EXPERIENCE IN THE MANUFACTURE AND PERFORMANCE OF CANDU FUEL FOR KANUPP

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ABSTRACT

Karachi Nuclear Power Plant (KANUPP) a 137 MWe CANDU unit is in operation since 1971. Initially, it was fueled with Canadian fuel bundles. In July 1980 Pakistani manufactured fuel was introduced in the reactor core, irradiated to a burnup of about 7500 MWd-teU^{-1} and successfully discharged in May 1984. The core was progressively fuelled with Pakistani fuel and in August 1990 the reactor core contained all Pakistani made fuel.

As of the present, 3 core equivalent Pakistani fuel bundles have been successfully discharged at an average burnup of 6500 MWd-teU^{-1}. with a maximum burnup of ~ 10,200 MWd-teU^{-1}. No fuel failure of Pakistani bundles has been observed so far.

This paper presents the indigenous efforts towards manufacture and operational aspects of KANUPP fuel and compares its behaviour with that of Canadian supplied fuel. The Pakistani fuel has performed well and is as good as the Canadian fuel.

1.0 INTRODUCTION :

The local fabrication of nuclear fuel for Karachi Nuclear Power Plant (KANUPP) began some fifteen years ago. The Canadian design [1] of brazed split spacer type 19-element bundles was adopted. In order to ensure that these bundles were compatible with the reactor coolant system and met the fuel transfer requirements vis-à-vis the fueling machine, the first few of these bundles underwent necessary out-of core pressure drop and endurance tests in a special test rig installed at KANUPP [2]. These tests were followed by in-core hot conditioning and thermal hydraulic tests of four test bundles [3].

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The ultimate performance assurance of a given fuel can, however, be obtained only after it has completed its duty cycle in the reactor system for which it was designed. In order to assess the capability of manufactured bundles to survive power changes due to fueling, reactivity mechanism or reactor power cycles and withstand the design burnup, these were finally subjected to fuel rating and burnup tests in the KANUPP reactor [4]. All the four test bundles performed satisfactorily in the reactor environment to which these were exposed. These were irradiated to the burnup in the range 7500 - 10,000 $MWd\text{-}teU^{-1}$.

Based on the satisfactory in-core performance, locally fabricated fuel bundles were utilized in increasing numbers for routine reactor fueling while the testing phase was still in progress. First of the test bundle was discharged in 1984 and the whole core transformed into a core consisting entirely of indigenously fabricated fuel bundles in 1990.

This paper updates the previously presented information [5] on the subject and describes the salient features related to manufacturing, in-core irradiation and performance besides post irradiation examination of these fuel bundles.

2.0 MANUFACTURE OF FUEL :

2.1 Uranium Dioxide Powder :

Laboratory scale studies to produce UO_2 from yellow cake (YC) were conducted as far back as 1973-1975 at PINSTECH [6]. After gaining confidence, a pilot plant for the production of natural UO_2 from the indigenous Uranium Ore Concentrate to meet the CANDU fuel specifications was established in 1978 [7]. The process is based upon the indigenous mining of Uranium Ore and producing crude YC. This YC is dissolved in Nitric Acid and Uranyl Nitrate so obtained is refined in pulse columns by solvent extraction using Tributyl Phosphate-Kerosine mixture. Purified Uranyl Nitrate is converted to Ammonium di-uranate (ADU). Pure ADU is dried, pulverized, calcined and reduced to UO_2 , conforming to physical and chemical characteristics suitable for the production of reactor grade UO_2 pellets.

2.2 Fuel Pellets :

At the Fuel Fabrication Plant samples of the as received UO_2 powder are sieved, inspected and tested for physical characteristics before subjecting them to the mandatory advanced process check (APC). The UO_2 pellets so produced are analyzed for chemical purity.

The incoming lot of UO_2 qualified for production on the basis of APC is released for production. Sieved powder (-10 mesh) is slugged (4.2 ± 0.2 g/cc) on a hydraulic rotary press followed by granulation through an built-in granulator. Any fines before granulation are removed before the slugs reach the granulator. The granulated powder is mixed with lubricant and pressed to green pellets (5.2 ± 0.2 g/c) on a hydraulic rotary press. The pellets are sintered at 1650 ± 25 °C in a molybedenum resistance heating furnace in dissociated ammonia atmosphere.

During the early stage of production a number of problems were encountered during pellet fabrication. However, with experience the chemical purity of powder and pellets has been controlled and as well the mismatch of the tooling e.g., punch-die clearance and punch entries. Ex ADU powder at times provided difficulties. Even when the physical characteristics conformed to the specifications the powder yielded low density pellets. A number of possible reasons have been investigated [8-9], but these factors have not been made part of the physical characteristic evaluation of the powder. Occasionally therefore resintering of pellets has been practiced but resintering often improves the sintered densities marginally i.e., 0.1 g/cc.

2.3 Zircaloy Components :

Zircaloy material received in the form of strips are punched into components (wear pads, spacers and end plates) using a fine blanking press. Quality control checks are exercised at each step. Improvements have been made in the punching of wear pads. The die has been modified so that the blanks and actual wear pads are punched of the same size. The blanks are further loaded in the magazine and stamped for serrations. Thus the number of wear pads produced from the same strip are doubled. End caps are machined out of Zircaloy bars and accepted after following the required QC/QA procedures. These are machined over a high precision, fully automatic turret lathe. Quality is also assured through patrol inspections.

2.4 Sub-Assemblies:

Both sides of spacers and wear pads are coated by vapourizing the Beryllium in an electron beam vacuum chamber using rotating magazines. Previous to this, beryllium was vaporized in Mo-boats by resistance heating in a vacuum chamber. The process losses were extremely high and the practice was discontinued.

The Be-coated appendages are tacked on to Zircaloy tubes and brazed in a vacuum induction furnace. The parameters are adjusted so that the product conforms to QC checks.

The sub-assemblies are internally coated with graphite slurry and baked at 350 °C under vacuum better than 10^{-4} mm Hg. To achieve coating thickness of 0.0025 - 0.015 mm.

2.5 Fuel Elements :

The Fuel elements are produced by using a high precision, turret incorporated, single head magnetic force upset resistance welding machine. The number of modifications were incorporated in tooling and their materials to achieve production worthiness. The weld parameters were studied and developed [10] to achieve the acceptable quality production welds.

The sub-assemblies are loaded with the sintered pellets and end caps welded in helium atmosphere. Setup and process control (PC) welds before and after the welding of 19-element kits are destructively tested for weld rating. 120% of wall thickness is the minimum acceptable weld rating for production welds.

2.6 Fuel Bundles :

Welded elements are machined to remove weld upset material, adjusted for length and preparation of end cap cone for bundle welding. These 19 pin elements are loaded in a specially designed fixture and welded with end-plates by using special resistance spot welding machine. To avoid oxidation, special electrodes have been designed. Built-in argon jets have been provided in the legs of ground electrodes to provide inert gas blanket around the spot welding area. The Process Control welds are evaluated before and after each shift. The bundles after assembly are deburred and checked for helium leak before the final inspection and packing.

3. 0 QUALITY CONTROL/QUALITY ASSURANCE:

A comprehensive quality assurance system has been devised and implemented at the fuel fabrication plant [11-12]. Material/Component Inspection system is presented in Fig. 1. The system provides the essentially required loop of activities to ensure quality and reliability of the product. The system is divided into the following three areas:

- In-process inspection/testing, process and product
- Statistical sampling
- Quality assurance review

3.1 In-Process Inspection:

All production related activities are monitored, evaluated and approved on the shop floor level. Prior production, first off and process control samples are taken and evaluated. No production is undertaken till the results of these samples are approved. These activities are controlled through petrol inspections of the product and evaluation of process parameters in laboratories.

3.2 Statistical Sampling:

The quality of each production batch/lot is evaluated/ assured through statistical sampling as per applied Military Standards. The product not conforming to the requirement is D.AD, kept aside from production lot and subsequently reviewed in the light of resampling procedures and actual product requirement.

3.3 QA Review :

Joint production and quality assurance group meetings are held for the review of previous experience and results. Engineering Change Notices, if essentially required are issued and followed during new production schedule. This philosophy has been very useful for the production activities.

4. 0 FUEL MANAGEMENT AT KANUPP:

The computational tools as well as the fueling strategies that have been in use during various phases of KANUPP are discussed below :

4.1 Fuel Management Tools:

Historically, KANUPP core has gone through three different phases. The first phase spanned a little over 800 full power days (fueling was based entirely on Canadian bundles) when the core having seen through the initial startup and recycling, gradually approached an equilibrium, operating with flux flattened central zone. The fueling schedule was based on the computer program STOKE [13]. In the STOKE calculations, the irradiation of all the fuel bundles in the inner zone was artificially reduced and the channels of this zone were not called for fueling when due. This led to an increased irradiation of the fuel in the central zone causing the flattening of neutron flux.

The second phase started when, at about 830 full power days (April, 1977), the fueling strategy was changed. It was decided to allow the flux to peak in the central zone in order to conserve fuel bundles. A computer code SIMFUP [14] was utilized in place of STOKE. SIMFUP did not artificially reduce the burnup of inner zone channels. The channels fueled, were the ones which naturally came up according to burnup and bundle power limit criteria. The fueling strategy adopted through SIMFUP led to neutron flux profile which peaked in the inner zone of the core. The generation capability of the plant was consequently reduced from 137 MWe to 105 MWe to keep the heat flux from exceeding the design limits in the central zone. The Pakistani fuel bundles were introduced during this phase.

The third phase commenced at 1574 full power days of reactor operation (July, 1986), when the process of reverting back to the designed flux shapes was initiated. A new fuel scheduling program FORESITE [15] was utilized. During the period (1574-1910 FPDs) (July 1986 to February 1990) partially flattened core corresponding to max limit of 112 MWe on generator load was realized (RFF = 0.6342 and AFF = 0.6201). In the subsequent period the flattening was further increased enhancing the allowable power to 120 MWe. The corresponding neutron flux flattening (RFF = 0.6736 and AFF = 0.630) has now been in effect for quite some time.

Both the SIMFUP and FORESITE made use of flux and irradiation data computed by the 3-D code PERIKAN [16].

4.2 Operational Constraints:

The assessment of core performance warrants a look at the presently existing operational constraints, which are:

4.2.1 Moderator and Coolant Isotopic :

At the time of commissioning the moderator and primary coolant heavy water isotopic was 99.75 wt%. These purity figures have over a period of time came down to the presently existing corresponding figures of 99.57 wt% and 98.80 wt% .

4.2.2 Moderator Operating Band :

The plant has not been operating in the design moderator operating band of 182-188 inches (~ 4620 - 4770 mm) for over a decade now. The current operating band is 177-183 inches (~ 4500 - 4650 mm).

4.2.3 Plant Operation With Defuelled Channels :

KANUPP has operated with two of its channels (G12 and F16) with out any fuel since October 1989. Channel F16 was normalized in December 1993 but G12 continues to be Defuelled [17].

5. 0 PERFORMANCE INDICATORS :

The core performance is evaluated by following the fueling frequency, monitoring the channel temperatures and analyzing the calculated results pertaining bundle and channel powers in addition to studying the variation of average core and fuel average discharge burnup.

In many cases the parameters that provide information on fuel performance such as bundle and channel powers besides the average core are not directly measurable. The computation of such parameters is based on the well tested and evaluated computer code, which in the case of KANUPP is PERIKAN. The PERIKAN code is being used for KANUPP fuel management since 420.3 FPDS (November, 1974).

5.1 Fueling Frequency :

The design equilibrium fueling rate of KANUPP is 4.2 fuel bundles/FPD corresponding to design discharge burnup of 8650 $MWd\text{-}teU^{-1}$. These ideal fuel performance figures have never been achieved in actual practice.

The rate of reactor fueling and consequently its discharge burnup depends on the impurities present in reactor materials, as well as on the operating reactor power and fueling scheme in effect during a given time period. No. of bundles fueled as a function of full power days of reactor operation are plotted in Fig. 2. During flattened power distribution period (i.e. from Commissioning to 829 FPDs) referred to as phase-1 above, the average fuel consumption rate was 4.9 bundles/FPD. During the second phase, when the fueling scheme was modified to allow flux peaking in the core center, the average fueling rate improved to 4.4 bundles/FPD (this was also due to operating the reactor at considerably reduced loads). Currently with partial flux flattening corresponding to 120 MWe generator load, the fuel consumption rate has increased to 5.2 bundles/FPD (contribution of deteriorated moderator purity and reduced reflector thickness is also a cause).

5.2 Maximum Bundle and Channel Powers :

The maximum bundle power variation with full power days of reactor operation is given in Fig. 3. which shows that MBP remained well within the operating band of 453 - 477 KW, except just after the Fuel Channel Integrity Assessment (FCIA) in December 1993 which reqquired 12 reactor channels to be examined. These channels were later fuelled with fresh fuel, resulting in an increase in maximum bundle power. The reactor as a result was required to operate at reduced powers to avoid fuel over rating.

The maximum channel power have also remained within the operating envelop of 2.8 - 3.2 MW in general.

5.3 Average Discharge Burnup :

The average discharge burnup during different phases of operating history of the plant is tabulated here under :

Phase	Fueling Scheme	Max Operating Capability (MWe)	Moderator Purity (Wt %)	Ave Discharge Burnup (MWd/teU)
1	Fully Flattened (Canadian Bundles)	137	99.7	6561
2	Centrally Peaked (Canadian + Local Bundles)	105	99.65	7985
3	Partially Flattened (Local Bundles)	120	99.57	6598

The maximum burnup achieved by a locally fabricated bundle is 10156 MWd/teU. The corresponding figure for Canadian bundle is 12724 MWd/teU.

6. 0 FUEL INTEGRITY ASSESSMENT:

An assessment of the integrity of the fuel bundles resident in the reactor core is carried out by monitoring the Rb-88 and Cs-138 activities and their ratio through the use off GFP monitoring system. Additional information to this effect could be obtained by monitoring the activity of I-131 in the primary coolant. The performance of locally fabricated fuel bundles can be assessed by the fact that all through the period that they have been in use, the GFP ratio remained in the range 0.2-0.6 well under alarm limit of 1.0 micro curie/litre. The I-131 concentration almost constantly remained below 5 micro curie litre as against the alarm limit of 500 micro curie/litre. None of over 6000 bundles that have so far been irradiated have defected. In comparison a total of 13 WCL bundles failed in the initial stages of plant operation. The reason was suspected to be the higher rate of power increase. A stringent fuel conditioning procedure is in effect since, which obviously has paid dividends.

6.1 Mechanical Failures :

As of the present KANUPP has experienced only one mechanical failure of a Pakistani made bundle, which occurred in 1990 due to development of end plate to end plate coupling between two bundles in the fuel channel. The problem was noticed when the magazine could not be rotated after receiving fuel from Channel H02. One bundle had been pulled partially into the magazine by the bundle being defuelled. As a result the pulled bundle was damaged. Removal of the fueling machine was accomplished sometime later after draining of the channel [18].

The bundles involved were, both locally fabricated. Their irradiation and in-core residence time were normal ~ 7000 MWd-teU^{-1} and ~ 500 FPDs respectively. It is possible that the end plate of the two bundles got coupled due to breaking of end plate of the bundle at 10th position and subsequent entanglement of its dislodged pencil with the end plate of 11th bundle. It was suspected that the plate had an inherent material or manufacturing defect. Such a pre-existing defect could potentially get further deteriorated leading to accelerated cracking under the effect of irradiation.

7.0 POST IRRADIATION EXAMINATION:

A large number of fuel bundles with varied irradiation histories have been subjected to post irradiation examination using high resolution gamma ray spectrometry [19]. Quite a few, specially at the test bundles, have also been inspected employing a high magnification underwater telescope [20]. These documented studies have in general indicated:

- A good correlation between the theoretically and measured burnup.
- Uniformity of irradiation, and
- Satisfactory structural integrity - occasional slight deformation of end-plates and bowing of pencils in bundles irradiated to high burnup ~ 10,000MWd/teU, have been observed.

8. 0 SAFEGUARDS APPLICATION:

The IAEA safeguards apply to the fuel whether it is fresh , residing in-core or stored under water after having been irradiated. The safeguards characteristics of the irradiated fuel are thoroughly documented [21]. KANUPP has actively participated, in the recent past, in a coordinated research programme (CRP) of the IAEA, culminating in the development of a spent fuel verifier that has now been adopted by the IAEA for the in-situ verification of CANDU spent fuel stored on stacked trays [22].

9. 0 CONCLUSION:

The local fuel is produced under strict QC/QA regime through indigenous resources and efforts. It has performed successfully under varied irradiation conditions during KANUPP operation for the last fifteen years. The in-core surveillance through temperature monitoring and analysis of Rb-80 and CS-138 ratios revealed no measurable defect in the fuel. The achieved burnups are also comparable to the initially imported fuel. The continuous efforts on the fuel management practices have also played major role in the performance of fuel despite operational constraints and problems that are integral to any power plant and cannot be avoided altogether.

The spent fuel is fully under IAEA Safeguards, the procedures are documented and have been improved from time to time in collaboration with IAEA.

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MATERIAL/COMPONENTS INSPECTION DURING CANDU FUEL MANUFACTURE

UO_2 As Received

Ave. Particle size O/U Ratio
Bigger Particle Size, Bulk
Density Surface Area, Tap Density
Metallography

UO_2 Slugs

Sieve Analysis (Granulated Power),
Bulk Density (Granulated Powder),
Slug Density.

UO_2 Green Pellets

Edge Chamferred Condition, Green Density, End Squareness, Land Width, Dish Depth, Double Ended Compaction.

Sintered Pellets

O/U Ratio
Grain Size
Sintered Density

Ground Sintered Pellets

Visual Inspection, Diameter Check, Land Width, Surface Finish, Dish Depth, End Squareness, Chemical Analysis.

Stacking

Cut Off Inspection

Step Dimension

Loading

Stack Assembly Check
Pellet Diameter Check
Stack Length Check(%)

Sheath As Received

Dimensional Check, Bow Check,
Segrigation for I.D Grouping.
Ultrasonic Test, Tensile Test,
Metallography, Visual Check,
Burst Test, Auloclaving.

Bar As Received

Visual & Dimentional Check
Ultrasonic Test
Tensile Test, Metallography

End Cap Manufacture

Dimentional Check
Visual Check

End Cap Welding

Metallography of Weld Joint

Elements Profiling

Dimensional Check

He-Leak Test

End Plate Welding

Visual Check

Torque Check

Bundle Final Inspection

End Square, Overall Height, Spacing, Visual, I.D, Droop Test, End Projection, Wear Pad, Position Test, Visual Inspection
Length Inspection, Kink Gauging, Bundle Welding, Convex/Concave, Outring
Flatness, Wear Pad Step Height, He-Leak Test, Alpha Monitoring, Autoclave And Pre-Packing Inspection

Strip for Wear Pads, Spacer, End Plate

Thickness with Flatness Check,
Tensile Test, Metallography,
Visual Check.

Punching Appendages

Visual Check

Dimention Check

Wear Pad Ramping

Visual Check
Dimension Check

Be-Coating (W.P./Spacers)

Thickness Inspection
Colour Check
Scratch Test

Tacking/ Brazing

Metallography of Brazed Joint, Visual Check, Dimensional Check.

Centre W.Pad Milling

Wear Pad Thickness Inspection
Visual Check

Graphite Coating

Dimentional Check

Visual Check

Chamfering

Dimensional Check
Visual Check

End Plate Pickling

Visual Check
Dimensional Check

FIG. 1

KANUPP Reactor Fuelling History (Commissioning - Todate)

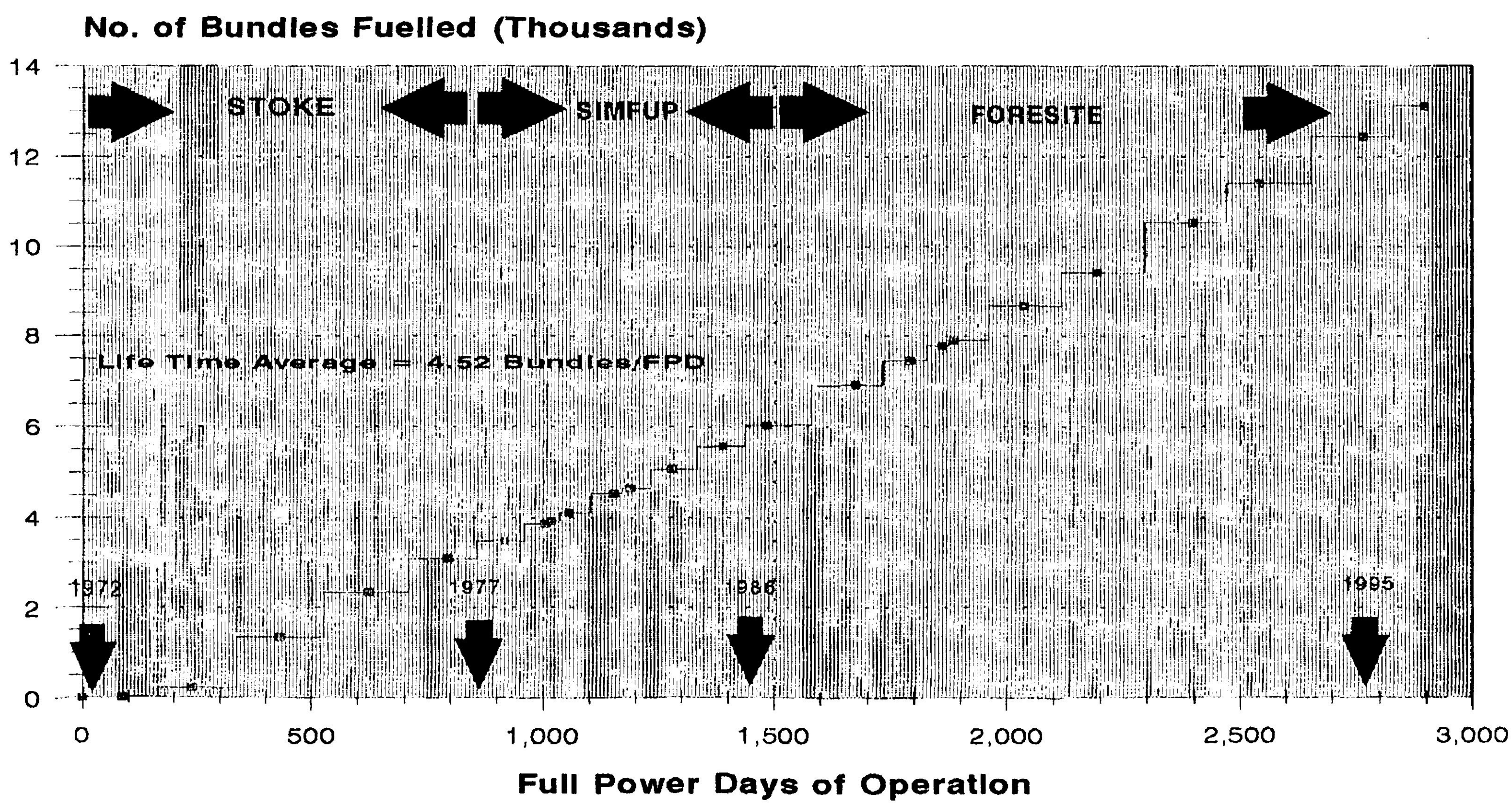

Fig. 2

Maximum Bundle Power Variation (January 1993 - August 1995)

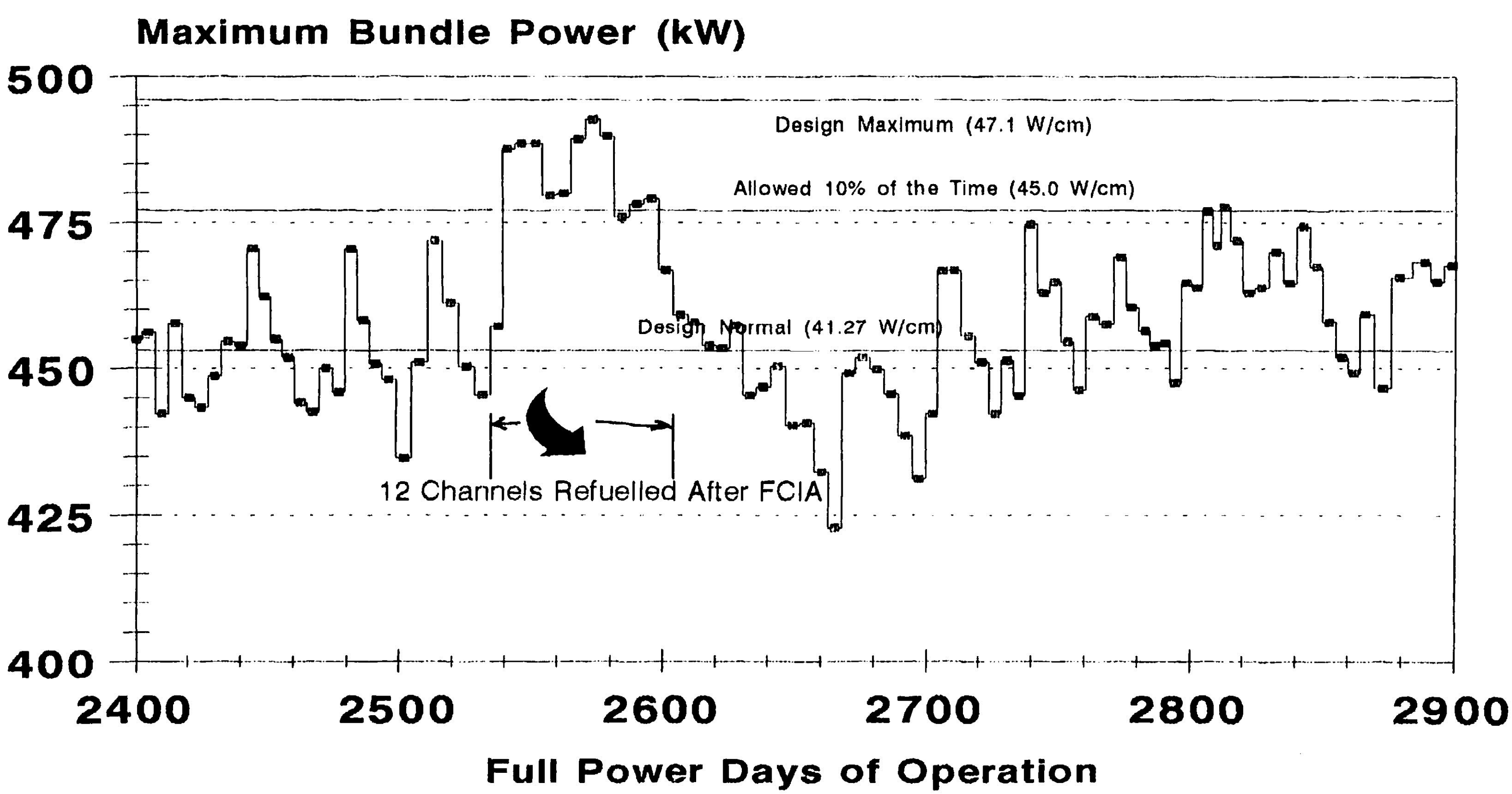

Fig. 3