EXPERIENCE IN CANDU FUEL FOR KANUPP AND ESTABLISHMENT OF SUPPORTING FACILITIES FOR SELF RELIANCE

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ABSTRACT

Karachi Nuclear Power Plant (KANUPP) was supplied and commissioned by Canada. It was a first generation of Candu type 137 MWe reactor in Pakistan which is in operation since 1971. To sustain its operation, Pakistan had to establish its own fuel fabrication plant, which successfully started fuel supply to KANUPP in 1980. Pakistan's fuel eventually replaced Canadian fuel. KANUPP is operational on indigenously produced fuel since August 1990.

Establishment of fuel fabrication plant made it imperative to establish supporting facilities for self reliance e.g. prospection, exploration, mining, ore processing, uranium refining and uranium dioxide production plants. In 1993 a plant was established for the production of Zircaloy-4 from Zircon. Another plant for the manufacture of seamless Zircaloy-4 tubes, strips and bars was made operational. This plant is supporting the entire Candu fuel Zircaloy-4 requirement for KANUPP.

This paper updates the previously presented indigenous efforts towards manufacture of KANUPP fuel and its performance. The establishment of supporting facilities for fuel manufacture are presented. The operational records of KANUPP are highlighted. Refurbishing of KANUPP has extended the life of KANUPP for another 10-15 years. Fuel fabrication plant is capable to supply fuel for KANUPP for this extended period.

1.0 INTRODUCTION

Candu fuel bundle for Kanupp is a split spacer type 19-element design [1]. The manufacture of these fuel bundles was started nineteen years ago as part of self-reliance programme of PAEC. The initially produced fuel bundles were successfully tested for out of core pressure drop and endurance tests in a special rig. [2]. The fuel bundles were also tested for in-core hot conditioning and thermal hydraulic tests [3]. Subsequently four fuel bundles for ultimate performance assurance were charged to KANUPP reactor. These bundles performed satisfactorily and were irradiated to the burnup in the range 7500-1000 MWD-TeU^{-1} [4]. First out of these four bundles was discharged in 1984 while the core transformed into core consisting entirely of indigenously fabricated fuel bundles in 1990.

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In order to sustain fuel production for KANUPP other supporting facilities had to be established. Thus all out efforts were made in geology, prospect ion, mining and production of yellow cake to the production of reactor grade UO_2.

Similarly to produce Zircaloy-4, a chain of facilities were established to produce nuclear grade ZrO_2 from Zircon, Zirconium sponge from ZrO_2 and subsequently zircaloy-4 ingots.

Based on zircaloy-4 ingots a facility to produce seamless tubing, strips and bars was established.

This paper supplements the previous presentation [5] on the subject and describes further experiences in the fuel performance, reactor operation, spent fuel storage and safeguards. Establishment of supportive facilities for current and future fuel manufacture programmes are also highlighted.

2.0 MANUFACTURE OF FUEL

2.1 Fuel Pellets

As received UO_2 powder is characterised for its physical characteristics i.e. surface area, Bulk density, Tap density, O/U ratio and particle size. Powder is also examined for colour and the presence of any hard agglomerates. The powder is then subjected to mandatory advance process check (APC) for production qualification. Green pellets and subsequently sintered pellets are analysed for acceptability criteria.

Received lot of UO_2 qualified for production is released for processing. Sieved powder (-10 mesh) is slugged (4.2 ± 0.2 g cm^{-3}) on a rotatory hydraulic press followed by on line granulator to produce granules of required range of size. The granulated powder is blended with lubricant and pressed to green pellets (5.2 ± 0.2 g cm^{-3}) and sintered at $1650 \pm 25^{\circ}$C in dissociated ammonia atmosphere.

Some difficulties were faced during initial stages of pellet manufacture due to the following reasons:

- Chemical purity of powder/pellets
- Morphology of Ex.ADU powder
- Presence of hard agglomerates

Mismatch of tooling i.e. punch-die clearance, die taper, punch entries were other factors. With experience these problems were rectified and good quality sintered pellets were produced.

2.2 Zircaloy Components

Indigenously produced zircaloy-4 materials such as bars and strips after QC/QA evaluation are released for the production of end caps, wear pads, spacers and end plates. Whereas tubes are released for the production of sub-assemblies.

2.3 Sub-Assemblies

Be-coating of appendages is accomplished in electron beam vacuum chamber using rotating magazines. Beryllium coated spacer and wear pads from both sides are tacked to tubes and brazed in vacuum induction furnace.

Zr-Be alloy so formed imparts strength and corrosion resistance. No incidence of detachment of these appendages has been witnessed so for.

The sub-assemblies are coated internally with graphite and baked under vacuum $> 10^{-4}$ mm Hg at 350°C. Graphite coating thickness is from 0.0025-0.015mm.

2.4 Fuel Elements

Subassemblies are loaded with fuel pellets and end-cap welded by magnetic force resistance welding under helium atmosphere. Extensive efforts are made to modify and develop tooling, to meet the process requirement. The process parameters were developed [6] to achieve the acceptable quality production welds. The acceptable weld rating of 120% that of wall thickness for the production welds is used.

2.5 Fuel Bundles

Welded elements are profiled to remove weld upset material and for cone preparation of end cap. Nineteen profiled elements are loaded in a special fixture and resistance welded with end plates. To avoid oxidation of spot welds special electrodes have been designed with build-in argon jets in the ground electrode legs to provide inert gas blanket. The process control welds (PC) are evaluated before and after each shift. The bundles are deburred, checked for helium leak and subjected to final inspection before packing.

3. QUALITY CONTROL/QUALITY ASSURANCE

A comprehensive quality assurance, quality control and inventory control system has been implemented at the fuel fabrication plant and presented in Fig 1. The system is primarily based on the following three components [7]:

- In process inspection/testing at process and product stage.
- Statistical sampling
- Quality assurance review

The system has proved to be reliable and has provided quality assured products.

4. SUPPORTIVE FACILITIES FOR SELF RELIANCE

In order to sustain fuel fabrication for KANUPP it was imperative to establish supportive facilities to undo the effects of world embargoes. The established facilities are summarized in Fig 2 and briefly described below:

4.1 Uranium Exploration and Mining

With the vision of nuclear energy programme and installation activities of KANUPP, exploration activities for the nuclear minerals were started. Extensive survey resulted in discovery of number of potential regions for uranium reserves. Uranium is being recovered employing both conventional mining and Insitu leach techniques.

4.2 Ore Processing Mill

The facility was established based on ore mined from uranium mine. The ore is fed from ore pads to vibrating screen. Over size > 50mm is crushed in jaw crusher. The ore is ball milled by open circuit wet grinding. The slurry with desired specific gravity is screened and transferred to leaching section. The slurry is leached with sulphuric acid in a cascade of tanks fitted with rubber lined mechanical agitators. The uranium from leach liquor is extracted through liquid-liquid solvent extraction using tricapryl amine 2.5%, Iso-decanol 1.5% and kerosene as diluent. Uranium is stripped with ammonium sulphate. Uranyl sulphate is converted to ammonium di-uranate and sent as Yellow Cake (Y.C.) to refining plant.

4.3 Insitu Leach Mining (ISL)

Where conventional mining was impracticable ISL technique had been applied after extensive studies on strata characteristics such as permeability, leach parameters and computer modeling of flow pattern etc. Oxygenated alkaline leach is applied. Five well pattern, four for lixiviant injection and one for leach liquid extraction is used. Uranyl tricarbonate liquor containing about 80-100 ppm U_3O_8 is fed to ion exchange columns. The loaded resin is eluted with NaCl and $NaHCO_3$ and precipitated with H_2O_2 to uranium peroxide.

4.4 ADU-Refining and UO2 Production Plant

This facility receives Y.C. from uranium-mill. Crude Y.C. is dissolved to give uranyl nitrate feed solution for solvent extraction. Tri-n-butyl phosphate (TBP) is used for uranium extraction in pulse columns. The loaded TBP is scrubbed to remove impurities and stripped with demineralized water.

Purified $UO_2(NO_3)_2$ is precipitated with NH_4OH in two stages to achieve ADU that is suitable to obtain UO_2 of desirable physical characteristics [8]. ADU is carefully dried to avoid any caking and is converted to UO_3 and U_3O_8. Subsequently U_3O_8 is reduced to UO_2 in cracked ammonia (N_2/H_2) atmosphere at suitable reduction temperature 600-650°C and stabilized. QC/QA checks are exercised at each step so that UO_2 produced meets the physical and chemical characteristics to produce sintered pellets of required specifications. The facility supplies reactor grade UO_2 for fuel fabrication.

4.5 Zirconium Production Plants

Restrictions on Zircaloy-4 tubing and other products endangered the fuel supply to KANUPP. In order to sustain the fuel supply zircaloy production facility was established indigenously.

4.5.1 Production of ZrO_2

Zircon ($ZrSiO_4$) was subjected to alkali fusion at 650°C when Na_2ZrO_3 and Na_2SiO_3 are produced. Sodium Zirconate is purified and converted to zirconium nitrate $Zr(NO_3)_4$ from which Hafnium is removed by solvent extraction in mixer-settlers by Nitrophos process. Purified $Zr(NO_3)_4$ is converted to $Zr(OH)_4$ which is calcined to produce nuclear grade ZrO_2.

4.5.2 Production of Zircaloy-4 Ingot

Refined ZrO_2 is converted to $ZrCl_4$ in a continuous graphite tube chlorinator. $ZrCl_4$ is collected in cyclone condensers and stored in air tight special containers. $ZrCl_4$ is purified and reduced to sponge with magnesium. Which is purified under vacuum better than 10^{-4} m bar at 750-800°C sponge is retrieved from the crucible by hydraulic chisel, analysed for O_2 & N_2 and grouped according to QC/QA requirement. Hardness of each batch is measured by melting a small sample.

The graded Zr-sponge is batched and compacts with alloying elements are pressed on a 600 ton hydraulic press. The compacts are TIG welded to form consumable electrodes which are melted in a vacuum arc furnace. These ingots are prepared for remelting after spectrochemical analysis and gas contents. Remelting is carried out in water-cooled copper crucible in vacuum arc furnace under vacuum. The ingot after chemical analysis, hardness evaluation and ultrasonic testing is shipped to seamless tube plant.

4.5.3 Seamless Tube Plant (STP)

Zircaloy-4 ingots after in-house inspection are hot forged to bars and swaged to round bars for tube and rod production. Forged bars are machined for slabs for the production of strip. Round bars are machined to billets, canned in copper canisters and sealed with copper end plates by hydraulic pressing. Canned billets are heated to 800°C and extruded in an 800 ton extrusion press. The tube reduced extrudes (TREX) are decoppered, straightened and under go honing to ensure inside cleaning from any adhered copper or scale. TREX cut to desired lengths are cold pilgered with intermittent annealing.

The pilgered tubes are further reduced to size on cold rolling mills The tubes are finally pickled and straightened on high precision cross rolls and are belt ground from outside. The tubes are finally degreased, annealed and inspected for the following:

- Ultrasonic inspection
- Metallography
- Mechanical testing
- Chemical assay.
- Gasseous contents (O_2, N_2 and H_2)
- Corrosion testing.

After acceptance these tubes are shipped to fuel fabrication plant for fuel manufacture.

4.6 Magnesium Production Plant

Magnesite ($MgCO_3$) is the starting material for $MgCl_2.1.5H_2O$. Calcined Magnesite is reacted with HCl. $MgCl_2$ hydrate is recrystalized, and dehydrated to $MgCl_2.1.5\ H_2O$. Feed is prepared by mixing appropriate quantities of KCl, $MgCl_2$ and Ca Cl_2 for use as electrolyte. The cell is operated at 10-12 volts and 7000 amperes. The cell is charged at regular intervals and Magnesium is collected from the top. Crude Magnesium is sublimed under vacuum and melted under flux to get pure metal ingot. The ingot is crushed to small pieces for use in the production of Zirconium sponge.

5. KANUPP CORE AND FUEL PERFORMANCE

The core performance is evaluated from the following performance indicators:

- Fueling frequency.
- Maximum Bundle and channel powers.
- Average discharge burnup.

The fueling frequency depends on the fuel management tools and operational constraints. Fuel management practices depend on fueling strategy based on neutron flux profile, through developed computer codes. Operational constraints depend on many factors e.g. Moderator and coolant isotopic, moderator operating band and defueled channel etc. These factors were discussed in detail elsewhere [9].

Maximum bundle and channel power as well as discharge burnup are not directly measurable. At KANUPP these are computed with well tested and evaluated computer code "PERIKAN" [10].

KANUPP has completed 3428 Full Power Days. (FPD) of operation as of 30th June 1999 (Average capacity factor = 28.48%). During this period, the plant has generated 121688 BBTUs of thermal energy. In this process a total of 15863 fuel bundles (6712 Canadian + 9151 Pak.) have been discharged to the spent fuel bay.

During the period 1998, the core average burnup was 3426.6 ± 96.6 MWD/TeU. The average discharge burnup of core was 6686.9 MWD/TeU and corresponding figures for inner and outer zone were 6844.4 and 6686.9 MWD/TeU respectively. The fueling scheme was "SIMFUP" with flux peaking in the core centre. The fuel performance is steady and comparable with that reported earlier [9]. The bundle power has remained within an operating band of 425-475 KW and channel power have also remained within the operating envelop of 2.8-3.2 MW in general. The fuel performance throughout KANUPP operation remained within design operational limits. The bundles have burnt more than 10,000 MWD/TeU.

6. FUEL INTEGRITY ASSESSMENT

Integrity assessment of fuel bundles in the reactor core has been carried out by monitoring the Rb-88 and Cs-138 activities and their ratio through the use of Gasseous Fission Product (GFP) monitoring system. Additional information has been derived by monitoring I-131 in the primary coolant. GFP ratio remained in the range of 0.2-0.6 well under the alarm limit of 1 micro curie per litre. The I-131 concentration also remained below 5 micro curie per litre as against the alarm limit of 500 micro curie per litre. All the indigenous fuel bundles irradiated so far have been found defect free.

7. KANUPP OPERATING HISTORY

Kanupp performance can be divided into five phases [11]. The first phase (1972-77) is considered as the period of development and smooth operation when the assistance of vendor country was available.

The second phase (1978-83) is a difficult phase due to embargoes on fuels, plant spares and vendors assistance. This phase can be considered as the leanest one in the KANUPP operation history.

The third phase (1984-89) is the period of indigenous efforts and improvements with the self reliance programmes.

Fourth phase (1990-95) is the phase of both performance and good prospects for the future as KANUPP amply demonstrated that nuclear power is as feasible in a developing country as any where else.

Fifth phase (1996-2002) is continuing and would be assessed after the completion of next four years.

Despite embargos fuel fabrication plant started supply of fuel in 1980 and gradually increased the fuel supply for successful operation of KANUPP at the same time. KANUPP struggled continuously for the indigenisation in the manufacture of spares. The operation history can be seen from the plant yearly availability Fig 3 as well as yearly generation in MKWh. Fig 4. and its operational records are tabulated below:

KANUPP RECORD PERFORMANCE

RECORD	CURRENT	YEAR	PREVIOUS	YEAR
Generation (MKWh)	586.5	1,994	583.9	1,974
Availability (%)	85.84	1,995	85.81	1,994
Capacity Factor(%)	48.8	1,994	48.67	1,974
Continuous Operation	113D-9H-42M	1,995	104D-5H-21M	1,984

Though KANUPP's 27 years operation history does not match international standards. It had to cater around 310 outages due to various reasons but under international restraints it is by all means quite successful. It is worth mentioning since 1980 no outage was due to lack of fuel supply.

After refurbishing of KANUPP, in the light of operating experience, results of inspections of critical components and the recommendations of foreign technical experts, KANUPP is now in a position to extend its economic life by ten years beyond its design life i.e. upto year 2012 AD.

8. SPENT FUEL STORAGE

Spent fuel bay in KANUPP is 12.5x7.6x6 meters, provided with water circulation system through heat exchanger for heat removal, filter and ion exchange for clarification and purification systems. It was anticipated in 1995 that fuel storage capacity would last for another five years. A program for dry storage design was started. At the same time, study to improve the stacking system was conducted. Consequently the trays were restacked. Each tray was loaded with 11 bundles and 18 trays are stacked one over the other. This system has created enough capacity of fuel storage for the next 7.5 years. At the same time stack level has been kept such that a water shield of 3.81 meter has been provided and radiation level 0.37 meter above water surface is 1 mr/hr. Any handling of fuel is carried out keeping in view the specified water shield for safety consideration.

9. FUEL SAFEGUARDS APPLICATION

The IAEA Safeguards apply to fuel once it is received at KANUPP, it may be fresh, in-core or spent fuel in storage bay. The safeguards of irradiated fuels are thoroughly documented [12]. KANUPP has actively participated in a coordinated research programme of IAEA, which resulted in the development of a spent fuel verifier, adopted by IAEA for the insitu verification of CANDU spent fuel stored on stacked trays [13].

10. CONCLUSION

The fuel fabricated for KANUPP is under strict inventory, QC/QA regime. It is manufactured through indigenous efforts and resources. For self reliance all the supportive facilities have been established on indigenous basis. Indigenously produced materials have been successfully used in KANUPP fuel. This has given further impetus to our confidence in undertaking future indigenisation programmes of PAEC. The fuel manufacturing practices at fuel fabrication plant and efforts on the fuel management practices at KANUPP have played major role in the performance of fuel despite operational constraints and problems faced by KANUPP. The refurbishing of KANUPP has extended its life by at least upto the year 2010. The fuel fabrication plant is quite capable to meet its fuel requirement during its operational life.

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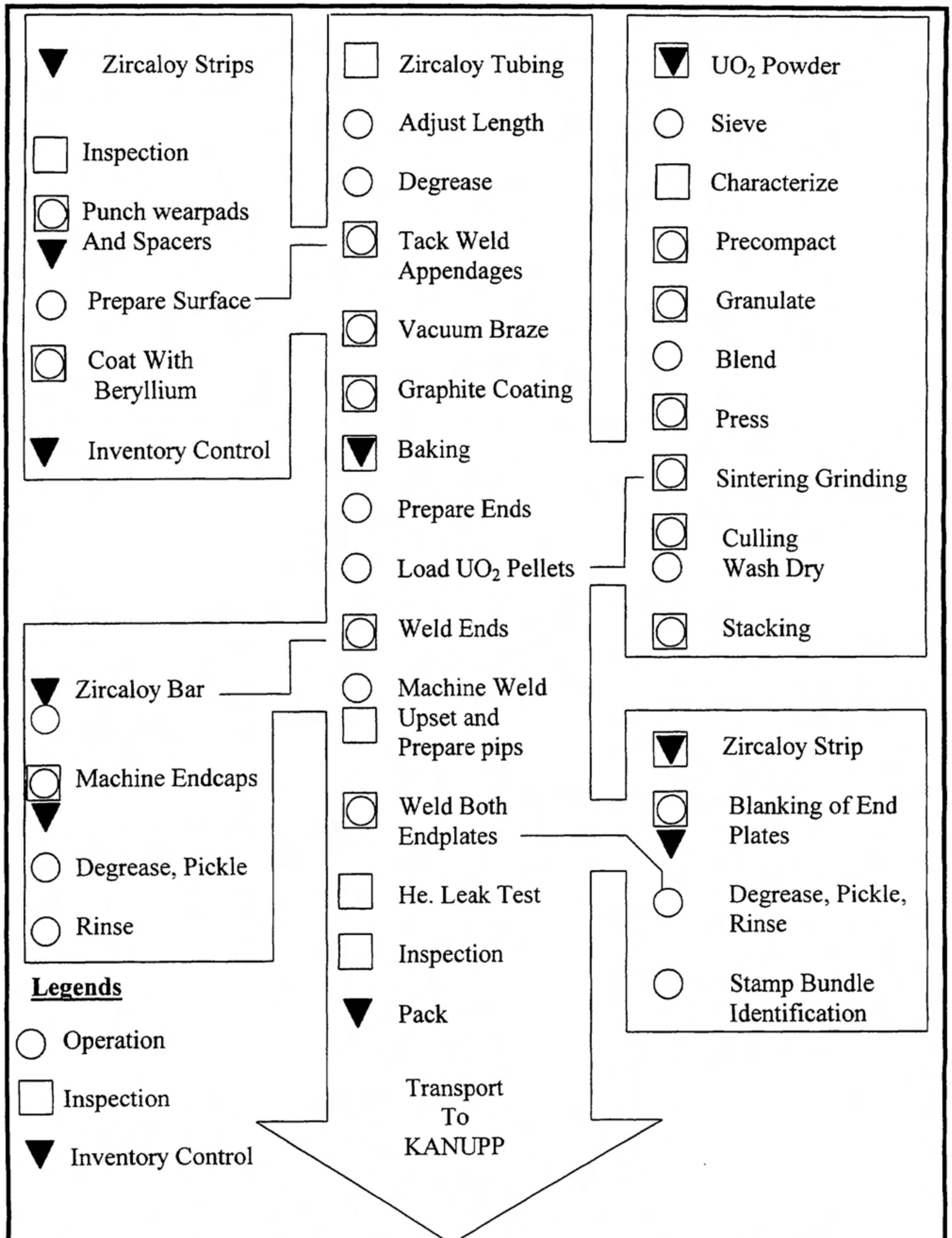

FIG.1 Role of QA/QC and Inventory Control in Fuel Fabrication Plant

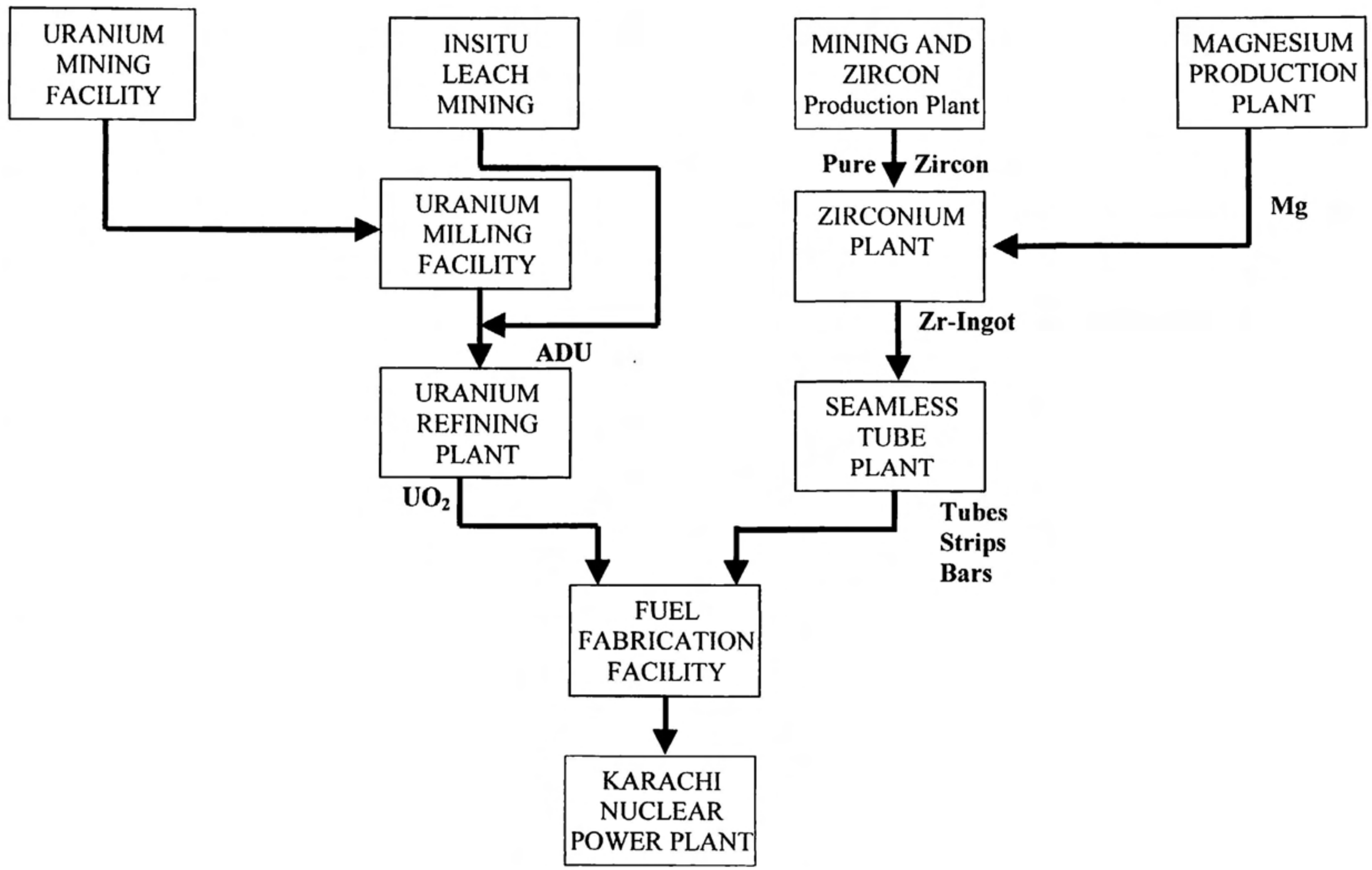

FIG. 2 NUCLEAR FUEL CYCLE FACILITIES FOR CANDU FUEL FABRICATION IN PAKISTAN

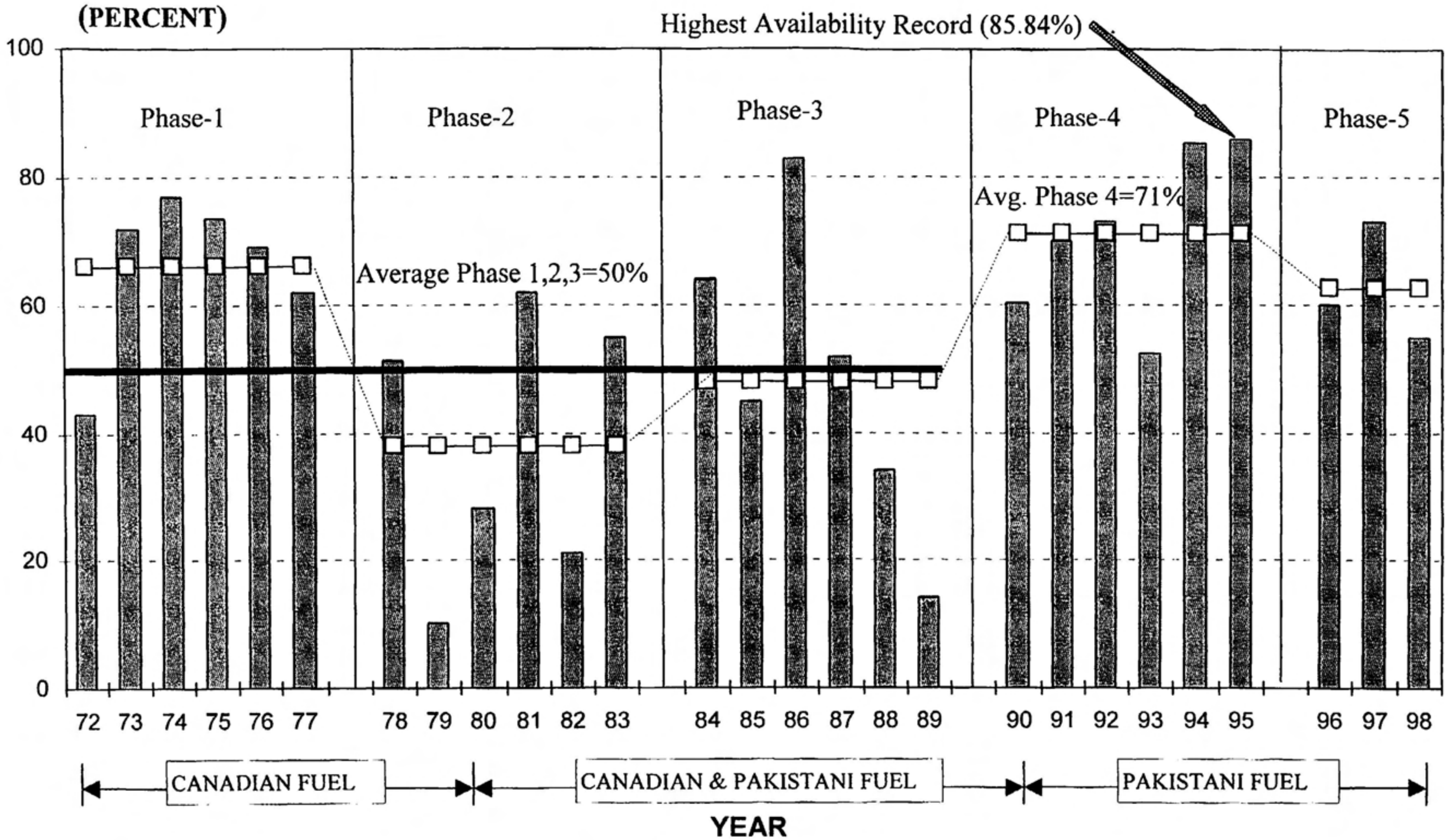

Fig. 3 **PLANT YEARLY AVAILABILITY**

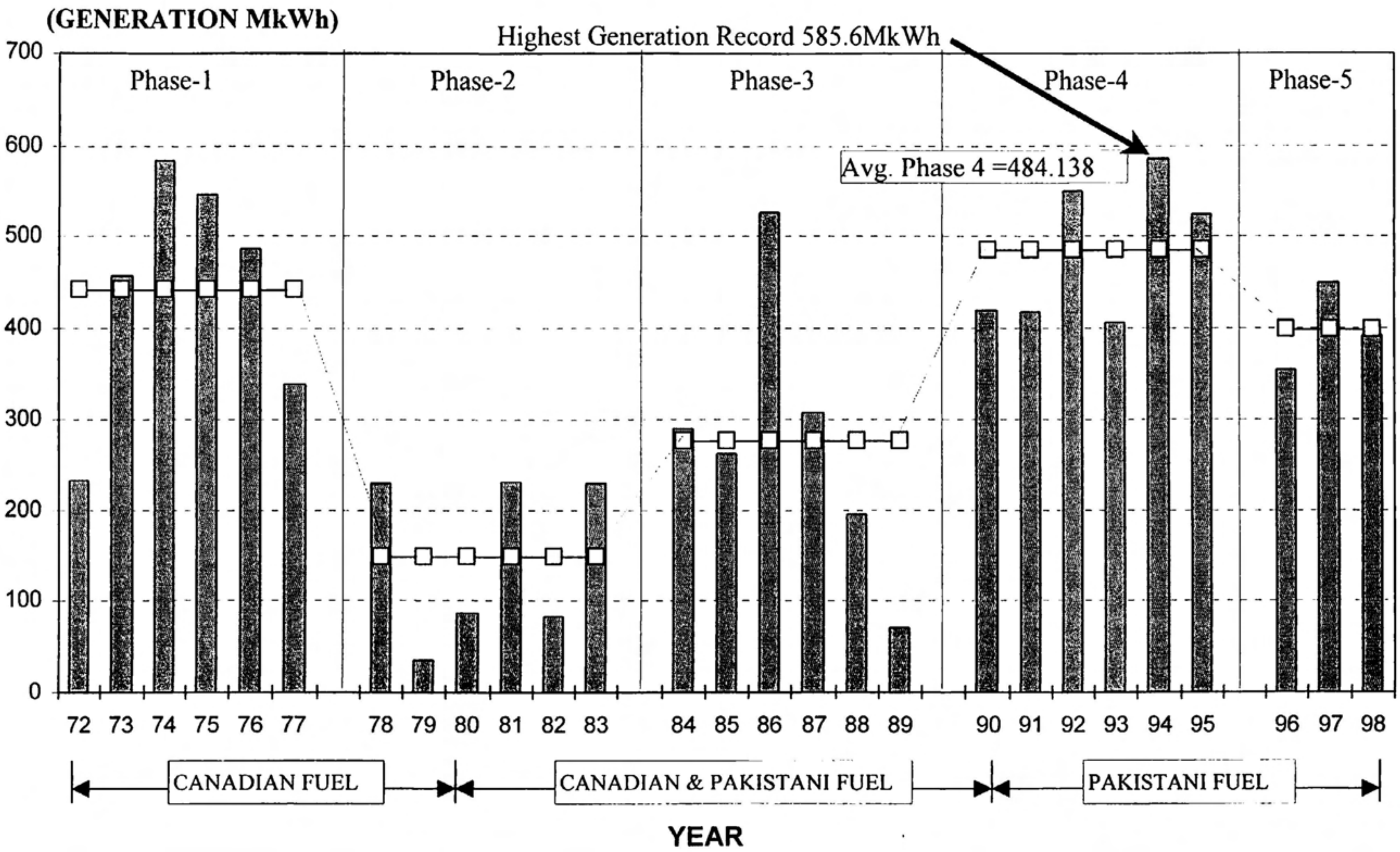

FIG.4 **PLANT YEARLY GENERATION**