Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Report, General

PHENOMENA IDENTIFICATION AND RANKING TABLE FOR A SEVERE ACCIDENT IN A CANDU IRRADIATED FUEL BAY

COMPANY WIDE

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1. INTRODUCTION

The purpose of this report is to describe the methods, assumptions, analysis and the results of a Phenomena Identification and Ranking Table (PIRT) process [1] to a severe accident in a CANDU Irradiated Fuel Bay (IFB)[1]. The PIRT process was conducted over two meetings:

- Meeting #1, held on 2016 May 10, and
- Meeting #2, held on 2016 June 23-24.

The PIRT process was sponsored by the Canadian Nuclear Safety Commission (CNSC), and executed by Canadian Nuclear Laboratories (CNL). CNSC staff have been tasked to develop independent code capabilities in estimating the consequences (source term) of severe accidents. The current codes developed do not model CANDU fuel bay severe accidents. In order to develop a code, the accident phenomena and key parameters need to be identified, the accident progression understood and credible models chosen. Hence, the ultimate objective of the PIRT process described in this report is to inform the development of a computer code to model severe accidents in a CANDU fuel bay.

The methodology used during the PIRT process is described in Section 2. The systems, structures, and components that were considered in the PIRT process are described in Section 3. The accident scenario considered is described in Section 4. The results of the PIRT process are presented in Section 5, with a summary presented in Section 6.

[1] In this document, Irradiated Fuel Bay (IFB), Spent Fuel Bay (SFB), and Spent Fuel Pool (SFP) are used interchangeably.

2. METHODOLOGY

In order to manage the risks associated with nuclear facilities, the consequences of potential accidents must be estimated. In some limited cases, the consequences can be quantified by experiments, but, in general, evaluation models (EMs) are required. To develop and use the EMs, a strong knowledge of the physical phenomena occurring within the system is required. Nuclear-related systems typically involve numerous phenomena, and without a method to rationalize the phenomena, the analysis of the system could become intractable.

The United States Nuclear Regulatory Commission (US NRC) provides a regulatory guide on transient and accident analysis methods [2], in which six basic principles have been identified for developing and assessing evaluation models. The first principle is [2]:

> *Determine requirements for the evaluation model. The purpose of this principle is to provide focus throughout the evaluation model development and assessment process (EMDAP). An important outcome should be the identification of mathematical modeling methods, components, phenomena, physical processes, and parameters needed to evaluate the event behavior relative to the figures of merit described in the SRP*[2] *and derived from the general design criteria (GDC) in Appendix A to 10 CFR Part 50. The phenomena assessment process is central to ensuring that the EM can appropriately analyze the particular event and that the validation process addresses key phenomena for that event.*

The PIRT process satisfies many of the components of the first principle, such as identifying the components, phenomena, physical processes, parameters and the figures of merit. Thus, the PIRT process is an important step in the development of an EM. The general PIRT process is described in Section 2.1, with the details of the application of the process for severe accidents in a CANDU IFB given in Section 2.2. A key component of the PIRT process is the panel of experts, or PIRT panel; the PIRT panel is described in Section 2.3.

2.1 General PIRT Process

The PIRT process used for this work was adapted from References [1] and [3] and is illustrated in Figure 1. The process consists of nine steps, which are described in Sections 2.1.1 to 2.1.9.

Note that the PIRT process shown in Figure 1 cascades from Step 1 to Step 9. Iteration can occur between steps. For example, at Step 7, additional information may be needed to evaluate the importance of a phenomena; this would result in revisiting the knowledge database (Step 5) to add new information.

2.1.1 Issues

The issues that are driving the need for a PIRT are identified. These issues may be licensing, operational, or programmatic. The definition may evolve as a hierarchy starting with federal

[2] Standard Review Plan

regulations or design or safety goals and descending to a consideration of key physical processes.

2.1.2 Objectives

The specific objectives of the PIRT are identified in the second step. The PIRT objectives are usually specified by the sponsoring agency. A clear statement of PIRT objectives is important because it defines the focus, content, and intended applications of the PIRT product. The PIRT objectives should include a description of the final products to be prepared.

2.1.3 Hardware and Scenario

The hardware, equipment and scenario that is considered during the PIRT process is identified in the third step. Generally, a specific hardware configuration and specific scenario are defined. Usually, but not always, the scenario is divided into phases. This is done because the importance of a phenomenon often varies during the course of a scenario. In addition, some system components may not be activated throughout the scenario.

Experience obtained from previous PIRT efforts indicates that any consideration of multiple hardware configurations or scenarios impedes PIRT development. After the baseline PIRT is completed for the specified hardware and scenario, the applicability of the PIRT to related hardware configurations and scenarios can be assessed.

2.1.4 Database

The fourth step of the process involves compiling and reviewing the contents of a database that captures the relevant experimental and analytic knowledge relative to the physical processes and hardware for which the PIRT is being developed. Each Panel member should review and become familiar with the information in the database.

2.1.5 Figure of Merit

The Figure of Merit (FOM) is the primary evaluation criterion used to judge the relative importance of each phenomenon. Therefore, it must be identified before proceeding with the ranking portion of the PIRT effort. It is extremely important that all PIRT Panel members come to a common and clear understanding of the FOM and how it will be used in the ranking effort. The characteristics of a well-defined FOM are that it is: (1) directly related to the issue(s) being addressed; (2) directly related to the phenomena expected to occur during the scenario; (3) easily comprehended, (4) explicit; (5) measurable, and (6) continuous (i.e., not a threshold effect). For design basis accident scenarios, the FOM is generally derived from regulatory requirements. For beyond design basis accident scenarios, the FOM may be derived from regulatory or design goals. As the PIRT process has rarely been applied to beyond design basis accidents, FOM development for such scenarios is evolving.

2.1.6 Identify Phenomena

In the sixth step, all plausible phenomena are identified. A primary objective of this step is completeness. In addition to preparing the list of phenomena, precise definitions of each phenomenon should be developed and made available to the PIRT Panel to ensure that Panel members have a common understanding of each phenomenon. Within the context of this PIRT, the term "phenomenon" encompasses phenomena, processes, conditions, characteristics, and state variables. In each PIRT effort, there is a phenomenological hierarchy beginning at the system level and proceeding in turn through the component level, local level, microscopic level, atomic levels and so on. Each PIRT Panel must determine the appropriate phenomenological levels to include in its list of identified phenomena. Insights into the levels to be included can often be derived by considering the data needs for analytic methods and the level at which data from experiments are collected. Usually, there is no need to proceed further down the phenomenological hierarchy than (a) the level at which physical processes are modelled with analytic methods or (b) the level at which data, either direct or indirect, are acquired.

2.1.7 Importance Ranking

After the phenomena are identified, they are ranked. Importance is ranked relative to the FOM adopted in Step 5. Several ranking scales have been used in the past. However, consistent application of the scale is of equal importance as the specifics of the scale. A word-based scale, e.g., High, Medium, Low or Inactive / Insignificant importance, has proven useful. Numerical scales, e.g., 1-5, have also been used. Outcomes are closely associated with the ranking process and the members of the PIRT Panel should understand the outcomes as they embark on the ranking effort. For example, a phenomenon assigned an importance-rank of High must be simulated with a high degree of accuracy in both experiments and analysis tools while a phenomenon with an importance rank of Low requires significantly less accuracy in both experimental and analytic simulations.

2.1.8 Knowledge Level

In addition to importance, the level of knowledge associated with each phenomenon is assessed. As with importance ranking, several scales have been used in the past. Again, a consistent application of the scale is of equal importance to the specifics of the scale. A numerical scale, e.g., 1-4, which includes in its definitions a statement on uncertainty, has been used. A word-based scale, e.g., Known, Partially Known or Unknown, has also been used. By explicitly addressing uncertainty due to a lack of knowledge, an observed defect of earlier PIRT efforts has been addressed, namely, the tendency of PIRT Panel members to assign high importance to a phenomenon for which Panel members concluded that there was significantly less than full knowledge and understanding.

A consistent outcome of PIRT efforts has been that phenomena found to be highly important relative to the FOM, but for which the knowledge level is insufficient, are carefully examined to determine if additional experiments or analytic efforts are warranted.

2.1.9 Documentation

The primary objective of this step is to provide sufficient coverage and depth that a knowledgeable reader can understand what was done (process) and the outcomes (results). The essential results to be documented are the phenomena considered and their associated definitions, the importance of each phenomena and associated rationale for the judgment of importance, the level of knowledge or uncertainty regarding each phenomenon and associated rationale, and the results and rationales for any assessments of extended applicability for the baseline PIRT. Other information may be included as determined by the Panel or requested by the Sponsor.

2.2 PIRT Process Application: Severe Accident in a CANDU IFB

The general PIRT process, outlined in Section 2.1, was followed for analyzing a severe accident in the CANDU IFB. The key results from each step are summarized in Sections 2.2.1 to 2.2.9.

2.2.1 Issues

The issues supporting the need for the PIRT process were outlined by the sponsor, the CNSC. The CNSC position on accidents involving a CANDU IFB is that, for design basis accidents (DBA), the CANDU IFBs are safe. Adequate time is available for operator action to return the IFBs to a stable state, resulting in no public dose. Furthermore, the safety case for CANDU IFBs during a beyond design basis accident (BDBA) is also adequate. Even without operator intervention, there would not be systematic fuel failures for a few days after the accident initiation. Safety margins exist, although the margins are not well quantified. Public doses are not expected, but minor land contamination could occur.

However, there is no computer code available that can model the consequences of a severe accident in a CANDU IFB. This is considered a gap, as the lack of a computer code makes safety margins difficult to quantify. As well, extreme events are more difficult to analyze. CNSC staff wish to develop a computer code to close this analysis gap, because there is a desire to develop independent code capabilities in estimating the consequences (source term) of severe accidents.

2.2.2 Objectives

The objective of the PIRT process is to inform the development of a computer code to analyze severe accidents in a CANDU IFB. To develop a computer program, the important phenomena must be identified so that appropriate models can be chosen. The PIRT process is an ideal starting point for code development, as it identifies the key phenomena involved in the accident scenario. As well, the importance of the phenomena is also established by the PIRT process, which will inform the level of detail needed for the modelling. Finally, the PIRT process identifies the level of knowledge associated with the phenomena, which will highlight areas in which further research and development is required for either code development or validation.

2.2.3 Hardware and Scenario

The hardware considered was based on the CANDU-6 station of the Point Lepreau Nuclear Generating Station (PLNGS), owned and operated by New Brunswick Power (NBPower). The reason for basing the PIRT process on this design was that it has many key features:

- No auxiliary storage,
- An exposed side-wall, and
- Above the water table

However, some additional hardware was considered, chiefly:

- Both epoxy and stainless steel liners, and
- All types of bundle storage racks used in Canadian CANDU stations.

With this hardware choice, it is expected that the PIRT process would encompass all the key features of Canadian CANDU stations. The hardware is described in additional detail in Section 3.

The accident scenario was one in which the IFB loses cooling and coolant for an extended period. The main assumptions of the accident were:

- A severe environmental event, such as a hurricane, earthquake or ice storm occurs.
- Both the nuclear power plant and the IFB cooling system is damaged.
- Class IV power is unavailable for the duration of the accident.
- Operators are busy or unable to access the IFB for a long period of time.
- The core has been recently discharged (e.g. for reactor refurbishment).
- The fuel is completely uncovered for a period of 7 days.

Additional details on the accident scenario is provided in Section 4.

2.2.4 Database

A literature review was conducted for information relevant for the accident scenario, and the relevant papers were supplied to the PIRT panel members electronically (DVD). The literature reviewed included the following items:

1. Open-literature from Canadian sources (35 references). The subject matter from these sources included:
    a. Fission product release in an air environment,
    b. Behaviour of defected fuel elements,
    c. Fuel bundle deformation,
    d. Fuel oxidation, and
    e. Modelling.

2. Open-literature from International sources (13 references). The subject matter from these sources included:
   a. Overview of spent fuel pool accidents,
   b. Fission product release, and
   c. Sheath oxidation kinetics in air, nitrogen, air/steam mixtures.
3. Open-literature specifically on Light Water Reactors (11 references). These consist of select key papers on the subject of light water reactor spent fuel pool accidents.

2.2.5 Figure of Merit

During the 1st PKPIRT meeting, the sheath temperature was chosen as the FOM. During the second meeting, it was noted that the use of sheath temperature as the FOM could result in some phenomena that are important to fission product/radiological releases to be ranked too low. Thus, during the PKPIRT process, the primary assessments were performed with sheath temperature while a secondary assessment was performed using "Fission product/radiological release, leading to a dose to workers or the public" as a second criteria. Therefore, two FOM were considered:

1. Sheath temperature
2. Fission product/radiological release, leading to a dose to workers or the public

2.2.6 Identify Phenomena

The PIRT panel considered the hardware and scenario, and developed a list of phenomena. The list of phenomena was based on previous PIRT processes (such as CANDU LLOCA), international fuel bay PIRT experience (OECD/NEA), and expert judgement. A total of 86[3] phenomena were identified. The phenomena are summarized in Appendix A.

2.2.7 Importance Ranking

The importance rank of each phenomena was identified for each stage of the accident scenario. The ranking scheme used was:

- High (H)
  Phenomenon has a controlling impact on the Figure-Of-Merit. Simulation of experiments and analytic modelling with a reasonable degree of accuracy (major/minor trends reasonably within range of data (includes scaling)) is required.
- Medium (M)
  Phenomenon has a moderate impact on the Figure-Of-Merit. Simulation of experiments

[3] During the PIRT panel deliberations, 92 phenomena were initially identified. However, 6 of these phenomena were found to be duplicates or not relevant to CANDU IFB severe accidents. In this report, only the unique and relevant phenomena are listed; for the original phenomena list refer to the summary memorandum of the 2nd PIRT panel meeting.

and/or analytic modelling with a moderate degree of accuracy (major trends generally within range of data) is required.

- Low (L)
  Phenomenon has a minimal impact on the Figure-Of-Merit. Modelling must be present to preserve functional dependencies.
- Inactive (I)
  Phenomenon has no impact on or is insignificant with respect to the Figure-Of-Merit. Modelling must be present if the functional dependencies are required.

The phenomena importance ranking is summarized in Appendix A, with the phenomena listed in the order of decreasing importance. As well, the rationale for the importance ranking was recorded in the phenomena assessment worksheets, which are provided in Appendix B.

2.2.8 Knowledge Level

The knowledge level on the phenomena was assessed for each stage of the accident as:

- 4 Fully known, small uncertainty
- 3 Known, moderate uncertainty
- 2 Partially known, large uncertainty
- 1 Very limited knowledge, uncertainty cannot be characterized
- N/A Not applicable, used if the phenomena importance is inactive (I)

The phenomena knowledge level are summarized in Appendix A. The rationale for the knowledge level assessment was recorded in the phenomena assessment worksheets, which are provided in Appendix B.

2.2.9 Documentation

The PIRT panel met on two occasions:

- 2016 May 10
- 2016 June 23-24

The outcomes of both meetings were summarized in a minutes of meeting (for the first meeting) and a memorandum (for the second meeting). The final results of the PIRT panel, including the ranking tables, are summarized in this report.

2.3 PIRT Panel

The PIRT panel consisted of 8 members, and are listed in Table 1. The panel chair was Jeffrey Baschuk. The other panel members were chosen for their expertise in fields relevant to the accident scenario. These fields were:

- Fuel/fission product behaviour (Ray Dickson, CNL),

- Pool boiling, fluid flow, thermal-hydraulics in a severe accident (Nithy Nitheanandan, CNL),
- Containment behaviour (thermal-hydraulics, gas-mixing, hydrogen) (Sammy Chin, CNL), and
- Concrete behaviour (Shahzma Jaffer, CNL).

In order to ensure a diversity of experience within the panel, additional members were added:

- Industry experience with CANDU fuel and IFB systems (Jonathan Judah, J. Judah & Associates, retired OPG),
- Academic experience in fuel behaviour (Brent Lewis, Royal Military College, Retired), and
- International expert on severe accidents (Robert Henry, Fauske & Associates).

In addition to the 8 members, the sponsors of the PIRT processes participated as observers. The following staff of the CNSC attended the panel meetings as observers:

- Wade Grant (CNSC)
- Quanmin Lei (CNSC)
- Kevin Dulhanty (CNSC, 2nd meeting only)

The role of the observers was to clarify the issues and objectives during the PIRT panel deliberations.

3. SYSTEMS, STRUCTURES, AND COMPONENTS

The hardware considered was based on the CANDU-6 station of the Point Lepreau Nuclear Generating Station (PLNGS), owned and operated by New Brunswick Power (NBPower). The IFB is located in the service building, adjacent to the reactor building. New fuel starts in the service building and, as needed, enters the reactor building and is loaded into the fueling machine. The fuelling machine inserts the fuel into the reactor (fuel channels). After the fuel is spent, it is discharged into the fuelling machine, and then into the spent fuel discharge room. The fuel then travels from the spent fuel discharge room, out of the reactor building, and into the reception bay. Fuel is typically stored in the reception bay for one to two weeks before being transferred to the main spent fuel bay. For the purposes of the PIRT process, only the spent fuel storage pools in the service building are considered, as they are outside of containment and thus fuel failure leading to fission product release would have a pathway to the outside environment. Defected fuel can also be present in the bays. The defected bundles can be stored in the same locations as intact bundles, segregated in separate area after inspection, or stored in sealed canisters. Some CANDU reactors produce medical isotopes (^{60}Co), which are also placed in the storage bay prior to shipping.

The fuel bays are constructed of reinforced concrete and have a double wall. One of the walls of the PLNGS fuel bay is exposed (not buried). This is one reason why the PLNGS design was chosen for the PIRT process, as the exposed wall could be breached by an extreme event, leading to loss-of-coolant. The base slab of the bays is lined with stainless steel and the walls are coated with fibreglass reinforced epoxy. However, other Canadian plants have full stainless steel liners or epoxy liners. As a result, both stainless steel and epoxy liners were considered during the PIRT process, in order to have the results applicable to all Canadian reactors.

When the fuel is discharged into the reception bay, it is loaded into trays, baskets or modules, depending on the reactor. Bundles in PLNGS are placed into trays (similar to the Bruce GS as shown in Figure 2), which are then arranged in racks, as shown in Figure 3. In order to have the PIRT be applicable to all Canadian power reactors, the fuel storage systems of Pickering, Bruce and Darlington were also considered during the PIRT process. The storage trays and modules for Pickering, Darlington and Bruce GS are also shown in Figure 2.

A summary of the systems, structures and components (hardware) considered for the PIRT panel is given in Table 2. The hardware is considered in 4 levels, with level 4 being the smallest components (such as the fuel pellets) and level 1 being the larger components (such as the service building).

4. ACCIDENT SCENARIO

The accident scenario was briefly described in Section 2.2.3, and the main assumptions were:

- A severe environmental event, such as a hurricane, earthquake or ice storm occurs.
- Both the nuclear power plant and the IFB cooling system are damaged.
- Class IV power is unavailable for the duration of the accident.
- Operators are busy or unable to access the IFB for a long period of time.
- The reactor core worth of fuel has been recently discharged (as might happen at the beginning of a refurbishment outage).
- The fuel is completely uncovered for a period of 7 days.

With these assumptions, the accident progression becomes as shown in Figure 4. The accident can be divided into 4 phases and it is assumed that the accident progresses to all 4 phases. In the first phase, after the initiating event, the IFB water level decreases, but the fuel remains covered (the shield water depth is a minimum of 4.5 m [4]). The level of the bay could be decreasing either due to a loss-of-coolant (such as a breach in an exposed wall); a loss-of-cooling which leads to the heat up, evaporation, or boiling of the water in the IFB; or a combination of loss-of-coolant and loss-of-cooling.

Once the fuel begins to become uncovered, the second phase of the accident begins. This phase is characterized by the fuel being partially uncovered, which is expected to initiate some fuel failures. After some time, the fuel will become completely uncovered and phase 3 of the accident begins. It is assumed that the entire inventory of fuel in the IFB is uncovered for a period of 7 days. The time period of 7 days was chosen to bound the range of applicability for the IFB computer code to be developed and not because this is a credible accident scenario. Additional fuel failures are expected during this phase, due to either fuel overheating or through-wall oxidation of the sheath. Finally, recovery of the IFB water inventory is initiated in Phase 4 of the accident. Operator action, potentially using portable pumps, refills the fuel bay such that the fuel becomes covered and cooling is restored.

5. PIRT RESULTS

A total of 86 phenomena were considered during the phenomena identification and ranking exercise. The phenomena, importance rank, and knowledge assessment are summarized in Appendix A, with the detailed justification of the ranking and knowledge assessment provided in Appendix B. Of the 86 phenomena, 37 were ranked as high (H) in at least one phase of the accident. These phenomena are:

1. Decay Heat
2. Geometry and configuration of the SFP building (dimensions, open/closed building)
3. Conduction in solid components (fuel, racks/modules, concrete, …)
4. Turbulent flow (gas space, liquid)
5. Epoxy liner degradation and failure
6. Stainless steel liner degradation and failure
7. Location, design, burnup, decay heat of individual spent fuel assemblies and locations and configurations of storage racks/modules
8. Sheath strain and failure
9. Heat transfer in sheath, pellets and through the gap, which affects distribution of temperature, strain and stresses
10. UO_2 oxidation
11. Concrete aging (including temperature and radiation effects)
12. Concrete cracking (thermally induced, stress-induced, creep, quench)
13. Convective heat transfer
14. Rack type (Pickering basket, CANDU 6/Bruce tray, Darlington module)
15. Single and two phase natural circulation (by convection) within the pool at large scale
16. Deflagration
17. Flame acceleration
18. Deflagration to detonation transition (DDT)
19. Detonation
20. Transport of released fission products
21. Fission product deposition
22. Fission product chemistry
23. Water evaporation at the pool surface
24. Fuel fragmentation and relocation (during ballooning, before and after sheath rupture)
25. Environment conditions (e.g., air temperature, humidity, pressure, wind speed, ground temperature)
26. Thermal Radiation Heat Transfer

27. Return of condensate to pool
28. Zircaloy oxidation in air-steam mixtures (including breakaway of pre-existing oxide layer)
29. Radionuclide releases from leaking fuel pins into the pool
30. Release of retained fission gases due to fuel fragmentation
31. Oxidation and releases from previously defected fuel into the pool
32. Behaviour of defected fuel
33. Deformation and integrity of structures (racks/modules/fuel bundle)
34. Fission product release from the fuel
35. Fuel cooling by sprays and makeup
36. Fuel particle entrainment in the gas outflow (during rewet)
37. Delayed ettringite formation

If phenomena that have at least a medium (M) importance rank are considered significant, then there are an additional 21 phenomena that should be considered:

1. SFP auxiliary systems status (ventilation, cooling, filters, strainers, pumps, heat exchangers)
2. Pool structure parameters, e.g., concrete composition, reinforcing design, liners, exterior interface (in-ground or above-ground)
3. Stratification in the gas space
4. Buoyancy induced mixing in the gas space
5. Building leakage of gases and aerosols
6. Hydrogen pick-up under steam + air + hydrogen
7. Liquid-phase transport of fission products to environment
8. Condensation heat transfer
9. Thermal expansion (mismatch between aggregate and cement paste, rebar and concrete, etc.)
10. Other pool contents (other than fuel stored in standard locations, like cobalt, scrap module, bundles and elements stored from fuel inspections, shield plugs)
11. Laminar flow (gas space, liquid)
12. Irradiation annealing and sheath recrystallization
13. Pool water radionuclide inventory and activity (including dissolved tritium)
14. Siphoning/leakage effects (e.g., leaking flow effect on established natural circulation patterns)
15. Initial atmospheric condition in the SFP building
16. Pool scrubbing of aerosols and gases from bubbles
17. Radioactive aerosol formation due to boiling at the free surface
18. Sheath Melt

19. Stainless steel oxidation
20. Water level swell
21. Effect of sea, river, lake, ground (impure) water injection

Thus, 58 of the 86 phenomena are at least of medium importance to the accident scenario.

With the high and medium importance phenomena identified, the accident scenario described in Section 4 can be expanded. This following discussion focuses on the 58 phenomena which are ranked as at least of medium importance (Figure 5 and Figure 6)). The numbers provided in {brackets} are the phenomena identification numbers provided in Appendix A and Appendix B.

During Phase 1 of the accident, the water level in the SFP slowly decreases. The reason for this decrease is not specified as it depends on the specific design of the fuel bay {9}, but it could be due to damage of the SFP liner {91}{92} and the concrete wall {84}{86}. Failure of the SFP cooling system and water make-up systems {8} or syphoning effects {20} could also result in decreasing water levels as the pool water evaporates away {13}. The rate of water level decrease may be reduced as some water will condense {44} in the higher elevations of the SFP building and will return to the pool {18}, and the volume of water in the pool may swell {24}. However, swelling and condensation will not be sufficient to maintain pool water inventory. As the quantity of water in the pool decreases, the fuel decay heat {1} will continue to add thermal energy to a decreasing quantity of water, and water temperature will increase, as will the rate of evaporation {13}. The decay heat load stored in the SFP will be an important factor. Associated with this will be the recent history of fuel transfer to the pool {4}. For example, recent full core discharge due to refurbishment or decommissioning activities will increase the heat load above that which is normal, perhaps to the point of pool license limits. Also important will be the status of SFP auxiliary systems such as the heat transfer systems {8}. For example, cooling systems are generally more efficient in the winter, so an accident in the summer will have more serious consequences.

As Phase 1 evolves, some fission products will begin to be released from the pool water {31}. Cooling of the bundles in the pool by turbulent {48} convection and natural circulation {16}{15} (even in the absence of forced cooling) will be sufficient to prevent fuel sheath failure; however, the pool water might already contain fission and activation products which were released from previously defected fuel bundles which were discharged to the pool. The release to the environment will be dependent on the structure and configuration of the SFP building {6}, on the initial and evolving atmospheric conditions within the building {5}{10} and on the history of fuel defect discharges prior to the SFP accident.

In the final assessment, Phase 1 of the accident will not result in additional fuel damage of any significance, because the fuel bundles are immersed in liquid water and therefore sufficiently cooled to prevent sheath failures. Releases of radioactive fission and activation products will be limited {3}.

The beginning of Phase 2 signifies the decrease in pool water level to the point at which the first fuel bundles begin to become uncovered. Phase 2 is defined to end when virtually all water has been lost from the SFP and all fuel bundles are exposed. The locations, burnups, discharge times and decay heats of individual fuel bundles and the storage locations and configurations of fuel bundles now become important {4}. Storage of a large number of recently discharged fuel bundles at the upper levels of the storage stacks will increase the severity of the consequences of this accident. Similarly, storage of irradiated fuel bundles in non-standard configurations such as scrap baskets and boxes (for damaged fuel bundles) should factor into any assessment of consequences. Other contents of the pool, such as stored adjusters for radio-nuclide processing would also require consideration {12}. Damage to SFP liners {91}{92} and concrete walls {84}{86} due to intense radiation fields and temperature gradients {83} would need to be considered.

Many of the factors discussed for Phase 1 will continue to be important for Phase 2, however the importance and consequences would accelerate as the quantity of available pool water decreases and as increasing numbers of spent fuel bundles lose water cooling altogether {15}. The design of the storage structures will become important because with loss of water, the remaining cooling will now be via conduction {39} through metal components, turbulent {48} air convection {16} through these structures, and thermal radiative heat transfer {26}.

As fuel bundles overheat {62}, the Zircaloy fuel cladding will begin to degrade {55}{57}, oxidize {27} and eventually rupture {56}{68}. In fuel elements with sheath ruptures (either due to the accident or fuel defected in-reactor {64}), fuel pellets inside the fuel sheaths will now become exposed to air and will oxidize {66} at the high temperatures which result from decay heats {1} and loss of cooling. Oxidation will result in the degradation of the structure of fuel pellets with the consequential release of fission products which had been contained within the matrix of the fuel pellet {69}{77}. Fission products will now be released from the ruptured fuel pins {31}{34}{60}{61}. Releases to the environment will increase as the remaining pool water and cover air become highly contaminated {73}{74}{75}{78}. Note: in the CANDU safety framework the Zircaloy fuel cladding and the matrix of the UO_2 fuel pellet are considered to be two of the credited barriers to fission product release. So, rupture of fuel cladding and degradation of the fuel pellet due to oxidation will be significant milestones in the evolution of this accident.

As water levels decrease and local temperatures increase due to decay heats, the structures supporting the fuel bundles such as modules, trays, baskets and stacking frames {4}{11} may lose some of their strength and their integrity might be compromised {41}.

High heat in the presence of water and Zircaloy will provide the conditions for the release of Hydrogen gas. This gas will be highly flammable and will require venting or recombination to mitigate the risk of deflagration and/or detonation {42}{50}{51}{52}{53}.

Phase 3 begins when the SFP is virtually dry and the fuel is completely uncovered. Irradiated fuel bundles are still resident in their normal storage locations/devices, such as baskets, trays and modules {4}, and these are still stacked in frames in the SFP {11}, however, there is now no water cooling at all. Convective cooling by air still continues {16}{45}{47}, as does conduction through the metal storage devices and stacking frames {39}.

The degradation of fuel will now accelerate because of the higher fuel and sheath temperatures and the availability of oxygen in the SFP atmosphere {27}{60}{61}. Fission and activation products will be released into the atmosphere of the SFP building {6} and from there, into the atmosphere outside the building {49}. Fuel storage components in the SFP will continue to degrade {41}{71}, as will components of the structure of the SFP {91}{92}.

Phase 3 is assumed to continue for 7 days until refilling of the SFP is attempted.

Phase 4 begins with attempts to refill the SFP and ends when these attempts are successful and the SFP now has the required inventory of water {59}.

The source of refill water is assumed to be local {70}, and this water could be as cold as zero degrees Celsius in winter. The sudden influx of large volumes of cold water on the SFP inventory of hot, irradiated and damaged fuel bundles can be expected to generate a large steam cloud. Significant amounts of fission and activation products can be expected to be entrained in this cloud {33}{34}{80}. The environmental release will depend on many factors such as the geometry and structure of the SFP {6} and on environmental conditions {10}. Degradation of the concrete structure of the SFP will continue {84}{86}{90}. The thermal shock due to the sudden influx of very cold water onto hot fuel, structural components and the SFP structure can be expected to accelerate the degradation of all of these. The accident will be considered terminated when the SFP has been refilled, which will provide sufficient cooling to prevent further fuel failures.

The phenomena identification and ranking process can also identify phenomena that require additional research. These phenomena are ranked high or medium in importance, and are assessed to have a low level of knowledge. Eighteen phenomena were identified as having an importance rank of either high or medium, with a low knowledge level of 1 or 2. These phenomena are listed below, along with their importance rank and knowledge level within parenthesis:

1. Epoxy liner degradation and failure (H-2)
2. Stainless steel liner degradation and failure (H-2)
3. Concrete aging (including temperature and radiation effects) (H-2)
4. Concrete cracking (thermally induced, stress-induced, creep, quench) (H-2)
5. Convective heat transfer (H-2)
6. Single and two phase natural circulation (by convection) within the pool at large scale (H-2)
7. Flame acceleration (H-2)
8. Deflagration to detonation transition (DDT) (H-2)
9. Fission product chemistry (H-2)
10. Zircaloy oxidation in air-steam mixtures (including breakaway of pre-existing oxide layer) (H-2)
11. Deformation and integrity of structures (racks/modules/fuel bundle) (H-2)

12. Fission product release from the fuel (H-2)
13. Fuel particle entrainment in the gas outflow (during rewet) (H-2)
14. Building leakage of gases and aerosols (M-2)
15. Liquid-phase transport of fission products to environment (M-2)
16. Other pool contents (other than fuel stored in standard locations, like cobalt, scrap module, bundles and elements stored from fuel inspections, shield plugs) (M-2)
17. Radioactive aerosol formation due to boiling at the free surface (M-2)
18. Stainless steel oxidation (M-2)

A detailed gap assessment was performed with the 86 phenomena identified in the four phases. In developing the gap assessment, each phenomenon/phase combination is considered an application point. For example, the phenomenon of sheath melt during the first phase (early phase) of the accident scenario is considered one application point, while the phenomenon of sheath melt during the second phase (mid phase) of the accident scenario is considered as a different application point. The total number of phenomena/accident phase combinations in the prolonged loss-of-coolant accident in the irradiated fuel bay provided 344 application points. The distribution of these application points is shown in Table 3 to illustrate the areas identified to have gaps in knowledge. Areas shaded red indicate that gaps in knowledge exist, and would benefit from further research and development (R&D) activities. There are no high or medium ranked phenomena with very limited knowledge; however, two phenomena were identified to have with limited knowledge with low importance. There are 28 phenomena application points ranked as high in importance and 16 ranked as medium importance, with partially known, large uncertainty. The PKPIRT process indicates that additional R&D is required to close the knowledge gap in these areas.

6. SUMMARY AND CONCLUSIONS

A PIRT was developed for a severe accident consisting of a prolonged loss-of-cooling/loss-of-coolant in CANDU IFB. The PIRT process mainly considered the PLNGS design, but included both stainless steel and epoxy liners, as well as all fuel storage schemes (modules, trays), to make the PIRT applicable to all Canadian CANDU reactors. The PIRT identified 86 phenomena, of which 58 were at least of medium importance in the accident scenario. As well, the PIRT indicates that additional R&D effort could be beneficial for 18 phenomena, because the phenomena had either high or medium importance, but a low level of knowledge.

The objective of the PIRT exercise was to inform the development of a computer code to model the behaviour and consequences of a severe accident in a CANDU IFB. The PIRT can form part of the reference material for code development and can be used as input to three phases of the code development process, as shown in Figure 7:

1. Problem Definition,
2. Theoretical Background, and
3. Requirements Specification.

The accident scenario considered by the PIRT panel will likely form the basis of the problem definition of a future computer code. The PIRT will provide key input to the development of the theoretical background. The PIRT identifies all phenomena associated with the accident. But, more significantly, the PIRT identifies the importance of the phenomena. This is significant because it is impractical to model all phenomena, to a fine level of detail, in a computer model. The PIRT provides a rationale for excluding phenomena, or reducing the level of detail needed to consider phenomena in the computer model. The requirements of the computer code will be derived from the problem definition and theoretical background, both of which will be influenced by the PIRT.

7. REFERENCES

[1] G.E. Wilson and B.E. Boyack, 1998, “The role of the PIRT process in experiments, code development and code applications associated with reactor safety analysis”, Nucl. Eng. Des. 186, 23-37

[2] US Nuclear Regulatory Commission, “Regulatory Guide 1.203: Transient and Accident Analysis Methods”, 2005 December

[3] B.E. Boyack and G.E. Wilson, “Lessons Learned in Obtaining Efficient and Sufficient Applications of the PIRT Process”, Best Estimate 2004, Washington, D.C., 2004 November 14-18

[4] H.Z. Fan, R. Aboud, E. Choy, W. Zhu and H. Liu, “Spent Fuel Response after a Postulated Loss of Spent Fuel Bay Cooling Accident”, Proc. 33rd CNS Annual Conference, Saskatoon, SK, Canada, 2012 June 10–13

8. LIST OF ACRONYMS

BDBA	Beyond Design Basis Accident
CANDU	CANada Deuterium Uranium
CFR	Code of Federal Regulations (United States)
CNL	Canadian Nuclear Laboratories
CNSC	Canadian Nuclear Safety Commission
DBA	Design Basis Accident
EM	Evaluation Model
EMDAP	Evaluation Model Development and Assessment Process
FMDB	Fuelling Machine Discharge Bay
FOM	Figure Of Merit
GDC	General Design Criteria
GS	Generating Station
HAZ	Heat Affected Zone
HEPA	High Efficiency Particulate Arresting
IFB	Irradiated Fuel Bay (used interchangeably with Spent Fuel Bay)
MSB	Main Storage Bay
NBPower	New Brunswick Power
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
PIRT	Phenomena Identification and Ranking Table
PLNGS	Point Lepreau Nuclear Generation Station
R&D	Research and Development
RB	Reception Bay
SFB	Spent Fuel Bay (used interchangeably with Irradiated Fuel Bay and Spent Fuel Pool)
SFP	Spent Fuel Pool (used interchangeably with Irradiated Fuel Bay and Spent Fuel Pool)
SRP	Standard Review Plan
SS	Stainless Steel

Table 1
Members for the PIRT Panel

Member Number	Role	Name
1	Chair	Jeffrey Baschuk (CNL)
2	Fuel/fission product behaviour	Ray Dickson (CNL)
3	Pool boiling, fluid flow, severe accidents	Nithy Nitheanandan (CNL)
4	Containment behaviour (thermal-hydraulics, gas-mixing, hydrogen)	Sammy Chin (CNL)
5	Concrete behaviour	Shahzma Jaffer(CNL)
6	Industry fuel behaviour expert	Jonathan Judah (J. Judah & Associates, retired OPG)
7	Academic fuel behaviour expert	Brent Lewis (Royal Military College of Canada, Retired)
8	International expert on severe accidents	Robert (Bob) Henry (Fauske & Associates)

Table 2
Hardware (Systems, Structures and Components) Chosen for the PIRT Panel[4]

System/Structure	Components
Level 1	
Fuelling Machine Discharge Bay (FMDB)	Spent Fuel Port, Elevator, Spray Cooling System, Transfer Cart, Transfer Conveyor, Fuel Bundle, Defected Fuel Handling System, Defected Fuel Cans, Concrete Bay Walls, SS Liner, Epoxy Liner, SFB Cooling and Purification System, Containment Gate, FMDB Air Space, Room Structure
Reception Bay (RB) (and flask loading area)	Transfer Conveyor, Tray, Tray Conveyor, Fuel Bundle, Defected Fuel Cans, Fuel Handling Tools, Concrete Bay Walls, SS Liner, Epoxy Liner, SFB Cooling and Purification System, RB Air Space
Main Storage Bay (MSB)	Concrete Bay Walls, SS Liner, Epoxy Liner, SFB Cooling and Purification System, Stack Locking System and Seal, Tray, Fuel Bundle, Fuel Handling Tools, MSB Air Space, Man-bridge
Service Building	Service Building Structure, SFB Ventilation System, Area Radiation Monitors
Level 2	
Spent Fuel Port	Ball Valve
Elevator	Ladle, Elevator Carriage, Elevator Track, Rack Indexer
Spray Cooling System	Discharge Bay Water, Pump, Piping, Headers
Transfer Cart	
Transfer Conveyor	Indexer, Conveyor, Control System
Fuel Bundle	End Plate, Fuel Element
Defected Fuel Handling System	Carousel, Bundle Canning Device, Defected Fuel Cans
Concrete Bay	Concrete, Reinforcing Bar
Stainless Steel Liner	Sheet, Weld Zones
Epoxy Liner	Epoxy, Adhesion to Concrete

[4] Components with this highlighter color handle a maximum of two (freshly discharged) or twelve fuel bundles at a time. Some of these systems may have too much detail, because they don't actually figure in the accident scenario unless fuel is being discharged at the time of the accident.

System/Structure	Components
SFB Cooling and Purification System	Demineralized Water Supply, Cooling Water Supply, Makeup Valves, Emergency Makeup Water Supply, Emergency Makeup Valves, Heat Exchanger, DB Skimmer, RB Skimmer, MSB Skimmer, Circulation Pumps, Loop Separation Valves, Particulate Filters, Ion Exchangers, Cold Water Return Pipes, Siphon Breaks, Water Temperature Indicators, Level Indicators, Low Level Alarm, Flow Indicators
Containment Gate	Canal Gate Assembly, Actuator Assembly, Actuator Control, Seal Leak Testing System
FMDB Air Space	
Room Structure	Ceiling, Walls
Tray, Basket and Module for Fuel Bundle Storage	The trays are used for PLNGS and Bruce GS (Figure 2). A stack of trays is shown in Figure 3. The Pickering GS basket and Darlington module are shown in Figure 2.
Tray Conveyor	Similar to Transfer Conveyor
RB Air Space	(similar to FMDB Air Space)
MSB Air Space	(similar to FMDB Air Space)
Stack Locking System and Seal	Mesh Walls, Top and Lock
Man-bridge	
Service Building Structure	
Area Radiation Monitors	
SFB Ventilation System	RB Air Space, MSB Air Space, Prefilter, HEPA Filter 1, Activated Carbon Filter, HEPA Filter 2, Exhaust Fans, Stack, Bypass Duct, Dampers, (Injection Ports, Sample Ports?)
Level 3	
Fuel Element	CANLUB, End-Cap, Fuel Sheath, Internal Gas, Fuel Pellet
Level 4	
Fuel Pellet	Chamfer, Dish, UO_2
Fuel Sheath	Bearing Pad, Spacer Pad, Be Braze Alloy, Zircaloy-4, HAZ Zircaloy-4

Table 3
Gap Identification and Distribution of Rank and Knowledge of Phenomena Assessed

Knowledge Base Gap Determination				
Adequacy of Knowledge	**Rank of Phenomenon**			
	H	**M**	**L**	**I**
(4) Fully known; small uncertainty	**18**	**21**	**35**	**89**
(3) Known; moderate uncertainty	**37**	**30**	**45**	
(2) Partially known; large uncertainty	**28**	**16**	**23**	
(1) Very limited knowledge; uncertainty cannot be characterized	**0**	**0**	**2**	

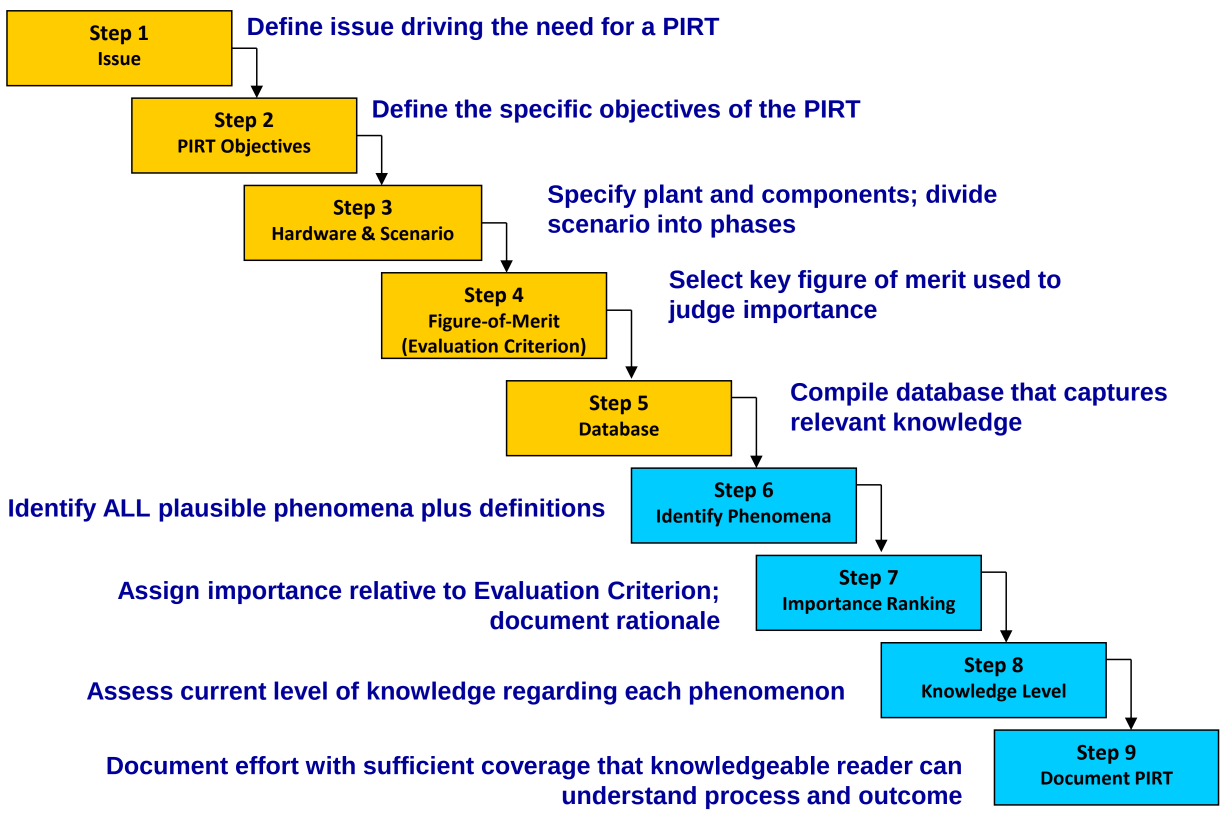


Figure 1 General PIRT Process

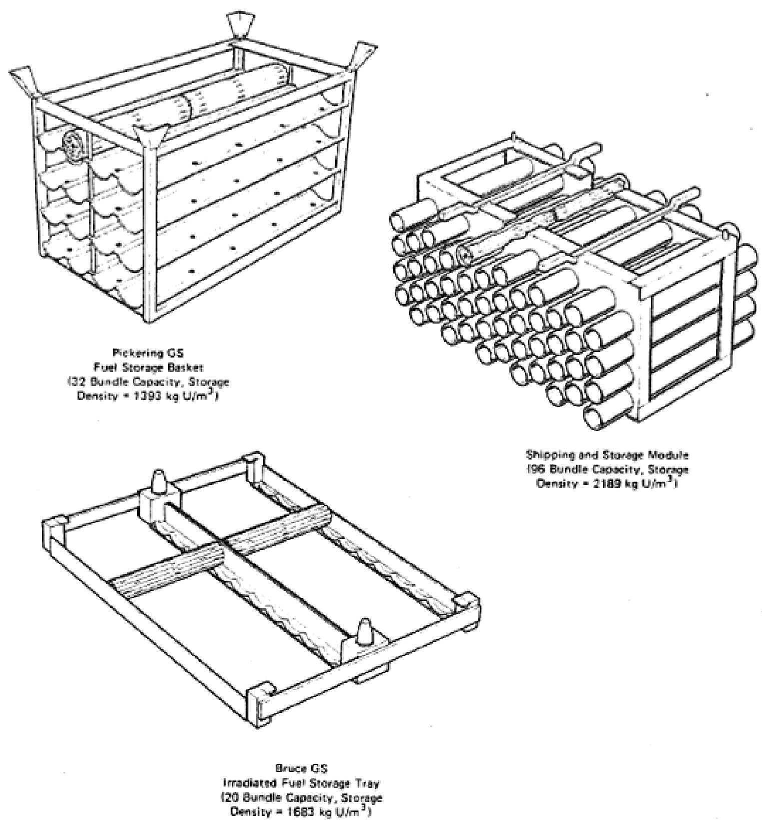


Figure 2 Fuel Storage Trays and Modules for a Pickering, Darlington (not labeled in figure) and Bruce GS. Fuel Storage Trays for PLNGS and Bruce GS are Similar.

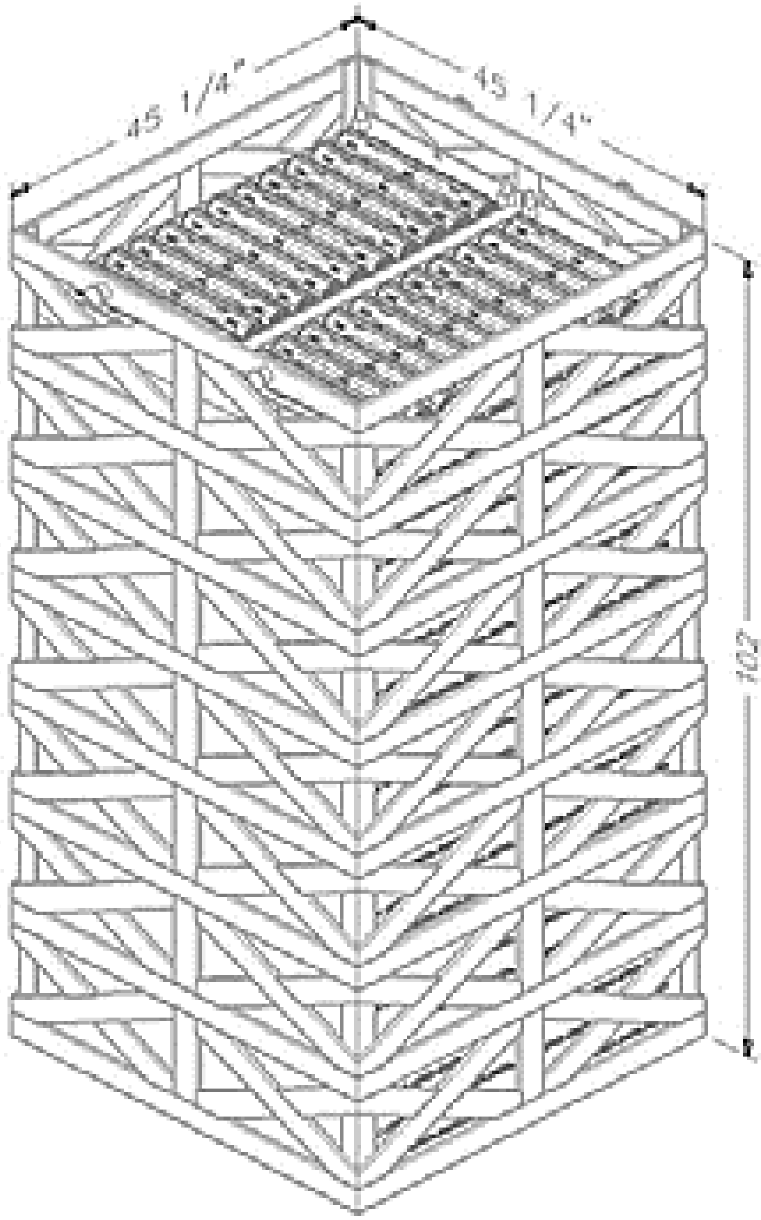


Figure 3 Stack of Fuel Storage Trays

Pool Water Status	Rapid Loss of Pool Coolant		Partial Water Loss	Complete Loss of Water	Level Recovery
	Pool Water Heat up	Pool Evaporation or Boiling			
Fuel Status	Fuel Covered		Partial Fuel Uncovery	Full Fuel Uncovery	Partial Fuel Uncovery → Fuel Covered
Accident Progression	Phase 1 (Early Phase)		Phase 2 (Mid Phase)	Phase 3 (Late Phase)	Phase 4 (Recovery)

Figure 4 Accident Progression

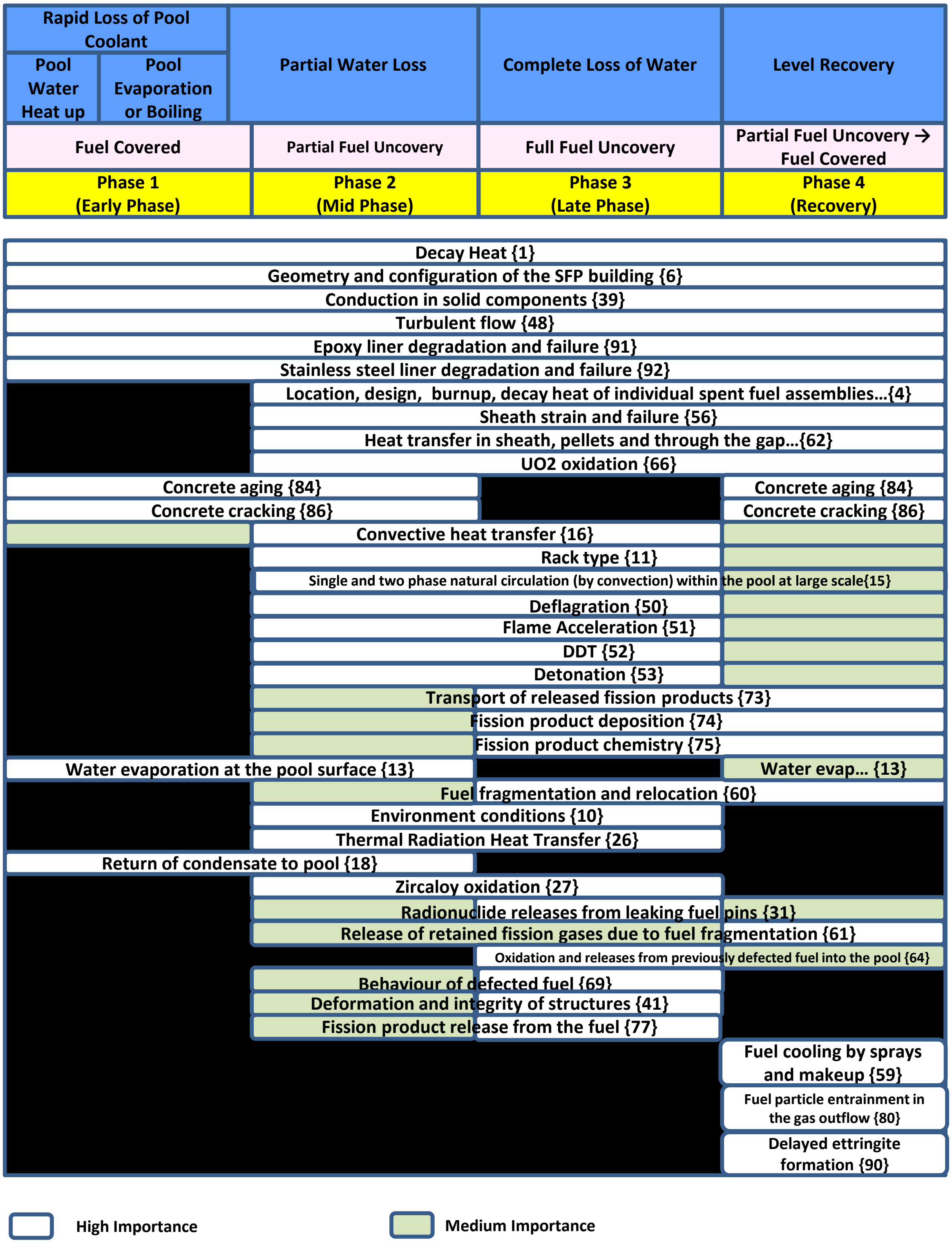


Figure 5 Accident Progression and Phenomena with High Importance

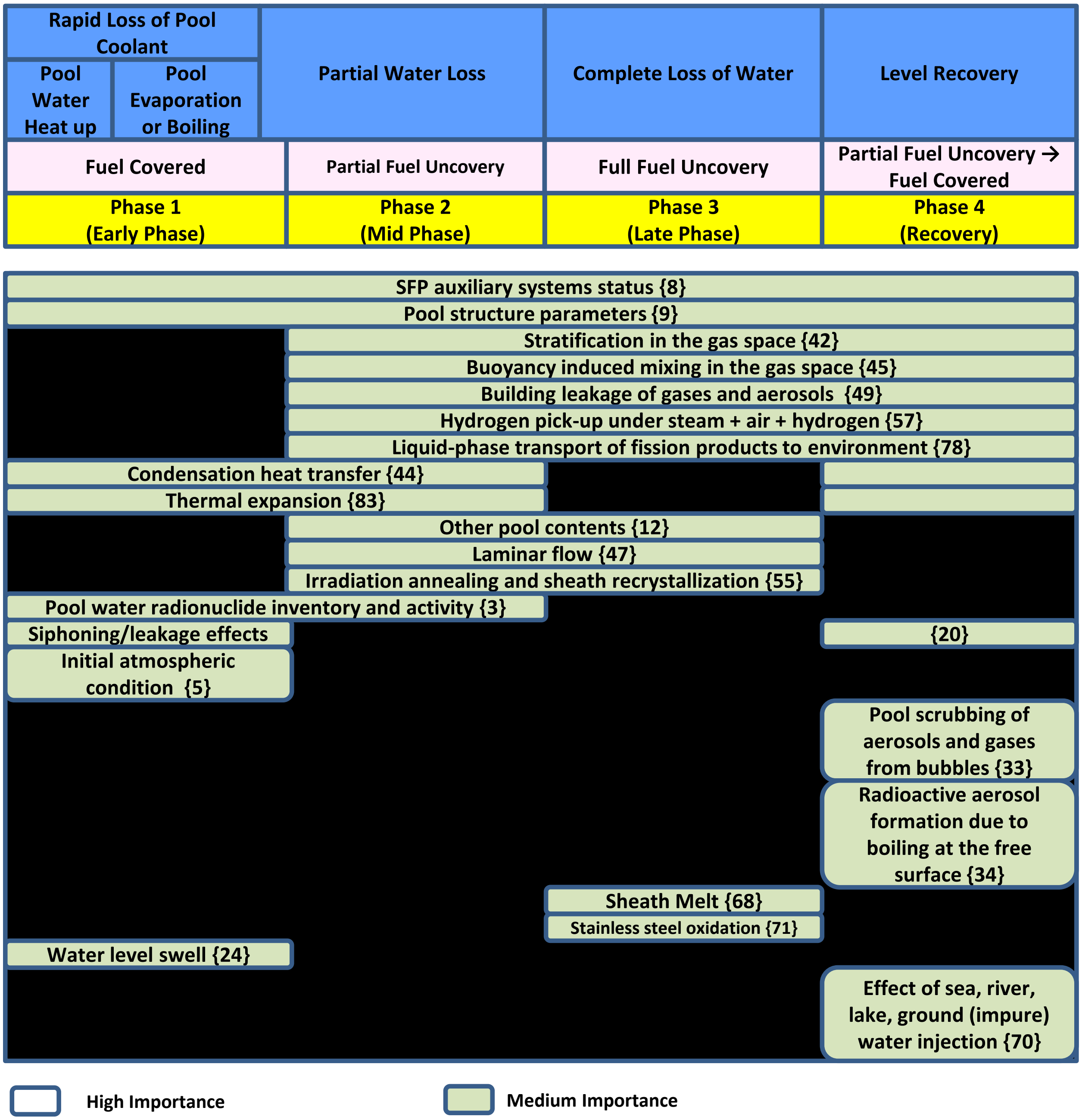
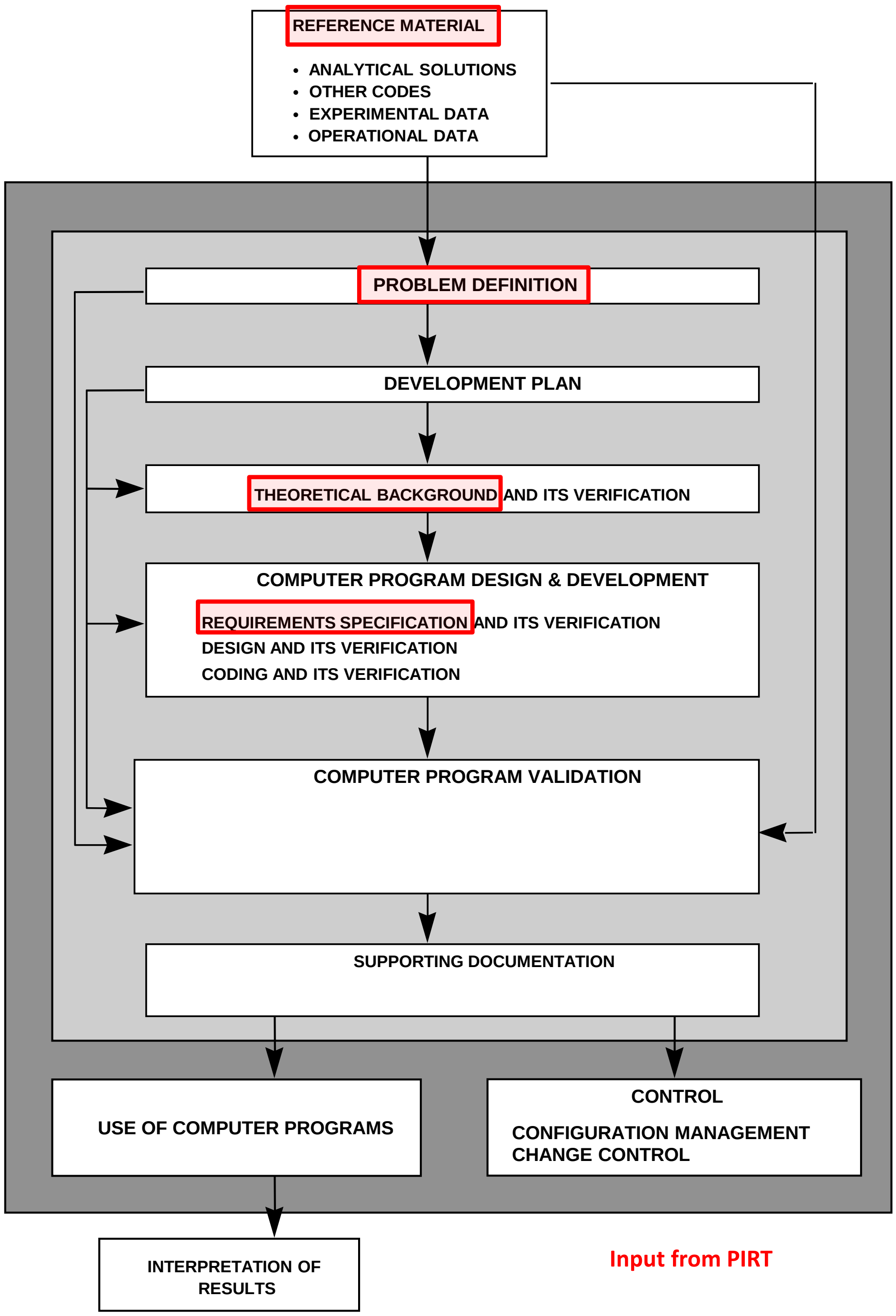


Figure 6 Accident Progression and Phenomena with Medium Importance



NOTE: ITERATIONS AMONG STEPS ARE NOT SHOWN

Figure 7 Computer Program Development and Usage Process

Appendix A

Phenomena Identification and Ranking Summary

A total of 86 phenomena were identified during the identification and ranking exercise. The phenomena, importance rank, and knowledge assessment are summarized in this appendix. The importance was ranked as:

- High (H)
  Phenomenon has a controlling impact on the Figure-Of-Merit. Simulation of experiments and analytic modelling with a reasonable degree of accuracy (major/minor trends reasonably within range of data (includes scaling)) is required.
- Medium (M)
  Phenomenon has a moderate impact on the Figure-Of-Merit. Simulation of experiments and/or analytic modelling with a moderate degree of accuracy (major trends generally within range of data) is required.
- Low (L)
  Phenomenon has a minimal impact on the Figure-Of-Merit. Modelling must be present to preserve functional dependencies.
- Inactive (I)
  Phenomenon has no impact on or is insignificant with respect to the Figure-Of-Merit. Modelling must be present if the functional dependencies are required.

The knowledge level on the phenomena was assessed as:

- 4 Fully known, small uncertainty
- 3 Known, moderate uncertainty
- 2 Partially known, large uncertainty
- 1 Very limited knowledge, uncertainty cannot be characterized
- N/A Not applicable is used if the phenomena importance is inactive (I)

In this appendix, the phenomena are listed in order of importance. The importance was determined with a numerical score, based on summing the importance rank from each stage of the accident (Phases 1 to 4). The numerical values were set as: L=1, M=5, and H=21. As a result, a phenomenon that ranks high in one phase of the accident would be considered more important (have a higher total importance) than a phenomenon that ranks M for all four phases of the accident.

The PIRT panel initially identified 92 phenomena, and each phenomenon was given a unique identification number (ID#). Upon further review, 6 of the phenomena were identified as duplicates and removed from consideration. As a result, the phenomena ID# 35, 37, 38, 40, 54, and 65 are not included in this appendix.

Importance				Knowledge Level						
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Phenomena**	**Description**	**ID**
H	H	H	H	4	4	4	4	Decay Heat	Outside of the reactor, irradiated fuel will continue to generate heat due to the radioactive decay of fission products.	1
H	H	H	H	4	4	4	4	Geometry and configuration of the SFP building (dimensions, open/closed building)	This phenomenon is defined as the influence of the dimensions, construction and operational configuration of the building containing the Spent Fuel Pool (SFP) on releases to the environment in an accident scenario.	6
H	H	H	H	3	3	3	3	Conduction in solid components (fuel, racks/modules, concrete, …)	The transfer of heat in solid components due to conduction. Scope includes transient conduction and contact between components	39
H	H	H	H	3	3	3	3	Turbulent flow (gas space, liquid)	A turbulent flow is a fluid flow that includes rapid variations in the velocity and pressure in time and space, and generally has stochastic components. Turbulence involves eddy formation at many different length scales, with the largest related to geometry and the smallest to viscosity. Turbulent flow is expected for all phases of the accident. Spacer pads (appendages) will induce turbulence. Even natural convective flows in the gas space will be turbulent.	48
H	H	H	H	2	2	2	2	Epoxy liner degradation and failure	Epoxy is used as a liner material in spent fuel bays. This phenomenon includes all mechanisms that could breach the liner.	91
H	H	H	H	2	2	2	2	Stainless steel liner degradation and failure	Stainless steel is used as a liner material in spent fuel bays. This phenomenon includes all mechanisms that could breach the liner.	92
L	H	H	H	4	4	4	3	Location, design, burnup, decay heat of individual spent fuel assemblies and locations and configurations of storage racks/modules	How bundles are arranged (hot, cold). Placement of racks in relation to each other, bay walls and bay floors.	4

Importance				Knowledge Level						
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Phenomena**	**Description**	**ID**
L	H	H	H	3	3	3	3	Sheath strain and failure	At high temperatures and under internal pressure from fill gas and released fission gas, the sheath will strain. The strain rate is affected by irradiation damage, Zircaloy crystallite size and texture, and by oxidation. At strains greater than the limit of plastic stability (~5%), excessive plastic deformation occurs and the sheath can fail (ballooning). Failures can also occur by cracking of oxide, stress corrosion cracking induced by released fission products, beryllium braze assisted crack penetration, fretting, or mechanical or thermal shock of embrittled sheath on quench. The sheath can also fail by through-wall oxidation (see Phenomenon 27), because the oxide has very poor structural integrity.	56
L	H	H	H	3	3	3	3	Heat transfer in sheath, pellets and through the gap, which affects distribution of temperature, strain and stresses	The decay heat generated within the fuel is conducted through the fuel material, through the fuel/sheath interface or fuel/sheath gap, and though the sheath. The sheath can be coated by oxide layers or CRUD, which would reduce the effectiveness of heat transfer through the sheath.	62
L	H	H	H	3	3	3	3	UO_2 oxidation	When UO_2 fuel in a breached fuel element is exposed to a water, steam or air environment especially at elevated temperatures the fuel can oxidize to other phases (in accordance with a Pourbaix diagram for aqueous corrosion or with the uranium-oxygen phase diagram for steam or air oxidation).	66
H	H	I	H	2	2	N/A	2	Concrete aging (including temperature and radiation effects)	The structural integrity of concrete might degrade with time, with elevated temperature and radiation fields accelerating the aging process. This phenomenon includes initial condition of the bay and degradation during the accident	84
H	H	I	H	2	2	N/A	2	Concrete cracking (thermally induced, stress-induced, creep, quench)	Concrete can crack due to thermal gradients, stresses, creep, and thermal shock from quenching.	86

Importance				Knowledge Level						
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Phenomena**	**Description**	**ID**
M	H	H	M	2	2	2	2	Convective heat transfer	Convection heat transfer is the energy transfer between a surface and a fluid moving over the surface. It occurs in both the liquid and vapour/gas phases. In the liquid phase, it occurs between the SFP water and the liner/concrete walls of the SFP structure, and the fuel surface and the SFP water. In the gas space, it occurs between the vapour-gas mixture and surfaces (fuel surface and surfaces inside the SFP).	16
L	H	H	M	4	4	4	4	Rack type (Pickering basket, CANDU 6/Bruce tray, Darlington module)	The fuel bundles are stored in structures while in the spent fuel bay. There are three types of structures: the Pickering basket, the CANDU-6/Bruce tray, and the Darlington Module.	11
L	H	H	M	4	2	2	3	Single and two phase natural circulation (by convection) within the pool at large scale	The decay heat from the spent fuel bundles will induce single phase, or potentially two phase, natural circulation within the spent fuel pool.	15
L	H	H	M	3	3	3	3	Deflagration	Deflagration deals with combustion with flame speeds on the order of several meters per second to several hundred meters per second. The burning rate can be affected by initial conditions (mixture compositions, pressure, and temperature), geometry of the confinement, location of ignition, and turbulence level. For slow flames, the maximum deflagration pressure is bounded by the adiabatic isochoric complete combustion (AICC) pressure.	50
L	H	H	M	2	2	2	2	Flame acceleration	In the presence of obstructions or confinement, a slow flame (several meters per second) can be accelerated and the burning rate can be significantly increased.	51
L	H	H	M	2	2	2	2	Deflagration to detonation transition (DDT)	In the presence of obstructions or confinement, a slow flame (several meters per second) can accelerate to a fast flame (hundred meters per second), and, under certain circumstances, lead to a transition to detonation (a few kilometers per second).	52
L	H	H	M	3	3	3	3	Detonation	A supersonic compression wave, with typical velocities on the order of a few kilometers per second, can be initiated via a strong ignition source or by sequential acceleration of a slow flame.	53

Importance				Knowledge Level						
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Phenomena**	**Description**	**ID**
L	M	H	H	3	3	3	3	Transport of released fission products	Transport of fission products in the bay volume and building will determine the amounts and nature of release of fission products to the environment. Fission products can be transported as gases or vapours (mainly noble gases and iodine, with the possible addition of ruthenium), or as aerosols (most other fission products).	73
L	M	H	H	3	3	3	3	Fission product deposition	Fission products can be deposited on solid or liquid surfaces as aerosols or by condensation or dissolution of vapours.	74
L	M	H	H	3	2	2	2	Fission product chemistry	Iodine in the pool undergoes a wide variety of chemical reactions with water radiolysis products and organic materials (including epoxy liners, paint and adventitious organic chemicals), some of which produce volatile forms of iodine (including molecular iodine and organic iodides). Chemical reactions of ruthenium deposits with air radiolysis products may also produce volatile ruthenium oxides.	75
H	H	I	M	4	4	N/A	4	Water evaporation at the pool surface	Water evaporation at the pool surface acts as a heat sink, transferring the latent heat of evaporation to the escaping water vapour. This process is the main heat removal mechanism to transport decay heat from the water pool before boiling occurs. Also, the loss of water due to evaporation could lead to fuel uncovery.	13
I	M	H	H	N/A	3	3	3	Fuel fragmentation and relocation (during ballooning, before and after sheath rupture)	Due to sheath embrittlement from oxidation and hydriding, fuel-element fragmentation can occur, especially on rewet/quench. Fuel ballooning/element failure may also result from significant sheath strain, which could allow for an ingress of water or air into the element. With subsequent oxidation of the fuel under the breached site, element deterioration can further occur with localized conversion of UO_2 to U_3O_8 that can split and crack the embrittled sheath due to a volume expansion of the underlying fuel.	60
L	H	H	L	4	4	4	4	Environment conditions (e.g., air temperature, humidity, pressure, wind speed, ground temperature)	The environmental conditions outside of the reactor building that have a direct influence on fission product transport from the containment boundary to offsite are defined by this phenomenon.	10
L	H	H	L	3	3	3	3	Thermal Radiation Heat Transfer	Radiative heat transfer from uncovered bundles to other bundles or structures and participating media	26

Importance				Knowledge Level						
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Phenomena**	**Description**	**ID**
H	H	I	L	3	3	N/A	3	Return of condensate to pool	Water that evaporates or boils can condense on surfaces and then rain/drain or be pumped (from the sump) back into the bay.	18
I	H	H	L	N/A	4	2	4	Zircaloy oxidation in air-steam mixtures (including breakaway of pre-existing oxide layer)	Steam and air reaction with the Zircaloy sheath can lead to sheath oxidation with the liberation of chemical heat with a release of either hydrogen (in steam) or nitrogen (in air).	27
L	M	H	M	4	4	4	4	Radionuclide releases from leaking fuel pins into the pool	A number of fuel elements may be defective during operation as subsequently stored in SFP so that fission products could leach into the pool water. During degraded cooling conditions in the pool, intact elements may also fail due to possible localized sheath strain resulting in a gap release, with possible leaching of fission products in aqueous conditions or vapour release at higher temperatures. The underlying fuel in contact with water, steam or air could also oxidize resulting in enhanced fission product release from the fuel matrix if fuel temperatures are sufficiently high.	31
I	M	M	H	N/A	4	4	3	Release of retained fission gases due to fuel fragmentation	Fission gases in fuel at the grain boundaries and in large intragranular bubbles may be released by cracking of the fuel, mainly along grain boundaries. Fuel fragmentation may occur during fuel oxidation in air, rapid heating, or rapid cooling.	61
L	L	H	M	3	3	3	3	Oxidation and releases from previously defected fuel into the pool	Previously defected fuel can oxidize during the temperature transient, causing fuel degradation, and release fission products and fuel particulate into the pool.	64
L	M	H	L	3	3	3	3	Behaviour of defected fuel	Fuel oxidation, fission product release, thermal performance. Defected fuel will behaviour different than an intact fuel. Includes both pre-defected fuel (defected in the reactor) and defects during the accident	69
I	M	H	L	N/A	2	2	2	Deformation and integrity of structures (racks/modules/fuel bundle)	At elevated temperatures, the fuel elements, bundles, and supporting structures such as the racks or modules will deform due to thermal expansion, elastic, plastic, or creep processes. In the case of excessive deformation, the structures may fail.	41

Importance				Knowledge Level						
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Phenomena**	**Description**	**ID**
I	M	H	L	N/A	3	2	3	Fission product release from the fuel	Fission products will be released from the fuel elements after the sheath fails. The fractional release of each fission product element is determined by fuel temperature, extent of oxidation of the fuel and sheath, and fuel degradation (e.g., fracturing of fuel and sheath), among other variables.	77
I	I	I	H	N/A	N/A	N/A	3	Fuel cooling by sprays and makeup	Heat will be transferred to cold water from hot fuel when water is returned to the fuel bays. By definition, if makeup is present then the accident has progressed to stage 4.	59
I	I	I	H	N/A	N/A	N/A	2	Fuel particle entrainment in the gas outflow (during rewet)	Fine fuel particles formed during the transient or during the rewet can be entrained by the high flows of steam that would result from cooling the fuel. Dispersal of fuel particles could lead to very high radiation fields in the vicinity of the fuel pool and possible suspension and transport of fuel particles off site.	80
I	I	I	H	N/A	N/A	N/A	3	Delayed ettringite formation	Ettringite is a needle-like crystal that may form in concrete upon cooling, and can cause cracking.	90
M	M	M	M	4	4	4	4	SFP auxiliary systems status (ventilation, cooling, filters, strainers, pumps, heat exchanges)	The operating status and capacities of SFP auxiliary systems may impact the evolution of an accident scenario.	8
M	M	M	M	4	4	4	4	Pool structure parameters, e.g., concrete composition, reinforcing design, liners, exterior interface (in-ground or above-ground)	The concrete and steel components forming part of the pool structure is defined as pool structure parameters.	9
L	M	M	M	3	3	3	3	Stratification in the gas space	Stratification of gases arising from density differences due to temperature and molar mass differences of gas compositions.	42
L	M	M	M	3	3	3	3	Buoyancy induced mixing in the gas space	Gas/vapour can be mixed by buoyancy induced motion due to pressure gradients created by local gas density differences in a gravitational field. These density differences are due to composition differences and/or temperature differences, induced by local mass and/or heat transport processes (e.g., gas injection, convection and condensation).	45

Importance				Knowledge Level						
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Phenomena**	**Description**	**ID**
L	M	M	M	2	2	2	2	Building leakage of gases and aerosols	The Spent Fuel Pool (SFP) is housed in an industrial building, not a containment building. Leakage will occur as the building atmosphere starts to be pressurized by the addition of steam (and to a lesser extent by hydrogen). The hot gases inside the SFP will tend to leak through the higher elevation openings, with an accompaniment of in-flow of cold air from the outside. This is especially enhanced if the leakage is through a large open doorway. The concern with the leakage is that the gas/vapour mixture will carry fission products (gases or aerosol) out of the spent fuel pool building.	49
L	M	M	M	3	3	3	3	Hydrogen pick-up under steam + air + hydrogen	During Zircaloy oxidation in environments containing steam and/or hydrogen, a fraction of the hydrogen generated during the oxidation is absorbed into the Zircaloy under the oxide layer. Precipitation of this hydrogen as hydrides can lead to embrittlement of the Zircaloy sheath, which may cause sheath failure during later stages of the accident.	57
L	M	M	M	2	2	2	2	Liquid-phase transport of fission products to environment	Fission products dissolved or suspended in water can go through cracks in the bay wall. Both wall layers (the liner and the structural wall) must be cracked to allow significant release to the environment by this path. If the bay wall faces the ground, some of the fission products will be sorbed on the soil particles. If the bay wall faces the air, the dissolved FP will flow down the outside face of the bay and onto the ground or the paved surface near the bay.	78
M	M	I	M	4	4	N/A	4	Condensation heat transfer	The pool water that is boiled or evaporated off is expected to condense on the building heat sinks (walls, ceiling, …).	44
M	M	I	M	3	3	N/A	3	Thermal expansion (mismatch between aggregate and cement paste, rebar and concrete, etc.)	The different materials of the fuel bay and liner have different coefficients of thermal expansion. As the fuel bay structure heats-up, non-uniform expansion between aggregate and cement paste, rebar and concrete, and other components is expected and can contribute to cracking.	83

Importance				Knowledge Level						
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Phenomena**	**Description**	**ID**
L	M	M	L	3	2	2	3	Other pool contents (other than fuel stored in standard locations, like cobalt, scrap module, bundles and elements stored from fuel inspections, shield plugs)	Many years of operations and operational trouble-shooting may result in off-normal storage configurations for some SFP contents. Fuel bundles and elements are known to be sometimes stored in configurations other than the baskets, trays or modules assumed in the SFP design. Also, the SFP has at times become the storage location of choice for a number of items other than irradiated fuel bundles (example: shield plugs, adjusters).	12
L	M	M	L	3	3	3	3	Laminar flow (gas space, liquid)	Laminar flow occurs when a fluid flows in parallel layers without disruption of these layers.	47
L	M	M	L	3	3	3	3	Irradiation annealing and sheath recrystallization	When Zircaloy is irradiated the strength increases and ductility decreases. Both of these property changes anneal out as sheath temperature increases.	55
M	M	I	I	4	4	N/A	N/A	Pool water radionuclide inventory and activity (including dissolved tritium)	The amount of radionuclides, including tritium, in the water of the spent fuel pool water prior to the accident. As the pool water evaporates or boils off, the activity in the pool water will be released and would contribute to the dose of workers and/or the public.	3
M	I	I	M	3	N/A	N/A	3	Siphoning/leakage effects (e.g., leaking flow effect on established natural circulation patterns)	The SFP water level control, circulation, temperature control and purification systems will have water inlet and outlet structures below the normal operating levels of the SFP but above the highest level of fuel storage. Damage to these auxiliary systems, either during the accident scenario or due to an abnormal operational occurrence (some sort of mechanical damage) could lead to siphoning water from the SFP until the locations of these water inlet/outlet pipes have been reached.	20
M	L	L	L	4	4	4	4	Initial atmospheric condition in the SFP building	The initial condition in the spent fuel pool building atmosphere includes, but is not limited to, air flows (forced convection due to ventilation system and natural convection), air space temperature, gas composition in the air space, air pressure, and activity in the air space.	5

Importance				Knowledge Level						
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Phenomena**	**Description**	**ID**
L	L	I	M	3	3	N/A	3	Pool scrubbing of aerosols and gases from bubbles	Aerosols and gases may be removed from bubbles by deposition on the surrounding water surface and dissolution in the surrounding water. Conversely, if the vapour pressure of a gas dissolved in the water is higher than its partial pressure in the bubble, there may be net vaporization of gas from the water to the bubble.	33
L	L	I	M	3	3	N/A	2	Radioactive aerosol formation due to boiling at the free surface	Fission product compounds may be resuspended from the pool as droplets formed by breaking of bubbles or by surface spray induced by rapid gas flows passing over the surface. Particulate material suspended in the water can also be resuspended by this mechanism.	34
I	L	M	L	N/A	3	3	3	Sheath Melt	At high temperatures (1850°C), the sheath will melt.	68
I	L	M	L	N/A	2	2	2	Stainless steel oxidation	The storage racks and modules are made of stainless steel (304L), which can oxidize at high temperatures in steam or air. Oxidation could threaten the integrity of the racks or modules and in the case of steam oxidation, would produce hydrogen.	71
M	L	I	I	4	4	N/A	N/A	Water level swell	Change in water level due to steam generation.	24
I	I	I	M	N/A	N/A	N/A	3	Effect of sea, river, lake, ground (impure) water injection	If water sources are utilized that have either dissolved or entrained materials, over time, these could eventually result in the accumulation of the materials within the SFP.	70
L	L	L	L	4	4	4	4	Thermal Conduction in fluid	Heat transfer by thermal conduction in gases and liquids.	43
L	L	L	L	4	4	4	4	Mass diffusion in vapour space	Mass diffusion is the relative motion of species in a vapour/gas mixture due to the presence of a concentration gradient. Mass diffusion will move a species down the concentration gradient, and tends to reduce the concentration gradient to result in a uniform concentration (well mixed) conditions. The diffusion mass transfer rate depends on the gas component diffusion coefficients for the multi-component mixture.	46
L	L	L	L	3	3	3	3	Hydride dissolution & precipitation	The formation of zirconium hydrides (deuterides for CANDU) is a secondary effect of fuel sheath failures and can lead to exposure of the fuel pellets. Hydrides have also been known to accumulate in the assembly welds, embrittling them when cold and causing some to break if loaded abnormally.	58

Importance				Knowledge Level						
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Phenomena**	**Description**	**ID**
L	L	L	L	2	2	2	2	Fission product (gas phase aerosol) removal in leakage paths	Fission product in the form of aerosols will be carried with the gas flow through leak paths out of the SFP building. Depending on the aerosol characteristics, flow conditions and the geometry of the leak path, aerosols (fission products) may be retained in the leak path.	82
L	L	I	L	4	4	N/A	4	Nucleate boiling on the spent fuel pins	Nucleate boiling is characterized by vapour generation as isolated bubble or jets and columns, and high heat transfer rates.	14
L	L	I	L	4	4	N/A	4	Leakage out of pool (operational leakage)	Leakage through small cracks in the pool/liner. Some amount of leakage is expected during normal operating conditions (operational leakage).	17
L	L	I	L	3	3	N/A	3	Hydrogen production (radiolysis)	Radiolysis of water generates H_2 and oxidizing species including H_2O_2 and O_2^{2-}. This can add to the hydrogen production in the course of an accident. The radiolysis of water will be affected by impurities dissolved or suspended in the bay water.	29
I	L	L	L	N/A	2	2	2	Fission product re-suspension (note this generally relates to dry depositions)	Fission products deposited on surfaces are re-suspended, due to a depressurization event or hydrogen burn.	76
I	L	L	L	N/A	3	3	3	Fuel volatilization	If the UO_2 fuel is exposed to an oxidizing environment, hyperstoichiometric UO_{2+x} or higher oxides will be produced. The vapour pressure of the uranium-bearing species is high, such that the solid phase can be vaporized at a high rate through incongruent vaporization. The loss of uranium will also result in the release of fission products. This phenomenon is also referred to as matrix stripping.	79
I	L	L	L	N/A	4	4	4	Heat generation from released fission products	Fission products released from the fuel will decay and generate heat.	81
L	L	I	L	2	2	N/A	2	Flow in cracks (erosion)	Crack enlargement due to erosion from the flow within the crack.	85
L	L	I	L	2	2	N/A	2	Corrosion of rebar	Processes and phenomenon related to corrosion of the rebar in the concrete structure of the spent fuel bay.	87
L	L	I	L	3	3	N/A	3	Leaching of calcium hydroxide	Calcium hydroxide is a constituent of concrete, and can be leached out.	88
L	L	I	I	4	4	N/A	N/A	Bubble swarm rise within the pool (dynamics, condensation process, etc.) - vapor behavior	Bubble dynamics in liquid water.	21

Importance				Knowledge Level						
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Phenomena**	**Description**	**ID**
I	L	L	I	N/A	1	1	N/A	Flow blockage in bundles due to ballooning and rupture	Due to the development of a differential pressure between the fuel-to-sheath gap and ambient pressure outside of the sheath in the spent fuel pool, the sheath may experience localized ballooning and possible sheath rupture (i.e., with sufficient strain from possible fission gas release during high-temperature conditions experienced during the event).	23
L	L	I	I	4	4	N/A	N/A	Degassing of hydrogen by water temperature increase	Hydrogen gas can dissolve in water, but the gas solubility decreases with increasing water temperature. As the temperature of the fuel bay water increases, dissolved hydrogen will be released.	30
I	L	L	I	N/A	2	2	N/A	Radionuclide releases from eroded CRUD into the pool	Magnetite deposits on fuel sheath are called CRUD and as these deposits form they are likely to capture fission products in the heat transport fluid.	32
L	L	I	I	4	4	N/A	N/A	Tritiated steam (DTO) releases by water evaporation	Leakage of heavy water from the heavy water side of the irradiated fuel handling system to the SFP allows some tritiated heavy water (DTO) into the SFP. Allowing for some chemical recombination, very small quantities of both HTO and DTO will be available for release from the SFP during the loss of water inventory accident.	36
L	I	I	I	3	N/A	N/A	N/A	Initial dissolved hydrogen concentration	Hydrogen gas dissolved in the bay water may come out of solution as the water temperature rises and particularly when the bay water boils. Hydrogen will be generated in the liquid water during the accident	2
L	I	I	I	4	N/A	N/A	N/A	Water chemistry	The chemistry parameters of interest include pH, temperature, dissolved O_2 concentration, concentration of organic chemicals, and, if groundwater ingress or seawater addition has occurred, sodium, magnesium, calcium and chloride concentrations. Fuel behaviour effects of seawater addition are covered under Phenomenon 70.	7
I	I	L	I	N/A	N/A	2	N/A	Radiolysis of water in concrete	The decomposition of water under radiation is called radiolysis. Both interstitial water and water in the pore structure of concrete may participate in the radiolysis process. The two main outcomes resulting from water radiolysis are: (1) buildup of internal overpressure that may lead to cracking of the concrete, and (2) the production of hydrogen gas.	89

Importance				Knowledge Level						
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Phenomena**	**Description**	**ID**
I	I	I	I	N/A	N/A	N/A	N/A	Flow instabilities within the spent fuels at low liquid level (flow reversal, flow excursions, etc.)	The flow instabilities created by liquid flow in the spent fuel bay as the water level decreases due to leakage is the domain of interest to this phenomenon.	19
I	I	I	I	N/A	N/A	N/A	N/A	Impact of cold water injection on the efficiency of natural circulation cooling	The injection of cold water into a hot spent fuel bay will disrupt the natural circulation cooling, especially if the injection location is at the bottom of the spent fuel pool. The cold water injection can cause local flow oscillations or flow reversals in LWR spent fuel assemblies, but is not applicable to CANDU spent fuel pools.	22
I	I	I	I	N/A	N/A	N/A	N/A	Air/steam inflow into the rack (including effect of rack deformation)	In the absence of liquid water, the flow of air and/or steam into the spent fuel racks of a LWR will have a significant effect on the peak clad temperature, and the onset of cladding ignition due to oxidation. The inflow will be highly influenced by the form and friction loss coefficients, which depend on the geometry of the rack.	25
I	I	I	I	N/A	N/A	N/A	N/A	Oxidation of debris	If severe fuel damage occurs, debris could be generated from the sheath (cladding), fuel, and/or rack disintegration. This debris could oxidize, generating additional heat loads.	28
I	I	I	I	N/A	N/A	N/A	N/A	Axial gas flow in rod after cladding rupture	The dynamics of axial gas-flow along the fuel rod, from the plenum to the clad ballooning location, can have a significant effect on the timing of fuel cladding rupture. Flow restriction will delay cladding rupture, due to a decrease in the pressure in the vicinity of the ballooning cladding.	63
I	I	I	I	N/A	N/A	N/A	N/A	Fuel Melt	The fuel (UO_2) turns to the liquid phase (melts) at high temperature.	67
I	I	I	I	N/A	N/A	N/A	N/A	Melting of fuel rack/module material	The fuel racks or modules are made of stainless steel (304L), which melts between 1400 and 1455°C.	72

Appendix B

Phenomena Assessment Worksheets

This appendix contains the detailed Phenomena Assessment Worksheets (total of 86 worksheets). These worksheets document the definition, importance rank, and knowledge assessment for each phenomenon considered for the accident scenario. The importance was ranked as:

- High (H)
  Phenomenon has a controlling impact on the Figure-Of-Merit. Simulation of experiments and analytic modelling with a reasonable degree of accuracy (major/minor trends reasonably within range of data (includes scaling)).
- Medium (M)
  Phenomenon has a moderate impact on the Figure-Of-Merit. Simulation of experiments and/or analytic modelling with a moderate degree of accuracy (major trends generally within range of data) is required.
- Low (L)
  Phenomenon has a minimal impact on the Figure-Of-Merit. Modelling must be present to preserve functional dependencies.
- Inactive (I)
  Phenomenon has no impact on or is insignificant with respect to the Figure-Of-Merit. Modelling must be present if the functional dependencies are required.

The knowledge level on the phenomena was assessed as:

- 4 Fully known, small uncertainty
- 3 Known, moderate uncertainty
- 2 Partially known, large uncertainty
- 1 Very limited knowledge, uncertainty cannot be characterized
- N/A Not applicable is used if the phenomenon importance is inactive (I)

The PIRT panel initially identified 92 phenomena, and each phenomenon was given a unique identification number (ID# in the phenomena assessment worksheets). Upon further review, 6 of the phenomena were identified as duplicates and removed from consideration. As a result, the phenomena assessment worksheets corresponding to ID# 35, 37, 38, 40, 54, and 65 are not included in this appendix.

Note that proprietary references are highlighted in the worksheet, and should be redacted prior to distribution of this memorandum to third parties.

ID #	Phenomenon Synopsis Title
1	Decay Heat

Phenomenon				Definition			
Decay Heat				Outside of the reactor, irradiated fuel will continue to generate heat due to the radioactive decay of fission products.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
H	H	H	H	Decay heat will be the major source of thermal load (heat) for the accident scenario.			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	4	4	Decay heat is a boundary condition, or input to the accident scenario. The decay heat can be calculated with existing codes or methods. For example, the average decay heat for a typical CANDU-6 is given in [1].			

Detailed description and rationale:
The decay heat is the major source of thermal load (heat generation) and will drive the accident progression. The decay heat can be considered at several levels: the total decay heat for the entire spent fuel bay, the decay heat for a single stack/rack of bundles, the decay heat of single fuel bundle, the decay heat of a single fuel element, or even the volumetric heat generation within the fuel material due to decay heat. The decay heat is known as in input to the accident analysis (see [1]).

Reference:
[1] H.Z. Fan, R. Aboud, E. Choy, W. Zhu and H. Liu, "Spent Fuel Response after a Postulated Loss of Spent Fuel Bay Cooling Accident", Proc. 33rd CNS Annual Conference, Saskatoon, SK, Canada, 2012 June 10–13

Champion: Jeffrey Baschuk

ID #	Phenomenon Synopsis Title
2	Initial dissolved hydrogen concentration

Phenomenon				Definition			
Initial dissolved hydrogen concentration				Hydrogen gas dissolved in the bay water may come out of solution as the water temperature rises and particularly when the bay water boils. Hydrogen will be generated in the liquid water during the accident			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	I	I	I		Almost all of the hydrogen would be released during the initial heating and boiling in Phase 1.	The amount of water remaining in the bay is small, so the hydrogen in it can be neglected.	The newly added bay water would not have any initial dissolved hydrogen.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	N/A	N/A	N/A	The initial condition is not measured as part of monitoring of the fuel bay chemistry, but can be estimated by modelling.	Almost all of the hydrogen would be released during the initial heating and boiling in Phase 1.	The amount of water remaining in the bay is small	The newly added bay water would not have any initial dissolved hydrogen.

Detailed description and rationale:

This is an initial condition. Dissolved hydrogen in the bay water can be released during heating and boiling of the bay water (mainly during Phase 1). A rough calculation indicates that the hydrogen concentration is too small to be significant by itself, but it could contribute as much as 2% to the hydrogen concentration in the building above the pool. This has no effect on the fuel sheath temperature figure of merit, but may affect the FP release figure of merit if an explosion occurs.

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
3	Pool water radionuclide inventory and activity (including dissolved tritium)

<table>
<tr><th colspan="4">Phenomenon</th><th colspan="4">Definition</th></tr>
<tr><td colspan="4">Pool water radionuclide inventory and activity (including dissolved tritium)</td><td colspan="4">The amount of radionuclides, including tritium, in the water of the spent fuel pool water prior to the accident. As the pool water evaporates or boils off, the activity in the pool water will be released and would contribute to the dose of workers and/or the public.</td></tr>
<tr><th colspan="4">Importance Rank
(by sub-scenario)</th><th colspan="4">Importance Rank Rationale
(by sub-scenario)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>M</td><td>M</td><td>I</td><td>I</td><td>In the first stage, about 1/3 of the pool water inventory will evaporate or boil off (before the fuel begins to be uncovered).</td><td>After the start of fuel uncovery, approximately 2/3 of the pool water remains to be boiled-off or evaporated until complete uncovery of the fuel.</td><td>The pool water is assumed to be gone during this stage of the accident</td><td>The recovery water is assumed to be free of radionuclides and dissolved tritium.</td></tr>
<tr><th colspan="4">Knowledge Assessment
(by sub-scenario)</th><th colspan="4">Knowledge Assessment Rationale
(by sub-scenario)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>4</td><td>4</td><td>N/A</td><td>N/A</td><td colspan="2">The pool water radionuclide inventory and activity (including dissolved tritium) is known as it is measured during station operation.</td><td colspan="2">Not applicable.</td></tr>
</table>

Detailed description and rationale:

The water in the spent fuel pool will have an initial inventory of radionuclides, including dissolved tritium, prior to the start of the accident. As the pool water is vaporized, due to boiling or evaporation, the radionuclides can be released to the atmosphere and would contribute to the dose to workers and/or the public. The radionuclide inventory and activity would be an initial condition and input to the accident analysis, and is known from measurements.

Champion: Jeffrey Baschuk

ID #	Phenomenon Synopsis Title
4	Location, design, burnup, decay heat of individual spent fuel assemblies and locations and configurations of storage racks/modules

Phenomenon				Definition			
Location, design (e.g., long bundles), decay heats and burnup of individual spent fuel assemblies				How bundles are arranged (hot, cold). Placement of racks in relation to each other, bay walls and bay floors.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	H	H	H	Location will not affect the sheath temperature until fuel becomes uncovered. Sheath temperature expected to be near constant or track the bay water temperature until fuel is uncovered	High power (decay heat) bundle locations will affect the sheath temperature and subsequent FP release (location relative to heat sinks). Configurations and locations of storage systems will the availability of cooling in degraded conditions.	As for stage 2 but now with all water coolant lost, and only convective air (and some steam) cooling operative, the locations of high decay heat bundles remains important or may increase in importance. Also of continued importance will be the configuration of bundle storage and the clearances between modules and storage racks, and the walls and floor of the bay.	As water is returned to the bay, decay heats and storage geometries will remain of high importance. High decay heat (hot) fuel bundles which were dry during Phases 2 and 3, are at risk to have failed fuel sheaths, and will potentially release fission products, activation products and fuel material when cold water is added to the bay during recovery.

Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	4	3	Everything is well known. Fuel sheaths are not expected to fail during Phase 1.	Fuel sheath behaviour in conditions of degraded cooling, steam and dryout in air has been extensively studied and is well known. Oxidation models for exposed fuel pellets are also well developed.		Although behaviour of damaged fuel during quenching has been studied, the impact of large scale quenching of damaged fuel elements while resident in storage racks and modules is not as well understood. The importance of geometries and positioning of storage racks may need to be assessed.

Detailed description and rationale:

Fuel bundle geometry, element design and particularly decay heat are all of importance in assessing the figure of merit (sheath temperature) in the assessment of a bay loss of coolant accident scenario. Also of importance will be the devices used for fuel bundle storage (trays, baskets or modules) and the design and positioning of the storage racks for these storage devices. The clearances between these storage racks and the bay sides and floor may become important during later stages of the accident when water levels are low or when all water has been lost.

The impact of full core discharges at the beginning of refurbishment outages will require assessment. In such a scenario, the bay content will not reflect the usual steady state fuelling of the reactors and discharge of well burnt fuel. A full core discharge has the potential to distort the normal distributions of decay heat and burnups in the irradiated fuel bay. After such a full core discharge the bay will contain a larger number of lower burnup fuel bundles with possibly higher decay heats and off-normal fission product and activation product inventories. Also note that recently discharged fuel bundles (higher decay heats) are often in upper (most accessible) storage locations, and may dry-out first.

Champion: Jon Judah

ID #	Phenomenon Synopsis Title
5	Initial atmospheric condition in the SFP building

<table>
<tr><th colspan="4">Phenomenon</th><th colspan="4">Definition</th></tr>
<tr><td colspan="4">Initial atmospheric condition in the SFP building</td><td colspan="4">The initial condition in the spent fuel pool building atmosphere includes, but is not limited to, air flows (forced convection due to ventilation system and natural convection), air space temperature, gas composition in the air space, air pressure, and activity in the air space.</td></tr>
<tr><th colspan="4">Importance Rank
(by sub-scenario)</th><th colspan="4">Importance Rank Rationale
(by sub-scenario)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>M</td><td>L</td><td>L</td><td>L</td><td>The pool evaporation rate is dependent on the temperature and humidity above the pool. Active ventilation system can help reduce the humidity and cool the gas above the pool to increase evaporation. Initial activity in the air space will also contribute to fission-product release as the building is pressurized by steaming and heat up.</td><td>By the time the fuel has been uncovered (1/3 of the water has evaporated), the gas space has essentially be replaced with whatever has been generated during the accident. The only initial condition that may have an effect is a continually operating ventilation system.</td><td colspan="2">Late in the accident, the gas space has essentially be replaced with whatever has been generated during the accident. The only initial condition that may have an effect is a continually operating ventilation system.</td></tr>
<tr><th colspan="4">Knowledge Assessment
(by sub-scenario)</th><th colspan="4">Knowledge Assessment Rationale
(by sub-scenario)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>4</td><td>4</td><td>4</td><td>4</td><td colspan="4">Initial condition is well known.</td></tr>
</table>

Detailed description and rationale:

The initial condition, required for accident analysis, of the spent fuel pool building atmosphere includes, but not limited to air flows (forced convection due to ventilation system and natural convection), air space temperature, gas composition in the air space, air pressure, and activity in the air space. The initial condition mainly affects the initial accident progression in the first phase. By the time Phase 1 has ended, the gas space of the SFP building has essentially been replaced by steam (and the degassed hydrogen that was initially in the pool water). The only initial condition that will affect Phases 2 to 4 is the operation of the ventilation system. Also, the amount of hydrogen that enters the gas phase in Phase 1 due to degassing of the initial hydrogen in the water pool becomes insignificant as compared to the hydrogen that can be produced in Phases 2 and 3. Likewise, the initial activity becomes minor as compared to what can be produced in Phases 2 to 4.

Champion: Sammy Chin

ID #	Phenomenon Synopsis Title
6	Geometry and configuration of the SFP building (dimensions, open/closed building)

Phenomenon				Definition			
Geometry and configuration of the SFP building (dimensions, open/closed building)				This phenomenon is defined as the influence of the dimensions, construction and operational configuration of the building containing the Spent Fuel Pool (SFP) on releases to the environment in an accident scenario.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
H	H	H	H	The walls and roof of the SFP building constitute a barrier to releases to the environment. The "openness" of the building can impact releases to the environment in all phases of the accident scenario.			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	4	4	The geometry, configuration and construction parameters are well known (drawings, measurements). Operating procedures would require review.			

Detailed description and rationale:
The configuration will affect the air flow, environment and ultimately the releases. Also important are the operating procedures related to the SFP building. The SFP buildings are at times opened either to adjacent buildings or sometimes directly to the environment to allow receipt and shipment of long term fuel storage dry casks. Other shipments also occur from the fuel bays such as the shipment of irradiated fuel for post-irradiation examinations, shipment of flasks containing Cobalt and routine equipment transfers. Although these activities are a part of normal operations, the extent to which operating procedures enforce the "normally shut" condition for all bay doors would need to be also assessed.
Champion: Jon Judah

ID #	Phenomenon Synopsis Title
7	Water chemistry

Phenomenon				Definition			
Water chemistry (e.g., pH, temperature)				The chemistry parameters of interest include pH, temperature, dissolved O_2 concentration, concentration of organic chemicals, and, if groundwater ingress or seawater addition has occurred, sodium, magnesium, calcium and chloride concentrations. Fuel behaviour effects of seawater addition are covered under Phenomenon 70.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	I	I	I	May affect dissolution of deposits on the fuel. Can also affect the clad oxidation during boildown, and conceivably liner integrity.	Effect is only significant as an initial condition.		
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	N/A	N/A	N/A	The initial condition is measured as part of monitoring of the fuel bay chemistry.	N/A		

Detailed description and rationale:
This is an initial condition. The main conditions that are monitored are temperature, conductivity and turbidity, with secondary monitoring of radionuclide concentrations and total anion concentration. Bicarbonate from atmospheric carbon dioxide is expected to be the dominant anion. Addition of seawater or ground water would be noticeable through the conductivity and total anion measurements. Degradation of the liner would lead to the dissolution of cement components, increasing the conductivity and the calcium, carbonate and hydroxide concentrations.
Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
8	SFP auxiliary systems status (ventilation, cooling, filters, strainers, pumps, heat exchanges)

Phenomenon	Definition
SFP auxiliary systems status (ventilation, cooling, filters, strainers, pumps, heat exchanges)	The operating status and capacities of SFP auxiliary systems may impact the evolution of an accident scenario.

Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
M	M	M	M	Auxiliary systems could have a significant impact. If they work, they may mitigate the consequences of the accident. However, the auxiliary systems would not have the capabilities to stop all potential accident progressions (such as a rupture in an exposed SFP wall).			

Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	4	4	The design descriptions and operating capabilities of the auxiliary systems will be available in station records. Maintenance histories and system health records will be available at all operating stations.			

Detailed description and rationale:

This is an initial condition. Depending on the scenario, the design, capacities and operating condition of the auxiliary systems may be of consequence to the evolution of the accident. The design of the auxiliary systems would be of importance as would be the maintenance histories and system health records. However, the importance is Medium, rather than High, because auxiliary systems for the SFPs would not normally have the capability to stop all types of accidents. Process capacities would be inadequate to stop many scenarios and there would be no design capability at all to stop the most severe scenarios such as a rupture in the SFP wall.

Champion: Jon Judah

ID #	Phenomenon Synopsis Title
9	Pool structure parameters, e.g., concrete composition, reinforcing design, liners, exterior interface (in-ground or above-ground)

Phenomenon				**Definition**			
Pool structure parameters, e.g., concrete composition, reinforcing design, liners, exterior interface (in-ground or above-ground)				The concrete and steel components forming part of the pool structure is defined as pool structure parameters.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
M	M	M	M	Need to know configuration in order to model the accident (calculate sheath temperature)			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	4	4	The design of the bay is well known (design drawings, measurements, …).			

Detailed description and rationale:

This is an initial condition.

The spent fuel storage pool is a reinforced concrete structure usually built above ground or at least at ground elevation. The details of the spent fuel pools for the OPG and BP reactors are given in Table 1. There can be two types of spent fuel storage facilities available on site to the unit: a spent fuel pool and an interim spent fuel storage facility. The spent fuel pool is usually located in the containment or in the reactor building next to the reactor to facilitate the transport of fuel from the reactor to the pool by a refuelling machine. The spent fuel pool is partially filled with water and the bundles are left in the water for several years to allow the fuel activity (decay heat) to decrease. After that, it may be transported to an on-site interim storage facility, where it can be stored for several decades before it is placed in a permanent repository.

The concrete and the reinforcement designs are required to conform to CSA standards [1]. The concrete composition is specified in CSA standards describing the temperature and environmental conditions the concrete is expected to sustain. The reinforced concrete structure of the pool, including the covering building, have been seismically qualified. Most pools are stainless steel lined [2], some are coated with epoxy resin based paint. However, there has been experience with degradation of the latter after a number of years. The pools are filled with deionized water with or without additive addition depending on the type of fuel to be stored and the adopted method of treatment. The water is either a fixed quantity or a once through pond purge. Water activity levels are maintained ALARA (as low as reasonably achievable) by either in-pool or external ion exchange systems or by limiting activity release to the bulk pool water. Leakage from the pool is monitored, either by means of an integrated leakage collection system or via the interspace in pools with two walls. In both cases any recovered pool water may be cleaned up and returned to the main pool. Maintenance of good water chemistry provides good water clarity and usually prevents the growth of micro-biological organisms.

The pool structure parameters are moderately important phenomena for spent fuel bay accidents and therefore the importance ranking of Medium is justified.

The knowledge level of pool structure parameters is very good because of the experience gathered over 50+ years of spent fuel pool construction. Therefore the rank of "4" indicating fully known with small uncertainty is justified.

References:

[1] CSA (2014), National Standard of Canada, Design of Concrete Structures, A23.3-14 Canadian Standards Association, Toronto, ON, Canada

[2] C.R. Frost and S.J. Naqvi, "Design Considerations for Water Pool Storage of Irradiated Fuel by Ontario Hydro", International Conference on CANDU Fuel, Canadian Nuclear Society, Chalk River laboratories, Chalk River, ON, Canada, 1986 October 6-8

[3] Survey of Wet and Dry Spent Fuel Storage, IAEA-TECDOC-1100, 1999 July

Champion: Nithy Nitheanandan

IRRADIATED FUEL BAYS AT ONTARIO HYDRO'S NUCLEAR GENERATING STATIONS

Station	Type	Dimensions** (m)	Capacity 000's of Bundles	In-Service Date	Bay Fill* Date	Liner Material
NPD	PIFB	4.3Wx7.3Lx5.5D	2	1962	***	All stainless steel (S/S)
Douglas Point****	PIFB(a) PIFB(b)	3.4Wx7.3Lx7.2D 7.6Wx20.9Lx7.2D	50	1966	****	All stainless steel (S/S)
Pickering A	PIFB***** AIFB	16.3Wx29.3Lx8.1D 17Wx34Lx8.1D	93 214	1972 1978	1995 1995	All epoxy All epoxy
Pickering B	PIFB	16.3Wx29.3Lx8.1D	158	1983	1995	Receiving bay - all S/S Storage bay, all epoxy
Bruce A	PIFB AIFB	10Wx41Lx6D 18Wx46Lx9D	21 352	1977 1979	1994 1994	S/S floor, epoxy walls S/S floor, epoxy walls
Bruce B	PIFB AIFB	10Wx46Lx6D 18Wx46Lx9D	36 330	1983 1987	2002 2002	All S/S All S/S
Darlington******	PIFB	(a) 9.65Wx20.6Lx5D (b) 17Wx32Lx9.2D (c) 17Wx4Lx9.2D	212	1987	1996	All S/S

* Based on combined capacity of all bays on-site.

** W = width, L = length, D = depth

*** Irradiated fuel is transported to AECL/CRNL for storage after six months cooling at NPD

**** PIFB consists of an IF receiving bay (a) and an IF storage bay (b). As unit was shut down in 1984, the PIFB will never fill.

***** Based on storage using baskets. Transfer of bundles to higher density module storage would increase the capacity and extend the bay fill date to the year 2000.

****** Darlington will have two identical PIFB's, the second (east) one will be in-service in 1991, with the fill date about 2007. Each PIFB consists of an IF receiving bay(a), an IF storage bay (b) and an IF cask handling bay (c).

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Table 1

ID #	Phenomenon Synopsis Title
10	Environment conditions (e.g., air temperature, humidity, pressure, wind speed, ground temperature)

Phenomenon				**Definition**			
Environment conditions (e.g., air temperature, humidity, pressure, wind speed, ground temperature)				The environmental conditions outside of the reactor building that have a direct influence on fission product transport from the containment boundary to offsite are defined by this phenomenon.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	H	H	L	Release to environment is small during evaporation.	Important for dose	Important for dose	If appropriate guidelines are followed, then there should be minimal release during the rewet.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	4	4	See description below	See description below	See description below	See description below

Detailed description and rationale:

This is an initial condition/boundary condition.

Basic meteorological variables such as: 1. Wind speed and direction; 2. Air temperature; 3. Precipitation; 4. Humidity; 5. Atmospheric pressure; and 6. Temperature inversions are monitored at the stations or from Environment Canada stations nearby. A program for meteorological measurements is typically prepared and carried out at or near the site with the use of instrumentation capable of measuring and recording the main meteorological variables at appropriate elevations, locations, and durations [1]. This program initially provides data for site evaluation, and then provides ongoing data for use in revisions to basis documents in response to safety analysis results during future phases of the Nuclear Power Plant life cycle.

The environment conditions (e.g., air temperature, humidity, pressure, wind speed, ground temperature) are an important phenomenon for radionuclide transport from the containment boundary to offsite locations. Since this phenomenon is the primary medium for dose, the rank of "High" is justified. The knowledge level on the measurement of environmental conditions is generally well developed and therefore the ranking of "1" to indicate fully known with small uncertainty is justified.

Reference:

[1] RD-346: Site Evaluation for New Nuclear Power Plants, Canadian Nuclear Safety Commission

Champion: Nithy Nitheanandan

ID #	Phenomenon Synopsis Title
11	Rack type (Pickering basket, CANDU 6/Bruce tray, Darlington module)

Phenomenon				**Definition**			
Rack type (Pickering basket, CANDU 6/Bruce tray, Darlington module)				The fuel bundles are stored in structures while in the spent fuel bay. There are three types of structures: the Pickering basket, the CANDU-6/Bruce tray, and the Darlington Module.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	H	H	M	While in the bay water, good heat transfer is expected for any rack/module.	Rack type will have a significant effect on the sheath temperature (natural convection will be less for module type)	Rack type will have a significant effect on the sheath temperature (natural convection will be less for module type)	Type of rack may affect rewet behaviour
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	4	4	The geometry of the racks/modules are known from drawings and/or measurements.			

Detailed description and rationale:
This is an input. There are significant differences in the three rack designs and these differences would influence the manner in which the spent fuel bundles could be cooled in the accident situations of interest. These differences are known (hence, the value of 4 for the knowledge assessment) and are input to the computer code and the phenomenological models in the code need to represent the influence of these differences.
Champion: Bob Henry

ID #	Phenomenon Synopsis Title
12	Other pool contents (other than fuel stored in standard locations, like cobalt, scrap module, bundles and elements stored from fuel inspections, shield plugs)

Phenomenon				Definition			
Other pool contents (other than fuel stored in standard locations, like cobalt, scrap module, …)				Many years of operations and operational trouble-shooting may result in off-normal storage configurations for some SFP contents. Fuel bundles and elements are known to be sometimes stored in configurations other than the baskets, trays or modules assumed in the SFP design. Also, the SFP has at times become the storage location of choice for a number of items other than irradiated fuel bundles (example: shield plugs, adjusters).			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	M	M	L	Minor	Non-standard storage is often at the higher elevations in the SFP (to allow easier access), so these might be among the first to be uncovered as SFP water level decreases. Irradiated fuel stored in non-standard ways could be less exposed to convective flows and may heat up faster.	The cobalt may be significant when the bay has no water. It could produce gamma damage to the concrete. It will also cause a dose to people, concrete, liner. Could also loose integrity. Fuel bundles stored in non-standard ways may be among the first to overheat and defect.	Refilling the SFP will restore cooling, however hot defected bundles may be expected to release a plume when cold water first contacts the exposed fuel.

Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	2	2	3	In liquid water, the alternate storage containers are well-cooled; uncertainty on the film coefficients would have a minor effect on the temperature of the contents.	In air/steam environments, cooling conditions are not well known for the alternate storage containers.	Cooling conditions are not well known for the alternate storage containers.	After refill, the cooling of the alternate storage containers would be as for Phase 1.

Detailed description and rationale:
This is an input.
Significant entities in the bay will be known (cobalt, scrap bins). Anything not well tracked will be too small to affect the analysis.
Storage configuration and cooling conditions are not well known for the unusual storage containers such as scrap modules and site-specific storage methods for broken bundles & loose elements which result from fuel inspection programs. This is really a configuration management issue. The normal (per-design) storage configuration should be restored as soon as possible. The importance is Medium for Phases 2 and 3 because, although the non-standard-stored fuel bundles or elements may heat up and fail, the number of non-standard items is small compared to the spent fuel bundles in the racks/modules. Also, the location of the non-standard will be known, but the coolability will have uncertainty when exposed to water vapour or air; hence, the knowledge level is 3 for Phases 2 and 3.
Champion: Jon Judah

ID #	Phenomenon Synopsis Title
13	Water evaporation at the pool surface

Phenomenon				Definition			
Water evaporation at the pool surface				Water evaporation at the pool surface acts as a heat sink, transferring the latent heat of evaporation to the escaping water vapour. This process is the main heat removal mechanism to transport decay heat from the water pool before boiling occurs. Also, the loss of water due to evaporation could lead to fuel uncovery.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
H	H	I	M	Before boiling, evaporation is the main mechanism to lose cooling water.	Before boiling, evaporation is the main mechanism to lose cooling water.	No water is left in the SFP.	Less significant because cooling water is recovered in the SFP.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	N/A	4	Phenomenon is well known and experimental data, at reactor conditions, are available from the TOSQAN sump tests [1].	Phenomenon is well known and experimental data, at reactor conditions, are available from the TOSQAN sump tests [1].		Phenomenon is well known and experimental data, at reactor conditions, are available from the TOSQAN sump tests [1].

Detailed description and rationale:

Water evaporation at the pool surface is limited to liquid evaporation only at the free surface of a pool that is, without vapor bubble formation in and release from the liquid pool. The free surface of a liquid pool is under a total pressure of the partial pressures of the noncondensable gases and water vapor in the atmosphere. The driving force is the density difference of water vapor between the gas mixture just above the water surface and the ambient surroundings. Evaporation increases the steam concentration at the pool surface, which must be moved away by diffusion or convection to permit further evaporation.

The conditions, under which water evaporation occurs, may be categorized according to the flow regime of the system (laminar/turbulent conditions in free or forced convection), and correlations that describe evaporation based on either empirical or heat and mass transfer analogy. The latter are more general and not restricted by experimental conditions.

This phenomenon is well known and experimental data, at reactor conditions, are available from the TOSQAN sump tests [1].

Reference:

[1] “Containment Code Validation Matrix”, NEA/CSNI/R(2014)3, 2014 May

Champion: Sammy Chin

ID #	Phenomenon Synopsis Title
14	Nucleate boiling on the spent fuel pins

Phenomenon				Definition			
Nucleate boiling on the spent fuel pins				Nucleate boiling is characterized by vapour generation as isolated bubble or jets and columns, and high heat transfer rates.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	I	L	With nucleate boiling, the sheath temperature would be basically fixed; independent of correlation used.	With nucleate boiling, the sheath temperature would be basically fixed; independent of correlation used.	No water	With nucleate boiling, the sheath temperature would be basically fixed; independent of correlation used.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	N/A	4	Nucleate boiling	Nucleate boiling	Dry fuel bundles	Nucleate boiling

Detailed description and rationale:

When submerged in water, the decay heat will be removed by natural convection and nucleate boiling. As a result, the sheath temperature would be limited by the temperature needed to support nucleate boiling, and the nucleate boiling heat flux varies approximately as the cube of the temperature difference between the sheath and the water. Since the surface heat flux (order of 10^3 to 10^4 W/m^2) would be well below the maximum (critical) pool boiling heat flux (order of 10^6 W/m^2), the fuel element energy generated would be removed and the sheath temperature would be only slightly greater than the saturation temperature.

Reference:

[1] F. Kreith and M.S. Bohn, 2001, Principles of Heat Transfer, Brooks/Cole, Thomson Learning, Australia

Champion: Bob Henry

ID #	Phenomenon Synopsis Title
15	Single and two phase natural circulation (by convection) within the pool at large scale

Phenomenon	Definition
Single and two phase natural circulation (by convection) within the pool at large scale	The decay heat from the spent fuel bundles will induce single phase, or potentially two phase, natural circulation within the spent fuel pool.

Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	H	H	M	When the fuel is fully covered by water, temperature differences in the bay will be small.	Natural circulation would determine the maximum temperature of the fuel elements	Natural circulation would determine the maximum temperature of the fuel elements	Recovery rate would determine the controlling heat transfer process

Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	2	2	3	Nucleate boiling	Knowledge level depends on the rack/module type. For PLNGS and Bruce storage trays, the knowledge level would be 3. For the Darlington and Pickering modules, the knowledge level would be less, 2.		Likely nucleate boiling

Detailed description and rationale: Temperature differences within the gaseous/steam region would cause density differences than would start global convection. When the fuel is partially or fully uncovered, the natural circulation will be the dominant heat transfer mechanism; hence the importance is high in Phases 2 and 3. The nature of the convection cells (flow velocities and directions), as well as how decay heat is extracted from the fuel elements would be influenced by the differences in the rack designs. For the open rack designs (CANDU-6 and Bruce), the knowledge level is higher, 3, than for the closed module designs (Darlington and Pickering), 2. The open rack designs have some modelling of convection; hence, the higher knowledge level [1].

Reference:

[1] C.J. Krasnaj and W. Grant, "Development of a 2-D Finite Element Model to Examine Both Natural Convection and Radiative Cooling of a Spent Fuel Bundle in Air", Proc. 19th PBNC Conference, Vancouver, BC, Canada, 2014 August 24-28

Champion: Bob Henry

ID #	Phenomenon Synopsis Title
16	Convective Heat Transfer

Phenomenon	Definition
Convective Heat Transfer	Convection heat transfer is the energy transfer between a surface and a fluid moving over the surface. It occurs in both the liquid and vapour/gas phases. In the liquid phase, it occurs between the SFP water and the liner/concrete walls of the SFP structure, and the fuel surface and the SFP water. In the gas space, it occurs between the vapour-gas mixture and surfaces (fuel surface and surfaces inside the SFP).

Importance Rank (by sub-scenario)				**Importance Rank Rationale (by sub-scenario)**			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
M	H	H	M	Convective heat transfer between the fuel and the SFP water will be the main mode of heat transfer until nucleate boiling occurs. If it is under-predicted, fuel will be heated up faster. The convective heat transfer to the SFP walls are expected to be low because of the low thermal conductivity of the thick concrete walls and also the possibility of high thermal conductivity gap resistance between the liner material and the concrete. Also, the SFP water temperature will be maximized at 100°C (boiling temperature of water at 1 bar), which limits the driving potential for convective heat transfer.	In this phase of the accident, convective heat transfer occurs between the fuel and both the liquid and vapour/gas phases, but the importance of liquid phase, is high until nucleate boiling starts. The uncovered fuel will mainly loose its heat by convective heat transfer to the steam-air mixture. Thus, this phenomenon has a high importance to the figure of merit. The convective heat transfer to the SFP walls are expected to be low because of the low thermal conductivity of the thick concrete walls and also the possibility of high thermal conductivity gap resistance between the liner material and the concrete. Also, the SFP water temperature is maximized at 100°C (boiling temperature of water at 1 bar), which limits the driving potential for convective heat transfer.	The fuel is uncovered in this phase of the accident. Heat transfer from the inner pins of the fuel (where thermal radiation with the cold surroundings is not possible), so convection is the major method to cool the fuel, thus its importance to the figure of merit is high. No significant amount of water in the pool (there may be some water remaining below the bottom of the fuel, less than 12 inches).	For the covered fuel, convective heat transfer with the water becomes important when the fuel is sufficient cooled and boiling ceases. Thus, the importance is moderate. The convective heat transfer to the SFP walls are expected to be low because of the low thermal conductivity of the thick concrete walls and also the possibility of high thermal conductivity gap resistance between the liner material and the concrete. During this phase, cold water is expected to be added to the pool. The hot walls would then slowly transfer heat back to the water pool, until the water temperature exceeds the liner surface temperature.

Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
2	2	2	2	The most important convective heat transfer is between the fuel and the surrounding fluid. The main uncertainty is in regards to the natural convective heat transfer coefficients for the fuel as stored in the racks.			

Detailed description and rationale:

Convection heat transfer is the energy transfer between a surface and a fluid moving over the surface. The fluid motion can be due to "free" or "natural" convection whereby the fluid motion results from density differences within the fluid arising from the temperature differences or fluid components (i.e., lighter gases). The fluid motion can also be forced convection, whereby the flow is driven by an external force. Diffusion can also result in fluid motion, but is dominated by natural or forced convection flows. Convective heat transfer occurs in both the liquid and vapour/gas phases. In the liquid phase, convective heat transfer occurs between the SFP water and walls of the SFP. The wall of the SFP consists of a thick concrete wall, lined with an epoxy film or a stainless steel layer. The convective heat transfer to the SFP wall is limited by thermal conduction through the concrete wall which has a low thermal conductivity and also the potentially high thermal conductivity gap resistance between the concrete and the liner material. When the fuel is covered, convective heat transfer occurs between the fuel and the pin, but if the fuel heats up sufficiently, nucleate boiling will become the main mode of heat transfer between the fuel and the water. As the fuel becomes uncovered, convective heat transfer with the air-steam mixture becomes the dominant mode of heat loss for the fuel, as thermal radiation is only effective for the outer fuel pins which sees the cold surroundings (inner fuel pins only radiate to its neighboring fuel pins). Convective heat transfer will also occur between the gas/vapour mixture and surfaces.

Convective heat transfer coefficients for fuel bundles are available for axial forced flow conditions. Free convection heat transfer coefficients for a fuel bundle (in air or water) may not be available from experimental data, especially for the various rack configurations used to hold the fuel bundle. Instead, they will have to be estimated based on existing theoretical or correlations for free convection from horizontally oriented tube and tube bundle arrangements, or experiments on the rack/module geometry. Heat transfer coefficients should be readily available for a stainless steel surface in a water pool. However, heat transfer coefficients for an epoxy surface may not be available. Other unknowns include fluid conditions, such as local temperature distribution and local velocities.

Reference:

[1] "Containment Code Validation Matrix", NEA/CSNI/R(2014)3, 2014 May

Champion: Sammy Chin

ID #	Phenomenon Synopsis Title
17	Leakage out of pool (operational leakage)

<table>
<tr><th colspan="4">Phenomenon</th><th colspan="4">Definition</th></tr>
<tr><td colspan="4">Leakage out of pool</td><td colspan="4">Leakage through small cracks in the pool/liner. Some amount of leakage is expected during normal operating conductions (operational leakage).</td></tr>
<tr><th colspan="4">Importance Rank
(by sub-scenario)</th><th colspan="4">Importance Rank Rationale
(by sub-scenario)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>L</td><td>L</td><td>I</td><td>L</td><td>There will be some leakage (operational leakage). The amount of leakage is low.</td><td>As for Phase 1.</td><td>N/A</td><td>As for Phase 1.</td></tr>
<tr><th colspan="4">Knowledge Assessment
(by sub-scenario)</th><th colspan="4">Knowledge Assessment Rationale
(by sub-scenario)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>4</td><td>4</td><td>N/A</td><td>4</td><td>Operational data on leakage rates will be known. Remedial actions will have been taken to locate and repair leaks if operational limits are approached. Amount, location and cause of any limiting leaks will have been investigated.</td><td>As for Phase 1.</td><td>N/A</td><td>As for Phase 1.</td></tr>
</table>

Detailed description and rationale:

This phenomenon is focused on “normal” leakage which can occur during operation of structures the size and capacity of SFPs. The operating stations would normally have good knowledge of the amount of such leakage and also possibly of the source of the leaks. This leakage will have been quantified and assessed with respect to design and operational limits. Remedial actions will have been taken if action or operational limits had been approached.

Operational leakage will not be of consequence to the loss of water inventory accident scenario, as the amount of leakage is small.

Champion: Jon Judah

ID #	Phenomenon Synopsis Title
18	Return of condensate to pool

Phenomenon				Definition			
Return of condensate to pool				Water that evaporates or boils can condense on surfaces and then rain/drain or be pumped (from the sump) back into the bay.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
H	H	I	L	Return of evaporated water to the bay will delay uncovery	Return of evaporated water to the bay will delay uncovery	Fuel is assumed uncovered.	Small compared to pumped water.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	N/A	3	There is uncertainty on the heat sinks, paths for steam flow, where is the water going to flow once it hits the floor. Uncertainty on where the water will collect.			

Detailed description and rationale:
It is likely that some, or perhaps most, of the lost water would return to the bay (the building is large). If the water would fill the inter-space between the concrete walls, any subsequent condensation would flow back into the spent fuel pool. This recirculation of water is called refluxing and could be the result of rain from condensation on the building ceiling and/or condensation on the vertical building walls. Refluxing is a natural aspect of the pool reaching temperatures that approach, or reach the saturation temperature, and the return of water to the SPF pool would extend the interval before the fuel bundles would experience uncovering. This phenomenon could also potentially be returning water to the pool, albeit at a lower rate, during the interval that the water level is decreasing in the pool. It is important to note that the heat losses from the building that would promote condensation are likely to be different for the different stations/building designs.
Champion: Bob Henry

ID #	Phenomenon Synopsis Title
19	Flow instabilities within the spent fuels at low liquid level (flow reversal, flow excursions, etc.)

Phenomenon				**Definition**			
Flow instabilities within the spent fuels at low liquid level (flow reversal, flow excursions, etc.)				The flow instabilities created by liquid flow in the spent fuel bay as the water level decreases due to leakage is the domain of interest to this phenomenon.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	I	I	I	Flow instabilities are only significant for forced flow. Not relevant for CANDU SFP			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	N/A	N/A	N/A	See description below			

Detailed description and rationale:

The high-velocity coolant flow is a source of energy that can induce component vibration and instability. There are three major excitation sources namely turbulent buffeting, vortex shedding and acoustoelastic vibration for tube banks in cross flow. These sources of excitation become significant at high flow velocities. The coolant flow inside spent fuel pools have low velocities (<1 m/s). At these low velocities viscous forces dominate over inertial forces. Flow instabilities that can apply structurally significant force on spent fuel bundles and racks must accompany high inertial forces well above the viscous forces. The spent fuel bundles and racks are structurally rigid, with the fuel bundles designed to withstand the forces associated with the flow velocities generated by a 25 kg/s liquid coolant flow existing in a fuel channel. Flow instabilities generated at low liquid level are unlikely to be significant to impart adequate force to cause mechanical damage on fuel racks, bundles, or sheaths. Therefore the effect of flow instabilities within the spent fuels at low liquid level will be insignificant on the Figure of Merit in all four phases of the accident.

As per the discussion given above the ranking of “Insignificant” to flow instabilities within the spent fuels at low liquid level (flow reversal, flow excursions, etc.) is justified.

Champion: Nithy Nitheanandan

ID #	Phenomenon Synopsis Title
20	Siphoning/leakage effects (e.g., leaking flow effect on established natural circulation patterns)

Phenomenon				**Definition**			
Siphoning/leakage effects (e.g., leaking flow effect on established natural circulation patterns)				The SFP water level control, circulation, temperature control and purification systems will have water inlet and outlet structures below the normal operating levels of the SFP but above the highest level of fuel storage. Damage to these auxiliary systems, either during the accident scenario or due to an abnormal operational occurrence (some sort of mechanical damage) could lead to siphoning water from the SFP until the locations of these water inlet/outlet pipes have been reached.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
M	I	I	M	Significant amount of water could be siphoned out – but cannot uncover the fuel.	Siphoning will cease before the highest fuel storage locations are reached.	N/A	Damaged auxiliary systems which allowed siphoning may still allow leakage during recovery. This may either hamper, delay or prevent full refill.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	N/A	N/A	3	Siphoning could aggravate the rate of water loss.	N/A	N/A	Leakage through auxiliary system piping will hamper recovery.

Detailed description and rationale:
Although the design of the auxiliary systems piping is such that fuel uncovery due to siphoning is prevented, siphoning can aggravate the loss of coolant inventory accidents and can hamper recovery. The initiating event for the accident scenario may also damage or break auxiliary system piping, leading to siphoning of water out of the SFP (during Phase 1). The rate of water loss could be significantly increased until water levels decrease to the levels of intake/outlet pipes of these systems. If undetected, the existence of such a break will impair attempts to refill the SFP during Phase 4. Phases 2 and 3 will be unaffected by siphoning. Although the design of the auxiliary systems is well known, the vulnerability of these systems to breaks during the accident scenario will need to be assessed. Hence, a knowledge level of 3 is justified.
Champion: Jon Judah

ID #	Phenomenon Synopsis Title
21	Bubble swarm rise within the pool (dynamics, condensation process, etc.) - vapor behavior

Phenomenon				**Definition**			
Bubble swarm rise within the pool (dynamics, condensation process, etc.) - vapor behavior				Bubble dynamics in liquid water.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	I	I	Limited water level swell	Very small water level swell	No liquid water	Recovery will use cold water – little or no boiling
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	N/A	N/A	The level swell can be estimated with sufficient uncertainty (see Phenomenon 24)			

Detailed description and rationale:
Influence of level swell would be low. Boiling within the bundle stacks with higher decay heat will cause some water level swell. As evaluated in Phenomena Assessment Work Sheet #24, this is a second order effect, i.e., the collapsed water level is essentially the same as that with swell.
Champion: Bob Henry

ID #	Phenomenon Synopsis Title
22	Impact of cold water injection on the efficiency of natural circulation cooling

Phenomenon				**Definition**			
Impact of cold water injection on the efficiency of natural circulation cooling				The injection of cold water into a hot spent fuel bay will disrupt the natural circulation cooling, especially if the injection location is at the bottom of the spent fuel pool [1]. The cold water injection can cause local flow oscillations or flow reversals in LWR spent fuel assemblies, but is not applicable to CANDU spent fuel pools.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	I	I	I	Phenomenon does not need to be considered for CANDU spent fuel bay accidents (see below).			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A				Phenomenon does not need to be considered for CANDU spent fuel bay accidents.			

Detailed description and rationale:

The panel consensus was that this phenomenon did not apply to CANDU spent fuel bays. The geometry of the LWR spent fuel assemblies (vertical orientation) is significantly different than for CANDU assemblies (horizontal orientation). As well, the significantly lower decay heat for CANDU fuel bundles means that flow reversals or oscillations will not have a significant effect on sheath or bundle temperature, as long as the bundle is immersed in liquid water.

Reference:

[1] M. Blaha and J. Freilich, "Multidimensional Modelling of Temperature Distribution in Spent Fuel Pools of VVER-1000 and VVER-440 Using FLUENT CFD Code", Proceedings of the 15th Symposium of Atomic Energy Research, 2005 October

Champion: Jeffrey Baschuk

ID #	Phenomenon Synopsis Title
23	Flow blockage in bundles due to Ballooning and Rupture

Phenomenon				Definition			
Flow blockage in bundles due to Ballooning and Rupture				Due to the development of a differential pressure between the fuel-to-sheath gap and ambient pressure outside of the sheath in the spent fuel pool, the sheath may experience localized ballooning and possible sheath rupture (i.e., with sufficient strain from possible fission gas release during high-temperature conditions experienced during the event).			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	L	L	I	Ballooning/rupture will not occur as fuel elements well cooled prior to uncovery.	Low because it will affect only a small number of the fuel bundles (high powered, freshly discharged bundles).		With cooling restored, ballooning/rupture will not occur.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	1	1	N/A	Ballooning/rupture will not occur at low sheath temperatures (~100°C) – supported by experiments and computer codes.	High uncertainty on the effect of a ballooned element on bundle coolability in air/water vapour.	High uncertainty on the effect of a ballooned element on bundle coolability in air/water vapour.	Ballooning/rupture will not occur at low sheath temperatures (~100°C) – supported by experiments and computer codes.

Detailed description and rationale:

Significant only for freshly discharged fuel (need high temperature). With localized degraded heat transfer, sheath ballooning may occur resulting in localized sheath strain. Ballooned fuel elements may restrict natural convective cooling in subchannels thereby degrading the coolability of the bundle. Deformed/strained fuel elements may rupture. For knowledge level, predicting the actual geometry of a ballooned/ruptured fuel element would have a large uncertainty and require a three-dimensional analysis, which is not within the capability of the current computer codes (ELOCA). No experiments on the coolability of bundles with ballooned elements in air/water vapour are available.

Champion: Brent Lewis

ID #	Phenomenon Synopsis Title
24	Water level swell

Phenomenon				Definition			
Water level swell				Change in water level due to steam generation.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
M	L	I	I	Small water level swell	Very small water level swell	Dry	Depends on the recovery rate
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	N/A	N/A	Nucleate boiling	Nucleate boiling/gas flow	Single phase gas circulation	No large effect on the level

Detailed description and rationale:

Not expected to be significant, as it is a localized phenomenon. Influence of level swell will be low. When the SFP approaches saturation, the resulting steam production would generate a level swell over the high power fuel stacks. However, the level swell would be minimal, or non-existent for the low power bundle stacks, so the level swell would spread radially. Following the approach proposed by Grolmes et al. [1], a bundle stack with a power level of 0.4 MW would develop an average void fraction of about 0.3, which in a one-dimensional pool would produce a level swell of almost 0.8 m. However, including radial flow into adjacent low power stacks would reduce this to about 0.08 m

Reference:

[1] M.A. Grolmes et al., 1985, “Large-Scale Experiments of Emergency Relief Systems”, Chemical Engineering Progress, August issue, pp. 57-62

Champion: Bob Henry

ID #	Phenomenon Synopsis Title
25	Air/steam inflow into the rack (including effect of rack deformation)

Phenomenon				**Definition**			
Air/steam inflow into the rack (including effects of rack deformation)				In the absence of liquid water, the flow of air and/or steam into the spent fuel racks of a LWR will have a significant effect on the peak clad temperature [1], and the onset of cladding ignition due to oxidation [2]. The inflow will be highly influenced by the form and friction loss coefficients, which depend on the geometry of the rack.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	I	I	I	Not important for CANDU spent fuel bays.			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A				Not important for CANDU spent fuel bays.			

Detailed description and rationale:

The consensus of the panel was that this phenomenon was applicable to LWR spent fuel pool accidents, but not significant for CANDU spent fuel bay accidents. The long, vertical orientation of LWR racks makes the air or steam flow significant if the pool is void of liquid water, and air/steam flow warrants a separate and distinct phenomena. However, the CANDU spent fuel bay fuel storage is horizontal and the air/steam flow is already captured in Phenomena 15 (Single and two phase natural circulation (by convection) within the pool at large scale), 16 (convective heat transfer), and 23 (Flow blockage in bundles due to Ballooning and Rupture).

References:

[1] D.H.P. Nourbakhsh, G. Miao and Z. Cheng, “Analysis of Spent Fuel Heatup Following Loss of Water in a Spent Fuel Pool A User's Manual for the Computer Code SHARP”, NUREG/CR-6441, 2001 February

[2] E.R. Lindgren and S.G. Durbin, “Characterization of Thermal-Hydraulic and Ignition Phenomena in Prototypic, Full-Length Boiling Water Reactor Spent Fuel Pool Assemblies After a Postulated Complete Loss-of-Coolant Accident”, NUREG/CR-7143, 2013 March

Champion: Jeffrey Baschuk

ID #	Phenomenon Synopsis Title
26	Thermal Radiation Heat Transfer

Phenomenon				Definition			
Thermal Radiation Heat Transfer				Radiative heat transfer from uncovered bundles to other bundles or structures and participating media			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	H	H	L	Fuel surface temperatures remain low as the fuel is fully covered with water. However, thermal radiation in the steam can affect the temperature distribution and gas mixing in the vapour space.	As the fuel is uncovered, the fuel temperature will rise. The thermal radiation increases with the forth power of the absolute temperatures. However, thermal radiation is only effective for the outer fuel pins, as the inner pins will only exchange thermal radiation with neighboring pins. Thermal radiation in the steam can affect the temperature distribution and gas mixing in the vapour space.	As the fuel is uncovered, the fuel temperature will rise. The thermal radiation increases with the forth power of the absolute temperatures. However, thermal radiation is only effective for the outer fuel pins, as the inner pins will only exchange thermal radiation with neighboring pins. Thermal radiation in the steam can affect the temperature distribution and gas mixing in the vapour space.	Fuel is covered, reducing the surface temperature and thus the importance of radiation heat transfer from the fuel surface. Thermal radiation in the steam can affect the temperature distribution and gas mixing in the vapour space.

Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Uncertainties arise from the characterization of the optical properties (emissivity, absorptivity and reflectivity of the surfaces and participating medium). As well, another source of uncertainty can be with the simplified models used to estimate thermal radiation (instead of solving the complete transport equations).	Uncertainties arise from the characterization of the optical properties (emissivity, absorptivity and reflectivity of the surfaces and participating medium). As well, another source of uncertainty can be with the simplified models used to estimate thermal radiation (instead of solving the complete transport equations). Another source of uncertainty lies in the evaluation of view factors for surface to surface thermal radiation.	Uncertainties arise from the characterization of the optical properties (emissivity, absorptivity and reflectivity of the surfaces and participating medium). As well, another source of uncertainty can be with the simplified models used to estimate thermal radiation (instead of solving the complete transport equations). Another source of uncertainty lies in the evaluation of view factors for surface to surface thermal radiation.	Uncertainties arise from the characterization of the optical properties (emissivity, absorptivity and reflectivity of the surfaces and participating medium). As well, another source of uncertainty can be with the simplified models used to estimate thermal radiation (instead of solving the complete transport equations).

Detailed description and rationale:

Thermal radiation is a form of electromagnetic radiation, which is detected as heat or light, and is generally composed of infrared and/or visible radiation. The intensity of thermal radiation heat transfer between two bodies is proportional to the difference between the fourth powers of the absolute temperatures. Therefore, the importance of radiation increases with the temperature levels. No medium needs to be present between the two bodies for radiant exchange to occur. If a medium exists between radiating surfaces, it can interact with radiative heat transfer, and is called a “participating” medium. In general, a medium absorbs, scatters and emits energy. Its capability to attenuate the radiation depends on the sum of the absorption and scattering coefficients, which is called extinction coefficient.

Thermal radiation heat transfer from the fuel pins to the cold surrounding surfaces (e.g., pool walls or other surfaces) is limited to only the outer fuel pins. The inner pins will have limited views of the cold surrounding surfaces and will only exchange thermal radiation heat transfer with the surrounding pins. So, this will limit the importance of thermal radiation on the figure of merit.

Thermal radiation heat transfer is governed by a nearly exact transport equation, but is computationally intensive to solve, especially for thermal radiation in a participating medium. A major source of uncertainty is the characterisation of the thermal radiation properties of surfaces and gases. For example, the emissivity of metallic surfaces varies with the age of the structure (oxidation, wear, etc.). Another source of uncertainty is in the evaluation of view factors, which are highly geometry dependent, for modelling surface to surface thermal radiation.

References:

[1] “Containment Code Validation Matrix”, NEA/CSNI/R(2014)3, 2014 May
[2] https://en.wikipedia.org/wiki/Electromagnetic_absorption_by_water

Champion: Sammy Chin

ID #	Phenomenon Synopsis Title
27	Zircaloy oxidation in air-steam mixtures (including breakaway of pre-existing oxide layer)

Phenomenon				**Definition**			
Zircaloy oxidation in air-steam mixtures (including breakaway of pre-existing oxide layer)				Steam and air reaction with the Zircaloy sheath can lead to sheath oxidation with the liberation of chemical heat with a release of either hydrogen (in steam) or nitrogen (in air).			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	H	H	L	The temperature of the sheaths is too low for oxidation when the bundle is covered with liquid water.	Can be significant depending on the scenario. If the sheath gets hot enough (>800°C for as received, >750°C for Heat Affected Zone) then air oxidation rates will be significant.	Can be significant depending on the scenario. If the sheath gets hot enough (>800°C for as received, >750°C for Heat Affected Zone) then air oxidation rates will be significant.	Temperature is decreasing rapidly. The temperature of the sheaths is too low for oxidation when the bundle is covered with liquid water.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	4	2	4		Expected to be in a steam environment during uncovery	If it is an air environment, then the uncertainty on the oxidation rate, transition to breakaway, can be high.	Expected to be in steam (or be a low temperature).

Detailed description and rationale:

At temperatures above the (α + β)β transformation temperature for zirconium alloys, steam reacts with the β-Zr in accordance with parabolic kinetics to form a superficial layer of zirconium oxide (ZrO_2) and an intermediate layer of oxygen-stabilized α-Zr. A discontinuity in the rate of growth of the combined ($ZrO_2 + \alpha\text{-}Zr$) layer can be attributed to a change in the oxide microstructure at the discontinuity temperature consistent with the zirconium-oxygen phase diagram. In particular, as the protective oxide forms in steam, it can spall away due to a decreased density exposing the underlying metal. Moreover, in the reaction between Zircaloy-4 and air and in steam and nitrogen-containing atmospheres at temperatures above 800°C, there is a degradation of the cladding material with the formation of zirconium nitride and its re-oxidation. Although parabolic correlations may be applied for oxidation in air, this is only appropriate for high temperatures (>1400°C) and for pre-oxidized cladding (≥1100°C), i.e., under all other conditions, faster kinetics are observed to occur with an enhanced breakaway with a less protective oxide layer caused by the crystallographic mismatch between zirconia and zirconium nitrides. This is consistent with similar behaviour reported for Zircaloy oxidation in environmental mixtures of steam and nitrogen. The transition point for such breakaway in air or in air/steam mixtures is not well understood at a mechanistic level so that it can be physically modelled in a code; hence the low knowledge level for Phase 2. Zr/steam oxidation kinetics is well known, and can be calculated by existing codes (for example, CATHENA, ELOCA).

Champion: Brent Lewis

ID #	Phenomenon Synopsis Title
28	Oxidation of debris

Phenomenon				Definition			
Oxidation of debris				If severe fuel damage occurs, debris could be generated from the sheath (cladding), fuel, and/or rack disintegration. This debris could oxidize, generating additional heat loads.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	I	I	I	Not important for CANDU spent fuel bays.			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A				Not important for CANDU spent fuel bays.			

Detailed description and rationale:

The consensus of the panel was that this phenomenon is not applicable to CANDU spent fuel bay accidents. Due to the low decay heat, the expected temperatures of the fuel bundles would be too low for severe fuel damage to occur (max sheath temperature ~933°C) [1,2]. Oxidation of the components of the system (fuel, sheath, module/rack material) are included under other phenomena.

References:

[1] C.J. Krasnaj and W. Grant, “Development of a 2-D Finite Element Model to Examine Both Natural Convection and Radiative Cooling of a Spent Fuel Bundle in Air”, Proc. 19th PBNC Conference, Vancouver, BC, Canada, 2014 August 24-28

[2] C.J. Krasnaj and W. Grant, “Finite Element Analysis of Heat Transfer Between Spent CANDU Fuel Bundles in Spent Fuel Pools”, Proc. 19th PBNC Conference, Vancouver, BC, Canada, 2014 August 24-28

Champion: Jeffrey Baschuk

ID #	Phenomenon Synopsis Title
29	Hydrogen production (radiolysis)

Phenomenon				Definition			
Hydrogen production (radiolysis)				Radiolysis of water generates H_2 and oxidizing species including H_2O_2 and O_2^{2-}. This can add to the hydrogen production in the course of an accident. The radiolysis of water will be affected by impurities dissolved or suspended in the bay water.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	I	L	The generation rate is low, compared to other hydrogen production mechanisms.		The amount of liquid water remaining in the bay is small, so the hydrogen in it can be neglected.	The newly added bay water would not have any initial dissolved hydrogen, but radiolysis would continue to generate hydrogen.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	N/A	3	Almost all of the hydrogen would be released during the initial heating and boiling.		The amount of liquid water remaining in the bay is small, so hydrogen production in it can be neglected.	

Detailed description and rationale:
Hydrogen produced by radiolysis is expected to be a minor in comparison to the hydrogen produced by the high temperature Zr/steam reaction [1]; hence the importance is Low. The phenomenon of radiolysis is well known, but moderate uncertainty in calculating the rate of radiolysis exists because of dose gradients near the fuel and potentially complex pool water flow patterns. Additional uncertainty is introduced if impure water is used for the recovery phase; hence, the knowledge level is assessed as 3.

Reference:
[1] Status Report on Spent Fuel Pools under Loss-of-Cooling and Loss-of-Coolant Accident Conditions, Nuclear Safety NEA/CSNI/R(2015)2, 2015 May

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
30	Degassing of hydrogen by water temperature increase

Phenomenon				Definition			
Degassing of hydrogen by water temperature increase				Hydrogen gas can dissolve in water, but the gas solubility decreases with increasing water temperature. As the temperature of the fuel bay water increases, dissolved hydrogen will be released.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	I	I	Possible gas release	Gas already released	Dry	Steam released to the SFP
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	N/A	N/A	Hydrogen solubility is known and can be calculated.			

Detailed description and rationale:

A bounding analysis results in a hydrogen concentration of 2% hydrogen, below the 4% threshold required for combustion in dry air. Hydrogen gas can dissolve in water, but the gas solubility decreases with increasing water temperature such that essentially nothing is dissolved if the water temperature reaches the saturation value. According to the U.S. National Institute of Standards and Technology (NIST), the Henry's Law constant for hydrogen dissolution is 0.00078 mol/(kg bar) at 298 K. Conservatively assuming that the Spent Fuel Pool is fully saturated with the gas at this temperature and that the pool is 38 m x 20 m x 11 m deep, the water volume would be 8360 m^3, with a mass of 8.36 x 10^6 kg and the dissolved hydrogen mass would be 13 kg. Further assuming that the building volume above the pool has the same volume as the SFP, if all of the dissolved hydrogen was accumulated in the building gas space at a temperature of 300 K, the hydrogen concentration would be 2%. The minimum hydrogen concentration for any type of combustion in dry air is 4%.

Champion: Bob Henry

ID #	Phenomenon Synopsis Title
31	Radionuclide releases from leaking fuel pins into the pool

<table>
<tr><th colspan="4">Phenomenon</th><th colspan="4">Definition</th></tr>
<tr><td colspan="4">Radionuclide releases from leaking fuel pins into the pool</td><td colspan="4">A number of fuel elements may be defective during operation as subsequently stored in SFP so that fission products could leach into the pool water. During degraded cooling conditions in the pool, intact elements may also fail due to possible localized sheath strain resulting in a gap release, with possible leaching of fission products in aqueous conditions or vapour release at higher temperatures. The underlying fuel in contact with water, steam or air could also oxidize resulting in enhanced fission product release from the fuel matrix if fuel temperatures are sufficiently high.</td></tr>
<tr><th colspan="4">Importance Rank
(by sub-scenario)</th><th colspan="4">Importance Rank Rationale
(by sub-scenario)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>L</td><td>M</td><td>H</td><td>M</td><td colspan="3">Leaching from existing defects</td><td>Leaching from existing defects, and additional defects induced from accident progression.</td></tr>
<tr><th colspan="4">Knowledge Assessment
(by sub-scenario)</th><th colspan="4">Knowledge Assessment Rationale
(by sub-scenario)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>4</td><td>4</td><td>4</td><td>4</td><td colspan="4">Operational experience and experiments exist.</td></tr>
</table>

Detailed description and rationale:

Fission product release/leaching from failed fuel in aqueous conditions during pool storage conditions is well known with many years of operational experience and a knowledge of fuel/fission product chemistry. In addition, there have been numerous annealing experiments conducted with fuel fragments and mini elements at CRL over 35 years at high-temperature under various environmental conditions in argon, steam and air.

Champion: Brent Lewis

ID #	Phenomenon Synopsis Title
32	Radionuclide releases from eroded CRUD into the pool

Phenomenon				**Definition**			
Radionuclide releases from eroded CRUD into the pool				Magnetite deposits on fuel sheath are called CRUD and as these deposits form, they are likely to capture fission products in the heat transport fluid.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	L	L	I		Releases from CRUD expected to be minor	Releases from CRUD expected to be minor	
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	2	2	N/A		Species are known. See description below.	See description below	

Detailed description and rationale:

Crud deposition can occur on the fuel sheaths of CANDU fuel under normal operating conditions. If this deposition were sufficiently large, it could affect the thermal response or mechanical behaviour of the fuel during a postulated accident. Crud is primarily magnetite which deposits on the fuel sheath. Precipitation fouling is one of the main fouling mechanisms taking place at high temperature whenever precipitating material has inverse solubility curve with temperature. Radionuclide capture in the crud material is significantly lower than the radionuclide release following fuel failures. The amount of radionuclide releases from eroded Crud into the pool is therefore insignificant to low.

The Importance ranking of “Low” for sub-scenarios 2 and 3 is justified because of the low level of contribution radionuclide releases from eroded Crud. The sub-scenarios 1 and 4 at low temperatures and therefore the contribution will be much lower and becomes insignificant. The knowledge level “2” indicating that the phenomenon is partially known with large uncertainty. The level of literature on CRUD is extremely low and the CRUD from one reactor may show different characteristics compared to another reactor. Hence the ranking given to this phenomenon is justified.

Champion: Nithy Nitheanandan

ID #	Phenomenon Synopsis Title
33	Pool scrubbing of aerosols and gases from bubbles

Phenomenon				**Definition**			
Pool scrubbing of aerosols and gases from bubbles				Aerosols and gases may be removed from bubbles by deposition on the surrounding water surface and dissolution in the surrounding water. Conversely, if the vapour pressure of a gas dissolved in the water is higher than its partial pressure in the bubble, there may be net vaporization of gas from the water to the bubble.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	I	M	FP releases are small during this phase	Unstable flow (sloshing, level swelling) could partially cover releasing fuel with liquid water.	No water is covering any fuel, so scrubbing will be negligible.	Fuel is being covered with liquid water again, so pool scrubbing will occur in the bubbles during the cooldown
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	N/A	3	Models exist, but moderate uncertainty and modelling gaps exist.	See Phase 1		See Phase 1

Detailed description and rationale:

The importance is low for Phases 1 and 2, as FP releases will be small. Only for Phase 4, recovery, will the phenomenon have a medium importance, as the fuel becomes covered by the reflood and pool scrubbing will occur. Most models and codes for pool scrubbing [1] [2] have been developed for bubbles passing through a pool, rather than for gas streams passing over the surface of a pool. Some aerosol and vapour deposition mechanisms will be affected by the non-zero liquid velocity parallel to the liquid surface in the boundary layer [1] (caused by water circulation within the pool or at the bubble interface). There may be net vaporization or condensation of water/steam, causing significant diffusiophoresis and Stefan flow effects within the bubble. Thus, the knowledge level is 3, as some uncertainty and modelling gaps exist for application to spent fuel pools.

References:

[1] A.T. Wassel, A.F. Mills, D.C. Bugby and R.N. Oehlberg, "Analysis of Radionuclide Retention in Water Pools", Nucl. Engin. Design 90 (1985) pp. 87-104

[2] P.C. Owczarski, R.I. Schreck and A.K. Postma, "Technical Bases and User's Manual for the Prototype of a Suppression Pool Aerosol Removal Code", USNRC, Report NUREG/CR-3317, 1985 May

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
34	Radioactive aerosol formation due to boiling at the free surface

Phenomenon				Definition			
Radioactive aerosol formation due to bubble breakup processes at the free surface				Fission product compounds may be resuspended from the pool as droplets formed by breaking of bubbles or by surface spray induced by rapid gas flows passing over the surface. Particulate material suspended in the water can also be resuspended by this mechanism.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	I	M	This is the only mechanism that could release some of the starting inventory of dissolved Cs from the pool, if boiling occurs. However, releases are expected to be low.	See Phase 1.	No bubbles in water pool.	Water will dissolve radioactive substances from the bay wall and suspend fine fuel particulate and other materials. Significant boiling may occur at the quench front.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	N/A	2	Experimental data under representative conditions are available [1] [2] [3] [5] and the physics of the process is reasonably well understood [3] [4] [5].	See Phase 1.	N/A	Uncertainty on the type of boiling experienced at the rewet front makes estimation of the resuspended fraction difficult.

Detailed description and rationale:
Resuspension factors in representative conditions were between 4×10^{-6} and 7×10^{-5} for soluble tracers [5], between 5×10^{-6} and 5×10^{-4} for alumina particles [5], and about 5×10^{-4} for $BaSO_4$ particles at high concentration in non-condensing atmosphere [1]. Resuspension factors are lower in condensing atmospheres by a factor of about 10.

References:
[1] W. Schöck and M. Wagner-Ambs, "Aerosol generation by bubble bursting from a boiling pool", J. Aerosol Sci. 20 (1989) 1405-1408
[2] H. Bunz, M. Koyro, B. Propheter, W. Schöck and M. Wagner-Ambs, "Resuspension of fission products from sump water", European Commission Report EUR-14635, 1992
[3] N. Reinke, A. Voßnacke, W. Schütz, M.K. Koch and H. Unger, "Aerosol Generation by Bubble Collapse at Ocean Surfaces", Water, Air and Soil Pollution: Focus, 1 (2001) pp. 333-340
[4] L. Duchemin, S. Popinet, C. Josserand and S. Zaleski, "Jet formation in bubbles bursting at a free surface", Phys. Fluids 14 (2002) 3000–3008

[5] J.O. Cosandey, A. Günther and Ph. Rudolph von Rohr, “Transport of salts and micron-sized particles entrained from a boiling water pool”, Experimental Thermal and Fluid Science 27 (2003) 877–889

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
36	Tritiated steam (DTO) releases by water evaporation

Phenomenon				Definition			
Tritiated steam (DTO) releases by water evaporation				Leakage of heavy water from the heavy water side of the irradiated fuel handling system to the SFP allows some tritiated heavy water (DTO) into the SFP. Allowing for some chemical recombination, very small quantities of both HTO and DTO will be available for release from the SFP during the loss of water inventory accident.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	I	I	DTO in the SFP will be released during loss of water inventory.	DTO in the SFP will be released during loss of water inventory.	N/A	N/A
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4			It is measured during operation	As for Phase 1.	N/A	N/A

Detailed description and rationale:

Irradiated fuel discharge mechanisms are designed to separate the heavy water side of the fuel handling system from the light water in the SFP. Irradiated fuel bundles are discharged through an air chamber which separates the heavy water in the fuelling machine from the light water in the SFP. This is important for both economic reasons and safety reasons. Heavy water is very expensive, and CANDU operations will work hard to minimize loss and maximize recovery. Minimizing the loss of heavy water is also a safety concern. Heat transport D_2O can become activated in reactor and will contain high levels of Tritium. The release of Tritium (Tritiated heavy water, DTO) is an environmental hazard.

Despite elaborate efforts to minimize loss, some Heavy water will be carried on fuel bundle surfaces into the irradiated fuel transfer mechanism and possibly into the SFP. DTO in the SFP will be released to the environment by evaporation or during loss of the SFP water inventory during an accident. CANDU operators will monitor pathways for heavy water loss to the SFP. Also, chemistry testing of SFP water is used to monitor heavy water and DTO content.

Champion: Jon Judah

ID #	Phenomenon Synopsis Title
39	Conduction in solid components (fuel, racks/modules, concrete, …)

Phenomenon				Definition			
Conduction in solid components (fuel, racks/modules, concrete, …)				The transfer of heat in solid components due to conduction. Scope includes transient conduction and contact between components			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
H	H	H	H	Heat conduction can be the limiting factor of the heat transfer.			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Gap and contact conductance is an uncertainty (fuel/sheath, gaps in concrete)			

Detailed description and rationale:

Thermal conduction is the transfer of heat thorough microscopic collisions of molecules, atoms, and electrons within and through the body itself [1]. The rate of heat transfer within a solid body is a function of the temperature difference (temperature gradient) between two locations within the solid and the thermal conductivity of the conductive medium through which the heat is transferred. The rate of heat transfer between two bodies through contacting surfaces is also a function of the temperature difference and the contact conductance (heat transfer coefficient).

The decay heat generated within the fuel will be conducted through the ceramic fuel to the fuel-to-sheath gap. The heat energy is then transferred through the gap via the contact conductance process to the sheath. Heat may then find its way to the coolant through molecular conduction (relatively small contribution) and convection (relatively large contribution). From the coolant or via direct contact, decay heat dissipation to components like racks, modules, and concrete may occur depending on the sub-scenario of the event.

Thermal conduction is a very well-known phenomenon for most of the materials within the spent fuel pool. The contact conductance in the gap is a less understood phenomenon. For the type of applications in the spent fuel pool, the bounding heat transfer coefficients are available, but the uncertainty may be higher.

Since the Spent Fuel Pool accidents due to loss-of-cooling or loss-of-coolant contribute to escalating temperatures and component failures, the primary mode of heat transfer that propels temperature escalation is conduction heat transfer and contact heat transfer. On this basis, the “High” ranking given to the phenomenon of Conduction in solid components (fuel, racks/modules, concrete, …) is justified. There is reasonable amount of knowledge on conduction, however, the knowledge level in the contact heat transfer area is less than sufficient requiring prototypic experiments to measure the contact heat transfer coefficient. On this basis, a knowledge ranking of “3” denoting adequate knowledge with moderate uncertainty in the knowledge is justified.

Reference:

[1] Vedat S. Arpaci, “Conduction Heat Transfer”, Addison-Wesley Publishing Company, Reading Massachusetts, 1966

Champion: Nithy Nitheanandan

ID #	Phenomenon Synopsis Title
41	Deformation and integrity of structures (racks/modules/fuel bundle)

Phenomenon				**Definition**			
Deformation and integrity of structures (racks/modules/fuel bundle)				At elevated temperatures, the fuel elements, bundles, and supporting structures such as the racks or modules will deform due to thermal expansion, elastic, plastic, or creep processes. In the case of excessive deformation, the structures may fail.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	M	H	L	Prior to fuel uncovery, the temperatures of the structural components is not high enough for significant deformation.	As the fuel uncovers, the uncovered fuel will attain a higher temperature, potentially resulting in bundle sag and dimension changes.	With all of the fuel uncovered, the fuel and racks/modules will be at elevated temperature and will deform in excess of the initial condition.	During reflood, the components cool and deformation due to elevated temperatures is no longer active.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	2	2	2		Change in geometry can affect flow through rack and sheath temperature. Knowledge level for bundle deformation is supported by experiments, but the system is complex and difficult to predict with a high level of certainty. Deformation and failure mechanisms of racks/modules under the accident conditions is not available.		

Detailed description and rationale:
If the fuel becomes uncovered, then the reduced cooling will increase the temperature of the fuel bundles and the supporting structures (racks or modules). Elevated temperatures can cause excessive deformation, because the yield stress decreases with increasing temperature and creep rates increase with increasing temperature. At the temperatures expected for a spent fuel bay accident, creep could be significant. Experiments on bundle deformation are available, but creep rates are subject to uncertainty and the current experiments do not consider bundle integrity over the longer time periods of the spent fuel bay accident. The knowledge level of rack/module deformation and failure mechanisms are not known at this time.
Champion: Jeffrey Baschuk

ID #	Phenomenon Synopsis Title
42	Stratification in the gas space

<table>
<tr><th colspan="4">Phenomenon</th><th colspan="4">Definition</th></tr>
<tr><td colspan="4">Stratification in the gas space</td><td colspan="4">Stratification of gases arising from density differences due to temperature and molar mass differences of gas compositions.</td></tr>
<tr><th colspan="4">Importance Rank
(by sub-scenario)</th><th colspan="4">Importance Rank Rationale
(by sub-scenario)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>L</td><td>M</td><td>M</td><td>M</td><td>Very little hydrogen present. However, this phase can help to establish a steam rich layer in the ceiling which can inhibit hydrogen transport in the later stages of the accident.</td><td>If the fuel is uncovered and heats up, Zr oxidation with steam will occur, producing hydrogen. However, the importance is ranked as medium because of the quantity of hydrogen that can be produced and a hydrogen deflagration will only damage the walls and roof of the spent fuel pool bay building. In a worst case scenario, all of the walls and roof are gone, causing a faster evaporation rate. Also, some of the debris may fall into the pool, reducing the amount of water available for boil-off.
Presence of high concentrations of steam would serve to inert the atmosphere. However, leakage of hot steam could draw in cold air into the building.</td><td>In this stage, all of the fuel is uncovered. There is less than 1 foot of water below the bottom of the fuel. So, the amount of available steam is limited to what may evaporate due to thermal radiation absorbed by the water.
Steam condensation could result in air ingress, which could Air infiltration could cause problems if you still have the hydrogen.
As well, leakage of hot gases from the spent fuel pool building could result in an inflow of cold air.</td><td>Reflooding of the spent fuel pool could result in the production of hydrogen on re-wet because of the generation of steam. However, atmosphere could become steam inerted.</td></tr>
<tr><th colspan="4">Knowledge Assessment
(by sub-scenario)</th><th colspan="4">Knowledge Assessment Rationale
(by sub-scenario)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>3</td><td>3</td><td>3</td><td>3</td><td colspan="4">Uncertainty lies with the ability of computer codes to predict stratification due to density differences and the breakup of the stratification layer.</td></tr>
</table>

Detailed description and rationale:

Fluid density differences can lead to stratification into layers. Density variation may be due to differences in temperature or composition. Stratification occurs when the driving forces to cause forced mixing are weaker than natural buoyancy forces. For an accident in a SFP, several stratification scenarios are possible:

1. The initial steaming will cause form of a steam rich layer in the upper gas space of the SFP building. This hot steam rich layer can inhibit or slow down the upward migration of hydrogen in the later stages of the accident.
2. Condensation of steam in the ceiling will lead to richer non-condensable gases (including air and hydrogen) near the ceiling.

What is most important for the FOM is the stratification (concentration) of hydrogen (with air) near the ceiling because of the threat of hydrogen combustion. A lot of experiments have been done to study stratification of hydrogen (or helium as a simulant) under postulated reactor accident conditions. Recent experiments are looking into the dissolution of an established hydrogen rich layer due to a steam jet or a buoyant steam plume. As well, a number of computer code validation/benchmark exercises have been done. In general, the prediction of a hydrogen stratification is well predicted by the codes, but there are sensitivities due to user effects and 3D modelling capabilities of the codes. What has more uncertainty is the prediction of the dissolution of a hydrogen rich layer, with on-going international experiments and benchmark exercises (OECD HYMERES project).

Reference:

[1] "Containment Code Validation Matrix", NEA/CSNI/R(2014)3, 2014 May

Champion: Sammy Chin

ID #	Phenomenon Synopsis Title
43	Thermal Conduction in fluid

Phenomenon				Definition			
Thermal Conduction in fluid				Heat transfer by thermal conduction in gases and liquids.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	L	L	Heat transfer within the fluid is dominated by mixing, either forced or natural convection.			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	4	4	Theory is well established and fluid properties are known.			

Detailed description and rationale:

This phenomenon covers thermal conduction in a fluid (water and vapour/gas), which is a mode of heat transfer due to a temperature gradient and is governed by the fluid's thermal conductivity, density and specific heat. The theory is identical to that for solids and is well known (governed by exact transport equations), along with the relevant properties for water and gases (steam, air and hydrogen). For water and vapour/gases, the main mode of heat transfer is by mixing, whether it is by forced or natural convection. Thus, conduction in fluids is expected to play a small role, as even under stagnant conditions, the temperature gradient needed for thermal conduction would also induce natural convection flows.

Reference:

[1] "Containment Code Validation Matrix", NEA/CSNI/R(2014)3, 2014 May

Champion: Sammy Chin

ID #	Phenomenon Synopsis Title
44	Condensation heat transfer

Condensation heat transfer				The pool water that is boiled or evaporated off is expected to condense on the building heat sinks (walls, ceiling, …).			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
M	M	I	M	The amount of water returning through condensation is expected to be small, but it can delay the accident. The amount of condensation can be affected by the weather (cold)	Even if some fuel bundles are uncovered, some condensate could be returning to the pool.	At this stage of the accident, all liquid water in the pool has evaporated or boiled-off.	The injection water is expected to be cold and the rate of evaporation/boiling would be low.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	N/A	4	Rainout due condensation on the SFP ceiling would return to the pool directly and condensate film drainage could return to the pool if the building sump becomes full of water.	Any return of water to the pool would slow the accident progression.		

Detailed description and rationale:

Condensation on the building heat sinks if evaporation or boiling of the SFP should occur would be expected and if this water could return to the pool by either rainout or drainage of condensate films, this would delay, or prevent the uncovering of the spent fuel bundles. If the condensate could fill the water sump (the region between the inner and outer walls of the SFP, then the condensate would be returned to the pool. The phenomena of rainout and condensate drainage need to be modeled by the computer code. Depending on the accident and the building configuration, this could change from MEDIUM to HIGH.

Champion: Bob Henry

ID #	Phenomenon Synopsis Title
45	Buoyancy induced mixing in the gas space

Phenomenon				Definition			
Buoyancy induced mixing in the gas space				Gas/vapour can be mixed by buoyancy induced motion due to pressure gradients created by local gas density differences in a gravitational field. These density differences are due to composition differences and/or temperature differences, induced by local mass and/or heat transport processes (e.g., gas injection, convection and condensation).			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	M	M	M	Effect on FOM (sheath temperature) is minimal, as its effect on the FOM is only to help remove steam from the pool surface and replace it with air (this will help the evaporation process).	It has a secondary effect on the FOM, as the evaporation rate is limited by the steam concentration at the pool surface and the potential for energetic hydrogen combustion is also affected by the mixing of the steam, air and hydrogen.	It has a secondary effect on the FOM, as the evaporation rate is limited by the steam concentration at the pool surface and the potential for energetic hydrogen combustion is also affected by the mixing of the steam, air and hydrogen.	It has a secondary effect on the FOM, as the evaporation rate is limited by the steam concentration at the pool surface and the potential for energetic hydrogen combustion is also affected by the mixing of the steam, air and hydrogen.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Knowledge level is high, but there is still on-going research into buoyancy induced gas mixing in multi-volume/room configurations. As well, there is some spread in the code benchmarks results leading to some uncertainty.			

Detailed description and rationale:

Gas/vapour can be mixed by buoyancy induced motion due to pressure gradients created by local gas density differences in a gravitational field. These density differences are due to composition differences and/or temperature differences, induced by local mass and/or heat transport processes (e.g., gas injection, convection and condensation). For an accident in a SFP, the concern is the mixing of the steam, air and hydrogen above the pool surface. If the ventilation system is off, the main mode of mixing will be due to buoyancy induced mixing. Its importance is ranked as medium mainly because it has a secondary effect on the FOM, as the evaporation rate is limited by the steam concentration at the pool surface and the potential for energetic hydrogen combustion is also affected by the mixing of the steam, air and hydrogen.

The knowledge level is quite high for this phenomenon with many experiments and code benchmarks. However, experimental work and the associated code benchmarks are still on-going, especially for buoyancy induced gas mixing in multi-volume/room configurations.

Reference:

[1] “Containment Code Validation Matrix”, NEA/CSNI/R(2014)3, 2014 May

Champion: Sammy Chin

ID #	Phenomenon Synopsis Title
46	Mass diffusion in vapour space

Phenomenon				Definition			
Mass diffusion in vapour space				Mass diffusion is the relative motion of species in a vapour/gas mixture due to the presence of a concentration gradient. Mass diffusion will move a species down the concentration gradient, and tends to reduce the concentration gradient to result in a uniform concentration (well mixed) conditions. The diffusion mass transfer rate depends on the gas component diffusion coefficients for the multi-component mixture.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	L	L	Diffusion will be less significant than convective transport. Very little impact on the figure-of-merit.			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
4	4	4	4	Theory is known and transport equations can be solved numerically. Diffusion coefficients for steam, air and hydrogen mixtures can be evaluated.			

Detailed description and rationale:

The gas space above the spent fuel pool (and also the rest of the spent fuel pool building) will consist of steam, air and hydrogen. The mixing of these gases will mainly be driven by mixing due to forced or natural convection. However, in stagnant regions, diffusion can play a role to reduce the gas concentrations. The theory is well known and the transport equation can be solved numerically. The kinetic theory of gases can be used to derive formulas for the binary diffusion coefficients. Which can then be used to evaluate the gas diffusion coefficient for a single species in a gas mixture.

References:

[1] "Containment Code Validation Matrix", NEA/CSNI/R(2014)3, 2014 May
[2] R.B. Bird, W.E. Stewart and E.N. Lightfoot, "Transport phenomena", Wiley, 1965

Champion: Sammy Chin

ID #	Phenomenon Synopsis Title
47	Laminar flow (gas space, liquid)

Laminar flow (gas space, liquid)				Laminar flow occurs when a fluid flows in parallel layers without disruption of these layers.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	M	M	L	Impact on FOM (sheath temperature) is low because the fuel is fully covered and with high heat transfer to the water.	Uncovered fuel will mainly loose its heat by convection heat transfer with the air (cooling by thermal radiation is not possible for the inner fuel pins). If laminar flow is occurring in the uncovered fuel, it will have a lower convective heat loss, as compared to if the flow was turbulent.		Fuel has been re-covered with water and heat transfer to the water is high.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Some uncertainty in modelling laminar flow			

Detailed description and rationale:

Laminar flow occurs when a fluid flows in parallel layers without disruption of these layers. Close to a wall, there is a thin layer (called viscous sublayer) where the flow is laminar. In the water pool itself, small sub-channel flows may have laminar flow. Other areas where laminar flow may occur are in the gas space in the transition between convection dominant zone and the stratified zone (zone without velocity where temperature or gas concentration gradients exists). In this transition, the flow can be laminar before the flow stops. This transition can also occur at the edges of dead end zones.

In CFD computer code models, this zone is usually not computed but modeled by the use of wall functions. Low Reynolds turbulence models address also this zone but they are presently not used at reactor scale.

The theory of laminar flow is well established and documented in the open literature. In CFD computer code models, this zone is usually not computed but modeled by the use of wall functions. Low Reynolds turbulence models address also this zone but they are presently not used at reactor scale. Thus, there are still some uncertainty in modelling laminar flow.

Reference:

[1] "Containment Code Validation Matrix", NEA/CSNI/R(2014)3, 2014 May

Champion: Sammy Chin

ID #	Phenomenon Synopsis Title
48	Turbulent flow (gas space, liquid)

Phenomenon				Definition			
Turbulent flow (gas space, liquid)				A turbulent flow is a fluid flow that includes rapid variations in the velocity and pressure in time and space, and generally has stochastic components. Turbulence involves eddy formation at many different length scales, with the largest related to geometry and the smallest to viscosity. Turbulent flow is expected for all phases of the accident. Spacer pads (appendages) will induce turbulence. Even natural convective flows in the gas space will be turbulent.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
H	H	H	H	Turbulence increases mixing and reduces thermal and concentration gradients in the fluids. It also increases convective heat transfer.			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Uncertainty arises from modelling turbulence.			

Detailed description and rationale:

Turbulent flow has a high impact on the figure of merit (sheath temperature) as it also increases convective heat transfer from the fuel to the surrounding fluid. It is also responsible for mixing the fluid, thereby reducing any thermal or concentration gradients.

The theory is well known, but there are many turbulence models available for CFD modelling and numerical benchmarks against experiments demonstrate that there is not a single one that works for all situations.

Reference:

[1] “Containment Code Validation Matrix”, NEA/CSNI/R(2014)3, 2014 May

Champion: Sammy Chin

ID #	Phenomenon Synopsis Title
49	Building leakage of gases and aerosols

Phenomenon				Definition			
Building leakage of gases and aerosols				The Spent Fuel Pool (SFP) is housed in an industrial building, not a containment building. Leakage will occur as the building atmosphere starts to be pressurized by the addition of steam (and to a lesser extent by hydrogen). The hot gases inside the SFP will tend to leak through the higher elevation openings, with an accompaniment of in-flow of cold air from the outside. This is especially enhanced if the leakage is through a large open doorway. The concern with the leakage is that the gas/vapour mixture will carry fission products (gases or aerosol) out of the spent fuel pool building.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	M	M	M	Leakage will define the SFP vapour space pressure and steam, which affects the FOM (sheath temperature) through the evaporation rate. As well, in this phase, there is only a small amount of fission gas and Tritium present.	Leakage will define the SFP vapour space pressure and steam, which affects the FOM through the evaporation rate. However, once fuel is exposed, then there will be more defects and more potential for release of FP.	Leakage will define the SFP vapour space pressure and steam, which affects the FOM through the convection heat transfer between the fuel and the vapour-gas mixture. However, the fuel is now fully exposed and there is a high potential for release of fission products.	Leakage will define the SFP vapour space pressure and steam, which affects the FOM through the convection heat transfer between the fuel and the vapour-gas mixture. However, the fuel is now fully exposed and there is a high potential for release of fission products due to reflooding.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
2	2	2	2	The building is just an industrial building and is not a pressure boundary. As such, leakage can be calculated assuming a maximum building pressure. What is a larger source of uncertainty is the amount of cold air than can leak into the building.			

Detailed description and rationale:
The importance with respect to the figure of merit (FOM), sheath temperature, is medium as leakage will only affect the vapour space pressure (but this is minimal as the building is not a pressure boundary) and steam concentration (at the pool surface), which affects the evaporation rate and also the convective heat transfer between the exposed fuel and the vapour-gas mixture. However, it is the pathway by which fission products are released to the environment. There is some uncertainty on the actual leakage paths, but the total amount of leakage can be calculated. A larger source of uncertainty is the amount of air that can leak back into the building. Air would contribute to the hydrogen combustion hazard.
Although this phenomenon does not have a significant effect on sheath temperature, it is an important factor for worker safety, and dose to the public.
Champion: Sammy Chin

ID #	Phenomenon Synopsis Title
50	Deflagration

Phenomenon				Definition			
Deflagration				Deflagration deals with combustion with flame speeds on the order of several meters per second to several hundred meters per second. The burning rate can be affected by initial conditions (mixture compositions, pressure, and temperature), geometry of the confinement, location of ignition, and turbulence level. For slow flames, the maximum deflagration pressure is bounded by the adiabatic isochoric complete combustion (AICC) pressure.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	H	H	M	As fuel is covered with water, H_2 production would be primarily from water radiolysis. Due to low H_2 production rate and active ventilation in the SFP building, the likelihood for H_2 accumulation and deflagration is low.	As fuel is uncovered but with continuous cooling, H_2 can be produced from Zr-steam reaction. H_2 can mix with air and become flammable. If ignited, deflagration may pose a danger to the SFP building. The continuous supply of steam from the pool will tend to inert the atmosphere. However, condensation may increase the local hydrogen concentration. Damage to the SFP building will increase the evaporation rate (increase loss of steam and inflow of air to the building), re-suspension of deposited radionuclides and reduced capability of building to retain radionuclides.	As SFP experiences total loss of coolant, the steam source is reduced to evaporation from the limited amount of water underneath the fuel and hydrogen production may continue. As well, with the reduced steam supply, the steam inerting effect is reduced and condensation will increase the local hydrogen concentration. Damage to the SFP building will increase the evaporation rate (increase loss of steam and inflow of air to the building), re-suspension of deposited radionuclides and reduced capability of building to retain radionuclides.	As cooling is recovered, Zr-steam reaction can be quenched, but the sheath temperature remains high, so some H_2 may still be produced from Zr-steam reaction, but the total H_2 should be low and the risk for combustion is reduced.

Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Uncertainties may arise from the H_2 production from water radiolysis at elevated water temperature.	Uncertainties may arise from the H_2 production from Zr-steam reaction and H_2 distribution in the SFP building.	Uncertainties may arise from the level of obstructions and confinement and H_2 distribution in the SFP building.	Uncertainties may arise from the H_2 production during the quenching.

Detailed description and rationale:

A deflagration, also referred to as a flame, is an expansion wave, with both pressure and density decreasing across the reaction front. The propagation of deflagration is caused by the diffusion of heat and intermediate reaction species from the flame into the unburned gas. In an accident involving a deflagration of pre-mixed flammable hydrogen-air mixture, if ignited, the flame starts as a slow flame with a velocity between several centimeters to several meters per second. In the absence of turbulence and confinement, the burning rate is slow and the overpressure generated will be small. The expansion of the gas generates a turbulent flow field, and feedback from this in turn increases the effective burning rate, as well as the rate of expansion. The burning rate can be affected by initial conditions (mixture compositions, pressure, and temperature), geometry of the confinement, location of ignition, and turbulence level. For instance, internal structures of a building can produce obstructions and confinement to the flame. When the flame passes obstacles, the intensity of the turbulent flow field will be increased, so the burning rate increases dramatically, which then increases both the flow velocity and turbulence ahead of the flame. An accelerated flame can reach a velocity on the order of several hundreds of meters per second. The strength of an accelerated flame depends on many different factors, but generally, mixture composition and uniformity. For deflagrations, the maximum deflagration pressure is bounded by the adiabatic isochoric complete combustion (AICC) pressure.

Reference:

[1] "Containment Code Validation Matrix", NEA/CSNI/R(2014)3, 2014 May

Champion: Sammy Chin (written by Zhe (Rita) Liang)

ID #	Phenomenon Synopsis Title
51	Flame acceleration

Phenomenon				Definition			
Flame acceleration (FA)				In the presence of obstructions or confinement, a slow flame (several meters per second) can be accelerated and the burning rate can be significantly increased.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	H	H	M	As fuel is covered with water, H_2 production would be primarily from water radiolysis. Due to low H_2 production rate, the risk for FA is low.	As fuel is uncovered but with continuous cooling, H_2 can be produced from Zr-steam reaction. H_2 can mix with air and become flammable. If ignited, deflagration may pose a danger to the SFP building. The continuous supply of steam from the pool will tend to inert the atmosphere. However, condensation may increase the local hydrogen concentration. A slow flame may accelerate to a fast flame due to obstructions in the SFP building. Damage to the SFP building will increase the evaporation rate (increase loss of steam and inflow of air to the building), re-suspension of deposited radionuclides and reduced capability of building to retain radionuclides.	As SFP experiences total loss of coolant, the steam source is reduced to evaporation from the limited amount of water underneath the fuel and hydrogen production may continue. As well, with the reduced steam supply, the steam inerting effect is reduced and condensation will increase the local hydrogen concentration. A slow flame may accelerate to a fast flame due to obstructions in the SFP building. Damage to the SFP building will increase the evaporation rate (increase loss of steam and inflow of air to the building), re-suspension of deposited radionuclides and reduced capability of building to retain radionuclides.	As cooling is recovered, Zr-steam reaction can be quenched, but the sheath temperature remains high, so some H_2 may still be produced from Zr-steam reaction, but the total H_2 should be low and the risk for FA is reduced.

Knowledge Assessment (by sub-scenario)				Knowledge Assessment Rationale (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
2	2	2	2	Uncertainties may arise from the H_2 production from water radiolysis at elevated water temperature. The knowledge for deflagration and detonation are well known. However, criterion for flame acceleration and DDT are not well defined, particularly for non-uniform mixtures.			

Detailed description and rationale:

The process immediately following a weak ignition in a combustible gas mixture is characterized as deflagration (Phenomenon 50), where the combustion propagates at subsonic speed into the unburned mixture. The initially smooth flame surface can be wrinkled due to the Landau-Darrieus instability, which can be stabilized or destabilized by thermal-diffusion effects. This can result in the formation of a cellular flame leading to an increase of the flame surface and the acceleration of the flow generated by the expansion of the combustion products. In addition, turbulence and the obstacles located along of the flame path (i.e., girders in the ceiling) can cause further increase in the flow velocity. Depending on the mixture properties and boundary conditions, the interaction of the flame with turbulence in the unburned gas can lead to either weak flame acceleration within relatively slow, unstable, turbulent flame regimes, or strong flame acceleration resulting in fast flames that propagate at supersonic speeds. The mixture expansion ratio is a key parameter that separates the potential for development of fast flames. With a sufficiently large run-up distance, supersonic combustion regimes can be developed as well.

References:

[1] "Containment Code Validation Matrix", NEA/CSNI/R(2014)3, 2014 May

[2] "Flame Acceleration and Deflagration to Detonation Transition in Nuclear Safety", NEA/CSNI/R(2000)7, 2000 August

Champion: Sammy Chin (written by Zhe (Rita) Liang)

ID #	Phenomenon Synopsis Title
52	Deflagration to detonation transition (DDT)

Phenomenon				Definition			
DDT				In the presence of obstructions or confinement, a slow flame (several meters per second) can accelerate to a fast flame (hundred meters per second), and, under certain circumstances, lead to a transition to detonation (a few kilometers per second).			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	H	H	M	As fuel is covered with water, H_2 production would be primarily from water radiolysis. Due to low H_2 production rate, the risk for DDT is low.	As fuel is uncovered but with continuous cooling, H_2 can be produced from Zr-steam reaction. H_2 can mix with air and become flammable. If ignited, deflagration may pose a danger to the SFP building. The continuous supply of steam from the pool will tend to inert the atmosphere. However, condensation may increase the local hydrogen concentration. A slow flame may accelerate to DDT due to obstructions in the SFP building. Damage to the SFP building will increase the evaporation rate (increase loss of steam and inflow of air to the building), re-suspension of deposited radionuclides and reduced capability of building to retain radionuclides.	As SFP experiences total loss of coolant, the steam source is reduced to evaporation from the limited amount of water underneath the fuel and hydrogen production may continue. As well, with the reduced steam supply, the steam inerting effect is reduced and condensation will increase the local hydrogen concentration. A slow flame may accelerate to DDT due to obstructions in the SFP building. Damage to the SFP building will increase the evaporation rate (increase loss of steam and inflow of air to the building), re-suspension of deposited radionuclides and reduced capability of building to retain radionuclides.	As cooling is recovered, Zr-steam reaction can be quenched, but the sheath temperature remains high, so some H_2 may still be produced from Zr-steam reaction, but the total H_2 should be low and the risk for DDT is reduced.

Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
2	2	2	2	Uncertainties may arise from the H_2 production from water radiolysis at elevated water temperature. The knowledge for deflagration and detonation are well known. However, criterion for flame acceleration and DDT are not well defined, particularly for non-uniform mixtures.			

Detailed description and rationale:

Deflagration to detonation transition (DDT) refers to an abrupt change in the mode of combustion from deflagration to detonation in the absence of a high energy source. An expanding deflagration wave resulting from a gas explosion is intrinsically unstable, susceptible to flame acceleration. As the flame speed increases, a compression wave (commonly referred to as a precursor shock) can be generated ahead of the combustion front as a result of the thermal expansion of the combustion products. The strength of this precursor shock depends on the speed of the deflagration wave. As the flame speed continues to increase, the precursor shock strength also increases. For a highly accelerated flame, or supersonic flame (speed greater than the speed of sound in the unburned gas), this precursor shock can be very strong, comparable to detonation peak pressures. Under suitable conditions, strong flame acceleration can sequentially lead to a detonation.

The dynamic pressure loads induced by propagating flames increase with the flame speed. The destructive potential of sonic deflagrations, DDT and detonations is substantial and pose a significant challenge to the integrity of structures.

Direct accidental initiation of detonation (the most energetic form of combustion) is very unlikely inside a post-accident SFP building, because it requires high energy ignition sources such as solid explosives, but DDT is likely to be the mechanism to initiate a detonation.

References:

[1] "Containment Code Validation Matrix", NEA/CSNI/R(2014)3, 2014 May
[2] "Flame Acceleration and Deflagration to Detonation Transition in Nuclear Safety", NEA/CSNI/R(2000)7, 2000 August

Champion: Sammy Chin (written by Zhe (Rita) Liang)

ID #	Phenomenon Synopsis Title
53	Detonation

Phenomenon				Definition			
Detonation				A supersonic compression wave, with typical velocities on the order of a few kilometers per second, can be initiated via a strong ignition source or by sequential acceleration of a slow flame.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	H	H	M	As fuel is covered with water, H_2 production would be primarily from water radiolysis. Due to low H_2 production rate, the risk for detonation is low.	As fuel is uncovered but with continuous cooling, H_2 can be produced from Zr-steam reaction. H_2 can mix with air and become flammable. If ignited, deflagration may pose a danger to the SFP building. The continuous supply of steam from the pool will tend to inert the atmosphere. However, condensation may increase the local hydrogen concentration. Detonation may be initiated from a slow flame by FA and DDT. Damage to the SFP building will increase the evaporation rate (increase loss of steam and inflow of air to the building), re-suspension of deposited radionuclides and reduced capability of building to retain radionuclides.	As SFP experiences total loss of coolant, the steam source is reduced to evaporation from the limited amount of water underneath the fuel and hydrogen production may continue. As well, with the reduced steam supply, the steam inerting effect is reduced and condensation will increase the local hydrogen concentration. Detonation may be initiated from a slow flame by FA and DDT. Damage to the SFP building will increase the evaporation rate (increase loss of steam and inflow of air to the building), re-suspension of deposited radionuclides and reduced capability of building to retain radionuclides.	As cooling is recovered, Zr-steam reaction can be quenched, but the sheath temperature remains high, so some H_2 may still be produced from Zr-steam reaction, but the total H_2 should be low and the risk for detonation is reduced.

Knowledge Assessment (by sub-scenario)				Knowledge Assessment Rationale (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Uncertainties may arise from the H_2 production from water radiolysis at elevated water temperature.	Uncertainties may arise from the H_2 production from Zr-steam reaction and H_2 distribution in the SFP building.	Uncertainties may arise from the level of obstructions and confinement and H_2 distribution in the SFP building.	Uncertainties may arise from the H_2 production during the quenching.

Detailed description and rationale:

A detonation, the most energetic form of combustion, is a supersonic wave, with typical velocities on the order of a few kilometers per second. It is a compression shock wave with pressure and density increasing across the wave. The detonation is caused by heating of the unburned gas via a shock wave (created by the energy release in the reaction zone) to temperatures capable of causing ignition in the unburned gas. As a result, the propagation mechanism for a detonation is "kinetic-controlled" and the reaction front is coupled to the shock wave and they propagate at the same velocity. Due to the much larger over-pressures generated in a detonation front, detonations can cause damages that are much more severe as compared to those associated with the blast waves produced by deflagrations. Detonation of hydrogen mixtures inside a SFP building can result in ultimate dynamic mechanical loads to the building structure.

There are two modes to initiate detonation in combustible gas mixtures: a fast mode and a slow mode. In the fast mode, detonation is formed instantaneously due to rapid deposition of a large amount of energy in a small volume of the combustible mixture, such as high energy explosive, strong shock waves and high voltage discharge. In the slow mode, detonation is initiated from a slow flame, but followed by FA and DDT.

In an accident situation, direct initiation of detonation in a SFP building is very unlikely because it requires strong shock source. However, transition from deflagration to detonation may be possible depending on both the initial conditions (such as mixture composition, pressure, temperature) and the boundary conditions (such as size of the enclosure, obstacle configuration and obstacle spacing).

References:

[1] "Containment Code Validation Matrix", NEA/CSNI/R(2014)3, 2014 May

[2] "Flame Acceleration and Deflagration to Detonation Transition in Nuclear Safety", NEA/CSNI/R(2000)7, 2000 August

Champion: Sammy Chin (written by Zhe (Rita) Liang)

ID #	Phenomenon Synopsis Title
55	Irradiation annealing and sheath recrystallization

Phenomenon				**Definition**			
Irradiation annealing and cladding recrystallization				When Zircaloy is irradiated the strength increases and ductility decreases. Both of these property changes anneal out as sheath temperature increases.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	M	M	L	Low temperature	Temperature of sheath increases as it is uncovered	Same as 2	Sheath temperatures drop on rewet.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	See details below	See details below	See details below	See details below

Detailed description and rationale:

Codes exist for modelling and calculating this phenomenon (ELESTRES, ELOCA).

Irradiation increases the strength of zirconium alloys and reduces their ductility. The change in property is related to the neutron exposure at fast flux. Irradiation temperature, metallurgical condition (heat treatment and cold work) and the alloy composition each affect the change in properties with irradiation. As sheath temperature rises the effects of irradiation strengthening anneals out.

At low temperatures (<700 K), Zircaloy fuel sheathing exhibits low ductility due to work hardening during the manufacturing process followed by irradiation hardening while in use. At Normal Operating Condition temperatures, the dislocations formed by the irradiation damage continually anneal out, and a steady-state is reached at which the rate of formation of the dislocations match the rate of annealing. This equilibrium is reached within the first few hours of irradiation, and at Normal Operating Condition temperatures it is such that the sheath is significantly strengthened and embrittled.

In Sub-Scenarios 2 and 3 the sheath temperature (FOM) is likely to rise and the influence of Irradiation annealing and sheath recrystallization is likely to anneal out, if the temperature rise is high and the time at temperature is sufficiently long. Therefore the Importance of this phenomenon ranked as Medium is justified. The knowledge level of “3” is also justified because adequate knowledge exists with moderate uncertainty.

Champion: Nithy Nitheanandan

ID #	Phenomenon Synopsis Title
56	Sheath strain and failure

Phenomenon				Definition			
Sheath strain and failure				At high temperatures and under internal pressure from fill gas and released fission gas, the sheath will strain. The strain rate is affected by irradiation damage, Zircaloy crystallite size and texture, and by oxidation. At strains greater than the limit of plastic stability (~5%), excessive plastic deformation occurs and the sheath can fail (ballooning). Failures can also occur by cracking of oxide, stress corrosion cracking induced by released fission products, beryllium braze assisted crack penetration, fretting, or mechanical or thermal shock of embrittled sheath on quench. The sheath can also fail by through-wall oxidation (see Phenomenon 27), because the oxide has very poor structural integrity.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	H	H	H	No failures expected	Failures will begin occurring	Failures expected in exposed fuel.	Failures can occur on quench if the sheath has been embrittled by oxidation or hydriding.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Models for sheath deformation exist, but uncertainty can be high, especially at high temperatures.			

Detailed description and rationale:

Sheath deformation (strain) can be modelled (ELOCA) and sheath failure criteria have been identified. However, moderate uncertainty exists in predicting failure locations and timing (sheath failure criteria tend to be conservative). If the pellet-to-sheath gap opens, heat transfer from the pellet to the sheath (Phenomenon 62) is affected.

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
57	Hydrogen pick-up under steam + air +hydrogen

Phenomenon				**Definition**			
Hydrogen pick-up under steam + air +hydrogen				During Zircaloy oxidation in environments containing steam and/or hydrogen, a fraction of the hydrogen generated during the oxidation is absorbed into the Zircaloy under the oxide layer. Precipitation of this hydrogen as hydrides can lead to embrittlement of the Zircaloy sheath, which may cause sheath failure during later stages of the accident.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	M	M	M	Pickup of hydrogen in boiling water at or near room pressure is a fraction of the rate of sheath oxidation, which is slow.	Sheath oxidation, with hydrogen production, will provide additional hydrogen for pickup.	Although the pool water is assumed to have evaporated or boiled-off, some steam may still be present to produce hydrogen.	Hydrogen content and hydride formation are significant for embrittlement failure on rewet.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Pickup of hydrogen under these conditions is related to the rate of oxidation. Experiments and models exist, with moderate uncertainty.			

Detailed description and rationale:

Pickup of hydrogen under BWR and PWR normal operating conditions is well documented, and indicate a pickup fraction of about 15%. Cladding with spalled oxide (75 µm to 110 µm thick) has higher hydrogen concentrations in the vicinity of the spallation, because the spalled area is cooler and hydrogen diffuses there from other regions of the cladding. Hydrogen content and hydride formation are significant for embrittlement failure on rewet in Phase 4. However, dissolution of the hydrides into the matrix of the Zircaloy is rapid at temperatures above 500°C [1], so the hydride embrittlement decreases during Phase 3 until the time of quenching.

Reference:

[1] P. Vizcaíno, A.D. Banchik and J.P. Abriata, "Hydride phase dissolution enthalpy in neutron irradiated Zircaloy-4", Journal of Nuclear Materials 336 (2005) 54–64

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
58	Hydride dissolution & precipitation

Phenomenon				Definition			
Hydride dissolution & precipitation				The formation of zirconium hydrides (deuterides for CANDU) is a secondary effect of fuel sheath failures and can lead to exposure of the fuel pellets. Hydrides have also been known to accumulate in the assembly welds, embrittling them when cold and causing some to break if loaded abnormally.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	L	L	Of limited concern and only in a small number of fuel bundles.	Of limited concern and only in a small number of fuel bundles.	Of lower concern. Hydrides will dissolve at higher temperatures. Assembly welds will be stronger.	Only of concern if storage structures (racks/baskets/modules) have lost integrity and element become abnormally loaded. Even so, only a small number of bundles would be at risk.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	OPEX and mechanisms for fuel defects are well documented and well known. OPEX for brittle assembly welds is available but the phenomenon has not been sufficiently studied and is not well understood.	As for Phase 1.	Of lower concern.	As for Phase 1.

Detailed description and rationale:

The formation of zirconium hydrides (deuterides for CANDU) is a secondary effect of fuel sheath failures. Large concentrations of Zr hydrides will result in fuel sheath embrittlement, breaking off of hydrided fuel sheath and exposure of the fuel pellets. Hydrides have also been known to accumulate in the assembly welds which are used to join fuel elements to the fuel bundle endplates (intact and defected elements). These dissolved hydrides will precipitate when the assembly welds become cool, embrittling them and causing some to break if loaded abnormally (transverse loads).

The dissolution and precipitation of Zirconium hydrides (deuterides) will not factor significantly in a SFP loss of water inventory accident scenario. The number of defected fuel elements in the SFP is small, and the impact of these on releases to the environment are discussed in other more relevant phenomena. Also, the embrittlement of assembly welds due to hydride precipitation is a high burnup phenomenon and so is restricted to only a small percentage of bundles. Assembly weld weakness has only been experienced in situations of transverse (non-axial) loading. These welds have not experienced problems at normal discharge burnups, during normal storage and if only axial loading forces are applied.

Champion: Jon Judah

ID #	Phenomenon Synopsis Title
59	Fuel cooling by sprays and makeup

Phenomenon				Definition			
Fuel cooling by sprays and makeup				Heat will be transferred to cold water from hot fuel when water is returned to the fuel bays. By definition, if makeup is present then the accident has progressed to stage 4.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	I	I	H	Inactive by definition.			Makeup water will cool the fuel bundles, returning the sheath to a low temperature.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	N/A	N/A	3				Experiments exist with moderate uncertainty

Detailed description and rationale:
Water may be returned to the fuel bays by portable pumps and fire hoses available at the sites, or via the makeup water system. The Canadian multi-unit CANDU stations only have makeup water systems in the main fuel bays, rather than engineered spray systems as found in the CANDU 6 fuel discharge bay. Heat transfer experiments with a bundle of electrical heaters were performed in spray cooling and with the lower region of the bundle immersed in water. Moderate uncertainty exist as the experiments are for single bundles, and the effect of multiple bundles or stack/rack/module arrangement is unknown.
Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
60	Fuel fragmentation and relocation (during ballooning, before and after sheath rupture)

Fuel fragmentation and relocation (during ballooning, before and after cladding rupture)				Due to sheath embrittlement from oxidation and hydriding, fuel-element fragmentation can occur, especially on rewet/quench. Fuel ballooning/element failure may also result from significant sheath strain, which could allow for an ingress of water or air into the element. With subsequent oxidation of the fuel under the breached site, element deterioration can further occur with localized conversion of UO_2 to U_3O_8 that can split and crack the embrittled sheath due to a volume expansion of the underlying fuel.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	M	H	H	Fuel is cool		Air oxidation to U_3O_8	Rewet will fragment the fuel
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	3	3	3		Phenomenon has been studied, with experiments and criteria available.		

Detailed description and rationale:

Sheath failure due to creep strain can occur at high-temperature resulting in a local bulge and a splitting of the sheath. A fuel sheath temperature in excess of the alpha–beta-Zircaloy transition temperature and an internal fission gas pressure higher than the external coolant pressure are pre-requisites for this latter type of failure mechanism. The sheath can particularly lose ductility due to hydriding, development of thick oxide layers and spalling of the oxide. Subsequent fragmentation of fuel elements can occur in a degraded bundle with cool down and/or quenching. Measurements have been made on the loss of ductility and embrittlement of Zircaloy-4 cladding by oxidation and hydriding under LOCA conditions and with a water quench. For example, the LOFT FP-2 test demonstrated that when coolant was introduced into a hot bundle, a resultant thermal shock caused fragmentation of the fuel rods with oxygen embrittlement of the fuel sheaths. For instance, based on measurements conducted by Sawatzky and other researchers, failure criteria have been derived for this phenomenon where if the oxygen concentration over half the sheath wall thickness exceeds 0.7 wt.%, the sheath will be sufficiently brittle to fail upon rewet. The criterion appears to be well founded and has the advantage of being very similar to a failure criterion used by the US nuclear industry. With the presence of stored defective fuel, additional element deterioration can occur as a combination of both sheath and fuel oxidation, where, for instance, an irradiated failed element exposed for 2.5 h in air at 900°C showed significant sheath deformation. This deterioration was associated with fuel oxidation and a phase change of the Zircaloy where solid UO_2 fuel fragments and U_3O_8 powder fell out of the enlarged defect location.

Champion: Brent Lewis

ID #	Phenomenon Synopsis Title
61	Release of retained fission gases due to fuel fragmentation

Phenomenon				**Definition**			
Release of retained fission gases due to fuel fragmentation				Fission gases in fuel at the grain boundaries and in large intragranular bubbles may be released by cracking of the fuel, mainly along grain boundaries. Fuel fragmentation may occur during fuel oxidation in air, rapid heating, or rapid cooling.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	M	M	H	Low temperature, no fragmentation	Fuel oxidation (steam or air) will promote fragmentation.		The addition of rapid cooling (in addition to the oxidation or high temperature UO_2-Zircaloy oxidation) will result in additional fragmentation and release of fission products.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	4	4	3		Models of fuel oxidation are available for both steam and air.		Fragmentation due to quenching is a stochastic process, with some uncertainty.

Detailed description and rationale:

Fuel fragmentation may occur on rapid heating [1] or fuel oxidation in air at low temperature [2]. Fuel fragmentation by these mechanisms tends to occur along grain boundaries, which are weakened areas in the fuel matrix. The main fission gases that are released by this mechanism are the grain boundary inventory.

Fuel oxidation in air at low temperature (~300°C to 650°C) to U_3O_8 occurs more rapidly along the grain boundaries. The resulting volume increase tends to pop the grains out of the surface and expose fresh fuel surface, giving rise to rapid fragmentation. At ~500°C, about 2.5% of the grain inventory of fission gases was also released by the fragmentation process.

Another mechanism of fuel fragmentation occurs when a sample is heated until UO_2-Zircaloy interaction occurs, and then is cooled below ~1000°C and oxidized in steam or air [3]. Metallic uranium precipitates form during cooling after UO_2-Zircaloy interaction, and these precipitates increase significantly in volume on oxidation, fragmenting some of the fuel pellet to <1 mm diameter. The fragmented fraction increases with increased duration at UO_2-Zircaloy interaction temperature and decreases with increasing steam oxidation temperature. This fragmentation mechanism is unlikely, because of the complicated temperature history and high temperatures (>1500°C) required.

Related phenomena:

60: Fuel fragmentation and relocation (during ballooning, before and after cladding rupture)

66: UO_2 Oxidation

References:

[1] R.S. Dickson, A.I. Belov, M.D. Gauthier, R.T. Peplinskie and C.A. Buchanan, “Fuel Behaviour and Fission Product Release in the Power Pulse 1 Experiment”, Proceedings of the 11th International Conference on CANDU Fuel, Niagara Falls, 2010 October 17-20, AECL Report CW-126320-CONF-004

[2] P.H. Elder, D.S. Cox, L.W. Dickson and R.V. Murphy, “New Post-Irradiation Examination Techniques at Chalk River Laboratories: Gamma Tomography and Grain-Boundary-Inventory Measurements on Irradiated Fuel”, Recent developments in post-irradiation examination techniques for water reactor fuel, Cadarache, France, 1994 October 17-21, IAEA-TECDOC-822

[3] D.G. Evans, P.M. Mathew and M.C. Arneson, “Effect of the UO_2/Zr Interaction on the Fragmentation of Unirradiated UO_2 Fuel Pellets”, Proc. 12th CNS Annual Conference, Saskatoon, SK, Canada, 1991

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
62	Heat transfer in sheath, pellets and through the gap, which affects distribution of temperature, strain and stresses

Phenomenon				**Definition**			
Heat transfer in sheath, pellets and through the gap, which affects distribution of temperature, strain and stresses				The decay heat generated within the fuel is conducted through the fuel material, through the fuel/sheath interface or fuel/sheath gap, and though the sheath. The sheath can be coated by oxide layers or CRUD, which would reduce the effectiveness of heat transfer through the sheath.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	H	H	H	Prior to fuel uncovery, sufficient cooling is available such that the sheath temperature will be close to the pool water temperature.	When the fuel is uncovered, the sheath temperature will be highly influenced by the heat transfer through the fuel and fuel/sheath gap or interface.		Heat transfer in the fuel element will affect the rate of temperature decrease during recovery. As well, reflooding the fuel bundles will take time, during which the sheath temperature will be influenced by the heat transfer within the fuel element.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Validated computer codes, such as ELOCA, exist to calculate the heat transfer within a fuel temperature. However, the effect of oxide or CRUD layers is not currently incorporated into the codes. Also, the current code is one-dimensional and a multi-dimensional analysis would be beneficial [1,2].			

Detailed description and rationale:

Heat transfer in the fuel element includes heat generation within the fuel (decay heat), diffusion through the fuel, heat transfer through the fuel/sheath gap or interface, and diffusion through the sheath and any oxide or CRUD coatings. If the fuel bundle is submerged in water, heat transfer in the fuel element does not significantly affect the sheath temperature, as sufficient cooling is available. However, if the fuel bundle is exposed to air or steam, then the sheath temperature will be influenced by the heat transfer in the fuel element. The knowledge level is high because validated computer codes, such as ELOCA, exist to model the heat transfer in a fuel element. However, some gaps exists such as the influence of oxide layers or CRUD on heat transfer. As well, the current code, ELOCA, is one-dimensional (radial) and a multi-dimensional analysis could be useful to incorporate the interaction between the fuel element/bundle and other bundles or racks/modules [1,2].

References:

[1] C.J. Krasnaj and W. Grant, "Development of a 2-D Finite Element Model to Examine Both Natural Convection and Radiative Cooling of a Spent Fuel Bundle in Air", Proc. 19th PBNC Conference, Vancouver, BC, Canada, 2014 August 24-28

[2] C.J. Krasnaj and W. Grant, "Finite Element Analysis of Heat Transfer Between Spent CANDU Fuel Bundles in Spent Fuel Pools", Proc. 19th PBNC Conference, Vancouver, BC, Canada, 2014 August 24-28

Champion: Jeffrey Baschuk

ID #	Phenomenon Synopsis Title
63	Axial gas flow in rod after cladding rupture

Phenomenon				**Definition**			
Axial gas flow in rod after cladding rupture				The dynamics of axial gas-flow along the fuel rod, from the plenum to the clad ballooning location, can have a significant effect on the timing of fuel cladding rupture [1]. Flow restriction will delay cladding rupture, due to a decrease in the pressure in the vicinity of the ballooning cladding.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	I	I	I	Phenomenon does not need to be considered for CANDU spent fuel bay accidents.			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A				Phenomenon does not need to be considered for CANDU spent fuel bay accidents.			

Detailed description and rationale:

The consensus of the panel was that this phenomenon is not significant for CANDU fuel. CANDU fuel is significantly shorter than LWR fuel, and also does not contain plenums.

Reference:

[1] G. Khvostov, W. Wiesenack, M.A. Zimmermann and G. Ledergerber, “Nuclear Engineering and Design”, 241(5), pp. 1500-1507, 2011 May

Champion: Jeffrey Baschuk

ID #	Phenomenon Synopsis Title
64	Oxidation and releases from previously defected fuel into the pool

Phenomenon				Definition			
Oxidation and releases from previously defected fuel into the pool				Previously defected fuel can oxidize during the temperature transient, causing fuel degradation, and release fission products and fuel particulate into the pool.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	H	M	Fuel is covered and is at a low temperature; oxidation rates will be low.	Fuel begins to uncover and some releases can occur.	Air oxidation could be an issue	Temperature is decreasing, so oxidation rates are also decreasing.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Experiments and models exist with moderate uncertainty.			

Detailed description and rationale:

The importance is low during Phase 1 because the temperatures are comparatively low and the gap inventory of fission products from the defected elements has already been released to the bay. The low-temperature oxidation in water is described in Phenomenon 66, "UO_2 Oxidation". In Phase 2, the environment will mainly be steam, so the oxidation will be comparatively slow unless the sheath temperature rises above ~800°C, partly because the oxidation in steam does not cause significant dimensional changes. In Phase 3, the temperatures are slightly higher, but the increasing incorporation of air into the environment will cause the defected fuel and sheaths to oxidize (see Phenomenon 66, "UO_2 Oxidation"), with the possibility of splitting the sheath [1], which would increase environment access to the fuel, and releasing FP [2], [3] (see Phenomenon 61, "Release of retained fission gases due to fuel fragmentation"). A temperature of 400°C will cause severe sheath splitting in less than 24 h, and extensive deterioration occurs in about 2 hours at higher temperatures (600°C and 900°C). In Phase 4, although the average temperatures are decreasing, the increased steam supply, greater state of fuel damage and possible consequential fuel damage may cause some further oxidation and releases. Note that the radiolysis products of air and water (NO_X, O_2^{2-}, H_2O_2, OH) will enhance the oxidation.

References:

[1] I.J. Hastings, "Behaviour in Air at 175-400°C of Irradiated UO_2 Fuel", Proc. International Workshop on Irradiated Fuel Storage – Operating Experience and Development Programs, Toronto, ON, Canada, AECL Report AECL-8562, 1984 October 17-18

[2] Z. Liu, D.S. Cox, R.S. Dickson and P.H. Elder, "Release of Semi- and Low-Volatile Fission Products From Bare UO_2 Samples During Post-Irradiation Annealing", Proc. 15th Annual Conference of the Canadian Nuclear Society, Montreal, QC, Canada, Session 5A, AECL Report AECL CONF 00087, 1994 June 5-8

[3] R.S. Dickson, R.T. Peplinskie and M.D. Gauthier, "Release of Fission Products from CANDU Fuel in Air Environment", Proc. 10th International Conference on CANDU Fuel, Ottawa, ON, Canada, AECL Report CW-126320-CONF-003, 2008 October 5-8

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
66	UO_2 oxidation

Phenomenon				Definition			
UO_2 oxidation				When UO_2 fuel in a breached fuel element is exposed to a water, steam or air environment especially at elevated temperatures the fuel can oxidize to other phases (in accordance with a Pourbaix diagram for aqueous corrosion or with the uranium-oxygen phase diagram for steam or air oxidation).			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	H	H	H	Fuel temperatures are low and little oxidation is expected.	Fuel oxidation can result in significant release of fission products.		
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Experiments and models exist, with moderate uncertainty.			

Detailed description and rationale:

Fuel oxidation can affect the thermal performance of the fuel element and associated fission product release. The element performance is directly affected as a result of: (i) a degraded fuel thermal conductivity with continued oxidation, and (ii) a lower incipient melting temperature in hyperstoichiometric fuel. It can also impact fuel volatilization and fission product release behaviour during the accident. As part of the initial state, the uranium dioxide fuel in a defective element can oxidize in-reactor to UO_{2+x} prior to discharge. In addition, the fuel can continue to slowly oxidize over several years while stored in water bays open to the air surface at ~30°C via: (i) solid-state diffusion to U_3O_7 (similar to dry oxidation), (ii) oxidative dissolution and precipitation of U(VI) as ~$(UO_3)\cdot 0.8\ H_2O$, and (iii) back-reduction of dissolved U(VI) on the UO_2/U_3O_7 surface to form U_3O_8. Oxidation of fuel in air occurs via a two-step nucleation-and-growth mechanism: $UO_2 \rightarrow U_4O_9 \rightarrow U_3O_8$, which has been extensively studied because of its importance to dry storage and disposal of used nuclear fuel. The "intermediate" phase(s) (U_4O_9/U_3O_7) forms as a discrete layer on the UO_2 surface sample that thickens with time, where the reaction occurs by a moving boundary process that is limited by oxygen diffusion through the surface layer. In the second step of the reaction, grain-boundary diffusion is relatively rapid compared to the rate of U_3O_8 formation since three-dimensional bulk formation of U_3O_8 will be slower than unhindered oxidation along the surface. Enhanced fuel oxidation also occurs with the production of nitrogen oxides formed by radiolysis of air, as well as production of radiolytic oxidants from water (O_2^{2-}, OH, H_2O_2). Numerous tests with irradiated defected fuel elements have shown significant diametral increases and sheath cracking due to localized U_3O_8 formation in air (with the accompanying density decrease of this phase), e.g., a 6% maximum diametral increase was observed in 4 h at 400°C leading to significant diametral increase/sheath splitting at defect locations in 24 h at this temperature due to local oxidation of UO_2 to U_3O_8, sheath cracking occurred at the defect site after 2 h at 600°C, while severe sheath deformation with a 45% diametral increase resulted along the entire element length after 2.5 h at 900°C.

Champion: Brent Lewis

ID #	Phenomenon Synopsis Title
67	Fuel Melt

Phenomenon				Definition			
Fuel Melt				The fuel (UO_2) turns to the liquid phase (melts) at high temperature.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	I	I	I	Fuel melting is not expected to occur for CANDU spent fuel bay accidents.			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A				Fuel melting is not expected to occur for CANDU spent fuel bay accidents.			

Detailed description and rationale:

Because of the low decay power and relatively low sheath temperature (<1200 K) expected in a spent fuel bay accidents [1,2], the fuel temperature is expected to be much less than melting (3113 K [3]). Hence, fuel melting is not expected to occur during a CANDU spent fuel bay accident. Note that the lack of fuel melting also precludes molten fuel/concrete interaction phenomenon.

References:

[1] C.J. Krasnaj and W. Grant, “Development of a 2-D Finite Element Model to Examine Both Natural Convection and Radiative Cooling of a Spent Fuel Bundle in Air”, Proc. 19th PBNC Conference, Vancouver, BC, Canada, 2014 August 24-28

[2] C.J. Krasnaj and W. Grant, “Finite Element Analysis of Heat Transfer Between Spent CANDU Fuel Bundles in Spent Fuel Pools”, Proc. 19th PBNC Conference, Vancouver, BC, Canada, 2014 August 24-28

[3] SCDAP/RELAP5-3D Code Manual Volume 4: MATPRO – A Library of Materials Properties for Light-Water-Reactor Accident Analysis, INEEL/EXT-02-00589, 2003 October

Champion: Jeffrey Baschuk

ID #	Phenomenon Synopsis Title
68	Sheath Melt

Phenomenon				Definition			
Sheath Melt				At high temperatures (1850°C), the sheath will melt.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	L	M	L	Temperature too low for melting.	Pool would be in the process of uncovering, so the sheath temperatures would be low.	Melting or liquefying of the sheath could occur at temperatures ~ 1800 K.	Temperature too low for melting.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	3	3	3	Sheath temperature is well known if covered	Comparatively low sheath temperatures.	Temperatures are not expected to reach this level due to natural convection within the fuel stacks.	Sheath temperature is well known if covered

Detailed description and rationale:

Melting of the Zircaloy sheath would not occur until the temperature would reach 1850°C (2123 K), but interactions with the UO_2 fuel could liquefy the sheath at temperatures of about 1800 K. However, with the low power in the fuel bundles, the natural circulation within the pool and radiation heat transfer from the highest power fuel elements, the sheath would not be expected to reach these temperatures. Nevertheless, if molten material were formed, it would likely fall into the water in the bottom of the SFP and be quenched. Therefore, it is considered to be of LOW to MEDIUM importance. The sheath melting temperature is known, but there is uncertainty in calculating the sheath temperature

Champion: Bob Henry

ID #	Phenomenon Synopsis Title
69	Behaviour of defected fuel

Phenomenon				Definition			
Behaviour of defected fuel				Fuel oxidation, fission product release, thermal performance. Defected fuel will behaviour different than an intact fuel. Includes both pre-defected fuel (defected in the reactor) and defects during the accident			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	M	H	L	There will be very low impact during Phase 1. Fission products from existing defects which had been dissolved in the SFP water will be released.	As fuel is exposed, fuel bundles will start to heat up. Defected elements will release fission and activation products.	The situation will be at its worst when all of the fuel is exposed and there is no longer any cooling. Some new fuel defects can be expected to be created.	Sheath failure is expected during rewet but the overall situation will be improved as cooling is restored.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	The properties and behaviour of defected fuel elements and of the exposed irradiated fuel pellets has been studied, and are understood.	As for Phase 1 with the additional possibility of new fuel defects being created. The properties of Zircaloy in air and at high temperatures has been studied. The risk of additional fuel defects can be assessed.	As for Phase 2 with increased possibility of fuel defects being created. The knowledge base exists to perform estimates of fuel defect creation. Modeling of heat transfer and decay heats will be required to estimate the number of bundles at risk	Some additional defects will be created during quenching of hot dry bundles containing oxidized fuel sheathing. Existing knowledge will allow estimation of the number of fuel elements at risk. Modeling of heat transfer and decay heats will be required to estimate the number of bundles at risk.

Detailed description and rationale:

The behaviour of both defected and intact fuel elements has been well studied and documented by the CANDU industry. The knowledge base exists to predict the release of fission and activation products from defected fuel elements in both wet and dry conditions. Similarly, the behaviour of fuel sheathing in both wet and dry conditions, and as a function of sheath temperatures is well known. The most challenging part of these calculations will be in the prediction of fuel and sheath temperatures in the complex geometries and cooling conditions which will exist during the evolution of this accident.

The release rate of fission products will be low during Phase 1 of the accident and will be limited to that which has already leached out from defected fuel elements and is already present in the SFP water. No new defects would be expected to be created.

As fuel bundles begin to be exposed during Phase 2, fuel elements will heat up. Releases will increase from existing fuel elements as these heat up and as water that had entered the fuel elements through defects heats up and is boiled away, carrying away dissolved and entrained fission products. Some new fuel defects might be created, especially at the top of the fuel stack which will have the longest exposure to air. Note that partially filled modules/baskets containing freshly discharged fuel bundles are often stored at the highest elevations of the SFP, so that they are accessible until they are completely full. These freshly discharged bundles might be at greatest risk of defecting.

Releases will continue during Phase 3 with a much higher risk of new fuel defects being created, since there is now no water or steam cooling at all. The fuel sheaths and fuel pellets of existing defected bundles will oxidize further, aggravating the releases of fission products and fuel. Fuel elements which had not previously been defected will heat up and accelerated sheath oxidation might lead to additional fuel defects. Recently discharged fuel bundles/elements will be most at risk. In particular, the impact of a recent full core discharge (as at the start of a refurbishment outage) will require assessment because the relatively high decay heats, and possible concentration of these hot bundles in certain locations of the SFP.

Phase 4 will be of overall benefit as cooling is restored, however, quick quenching of hot fuel and hot Zircaloy would present the risk of creation of some additional fuel defects, and of release of a plume of fission products and fuel debris as hot material is quickly cooled in a relatively uncontrolled way (we could be pumping in cold lake water in winter).

Champion: Jon Judah

ID #	Phenomenon Synopsis Title
70	Effect of sea, river, lake, ground (impure) water injection

Phenomenon				**Definition**			
Effect of sea water injection				If water sources are utilized that have either dissolved or entrained materials, over time, these could eventually result in the accumulation of the materials within the SFP.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	I	I	M	Only relevant for Phase 3			Recovery actions could make use of other water sources available to the plant
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	N/A	N/A	3	Only relevant for Phase 3			Long term use of water sources that have dissolved or entrained materials could result in the accumulation of these materials within the pool.

Detailed description and rationale:
As a last resort, makeup in Phase 4 to cool the spent fuel bundles and retain fission products could be accomplished with other water sources available to the plant personnel. If water sources are utilized that have either dissolved or entrained materials, over time, these could eventually result in the accumulation of the materials within the SFP. Therefore, depending on the accident sequence, these sources should be considered as temporary and replaced by demineralized water whenever possible. Nevertheless, a decision tree should be formulated ahead of time so the when, where and how issues do not have to be generated in the confusion of a major event. Note that long term effect of Cl in seawater on concrete could be significant.

Champion: Bob Henry

ID #	Phenomenon Synopsis Title
71	Stainless steel oxidation

Phenomenon				Definition			
Stainless steel oxidation				The storage racks and modules are made of stainless steel (304L), which can oxidize at high temperatures in steam or air. Oxidation could threaten the integrity of the racks or modules and in the case of steam oxidation, would produce hydrogen.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	L	M	L	Before fuel uncovery, the temperature of the racks or modules will be too low for oxidation.	As the fuel uncovers, the temperature of the racks/module will increase and oxidation may occur. However, the temperature of covered racks/modules will remain too low for oxidation.	During complete fuel uncovery, the temperature of the racks/modules will be at a maximum. Steam oxidation may still occur if steam is still available. Oxidation could result in rack/module structural failure.	During reflood, the temperature of the racks/modules will decrease, reducing and stopping oxidation.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	2	2	2	Not applicable.	The oxidation of stainless steel, particularly in steam, is not as well studied as for Zirconium alloys. A comprehensive literature review would be needed and if gaps exists, additional experiments.		

Detailed description and rationale:

In an air environment, the maximum service temperature for intermittent exposure is approximately 815°C, and for continuous exposure is 900°C [1]. Since bundle temperatures could potentially reach 933°C [2], the rack/module temperatures may also reach temperatures that bring the potential of air oxidation. In general, oxidation rates of stainless steels in wet air is higher than for dry air [3]. The oxidation of stainless steel, particularly in steam, is not as well studied as for Zirconium alloys. Thus, the knowledge level is low (2), requiring at minimum a comprehensive literature review and, if gaps exists, additional experiments.

References:

[1] ASM Alloy Center Database, AISI Type 304L, http://mio.asminternational.org/ac/index.aspx?profileKey=grantami_ac_datasheets, accessed 2016 August 2

[2] C.J. Krasnaj and W. Grant, "Development of a 2-D Finite Element Model to Examine Both Natural Convection and Radiative Cooling of a Spent Fuel Bundle in Air", Proc. 19th PBNC Conference, Vancouver, BC, Canada, 2014 August 24-28

[3] *High-Temperature Characteristics of Stainless Steels*, American Iron and Steel Institute, https://www.nickelinstitute.org/~/Media/Files/TechnicalLiterature/High_TemperatureCharacteristicsofStainlessSteel_9004_.pdf, accessed 2016 August 2

Champion: Jeffrey Baschuk

ID #	Phenomenon Synopsis Title
72	Melting of fuel rack/module material

Phenomenon				Definition			
Melting of fuel rack/module material				The fuel racks or modules are made of stainless steel (304L), which melts between 1400 and 1455°C [1].			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	I	I	I	Melting of the fuel rack/module material (304L stainless steel) is not expected due to the low temperatures expected of the bundles (maximum 933°C [2])			
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A				Not assessed as rack/module melting is not expected to occur during the accident.			

Detailed description and rationale:

The melting temperature is significantly higher than the maximum sheath temperature expected in a CANDU spent fuel bay accident (933°C [2]). Hence, melting of the rack/module material is expected to be inactive during the accident sequence.

References:

[1] ASM Alloy Center Database, AISI Type 304L, http://mio.asminternational.org/ac/index.aspx?profileKey=grantami_ac_datasheets, accessed 2016 August 2

[2] C.J. Krasnaj and W. Grant, “Development of a 2-D Finite Element Model to Examine Both Natural Convection and Radiative Cooling of a Spent Fuel Bundle in Air”, Proc. 19th PBNC Conference, Vancouver, BC, Canada, 2014 August 24-28

Champion: Jeffrey Baschuk

ID #	Phenomenon Synopsis Title
73	Transport of released fission products

Phenomenon				Definition			
Transport of released fission products				Transport of fission products in the bay volume and building will determine the amounts and nature of release of fission products to the environment. Fission products can be transported as gases or vapours (mainly noble gases and iodine, with the possible addition of ruthenium), or as aerosols (most other fission products).			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	M	H	H	Small amount of fission product release is expected while the fuel remains covered.	As the fuel becomes uncovered, fuel failure is expected, although not as extensive as Phases 3 and 4.	The air environment will cause more fuel failures.	Rewet is expected to cause additional sheath failure.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Fission product vapour transport phenomena have been extensively studied, but there are still uncertainties related to chemistry and production of vapour-phase iodine and ruthenium compounds. Aerosol behaviour has been extensively studied for severe reactor accident conditions in the primary heat transport system and containment, but not as extensively for fuel bay accident conditions			

Detailed description and rationale:

The transport of vapours can be affected by reactions between vapours and between vapours and solids or liquids. Deposited fission products can revaporize by re-vaporization of a deposited vapour species, or by chemical reaction with the gaseous environment (possibly including air and water radiolysis products) or with the substrate if the temperature increases.

The transport of aerosols can be affected by condensation of water on solid, liquid and hydrophilic aerosol particles, agglomeration of aerosols, the presence of structural material aerosols, and the formation of mixed fission product-structural material-water aerosols. In the event of flame acceleration or explosion events, or rapid production of steam, aerosol and particulate material can be resuspended by rapid turbulent gas flows.

The importance of this phenomenon is directly related to the amount of fission products released during the phase, which is related to dose to the public and to local workers. The phenomenon is less important when fewer sources are available from failed fuel (Phases 1 and 2), than when failed fuel is expected (Phases 3 and 4). Fission product vapour transport phenomenon have been extensively studied, but there are still uncertainties related to chemistry and production of vapour-phase iodine and ruthenium compounds.

Aerosol behaviour has been extensively studied for severe reactor accident conditions in the primary heat transport system and containment, but not as extensively for fuel bay accident conditions. The conditions of fuel bay accidents are closely related to those of containments in severe accidents, but uncertainties in aerosol behaviour remain under containment conditions as well. For example, the nucleation of solid aerosols from mixed condensable species is still not well understood, and depends on the interactions of the vapour and solid species involved.

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
74	Fission product deposition

Phenomenon				Definition			
Fission products deposition				Fission products can be deposited on solid or liquid surfaces as aerosols or by condensation or dissolution of vapours.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	M	H	H	The only FP release comes from pool water, and limited additional releases from defected fuel.	More FP releases (and deposition) will occur as more fuel elements defect.	The highest fuel temperatures and greatest releases will occur during this phase, while the lower gas and steam flow rates will tend to increase the fractional deposition.	Until the fuel is covered, Phase 4 will be similar to Phase 3 (uncovered fuel, exposed to air); hence importance similar to Phase 3.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	3	3	Mechanisms are reasonably well understood, but the correct way to combine the behaviour of several simultaneously operating mechanisms is not always clear.			

Detailed description and rationale:

Deposition of aerosols can occur from laminar or turbulent flows, and by inertial, gravitational, thermophoretic, diffusiophoretic/Stefan flow and diffusional mechanisms. Most of these mechanisms are reasonably well understood, but the correct way to combine the behaviour of several simultaneously operating mechanisms is not always clear. Also, correct application of aerosol deposition phenomena requires good knowledge of the thermal-hydraulic conditions; poor knowledge of thermal-hydraulic conditions will lead to poor estimation of aerosol deposition.

The significance of vapour deposition is limited because of the low gas-phase temperatures at most locations away from the immediate vicinity of the fuel bundles. Released vapours will deposit on cooler surfaces such as the pool walls, or dissolve in pools or films of liquid water. Decay product ^{132}I may be released from deposited ^{132}Te, but this will have limited significance because of the small inventories of fuel with short decay times.

The significance of fission product deposition is similar to that of Phenomenon 73 (Fission product transport).

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
75	Fission product chemistry

Phenomenon				Definition			
Fission product chemistry				Iodine in the pool undergoes a wide variety of chemical reactions with water radiolysis products and organic materials (including epoxy liners, paint and adventitious organic chemicals), some of which produce volatile forms of iodine (including molecular iodine and organic iodides). Chemical reactions of ruthenium deposits with air radiolysis products may also produce volatile ruthenium oxides.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	M	H	H	Iodine content of the pool is low, because it only originates from defected fuel.	Iodine releases from freshly discharged fuel will begin during this phase.	Releases of iodine from fuel will continue during this phase, and ruthenium release may occur because of increased air entrainment.	Pool returns, washing deposited iodine and other fission products into the pool.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	2	2	2	The pool is closer to NOC conditions, and iodine content is low.	Iodine chemistry under accident conditions has significant uncertainties, and reactions of iodine with paints and other materials is still an active research area.		

Detailed description and rationale:

The initial iodine concentration is low, but increases during Phases 2 and 3 due to increased numbers of sheath failures. The iodine will be concentrated in the pool by boildown, and by washing of deposited iodine off of surfaces by condensation, and washdown during refilling of the irradiated fuel bay in Phase 4. Ruthenium release may occur during Phase 3 because of increased air entrainment and fuel damage, and reactions generating gaseous ruthenium from deposits may occur during Phases 3 and 4.

The iodine chemistry is strongly influenced by the pH, temperature and other chemical contents of the pool. The irradiated fuel bay water is at much lower initial pH than the water pool in a reactor accident, probably leading to higher fractional iodine volatility. Some of the available models are capable of modelling some of the effects of the different chemical environment. However, iodine chemistry under accident conditions has significant uncertainties, and reactions of iodine with paints and other materials is still an active research area.

Initial investigations have been performed on ruthenium volatility [2] [3], and investigations are continuing under the OECD START project, but the level of knowledge is much lower than for iodine volatility.

References:

[1] G.A. Glowa, C.J. Moore and J.M. Ball, "The main outcomes of the OECD Behaviour of Iodine (BIP) Project", Annals of Nuclear Energy 61 (2013) 179–189

[2] Holm, H. Glänneskog and C. Ekberg, "Deposition of RuO_4 on various surfaces in a nuclear reactor containment", Journal of Nuclear Materials 392 (2009) 55–62

[3] C. Mun, L. Cantrel and C. Madic, "Radiolytic Oxidation of Ruthenium Oxide Deposits", Nucl. Technol. 164 (2008) 245-254

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
76	Fission product re-suspension (note this generally relates to dry depositions)

Phenomenon				Definition			
Fission product re-suspension				Fission products deposited on surfaces are re-suspended, due to a depressurization event or hydrogen burn.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	L	L	L	No event to initiate re-suspension expected.	Deposited fission products could become airborne as the result of a depression event or a hydrogen burn.		Less likely than in “3” because a wet recovery would be underway.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N.A	2	2	2	Limited or no hydrogen gas	Extent of the hydrogen gas is scenario dependent	If a burn were to occur, this is the most likely time.	Likely to be steam inerted in the SFP.

Detailed description and rationale:

A depressurization event or a hydrogen burn would be needed for this to occur. Knowledge level has high uncertainty as it depends on the nature of the deposits. More specifically, the deposits need to be dry and more that a single particular layer thick. Since there are no pressurized volumes other than the fuel elements which have a limited mass of pressurized gas, a hydrogen burn is the only event that could potentially cause a resuspension of deposited fission products. Data related to wind erosion suggest that the resuspension rate is the largest for dry air and varies as the cube of the surface velocity. This data also shows that the rate is an order of magnitude less for moist conditions. The References [1-3] are relevant.

References:

[1] G.A. Sehmel, 1975, “Initial Correlation of Particle Resuspension Rates as a Function of Surface Roughness Height”, Pacific Northwest Laboratories Annual Report for 1975 to USAEC/DBER, Part 3

[2] G.A. Sehmel and F.D. Lloyd, 1977, “Wind-Caused Particle Resuspension Rates”, Pacific Northwest Laboratories Annual Report for 1976 to USERDA/DBER,BNWL-2100, Part 3

[3] B.W. Reynolds and W.G.N. Slinn, 1979, “Experimental Studies of Resuspension and Weathering of Deposited Aerosol Particles”, Oregon State University Report SR-0980-5 for USDOE

Champion: Bob Henry

ID #	Phenomenon Synopsis Title
77	Fission product release from the fuel

Phenomenon				Definition			
Fission product release from the fuel				Fission products will be released from the fuel elements after the sheath fails. The fractional release of each fission product element is determined by fuel temperature, extent of oxidation of the fuel and sheath, and fuel degradation (e.g., fracturing of fuel and sheath), among other variables.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	M	H	L	No releases from uranium dioxide during pool boildown. Gap inventory of previously defected fuel may release to pool.	Fuel will fail during this phase, and release of volatile FP (e.g., iodine, cesium) will start.	Higher temperatures, more fuel failures, increased fuel degradation (e.g., through-wall oxidation) and increased air fraction in the environment will increase releases of volatile and semi-volatile FP (e.g., ruthenium, molybdenum).	Most FP releases will effectively cease when the fuel rewets. Some additional releases of fission gases may occur by fuel fracturing, but the radiological consequences will be low. Other FP (e.g., strontium, antimony) may release slowly by leaching of failed fuel or fragments.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	3	2	3		Releases in steam environment are reasonably well understood.	The data on long-term FP releases from fuel at low temperature in air or air/steam mixtures is not very extensive. The modelling of FP releases from fuel in air-steam environments is not very well developed.	Releases due to fuel fracturing and leaching are reasonably well understood.

Detailed description and rationale:

During pool boildown, there will be no additional FP releases from the UO_2 fuel because the temperature is too low, and most of the fuel element sheaths are intact. The gap inventory of previously defected fuel may release to the pool during this phase, but most of the releasable FP in the gap will already have been

released by leaching during storage in the pool. After fuel is exposed to steam environment, the sheaths may fail (see Phenomenon 56, “Sheath strain and failure”), and release of volatile FP (e.g., iodine, cesium, tellurium) will start. Release of other FP is largely precluded by the low temperatures (<1000°C), incomplete sheath oxidation and predominantly steam environment in this phase. After all of the fuel is uncovered, the higher temperatures, increased number of fuel failures, increased fuel degradation (e.g., through-wall sheath oxidation, fuel oxidation) and increased air fraction in the environment will increase releases of volatile and semi-volatile FP (e.g., ruthenium, molybdenum). During the refill phase, some additional releases of fission gases may occur by fuel fracturing and by leaching of fuel, but most FP releases from fuel will effectively cease when it rewets.
Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
78	Liquid-phase transport of fission products to environment

<table>
<tr><th colspan="4">Phenomenon</th><th colspan="4">Definition</th></tr>
<tr><td colspan="4">Transport of released fission products to environment</td><td colspan="4">Fission products dissolved or suspended in water can go through cracks in the bay wall. Both wall layers (the liner and the structural wall) must be cracked to allow significant release to the environment by this path. If the bay wall faces the ground, some of the fission products will be sorbed on the soil particles. If the bay wall faces the air, the dissolved FP will flow down the outside face of the bay and onto the ground or the paved surface near the bay.</td></tr>
<tr><th colspan="4">Importance Rank
(by sub-scenario)</th><th colspan="4">Importance Rank Rationale
(by sub-scenario)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>L</td><td>M</td><td>M</td><td>M</td><td>Limited amount of FP in the pool at this stage.</td><td>Liquid water present in the fuel pool and fuel failures from uncovered fuel would produce fission products.</td><td>Even though the pool water is assumed gone in this stage of the accident, some liquid water would remain at the bottom of the bay.</td><td>During refill of the bay, fuel may fail (due to embrittlement) and fission products could be transported out via liquid pathways.</td></tr>
<tr><th colspan="4">Knowledge Assessment
(by sub-scenario)</th><th colspan="4">Knowledge Assessment Rationale
(by sub-scenario)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>2</td><td>2</td><td>2</td><td>2</td><td colspan="4">Uncertainty on pathways (crack size, distribution).</td></tr>
</table>

Detailed description and rationale:

The impact of FP release via water pathways will generally be somewhat less than a comparable release by air pathways, because transport via water will be more localized than air transport. The flow path will usually be through a set of fairly narrow cracks, so an uncertain fraction of FP will stick on concrete by sorption and by physical retention of particles (including suspended fuel particles). If the cracks are wide (due to earthquake or similar damage), the retention will be negligible. Retention of individual FP in soils will usually be reasonably well known because of research for waste management and dose calculation. The speciation from the fuel bay may differ slightly from the speciation assumed for the environmental studies because of the lower concentration of organic and inorganic species in the bay water relative to the ground water used for environmental studies, which increases the uncertainty in behaviour.

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
79	Fuel volatilization

Phenomenon				Definition			
Fuel volatilization				If the UO_2 fuel is exposed to an oxidizing environment, hyperstoichiometric UO_{2+x} or higher oxides will be produced. The vapour pressure of the uranium-bearing species is high, such that the solid phase can be vaporized at a high rate through incongruent vaporization. The loss of uranium will also result in the release of fission products. This phenomenon is also referred to as matrix stripping.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	L	L	L	If the fuel is covered with liquid water, the fuel temperature will not be high enough for the phenomenon to be active.	A fuel temperature of at least 1200°C is needed for this phenomenon to be significant [1]. It is unlikely that fuel temperatures >1200°C will be achieved for a significant number of fuel bundles, as the maximum potential sheath temperature is expected to be less than 933°C [2].		
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	3	3	3	N/A	Experiments and models exist for the phenomenon, but little experimental information is available on the effect of concentration and pressure on the volatization rate of low-volatile fission products.		

Detailed description and rationale:

A fuel temperature of at least 1200°C is needed for this phenomenon to be significant [1]. It is unlikely that fuel temperatures >1200°C will be achieved for a significant number of fuel bundles, as the maximum potential sheath temperature is expected to be less than 933°C [2]. Thus, this phenomenon is not expected to contribute significantly to the fission product releases to the environment. Experiments and models exist for the phenomenon, but little experimental information is available on the effect of concentration and pressure on the volatization rate of low-volatile fission products.

References:

[1] D.S. Cox, F.C. Iglesias, C.E.L. Hunt, N.A. Keller, R.D. Barrand, J.R. Mitchell and R.F. O'Connor, "Oxidation of UO_2 in Air and Steam With Relevance to Fission Product Releases", Proc. Symposium on Chemical Phenomena associated with Radioactivity Releases during Severe Nuclear Plant Accidents, Anaheim, CA, USA, 1986 September 8−12

[2] C.J. Krasnaj and W. Grant, "Development of a 2-D Finite Element Model to Examine Both Natural Convection and Radiative Cooling of a Spent Fuel Bundle in Air", Proc. 19th PBNC Conference, Vancouver, BC, Canada, 2014 August 24-28

Champion: Jeffrey Baschuk

ID #	Phenomenon Synopsis Title
80	Fuel particle entrainment in the gas outflow (during rewet)

Phenomenon				**Definition**			
Fuel particle entrainment in the gas outflow (during rewet)				Fine fuel particles formed during the transient or during the rewet can be entrained by the high flows of steam that would result from cooling the fuel. Dispersal of fuel particles could lead to very high radiation fields in the vicinity of the fuel pool and possible suspension and transport of fuel particles off site.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	I	I	H	Only active during rewet.			If water is added suddenly to the pool, the formation of fuel particulate and its transport may both be enhanced.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	N/A	N/A	2				Some data are available on particle size from air oxidation of UO_2. The data on fuel particulate formation by quenching are limited, but they indicate limited formation of fine particulate (<1 mm diameter).

Detailed description and rationale:

At the time of rewet, most of the fuel fragments inside any intact fuel elements will be large (~1-3 mm) and therefore difficult to suspend by this mechanism. Fine fragments may be formed by thermal shock during cooling [1]. Very fine fuel powder (mostly U_3O_8) is formed by oxidation of irradiated or unirradiated UO_2 in air at temperatures between 300°C and 900°C [2]. The entrainment mechanism will be similar to that in Phenomenon 34 (Radioactive aerosol formation due to boiling at the free surface).

Before the rewet, some of the fuel may already have been powdered by oxidation in air at low temperatures (<800°C), which results in significant fractions of particles between 0.3 micron and 10 micron in diameter [2]. The experimental data on formation of fuel particulate by thermal shock during cooling was collected under loss-of-coolant accident (LOCA) conditions [1], and may therefore not be completely applicable. However, it indicates limited formation of fine particles (<1 mm in size), with most of the fuel remaining as larger particles. The particulate materials used in the aerosol re-entrainment tests [3] [4] had lower densities than UO_2 or U_3O_8, and were very fine particles. Also, the boiling during rewet may be more violent than the bubbly regime boiling used in these experiments.

References:

[1] OECD NEA Working Group on Fuel Safety, "Nuclear Fuel Behaviour in Loss-of-coolant Accident (LOCA) Conditions: State-of-the-art Report", NEA Document 6846, 2009

[2] Z. Liu, D.S. Cox, R.D. Barrand and C.E.L. Hunt, "Particle Size Distributions of U3O8 Produced by Oxidation in Air at 300-900°C", 13th Annual Canadian Nuclear Society Conference, Saint John, NB, CA, 1992 June 7-10

[3] W. Schöck and M. Wagner-Ambs, "Aerosol generation by bubble bursting from a boiling pool", J. Aerosol Sci. 20 (1989) 1405-1408.

[4] J.O. Cosandey, A. Gunther and P. Rudolf von Rohr, "Transport of salts and micron-sized particles entrained from a boiling water pool", Experimental Thermal and Fluid Science 27 (2003) 877–889

Champion: Ray Dickson

ID #	Phenomenon Synopsis Title
81	Heat generation from released fission products

Phenomenon				Definition			
Heat generation from released fission products				Fission products released from the fuel will decay and generate heat.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	L	L	L		Most of the decay heat would remain within the fuel elements.	Most of the decay heat would remain within the fuel elements	Most of the decay heat would remain within the fuel elements
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	4	4	4		Since the temperatures of the fuel elements are expected to be less than 1500°C, most of the fission products would remain in the fuel pellets.	Since the temperatures of the fuel elements are expected to be less than 1500°C, most of the fission products would remain in the fuel pellets.	Since the temperatures of the fuel elements are expected to be less than 1500°C, most of the fission products would remain in the fuel pellets.

Detailed description and rationale:

Very little heat generation would result from the released fission products with most of this being noble gases, iodine gas and methyl iodide. These gases would add some heat to the building atmosphere and should be part of the energy balance for the code. However, it would be small compared to the total decay that would be transferred to the steam or air building atmosphere by the natural circulation within the building, thus it is of LOW importance.

Champion: Bob Henry

ID #	Phenomenon Synopsis Title
82	Fission product (gas phase aerosol) removal in leakage paths

Phenomenon				**Definition**			
Fission product (gas phase aerosol) removal in leakage paths				Fission product in the form of aerosols will be carried with the gas flow through leak paths out of the SFP building. Depending on the aerosol characteristics, flow conditions and the geometry of the leak path, aerosols (fission products) may be retained in the leak path.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	L	L	Building is not air-tight and there are plenty of low resistance, relative large openings to carry fission products out of the building. As well, the quantity of fission product is low because the fuel is covered by water.	Building is not air-tight and there are plenty of low resistance, relative large openings to carry fission products out of the building	Building is not air-tight and there are plenty of low resistance, relative large openings to carry fission products out of the building	Building is not air-tight and there are plenty of low resistance, relative large openings to carry fission products out of the building
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
2	2	2	2	If the main doors are open, then there is no chance for aerosol retention in this large opening. If the main doors are closed, it will be difficult to pre-define the actual leak paths out of the spent fuel pool building.			

Detailed description and rationale:

Aerosol and gas can leak from a post-accident pressurized containment through a variety of paths. Gas flow hydraulics affects drastically the aerosol transport so that leak pathways have been classified accordingly: short pathways with sudden changes in flow cross-section area (i.e., valves and seals); tortuous and relatively long pathways (i.e., concrete joints, cracks and penetration gaps); and small diameter, long channels with high flow resistance (i.e., pores in intact concrete).

There are experimental and theoretical evidences of strong retention of particles in leak paths. The main working aerosol removal mechanisms are Brownian diffusion, gravitational sedimentation and, occasionally, inertial impaction as deposition mechanisms. If particle deposition is large enough, pathway plugging may occur. Nonetheless, under turbulent flows deposition may not be permanent and particles can bounce off surfaces they impact and/or resuspend from deposits due to changes in gas flow over deposits, to particle impact and/or to substrate vibration. A key condition for aerosol transport through leakage paths is steam content of gas (as steam condensation will contribute to flow blockage).

However, the leakage conditions in a building housing the spent fuel pool is drastically different from nuclear containment: (1) spent fuel pool buildings are not leak tight so driving pressures are only a few kPa, (2) leakage paths may be small (e.g., gaps between a closed door), large (e.g., opened fuel bay doors) or long (e.g., ventilation ductwork). It is the small and long leakage paths that may have the potential for aerosol retention. It is unlikely that conditions will develop to completely block a leakage paths from the spent fuel pool building. This phenomenon should be ranked low (or inactive) because even if leakage paths suitable for aerosol retention are present, the flow will be directed towards larger (less flow resistance) openings which are available to carry the fission products out of the building.

Furthermore, there is a large uncertainty regarding the actual leak paths available for aerosol flow out of the spent fuel pool building. As such, it will be difficult to quantify the degree of aerosol/fission product retention in the leak paths. Thus, this aerosol/fission product removal mechanism should be neglected to provide conservative (maximize) source term release.

Reference:

[1] "Containment Code Validation Matrix", NEA/CSNI/R(2014)3, 2014 May

Champion: Sammy Chin

ID #	Phenomenon Synopsis Title
83	Thermal expansion (mismatch between aggregate and cement paste, rebar and concrete, etc.)

Phenomenon				**Definition**			
Thermal expansion (mismatch between aggregate and cement paste, rebar and concrete, etc.)				The different materials of the fuel bay and liner have different coefficients of thermal expansion. As the fuel bay structure heats-up, non-uniform expansion between aggregate and cement paste, rebar and concrete, and other components is expected and can contribute to cracking.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
M	M	I	M	Thermal mismatch can create cracks and drain the water.	Thermal mismatch can create cracks and drain the water.	Cracks in bay will not affect the sheath temperature (fuel uncovered)	Potential cracking due to rewet-induced temperature gradient (cold on the inside)
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	N/A	3	Assumed values of coefficients of thermal expansion may have to be used for the fuel bay	Assumed values of coefficients of thermal expansion may have to be used for the fuel bay	N/A	Assumed values of coefficients of thermal expansion may have to be used for the fuel bay

Detailed description and rationale:

Non-uniform expansion between aggregate and cement paste & rebar and concrete could lead to concrete cracking. If the liner is breached, then cracks in the concrete can allow pool water to escape, accelerating the accident progression and providing an addition path for fission product release. Thermal mismatch during accident is not expected to be significantly more than normal operation, and the cracking is not expected to be significant; hence, the importance is medium. Coefficients of thermal expansion are available from the literature, but there is some uncertainty due to the variability in concrete composition.

Champion: Shahzma Jaffer

ID #	Phenomenon Synopsis Title
84	Concrete aging (including temperature and radiation effects)

Phenomenon				**Definition**			
Concrete aging (including temperature and radiation effects)				The structural integrity of concrete might degrade with time, with elevated temperature and radiation fields accelerating the aging process. This phenomenon includes initial condition of the bay and degradation during the accident.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
H	H	I	H	Concrete aging can lead to cracking. Cracking can lead to water loss.	Concrete aging can lead to cracking. Cracking can lead to water loss.	N/A	Concrete aging can lead to cracking. Cracking can lead to water loss. If leakage occurs during refill, continued addition of water may be needed. If leakage is significant, it can affect the surrounding environment and accident management.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
2	2	N/A	2	Processes that contribute to aging are known, but quantification of the aging effects is not available.	Processes that contribute to aging are known, but quantification of the aging effects is not available.	N/A	Processes that contribute to aging are known, but quantification of the aging effects is not available.

Detailed description and rationale:
The structural integrity of the concrete might degrade with age, and can be accelerated at high temperature and in radiation fields. Aging can result in cracking and if the liner is breached, water loss and an additional pathway for fission product release. The importance is high, because if liner is breached, cracks in the concrete will provide a pathway for fission product release. Quantitative information on aging specific to fuel bay concrete may not be readily available. Any information available in the literature will have to be analysed for application to fuel bay.
Champion: Shahzma Jaffer

ID #	Phenomenon Synopsis Title
85	Flow in cracks (erosion)

Phenomenon				Definition			
Flow in cracks (erosion)				Crack enlargement due to erosion from the flow within the crack.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	I	L	Path of cracks unclear. Removal of material in cracks may not be prominent if crack paths are tortuous.	Path of cracks unclear. Removal of material in cracks may not be prominent if crack paths are tortuous.	N/A	Path of cracks unclear. Removal of material in cracks may not be prominent if crack paths are tortuous.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
2	2	N/A	2	Path of cracks unclear. General information on erosion available, but quantifying erosion may be difficult.	Path of cracks unclear. General information on erosion available, but quantifying erosion may be difficult.	N/A	Path of cracks unclear. General information on erosion available, but quantifying erosion may be difficult.

Detailed description and rationale:

This phenomenon involves the removal of material in cracks as a result of water flow resulting in enlarged crack and thus more flow through cracks. The importance of this phenomenon is low because the material removal rate is expected to be low. There is a lot of general information on concrete erosion, but quantifying and applying to fuel bay may be difficult, due to the variability of concrete material properties and high uncertainty on the cracking patterns.

Champion: Shahzma Jaffer

ID #	Phenomenon Synopsis Title
86	Concrete cracking (thermally induced, stress-induced, creep, quench)

Phenomenon				**Definition**			
Concrete cracking (thermally induced, stress-induced, creep, quench)				Concrete can crack due to thermal gradients, stresses, creep, and thermal shock from quenching.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
H	H	I	H	Loss of water can occur due to cracking of concrete	Loss of water can occur due to cracking of concrete	N/A	Loss of water can occur due to cracking of concrete
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
2	2	N/A	2	Uncertainty regarding crack path, location and size of cracks. Uncertainty due to: (i) Temperature at which cracks occur unknown (design of structure, concrete properties & temperature gradient can have an influence), (ii) Changes in internal concrete stresses	Uncertainty regarding crack path, location and size of cracks. Uncertainty due to: (i) Temperature at which cracks occur unknown (design of structure, concrete properties & temperature gradient can have an influence), (ii) Changes in internal concrete stresses	N/A	Uncertainty regarding crack path, location and size of cracks. Uncertainty due to: (i) Temperature at which cracks occur unknown (design of structure, concrete properties & temperature gradient can have an influence), (ii) Changes in internal concrete stresses

Detailed description and rationale:

The fuel bay is made of concrete, which can crack if subjected to thermal gradients or stress. As well, creep processes can produce cracks in concrete. Thermal shock, due to the rewet of the concrete in the recovery phase of the accident (Phase 4) may also result in cracks. If the liner is breached, these cracks could accelerate water loss and provide a leakage path for fission products. The phenomenon is of high importance, because cracks in the concrete would provide a pathway for fission product release into the environment, if the liner is also breached. A high level of uncertainty is associated with prediction concrete cracking, with uncertainty in the path, location and size of cracks. As well, the driving forces, such as the temperatures associated with cracking and knowledge of the stresses within the concrete are uncertain.

Champion: Shahzma Jaffer

ID #	Phenomenon Synopsis Title
87	Corrosion of rebar

Phenomenon				**Definition**			
Corrosion of rebar				Processes and phenomenon related to corrosion of the rebar in the concrete structure of the spent fuel bay.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	I	L	Corrosion may not be significant as chlorides are not expected to be present.	Corrosion may not be significant as chlorides are not expected to be present.	No or minimal water in the fuel bay.	Chloride may be introduced if sea water is used as refill water; however, corrosion kinetics are expected to be slow.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
2	2	N/A	2	Initial condition of fuel bay concrete with respect to corrosion may be difficult to establish (e.g., if fuel bay has corrosion, how much rebar loss, cracking, etc.). Information on corrosion of rebar available in the literature, but application to fuel bay requires estimation and leads to uncertainty. Effect of other ions (e.g., from fuel) on corrosion of rebar unclear.			See Phases 1 and 2.

Detailed description and rationale:

This phenomenon deals with corrosion of rebar in fuel bay concrete. The initial state of the concrete/rebar corrosion is more important that corrosion during the accident as the corrosion kinetics are slow. Because of the slow corrosion kinetics, the importance of this phenomenon is low. While information on rebar corrosion in the literature is available, the uncertainty for application to spent fuel bays is high, as the initial condition of the fuel bay concrete would be difficult to establish and the effect of ions from fission products is not known.

Champion: Shahzma Jaffer

ID #	Phenomenon Synopsis Title
88	Leaching of calcium hydroxide

Phenomenon				Definition			
Leaching of calcium hydroxide				Calcium hydroxide is a constituent of concrete, and can be leached out.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
L	L	I	L	Not expected to have a significant effect figure of merit	Not expected to have a significant effect figure of merit	N/A	Not expected to have a significant effect on figure of merit
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
3	3	N/A	3	Solubility limits in water known, but depth of concrete affected by calcium hydroxide leaching unclear.	Solubility limits in water known, but depth of concrete affected by calcium hydroxide leaching unclear.	N/A	Solubility limits in water known, but depth of concrete affected by calcium hydroxide leaching unclear.

Detailed description and rationale:
Leaching of calcium hydroxide is not expected to influence the figure of merit (sheath temperature) and thus the importance is low. The effect of leaching would be to increase the porosity of concrete and influence crack size. Leaching of calcium hydroxide could be active as both an initial condition and during the accident (if the liner the breached). The knowledge level is high, but moderate uncertainty exists in determining the depth of concrete that would be affected by the leaching process.
Champion: Shahzma Jaffer

ID #	Phenomenon Synopsis Title
89	Radiolysis of water in concrete.

Phenomenon				**Definition**			
Radiolysis of water in concrete				The decomposition of water under radiation is called radiolysis. Both interstitial water and water in the pore structure of concrete may participate in the radiolysis process. The two main outcomes resulting from water radiolysis are: (1) buildup of internal overpressure that may lead to cracking of the concrete, and (2) the production of hydrogen gas [1].			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	I	L	I	N/A	N/A	No water to shield from gamma radiation. Effect on figure of merit not considered to be significant.	N/A
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	N/A	2	N/A	N/A	N/A	Although some information may be available in the literature, effect of radiation on concrete is still an active research area.	N/A

Detailed description and rationale:

The liquid water in the pool provide shielding of gamma radiation; hence, the phenomenon is inactive Phases 1, 2, and 4. Although the radiolysis process can damage concrete, causing cracking, the effect is expected to be small.

This phenomenon is only expected to be active in Phase 3 of the accident, where the liquid water is gone and does not provide shielding. During the phases of the accident in which liquid water is present in the spent fuel bay, the water provides a shield

Radiation damage to concrete is an active research area, with large uncertainty in predicting the effects of radiolysis.

Reference:

[1] K. William, Y. Xi, D. Naus and H. Graves, “A Review of the Effects of Radiation on Microstructure and Properties of Concretes Used in Nuclear Power Plants”, NUREG/CR-7171, 2013 August

Champion: Shahzma Jaffer

ID #	Phenomenon Synopsis Title
90	Delayed ettringite formation

Phenomenon				Definition			
Delayed ettringite formation				Ettringite is a needle-like crystal that may form in concrete upon cooling, and can cause cracking.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
I	I	I	H	N/A	N/A	N/A	Formation can cause cracks and water may be lost through the cracks, if liner is breached. However, refill water would be available.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
N/A	N/A	N/A	3	N/A	N/A	N/A	Difficult to predict location of delayed ettringite formation (DEF), if there is a potential for DEF to occur.

Detailed description and rationale:
Delayed ettringite formation (DEF) depends on sources of sulphates. The phenomenon would only be active in Phase 4, as the concrete cools during the recovery phase of the accident. The importance is high, as cracks in the concrete would provide a pathway for fission product release to the environment, if the linear is also breached. As well, the DEF-induced cracks would delay the refilling of the bay. The phenomenon of DEF is well documented in the open literature, but there is moderate uncertainty in predicting if and where ettringite will form.
Champion: Shahzma Jaffer

ID #	Phenomenon Synopsis Title
91	Epoxy liner degradation and failure

Phenomenon				**Definition**			
Epoxy liner degradation and failure				Epoxy is used as a liner material in spent fuel bays. This phenomenon includes all mechanisms that could breach the liner.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
H	H	H	H	Breach of liner below the water level could accelerate water loss. Liner breach above the water level could increase the FP release	Breach of liner below the water level could accelerate water loss. Liner breach above the water level could increase the FP release	Breach of liner below the water level could accelerate water loss. Liner breach above the water level could increase the FP release	Submergence of the breach during recovery could reduce or eliminate gaseous releases. Liquid releases still would need to be monitored.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
2	2	2	2	The accident sequence could cause the liner to tear.	Overheating an epoxy above the water level could cause blistering and burn-through of the liner. Thermal expansion of the concrete wall could cause the liner to tear.	Overheating an epoxy above the water level could cause blistering and burn-through of the liner. Thermal expansion of the concrete wall could cause the liner to tear.	

Detailed description and rationale:

The loss of liner integrity would result in an increase in the rate of water loss from the spent fuel bay, as the concrete structure of the bay is expected to crack. A seismic event could cause the liner to tear. Also, thermal expansion of the wall could generate a mismatch in the expansion and possibly tear the epoxy liner. Should this occur, it is important to represent: (i) the extent of cracking (how large is the total crack area), (ii) would water flow in or out (depends on the location of the failure site compared to the ground water level), and (iii) the water flow rate. The importance is rated as high, as a breached liner will result in increased water loss (faster accident progression) and provide a pathway for the transport of fission products.

Some pieces of information required to assess the integrity of the liner are available, but additional work may be required. Currently, there are no “rules” to determine the integrity of the liner. Some effort should be directed toward formulating “rules” to guide the modeling development.

Champion: Bob Henry

ID #	Phenomenon Synopsis Title
92	Stainless steel liner degradation and failure

Phenomenon				**Definition**			
Stainless steel liner degradation and failure				Stainless steel is used as a liner material in spent fuel bays. This phenomenon includes all mechanisms that could breach the liner.			
Importance Rank (by sub-scenario)				**Importance Rank Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
H	H	H	H	Breach of liner below the water level could accelerate water loss. Breach of liner above the water level could increase the FP release			Submergence of the breach during recovery could reduce or eliminate gaseous releases. Liquid releases still would need to be monitored.
Knowledge Assessment (by sub-scenario)				**Knowledge Assessment Rationale** (by sub-scenario)			
1	**2**	**3**	**4**	1	2	**3**	**4**
2	2	2	2	The accident sequence could cause the liner to tear.	Melting of the SS liner above the water level is unlikely. Differential thermal expansion between the liner & concrete wall could cause the liner to tear.		

Detailed description and rationale:
The loss of liner integrity would result in an increase in the rate of water loss from the spent fuel bay, as the concrete structure of the bay is expected to crack. A seismic event could cause the stainless steel liner to tear. Also, differential thermal expansion between the liner and the wall could generate a mismatch in the expansion and possibly tear the liner. Should this occur, it is important to represent: (i) the extent of cracking (how large is the total crack area), (ii) would water flow in or out (depends on the location of the failure site compared to the ground water level), and (iii) the water flow rate. The importance is rated as high, as a breached liner will result in increased water loss (faster accident progression) and provide a pathway for the transport of fission products.
Some pieces of information required to assess the integrity of the liner are available, but additional work may be required. Currently, there are no “rules” to determine the integrity of the liner. Some effort should be directed toward formulating “rules” to guide the modeling development.
Champion: Bob Henry