

Allowable Maximum Storage Temperatures for CANDU Fuel in Air in Interim Storage Systems and Used Fuel Containers for a DGR

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Abstract

The use of ambient air in the storage of used fuel instead of an inerting atmosphere such as helium is a desirable engineering feature. The potential presence of undetected defective fuel with through the wall fuel element cladding defects requires the determination of the allowable maximum temperature fuel can be exposed to during its storage. This is because oxidation of the UO_2 fuel pellets in the defective fuel elements by air can lead to the unzipping of the fuel element cladding containing the fuel.

Both defective and non-defective CANDU fuel stored in air at constant temperature of 150°C from 1980 to 1997 at the former AECL-Whiteshell Laboratories as part of the Controlled Experiment Program (CEX-1) maintained its mechanical integrity with insignificant change. Defective CANDU fuel showed gross oxidation of the UO_2 pellets to $\text{U}_3\text{O}_7/\text{U}_4\text{O}_{9+x}$ without breaching the fuel cladding. These experiments failed to provide a kinetic relation for the oxidation of defected fuel. However, the USA DOE developed an empirical relation for the oxidation of LWR fuel. Because of the similar oxidation mechanisms in both fuels, the DOE relation was expanded to CANDU fuel and applied to typical storage systems for CANDU fuel including permanent storage in the proposed NWMO Used Fuel Containers (UFCs) in a DGR.

The temperature of the used fuel in storage is a function of time, the storage system design characteristics, the age of the fuel and the fuel heat of decay. It was determined that fuel older than 7 years can be stored for up to 100 years at an initial maximum fuel temperature of 160°C without the fuel cladding being breached, and indefinitely in UFCs in a DGR if the initial fuel peak temperature is below 150°C .

1. Introduction

The technical basis supporting the use of air in UFCs rather than inerting is not documented in the literature. In this paper, this concern is addressed for CANDU fuel. The main work found on inerting comes from the USA for storage of PWR and BWR fuel and was started in the 1980s.

To date, all commercial dry storage systems for the long-term storage of Light Water Reactor (LWR) fuel are being inerted due to the high temperatures of storage, normally above 200°C and 300°C or higher for MOX fuel. At these temperatures, oxidation of defected fuel leads to unzipping of the fuel cladding when stored in air. Also, the oxidation of the fuel cladding can be significant resulting in the thinning of the cladding which can lead to fuel cladding creep. By contrast, fuel temperatures are normally well below 150°C for CANDU fuel stored in AECL reinforced concrete

dry storage canisters or silos, the AECL CANSTOR vault storage system and the Ontario Power Generation Inc. Dry Storage Containers (DSCs). At this lower temperature, the oxidation of the fuel pellets is considerably reduced and the oxidation of the fuel cladding is negligible.

With dry storage systems expected to store fuel for 100 years or longer before the fuel is moved to a Deep Geological Repository (DGR), it becomes important to ensure that the cladding is not breached during storage and the fuel assembly maintains its mechanical integrity. This is required to safely handle the fuel when it is being transferred from the storage systems to the used fuel containers for emplacement in the DGR. Oxidation of defected fuel leading to breachment and unzipping of the cladding, for instance, would complicate its handling and lead to contamination of the handling equipment and fuel handling facilities with the potential for lengthy processing downtimes. Inerting of the storage systems and the used fuel containers would achieve these requirements but at an additional significant cost and, in the case of the used fuel containers (UFCs) used in a DGR, the technical complexity of their processing is increased.

2. Evidence on the Behaviour of CANDU Fuel Stored in Air

AECL jointly with Ontario Hydro carried out a demonstration program to establish the performance of CANDU fuel bundles in dry storage. The demonstration took place at AECL Whiteshell Laboratories from 1980 to 1997. Two different experiments were conducted in ambient air known as ERB and CEX-1. The ERB (Easily Retrievable Basket Experiment) was to demonstrate that fuel could be stored outdoors and sustain thermal seasonal cycles including below freezing temperatures without degradation. The CEX-1 experiment maintained four non-defected and four deliberately defected irradiated commercial CANDU fuel bundles at a constant temperature of 150°C in ambient air. The two sets of defected and non-defected bundles each had two Pickering and two Bruce type fuel.

2.1 Undefected Fuel Behaviour

The experimental evidence with the undefected fuel bundles stored in the CEX-1 and ERB experiments is that no significant physical changes were observed. The fuel cladding did not oxidize in a significant way. Other processes that could lead to fuel degradation such as Delayed Hydride Cracking (DHC) and creep were not observed. Diametral measurements of the fuel cladding showed no significant changes over time. Torque tests of the endcap/endplate welds similarly indicated no significant changes to the mechanical properties of the welds confirming that the bundles should be able to maintain their structural integrity during storage and beyond.

A similar demonstration in Spain involving the storage of six undefected high burnup (>50 GWd/MgU) LWR fuel rods or elements stored in air at temperatures below 175°C, showed the cladding to remain intact and without any degradation during the storage time of more than 25 years [1]. Based on the available data, it can be concluded that undefected CANDU fuel, can be similarly stored without degradation in air at the lower temperatures of CANDU fuel storage. The experimental results of the CEX-1 program on undefected fuel also support this conclusion.

The two commercially irradiated undefected CANDU fuel bundles of the Pickering type stored outdoors in AECL concrete canisters and monitored in the Easily Retrievable Basket (ERB) experiment showed that fuel could experience cyclic sub-freezing temperatures without observable

changes. These results further reinforce the conclusion that at the low temperatures of storage of CANDU fuel (150°C and lower), undefected fuel stored in air is expected to maintain its mechanical integrity without significant effects.

2.2 Defected Fuel Behaviour

Since undefected CANDU fuel elements or LWR rods from fuel bundle assemblies have been shown capable of dry storage in air at temperatures below 175°C, the oxidation of the UO₂ pellets to U₃O₈ in defected fuel elements is the main concern in the storage of fuel stored in air. The experience from the CEX-1 experiment showed that the oxidation of the UO₂ is a two stage process leading to oxidation of the UO₂, first, to U₃O₇/U₄O₉ and, then, to U₃O₈. It is the conversion to U₃O₈ that causes a 36% volumetric increase of the pellets and results in the breachment and unzipping of the cladding. This is usually along its length although radial breachment across the cross section of the fuel element at the site of the defect has been observed in LWR fuel. In any event, the oxidation to U₃O₈ of the affected pellets makes them lose their cohesion and to become powdery. The eventual disintegration of the pellets leads to the release of fission products contaminating the storage system and complicating downstream fuel handling operations.

The main conclusion from the CEX-1 experiment is that bulk oxidation to U₃O₈ throughout the element of intentionally defected fuel was not observed during 15.5 years of exposure to ambient air at a temperature of 150°C. Minor amounts of U₃O₈ were, however, detected around the fuel element defect but without showing obvious swelling or damage to the cladding or diametral changes to the fuel cladding.

Experiments of CANDU fuel elements oxidized in air at temperatures above 200°C showed rather rapid oxidation to fuel cladding breachment of few months to days with increasing temperatures and shorter times at the higher temperatures of 300°C and beyond [2] to [4]. As the CEX-1 experiments at 150°C showed fuel oxidation slows down considerably below 200°C. However, the data obtained from the CEX-1 experiments was insufficient to develop a kinetic relation for the oxidation of defective fuel elements which could be used to determine the threshold temperatures when storing CANDU fuel in air below which breachment of the fuel cladding would not be expected to occur due to oxidation of the fuel pellets to U₃O₈.

3. Modelling UO₂ Conversion to U₃O₈ in Defective CANDU Fuel

The initial temperature at which fuel can be placed in a dry storage system so that defected fuel will not oxidize sufficiently to unzip the fuel cladding is being termed the threshold temperature for storing the fuel in the dry storage system under consideration. The threshold temperature is a function of:

1. Type and characteristics of the spent fuel such as fuel age, burnup and decay heat.
2. The oxidation rate of the defective fuel as a function of the temperature of the storage environment.
3. The heat transport characteristics of the storage facility or system.

These factors control the temperature of the fuel as a function of time. Calculating the fuel temperature as a function of time is key to establishing whether defective fuel will oxidize and breach the fuel cladding during the storage period.

As mentioned earlier, the rate of oxidation of the fuel could not be obtained from the data of the fuel demonstration conducted at AECL at 150°C. However, purposely defected CANDU fuel elements were oxidized in air in the temperature range 220°C-300°C [2] to [4]. It was this database along with a LWR database that was used for the development of the USA DOE semi-empirical equations to estimate the rate of oxidation of UO₂ to U₃O₈ [5]. The model is based on the oxidation of UO₂ to U₃O₈ being a two-step process consisting first, in the oxidation of UO₂ to U₄O₉ that results in a volumetric decrease of the fuel pellet. This is consistent with the observations of the CEX-1 dry storage experiment at AECL where bulk oxidation of the UO₂ matrix to U₃O₇/U₄O₉ was only observed in the 15.5 years the experiment was conducted. After this step, the USA DOE model considers the oxidation of the pellet to U₃O₈ from oxidation of the formed U₄O₉ as a second oxidation stage independent of the first. The second stage oxidation takes into account the contribution of the fuel burnup. High burnup fuel showing higher resistance to oxidize to U₃O₈ translates to very long times of oxidation. The model also indicates that the oxidation taking place in the second stage is slower than the oxidation of the first step at temperatures below about 150°C. The USA DOE model was used to develop general equations of the Arrhenius type that describe the oxidation of the pellets. Details of this derivation are given in [7].

Based on the results of applying the DOE model, correlations to predict incubation time to breaching the cladding were derived for CANDU fuel of average burnup (8.3 GWd/Mg U or 200 MWh/kgU) as given in Table 1 for two temperature ranges. These correlations fit the values obtained from the USA DOE model with a variance of $R^2 \geq 0.99$. Deviations for values calculated from these correlations are at most a few per cent of the calculated values from the adapted DOE model for CANDU fuel, and, therefore, they provide a precise estimate of the incubation times.

Table 1: Correlations Estimating Incubation Times (Years) as a Function of Temperature (°K) for Defected Used CANDU Fuel of Average Burnup (8.3 GWd/MTU)

Temperature Range (°C)	Bruce Fuel	Pickering Fuel
25-150	$t_{inc} = 4.016 \times 10^{-18} e^{\frac{18330}{T}}$	$t_{inc} = 4.514 \times 10^{-18} e^{\frac{18360}{T}}$
150-300	$t_{inc} = 8.84 \times 10^{-13} e^{\frac{13000}{T}}$	$t_{inc} = 8.30 \times 10^{-13} e^{\frac{13000}{T}}$

where T is in degrees Kelvin and t_{inc} is time in years.

When applying these correlations to a storage system, it is essential to know the temperature of the fuel as a function of time. As the fuel decays, the temperature of storage steadily decreases exponentially resulting in a significant decrease in the rate of conversion of UO₂ at temperatures below 150°C. If the conversion of the UO₂ leading to fuel cladding breach is given by x_f , then conversion as a function of time t can be written as:

$$dx_f = dt/t_{inc}(t) \quad \dots\dots\dots (1)$$

The value of t_{inc} is given by the above correlations in their generic form as:

$$t_{inc} = Ae^{\frac{B}{T(t)}} \dots \dots \dots (2)$$

where A and B are constants, and $T(t)$ is the fuel temperature which depends on the design of the storage system where the fuel is stored. Introducing equation (2) into equation (1), then by integration,

$$x_f = \int_0^t \frac{dt}{Ae^{\frac{B}{T(t)}}} \dots \dots \dots (3)$$

This is the extent of conversion of the fuel to breachment. When t is the time of breachment or t_f then x_f is equal to 1 and the equation becomes

$$1 = \int_0^{t_f} \frac{dt}{Ae^{\frac{B}{T(t)}}} \dots \dots \dots (4)$$

The equation can be solved by approximation and by trial and error to obtain the initial allowable peak fuel temperature, T , at time $t=0$ and the time t_f to determine whether fuel cladding breachment could occur during its storage time.

4. Estimating CANDU Fuel Temperature in Dry Storage Systems

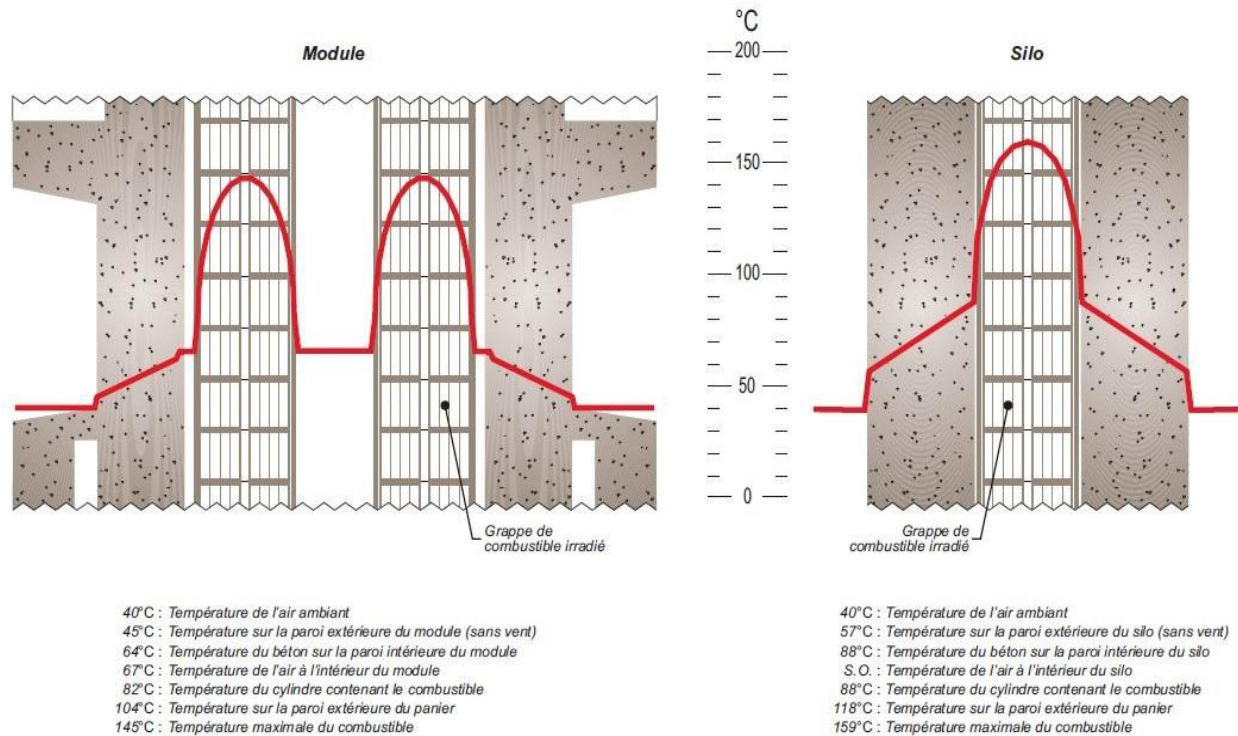
The allowable or threshold initial temperature of the fuel in a dry storage system is a function of the design of the storage facility. For CANDU fuel, dry storage systems using air to store the fuel are the AECL modular convection vaults known as CANSTOR and MACSTOR and the concrete silos (Figure 1). There is little difference between the thermal characteristics of the CANSTOR and MACSTOR systems. The OPG DSCs are designed to store 10 year old fuel below 150°C but use helium as the storage medium. Their design characteristics are similar to the AECL concrete silos but use the OPG storage modules for storing the fuel resulting in a rectangular prismatic shape for the concrete DSCs.

As part of the licensing process for the CANSTOR storage at the Gentilly-2 reactor at Hydro Quebec, the temperature profiles in the CANSTOR system and AECL concrete silos were provided for 7 year old fuel and are reproduced in Figure 1 in their original form [8]. It will be noted that the temperature profiles shown are the steady state solution to the storage of the fuel (60 bundles per storage basket) for both the MACSTOR and concrete silos and were confirmed by measurement.

The CANDU fuel bundles are stored inside seal-welded stainless steel baskets in ambient air. The bundles are positioned vertically on their endplates in a single layer of 60 bundles and held in place by a single stainless steel plate perforated with 60 circular openings to hold them. Typically, in other concepts, the bundles are held within cylindrical tubes. This adds an additional barrier to heat transfer and results in fuel bundle temperature estimated to be higher by about 5-10°C than the AECL basket. The steady-state temperature profile of the fuel in the storage basket is identical.

The temperature of the fuel, however, inside the storage baskets could be increased or decreased by increasing or decreasing the resistance to heat transfer by changing the design of the storage configuration and, also, when storing fuel of a higher or lower decay heat than the average burnup (200 MWh/kgU) seven year old fuel used in Figure 1. It also shows that the ambient air temperature was assumed constant at 40°C. This is a conservative design assumption.

The temperature profile of the concrete silos shown in Figure 1 can be used to advantage to estimate the temperature profiles at various timeframes of storage to calculate the degree of



Note : Distribution des températures lorsque le silo ou le module est rempli à pleine capacité et que les grappes ont séjourné six ans dans la piscine de stockage.

Figure 1: Temperature Profiles for a CANSTOR Module and an AECL Concrete Silo/Canister as per Hydro-Quebec (2003) [8]

conversion of the UO₂ leading to fuel cladding breachment. In estimating the temperature of the fuel as a function of time, it is assumed that the change of the heat of decay of the fuel over time as the heat source decays is slow enough that the system can be considered to be in a quasi-steady state. Further, the transfer of heat from the fuel to the storage basket is well represented by an effective thermal conductivity that is constant as the fuel cools off. Due to the close spacing of the fuel bundles and the fuel elements in the fuel assembly inside the storage basket, the convective component of the heat transport is small and rather limited. As a result, the temperature drop of the fuel in the storage basket can be estimated readily from the solution of the one dimensional steady state heat transfer equation with a generating heat volumetric source in the medium written as:

$$\frac{d^2T}{dr^2} + \frac{dT}{rdr} = - \frac{q}{k_{eff}} \dots\dots\dots (5)$$

where T is the temperature of the medium, q is the volumetric heat source, r is the radius and k_{eff} is the effective thermal conductivity.

Equation (5) yields:

$$T_{max} - T_w = \frac{q r_w^2}{4 k_{eff}} \dots\dots\dots (6)$$

where r_w is the inner radius of the storage basket. This equation allows the estimation of the temperature drop for container systems of different size such as the UFC container and the storage basket of the AECL concrete silos, for instance.

From equation (6), also the temperature drop for a different value of the heat source with all other variables remaining the same when only the value of the heat source changes such as q_2 is readily calculated as:

$$\Delta T_2 = \frac{q_2}{q_1} \Delta T_1 \dots\dots\dots (7)$$

If the temperature of the fuel is artificially increased by changing the effective thermal conductivity of the storage basket but maintaining the same heat source then, the temperature increase or decrease for the fuel can be estimated as:

$$\Delta T_2 = \frac{k_{eff1}}{k_{eff2}} \Delta T_1 \dots\dots\dots (8)$$

and, similarly when both q and k_{eff} change:

$$\Delta T_2 = \frac{k_{eff1}}{k_{eff2}} \frac{q_2}{q_1} \Delta T_1 \dots\dots\dots (9)$$

For transfer of the heat normal to the storage container, the heat flux at the walls of the container is used for the transfer of heat through the various heat barriers of the storage system assuming as before a quasi-steady state assumption. The temperature drop through the barriers is then estimated similarly as given by equation (7). It is assumed that the overall heat transfer coefficient across the dry storage walls is constant. Considering the relatively small temperature difference of 17°C between the outer wall of the container and the ambient air of 40°C, it is found that assuming the convective heat transfer coefficient as a constant at the wall is reasonable since the coefficient is proportional to the temperature difference between the wall and ambient air to the power of 0.25 from the free convection correlation using the Nusselt number and leads to a small temperature difference error of about one to two degrees for the wall to air temperature difference.

5. Threshold Temperatures for Defective CANDU Fuel in Interim Dry Storage Systems

Based on the temperature profiles shown in Figure 1 as a starting point and using the appropriate equations introduced above, the degree of conversion to UO₂ as a function of time can be estimated. The licensing temperature of 160°C was used as the initial temperature of the used fuel since it bounds all CANDU fuel dry storage systems. A summary of the results of the calculations for 7 year old average burnup fuel (200 MWh/kgU) is shown in Table 2 as a function of

temperature. Also, the results establishing the allowable or threshold temperature at which average burnup CANDU fuel may be stored without fuel cladding breachment is documented.

Table 2 : Defective CANDU Fuel Oxidation in Interim Dry Storage

	Fuel Age = 7 years old; Initial T=160°C		Fuel Age = 7 years old; Initial T=174°C	
Storage time (years)	Fuel Temperature (°C)	Conversion (X _f)	Fuel Temperature (°C)	Conversion (X _f)
0	160	0.0	176	0.0
1	155.9	0.08	171.3	0.31
5	143.5	0.21	157.2	0.86
7	135.2	0.23	147.8	0.96
10	122.8	0.23	133.8	1.0
11	118.6	0.23	129.5	1.0
13	110.4	0.24	119.8	1.0
15	102.1	0.24	110.4	1.0
20	81.5	0.24	87.0	1.0
Time to Stage 2 (U ₃ O ₈)	10 years only trace U ₃ O ₈		10 years full conversion leading to breaching the cladding	

The rate of conversion of UO₂ as a function of storage time at the prescribed licensing storage temperature limit of 160°C confirms that the fuel oxidizes quickly to U₄O₉ in the first stage of oxidation upon storing but the rate of conversion decreases rapidly and asymptotally to zero after 13 years in storage. The final conversion value of UO₂ is 0.24 when the fuel has cooled to about 110°C. Full conversion to U₄O₉ was achieved by the 10th year but oxidation to U₃O₈ was only trace amounts and it essentially arrested. As a result, the fission products remain fixed in the fuel precluding any risk of contamination. The resultant extent of conversion of the defective fuel stored at an initial temperature of 160°C supports the regulatory licensing limit of 160°C for interim storage of CANDU fuel in air and suggests it may be stored beyond 100 years.

The allowable temperature or threshold temperature for storing average burnup fuel before fuel cladding breachment occurs was found to be 174°C (Table 2). At this temperature, full conversion of the fuel to U₃O₈ is first observed prior to breaching the cladding by the 10 year of storage for 7 year old fuel. The higher temperature at which the fuel cladding will breach is significantly beyond

the regulatory limit further suggesting that inerting of interim dry storage systems for CANDU fuel is unnecessary.

6. Threshold Temperatures for Defective CANDU Fuel in Used Fuel Containers

The Used Fuel Container (UFC) being proposed for a Deep Geological Repository by the Nuclear Waste Management Organization has a capacity for 48 bundles stacked in a basket of 12 tubes with four bundles in each tube. Figure 2 shows the proposed UFC with the fuel basket. The details of the container are yet being developed. However, CANDU fuel to be stored in the basket is at least 30 years old. A detailed numerical analysis of the fuel temperature in the UFC when emplaced in a sedimentary rock predicts a peak temperature for the fuel of 126°C at 14.7 years after emplacement [9]. At this low temperature, the fuel in a defective bundle will hardly oxidize at all when stored indefinitely in a Deep Geological Repository (DGR). The degree of conversion of the UO_2 for this peak fuel temperature of 126°C is shown in Table 3 as a function of time with the temperature of the fuel over time approximated from the temperature curve shown in Figure 3. UO_2 conversion to cladding breachment is 0.049 with trace oxidation to U_3O_8 starting about 300 years after initial storage over the 200,000 year storage projection.

The question as to how high the allowable fuel temperature can be before the cladding is breached



Figure 2: Copper Coated Used Fuel Container for CANDU Used Fuel proposed by the NWMO (48 bundle capacity).

is of interest. Fuel temperatures higher than the UFC fuel temperature of 126°C are achievable with fuel younger than 30 years and with containers that have lower effective thermal conductivities than containers using the AECL baskets for interim storage described earlier.

The temperature of the fuel as a function of time for these other conditions can be approximated by assuming quasi-steady conditions and making use of the temperature of the wall of the container as a function of time for the specific layout of the DGR. A typical decay temperature curve for an UFC container emplaced in an In-Room Placement DGR is shown in Figure 3 [10]. The container

shows a maximum surface peak temperature of 80°C for 10 year old fuel. A similar temperature curve was developed for a container with 30 year fuel emplaced horizontally in sedimentary rock DGR with peak container wall temperature of 100°C meeting the NWMO criteria [11]. When



Figure 3: Predicted Variation of the Used Fuel Container Surface Temperature with Time for the In-Room DGR

normalized both temperature profiles are identical except for the 20°C difference in the container peak wall temperature. This is the result of adjusting the repository layout by distancing the containers and the repository tunnels as necessary to meet the prescribed peak temperature of the container. Based on these assumptions, the temperature of the UFC wall given in Figure 3 is well represented by a best fit line of the form:

$$T_{UFC} = -5.645 \ln t + 92.4 \quad \text{when } t \geq 10 \text{ years} \dots (10)$$

where T_{UFC} is the UFC wall temperature in degrees Celsius and t is time in years from the time of the UFC emplacement in the DGR.

Results of the calculations for the oxidation of defected fuel at fuel peak temperatures of 126°C for 30 year old fuel and 150°C for 10 and 30 year old fuel when initially loaded in the UFC are shown in Table 3 for UFCs with peak wall temperatures of 100°C. The achieved fuel peak temperature of 150°C is for containers with fuel baskets that have lower effective thermal conductivities than the NWMO container shown in Figure 2. So that, for instance, a direct comparison between the 30 and 10 year old fuel is not possible here because the thermal characteristics of the two fuel baskets are not equivalent. The 10 year old fuel is in a basket with higher thermal conductivity than the 30 year old fuel. If the 10 year old fuel were placed in the same basket as the 30 year old fuel, its fuel peak temperature would be 200°C and the fuel would breach soon after storage.

Table 3: Defective CANDU Fuel Oxidation in DGR Used Fuel Containers

	Fuel Age = 30 years old at initial time of storage in UFC at the DGR; Initial Peak T=126 ⁰ C		Fuel Age = 30 years old at initial time of storage in UFC at the DGR; Initial Peak T=150 ⁰ C		Fuel Age = 10 years old at initial time of storage in UFC at the DGR; Initial Peak T=150 ⁰ C	
Storage time (years)	Fuel Tempe- rature (⁰ C)	Conver- sion (X _f)	Fuel Tempe- rature (⁰ C)	Conver- sion (X _f)	Fuel Tempe- rature (⁰ C)	Conver- sion (X _f)
10	126	0.0	150	0.0	150	0.0
20	119	0.017	141	0.22	138	0.19
50	108	0.035	126	0.44	120	0.31
100	97	0.042	109	0.50	107	0.36
1,000	69	0.047	71	0.51	70	0.37
100,000	32.3	0.049	32.9	0.52	32.6	0.38
200,000	31.5	0.049	32.0	0.52	31.8	0.38
Time to Stage 2 (U ₃ O ₈)	At about 300 storage years but only trace conversion to U ₃ O ₈		32 storage years		34 storage years	

The data shows that for an initial peak temperature of 150⁰C, 30 year old fuel does not breach the cladding and conversion to U₃O₈ starts at about 32 years into storage in the UFC but nearly ends at a conversion of 0.50 around 100 years into storage without leading to breachment. However, breaching of the cladding for 30 year old fuel was found to occur at about 156⁰C. In the case of 10 year old fuel, the results are similar to 30 year old fuel with oxidation to U₃O₈ beginning at 34 years of storage but arresting to a conversion value of 0.36 at 100 years of storage. Breaching of the 10 year old fuel occurs at about 160⁰C. Further, the conversion values given in Table 2 for fuel stored in dry storage prior to its emplacement in the UFC when added to the conversion in the UFC are not sufficient to breach the fuel cladding. As a result of these findings, a temperature of 150⁰C is chosen as the allowable temperature to store fuel in used fuel containers as a practical threshold that leaves a significant safety margin to maintain the integrity of the fuel indefinitely when stored in air.

7. Conclusions

Based on experience, licensing approval and the results of the experimental dry storage demonstration program (CEX-1) at AECL-Whiteshell (1980-1997), it can be concluded that commercial CANDU fuel can be stored in air at temperatures below 160⁰C for interim storage for over 100 years. Results from the DOE model applied to interim dry storage of CANDU fuel

storage systems confirm this upper temperature limit and indicate inerting with helium might not be required.

For permanent storage of CANDU fuel in the proposed NWMO Mark II container in a DGR with an internal air environment, the fuel will preserve its integrity and oxidation of any defected fuel to U_3O_8 will be negligible and will not lead to fuel cladding breachment. The threshold peak fuel temperature leading to cladding breachment is above 150°C indicating that inerting is not required below this temperature.

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