The Demonstration Irradiation Of The CANFLEX-NU Fuel Bundle In Wolsong Ngs 1

J. S. Jun(1), J. Y. Jung(1), M. S. Cho(1), H. C. Suk(1,2), Y. B. Kim(3) , And H. B. Seo(4)

(1) Korea Atomic Energy Research Institute, P. O. Box 105, Yusong, Daejon City, 305-600, Korea)

(2) New address: Canadian Nuclear Safety Commission, P.O. Box 1046, Station B, 280 Slater St., Ottawa, Ontario, Canada, K1P 5S9

(3) Korea Electric Power Research Institute, #103-16 Mun-Gi-Dong, Yusong, Daejon City, 305-380, Korea

(4) Korea Hydro & Nuclear Power Co., Ldt, Wolsong Nuclear Power Site, 260 Na-A-Ri, Yangnam-Myun, Kyongiu City, Kyung-Buk Province, 780-715, Korea)

ABSTRACT

A demonstration irradiation (DI) of 24 CANFLEX-NU fuel bundles in the high power Q07 channel and low power L21 channel of Wolsong Power Generation Station–1 had been successfully conducted jointly by KEPRI/KHNP/KAERI in the period of 2002 July to 2004 January. The tracking of the reactor operation data showed 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, where the maximum element linear power rating was ~ 42 kW/m at the burnup of ~ 50 MWh/kgU and ~ 35 kW/m at the discharge element burnup of ~ 210 MWh/kgU. While, another CANFLEX bundles also irradiated in the Q07 channel had a typical history of power ramping, where the maximum element power ramping-up or -down rate was 28 kW/m. The unusual performance and integrity of the CANFLEX elements could not be found in the ELESTRES predictions and also the in-bay visual examinations showed that all the bundles were intact, free of defects and appeared to be in good condition as expected. Therefore, it is concluded that the demonstration irradiation shows the validation of the CANFLEX bundle performance with direct conditions of relevance under the Korean licensing requirements and the KNFC fuel fabrication capability, and provides the rationale for the decision to perform the full-conversion of CANFLEX fuel in WPGS-1.

1. INTRODUCTION

Since 1991, the CANFLEX®[1](CANDU®[2] Flexible Fuelling) bundle as an advanced nuclear-fuel carrier for CANDU reactors had been jointly developed by Korea Atomic Energy Research Institute (KAERI) and Atomic Energy of Canada Limited (AECL). The CANFLEX bundle has been verified through extensive testing by KAERI and AECL. A demonstration irradiation (DI) of 24 CANFLEX- natural uranium (NU) bundles fuel at the Pt. Lepreau Generating Station (PLGS) in Canada was successfully performed between 1998 September and 2000 August [1].

A DI program of 24 CANFLEX-NU bundles in WPGS-1 [2] was conducted jointly by Korea Electric Power Research Institute (KEPRI)/Korea Hydro and Nuclear Power Company (KHNP)/KAERI from 2000 November to 2004 March, 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 2001 April.

The CANFLEX bundle 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

[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

subdivision and the use of two element sizes lower the peak linear-element rating, and give a more balanced radial power distribution [6, 7]. 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.

This paper describes the DI licensing, 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, and the evaluation of the fuel performance and its integrity.

2. STATUS OF THE DEMONSTRATION IRRADIATION IN WPGS-1

2.1 Preparation for the DI

As part of the Korean licensing process for the design of the CANFLEX-NU (Mk-IV) bundles and the DI of 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. The channel selection criteria for the DI inWPGS-1 were taken from those for the DI of 24 CANFLEX-NU bundles in the PLGS [8]. And then 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.

KEPCO Nuclear Fuel Co. Ltd. (KNFC) completed the supply of the 26 CANFLEX-Mk4 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

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Canada Limited(AECL)

all the technical specifications referenced from the bundle specification. The Wolsong DI CANFKEX-Mk 4 bundles had the spacers of slightly higher heights in order to prevent the inter-element interlocking spacers, comparing with the CANFLEX-Mk 4 bundles used in the Point Lepreau DI. 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.

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

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 was a high power channel, Q07, near the mid-level of the Liquid Zone Controllers and two regular eight-bundle shift fuellings of CANFLEX fuel. The other was a low power channel, L21, and would receive one eight-bundle shift fuelling of CANFLEX fuel. The fuelling sequences of the Q07 and L21 DI channel are well illustrated in the fuelling histories of Figures 1 and 2. The net duration of the DI was 16 months from the period of July 10, 2002 to January 29, 2004, where a period of the reactor's planned outage from January 31 to March 16, 2003 during the DI are not included.

2.3 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. The WPGS-1 operated 100 % reactor full power during the DI. The daily data of the reactor operation during the DI was recorded and detailed in the 8th International CNS CANDU Fuel Conference Proceedings [9]. As an example, the outlet temperatures of Q07 and L21 channels during the DI period between July 11, 2002 and April 21, 2003 were 308.183 ± 0.237 °C and 306.510 ± 0.850 °C, respectively. The channel flow rates of the Q07 and L21 channels for the DI period from September 25, 2002 to January 29, 2004 were 26.57±0.92 kg/s and 20.04±0.16 kg/s, respectively.

Figures 3 and 4 show the outlet temperature variations of the Q07 and L21 channels for their fuelling periods, which are not different from those of the channels with 37-element NU fuel bundle's fuelling periods. As expected, 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. 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 5 (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. The trends of the CANFLEX-NU fuel power-burnup histories were detailed in the 8th International CNS CANDU Fuel Conference Proceedings [10]:

- maximum element linear power rating: ~42 kW/m (See Figure 5(a) for KF0119 bundle irradiated in Q07 channel)
- maximum element burnup: 210 MWh/kgU (See Figure 5(a) for KF0119 bundle irradiated in Q07 channel
- maximum power ramp-down and –up element linear powers: ~ 28 kW/m (See Figures 5(b) and 5(c) respectively for KF0121 and KF 0124 bundles irradiated in Q07 channel)
- maximum bundle residence time in core(except the period of the reactor overhauling): 411 days for KF0106 ~ KF0109 bundles in Q07 channel (Note: 401 days for KF0101, KF0104, KF0105 and KF0125 bundles in L21 channel)

3.2 The Fuel Element Performance Evaluations and the In-Bay Visual Examinations

Using the ELESTRES computer [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 computer code, it predicted the element internal gas pressure, the center temperature of pellet, the inside temperature of sheath, and the total hoop strain of sheath at the ridge as shown in Figures 6 (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:

As shown in Figure 6(a), 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. The highest element-internal gas pressure: 0.73 MPa ~ 0.78 MPa in the burnup range of ~ 65 MWh/kgU to ~ 188 MWh/kgU of outer element of CANFLEX KF0124 bundle having a typical element power history with a power ramp-up in L21 channel, which are considerably lower than the reactor coolant pressure.

Figures 6 (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:

- Maximum pellet centerline temperature: 1250 °C right after the bundle fuelling, which is considerably below the UO_2 pellet melting point of 2840 °C (See Figure 6(b)).
- Maximum sheath-inside-surface temperature of the outer elements: ~ 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 (See Figure 6(c)).
- Highest total hoop strain of sheath at the ridge: ~ 0.75 % also right after the fuelling, which resulted in the zero defect probability.

By reviewing the power-burnup histories of all DI CANFLEX-NU bundles irradiated in WPGS-1, 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.

In November 2003, at the WPGS-1 irradiated fuel storage, the in-bay visual examinations on the 4 bundles (KF0119, KF0117, KF0111, KF0121) discharged from Q07 channel and the 1 bundle (KF0115) discharged from L21 channel were conducted with an AECL expert. As shown in Figures 7 and 8 as examples, the examinations were focused into the observations of side stop interaction, refuelling impact, cross flow fatigue/fretting, spacer fretting of non-outer element, fuel element bow and longitudinal ridge, appendage wear and crevice corrosion, weld points, sheath oxidation, endplate integrity. As the examination results, it was concluded that all the bundles were intact, free of defects and appeared to be in good condition as expected.

4. SUMMARY AND CONCLUSIONS

A DI program of 24 CANFLEX-NU fuel bundles in WPGS-1 was successfully conducted jointly by KEPRI/KHNP/KAERI for the period of November 2000 to March 2004. The licensing approvals for the fuel design/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. The selection criteria of the Q07 and L21 DI channels were the same as those for the DI of the 24 CANFLEX-NU fuel bundles in the PLGS [8].

Using 8-bundle refuelling scheme, 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. All CANFLEX bundles were discharge from the L21 channel on November 6, 2003 and from Q07 channel on January 29, 2004. So, the net duration of the DI was 16 months, where a period of the reactor’s planned outage from January 31 to March 16, 2003 during the DI are not included.

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 CANFLEX bundle and element power histories were derived by using the codes of RFSP [10], POWERDERPUPS-V [11] and WIMS-AECL [12], from which the following maximum power, maximum burnup, maximum power ramp were derived: (i) The maximum element linear power rating was ~42 kW/m of KF0119 bundle irradiated in Q07 channel, (ii) The maximum element burnup was 210 MWh/kgU of KF0119 bundle irradiated in Q07 channel, (iii) The maximum element linear powers of power ramp-down and –up were 28 kW/m of KF0121 and KF0124 bundles irradiated in Q07 channel, and (iv) the maximum bundle residence time in core (except the period of the reactor overhauling) was 411 days for KF0106 ~ KF0109 bundles in Q07 channel.

By reviewing the power-burnup histories of all DI CANFLEX-NU bundles irradiated in WPGS-1, 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 highest internal gas pressure of element (KF0124 outer elements) was 0.78 MPa (which is considerably lower than the reactor coolant pressure of 10.7MPa). From the KF0119 CANFLEX outer element, it was found that (i) the highest maximum pellet center temperatures was ~ 1250 °C (which is quite lower than the UO_2 pellet melting point of 2840 °C), (ii) the highest sheath inside surface temperature was ~ 339 °C right after the fuelling (This sheath inside surface temperature is quite below the Zircaloy-4 sheath surface temperature limits of around 400°C to preclude a condition of accelerated oxidation which would lead to sheath failure), and (iii) the highest sheath total hoop strains at the ridge was ~ +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. No indications of any defect in the CANFLEX elements have been shown in the ELESTRES predictions. As the results of the in-bay examinations on 5 CANFLEX-NU bundles irradiated in WPGS-1, it was concluded that all the bundles were intact, free of defects and appeared to be in good condition as expected.

It is consequently concluded that the DI shows the validation of the CANFLEX bundle performance with direct conditions of relevance under the Korean licensing requirements and the KNFC CANFLEX fabrication capability, and provides the rationale for the decision to perform the full-conversion of CANFLEX fuel in WPGS-1.

ACKNOWLEGEMENT

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(a) 1st Fuelling (July 10, 2002) : (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 (April 1, 2003) : (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(November 6, 2003):(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*

• 4 CANFLEX-NU fuel bundles are discharged: KF0101, KF0104, KF0105, KF0125

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

(a) 1st Fuelling (July 10, 2002) : (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 (January 6, 2003) : (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 (August 11, 2003) : (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

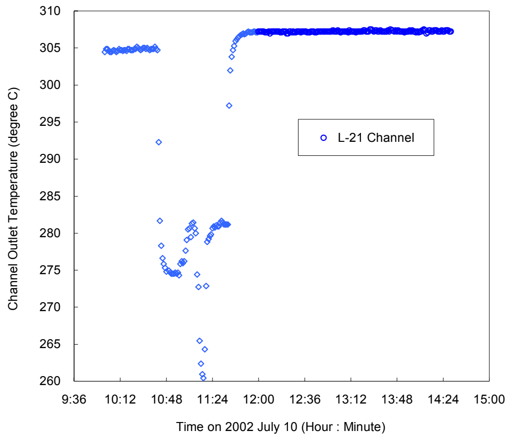
(d) 4th Fuelling(January 29, 2004) :(A→C Refuelling) & Bundle's Serial umbers

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

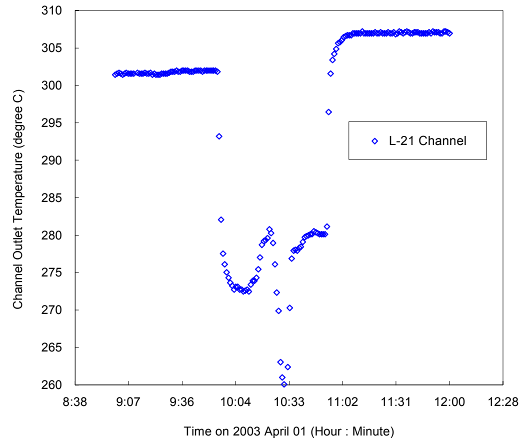
1	2	3	4	5	6	7	8	9	10	11	12
37ELEM	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*	*37ELEM*

• 4 CANFLEX-NU fuel bundles are discharged: KF0106 to KF0109

Figure 2. Fuelling History of CANFLEX-NU (Mk-IV) Fuel Bundles in the High Power Channel Q07 in WGS-#1

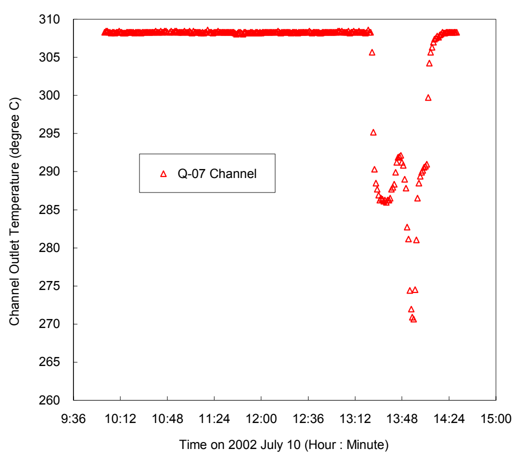


(a) L21 Channel Data on 2002 July 10
(Fuelling of the 8 CANFLEX bundles)

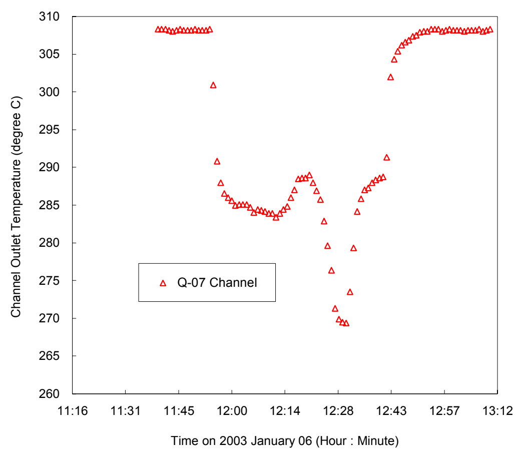


(b) L21 Channel Data on 2003 April 01
(Fuelling of the 8 37-element bundles)

Figure 3. L21 Channel Outlet Coolant Temperature Data during the Fuellings on 2002 July 10 and 2003 April 01

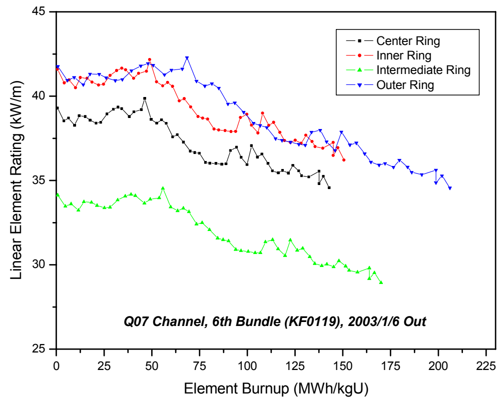


(a) Q07 Channel Data on 2002 July 10
(Fuelling of the 8 CANFLEX bundles)

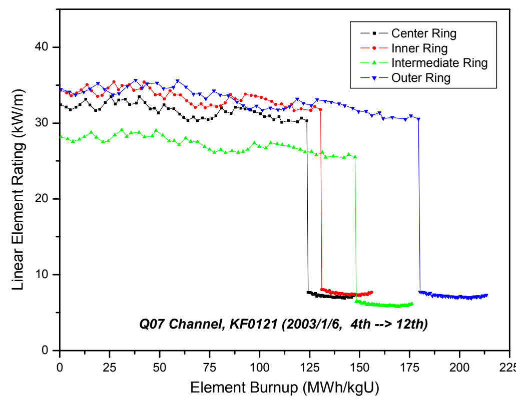


(b) Q07 Channel Data on 2003 January 06
(Fuelling of the 8 CANFLEX bundles)

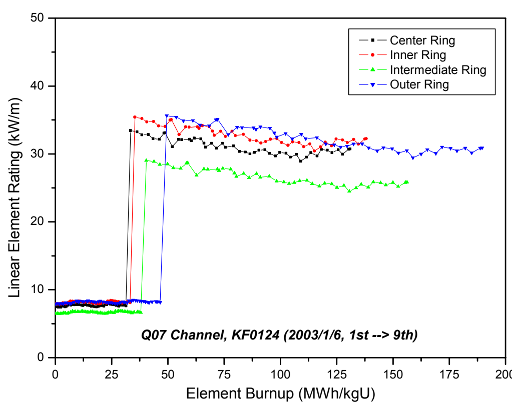
Figure 4. Q07 Channel Outlet Coolant Temperature Data during the Fuellings on 2002 July 10 and 2003 January 06



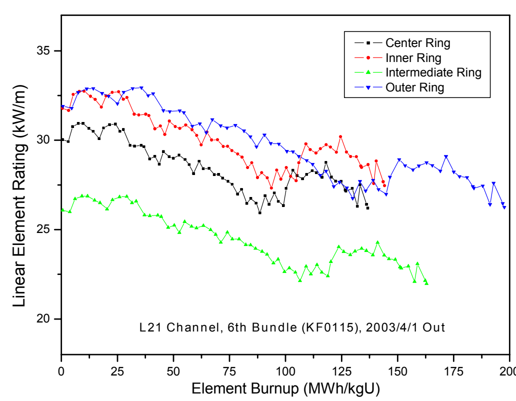
(a) KF0119 element power histories



(b) KF0121 element power histories



(c) KF0124 element power histories



(d) KF0115 element power histories

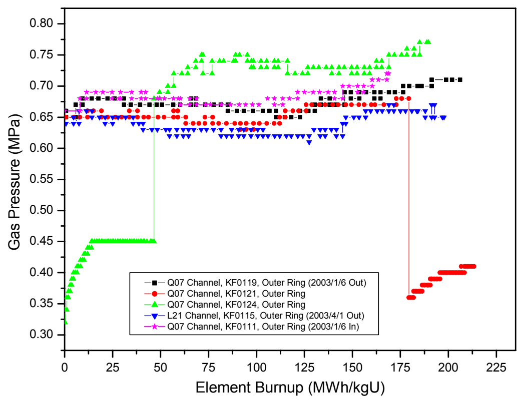
Figure 5. Element Power Histories of KF0119, KF0121, KF0124, and KF0115 CANFLEX Bundle Irradiated in WPGS-1(see Notes 1 to 4)

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

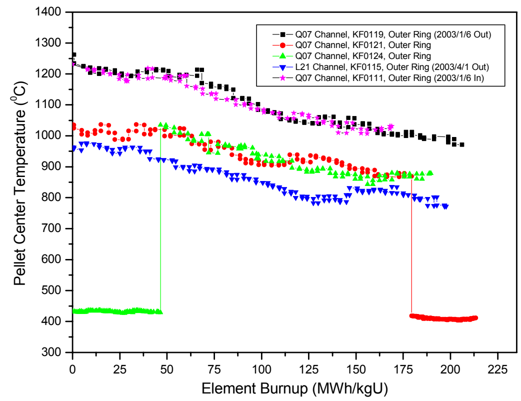
Note 2. KF0121 CANFLEX Bundle Irradiated in the 4^{th} Bundle Position from 2002 July 10 to 2003 January 6 and then Being Irradiated in the 12^{th} Channel Position from 2003 January 6.

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

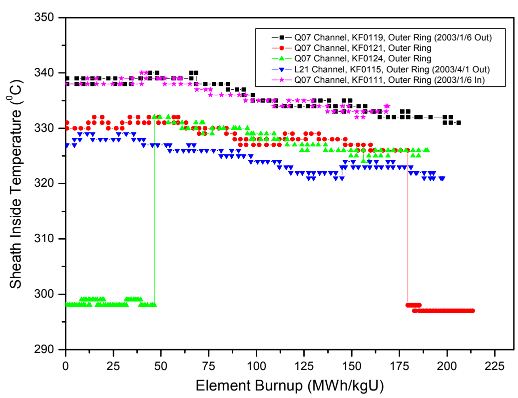
Note 4. KF0115 CANFLEX Bundle Irradiated in the 6^{th} Bundle Position from 2002 July 10 to 2003 April 1



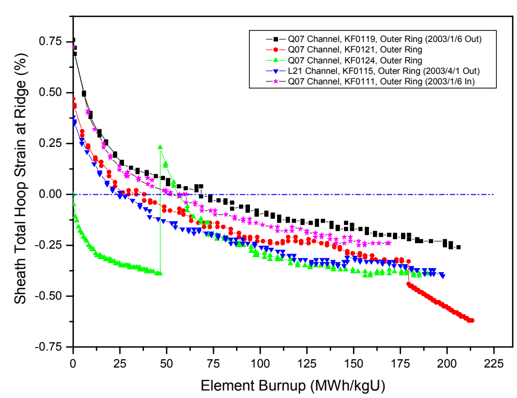
(a) Element Internal Gas Pressures



(b) Pellet Center Temperatures



(c) Sheath Insides Surface Temperatures



(d) Sheath Total Hoop Strains at the Ridges

Figure 6. 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

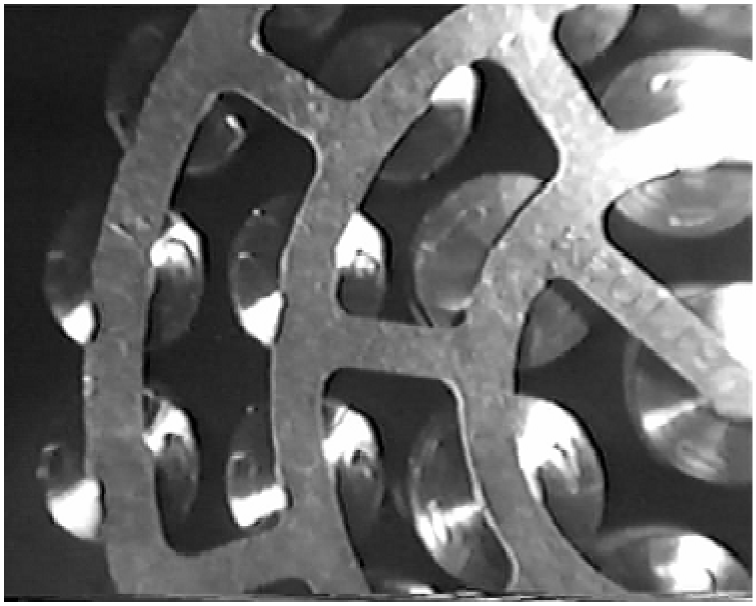


Figure 7. CANFLEX-NU KF0119 Bundle - Serial Number

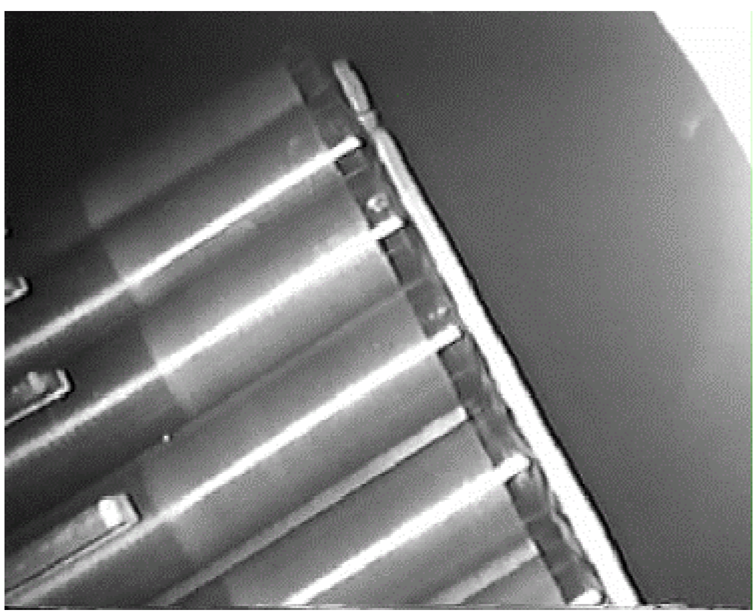


Figure 8. CANFLEX-NU KF0119 Bundle - Endcaps-Endplate Welding