FUEL PERFORMANCE, DESIGN AND DEVELOPMENT IN INDIAN REACTORS

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ABSTRACT

Presently twelve 220 MWe Pressurized Heavy Water Reactors (PHWRs) and two Boiling Water Reactors (BWRs) are in operation in India. The normal fuel configuration for operating 220 MWe PHWRs is natural uranium dioxide nineteen element fuel bundle. So far, 65 full power years of PHWR operation and 38 full power years of BWR operational experience has been accumulated. This corresponds to irradiation of 250 thousand PHWR fuel bundles and 2700 BWR bundles. Fabrication of 37-element fuel bundle for two 540 MWe units under construction is being taken up. Design and development studies of 680 MWe PHWR units by introducing boiling in channels has been taken up

Based on the reactor operating experience; the fuel design, manufacturing quality control and the reactor operating practices; are under continuous evolution in order to improve the fuel performance and ease fuel fabrication. The overall fuel failure rate currently is about 0.1% and efforts are on to further reduce it. The core discharge burnup in different reactors is around 7000 MWD/TeU. In addition to natural uranium fuel bundles, 232 numbers of Thorium dioxide bundles have been irradiated as a part of initial flux flattening in different reactors.

It is planned to irradiate, in addition to natural uranium fuel bundles, depleted uranium and mixed oxide fuel bundles in PHWRs. The fuel design for the MOX bundle has been completed. The fuel fabrication specifications have been prepared. The reactor physics lattice and core calculations optimising the core loading pattern with these bundles has been finalised. The loading is planned to be carried out in an operating unit. The safety analyses for the core using these bundles has been reviewed by regulatory authorities.

1. INTRODUCTION

At present, twelve PHWR units of 220 MWe capacity and two BWRs are in operation in India. Construction of the two PHWR 540 MWe units and four additional PHWR 220 MWe units is progressing. These six units which are in various stages of construction will go in operation from the year 2004 onwards. Two VVER-1000 reactors, in collaboration with Russian Federation, are also under construction at present. The Department of Atomic Energy (DAE) has drawn a plan to have an installed nuclear power capacity of approximately 20,000 MWe; consisting of PHWRs, Light Water Reactors, 500 MWe Fast Breedor Reactor and Advanced Heavy Water Reactor (AHWR), by the year 2020. The PHWRs in this subsequent part of the programme are planned to be of 680 MWe capacity. Design and development studies of 680 Mwe PHWR units by introducing boiling in channels have been taken up. Preliminary safety analysis report for this type of units has been prepared.

In India the performance of Nuclear Power Plants has continuously improved over the years. The average plant capacity factor of these units has been 90% for the last financial year. Unit-1 of the Kakrapar Atomic Power Station (KAPS) was second in the ranking of PHWR type reactors in terms of annual capacity factor during the year 2002 and three other Indian PHWR units have been indicated by COG as among the first ten. So far, 65 full power (FP) years of PHWR operation and 38 FP years of BWR operational experience has been accumulated. The fuel performance in both PHWRs and BWRs of natural and enriched uranium oxide fuels respectively has improved over the years and is satisfactory.

Indian nuclear power programme is guided by optimum utilisation of limited natural uranium and the vast amount of thorium resources available in the country. The fuel cycles, fuel utilisation schemes and the fuel design and development strategies are planned keeping this resource base in view. This paper summarises the status of fuel design and development being carried out in India for PHWR type of reactors in this regard.

2. FUEL PERFORMANCE

The fuel performance in Indian reactors has progressively improved over the years. So far, more than 2, 50,000 fuel bundles have been irradiated in the 12 PHWRs. The average fuel bundle discharge burnup varies from 6700 to 7250 MWD/TeU. Efforts are on to improve fuel burnup further. Fuel Performance can be gauged by the fuel failure rate and also by the iodine activities in the coolant. Close monitoring of the Iodine activity in coolant system is done in operating stations. Even though the technical specifications for operation accepted by regulatory authorities permits 100 micro curies per liter of I-131 in coolant, a significantly low alert level of 10 micro curies is adopted in operation of the reactors. The iodine activities in coolant circuit in most of the reactors is usually less than 5 micro Ci/litre.

The current fuel bundle failure rate (including suspected failures) for the last one year is 0.09%. The fuel failures are random in nature as seen by the operational history of suspected / failed bundle burnup and power. There are failures at low burnup, which means that they may be due to either manufacturing or caused by improper fuel handling. Fuel failures have been experienced recently due to fuel handling events. These are primarily traced back to misalignment of tubes in fresh fuel transfer system. Appropriate surveillance checks have been introduced in the operating stations to avoid such failures

Over the years, the fuel bundle design (Ref. 1, 2& 3), manufacture and reactor operations have gone through the process of continuous updating. Some salient activities in this regard are:

Design, Manufacturing and Quality Control

- Split spacer design
- Graphite coating on inside surface of sheath
- Modified scooped end plug
- Chamfered and double dish pellets

- Stringent quality control plan on end plug weld
- Ultrasonic testing of end plug welds

Reactor Operation

- Reactor Physics simulations at closer intervals at Plants to ensure that fuel rescheduling is strictly based on fuel power ramp failure criteria
- Early detection and removal of defective fuel based on Delayed Neutron (DN) trend analysis
- The frequency of checking the misalignment of tubes in fresh fuel transfer system has been increased

3. HIGH BURNUP FUEL DEVELOPMENT

Indian nuclear power programme is guided by the limited available natural uranium and the vast amount thorium resources available. Therefore the fuel design, development and fuel utilization are planned accordingly. As a part of this fuel bundle design using thorium and mixed oxide fuel materials which can be irradiated to burnups of 20000 to 50000 MWd/TeHE are being developed. The fuel bundle design in use at present is limited to irradiation up to 15000 MWd/TeU burnup.

3.1 Design Studies: The fuel element design analysis has been carried out using Fuel Design Analysis code FUDA to check the limiting parameters at higher burnups like fission gas release, internal gas pressures, plenum volume requirements etc,. The analysis details are given Table-1. The studies indicated that, present fuel design is suitable upto 20000 MWd/TeU with minor modifications like use of higher grain size, more dish depth etc. For burnups beyond that either annular pellets or the earlier developed 22-element fuel bundle (Ref. 4), shown in Figure 1. is being considered. The fuel materials which are being considered for use are MOX and Thorium. The cladding material proposed is a new zirconium alloy (Ref. 5). The optimized zircaloy with low Tin and higher Iron content are being investigated by R&D Units for this purpose.

3.2 Fuel Bundle Irradiation to High Burnup: To investigate fuel behavior at high burnup with regard to fission gas release, fuel swelling and sheath material behavior, fuel bundle integrity and power ramp performance; it was decided to irradiate few present natural uranium bundles to higher burnups. For this purpose natural uranium bundles in two channels (H-13 and O-08 of KAPS-2 core) were selected and fuel irradiated upto a discharge burnup of 20000 MWD/TeU. Bundles in these channels were irradiated to about 1100 FPD which is about 35% more compared to normal irradiation time. Performance of these channels was assessed by Delay Neutron Monitoring (DNM) system and by comparing the measured Channel Outlet Temperature (COT) with the estimated values by the fuel management code TRIVENI. The variation of DN counts of these channels during this period and also during refueling of these channels indicated successful performance of the fuel bundles including the power ramps seen during operation at high burnup. Fourteen fuel bundles of these two channels have seen burnups more than 15000 MWd/TeU the maximum being 22300 MWd/TeU. The bundle burnup details are given in Table-2.

The estimated Channel Outlet Temperatures of channels H-13 and O-08 with FPD were in tune with those measured during operation and are given in the Figure-2. With increase in burnup the rate of decrease of bundle power is expected to reduce and at high burnups the change in bundle power is expected to be very small. This has been confirmed from estimated and measured Channel Outlet Temperature readings which remained almost constant at 284° C beyond 15000 MWd/TeU. Typical fuel bundle power as a function of burnup is given in the Figure 3. The bundle powers varied with time from 440 kW (Element Linear Heat Rating of 52 kW/m) initially to 300 kW (36 kW/m) at end of life. It is planned to conduct post irradiation examination of these bundles for detailed study. Irradiations of this type are further planned with induced power ramps in high burnup range.

4. ALTERNATIVE FUEL DESIGNS AND CORE LOADING CONCEPTS

Short length fuel bundles and on-power refueling provision in PHWRs provides flexibility to use variety of fuel loading patterns and different fuel types and consequently permits optimum use of fuel in the reactor. Following paragraphs cover the alternative fuel designs and core loading concepts in use or under consideration for use in Indian PHWRs.

4.1 **Thorium Bundles:** India has a long term strategy of use of thorium (Ref. 6) in its nuclear power programme. An advanced heavy water reactor is being designed (Ref. 7), in addition to deploying Thorium in FBRs (Ref.6) in future. It is thus planned to have experience of irradiation of thorium in present power reactors. In the 220 MWe PHWRs, 35 Thorium bundles have been used for flux flattening in the initial core such that the reactor can be operated at rated full power in the initial phase. These bundles are distributed throughout the core in different bundle locations, both in the high power and low power channels. The criterion used for selection of these locations is such that the worths of the shutdown systems are unaffected. This loading was successfully demonstrated in KAPS-1 and subsequently adopted in the initial reactor loading of KAPS-2, KAIGA-1 & 2 and RAPP 3&4. A special 18 thorium bundle loading configuration was used for flux flattening in the fresh core of RAPS-2 after enmass coolant channel replacement (EMCCR) job. So far 232 thorium dioxide bundles have been successfully irradiated in different reactors. The maximum fuel bundle power and burnups seen are 408 kW and 13000 MWd/TeHE respectively. The power profile of these bundles is shown in Figure 4 along with natural uranium dioxide bundle power profile. These bundles withstood the power ramps normally experienced in reactor while the typical power envelope of thorium fuel is such that power increases with irradiation. Out of the 232 bundles, one bundle is suspected to have failed during operation at relatively low burnup. The thorium dioxide fuel bundle fabrication and irradiation has provided valuable experience.

It is now planned to irradiate thoria bundles to higher burnups with suitable modification in design. It is also planned to take up loading few thorium bundles regularly during equilibrium reactor operation.

4.2 MOX-7 bundles: It is also proposed to load MOX fuel in one of the existing PHWRs. For this purpose, MOX-7 bundle design has been evolved, which is a 19-element cluster, with inner seven elements having MOX pellets consisting of 0.4 wt % Plutonium dioxide (about 70% fissile) mixed in natural uranium dioxide and outer 12 elements having only natural uranium dioxide pellets.

Based on detailed studies, an optimised loading pattern and refuelling scheme has been evolved for loading the bundles in an existing operating reactor. The conditions imposed for selection of loading pattern in core are that the reactor is always to be operated at full power, i.e. permissible limit on bundle power and channel outlet temperature are to be maintained while change over from all natural uranium core to MOX core is gradually done. The scheme evolved is to load MOX-7 bundles in outer burnup zone and retain natural UO2 fuel bundles in inner burnup zone. The present natural uranium core will be converted gradually to a mixed MOX - natural UO2 core in a span of about 3 years. The core average discharge burnup in equilibrium core increases to around 9000 MWd/TeHE with this scheme. Due to this the fuelling rate comes down from 9.4 bundles / FPD in the case of Natural Uranium core to 6.8 bundles/FPD in the proposed MOX-7 / Natural Uranium core. The reactivity worths of the shutdown systems are calculated to come down marginally (maximum by 1 mk)which is found acceptable as sufficient subcriticality margins exist between the negative reactivity requirements and availability for all normal shutdowns and anticipated accidental scenarios. Relevant reactor physics parameters for this type of core have been evaluated.

The fuel bundle power burnup envelope for MOX-7 bundle is also shown in Figure-4. The MOX-7 fuel bundle design has been completed. The fuel bundle subchannel analysis has been carried out to check for dryout margins (Ref. 8). The fuel bundle thermo-mechanical analysis has been carried out for MOX fuel elements and different parameters like fuel temperatures, sheath strain and fission gas releases are checked for acceptance. The structural design of end plates has been evaluated with respect to strains induced due to difference in power ratings of inner ring of MOX bearing elements as compared to present all natural uranium elements. MOX elements of same dimensions were earlier test irradiated in CIRUS research reactor.

The fuel bundle drawings and fabrication specification have been prepared. Earlier experience of MOX fuel fabrication and irradiation experience in the two BWRs at Tarapur has provided valuable feed back for this purpose. Initially trial irradiation of 50 number of MOX-7 bundles in one of the KAPS reactors is being taken up this year. Regulatory review has been completed and permission has been obtained for this purpose. Special bundle transport package and storage racks have been developed such that criticality accidents do not occur. The 50 fuel bundles are currently under fabrication and loading of these in the reactor would commence by this year end.

4.3 Fuelling Schemes prior to shut down for EMCCR: The MAPS-2 unit was taken for enmass coolant channel replacement(EMCCR) job in January 2002 and the unit restarted after core reloading in July 2003. The zircaloy – 2 coolant channels have been changed to zirconium 2.5% niobium alloy tubes. The flexibility in fuelling scheme in PHWRs has been effectively utilized in MAPS-2 to irradiate the fuel bundles to highest burnup in core before shutting down the unit for EMCCR and discharging all the fuel. This has been achieved through a refueling scheme incorporating large scale radial shuffling of fuel. Indian PHWR normally adopt 8 bundle refueling scheme, however about four months prior to planned shut down for EMCCR refueling scheme was changed to 4 bundle fuelling scheme with radial reshuffling of discharged fuel from channel. Under this scheme four fresh fuel bundles are loaded into a central channel and the discharged bundles from this channel loaded into an outer burnup zone low power channel. The bundles discharged from this channel could further be loaded into another outer burnup zone channel. This scheme has been followed for 110 FPDs before reactor shutdown and has resulted in improving fuel utilization by 12.5% for this period.

4.4 Use of Depleted Uranium Bundles in Initial core fuel charge: In earlier years RAPS, MAPS and NAPS reactors were loaded with 384 to 550 depleted uranium fuel bundles as a part of initial core fuel loading for the purpose of flux flattening. It was decided in MAPS-2 that the depleted uranium fraction in intial core be maximized. Therefore after enmass coolant channel replacement large number of depleted uranium bundles, which is 40% of initial core fuel, were loaded. The depleted uranium bundles are loaded in string positions 5 to 12 in central channels and first and last two string positions in the outer channels. As a part of preloading studies, reactor physics simulation of reactor operation with this core configuration was carried out upto 500 FPDs of operation. It is predicted that the refueling operations in this core would need to be started at about 20 FPD ahead of earlier used initial core loading patterns. The subsequent refueling strategy and rate of refueling in this case is almost comparable to those other initial loading schemes.

Similar reactor physics studies have been carried out for use of large of number depleted Uranium bundles as a part of initial fuel loading in 540 MWe Reactors coming up at Tarapur. Fuel loading in first of these units will be taken up around mid 2004. The loading scheme consists of loading of depleted uranium bundles with different uranium235 contents.

Theoretical studies, to use depleted uranium in combination with natural uranium for regular refueling in some of the current operating 220 MWe PHWRs has been completed.

5. FUEL FOR 540 MWe AND 680 MWe PHWR UNITS

The fuel for 540 MWe PHWR is of 37-element fuel bundle type, with element diameter of 13 mm. Before the fuel is introduced, a specific testing program has been completed to satisfy requirements like wear, fretting, strength, impact strength, fuelling machine compatibility, pressure drop, bundle dropping, vibration and in-pile performance etc. The tests include semi-prototype tests in which major influencing parameters are simulated and prototype tests in which reactor conditions are simulated. From the parametric data obtained from the prototype tests, the variation of the parameter in reactor conditions are derived. In addition, results of tests conducted for 19-element fuel bundle and their performance in reactors are also utilised to qualify the present design. For each test, the testing conditions and the acceptance limit for the parameter have been identified and test specifications have been followed. Tests have been conducted for each of the above requirements in Bhabha Atomic Research Center (BARC). The fuel bundle drawings and specifications have been finalised. The production trials are in progress.

It is now proposed to enhance the output of the 540 MWe units to 680 MWe by introducing boiling in channels. It is planned to have maximum 3% steam quality at coolant channel exit, with slight increase in coolant temperature, without altering coolant pressure as in the present 540 MWe units. By slightly modifying the radial flux flattening and increasing the maximum time averaged channel power up to 6.5 MWth, it is possible to extract a power of 2152 MWth from the reactor.

The 37-element fuel bundles to be used in 540 MWe units will also be used in the uprated 680 MWe reactors. The peak channel power and bundle powers estimated for 680 MWe reactors are 7 MWe and 905 kW respectively. This bundle power corresponds to a fuel element linear heat rating of 55 kw/m. The total core average exit burnup at nominal parameters of core is around 6500 MWd/TeU.

6. FABRICATION DEVELOPMENT

Indian PHWR fuel bundles, bearing pads and spacer pads are spot welded to sheath, unlike brazed ones in CANDU fuel designs. At present the fuel pellets loading into the tubes and welding of the end plugs is done prior to the spot welding of bearing pads and spacer pads on to the sheath of the loaded elements. This procedure has the possibility of chipping of pellets due to welding electrode pressure. It is now proposed to weld the spacer and bearing pads on empty tube first and then load the fuel pellets in the welded tube. This procedure will eliminate any possibility of chipping of pellets. The quality of welds also can be ascertained prior to loading of pellets, thus possibility of rejection of loaded fuel elements is absent. Empty tube welding is in advanced stage of implementation

As a production qualification of this process about 120 number of 220 MWe 19-element fuel bundles were fabricated by Nuclear Fuel Complex (NFC) and were loaded in MAPS and KAPS stations in 2001. The performance of this design has been cofirmed to be satisfactory. The fuel bundles for 540 MWe PHWRs are being fabricated by this process.

Ultrasonic testing of end plug-sheath welds has been introduced along with metallographic examination for random welds. This has been introduced after deficiencies in end plug welds was seen to be one of the causes of fuel defects.

7. CONCLUSION

Indian nuclear power programme is based on optimum utilisation of available uranium and thorium resources in the country. The fuel designs and fuel usage strategies are evolved based on this objective. The current fuel technology has been successfully demonstrated by satisfactory performance of the fourteen operating stations. Improvements in fuel design, fabrication, quality control and operating practices are being carried out towards reducing fuel failure rate as well as improving fuel utilization.

8. REFERENCES

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Table -1 Fuel Element Thermo-mechanical Analysis for High Burnup

Sl. No	Bundle	LHR	Variable Parameter	Burnup	Centre	Fisson Gas	Internal gas
	Power (KW)	KW/M		MWd/TeHE	Temperature (C)	Rel (%)	Pressure (Mpa)
	19-element fuel bundle Peak power element						
1	483	58	Normal Parameters	20,000	2040	15.3	9.8
2			Double Dish Pellet	20,000	2040	14.8	5.5
3			Fuel Pellet Grain Size 40 Micro M	20,000	2040	14.7	8.9
4			Low Fuel Density	20,000	2080	18.4	7.4
5			Pellet Central Hole	25,000	1950	14.2	6.4
	22-element fuel bundle Peak power element						
6	483	50	Normal Parameters	25,000	1670	3.7	6.4

Table -2 High Burnup Bundle Irradiation Data

Channel No.	Number of Bundles	Residence Time FPDs	Burnup MWd/TeU
O-08	2	796	22300
	2	796	21000
	2	1196	19000
	1	1196	17000
		-	
H-13	2	724	20000
	2	724	19000
	2	1109	17000
	1	1109	15000

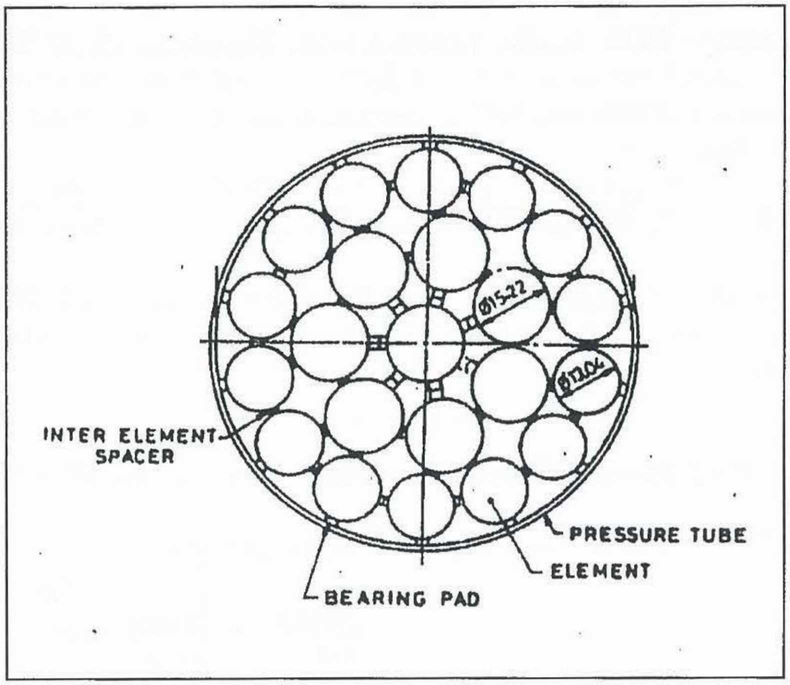

Figure 1. 22-Element Fuel Bundle

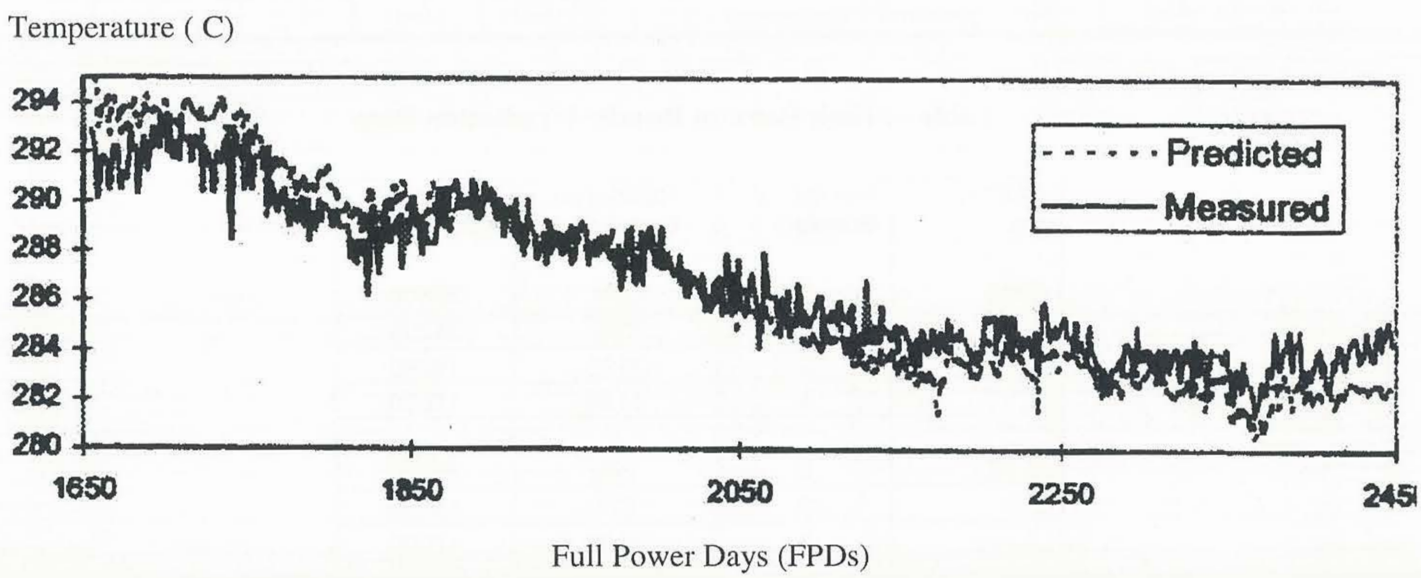

Figure 2. Variation of Channel Outlet Temperature With Reactor Operation of O-8 Channel

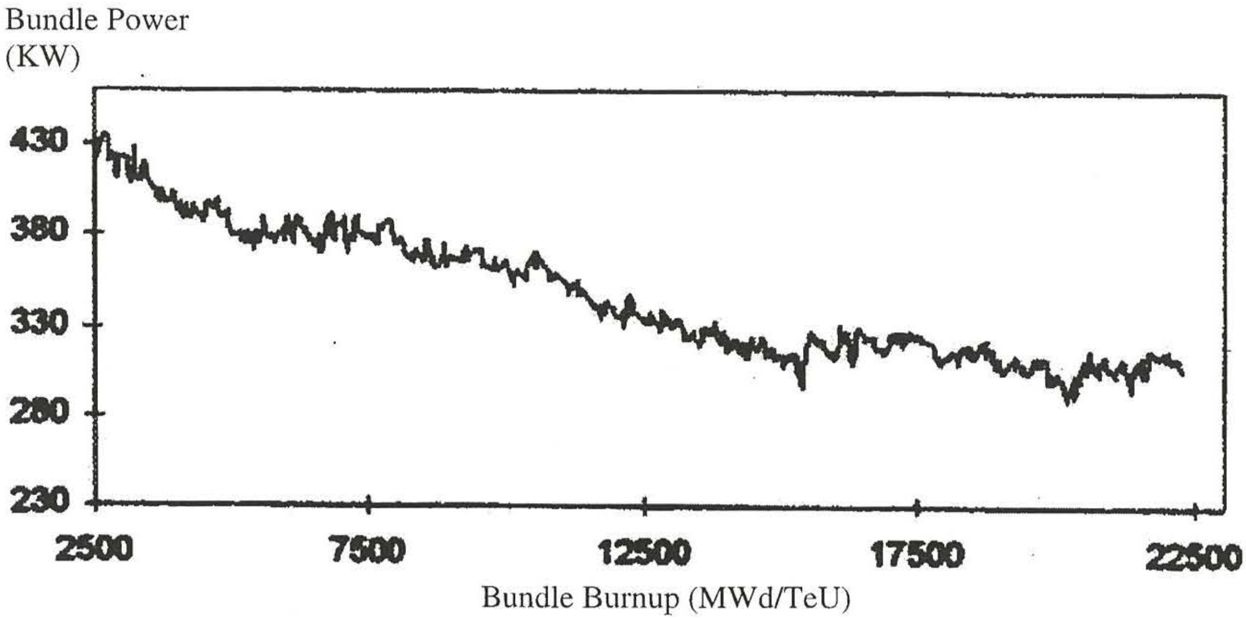

Figure 3. Bundle Power variation with Burnup for 7th bundle of Channel O-8

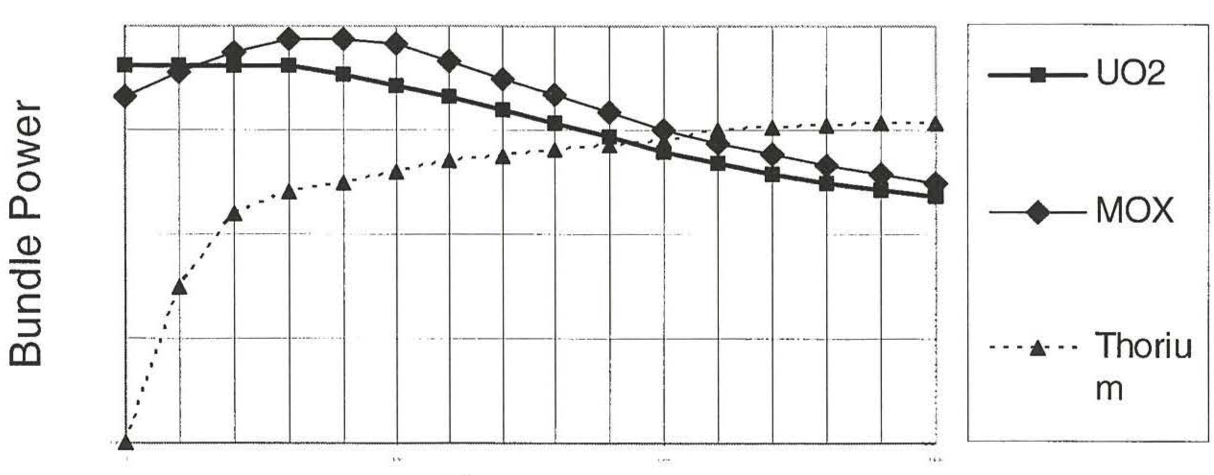

FIGURE 4. Bundle Power Envelopes for Different Fuel Types