loss of spent fuel bay cooling accident is postulated.

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The spent fuel bay for Cernavoda CANDU 6 plants is built below ground level and designed to prevent SFB water drain for design basis accidents with a sufficient margin. The spent fuel bay has a liner system (e.g., stainless steel liner for Cernavoda 2) to provide an impermeable membrane that creates a leak tight boundary to prevent seepage and loss of water from the spent fuel bay. Therefore, SFB leakage or drainage due to severe accident conditions is not postulated. In this subtask of stress tests, the study is on spent fuel response due to the loss of SFB cooling.

2. Event and Assessment Performed

In this study, a loss of spent fuel bay cooling event is postulated where it is assumed that there is a prolonged loss of all electrical power and water make-up to the spent fuel bay. During this severe accident event for a CANDU 6 plant, the spent fuel bay water would gradually heat up under the spent fuel decay power.

The topics of the study at certain event stages are described as follows:

1. When will the spent fuel bay water start boiling, given the volume of water and the number of spent fuel bundles in the bay;
2. When will the level of the spent fuel bay water reach the top row of the spent fuel bundle stack to start uncovering the fuel;
3. Once the top layers of fuel bundles are exposed to steam and air, what is the potential for hydrogen generation, if any; and
4. How long will it take for the entire inventory of spent fuel bay water to boil off?

These study results will provide the information about the time available to re-supply the electrical power or to find alternate sources of water to the spent fuel bay before significant hydrogen is generated. It has to be pointed out that several spent fuel bay measurements are provided at the CANDU 6 station. Such indications are given at the local panel and on the station computers in the main control room, backed up with emergency power systems, to monitor and alarm the bay water abnormal levels, temperatures, and coolant flow for the operator to take actions in a timely manner. These measurements are not credited in this work.

3. Spent Fuel Bay Systems and Assessment Assumptions

3.1 Spent Fuel Bay Systems

The SFB is a rectangular pool for the CANDU 6 reactor (Figure 1). The spent fuel storage bay contains stainless steel storage trays (racks) to hold spent fuel bundles (Figure 2). The storage tray is designed to permit the free flow of bay water for cooling the spent fuel bundles, and is capable of supporting in a stable manner, from 1 to 24 fuel bundles in the same layer during storage and/or transfer of the trays. The tray is made of ANSI 304L stainless steel with a layout height slightly larger than the spent fuel bundle diameter.

The trays and supports are designed with sufficient structural stability to avoid toppling and prevent sliding of the stacks either prior to or after a design basis earthquake. The supports also provide the clearance between the bottom layer of fuel bundles and the bay floor, and permits flow of water around the trays.

The spent fuel bay has a 6-inch diameter supply line from the hydrants fire protection system provided in case of emergency. Note that there is no need to add neutron absorbing poison to the fuel bay water or make-up water as there is no criticality concern for natural uranium spent fuel in light water. This makes the post-accident tasks for a CANDU reactor simpler.

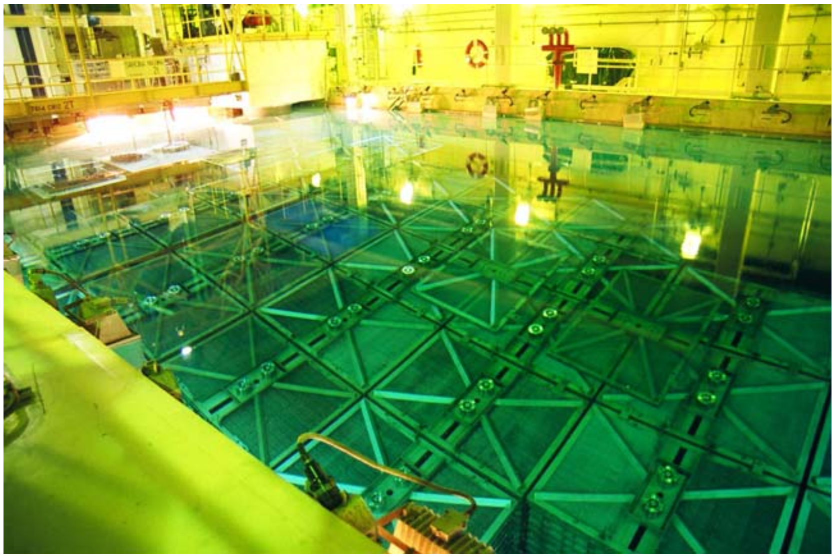

Figure 1 CANDU 6 Spent Fuel Bay Overview

Figure 2 Storage Trays in Spent Fuel Bay

The normal discharge of 8 bundles per refuelling cycle requires three cycles to completely fill a storage tray with a 24-bundle capacity (Figure 2). When the storage tray is full, it is temporarily stored in the reception bay which has a storage capacity of four trays. The storage trays are transferred individually to the SFB, and placed on the base supports located on the bay floor. Trays may be stacked up to a height of 19 layers per stack. Cernavoda Unit 1 is operated with up to 19 layers per stack, while Cernavoda Unit 2 is operated with up to 18 layers per stack.

In this study, the following key assumptions are made for the spent fuel bay systems:

- No make-up water is supplied to the spent fuel bay after the initiation of event

  In additional to the stoppage of circulated cooling water to the SFB, it is assumed the SFB is completely isolated from the auxiliary bays (reception bay, failed fuel bay, and discharge bay). Also, no evaporated steam would be credited to condense and return back to the bay. These assumptions conservatively minimize the available inventory for the SFB, and underestimate the time to SFB water boiling.

- The minimum shield water volume used is based on the design requirement of the safety marker.

  The spent fuel bay is operated with a minimum shield water depth of 4.5 m, which ensures that the fuel load shall be immersed in water to a minimum depth of 4.11 m at all times including a tray passing over the top fuel tray (Figure 1) (Figure 2). This gives the minimum shielding water volume of slightly over 1000 m^3 covering all the spent fuel bundles, and provides the passive inherent feature to mitigate or delay the consequence of loss of SFB cooling.

- It is assumed that the each tray layer in the bay is completed filled with spent fuel bundles.

  It is assumed that each tray has a full load (i.e., 24 fuel bundles per tray) for all 112 tray stacks, yielding 2688 bundles per tray layer. During operation, the first two rows of tray stacks are left empty for dry storage equipment. However, assuming these rows are also filled with bundles is conservative with respect to boiling, since the ratio of the bay water volume to the fuel bundle volume is minimized. Hence, the solid materials (mainly bundles and trays) per layer would occupy space up to about 8.42 m^3. There is a gross volume of 32.2 m^3 for each tray layer. Therefore, the water volume would have at least 23.8 m^3 per layer, which still indicates that CANDU 6 SFB has a large ratio of water volume to the spent fuel volume per layer.

- Designed normal heat load in the SFB is assumed.

  The spent fuel bay cooling system is designed for a normal heat load of 2 MW, which is used in this study (2 MW case). This is primarily based on the removal of decay heat from 10 years of accumulation of spent fuel at an 80% load factor, which is less than 2 MW(th). Transfer to dry spent fuel storage will start after they have been cooled in the bay for about 7 years with the bundle power of about 6 W or below. Therefore, this 2 MW case assumption conservatively maximizes the total normal heat load in the spent fuel bay for determining the time to water boiling. For other heat loads such as emergency core unload are not postulated.

- Limited heat removal mechanisms are considered.

  To conservatively minimize the time to onset of boiling, bay water heat removal is considered only by bay water evaporation. Other heat transfer mechanisms such as the heat stored in the spent fuel and heat lost through the bay wall and floor are not credited.

These key assumptions set up reasonable worse-case SFB conditions (i.e., less water inventory and more heat load) to assess the spent fuel response after a postulated loss of spent fuel bay cooling accident.

3.2 Spent Fuel Bay Room

The spent fuel bay room is a single-storey structure which forms part of the service building structural complex, and is qualified against wind and seismic events. The SFB exhaust system filters exhaust through its own high efficiency filter bank to remove all forms of radioiodine that might be present in the SFB room, prior to discharge via the stack by venting systems or natural venting due to stack effects. It has been estimated for this work that the SFB room volume above the ground is about 3000 m^3. This SFB room volume will be used to assess potential hydrogen concentration. Note that the SFB room has a relatively large ratio of total water to space (roughly about 1:2) upon onset of boiling of the SFB water.

3.3 Decay Power

The spent fuel bundle power varies with discharge age as the power decays from the power level in the core prior to discharge. Table 1 lists average decay power values, which is acceptable for a severe accident, such as in this study of postulated loss of SFB cooling.

The fuel bundle power in general varies in the core over a wide range up to 800 kW at the nominal design level. With a normal CANDU 6 refuelling process, about one third of fuel bundles have a discharge power above 600 kW, and 80% above 300 kW.

Table 1 Long Term Decay Power

Decay time (s)	Decay Time	Normalized Decay Power	Design Bundle Power (kW)	Typical Bundle Power (kW)
0.0	Leaving the core	1.000000000	800.0	600.0
2.59E+05	3 days	0.003800000	3.040	2.280
1.00E+06	11.6 days	0.001940000	1.552	1.164
2.59E+06	1 month	0.001180000	0.944	0.708
1.00E+07	4 months	0.000500000	0.400	0.300
3.15E+07	1 year	0.000174800	0.140	0.105
1.00E+08	3.2 years	0.000043320	0.035	0.026
1.58E+08	5 years	0.000022740	0.018	0.014
3.15E+08	10 years	0.000013942	0.011	0.008

The spent fuel bay heat load mainly comes from spent fuel discharged in recent years, about 50% and 80% for that within one year and three years, respectively. While the average bundle power for the 2 MW case is about 0.0426 kW, the power of recently discharged bundles in the SFB is significantly higher than that. Based on the decay power profile and discharge power level, it is estimated that there are about 200 bundles with the power higher than 0.600 kW among recently discharged within 10 weeks (about 900 bundles). The SFB is designed to hold a total of over 45,000 spent fuel bundles. The accumulation rate of spent fuel bundles in the SFB is about 90 bundles/week. Within a month of decay, all of the bundle powers are below 1.0 kW, and within three years of decay, all of the bundle powers are below 0.0426 kW (the average bundle power in the SFB of 2 MW case).

3.4 Hydrogen Generation

Hydrogen (H_2) generation is due to sheath oxidation in steam (Zr/steam reaction), when the sheath (Zr) is hot enough, sufficient steam (H_2O) is present, and the reaction is accompanied by additional heat generation (Q):

$$Zr + 2\,H_2O = ZrO_2 + 2\,H_2 + Q$$

The Urbanic & Heidrick correlations [3] are established and validated for Zr/steam reaction calculation. It indicates the key temperature ranges:

- Onset temperature: 827 °C
- Transition temperature: 1577 °C
- Fast reaction temperature: >1850 °C

Hydrogen generation for different bundle powers will start when the sheath temperature reaches 827 C. When there is no additional notable heat removal from the fuel sheath, Zr/steam reaction has a positive feedback on the fuel temperature until all of the sheath material or steam is consumed. There is about 2.21 kg of Zirconium material per bundle (about 2 kg for sheath, the rest for the endplates and appendages) or 24.2 mol per bundle. Zirconium has the molecular weight of 91.22 g/mol. Hence, each bundle has a potential to generate up to 48.5 mol of hydrogen (H_2).

Hydrogen would also be produced due to radiolysis, in the process of water being dissolved by radiation in a spent nuclear fuel pool experiencing boiling. This has been postulated as one of hydrogen sources at Fukushima nuclear reactor Unit 4, while the main hydrogen source would be from adjacent units. Gas generation by radiolytic decomposition of hydrogen-containing materials has been an area of concern for the transport and storage of radioactive materials and waste for a number of years. Potentially combustible and corrosive gases can be generated while at the same time, chemical reactions can remove hydrogen, and these reactions can be enhanced by the presence of radiation. The balance between these competing reactions is not well known at this time. It is also understood that the radiolysis process is relatively slow and needs high-energy flux. CANDU spent fuel bundles generate relatively low-energy fluxes under the water. Therefore, it is expected that hydrogen generation is insignificant if there is available shielding water in chemical equilibrium which is provided in the spent fuel bay until the top of the spent fuel is uncovered. However, with bundles exposed to the steam, it is expected that radiolysis would induce a hydrogen source, even through relatively small and slow, in additional to Zr/steam reaction.

3.5 Assessment Approaches

Prior to spent fuel uncovering, the spent bay water boiling is assessed with total water inventory and total bulk power of spent fuel. With the key assumptions given in Section 3.1, a simple hand calculation can be used based on the mass and heat balances.

After spent fuel uncovering, these spent fuel bundles are subject to steam cooling and radiation heat removal with complicated surrounding conditions. The approach with a long horizontal cylinder [4] would be taken accounting for natural convection process (Figure 3) and radiation effects to assess the maximum heat removal for the potential of the onset of hydrogen generation.

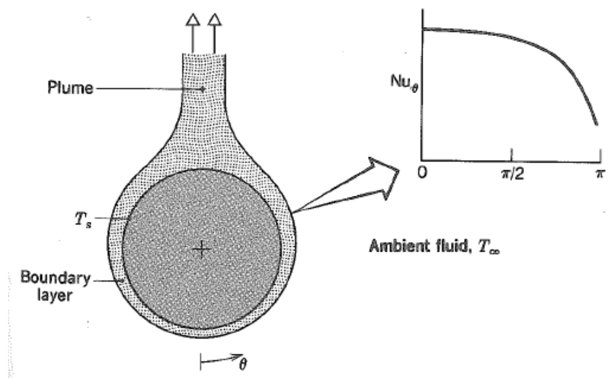

Figure 3 An Idealized Cooling for a Long Horizontal Cylinder Based on Reference [4]

Another approach would be taken using the CATHENA computer code [5]. Figure 4 shows the CATHENA model established for assessing fuel response to loss of spent fuel bay cooling. A hydraulic component (BDLA1 in Figure 4) represents the bay water or steam at the top layer. This component is connected to hydraulic components (PIPE99 and OUTLET in Figure 4) above for the SFB room environment, and a hydraulic component (INLET in Figure 4) underneath for the heat and steam conditions provided from underneath the fuel bundles and the bay water. A set of fuel wall models with a specified bundle power can be attached to this hydraulic component to assess fuel response during and after the surrounding water boil-off. With these fuel wall models, the effects of both convection process and radiation heat transfer toward the surrounding tray and supporting material, as well as potential Zr/steam reaction for hydrogen generation, can be accounted for. The remaining fuel wall model (MBDLR1 in Figure 4) represents the rest of the bulk fuel bundles at the same layer with an average bundle power.

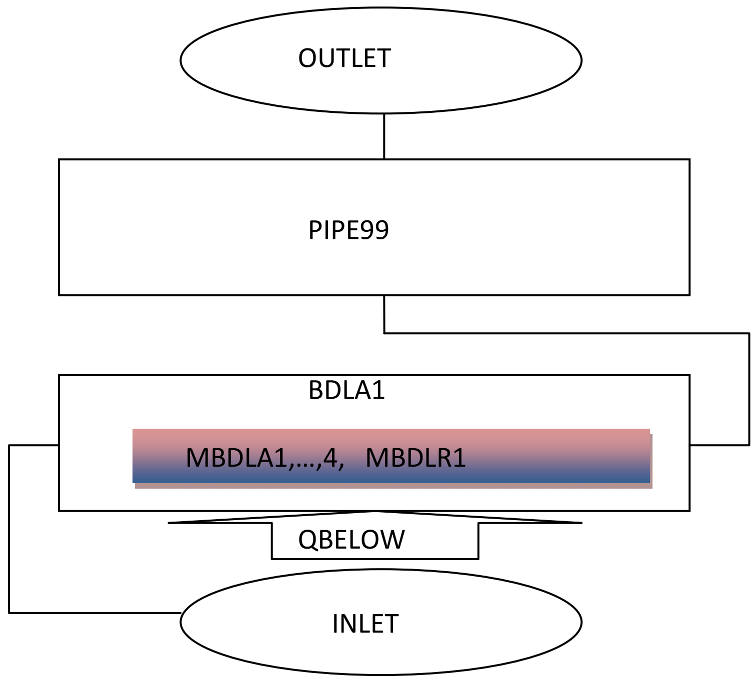

Figure 4 CATHENA Model to Assess Fuel Response to Loss of Spent Fuel Bay Cooling

4. Assessment Results

4.1 Onset of Spent Fuel Bay Water Boiling

Based on minimum bay water volume and maximum operating temperature, onset of the spent fuel bay water boiling for the 2 MW case has been estimated at 60 h 23 min, or about 2.5 days, after loss of the spent fuel bay cooling (Table 2). This estimation has assumed that the SFB has a net water volume of about 1600 m^3 with initial water temperature of 38 ºC for the normal operating conditions. The shield water depth is still maintained by the time onset of boiling occurs.

With the bay water covering the spent fuel, the spent fuel is expected to stay in the nucleate boiling even if the water has zero subcooling (i.e., reached the boiling point). In the SFB, the highest spent fuel bundle power is about 10 kW (Table 1), considering the decay time of fuel handling process from the core to the reception bay then to the SFB. Such spent fuel needs heat removal flux of only about 15 kW/m^2, which is much lower than the critical heat flux, CHF (over 600 kW/m^2) estimated for the bay pool water. Hence, all spent fuel temperatures are just slightly higher (a few degrees in Kelvin at the most) than the bay saturation temperature (100 °C), but the heat flux is well below the CHF value.

No Zr/steam reaction is expected for sheath temperature lower than 827 °C (Section 3.4) prior to spent fuel bundle uncovering. By this time, it is also expected that hydrogen generation due to radiolysis is insignificant as available shielding water remaining in chemical equilibrium and low-energy flux from CANDU spent fuel bundles, as discussed in Section 3.4.

Table 2 Estimated Uncover Time for Top Layer

	Bay Water Surface Area (m^2)	Shielding Water Depth (m)	Cover Water Volume (m^3)	Cover Water Evaporation time (days)	Onset of Boiling (days)*	Minimum Decay days**	Notes
2 MW case	235.90	4.50	1061.5	13.28	2.50	15.8	19 trays (Unit 1)
2 MW case	235.90	4.64	1093.8	13.68	2.50	16.2	18 trays (Unit 2)
Safety marker			4.11	m			
Shielding water for 19 trays			4.50	m			
H Evaporation							
= HG-HF = 2.675-0.419			2.26	MJ/kg			
Density			958	kg/m^3			
tray height			136.65	mm			
* Onset boiling time			60h 23 min (2.50 days)				
** Minimum decay time accounting for normal discharge just out of the core upon loss of SFB cooling							

4.2 Onset of Spent Fuel Bundle Uncovering

As the spent fuel bay water is heating up and boiling off, the water level in the spent fuel bay will start to decrease. Prior to the top row of the spent fuel becoming exposed to steam and air, all fuel bundles are at temperatures just slightly higher than the bay water temperature.

After onset of boiling, the spent fuel bay heat removal mainly depends on the bay water evaporation. The water available for evaporation prior to the onset of uncovering is conservatively based on the low limit of shield water depth (4.5 m above the top bundles), which gives a water volume of about 1000 m^3, as discussed in Section 3.1.

For the SFB as an open pool, the enthalpies for water liquid and steam are 2.675 MJ/kg and 0.419 MJ/kg, respectively. Hence, the heat removal due to evaporation after onset of boiling is about 2.26 MJ/kg. The onset of uncovering will take longer time for sites with 18 stacks, as more shielding water is available for evaporation (Table 2). It should be noted that to remove 2 MW power, a continuous water make-up of about 0.89 kg/s can maintain the bay water level.

Given the inventory of water and the heat load to the spent fuel bay water, it is calculated that the boiling of the spent fuel bay water will commence at approximately 2.5 days after the event initiation for 2 MW case. Based on evaporation enthalpy and the heat load, it is calculated that it will take an additional 13.3 days for the water to boil-off where the top row of fuel bundles will start to get uncovered for the 2 MW case (Table 2). At this point, 15.8 days after the event initiation, sufficient pool water cooling will not be available for the top spent fuel bundles.

4.3 Bay Water Boiling-Off

With more fuel bundles uncovered, the bay water boiling slows down. Only these bundles remaining submerged in the bay water would be the heat source to boil the bay water. The number of the spent fuel bundles remaining submerged in the bay water is about proportional to the SFB water level. Hence, the decay power, directly heating the SFB water is assumed proportional to the remaining SFB water inventory. Similar to the estimation of onset of boiling and uncovering, bay water heat removal other than evaporation is not considered to analytically assess the time of bay water boiling-off process.

For the SFB water with 2 MW and 18-trays stack height upon the onset of uncovering, it takes about 7.36 hours to have the top layer of water boiled-off. The SFB water boiling-off slows down with more bundles uncovered. To have the top three layers of water boiled-off, it takes about 23.5 hours. If the full power would continuously heat the remaining bay water, it would take about another 5.37 days to have the low level layers uncovered. With the decreasing power in fact heating the remaining bay water and considering high ratio (about 1:2) of water to space in the SFB room (Section 3.2) and other environment cooling and condensation effects, it is expected that the SFB water would take a long time in days, if not weeks, to have the low level layers uncovered. There are some residual water without direct heating remaining in the bay underneath all of the bundles, since storage trays are placed on the supports about 0.20 m above the bay floor. Also, it is expected that moisture content in the spent fuel bay room is extremely high by onset of boiling, such that some steam can return to the bay by ‘raining’ or ‘fogging’.

However, whether the SFB continues boiling off may not be relevant to assess further for hydrogen generation and other consequences, as the idealized boiling conditions would not exist if there would be a potential with high temperatures of the uncovered spent fuel bundles and their supports.

4.4 Response of Uncovered Spent fuel

Not all uncovered spent fuel would heat up rapidly and reach a high temperature. The heat transfer is driven by natural convection process, which can be either laminar or turbulent, plus the radiation effect to the surroundings. It is estimated that with an ambient temperature of 100 °C, when a spent fuel bundle reaches 500 °C, the total heat removal would be around 1.5 kW. The heat removal rate is greater than any spent fuel bundle power after 2 weeks in the bay. It is checked by either the approach with a long horizontal cylinder (Figure 3) or the approach using CATHENA model (Figure 4). Such ambient surrounding conditions (Figure 3) would be applicable to the spent fuel bundles just above the water or near the edges of trays. Therefore, no immediate hydrogen generation would occur with onset of the spent fuel uncovering.

Once the level of the spent fuel bay water drops to below the first layer of spent fuel bundles, the ambient surrounding conditions gradually change to that with superheat steam and hot adjacent bundles/trays. The extent of temperature changes of some high power spent fuel and potential hydrogen generation would be assessed with both approaches as discussed in Section 3.5, providing more detailed assumptions on complicated heat transfer. However, by this stage after a postulated prolonged and unmitigated loss of spent fuel bay cooling, there would be a potential for the consequence getting worse.

4.5 Discussion on Potential Consequence and Prevention/Mitigation Actions

Based on the above assessments, with a large amount of shield water in the CANDU spent fuel bay, as a passive inherent feature, it is expected that there would be no cliff-edge effects, till onset of spent fuel uncovering, for a long period (i.e. 15.8 days for 2 MW and 4.5 m shield water depth) after the loss of the spent fuel bay cooling for the spent fuel bay design with normal load. There would be another additional day wherein the spent fuel remains intact with stabilized convection (water or steam/air) and radiation heat removal.

If make-up continues to be unavailable, with multi layers of spent fuel uncovered over days or weeks, there would be a potential for the consequence getting worse (cliff-edge effects), which are briefly discussed as follows.

The tray can maintain its structural function to support bundles up to about 500 °C based on its stainless steel material strength. With radiation and contact heat transfer effects from the high power bundles which are uncovered, some parts of the tray would heat up beyond this temperature and experience a loss of integrity. The similar structure failure would occur in the uncovered portions of the tray supports.

With the surrounding environment getting hot, it could not be precluded that some spent fuel temperatures would increase substantially as there is less cooling available. Hence, onset of Zirconium-steam reaction with hydrogen generation could occur, accompanied with Zirconium-air reaction which does not produce hydrogen.

With prolonged high temperature and heavy oxidation (whether in steam or in air), the fuel sheath might not be able to maintain its integrity to retain the fission product inventory inside. Furthermore, with bundles exposed to the steam and significant fission product release from failed fuel bundles, it is expected that radiolysis would induce an additional and continuous hydrogen source, even through relatively small and slower compared with Zr/steam reaction.

With spent fuel bay water boiling off, the generated steam and hydrogen would migrate to the upper parts of the spent fuel bay building room. The steam there would undergo condensation and drop down, but the hydrogen would be believed to have remained in gas form and increase its local concentration.

However, simple and effective mitigation measures can be taken to prevent these consequences getting worse by restoring power or providing cooling water into the spent fuel bay, preferably prior to spent fuel uncovering. Within a relatively long period after loss of the spent fuel bay cooling, the various types of actions could be taken, including supply of make-up water to the spent fuel bay using the normal demineralised water, back-up fire water system, and fire truck or mobile pump via 6-inch diameter supply line connections provided in the spent fuel bay design. As the SFB is still accessible, directly adding water into the bay is achievable to maintain the water level. Collecting condensed water back the SFB can also be considered.

5. Summary

With the passive inherent feature of the CANDU spent fuel bay, there is a significant amount of time to take corrective actions to prevent uncovering of the spent fuel bundles. It is estimated that the onset of uncovering takes more than two weeks after a loss of the spent fuel bay cooling for the spent fuel bay design heat load. Such estimation can be simply performed for different shield water depth and heat load based on the amount of spent fuel in the bay and decay ages.

Hydrogen generation is insignificant as long as the spent fuel remains submerged. The potential consequence is also discussed after the water level drops below the first few layers of spent fuel bundles due to boil-off/evaporation. However, there is a significant amount of time to take corrective actions using a number of backup design provisions to prevent spent fuel bundle uncovering. Based on the estimated boil-off rate, a water make-up rate of about 1 kg/s is sufficient to maintain the bay water level for the spent fuel bay normal load (2 MW) for evaporative cooling. The backup design options being considered include supplying make-up water to the spent fuel bay using the demineralised water, back-up fire water system, fire truck or mobile pump directly or via the 6 inch diameter supply line connections provided in the spent fuel bay design.

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