THE PARALLEX PROJECT: IRRADIATION TESTING AND PIE OF THE FIRST BUNDLE

F.C. DIMAYUGA

AECL
Chalk River Laboratories
Chalk River, Ontario, Canada K0J 1P0

ABSTRACT

The Parallex Project is a parallel experiment demonstrating the use of U.S. and Russian weapons-derived plutonium (WPu) in CANDU mixed-oxide (MOX) fuel elements. A major component of the Parallex Project is the irradiation testing of MOX fuel elements containing WPu manufactured in both the U.S. and Russia. A total of three fuel bundles were manufactured for irradiation testing in the NRU reactor in Chalk River. A significant milestone in the project was achieved earlier this year, with the completion of the irradiation testing of the first fuel bundle containing MOX elements received from both the U.S. and Russia.

The MOX fuel elements for the first Parallex bundle were supplied by the Los Alamos National Laboratory in the U.S. and by the Bochvar Institute in Russia. The MOX fuel pellets with 3.1% WPu in depleted uranium MOX are contained in the intermediate and inner elements, and the bundle is configured such that the Russian and U.S. elements are tested side-by-side. The MOX fuel elements were assembled into a bundle in Chalk River and the first bundle was inserted into the NRU fuel test loop in February 2001. The bundle was irradiated at midplane linear powers up to 40 kW/m and achieved its target burnup of 15 MWd/kgHE (360 MWh/kgHE) in January 2003. Post-irradiation examination of the fuel has been started to determine the performance of CANDU MOX fuel made from WPu. Irradiation testing of the other two bundles is continuing.

This paper highlights the irradiation testing of the first Parallex bundle and presents the results obtained to-date from the post-irradiation examination.

BACKGROUND

As part of major arms control initiatives in the aftermath of the Cold War, the United States (U.S.) and Russia have each declared about 50 tonnes of weapons plutonium (WPu) to be surplus to their defence needs. One of the options being assessed to ensure that surplus WPu is permanently removed from defence inventories, involves utilizing the plutonium as mixed oxide (MOX) fuel in commercial nuclear power reactors [1].

One option for the disposition of excess WPu involved incorporating the WPu into MOX fuel for utilization in CANDU power reactors. The feasibility of the CANDU MOX fuel option was established in a study that was sponsored by the U.S. Department of Energy (USDOE) in 1994. This study concluded that MOX fuel could be fabricated in the United States, transported to Canada, and used as fuel for the Bruce reactors without significantly modifying the reactors, and utilize 50 tonnes of weapons-derived Pu as MOX fuel in CANDU reactors over a 25-year period [2]. An extension to this study in 1996 further concluded that the duration of the Pu disposition mission could be reduced to 15 years [3].

A similar study was jointly conducted by Canada and Russia in 1996, to assess the feasibility of fabricating CANDU MOX fuel in Russia and transporting the fuel to Canada. The study established the feasibility of utilizing Russian MOX fuel in CANDU reactors, with technical, environmental, regulatory and economic issues being taken into consideration [4].

THE PARALLEX PROJECT

The Parallex project represents the first step towards demonstrating the feasibility of the CANDU MOX option to disposition WPu. It is a joint effort among Russia, the U.S., and Canada to simultaneously test laboratory-produced quantities of U.S. and Russian MOX fuel in the National Research Universal (NRU) research reactor at Chalk River Laboratories (CRL). The project is funded by the U.S. Department of Energy (USDOE) in cooperation with the Canadian and Russian governments, and is managed on behalf of the USDOE by the Oak Ridge National Laboratory (ORNL). The test is significant because it combines U.S. and Russian MOX fuel made from WPu into one test bundle, and it is the first time WPu has been shipped outside Russia as part of international efforts to reduce the stockpile of surplus weapons plutonium.

The objectives of the Parallex project are two-fold [3]:

- to contribute to the database that would eventually qualify MOX fuel for use in CANDU reactors, and
- to demonstrate the feasibility of the infrastructure that is involved in the disposition of excess weapons plutonium as MOX fuel in nuclear reactors.

The scope of the test is limited to fabricating CANDU MOX fuel in the U.S. and Russia, transporting the fuel to Canada, and irradiating three experimental CANDU MOX fuel bundles in the NRU research reactor at CRL. The test conditions in the NRU reactor will bound the conditions that are expected in a CANDU power reactor, and will provide meaningful data regarding the performance of the MOX fuel. The test will also produce data showing how production and processing variables, as well as the detailed design of the pellets themselves, affect the performance of the CANDU MOX fuel. These comparisons will also be used to optimize the MOX fuel specifications and fabrication methods.

NRU IRRADIATION TEST

Objectives

The objectives of the irradiation testing of the Parallex bundles are:

a. To evaluate the effect of controlled fabrication process variations on irradiation performance of CANDU MOX fuel containing WPu. Specifically, data will be generated on the effect of Pu homogeneity and pellet geometry on WPu MOX fuel performance.

b. To evaluate the performance of MOX fuel representative of that to be utilized in CANDU reactors under representative and bounding operating conditions. This will include irradiation of 3.1% and 4.6% WPu elements at midplane powers of 20-60 kW/m to burnups ranging from 12 – 25 MWd/kg HE (300 - 600 MWh/kg HE).

c. To evaluate the performance of the MOX fuel relative to that of UO_2 fuel operating at similar powers to similar burnups. This will be accomplished by including "witness" elements of appropriate U-235 enrichment to achieve a similar operating history to that of the MOX fuel.

MOX Fuel Composition

Several CANDU MOX fuel designs have been analyzed in various feasibility studies, with burnups ranging from 10 to 25 MWd/kg HE, WPu disposition rates of 0.8 to 1.5 tonnes per reactor/year, and corresponding fabrication plant capacities between 28 and 80 tonnes MOX/year. The MOX designs are based on either the standard 37-element bundle geometry, or the more advanced design of the 43-element CANFLEX® bundle for extended burnup applications. Table 1 provides a summary of some of these and other parameters, such as Pu destruction efficiencies and the energy produced [5].

The fuel for the first Parallex bundle is based on the 1996 37-element design of CANDU MOX fuel (3rd column in Table 1). This design has the advantage of being very similar to the current fuel designs in use in CANDU power reactors, i.e., the same 37-element geometry, similar burnups, and similar power ratings. As shown in Figure 1, the highest Pu content of 3.1% is contained in the intermediate ring of elements. The first Parallex test bundle was then designed and built to assess the performance of 3.1% WPu fabricated in the U.S. and Russia.

The fuel for the second and third Parallex bundles is based on the 1997 43-element CANFLEX bundle design (4^{th} column in Table 1). This design is the more advanced option, with higher burnups and using the CANFLEX geometry. Its advantage is a higher Pu utilization rate

---

CANFLEX® is a registered trademark of Atomic Energy of Canada Limited (AECL).

and a lower throughput in the fuel fabrication plant. As shown in Figure 2, the highest Pu content of 4.6% is contained in the intermediate ring of elements. The second and third Parallex test bundles were then intended to assess the performance of 4.6% WPu fabricated in Russia.

Fabrication Variables

For the Parallex project, it was intended to produce MOX fuel with a range of characteristics that bound those that are expected to be found in the actual mission MOX fuel. The Parallex MOX fuel fabrication work involved the Los Alamos National Laboratory (LANL) in the U.S. and the A.A. Bochvar All-Russia Scientific Research Institute of Inorganic Materials (VNIINM) in Russia. Both laboratories produced the MOX fuel in accordance with a common set of technical specifications provided by AECL, and are based on those used for the fabrication of commercial CANDU fuel.

The manufacturing methods employed in both laboratories followed the industrial process of MOX fuel production, i.e., milling and blending of the depleted UO_2 and PuO_2 powders, pressing into green pellets, high temperature sintering, and grinding to final dimensions and surface finish. The finished pellets were then inspected and loaded into zircaloy sheaths, which were subsequently enclosure-welded into finished elements. However, there were some differences in the fabrication process that will be evaluated as part of the tests.

One difference is the process used to obtain the starting PuO_2 feedstock. The starting PuO_2 powder for the U.S. MOX fuel was obtained from metallic WPu via a dry conversion process. In LANL, the starting PuO_2 powder was subjected to several conditioning steps, including a thermal treatment to remove gallium, and vibratory milling to obtain suitable particle size distributions. In the case of VNIINM, the starting PuO_2 powder was converted from metallic WPu through a wet chemical process.

Another difference between the U.S. and Russian MOX was the milling/blending method. At LANL, blending of the depleted UO_2 and PuO_2 powders was achieved through a two-step process, with the first step involving the ball milling of a master mix containing 10% WPu in UO_2. The second step consisted of adding an appropriate amount of UO_2 to the master mix to obtain the final Pu concentration (3.1 wt.% WPu) and ball milling the whole mixture. At VNIINM, the appropriate amounts of starting PuO_2 and UO_2 powders were mixed into a final blend, and the whole blend was milled using electro-magnetically oscillated steel needles. This was called the ABS-150 milling process. Although two different milling/blending methods were used, the resulting levels of Pu homogeneity appear to be similar, i.e., both fuel types had most of the Pu in solid solution within the uranium matrix, as reported by both laboratories.

As a result of the U.S. decision to focus its efforts on using its domestic light water reactor (LWR) options to disposition WPu, the second and third Parallex test bundles have been redesigned to contain MOX fabricated by VNIINM and AECL (with no U.S. MOX fuel).

If Russia proceeds with the actual mission, then an industrial-scale MOX fuel fabrication plant will have to be designed and built. It will be necessary to assess the performance of fuel (under CANDU conditions) that is manufactured by the process to be used in that plant. At present, there are two leading techniques being considered for the process to be used in Russia—ABS-150 and MIMAS. MIMAS (for MIcronized MAStermix) is the fabrication process developed by Belgonucleaire and now also used by COGEMA in their commercial production of MOX fuel in Europe [6]. In this process, the PuO_2 powder is first micronized, usually by ball milling, with a part of the UO_2 powder to form a primary (or master) mix of 30% or higher Pu content. This mastermix is then mechanically blended with UO_2 powder to obtain the final specified Pu content of the MOX fuel.

The Russian MOX fuel contained in the Parallex bundles was made using the ABS-150 milling process. It was decided that, in order to include some MIMAS-made MOX fuel in the test, MIMAS MOX fuel would be fabricated in the Recycle Fuel Fabrication Laboratories (RFFL) at Chalk River, but using civilian Pu (civPu). Although the actual MIMAS process was not used, a fabrication process that produces a pellet microstructure comparable to MIMAS, i.e., particles of UO_2 and PuO_2 in solid solution homogeneously dispersed within a UO_2 matrix, was employed. The overall Pu concentration in the AECL-simulated MIMAS fuel was increased to account for the reduced concentration of fissile isotopes in civPu compared to WPu. This approach broadens the parallel nature of the program to include a direct comparison of the two candidate fabrication processes that have potential to be used in Russia.

Test Bundle Configuration

The center element in each bundle is removed to accommodate a guide tube for assembling the bundles vertically in the NRU test loops. Throughout the test, data will be acquired on loop power and reactor conditions, and fuel bundle powers will be calculated and documented for each irradiation period. At the completion of irradiation, elements will be cooled for about 3 months in the irradiated fuel bays, before being sent to the hot cells for post-irradiation examination (PIE).

The first Parallex bundle contains U.S. and Russian MOX fuel, both containing 3.1% WPu in heavy element. The configuration of this bundle is such that a MOX element from the U.S. is located next to a MOX element from Russia (see Figure 3). The second and third Parallex bundles contain intermediate and inner elements with 4.6% WPu in depleted UO_2, and 5.3% civPu in depleted UO_2. The configuration of both bundles is designed such that MOX fuel made via the Russian ABS-150 process is tested side-by-side with the fuel made via the simulated MIMAS process (see Figure 4). The outer ring of elements in all three bundles contains Dy-doped natural UO_2, in order to achieve the desired ranges of powers for the intermediate and inner elements at the flux levels that are available in the NRU loops. The amount of Dy in the second and third bundles is higher than that in the first bundle to account for the higher Pu enrichments.

Status of Irradiation Tests

The first Parallex bundle was inserted into the NRU reactor to commence its irradiation testing in 2001 February. It completed its irradiation in January 2003 achieving a burnup of about 380 MWh/kg HE (16 MWd/kg HE) for the intermediate elements, with a peak rating of about 42 kW/m (Figure 5). In general, the intermediate MOX elements in the bundle experienced a declining power history (from 42 to 32 kW/m), while the inner MOX elements had a slightly increasing power history to a burnup of 250 MWh/kg HE (10 MWd/kg HE) but at relatively low powers, from around 20 to 25 kW/m.

The second and third bundles were inserted into the NRU reactor in October 2002. To ensure that both bundles experience similar power histories, they are being irradiated in flux-equivalent axial positions. As shown in Figure 6, one bundle will be irradiated until the intermediate MOX elements achieve a burnup of about 290 MWh/kg HE (12 MWd/kg HE); the other bundle will continue irradiation until the intermediate MOX elements achieve burnups of about 600 MWh/kg HE (25 MWd/kg HE). Both bundles were expected to operate at peak powers of 50 kW/m, and then have a declining power history. At the time of writing, the bundles are estimated to have achieved burnups of around 120 MWh/kg HE representing 40% and 20% of the target burnup for bundles 2 and 3, respectively.

Preliminary Results from PIE of the First Bundle

After several months of cooling in the irradiated fuel bays, Test Bundle 1 was transferred to the hot-cells to begin PIE in June 2003. All non-destructive examination has been completed. The bundle was examined visually and no signs of defects or unusual features were found (Figure 7). The bundle was disassembled into individual elements, and each element was inspected, including the area around the gas-tungsten arc welding (GTAW) welded endcap. Again, no signs of defects or unusual features were observed. Profilometry of the intermediate and inner elements showed that the residual strains were within acceptable ranges. Specific fuel elements were gamma scanned, and the results indicate some evidence of end flux peaking even with use of natural uranium pellets at the ends of the pellet stacks. Further analysis is being conducted on the gamma scanning data for the elements.

Destructive examinations are in progress, including gas puncture and fission gas analysis, ceramography, fuel sample dissolution for burnup and isotopic analysis, oxygen-to-metal (O/M) ratio measurements, etc. The PIE activities, including data analysis and reporting, are expected to be complete by end of 2003.

SUMMARY

The Parallex project is an important first step towards demonstrating the feasibility of dispositioning weapons-derived Pu as MOX fuel in CANDU reactors. It is a joint effort among Russia, the U.S., and Canada to simultaneously test laboratory-produced quantities of U.S. and Russian MOX fuel in the NRU reactor. The project is significant because it combines U.S. and Russian MOX fuel made from WPu into one test bundle, and it is the first time WPu has been shipped outside Russia as part of international efforts to reduce the stockpile of surplus weapons plutonium.

The scope of the test involves fabrication of CANDU MOX fuel in the U.S. and Russia, transporting the fuel to Canada, and irradiating three experimental CANDU MOX fuel bundles. The test conditions in NRU will bound the conditions that are expected in a CANDU power reactor, and will provide meaningful data regarding the performance of the MOX fuel. The test will also produce data showing how processing variables affect the performance of the CANDU MOX fuel.

A total of three fuel bundles were manufactured for irradiation testing in the NRU reactor in Chalk River. A significant milestone in the project was achieved earlier this year, with the completion of the irradiation testing of the first fuel bundle containing MOX elements received from both the U.S. and Russia. The bundle was irradiated at midplane linear powers up to 40 kW/m and achieved a burnup of 380 MWh/kg HE (16 MWd/kg HE) in January 2003. Post-irradiation examination of the fuel has been started. All non-destructive examination has been completed, and results to-date indicate good performance of CANDU MOX fuel made from WPu. Destructive examinations are in progress, and the PIE activities, including data analysis and reporting, are expected to be complete by end of 2003.

It is expected that irradiation testing of the second and third bundles will be completed in 2005. The performance data from these tests will be applicable to qualifying MOX fuel for use in CANDU reactors. The test will assess important technical aspects of the suitability of CANDU MOX fuel for rendering weapons-derived plutonium permanently inaccessible for use in nuclear weapons.

ACKNOWLEDGEMENTS

Many people in various groups within AECL have contributed to achieving significant milestones for the Parallex project, including NRU operations, Reactor Physics, Fuel Channel Thermalhydraulics, Universal Cells, Fuel and Materials Hot Cells, and Fuel Development. Their contributions are gratefully acknowledged.

REFERENCES

1. "Management and Disposition of Excess Weapons Plutonium", Committee on International Security and Arms Control, National Academy of Sciences, National Academy Press (1994 January).

2. Boczar, P.G., Hopkin, J.R., Feinroth, H. and Luxat, J.C., "Plutonium Dispositioning in CANDU", in Proceedings of the IAEA Technical Committee Meeting, Recycling of Plutonium and Uranium in Water Reactor Fuels, Windermere, U.K., 1995 July 3-7. Reprinted as AECL Report, AECL-11429.

3. Dimayuga, F.C., Cox, D.S., Horning, T.W., Chidester, K., Bibilashvili, Y.I., Antipov, S.A., "Status of the Parallex Project – Testing CANDU MOX Fuel with Weapons-Derived Plutonium", in Proceedings of the Seventh International Conference on CANDU Fuel, 2001 September 23-27, Kingston, Ontario, Canada, Canadian Nuclear Society (2001), pp. 4B-3 – 4B-15.

4. Kudriavtsev, E.G., Tyurin, E.I., Petrova, L., Tokarenko, A.I., Gadsby, R.D., Jones, L.R., Saroudis, J.I. and Bazeley, E.G., "The Utilization of Russian Weapons Plutonium in Canadian CANDU Reactors: A Feasibility Study", in Proceedings of the Fifth International Conference on CANDU Fuel, 1997 September 21-24, Toronto, Canada.

5. Chan, P.S.W., Gagnon, M.J.N., Boczar, P.G., Ellis, R.J. and Verrall, R.A., "CANDU - A Versatile Reactor for Plutonium Disposition or Actinide Burning", proceedings of Global '97 International Conference on Future Nuclear Systems, Yokohama, Japan, October 5-10, 1997, Reprinted as AECL Report AECL-11853.

6. Haas, D., "MOX Fuel Fabrication Experience at Belgonucleaire", in Recycling of Plutonium and Uranium in Water Reactor Fuel, Tech. Comm. Meeting, U.K., 1995, IAEA-TECDOC-941, pp. 77-89.

Table 1. Summary of CANDU Weapons-Derived Pu Management Options

	37-el MOX (1994)	CANFLEX MOX (1994)	37-el MOX (1996)	CANFLEX MOX (1997)
Burnup (GWd/Mg HE)	10	17	10	25
Fabrication Plant Capacity (Mg MOX/year)	80	37	78	28
Pu-Disposition Rate (Mg Pu/year/reactor)	1.0	1.05	1.5	0.8
Pu-Disposition Rate (Mg Pu/GWe-year)	1.56	1.65	2.22	1.23
Net Pu-Destruction Efficiency (%)	34	23	23	46
Net Fissile Pu-Destruction Efficiency (%)	58	41	41	70
Energy Produced (GWe-year/Mg Pu)	0.64	0.64	0.45	0.81

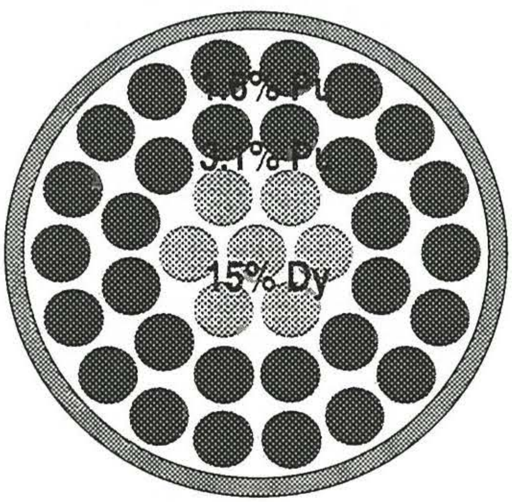

Figure 1: Schematic of 37-element MOX Fuel Design from 1996 Study.

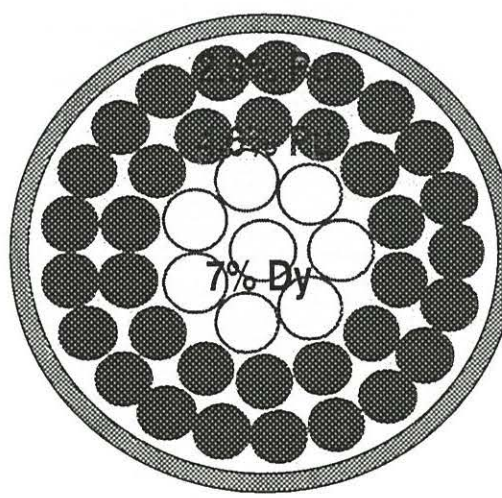

Figure 2: Schematic of 43-element MOX Fuel Design from 1997 Study.

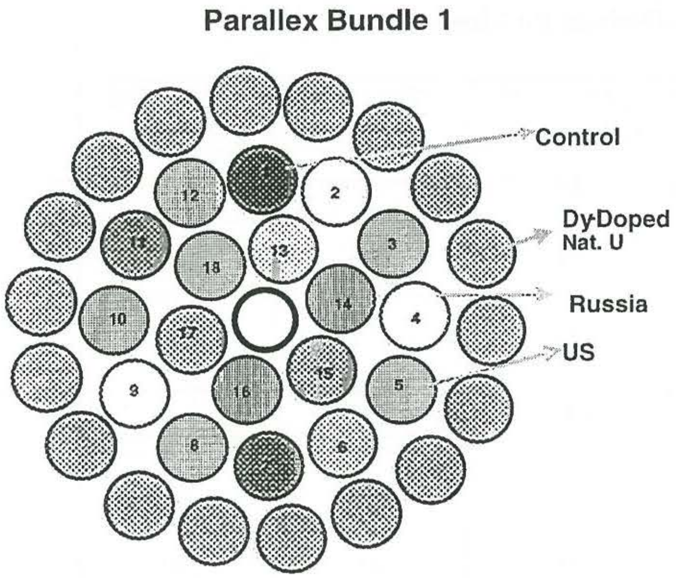

Figure 3: Configuration Of First Parallex MOX Bundle In NRU

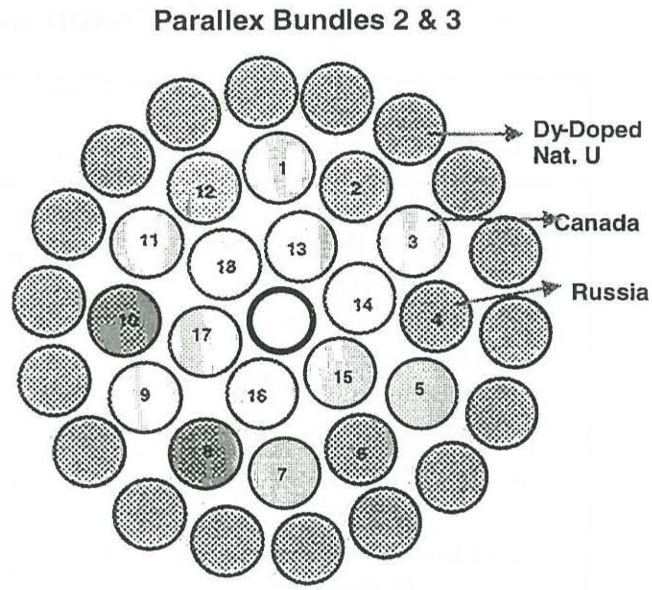

Figure 4: Configuration Of 2nd and 3rd Parallex MOX Bundles In NRU

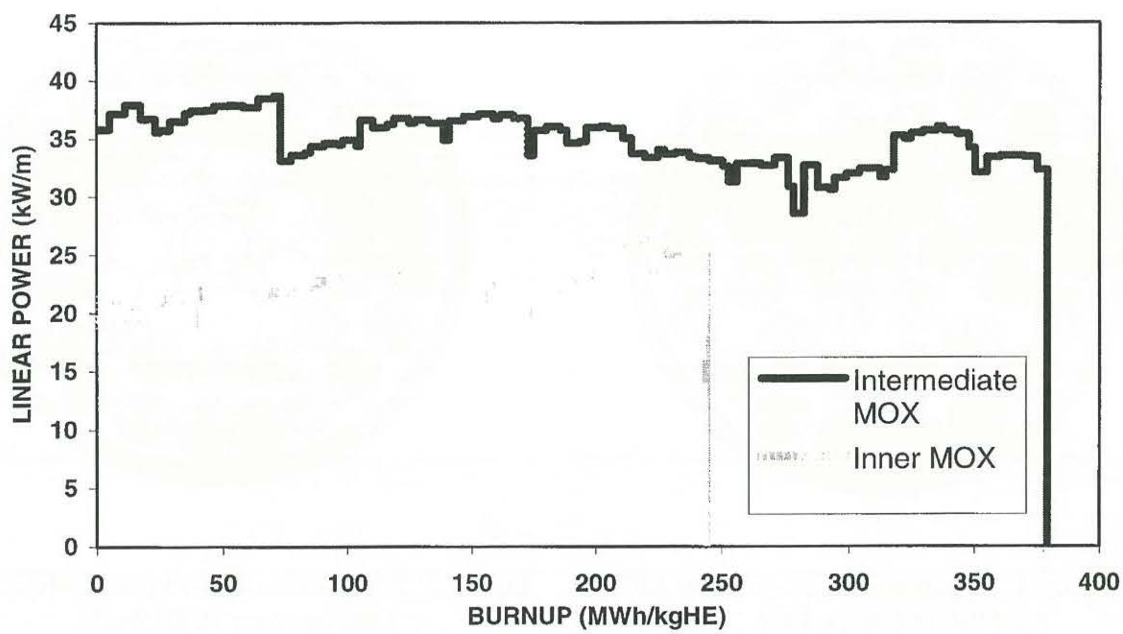

Figure 5. Plot Showing the Power History Experienced by First Parallex Bundle.

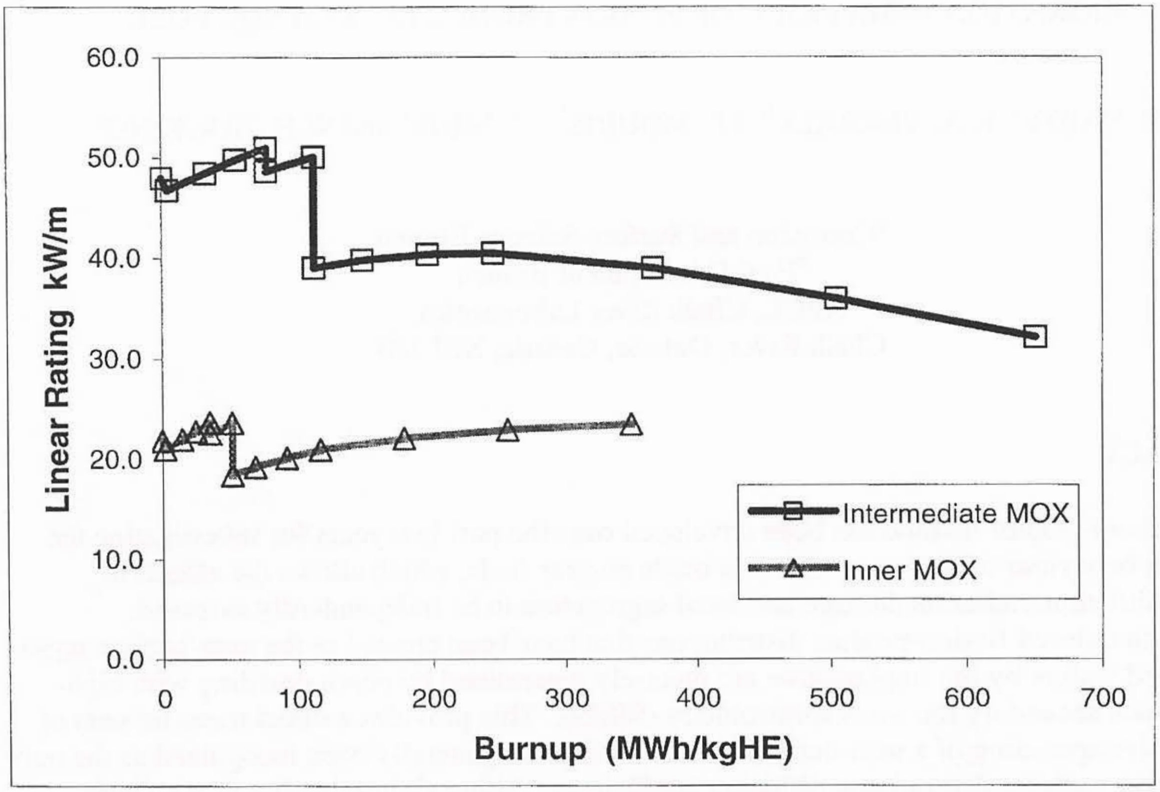

Figure 6. Plot Showing the Proposed Power History for Parallex Bundles 2 and 3.

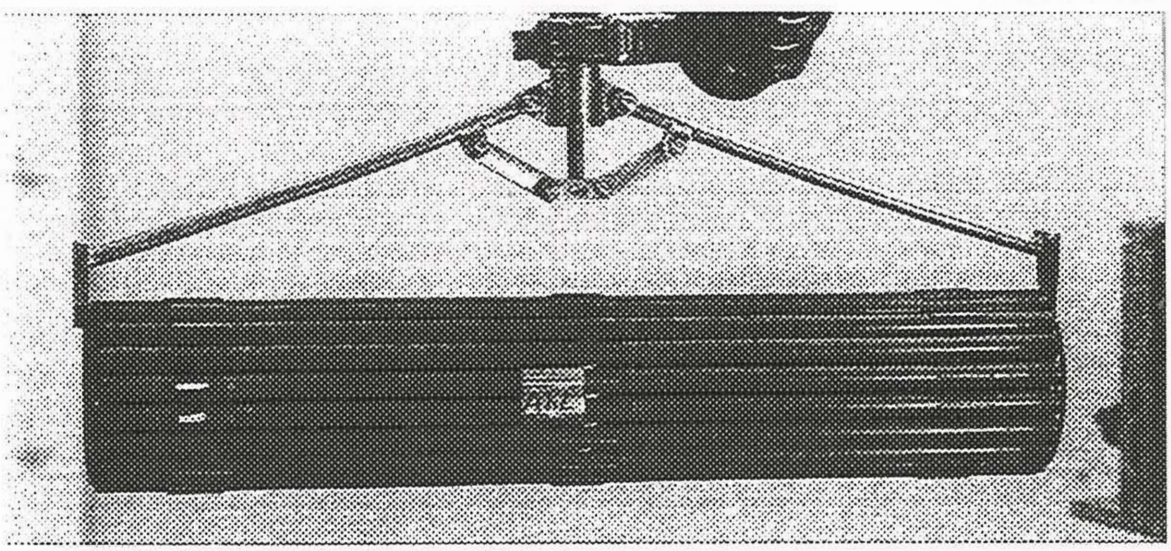

Figure 7. Photograph Showing Irradiated Parallex Bundle 1 (Bundle AKL) During Visual Examination in the Hot Cells.