Integrity of Spent CANDU Fuel During and Following Dry Storage

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Abstract

This report examines the issue of CANDU fuel integrity at the back end of the fuel cycle and outlines a program designed to provide assurance that used CANDU fuel will retain its integrity over an extended period. In specific terms, the program is intended to provide assurance that during and following extended dry storage the fuel will remain fit to undergo, without loss of integrity, the handling, packaging and transportation operations that might be necessary until it is placed in disposal containers.

The first step in the development of the program was a review of the available technical information on phenomena relevant to fuel integrity. The major conclusions from that review were the following:

Under normal storage conditions it is unlikely that the spent fuel will suffer significant degradation during a one-hundred year period and it should be possible to retrieve, re-package and transport the fuel as required, using methods and systems similar to those used today. However, to provide increased confidence regarding the above conclusion, investigations should be conducted in areas where there is higher uncertainty in the prediction of fuel condition and on some degradation processes to which the fuel appears to present higher vulnerability.

The proposed program includes, among other tasks, irradiated fuel tests, analytical studies on the most relevant fuel degradation processes and the development of a long-term fuel verification program.

1. INTRODUCTION

This report describes a proposed work program aimed at establishing the methods required to provide assurance that used CANDU fuel will retain its required integrity during and following dry storage. In the present context, fuel integrity means fuel keeping its physical configuration, such that it can be efficiently and safely handled by automated equipment for the purpose of retrieval from storage and all the required subsequent operations until it is transferred to a disposal container. The estimated time scale for execution of the work is five years, not taking into account a long-term plan for fuel examinations that should be strategically placed along the
fuel storage period. For the purposes of developing the program it was assumed that the duration of the dry storage period is up to 100 years.

The need for this program derives from developments in nuclear legislation which have taken place in Canada during the past two years. The Nuclear Waste Act, which came into force on November 15, 2002, requires the producers of Nuclear Power in Canada propose a method and an implementation plan for the long-term management of spent nuclear fuel by November 15, 2005. The option of storing fuel in a dry environment for extended periods as part of an integrated national approach for the long-term management of spent nuclear fuel creates the need for studies in long-term fuel integrity. A proposed work program to address the identified need is outlined in this report.

Assurance of fuel integrity will be provided by a combination of experimental and analytical methods. The most critical areas of work include the susceptibility to shock and fatigue failure of Zircaloy components caused by hydrogen effects, and susceptibility to delayed hydride cracking caused by the combined effect of hydrides, residual stresses, and incipient cracks. Additional work is also required to evaluate the possible effect on the fuel of abnormal storage conditions. The recommended work includes also a fuel verification program that will provide evidence of the condition of the fuel during the storage period.

2. SCOPE

The tasks required to show that used fuel bundles will retain their integrity can be divided into two classes:

♦ Tasks aimed at defining long-term fitness criteria or performance requirements for the fuel, and
♦ Tasks aimed at developing the tools and methods needed to provide assurance that the fuel will meet those criteria.

Fuel integrity is the fundamental requirement and it shall be used as the basis for derivation of more detailed requirements expressed in terms of measurable fuel parameters against which fuel condition could be verified. The development of detailed fuel performance requirements is discussed in Section 3.

Predictions of fuel condition will be based of relevant fuel degradation models. Failure modes leading to loss of bundle integrity under different dry storage scenarios will be used to identify the critical processes. A thorough review of those processes will determine to what degree of accuracy and certainty fuel condition can be predicted with existing models, and in which cases enhancement of those models or of the existing data bases can make predictive analysis more effective. Recent work in this area has been reported by Cann and Tait, [2002], Ikeda [2002] and Taylor [2002], however, further work is required to fully assess processes such as stress corrosion cracking (SCC) and hydrogen effects on cladding. The use of analytical tools for predicting fuel condition is discussed in detail in Section 4.

Experimental work will be required in support of spent fuel integrity program, as follows:
a) measurement of physical parameters needed to support model development or to validate process models,  
b) experimental tests to determine fuel performance requirements,  
c) monitoring of storage parameters in dry storage containers, and  
d) examination of fuel bundles in dry storage to verify predictions of fuel condition.

The need for different experimental tasks, including examination and testing of fuel in dry storage at long-time intervals is discussed in Section 5.

Section 6 itemizes the tasks deemed to be a necessary part of the fuel integrity program.

Prior to the investigations on fuel degradation it will be necessary to define the characteristics of the used fuel to be considered for this study, establishing the initial condition of the reference fuel bundle at the start of dry storage.

The definition of a reference bundle should include fuel burnup, high-energy neutron fluence, post-discharge maximum cladding temperature, internal pressure, fuel bundle distortion and any other parameters relevant to its future behaviour. The results from this task will constitute the base information representing the fuel placed in dry storage at Canadian facilities.

3. FUEL PERFORMANCE REQUIREMENTS

3.1 CANDU Fuel Characteristics

CANDU fuel elements consist of a string of UO₂ pellets clad in a Zircaloy-4 tube approximately 50 cm in length. The tube is closed at each end by a resistance welded cap also made of Zircaloy-4. The cladding dimensions and fabrication details are described by Cann and Tait [2002]. CANDU fuel assemblies consist of bundles of either 28 or 37 fuel elements held together by means of welds attaching the end-caps of each fuel element to two Zircaloy-4 end plates. This kind of assembly, unique to CANDU fuel, makes each fuel element an active component of the bundle structure and mechanically constrains each Zircaloy tube via a rigid attachment of each end cap to an end plate.

The fuel elements have Zircaloy spacers attached to their outer surface with Zr–5wt% Be brazing. The induction heating used for the brazing raises the temperature of the cladding near the spacers into the beta phase region of the Zircaloy phase diagram, causing the formation of large beta grains and changing the cladding mechanical properties, primarily by enhancing its ductility and decreasing its strength. The heat-affected material (up to 30% of the cladding surface) is expected to creep at a higher rate than the as-fabricated Zircaloy but it would sustain higher strain before rupture. [Cann and Tait 2002].

The stresses applied on the cladding and other fuel bundle components during in-reactor service include the inner pressure from fission gases, the reactor coolant pressure and cladding-pellet interaction forces. They also include forces from contact with other fuel elements and with the reactor pressure tube, applied at the spacers and bearing pads welded to the cladding, as well as vibration loads and temperature gradients resulting from power ramps during operation. Under
this combination of stresses and temperature, each fuel element and the fuel bundle undergo strains, which results in distortion of the bundle’s original shape.

During reactor operation the fuel cladding receives a significant radiation dose and is subjected to chemical corrosion, processes which also affect the Zircaloy properties. Typically, under normal operation, CANDU fuel cladding is exposed to high-energy neutron fluences in a range from 5.7 to 9.7 x 10^24 n/m². The effects of neutron irradiation on the mechanical properties of Zircaloy are described by Cann and Tait [2002]. The most important chemical effect is the incorporation of hydrogen and deuterium in the Zircaloy cladding. The hydrogen content in irradiated fuel results in the precipitation of hydrides, which in certain cases results in cladding failures during reactor operation. These hydrogen effects are discussed in detail by Ikeda (2002) and Wadsworth [2000, 2001].

Following their service life the fuel bundles are removed from the reactor and transferred dry to the irradiated fuel bay. This transfer normally takes less than three minutes, during which time the fuel temperature rises, with the fuel sheath reaching values of up to 300 - 400°C. Following this, the fuel is cooled off by contact with the water of the fuel bay. After more than 10 years in wet storage at temperatures below 40°C the fuel undergoes another temperature excursion when it is packaged in dry storage containers, reaching peak values of about 200°C. Following the loading operation the fuel temperatures settle into a slow declining regime. The maximum cladding temperature under normal storage conditions is not expected to exceed 175°C.

The amount of fission gas in a fuel element, the neutron damage and hydrogen content of the cladding all increase with burnup. In turn, burnup depends on both the time the fuel spends in the reactor and with its position within the core and within the bundle. The burnup of outer fuel elements is about 1.4 times higher than that of fuel elements at the centre of the bundle [Cann and Tait, 2002]. The associated inner pressure in the individual fuel elements also varies over a substantial range but under dry storage conditions it remains below 80 MPa for most of the fuel. 100 MPa can be considered the maximum inner pressure value to which the cladding might be subjected at storage temperatures, for fuel irradiated in Canadian reactors.

The above paragraphs describe the processes CANDU fuel undergoes during and following reactor service. Reviews of existing data relevant to mechanical and chemical degradation of CANDU fuel have been reported by Cann and Tait [2002], Ikeda [2002] and Taylor [2002]. Results of physical tests done on cladding samples to evaluate the susceptibility of irradiated Zircaloy-4 to stress corrosion cracking (SCC) have been reported by Wood et al [1985, 1986].

3.2 Development of Fuel Performance Requirements

Fuel integrity as defined in Section 1 is a requirement for the safety and practicality of fuel handling operations. There are two concepts associated with fuel integrity: bundle integrity and fuel element integrity. Cladding integrity, is not an absolute requirement to maintain fuel bundle integrity since, as long as the fuel remains stored in an inert atmosphere, minor cladding failures would not lead to loss of bundle integrity. However, they would result in leakage of radioactive contaminants. End-plate fractures or failure of end-plate welds in the fuel bundle could, on the other hand, result in loss of fuel bundle integrity even if the cladding remained undamaged.
Although small cladding defects may not affect fuel bundle integrity, widespread cladding failure is not a desirable scenario and cladding degradation should be prevented so that the overall integrity of the fuel is preserved to simplify future handling operations. In cases where the fuel can be exposed to oxygen, even small cladding defects would allow oxidation of the UO$_2$ matrix and might result in further cladding damage [Taylor, 2002].

Retaining fuel integrity, as a fundamental requirement, should be translated into a set of performance requirements specified in terms of parameters that can be quantified by either analytical or experimental methods and used to describe fuel condition. The objective of these requirements will be to serve as a standard against which the used fuel’s condition can be compared. The process of defining these requirements should involve a formal analytical approach to ensure that to the extent possible all causes leading to loss of fuel integrity are considered. It is recommended that the derivation of used fuel performance requirements be based on fault-tree analyses of a set of specified dry storage scenarios.

Useful data for defining specific fuel requirements is available from previous experimental work on CANDU fuel by Forest [1982, 1985] and from post-irradiation examinations (PIE) of Ontario Power Generation’s (OPG) fuel, which are conducted annually. Tests, using fuel bundles with a representative range of burnup values may, however, be required to complete the required experimental data base.

4. ANALYTICAL PREDICTION OF FUEL CONDITION

Establishing whether used fuel of given characteristics is fit to undergo a certain operation (e.g. transportation) requires assessment of its condition in terms of parameters relevant to that specific operation. In order to predict fuel condition as a function of time in storage, the effect of several fuel degradation processes must be assessed. The processes considered here include cladding creep, UO$_2$ oxidation, SCC and hydrogen effects on Zircaloy-4, as well as mechanical stresses and potential synergistic effects from combinations of these factors.

4.1 Cladding Creep

The end of LWR fuel pencils are not held rigidly by the fuel assembly structure, and as a result they are free to grow in the axial direction during reactor irradiation. This phenomenon is clearly documented in reports of recent examinations of spent fuel following approximately 15 years in dry storage, conducted at INEEL and Argonne National Laboratory in the U.S [see EPRI report 1003010]. In general, the effect of creep in dry storage is strictly assessed on the basis of the axial and hoop strain resulting from internal fission gas pressure. The expected lifetime of the fuel is estimated on the basis of known temperature-dependent creep rates and predicted cladding temperatures, using creep strain limits to define cladding failure. Similar criteria have been applied in the past [Cann and Tait, 2002] to rule out creep as a critical degradation mechanism for CANDU fuel. Based on such analyses, creep is considered unlikely to constitute a risk to fuel integrity over dry storage time scales. However, for CANDU fuel, the assessment of cladding deformation must include the effect of interactions between the fuel element and the bundle end-plates via the end-cap to end-plate welds.
In CANDU fuel, creep strain results in changes to the bundle geometry. After irradiation, fuel elements are no longer straight and bundles no longer have a straight cylindrical shape, they are slightly bowed, and the end plates are no longer parallel to each other. The deformation induced on a fuel element during irradiation results from the harsh reactor environment and interactions with the rest of the bundle structure and the reactor pressure tube. Subsequent cooling of the bundle, upon removal from the reactor, results in residual stresses which are reflected in the distortion of the bundle geometry.

In terms of a conventional strain-to-failure criterion, creep is not likely to be a limiting factor for dry storage over a period of 100 years, however, the residual stresses resulting from creep strain during reactor irradiation and subsequent cooling may present a significant risk to bundle integrity over the long term. Evidence that those stresses are significant has been seen in post-irradiation fuel examinations conducted by OPG.

An assessment of creep deformation during irradiation and an evaluation of the generated residual stresses should be conducted. This assessment should use the recently developed methodology discussed in EPRI report 1003135, and should include the effect of restraining forces applied to the end-caps by the bundle end-plates. The scenarios considered in the assessment should include fuel with different thermal histories and different hydrogen content. The objective of this assessment will be to establish/confirm that creep strain will not be a contributor to the failure of cladding or welds, leading to loss of fuel integrity.

4.2 UO$_2$ Fuel Oxidation

Taylor [2002] describes the fundamental data and equations for a detailed model of UO$_2$ oxidation and provides suggestions for refining and calibrating the model. UO$_2$ oxidation does not present a risk to fuel integrity under normal storage conditions, however, it would be of benefit having available a flexible tool to assess fuel oxidation under abnormal storage scenarios and special operating conditions such as short-term storage of unsealed containers.

The model proposed by Taylor describes the oxidation kinetics of UO$_2$ pellet fragments by calculating the simultaneous oxidation of grain boundaries, diffusion-controlled oxidation of grains to U$_3$O$_7$/U$_4$O$_{9+3x}$, and further oxidation to U$_3$O$_8$ by a nucleation-and-growth process. Currently the model does not account for reduced oxygen partial pressure and does not include the effect of nitrogen oxides on the oxidation processes.

The UO$_2$ oxidation model should be updated to include some of the model improvements and enhancements recommended by Tait [2003], in particular the capability for evaluating the effect of moisture and nitrogen oxides on fuel oxidation rates.

4.3 Stress Corrosion Cracking of Zircaloy

Experiments were conducted at the Chalk River Laboratories during the period 1983-86 to investigate the cracking behaviour of Zircaloy cladding rings when exposed to known SCC agents [Wood et al, 1985, 1986]. They specifically looked at the question of whether or not iodine vapour or mixtures of cesium and cadmium vapours are capable of causing crack propagation in Zircaloy cladding at dry storage temperatures.
The studies found that samples of cladding exposed to low fast-neutron fluences would fail only at high stress intensities, above failure thresholds previously established for unirradiated Zircaloy, when exposed to iodine or cesium/cadmium vapours. On the other hand, samples of cladding exposed to high fast-neutron fluences would fail at substantially lower stress intensities under the same test conditions. The experiments used smooth samples as well as samples with incipient cracks, covering a range of hydrogen content in Zircaloy from 20 to 130 ppm and were conducted at temperatures from 100°C to 300°C.

The results from the above studies [Wood et al, 1985, 1986] provide valuable data on SCC of CANDU fuel and indicate a path for establishing the risk of fuel failure from SCC. Wood’s results indicate a clear dependence of SCC on fast-neutron fluence and on the existence of previous notches or marks on the cladding surface. Since both these parameters can be estimated from fuel statistics using available information from PIE of OPG’s fuel, an estimate of the risk from SCC could be derived largely based on existing information.

A study should be implemented based on the above-described process. The study should consist of the following steps:

a) Integrate the data from Wood et al [1985,1986] with other available experimental data on SCC of Zircaloy and re-interpret the collective data using current methodology to obtain threshold values of stress intensity and SCC agent concentrations.

b) Perform additional tests if required to establish process thresholds.

c) Examine/analyze PIE data from discharged OPG fuel and from used fuel statistics relevant to SCC (e.g. fast-neutron fluence, existence of cladding marks/flaws).

d) Determine storage scenarios in which SCC conditions exist and calculate the concentration of SCC agents and stress/stress intensities.

e) Based on fuel statistics and the predicted SCC-relevant conditions calculate the probability of occurrence of SCC in the used fuel population as a function of time for each scenario.

f) Assess the consequences of the predicted SCC occurrence in terms of loss of fuel integrity

There are two different types of threat from SCC, one constituted by cracks in the inner surfaces of cladding or end-cap welds induced by the iodine in the gap of intact fuel. This is largely prevented by the Canlub coating in higher-risk fuel elements. The other threat is that of SCC initiating on the outside surface of a fuel element in cases where the DSC cavity becomes contaminated with SCC agents. This case falls under abnormal storage scenarios. To analyze the risk associated with this scenario it is necessary to determine the concentration of SCC agents in the DSC cavity. Measuring the concentrations of SCC agents would be possible under the dry storage monitoring program described in Section 5.3.

4.4 Hydrogen Effects on Zircaloy

The two major potential effects on the fuel Zircaloy components from the hydrogen incorporated during irradiation in the reactor are delayed hydride cracking (DHC) and embrittlement, which would increase the susceptibility to fuel failure when subjected to impact loads or vibration (e.g. from handling and transportation). These phenomena occur as a result of hydrogen and deuterium precipitation in the Zircaloy and they constitute perhaps the biggest concern for long-term integrity of the fuel. The hydrogen and deuterium precipitate in the form of hydrides.
morphology and geometric orientation of the hydrides, as well as their size have significant effect on the properties of the material.

Temperature cycling of the fuel induced by ambient temperature oscillations and the progressive decrease in temperatures during dry storage may result in a cycle of dissolution and precipitation of the hydrogen in the fuel Zircaloy components. Coupled with residual stresses in the cladding and welds, and with the temperature gradients within the DSC, these processes could result in migration of the hydrogen to high stress points and in growth or re-orientation of the hydrides [EPRI Report 1002882, Part II, Section 4.3]. These phenomena might create the conditions for fuel failure. As time in storage increases, the susceptibility to DHC is expected to increase, as well as the brittleness of the Zircaloy components, which would become more vulnerable to failure as a result of shock or vibration.

A report by Rashid et al [EPRI Report 1001281], published in 2001, presents an analysis defining five conditions that should exist for DHC to be an active mechanism in LWR fuel during dry storage. The analysis provides a convincing argument that DHC is not an operative mechanism for LWR fuel in dry storage. It shows that stress intensities in the LWR fuel cladding are below the critical stress intensities for both crack initiation or for sustaining crack growth.

The applicability of the above argument to the CANDU fuel Zircaloy components should be investigated. If DHC cannot be ruled out on that basis, a study similar to the one outlined above for SCC should be conducted to assess the hydrogen effects on the Zircaloy components. The steps of this study should be as follows:

b) Determine the fuel characteristics of the spent fuel population which are related to the relevant hydrogen effects (hydrogen concentration, hydride distribution, etc.).

c) Based on those parameters and using the appropriate process models, predict the evolution of Zircaloy properties in the storage environment. This would include hydrogen migration, hydride growth and re-orientation and embrittlement of the Zircaloy.

d) Compare those properties with the established fuel performance requirements to determine the probability of loss of fuel integrity resulting from hydrogen-induced failure of Zircaloy components under the applicable storage, fuel handling or transportation scenarios.

4.5 Synergistic Effects

The combined effects of SCC and DHC has been observed to cause failure of cladding samples in tests conducted at CRL [Wood et al, 1985, 1986] to investigate SCC and metal vapour embrittlement (MVE) of Zircaloy. During those tests, Cs/Cd vapours were found to initiate cracks on smooth Zircaloy specimens subjected to stress, at a temperature of 100°C. Those cracks then triggered DHC (a faster crack propagation mechanism) which caused the failure of the samples.

Such phenomena and/or synergistic effects between other fuel degradation processes could take place during or following dry storage and they should be considered as possible causes of fuel failure. The study of these effects should be included in the examination of fuel failure modes and, if applicable, their effect on fuel integrity should be quantified.
5. EXPERIMENTAL WORK AND FUEL VERIFICATION

This section describes the experimental work that may be required as part of both development and benchmarking of process models as well as to verify the condition of fuel.

5.1 Work in Support of Analytical Models

Implementation of the enhancements recommended for the UO\textsubscript{2} oxidation model may require experimental work or re-analysis of existing experimental data [Tait, 2003]. Some of the tasks supporting development of the UO\textsubscript{2} oxidation model identified by Tait would include experimental work, however, the precise scope of this task has not been defined yet.

Similarly, experimental work may be required to expand the data base needed for assessment of SCC and hydrogen effects, including DHC. Evaluation of these processes is included in the fuel integrity program plan, as outlined in Section 4. These evaluations begin with an assessment of the existing data. This will help define the need for specific tests to complete the required data base.

5.2 Monitoring of Fuel in Dry Storage

A report by Villagran [1997] proposes a plan to monitor four loaded containers at the Pickering Dry Storage Facility. The load of four Pickering DSCs consists 1,536 fuel bundles with and a total of 43,008 fuel elements. The test DSCs would be instrumented for temperature and pressure and a sampling loop connected to the fuel cavity would allow periodic sampling of the cavity atmosphere. The design of the sampling loop includes iodine and particulate filters and a gamma-compensated beta-radiation detector to measure the concentration of krypton-85 in the cavity gas. The capability of measuring krypton-85 on a daily basis would enable the system to detect the occurrence of individual cladding failures.

The proposed monitoring program would enable the following:

a) Detecting the occurrence of cladding failures in the DSC. This capability will exist for a period of at least ten years, until the activity of krypton-85 decays below detectable limits.

b) Verifying the predictions of the storage containers thermal analysis.

c) Determining the concentration levels of fission products and other contaminants that might occur in the DSC cavity and their long-term behaviour.

Implementation of the monitoring program should be examined within the context of the irradiated fuel integrity program to determine in which form will the monitoring program contribute to increasing confidence in the predictions of long-term fuel condition. The DSC monitoring program could be combined with the proposed fuel verification program to enhance the information that can be extracted from both activities. There would be a clear benefit in examining fuel that has been in storage in a monitored environment. This benefit could be enhanced by placing fuel with known cladding defects in one or more of the test DSCs. Such a test would allow correlating the size and number of cladding failures with the measured levels of contamination in the DSC cavity and, by examining samples from the test fuel, to assess the effect of the contaminant concentrations on the stored fuel.
5.3 Verification of Fuel Condition

Examination of fuel bundles stored in dry storage every few decades is considered necessary to verify the accuracy of predictions regarding fuel condition. This would involve opening a storage container and testing selected fuel bundles. The time period between fuel examinations should be determined on the basis of predicted rates of fuel degradation in storage and also on socio-political factors. It is anticipated that a reasonable period would be about 20 to 30 years.

As suggested under Section 5.2, examination of fuel contained in test DSCs used in the dry storage monitoring program would be of benefit. In terms of methods and logistics, it would be relatively simple to load the test containers with fuel of known characteristics and place them in an accessible area.

In the U.S.A., examinations of stored fuel in a Castor cask were performed following approximately 15 years in storage. The results of the examinations covering both cask and fuel are included in EPRI Reports 1003010 and 1002882. The tests were conducted at the INEEL and Argonne Laboratories under the sponsorship of EPRI, DOE and the U.S.NRC. It is expected that some benchmarking of the predictions of fuel condition will be required also for CANDU fuel after a few decades in storage. Some initial information potentially useful for benchmarking analytical models of fuel degradation could be obtained by examining fuel that has been in storage in Canada for an extended period.

A plan for fuel tests should be prepared and implemented to collect experimental data required for defining fuel performance requirements and for establishing thresholds and limits for parameters relevant to fuel degradation in dry storage. Following approval by OPG, the plan should be implemented. This task should include the examination of Pickering fuel bundles A01789W and A01790W, currently in storage at Whiteshell Laboratories. This will allow the measurement of relevant parameters on characterized fuel which has been in dry storage since October of 1978. These examinations and tests can be used to determine parameters such as the fracture toughness of the Zircaloy components and welds and the size and characteristics of hydride deposits as well as to assist in defining the scope of future fuel examinations.

6. PROPOSED PROGRAM

The required tasks for the proposed fuel integrity program are listed together with a summary description in Table I.

Table I –Task list

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
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<tbody>
<tr>
<td>1</td>
<td>Describe reference fuel characteristics at the start of Dry Storage. Based on fuel statistics, including results from post irradiation examinations (PIE), provide a description of fuel characteristics which represent the CANDU fuel population currently in dry storage, or to be placed in dry storage. Based on the reference fuel characteristics, review the existence of data relevant to long-term fuel integrity. Prepare a summary of existing data and a list of gaps, to assist in prioritizing future work.</td>
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<td>Task</td>
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<td>2</td>
<td>Prepare thermal analyses for the DSCs under various storage scenarios.</td>
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<tr>
<td>3</td>
<td>Determine long-term fuel performance requirements.</td>
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<tr>
<td>4</td>
<td>Develop a computer code for UO2 oxidation under dry storage conditions.</td>
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<td>5</td>
<td>Quantify residual stresses in the CANDU fuel bundle and evaluate the risk to fuel integrity derived from the associated creep strain.</td>
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<td>6</td>
<td>Evaluate the risk to fuel integrity from SCC of Zircaloy.</td>
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<td>7</td>
<td>Evaluate the risk to fuel integrity from hydrogen effects, including DHC and Zircaloy Embrittlement.</td>
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<tr>
<td>8</td>
<td>Prepare and implement a plan for examination and testing of fuel bundles in dry storage.</td>
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<td>9</td>
<td>Develop a plan for future fuel examinations.</td>
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<tr>
<td>10</td>
<td>Evaluate the need for the earlier proposed dry storage monitoring program. If confirmed, initiate implementation.</td>
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REFERENCES


