STATUS OF THE DEMONSTRATION IRRADIATION OF THE CANDU NEW FUEL BUNDLE CANFLEX-NU IN KOREA

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ABSTRACT

A demonstration irradiation (DI) of 24 KNFC made CANFLEX-NU fuel bundles in the Wolsong Power Generation Station–1 has been conducted jointly by KEPRI/KHNP/KAERI since July 10, 2002. By selecting the Q07 (high power) and L21(low power) channels, the total 24 and 16 CANFLEX bundles were respectively loaded into and discharged from the reactor by 2003 August, and the final discharge of the other 8 CANFLEX bundles is expected on around February 2004. Tracking the reactor operation data, it is noted that the reactor has been stably operated during the DI. One CANFLEX bundle irradiated in the Q07 channel had a typical history of high power and high burnup, having the outer element power rating of ~ 41 kW/m at the fuelling, ~ 42 kW/m as a maximum power rating at the burnup of ~ 50 MWh/kgU, and ~ 35 kW/m at the discharge burnup of ~ 210 MWh/kgU. While, another CANFLEX bundle also irradiated in the Q07 channel had a typical history of power ramping, having a outer element power rating of ~7 kW/m from the fuelling to the burnup of ~ 48 MWh/kgU at which the element powers were ramped to a ~35 kW/m maximum element power rating, and ~30 kW/m at the discharge burnup of 188 MWh/kgU. An unusual performance and integrity of the CANFLEX elements could not be found in the ELESTRES predictions. By looking at the discharged CANFLEX bundles in the bay, all the bundles were intact, free of defects and appeared to be in good condition. A detailed in-bay visual examinations and dimensional measurements of the discharged CANFLEX bundles will be made at the end of 2003.

1. INTRODUCTION

Since 1991, the CANFLEX®[1](CANDU®[2] Flexible Fuelling) bundle as an advanced nuclear-fuel carrier for the CANDU pressurized-heavy-water reactor has been jointly developing by Korea Atomic Energy Research Institute (KAERI) and Atomic Energy of Canada Limited (AECL). The CANFLEX fuel bundle has been verified through extensive testing by KAERI and AECL. A demonstration irradiation (DI) of the 24 bundles with natural uranium (NU) fuel at the Point Lepreau Generating Station (PLGS) in Canada was successfully performed between 1998 September and 2000 August[1]. For this period, a similar DI irradiation program of the 24 CANFLEX bundles with NU fuel was also prepared for the Wolsong Power Generation Stations-1 (WPGS-1) [2]. The WPGS-1 is commercially operating since 1983 April.

The CANFLEX bundle, as shown in Figure 1, contains about the same amount of uranium in weight as the 37-element bundle but uses 43 fuel elements. It is characterized by a moderately flat radial-power profile, with the outer and intermediate rings consisting of 21 and 14 elements of 11.5 mm O.D. and the inner ring and center rod consisting of 7 and 1 element(s) of 13.5 mm O.D.. The CANFLEX bundle assembly and its critical-heat-flux (CHF) enhancement appendages offer higher operating and safety margins than the 37-element bundle, while maintaining a full compatibility with the existing CANDU reactors. It enables a higher power to be realized before CHF occurs, leading to a net gain in critical channel power (CCP) typically of 3 to 9% over the existing 37-element NU fuel, which is based on the results of the full scale water CHF testing of the CANFLEX bundle in the high pressure steam-water loop at the Stern Laboratories in Canada [3,4,5]. The greater element subdivision and the use of two element sizes lower the peak linear-element rating, and gives a more balanced radial power distribution [6,7,8]. The maximum linear element rating in a CANFLEX bundle is 20 % lower than that of a 37-element bundle, reducing the consequence of most design basis accidents. Therefore, the bundle is well suited for the use of advanced fuel cycles, particularly those that can attain high fuel burnup. The higher operating and safety margins offer the potential of reactor power uprating, which would further increase the economic competitiveness of the CANDU reactor.

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1 CANFLEX® is a registered trademark of Atomic Energy Canada Limited (AECL) and Korea Atomic Energy Research Institute (KAERI).

2 CANDU®(Canadian Deuterium Uranium) is a registered trademark of Atomic Energy of Canada Limited(AECL)

A DI program of 24 CANFLEX-NU fuel bundles in WPGS-1 has been conducted jointly by Korea Electric Power Research Institute (KEPRI)/Korea Hydro and Nuclear Power Company (KHNP)/KAERI since 2000 November, in order to validate the CANFLEX bundle performance with direct conditions of relevance under the Korean licensing requirements, to evaluate the fuel fabrication capability, and to provide the rationale for the decision to perform the full-conversion of CANFLEX fuel in WPGS-1. KHNP has been one of the subsidiary companies of the Korea Electric Power Corporation (KEPCO) since April 2, 2001.

As for the status of the DI of the 24 CANFLEX-NU bundles in WPGS-1, This paper describes the statements of the DI licensing and the channel selection criteria for the DI, the fuel bundle manufacture and QA, the fuelling history, the thermalhydraulic behaviour of the CANFLEX fuel channels, the power histories of the CANFLEX fuel elements, the evaluation of the fuel performance and its integrity.

2. STATUS OF THE DEMONSTRATION IRRADIATION IN WPGS-1

2.1 DI Licensing Approval and Channel Selection Criteria for the DI

As part of the Korean licensing process for the design of the CANFLEX-NU (Mk-IV) bundles and the DI of the 24 CANFLEX bundles in Korea, KAERI prepared a CANFLEX-NU fuel design report describing the fuel design and fabrication method (FD/FM) and a safety assessment report for the DI by July 1996 and June 2001, respectively. After KINS completed the review of these documents, the licensing approvals of the FD/FM and the DI were released from the Korea Ministry of Science and Technology (KMOST) on August 6, 1999 and June 21, 2002, respectively.

The channel selection criteria were intended to fulfill and established a set of DI objectives taken from the DI of 24 CANFLEX-NU fuel bundles in the PLGS[9].

2.2 CANFLEX Bundle Manufacture and QA

KEPCO Nuclear Fuel Co. Ltd. (KNFC) completed the supply of the 26 CANFLEX-NU DI bundles (24 fuel bundles for the DI and 2 for archival purpose) to WPGS-1 by May 2002. Also, KNFC provided the manufacturing history dockets including the manufacturing drawing (showing manufacturing-specific details) and the product specifications. Where the CANFLEX fuel design was defined by a KAERI/AECL joint reference drawing and a technical specification of the CANFLEX 43 element bundle, and all the technical specifications referenced from the bundle specification. These CANFLEX bundles were manufactured at a KAERI facility by KNFC engineers in accordance with the Quality Assurance levels equivalent to the CSA Z299.2 standard normally applied to the 37-element fuel supplied to WPGSs. It is noted that KNFC has made about 100 CANFLEX bundles for the in- and out-reactor tests since 1991.

2.3 Fuelling History of CANFLEX-NU (Mk-IV) Fuel Bundles for the High and Low Power Channels in WPGS-1

With the channel selection criteria above, the fuelling of the 24 CANFLEX fuel bundles into two separate fuel channels of WPGS-1 was planned in order to maintain a minimum risk and maximum flexibility of the reactor operation. One would be a high power channel near the mid-level of the Liquid Zone Controllers and two regular eight-bundle shift fuellings of CANFLEX fuel. The other would be a low power channel and would receive one eight-bundle shift fuelling of CANFLEX fuel. The fuelling sequence was established as illustrated in the fuelling histories of Figures 2 and 3. It is noted that, during the DI, there was a period of the reactor's planned outage from January 31 to March 16, 2003 as mentioned in the figures. The duration of the DI was expected to be approximately 18 months.

In the morning of July 10, 2002, 8 CANFLEX bundles (KF0114, KF0115, KF0102, KF0103, KF0101, KF0104, KF0105, KF0125) were loaded into the 5th to 12th bundle positions of the low power channel L21 as shown in Figure 2. By fuelling 8 37-element bundles into the 5th to 12th bundle positions on April 1, 2003, the 4 CANFLEX fuel bundles (KF0101, KF0104, KF0105, KF0125) irradiated in the 9th to 12th bundle positions were shifted, respectively, to the 1st to 4th bundle positions and the 4 CANFLEX bundles irradiated at the 1st to 4th bundle positions were discharged. The remaining 4 CANFLEX bundles (KF0101, KF0104, KF0105, KF0125) being irradiated in the 1st to 4th bundle positions will be finally discharged on, or around February 2004.

In the afternoon of July 10, 2002, 8 CANFLEX bundles (KF0124 ~ KF0117) were loaded into the 1st to 8th bundle positions of the high power channel Q07 as shown in Figure 3. By fuelling 8 CANFLEX bundles (KF0106 ~ KF0113) also into the 1st to 8th bundle positions on January 6, 2003, the 4 CANFLEX bundles (KF0124 ~ KF0121) irradiated in the 1st to 4th bundle positions were shifted, respectively, to the 9th to 12th bundle positions and the 4 CANFLEX bundles (KF0120 ~ KF0117) irradiated in the 5th to 8th bundle positions were discharged. Fuelling the 8 37-element bundles also in the 1st to 8th bundle positions on August 11, 2003, the 4 CANFLEX fuel bundles (KF0106 ~ KF0109) irradiated in the 1st to 4th bundle positions were shifted, respectively, to the 9th to 12th bundle positions, and the 8 CANFLEX fuel bundles (KF0110~KF0113, KF0124~KF0121) irradiated in the 5th to 12th bundle positions were discharged. The remaining 4 CANFLEX bundles being irradiated in the 9th to 12th bundle positions will be finally discharged on, or around February 2004.

2.4 Thermalhydraulic Behaviour of the CANFLEX Fuel Channels

In order to track the core during the DI, the reactor operation data such as the inlet and outlet header pressures and temperatures, the CANFLEX fuel channel pressures and temperatures, and others were obtained from WPGS-1, where the data was measured every day, and every minute for the fuelling periods of the CANFLEX or 37-element fuel bundles into the Q07 and L21 channels. During the DI period of the 100 % reactor full power operation from July 11, 2002 to April 21, 2003, the daily data of the reactor operation was recorded as the following examples. The Q07 and L21 channels' outlet temperatures were 308.183 ± 0.237 °C and 306.510 ± 0.850 °C, respectively, where the data were ~ 2 °C less than the actual channel exit temperatures because of the data measurements at the outlet positions of the feeders. As the headers piped to the L21 channel, the RIH4 header pressure and temperature were 110.944 ± 1.296 bar and 263.004 ± 0.558 °C, respectively, and the ROH1 header pressure and temperature were 98.307 ± 0.513 bar and 309.211 ± 0.523 °C, respectively. As the headers piped to the Q07 channel, the RIH6 header pressure and temperature were 111.202 ± 1.064 bar and 263.375 ± 0.688 °C, respectively, and the ROH7 header pressure and temperature were 98.215 ± 0.308 bar and 308.937 ± 0.547 °C, respectively. This daily data of reactor normal operation illustrated that the reactor was being stably operated during the DI.

Figures 4 and 5 show the outlet temperature variations of the Q07 and L21 channels for their fuelling periods, where the channel temperatures were recorded every minute for the fuelling periods. As shown in these figures, the channel outlet temperatures were dropped by ~ 45 °C to 48 °C for the fuelling periods, due to the heavy water injection flows of the fuelling machine into the channels during the fuellings, where the temperature and flow rate of the injection flow were 93 °C and 1.9 kg/s, respectively. As shown in Figure 4, the L21 channel outlet temperature after the fuelling was increased by ~ 3 °C because of the increased channel power due to the fuelling of the fresh fuel, compared with the channel outlet temperature prior to the fuelling. The outlet temperature change of the low power channel L21 is quite sensitive to the fuelling, in comparison with that of the high power channel Q07. As shown in Figure 5, however, the Q07 channel outlet temperature change between the periods just before and after the fuelling is not recognized, because the outlet temperatures of the high power channel are already saturated. . The average temperatures of the Q07 high power channel outlet are ~ 2 to 3 °C higher than those of the low power channel L21.

3. POWER HISTORIES AND PERFORMANCE OF THE CANFLEX ELEMENTS

3.1 Power Histories of the CANFLEX-NU Elements

As shown in Figures 6 (a) to (d), the element power histories of the CANFLEX bundles irradiated in the high power channel Q07 as well as in the low power channel L21 were derived to evaluate the performance and integrity of the CANFLEX fuel elements with a high power and high burnup history and a power ramp history, as specified for a CANDU fuel qualification, using the RFSP code [10] for the analysis of CANDU cores and the POWERDERPUPS-V code [11] and WIMS-AECL code [12] for the lattice calculations.

Figure 6(a) shows the element power histories of the CANFLEX-NU fuel bundle, KF0119, irradiated in the 6th bundle position of the high power channel Q07 from July 10, 2002 to January 6, 2003. As shown in this figure, the irradiation history of the outer elements is a typical power history of high power – high burnup, showing that the element power linear ratings were ~ 41 kW/m right after the fuelling, ~ 42 kW/m as the maximum power rating at the burnup of ~ 68 MWh/kgU and then, monotonically decreasing to ~ 35 kW/m at the discharge burnup of ~ 210 MWh/kgU.

Figure 6(b) shows the element power histories of the CANFLEX-NU fuel bundle, KF0121, irradiated in the 4th bundle position of the high power channel Q07 from July 10, 2002 to January 6, 2003, and then irradiated in the 12th bundle position from January 6, 2003. This bundle was discharged from the channel on August 11, 2003. As shown in this figure, the power ramped irradiation history of the outer elements indicates that the element power linear ratings were ~ 35 kW/m from right after the fuelling to the burnup of ~ 50 MWh/kgU, and ~ 30 kW/m at the burnup of ~ 180 MWh/kgU. At this burnup, the bundle was shifted to the 12^{th} bundles position and so the outer element power was ramped down to ~7 kW/m which was kept almost constantly to the burnup of ~ 213 MWh/kgU.

Figure 6(c) shows the element power histories of the CANFLEX bundles KF0124 irradiated at the 1^{st} bundle position of the high power channel Q07 from July 10, 2002 to January 6, 2003, and irradiated in the 9^{th} bundle position from January 6, 2003. This bundle was discharged from the channel on August 11, 2003. As shown in this figure, the power ramped irradiation history of the outer elements indicated that the element power linear ratings were ~ 7 kW/m from right after the first fuelling to the burnup of ~ 48 MWh/kgU. At this burnup the outer element power was ramped up to ~ 35 kW/m which was monotonically decreased to ~30 kW/m at the burnup of ~188 MWh/kgU.

Figure 6(d) shows the element power histories of the CANFLEX-NU fuel bundle, KF0115, irradiated in the 6^{th} bundle position of the low power channel L21 from July 10, 2002 to April 1, 2003. As shown in this figure, the outer element power linear ratings were ~ 32 kW/m right after the fuelling, ~ 33 kW/m as the maximum power rating at the burnup of ~ 38 MWh/kgU and then, monotonically decreasing to ~ 27 kW/m at the burnup of ~ 131 MWh/kgU. After this burnup, the element power linear rating was monotonically raised up to ~29 kW/m at the brunup of ~ 170 MWh/kgU, and then was monotonically decreased to ~26 kW/m at the discharge burnup of ~ 199 kW/m.

Reviewing not only the element power histories mentioned in this paper but also those of the other CANFLEX bundles used in the DI, it was consequently found that, during the DI, there were no unusual element power histories which could make a element internal gas pressure induced strain rates of greater than 10^{-9}/sec and a limit for the incremental plastic strain of more than 0.3 % following a power increase when the element internal gas pressure exceeds the coolant pressure,

3.2 The Fuel Element Performance Evaluations

Using the ELESTRES code [13] designed for the design and performance evaluation of the CANDU fuel during the normal operation and incorporating the CANFLEX-NU element power histories and physical dimensions into the code, it predicted the element internal gas pressure (MPa), the pellet's center temperature (°C), the sheath's inside temperature (°C), and the sheath's total hoop strain at the ridge (%) as shown in Figures 7

(a) to (d). A representative evaluation of the in-reactor CANFLEX-NU fuel element performances for the element design qualification can be made with the outer elements.

Figure 7 (a) shows that the ELESTRES predictions of the internal gas pressures of the outer elements of the CANFLEX bundles (KF0119, KF0121, KF0124, KF0115, KF0111) irradiated in the high power channel Q07 and the low power channel L21 of WPGS-1. As shown in the figure, the highest element-internal gas pressure is found in CANFLEX KF0124 outer element with a typical element power history of a power ramp-up: 0.73 MPa ~ 0.78 MPa in the burnup range of ~ 65 MWh/kgU to ~ 188 MWh/kgU, which are considerably lower than the reactor coolant pressure.

Figures 7 (b) to (d) show the ELESTRES predictions of the pellet center temperatures, the sheath-inside-surface temperatures, and the sheath total hoop strains at the ridges of the CANFLEX outer elements mentioned above. As shown in these figures, the highest values of those performance parameters are found in the outer element of the KF0119 CANFLEX bundle with a typical high power and high burnup history in the high power channel Q07.
As shown in Figure 7(b), the maximum pellet centerline temperature was ~ 1250 °C right after the bundle fuelling, which is considerably below the UO_2 pellet melting point of 2840 °C. As shown in Figure 7(c), the maximum sheath-inside-surface temperature of the outer elements was ~ 339 °C right after the fuelling, which is below the Zircaloy-4 sheath surface temperature limits of 398°C for a steady-state operation and 426°C for a short-term transient operation, where the sheath temperature limits are required to preclude a condition of accelerated oxidation which would lead to sheath failure. As shown in Figure 7(d), the highest sheath's total hoop strain at the ridge was ~ 0.75 % also right after the fuelling, which resulted in the zero defect probability.

By looking at the irradiated CANFLEX bundles in the bay, all the bundles were intact, free of defects and appeared to be in good condition. A detailed in-bay visual and dimensional examination of the irradiated CANFLEX bundles will be made at the end of 2003.

4. SUMMARY AND CONCLUSIONS

A DI program of 24 CANFLEX-NU fuel bundles in WPGS-1 has been conducted jointly by KEPRI/KHNP/KAERI since November 2000, to validate the CANFLEX fuel bundle performance in direct conditions of relevance under the Korean licensing requirements, to evaluate the fuel fabrication capability, and to provide the rationale for the decision to perform the full-conversion of the CANFLEX fuel in WPGS-1. The licensing approvals for the fuel design and fabrication method and the DI were obtained from the KMOST in August 1999 and June 2002, respectively. KNFC supplied the 26 CANFLEX DI bundles (24 fuel bundles for the DI and 2 for archival purpose) made with the Quality Assurance levels equivalent to the CSA Z299.2 standard, KAERI/AECL joint reference drawing, and the technical specification of the CANFLEX 43 element bundle.

Based on the channel selection criteria as taken for the DI of the 24 CANFLEX-NU fuel bundles in the PLGS [9], the 8 and 8 CANFLEX bundles were firstly fuelled into the L21(low power) and Q07 (high power) channels of the WPGS-1 reactor, respectively, on July 10, 2002. Up to now, a total of 8 and 4 CANFLEX bundles have been fuelled into and discharged from the L21 channel, respectively, and the total of 16 and 12 CANFLEX bundles have been fuelled into and discharged from the Q07 channel, respectively. The CANFLEX bundles being irradiated in each channel will be finally discharged on, or around February 2004, by expecting a DI duration of approximately 18 month. During the DI, there was a period of the reactor's planned outage from January 31 to March 16, 2003.

The WPGS-1 operation data such as the inlet and outlet header pressures and temperatures and others were reviewed to track the core during the DI. The small variations in the daily reactor normal operation data indicate that the reactor was stably operated during the DI. For example, the inlet and outlet temperatures and pressures in both the channels varied within the ranges of ~ 0.4 % and 1.3 %, respectively. The reactor operation data during the fuelling days indicate that, as expected, the channel power increases right after the fuelling of fresh fuel in the low power channel and leads the channel outlet temperature increase by ~ 3 °C, compared with the channel outlet temperature just before the fuelling. That is, the outlet temperature change of the low power channel is quite sensitive to the fuelling in comparison with that of the high power channel. While the high power channel outlet temperature change between the periods just before and after the fuelling is negligible, because the high power channel outlet temperatures are already saturated and remain steady. The average outlet temperature of the high power channel is ~ 2 to 3 °C higher than that of the low power channel

The CANFLEX bundle and element power histories were derived by using the codes of RFSP[10], POWERDERPUPS-V [11] and WIMS-AECL [12]. The outer elements of the KF0119 CANFLEX bundle irradiated in the 6^{th} bundle position of the Q07 channel shows a typical history of high power and high burnup : ~ 41 kW/m at the fuelling, ~ 42 kW/m as a maximum power rating at the burnup of ~ 68 MWh/kgU, and ~ 35 kW/m at the discharge burnup of ~ 210 MWh/kgU. While the KF0124 CANFLEX bundle irradiated in the 1^{st} bundle position of the Q07 channel from July 10, 2002 to January 6, 2003 and then continuously irradiated in the 9^{th} bundle position shows a typical history of power ramping: ~ 7 kW/m from the fuelling to the burnup of ~ 48 MWh/kgU at which the element powers were ramped to a ~ 35 kW/m maximum element power rating, and ~30 kW/m at the discharge burnup of 188 MWh/kgU. Reviewing not only the element power histories mentioned in this paper but also those of the other CANFLEX bundles used in the DI, it was consequently found that there were no unusual element power histories which could make a element internal gas pressure induced strain rates of greater than 10^{-9}/sec and a limit for the incremental plastic strain of more than 0.3 % following a power increase when the element internal gas pressure exceeds the coolant pressure,

As for the results of the ELESTRES predictions of the in-reactor performances of all the CANFLEX elements irradiated in WPGS-1, it was found that: a) A highest element internal gas pressure of 0.78 MPa at the burnup of ~ 188 MWh/kgU was built up in the KF0124 CANFLEX outer element, which is considerably lower than the reactor coolant pressure of 10.7MPa, b) The highest maximum pellet center temperatures of ~ 1250 °C (which is quite lower than the UO_2 pellet melting point of 2840 °C) and the highest sheath inside surface temperature of ~ 339 °C right after the fuelling were shown in the KF0119 CANFLEX outer element. This sheath inside surface temperature is below the Zircaloy-4 sheath surface temperature limits of 398°C for a steady-state operation and 426°C for a short-term transient operation, where the sheath temperature limits are required to preclude a condition of accelerated oxidation which would lead to sheath failure. The highest sheath total hoop strains at the ridge also happened in the KF0119 CANFLEX outer element: ~ +0.75% in the outward direction right after the fuelling, 0 % at the burnup of ~ 68 MWh/kgU, and then – 0.25 % at the discharge burnup, and c) No indications of any defect in the CANFLEX elements have been shown in the ELESTRES predictions.

By looking at the irradiated CANFLEX bundles in the bay, all the bundles were intact, free of defects and appeared to be in good condition. A detailed in-bay visual and dimensional examination of the irradiated CANFLEX bundles will be made at the end of 20003.

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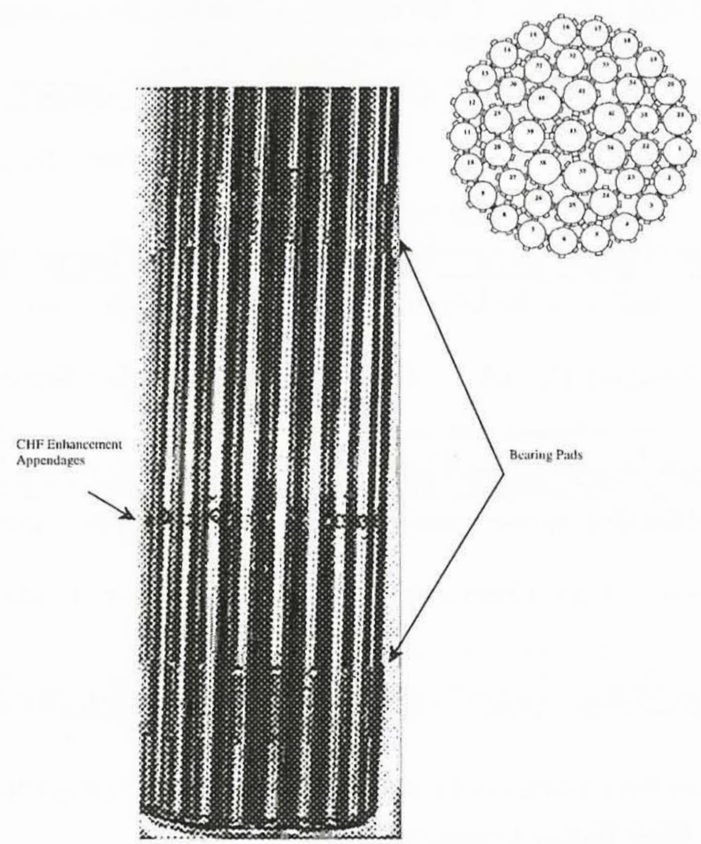


Figure 1. CANFLEX 43-Element Bundle

(a) 1st Fuelling (2002 July 10) : (C . A Refuelling)) & Bundle's Serial Numbers

A-Side — Bundle Position in L21 Channel — C-Side

1	2	3	4	5	6	7	8	9	10	11	12
37ELEM	*37ELEM*	*37ELEM*	*37ELEM*	KF0114	KF0115	KF0102	KF0103	KF0101	KF0104	KF0105	KF0125

(b) 2nd Fuelling (2003 April 1) : (C → A Refuelling)) & Bundle's Serial Numbers

A-Side — Bundle Position in L21 Channel — C-Side

1	2	3	4	5	6	7	8	9	10	11	12
KF0101	KF0104	KF0105	KF0125	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*

• 4 CANFLEX-NU fuel bundles are discharged: KF0114, KF0115, KF0102, KF0103

(c) 3rd Fuelling(Expected on 2004 January):(C→A Refuelling) & Bundle's Serial Numbers

A-Side — Bundle Position in L21 Channel — C-Side

1	2	3	4	5	6	7	8	9	10	11	12
37ELEM	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*

Figure 2. Fuelling History of CANFLEX-NU (Mk-IV) Fuel Bundles in the Low Power Channel L21 in WPGS-1

(a) 1st Fuelling (2002 July 10) : (A . C Refuelling) & Bundle's Serial Numbers

A-Side — Bundle Position in Q07 Channel — C-Side

1	2	3	4	5	6	7	8	9	10	11	12
KF0124	KF0123	KF0122	KF0121	KF0120	KF0119	KF0118	KF0117	37ELEM	*37ELEM*	*37ELEM*	*37ELEM*

(b) 2nd Fuelling (2003 January 06) : (A → C Refuelling) & Bundle's Serial Numbers

A-Side — Bundle Position in Q07 Channel — C-Side

1	2	3	4	5	6	7	8	9	10	11	12
KF0106	KF0107	KF0108	KF0109	KF0110	KF0111	KF0112	KF0113	KF0124	KF0123	KF0122	KF0121

• 4 CANFLEX-NU fuel bundles are discharged: KF0120, KF0119, KF0118, KF0117

(c) 3rd Fuelling (2003 August 11) : (A → C Refuelling) & Bundle's Serial Numbers

A-Side — Bundle Position in Q07 Channel — C-Side

1	2	3	4	5	6	7	8	9	10	11	12
37ELEM	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	KF0106	KF0107	KF0108	KF0109

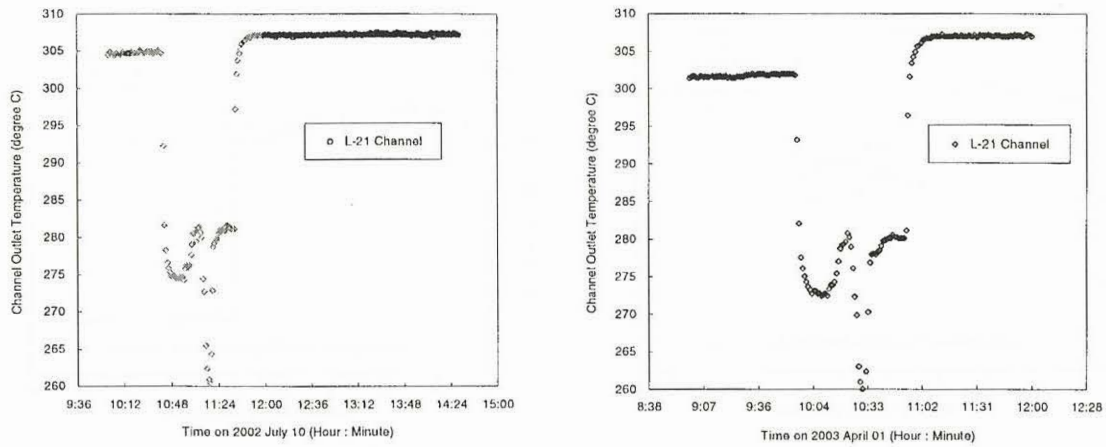
• 8 CANFLEX-NU fuel bundles are discharged: KF0110 to KF0113, KF0124 to KF0122, KF0121

(d) 4th Fuelling(Expected on 2004 February) :(A→C Refuelling) & Bundle's Serial umbers

A-Side — Bundle Position in Q07 Channel — C-Side

1	2	3	4	5	6	7	8	9	10	11	12
37ELEM	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*

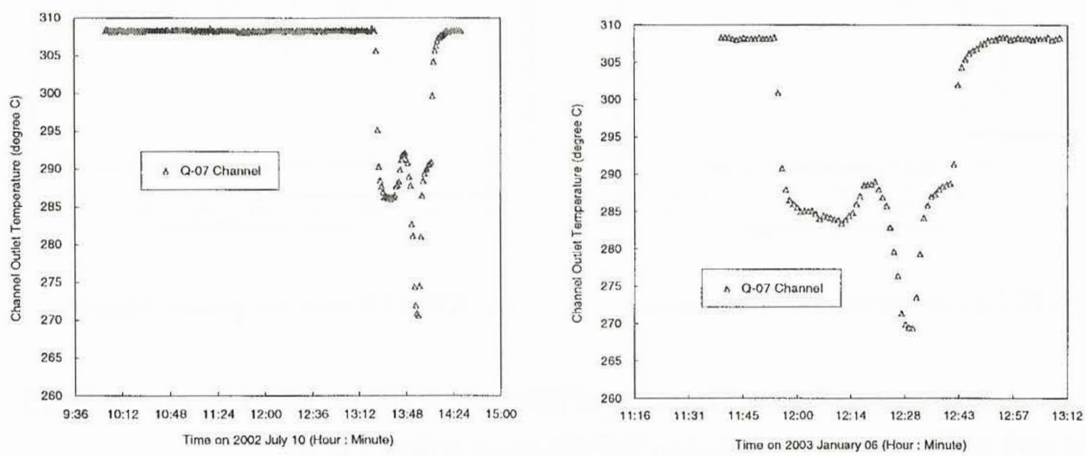
Figure 3. Fuelling History of CANFLEX-NU (Mk-IV) Fuel Bundles in the High Power Channel Q07 in WGS-#1



(a) L21 Channel Data on 2002 July 10
(Fuelling of the 8 CANFLEX bundles)

(b) L21 Channel Data on 2003 April 01
(Fuelling of the 8 37-element bundles)

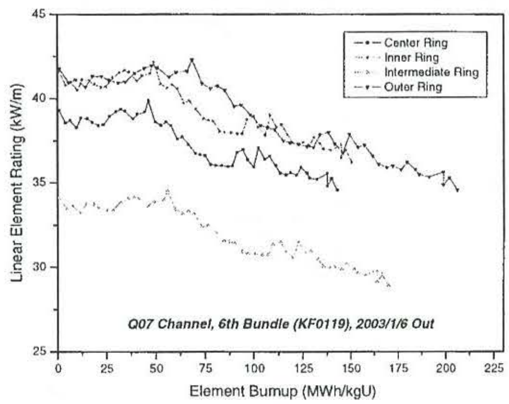
Figure 4. L21 Channel Outlet Coolant Temperature Data during the Fuellings on 2002 July 10 and 2003 April 01



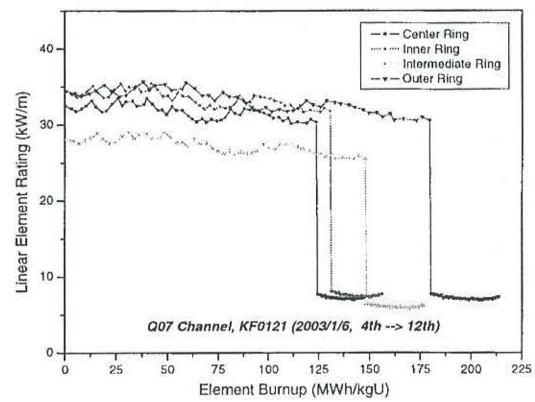
(a) Q07 Channel Data on 2002 July 10
(Fuelling of the 8 CANFLEX bundles)

(b) Q07 Channel Data on 2003 January 06
(Fuelling of the 8 CANFLEX bundles)

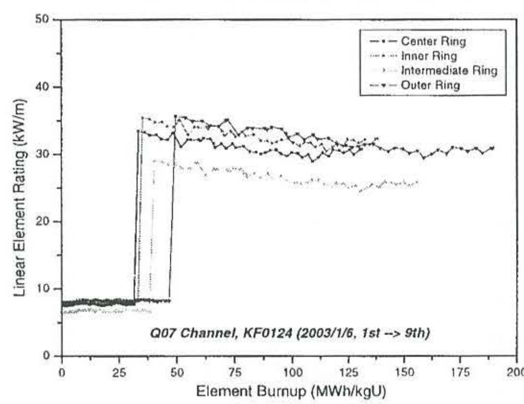
Figure 5. Q07 Channel Outlet Coolant Temperature Data during the Fuellings on 2002 July 10 and 2003 January 06



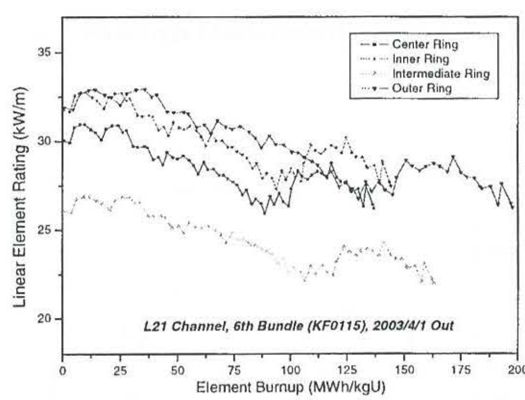
(a) KF0119 element power histories



(b) KF0121 element power histories



(c) KF0124 element power histories



(d) KF0115 element power histories

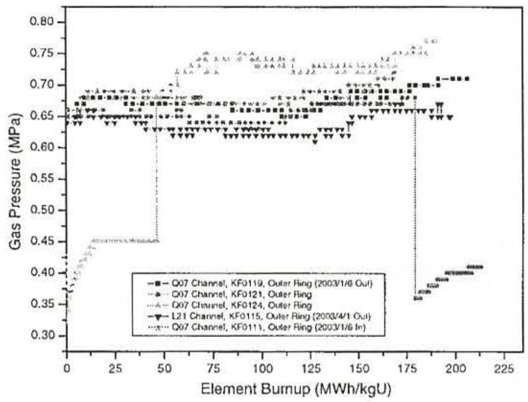
Figure 6. Element Power Histories of KF0119, KF0121, KF0124, and KF0115 CANFLEX Bundle Irradiated in WPGS-1(see Notes 1 to 4)

Note 1. KF0119 CANFLEX Bundle Irradiated in the 6th Bundle Position from 2002 July 10 to 2003 January 6.

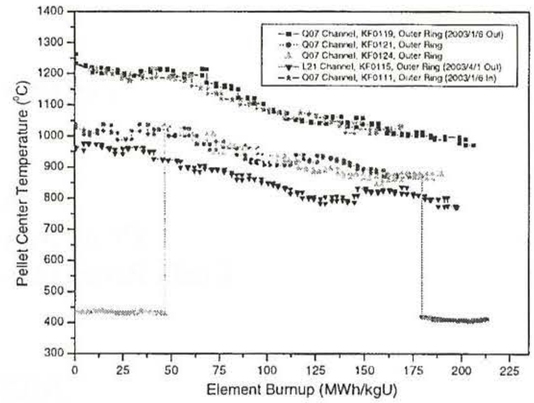
Note 2. KF0121 CANFLEX Bundle Irradiated in the 4th Bundle Position from 2002 July 10 to 2003 January 6 and then Being Irradiated in the 12th Channel Position from 2003 January 6.

Note 3. KF0124 CANFLEX Bundle Irradiated in the 1st Bundle Position from 2002 July 10 to 2003 January 6 and then Being Irradiated in the 9th Channel Position from 2003 January 6.

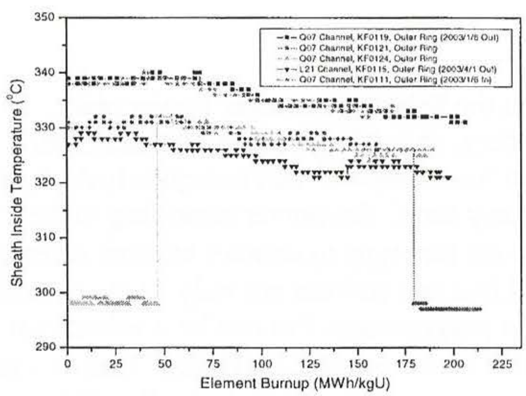
Note 4. KF0115 CANFLEX Bundle Irradiated in the 6th Bundle Position from 2002 July 10 to 2003 April 1



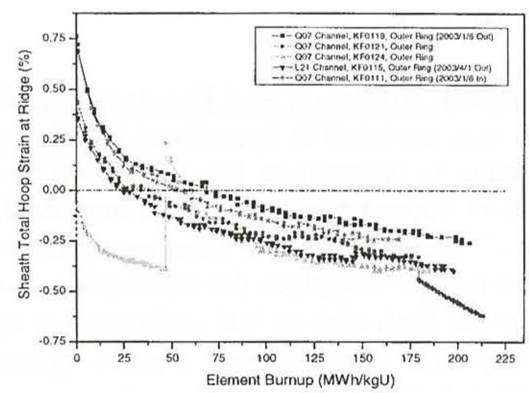
(a) Element Internal Gas Pressures



(b) Pellet Center Temperatures



(c) Sheath Insides Surface Temperatures



(d) Sheath Total Hoop Strains at the Ridges

Figure 7. ELESTRES Predictions of the Internal Gas pressures, Pellet Center Temperatures, Sheath Insides Surface Temperatures, and Sheath Total Hoop Strains at the Ridges of the CANFLEX Outer Elements Irradiated in WPGS-1