Proceedings of the Korean Nuclear Autumn Meeting
Yongpyong, Korea, October 2002

Evaluation of Maximum Allowable Temperature inside Basket of Dry Storage Module for CANDU Spent Fuel

Kyung Ho Lee, Jeong Hyoun Yoon, Kyoung-Myoung Chae, Byung Il Choi,
Heung Young Lee, Myung Jae Song, Gyuseong Cho*

KHNP/NETEC, *KAIST
DukJin 150 Yusong, Daejeon

ABSTRACT

This study provides a maximum allowable fuel temperature through a preliminary evaluation of the UO_2 weight gain that may occur on a failed (breached sheathing) element of a fuel bundle. Intact bundles would not be affected as the UO_2 would not be in contact with the air for the fuel storage basket. The analysis is made for the MACSTOR/KN-400 to be operated in Wolsong ambient air temperature conditions. The design basis fuel is a 6-year cooled fuel bundle that, on average has reached a burnup of 7,800 MWd/MTU. The fuel bundle considered for analysis is assumed to have a high burnup of 12,000 MWd/MTU and be located in a hot basket. The MACSTOR/KN-400 has the same air circuit as the MACSTOR and the air circuit will require a slightly higher temperature difference to exit the increased heat load. The maximum temperature of a high burnup bundle stored in the new MACSTOR/KN-400 is expected to be about 9°C higher than the fuel temperature of the MACSTOR at an equivalent constant ambient temperature. This temperature increase will in turn increase the UO_2 weight gain from 0.06% (MACSTOR for Wolsong conditions) to an estimated 0.13% weight gain for the MACSTOR/KN-400. Compared to an acceptable UO_2 weight gain of 0.6%,, we are thus expecting to maintain a very acceptable safety factor of 4 to 5 for the new module against unacceptable stresses in the fuel sheathing. For the UO_2 weight gain, the maximum allowable fuel temperature was shown by 164℃.

INTRODUCTION

The MACSTOR/KN-400 storage module is a new generic high capacity dry storage structure made of regular density reinforced concrete for Wolsong CANDU reactors. The design reuses the design features of the MACSTOR storage module that are used at Gentilly 2. It is simply made wider to accommodate a capacity of 24,000 bundles instead of 12,000 bundles. Figure 1 shows existing MACSTOR in operation at Gentilly 2 Canada which becomes basis for MACSTOR/KN-400, a consolidated dry storage module for Wolsong CANDU reactors.

A specific fuel weight gain assessment is necessary for the Wolsong dry storage module for two reasons. The first is the slightly higher ambient air temperature of 14.2°C (yearly average), compared to 5°C for Gentilly 2 site. The second reason is the higher fuel storage temperature (by about 9°C) expected in the MACSTOR/KN-400 storage module, compared to he MACSTOR storage module in use at Gentilly 2 and being implemented at Cernavoda, Romania. The MACSTOR was initially equipped with a large size air circuit aimed at dissipating the large heat release from LWR fuel. The air circuit was thus oversized for storage of lower power CANDU fuel. Due to its large size, the MACSTOR air circuit can easily dissipate the higher power from the MACSTOR/KN-400 storage module with little temperature increase to the fuel.

The bundles are stored in a fuel basket holding 60 bundles. Fuel baskets are stacked 10 high into storage cylinders. Each MACSTOR module contains 20 storage cylinders laid in two rows of ten. Meanwhile, the MACSTOR/KN-400 has 40 storage cylinders laid in four rows of ten cylinders. The same air circuit is used for both designs. The planned storage period of the spent fuel is 50 years.

With the above conditions, evaluation of maximum allowable temperature inside basket of the module was performed for a CANDU spent fuel dry storage.

Figure 1. MACSTOR CANDU Spent Fuel Dry Storage Module in Operation

DESIGN BASIS FUEL AND POWER GENERATION IN STORAGE MODULE

The design basis fuel is a standard CANDU 6 bundle that has reached an average burnup of 187.2 MWh/kgU (7,800 MWd/MTU) and that has been cooled for 6 years in the storage bay. Decay heat of the design basis fuel bundle has previously been estimated by ORIGEN2.1 to release 6.08 Watts. From this average bundle, a high burnup bundle of 290 MWh/kgU (12,000 MWd/MTU) is derived, releasing 9.76 W. A CANDU 6 reactor like Wolsong produces few bundles having such a high burnup during a year. The bundle for which the weight gain is calculated is assumed to be a high burnup bundle of 290 MWh/kgU, releasing 9.76 Watts. To cater for the possibility of the presence of one or more similarly high burnup bundles in a fuel basket, six other high burnup bundles are conservatively assumed to be surrounding the bundle for which the weight gain analysis is made. This is very unlikely condition in terms of geometrical configuration. In supplement, this cluster of seven high burnup bundles is conservatively assumed to be positioned at the worse possible location in the fuel basket. The remaining 53 bundles are average burnup ones. The resulting hot basket thus generates a power of 53*6.08W + 7*9.76W = 390.6 Watts. This hot basket is defined to provide a conservative estimate of the maximum fuel bundle temperature in a basket and a conservative estimate of the UO_2 weight gain.

In supplement to assuming the bundle is stored in a hot basket, it is also postulated that the hot basket is stored at the top of the storage cylinder. The other nine baskets in the storage cylinder are also conservatively assumed to be hot baskets resulting in a total of 3.9kW per storage cylinder. This is a very conservative case as it is unlikely that a storage cylinder would get loaded with such a combination. To simplify thermal calculations, is also assumed that all storage cylinders in the module are filled with hot baskets, releasing a total of 78 kW per storage module. The assumption of storing hot baskets in a hot module increases the power level by 7% compared to the nominal average power of the 73 kW.

CALCULATION OF FUEL WEIGHT GAIN

The UO_2 fuel oxidation process, rate of weight gain as a function of temperature and calculation methods are described by $3UO_2$ + O_2 U_3O_8 In case of that, rate of volume increase is approximately 30% and allowable weight gain is calculated by 0.6% to prevent from splitting of clad of fuel rod[1].

The conservative limit of 0.6% total weight gain of the UO_2 would correspond to a 2% diametral increase caused by conversion of the UO_2 to non-swelling intermediate oxides and to swelling U_3O_8. The swelling from U_3O_8 will cause a diametral increase that will stress and open further (if above 2% sheath strain), an existing sheath failure along a crack of the fuel element sheathing. Such phenomenon only occurs on a fuel bundle that would have one of its elements failed, exposing the UO_2 to the air of the fuel basket. Two methods of inputting the ambient temperature over years of storage were used; both provided the same results. The first method maintained the ambient air at a constant value set as the monthly average temperature during a particular month. To cover for temperature variations, the first year is assumed to be subjected to record high monthly averages during each of the 12 months. This assumption represents a very unlikely sequence of temperatures and is very conservative. As the record high monthly average temperatures for Wolsong were not available for this preliminary analysis, the average monthly temperatures were increased by the difference between the record data and the average data found at the Cernavoda site. The second method inputs temperature data as degree-hours cumulated over the year. This is the most accurate method, but the previous method that uses average was found to give the same results. So either can reliably be used. For the degree-hours method, during the first year, all ambient air temperatures are increased by 5.6°C. This is the average difference between record monthly averages and the monthly averages. The bundle power and temperature are decreased each year in accordance to decay but is conservatively kept stable during a specific year. Figure 1 and Figure 2 show that comparison.

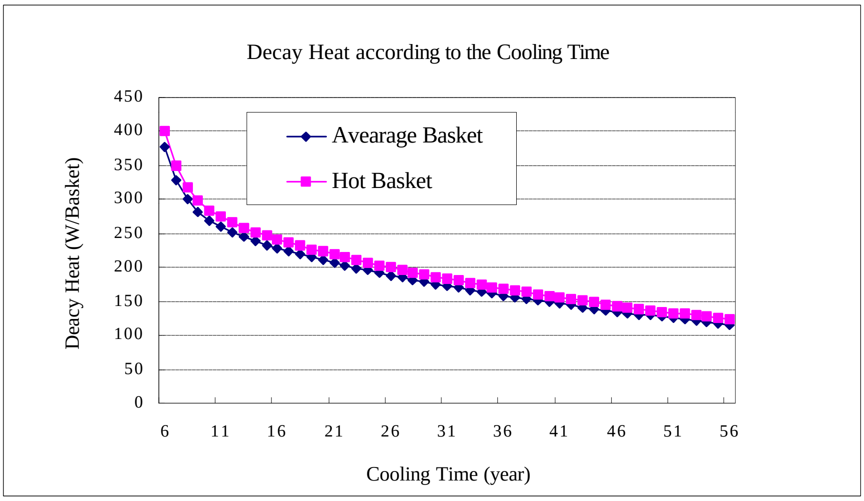

Figure 1. Comparison of Decay Heat between Average and Hot Baskets as a function of Cooling Time

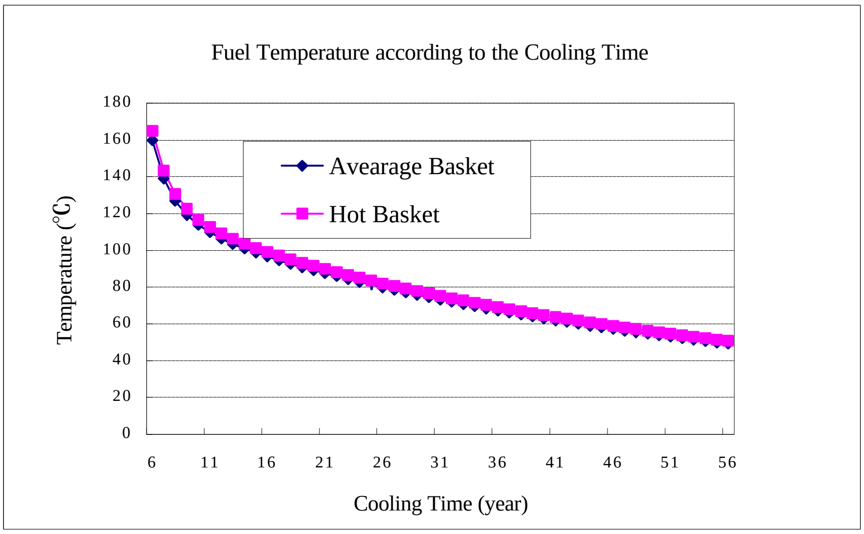

Figure 2. Comparison of Fuel Temperatures between Average and Hot Baskets as a function of Cooling Time

CALCULATION RESULTS

For a MACSTOR storage module operating in Cernavoda conditions, the maximum fuel weight gain is evaluated at 0.045%. This provides a comfortable safety factor of 13 with respect to the allowable fuel weight gain for the Cernavoda storage facility. The Wolsong ambient air yearly average is 14.16°C; that is 3°C higher than the Cernavoda average of 11.16°C. The Wolsong specific ambient air temperature was inputted to the fuel weight gain model and run for the MACSTOR and the estimated MACSTOR/KN-400 cases. A MACSTOR module was first analysed for operation with Wolsong specific ambient air temperature data. For these conditions, a preliminary estimate for 50 years of dry storage is a 0.06% weight gain. Thus, a MACSTOR storage module operating at Wolsong specific ambient air conditions would maintain a safety factor of 10 with respect to the allowable weight gain.

The fuel weight gain model (with Wolsong specific temperature data) was then modified to increase the initial fuel temperature by 9°C, simulating the MACSTOR/KN-400 conditions. This ÄT is reduced over the years as the heat release decreases from decay of radionuclides. For these conditions, the preliminary estimate of the lifetime weight gain is 0.013%. Thus, a MACSTOR/KN-400 operating at Wolsong specific ambient air conditions would maintain a safety factor of the order of about 5 with respect to the conservative allowable weight gain.

To oxidize the spent fuel to the maximum allowable weight gain of 0.6%, an initial temperature of 164°C (32.7°C record monthly ambient air temperature and 500W hot basket) would be required. This temperature would be obtained with a hot basket power of 500W, significantly higher than the 390W power of the design basis hot basket case. Thus, for a hot basket, the power would need to be increased by approximately 28% (500W/390W) before fuel oxidation becomes a concern.

Table 1 provides a summary of data for a MACSTOR storage module and a MACSTOR/KN-400 storage module supposing that will be operating at Wolsong and using the preliminary projected operating temperature of the fuel.

The fuel temperature decreases quickly with time and the rate of weight gain even faster due to the exponential behaviour of the fuel weight gain. Following a few years of storage, the weight gain rate becomes negligible, preventing further weight gain during the planned 50 years storage period and for decades beyond.

Table 1. Summary of Fuel Weight gain for the MACSTOR and MACSTOR/KN-400 Storage Modules

ITEM	MACSTOR – Wolsong	Wolsong MACSTOR/KN-400
Average yearly temperature	14.5°C	14.16°C
Monthly average temperature (July or August of years 2-50)	25.7°C	25.7°C
Record monthly average temperature (July or August of first year)	32.7°C (See note 1)	32.7°C (See note 1)
Maximum initial monthly average fuel temperature (hot basket)	136°C *(143-40+32.7)*	145°C *(152-40+32.7)*
Maximum initial temperature (to obtain 0.6% weigh gain)	164°C	164°C
Total fuel weight gain over 50 years (hot basket, hot module)	0.06%	0.13%
Allowable weight gain (%weight gain)	0.6%	0.6%
Safety factor with respect to maximum allowable weight gain	10	4 to 5
Maximum allowable hot basket power	550W	500 W
% power increase by which the hot basket would need to be increased to reach the conservative limit of 0.6% UO_2 weight gain	41% (550W/390W)	28% (500W/390W)

Note 1: The record ambient temperature for Wolsong has been determined by adding 7°C to the maximum monthly ambient air temperature. The 7°C difference is the one found at Cernavoda will be used Wolsong specific data in future study.

The maximum allowable initial temperature at which we can store fuel has been calculated at 164°C. The maximum allowable initial temperature has been found to be quite constant for spent fuel of a specific cooling period and for a specific storage structure. To be reached, the maximum initial temperature would require all baskets to have a power of 500W, at an ambient air temperature of 32.7°C.

PARAMETRIC FUEL WEIGHT GAIN OF MACSTOR/KN-400 STORAGE MODULE: Fixed Power and Variable temperature

A preliminary parametric fuel weight gain analysis was made for the MACSTOR/KN-400 storage module using Wolsong ambient air conditions. The MACSTOR has a wide temperature margin of approximately 30°C. With an expected increase of 9°C, the MACSTOR/KN-400 would maintain a temperature margin of the order of 20°C . Figure

3 provides for a hot basket power of 390.4Watts, the level of fuel weight gain as a function of the temperature increase of the MACSTOR/KN-400.

And Figure 4 provides, for a hot basket power of 390.4Watts, the level of fuel weight gain as a function of the temperature increase of the MACSTOR/KN-400.

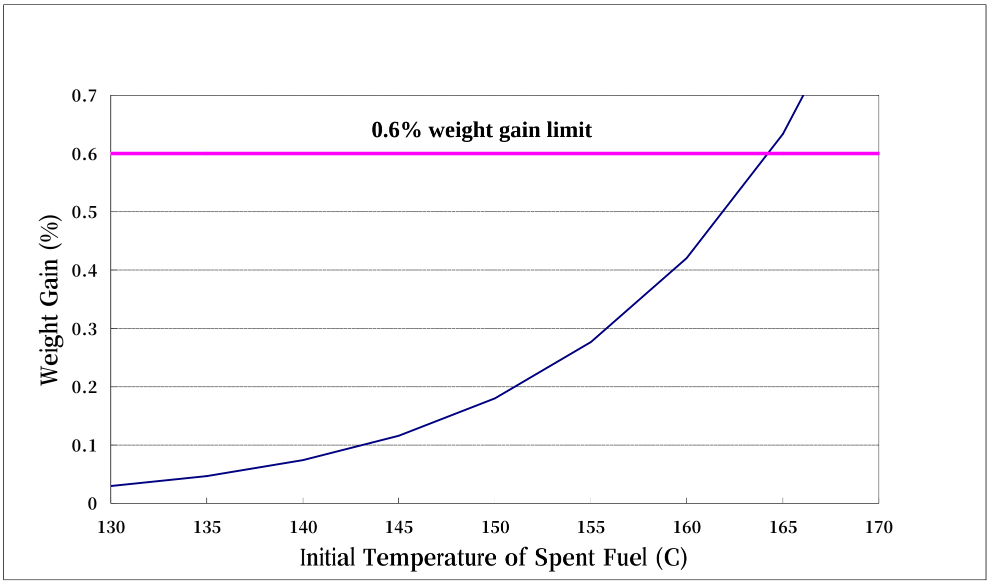

Figure 3. Expected UO_2 Fuel Weight Gain as a function of Initial Fuel Temperature

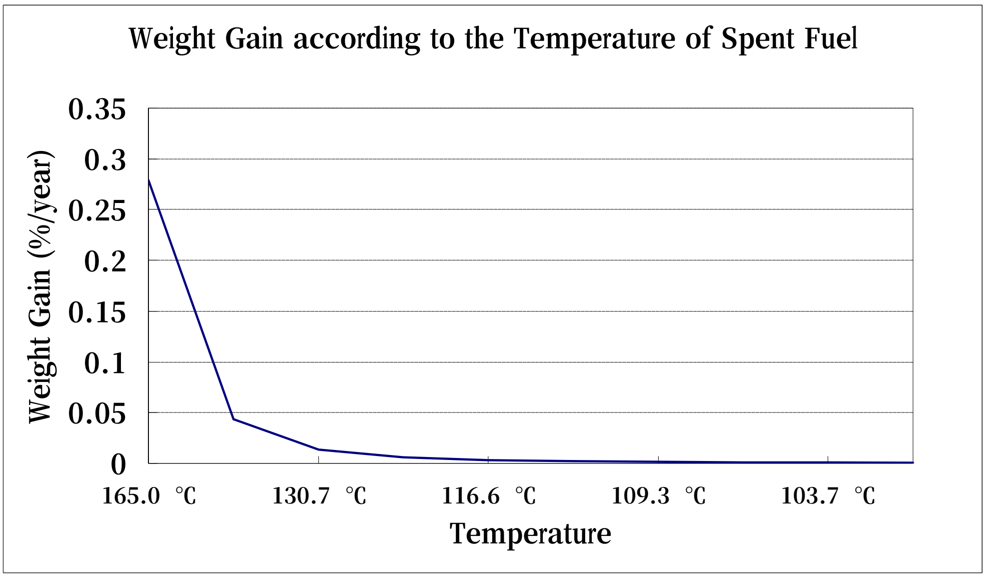

Figure 4. Expected UO_2 Fuel Weight Gain as Function Temperature Decrease Over MACSTOR/KN-400 Module

CONCLUSION AND FUTURE STUDY

Increasing volume of fuel rod due to oxidation can generate crack. Therefore, the maximum allowable fuel temperature should be determined within the range that crack can not be propagated by increase of sheath stress. This study was performed to evaluate the oxidation rate of spent fuel under the quite a conservative assumption that abnormally highly burned 7 spent fuel bundles are loaded in the basket with unlikely configuration. From the result of the study, it can be shown that there is sufficient margin to protect the fuel against degradation, when stored in the MACSTOR/KN-400 during the planned 50 years of storage. For the future study, detail analysis will be carried out to determine the maximum allowable temperature inside basket within storage module.

REFERENCES

[1] R. Shill, Étude du Comportement Thermique du Module CANSTOR #2, File 66-62500-220-002 Rev. D0, 08/08/00,AECL.