# TRENDS IN DESIGN & MANUFACTURE OF NUCLEAR FUELS IN INDIA

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**ABSTRACT**

India has adopted PHWR technology as a major contributor in its nuclear power generation programme. Over the years the engineers and scientists of Department of Atomic Energy have contributed immensely in realising total self reliance in all fields of this technology. The paper highlights the achievements made so far and also action plans for further advancing the nuclear technology in the country.

## 1.0. INTRODUCTION:

Development and application of nuclear energy for peaceful purposes has been the main objective of Department of Atomic Energy, India. While generation of nuclear power constitutes a major portion of this activity the other interests include application of nuclear technology in the fields of agriculture and medicine. Nurtured over four decades, today the Department has acquired a good deal of indigenous capability in all spheres of nuclear fuel cycle.

Better design and improved methods of manufacture are integral to safer and more reliable operation of nuclear power stations and to achieve this goal various units of the Department work in close co-ordination through feed-back methods. Fig-1 shows the facilities established in India, their functions and networking relationships. Nuclear Power Corporation of India Limited (NPCIL) playing the role of nodal agency, designs, constructs and operates nuclear power plants by taking R&D support from Bhabha Atomic Research Centre (BARC). The R&D functions include evolution of new reactor concepts, ratification of new fuel designs through out-of-pile tests in engineering loops and in-pile tests in research reactors, development of computer codes for fuel designs & it's in-reactor behavior, PIE of irradiated fuel in hot cells, etc.

The Nuclear Fuel Complex set up at Hyderabad, India, 25 years ago is the sole manufacturer and supplier of nuclear fuels and core structural components / assemblies for all the nuclear power reactors in India. These reactors include PHWRs, BWRs and FBRs. The complex is unique in the world where all the above mentioned activities are carried out right from ore to finished products under one roof. Starting from Magnesium Di-Uranate received from Uranium Corporation of India Limited, and Zircon sand from Indian Rare Earths, NFC has been fabricating the required quantity of nuclear fuel assemblies and zircaloy structurals to sustain the nuclear power programme drawn up by the Department of Atomic Energy.

As depicted in Fig-1, there has been continuous interaction among various units of the department to develop and upgrade various process technologies and optimise the reactor operating conditions so as to achieve the goal of commercial power generation in conformity with the stipulations of the Atomic Energy Regulatory Board.

## 2.0. FUEL DESIGNS & MANUFACTURE:

Based on the fuel manufacturing and reactor operating experience the developments that have taken place in design, manufacturing and fuel management are enumerated below:

### 2.1. 19-Element Split Spacer Fuel Bundle:

The nineteen element wire wrap fuel design was used for RAPS Unit-I, which was drawn from Canadian design initially. Subsequently designs were frozen for 19-element split spacer fuel bundles and at NFC the flow sheets were standardised for manufacture and quality control of this type of fuel. The special feature of this fuel bundle is the attachment of split spacers and bearing pads by employing resistance welding techniques in place of conventional beryllium brazing methods (1).

This 19-element split spacer bundle design has become a standard fuel for all the 220 MWe reactors in India since 1986.

### 2.2. 22-Element Fuel Bundle:

Prominent among the new designs is the concept of 22-element fuel bundle having split spacer attachments. This design was evolved aiming for generating 15% higher power yet making it compatible with the existing 220 MWe reactor systems. The other strength of this design is its graded structure which permits improved distribution of heat generation amongst the outer and inner fuel elements thus making the average LHGR low. This design is a promising candidate for fuel being developed for achieving high burn-up in advanced fuel cycles that would employ U-Pu MOX fuel. NFC had successfully developed necessary equipment and standardised production parameters for manufacturing these bundles. 560 bundles of this design have been successfully evaluated for their performance in the core (2).

## 2.3. 37-Element Fuel Bundle:

37-element split spacer fuel bundle design was explored for 500 MWe PHWRs which is an extension of 19 element fuel design. In this design one more ring of elements has been added. This fuel bundle is designed to generate a bundle power of about 1 MW and has been studied for physics, fuel management and safety aspects. Proto-type fuel bundles fabricated by NFC are undergoing extensive type tests like pressure drop tests, endurance test, fuelling machine compatibility test, etc. Thus NFC has established capability in the production of fuel for 500 MWe PHWRs.

## 2.4. Depleted UO2 Bundles:

Since inception, NFC has produced about 3,000 depleted fuel bundles which were used for flux flattening purpose during the commissioning of new reactors.

# 3.0. FUELS FOR ADVANCED CYCLES:

India has taken-up studies for improvements of fuel utilisation through Advanced Fuel Cycles which will increase the fuel burn-up and decrease spent fuel volume. Various design options were worked out and the action plans are initiated for the manufacture of fuels for these cycles.

## 3.1. MOX Fuel for PHWRs:

From the beginning of nuclear power programme based on PHWRs, India has decided to go in for reprocessing option. Though the most desirable way of utilizing the Pu available from reprocessing of PHWR fuel is to use it in Fast Breeder Reactors, a programme to recycle the self-generated Pu in the PHWRs has been thought of as a short-term option (3). Towards this end, a MOX fuel bundle design of 19-element type containing 0.4% PuO2 along with natural UO2 is under study. Out of the total 306 channels in a PHWR reactor, only the peripheral channels will contain MOX fuel bundles of the above design. The core composition in terms of the number of fuel elements containing natural UO2 and MOX is indicated in Fig-2. With this scheme of refuelling the following objectives will be achieved:

- Improvement in fuel utilization
- Shrinking of spent fuel discharge rate due to improved burn up of fuel & thereby reducing the back-end costs of fuel cycle
- Saving in uranium requirement

A flowsheet consisting of physical mixing, cold compaction and high temperature sintering will be followed for fuel fabrication. Work is planned to be carried out for introducing a number of MOX fuel bundles in one of the PHWRs, following fabrication in the MOX fuel fabrication plant at Tarapur, where at present BWR-MOX programme has been in progress for some time. The experience obtained in the production of MOX fuel for our Tarapur reactors, which has been performing quite satisfactorily, will enable fabrication of fuel to high quality standards expected of this fuel. A test fuel cluster fabricated by the above route is undergoing irradiation in the Pressurized Water Loop (PWL) of our research reactor and has reached a burn up of 9,000 MWD/Te successfully (planned target burn up of 15,000 MWD/Te).

### 3.2. Throrium Oxide Bundle for PHWRs:

India's 3-stage nuclear power programme has been drawn up with an aim to use the large thorium resources available in the country in the second and subsequent stage of the power programme, which envisages Fast Breeder Reactors and Heavy Water Reactors using advanced fuel cycles. In this context, there has been a need to gain experience in manufacture, irradiation and subsequent reprocessing of thorium.

The use of thorium bundles in the existing PHWRs is envisaged for flux flattening during the initial start-up of the reactors having all fresh fuel in the core. Based on the properties of thorium, the fuel bundle design was prepared, engineered and the necessary physics calculations were completed for identifying the location and the string in the core so as to get the desired flux flattening effect. Based on these calculations, it has been finalised that 35 thorium bundles in the fresh core will suffice for flux flattening as against about 400 depleted uranium oxide bundles that were needed for the same purpose earlier. After gaining first hand operational experience of this design by irradiating few bundles in Madras Atomic Power Station, a decision was taken for use of these bundles during start-up of Kakrapara Atomic Power Stations I & II. These bundles have been successfully used in both these reactors during start-up and similar initial fuel loading pattern is being adopted for all new PHWRs in India.

NFC, having already established its capability in processing of thoria for Fast Breeder Test Reactor by innovative techniques (4), has played a vital role in fabricating these bundles.

### 3.3. Fuel for Advanced Heavy Water Reactor (AHWR):

The strategy of realising large scale power generation from thorium has been clearly laid down right from the inception of Indian Nuclear Power Programme. An Advanced Heavy Water Reactor is being developed as a part of this strategy which generates most of its energy from U-233, bred *in situ* from thorium (5). The reactor is of the vertical tube type construction with heavy water as moderator, the coolant being boiling light water.

AHWR fuel cluster of about 4 meters overall length will have 52 fuel pins arranged in a square array. The cluster shall incorporate MOX as well as ThO2 fuel pins, the ThO2 pins surrounding the MOX pins, and zircaloy-2 being the clad material. The fuel pins will be separated at regular intervals along their length by suitable spacers.

## 4.0. IMPROVEMENTS IN PHWR FUEL:

Consequent to the decision taken to switch over from wire wrap to split spacer design, extensive studies were carried out at NFC and BARC to carry out the attachment of spacers / bearing pads on fuel sheath by employing resistance welding techniques. This involved design of specially coined components and standardisation of their fabrication route, design and manufacture of special purpose equipment for welding, standardisation of process parameters, testing and qualification procedures. Since 1986, NFC has been continuously producing split spacer fuel bundles and has so far manufactured about 100,000 bundles of this type. It may be mentioned here that today India is the only country employing resistance welding for appendages which is safe, cost effective and superior process as compared to beryllium brazing (1).

Keeping in pace with the developments taking place the world over, NFC had successfully developed and standardised the process for graphite coating the inner surface of fuel tubes. The equipment required for graphite coating and baking has also been indigenously developed and used for regular production. As expected, the provision of this layer of graphite coating has reduced the incidence of fuel failures due to reduced pellet clad interaction during power ramp situations.

In addition to the above, NFC had incorporated innovative process changes at various stages of fuel production and has established indigenous capability in equipment manufacture for the entire fuel fabrication route. These points will be discussed in detail in another paper at this Conference.

## 5.0. FUEL DEMAND AND MANUFACTURING PROGRAM:

NFC is the only facility in India, where the fuel required for all the nuclear power reactors is manufactured. Hence, as Nuclear Power Corporation decided to establish more nuclear power stations at Kaiga and RAPS III & IV, NFC took upon itself the task of increasing its fuel manufacturing capacity. Accordingly, NFC has drawn time bound schedules to manufacture and supply the required quantity of fuel bundles to sustain the targeted nuclear power generation by indigenously developing additional equipment for the new production plants.

## 6.0. QUALITY CONTROL AND QUALITY ASSURANCE:

Over the years NFC has evolved Quality Control and Quality Assurance procedures to be adopted at various stages of fuel manufacturing so as to meet the stringent nuclear standards. NFC is also currently in the process of developing IPM (Intelligent Processing of Materials) techniques by employing latest NDT tools like Acoustic Emission, Thermography, etc., in the critical areas like end cap welding, spacer / bearing pad welding and calandria tube welding. These techniques, apart from monitoring the parameters employed in the production process, can also give feed back for corrections as necessary if the quality is suspected to be going out of accepted band.

## 7.0 ZIRCALOY STRUCTURALS:

Starting from zircon sand, NFC has full-fledged facilities for converting it to zircaloy material of various shapes like sheets, rods and tubes. While the production of zircaloy structurals has been taking place since its inception, NFC has standardised and produced different grades of zircaloys equivalent to Zircaloy-2, Zircaloy-4, Zirc-Niobium and ZIRLO materials for reactor applications. The rigid production parameters and quality control steps adopted during the production of zirconium hardware has resulted in NFC becoming a significant exporter of nuclear grade fuel materials to advanced countries. The first consignment of Indian Hafnium-free Zirconium Oxide to be exported to America consists of 40 tonnes of nuclear grade Zirconium Oxide, a key material in production of nuclear fuel bundles. In the recent past NFC has already executed three orders from Korea Nuclear Company for supply of zircaloy-4 bars.

NFC has developed the production of pressure tubes by hot extrusion followed by two passes of cold pilgering instead of extrusion and cold drawing. This change has resulted in better recoveries, homogenous microstructure, better ductility coupled with high strength and good roll joints. The mechanical properties were found to be in a narrow band. NFC also achieved the distinction of making very thin walled calandria tubes (D/t ratio of 80 to 90) by the seamless route. The expanded ends of these tubes are more concentric with the rest of the tube as compared to welded tubes. The absence of three distinct zones namely welded, heat affected and unaffected zones is a distinct feature of these tubes. The seamless route of manufacturing process has additional advantages of better material recovery, amenability to ultrasonic and eddy current testing, better roundness, etc.

## 8.0. PLANT AUTOMATION:

Keeping pace with the technological changes taking place in the manufacturing lines, NFC has initiated actions for construction of new fuel manufacturing plants having state-of-the-art technologies in the areas of automation and mechanisation. This has resulted in the construction of New Fuel Plants, likely to be commissioned shortly, having inter-machine and intra-machine automation systems for material movements. Feed-back control of process parameters at various critical stages such as powder production, pelletisation and assembly operations has been successfully incorporated in these plants.

## 9.0. FUEL PERFORMANCE:

Matured over 25 years of fuel fabrication experience, NFC has introduced a number of improvements in the process lines and quality control areas as mentioned in the preceeding paragraphs. This has resulted in significant reduction in the fuel failure rates as compared to the initial periods. More details about fuel performance in Indian PHWRs will be discussed in the subsequent sessions of this Conference.

In order to understand the mode of fuel failure in the reactor, NPC has drawn-up a scheme for detection of failed fuel and subsequently subjecting it to Post Irradiation Examination. This facility established at pool side, consists of specially designed sniffing equipment, sample collection unit and vacuum pump which can confirm the presence of failed fuel bundle qualitatively from a pair of suspected failed fuel bundles (Fig-3). This facility is supplemented to the already existing systems such as DN Scan and Dry Sipping method which are being used in fuel transfer system. After detecting the failed bundle qualitatively it is sent for PIE for further quantitative analysis.

## 10.0. INDIGENOUS RECONSTRUCTION OF RAPS:

Rajasthan Atomic Power Station Unit-I was malfunctioning because of problems in the end-shield as also because of leakage in pressure relief valves. The Unit-II was also under shut down for defects observed in coolant channels which required total replacement and system upgradation. Repair works on both these units required the job to be carried out in totally hostile environment, impossible to approach manually. It is the marvel of the Indian engineers and scientists who have taken up the task of developing technological hardware for the repair operation and sophisticated robots which alone could tackle repairs in the highly radioactive areas in the reactor chamber, that has made the success story. The Unit-I has come back on line and is fully operational, while the work on the replacement of coolant channels of Unit-II is well ahead of schedule. Not only these excellent works are completed at a fractional cost as compared to the global quotations, these technological investments have become permanent assets for India for tackling future radioactive-sensitive repairs.

## 11.0. OTHER ACTIVITIES OF THE DEPARTMENT:

Apart from some of the important mile stones reached by DAE like commissioning of U-233 fuelled research reactor "KAMINI" and pre-commissioning trials of the most sophisticated Indian Fuel Reprocessing plant, the following are the other activities of the Department in specialised fields:

### 11.1. Development of Computer Codes:

A three-dimensional computer code TRIVENI is used to simulate the reactor operation to arrive at the bundle power and burnup. A post processor ITIHAS, further uses the output from TRIVENI to keep up-to-date history of any bundle in the core. Reactor physicists at each station, use the bundle power and burnup values along with fuel defect criteria and fuel rescheduling ground rules to arrive at a channel to be fuelled.

India has participated in the IAEA sponsored Coordinated Research Programme on "Fuel Modelling at Extended burnups" (FUMEX). Out of a total of 19 agencies all over the world, three computer codes were presented from India with code names "PROFESS", "FAIR" and "FUDA" (6). These codes were successfully evaluated for accounting the interdependence of different parameters like fuel pellet temperatures, pellet expansions, fuel-sheath gap heat transfer, sheath strain and stresses, fission gas release and gas pressure, fuel densification, etc.

### 11.2 . Production of Cobalt-60:

Apart from generation of nuclear power, the Department has been working continuously on the production of Cobalt-60 for use in medicine and industry. Over the years NPCIL has evolved various designs of cobalt elements which are being successfully fabricated and supplied by NFC to various reactor sites. The aim of continuous evolution of cobalt pencil designs has been to further simplify the process of fabrication of the pencils and also to easily retrieve the cobalt slugs from the pencils after irradiation.

### 11.3. Dry Storage of Spent Fuel:

In view of the increased quantity of fuel discharged from the reactors at RAPS the need has been felt for the dry storage of spent fuel. One of the strategies employed for management of spent fuel prior to their final disposal / reprocessing is their dry storage in casks, after they have been sufficiently cooled in spent fuel pools. Accordingly, NPCIL in co-ordination with BARC has taken-up interim dry storage of RAPS fuel by taking into consideration suitable limits on maximum burn-up of fuel, minimum cooling period in storage pool and optimum arrangement of fuel bundles in the storage cask from the heat removal point of view (7). Storage is planned in concrete flasks which can be latter opened to transfer fuel to standard fuel shipment flasks for transportation to reprocessing plants.

## 12.0. CONCLUSIONS:

The Department of Atomic Energy, India has achieved indigenous capability in PHWR technology. Nuclear Power Corporation of India Limited (NPCIL)has gained expertise not only in design, construction and operation of PHWRs, but also in reconstruction / repair of reactors. Nuclear Fuel Complex has made strides in introducing innovative process techniques in the manufacturing lines of fuel and zircaloy. NFC has also achieved success in manufacturing all the equipment required for fuel production indigenously. Currently NFC is setting up new fuel / zircaloy fabrication plants having state-of-the-art technologies to meet additional fuel demands, thus adapting itself to the changing needs of fuel technology. R&D Programmes are also in progress for evolving designs for Advanced Fuel Cycles, development of Codes for Fuel Modelling and Spent Fuel Management.

## 13.0. ACKNOWLEDGMENTS:

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## 14.0. REFERENCES:

1. JAYARAJ, R.N. *et al,* "Improved Techniques for Appendage Attachment to PHWR Fuel Elements", Fourth International Conference on CANDU Fuel, October 1-4, 1995, Pembroke, Canada.
2. DAS, M. *et al,* "Fuel Development & Manufacturing Programme in India and Advanced Fuel Designs", Fourth International Conference on CANDU Fuel, October 1-4, 1995, Pembroke, Canada.
3. PURUSHOTHAM, D.S.C. "Experience in Advanced Fuel Fabrication and Developments in Quality Assurance Procedures", WANO Conference, 1994, Bombay, India.
4. BALAKRISHNA, P. *et al,* "Low Temperature Sintering of Thoria", Journal of Materials Science Letters, 160 (1988) 657-660.
5. VYAS, H.P. *et al,* "Development of Advanced Heavy Water Reactor", IAEA-TCM on "Advances in Heavy Water Reactors", Jan 29 - Feb 1, 1996, Bombay, India.
6. SWAMY PRASAD, P. *et al,* Report BARC/1996/E/022.
7. SHIVA KUMAR,V. *et al,* "Spent Fuel Behaviour During Dry Storage - A Review", IAEA Conference on 'Safety & Engineering Aspects of Spent Fuel Storage', IAEA-SM-335-1995.

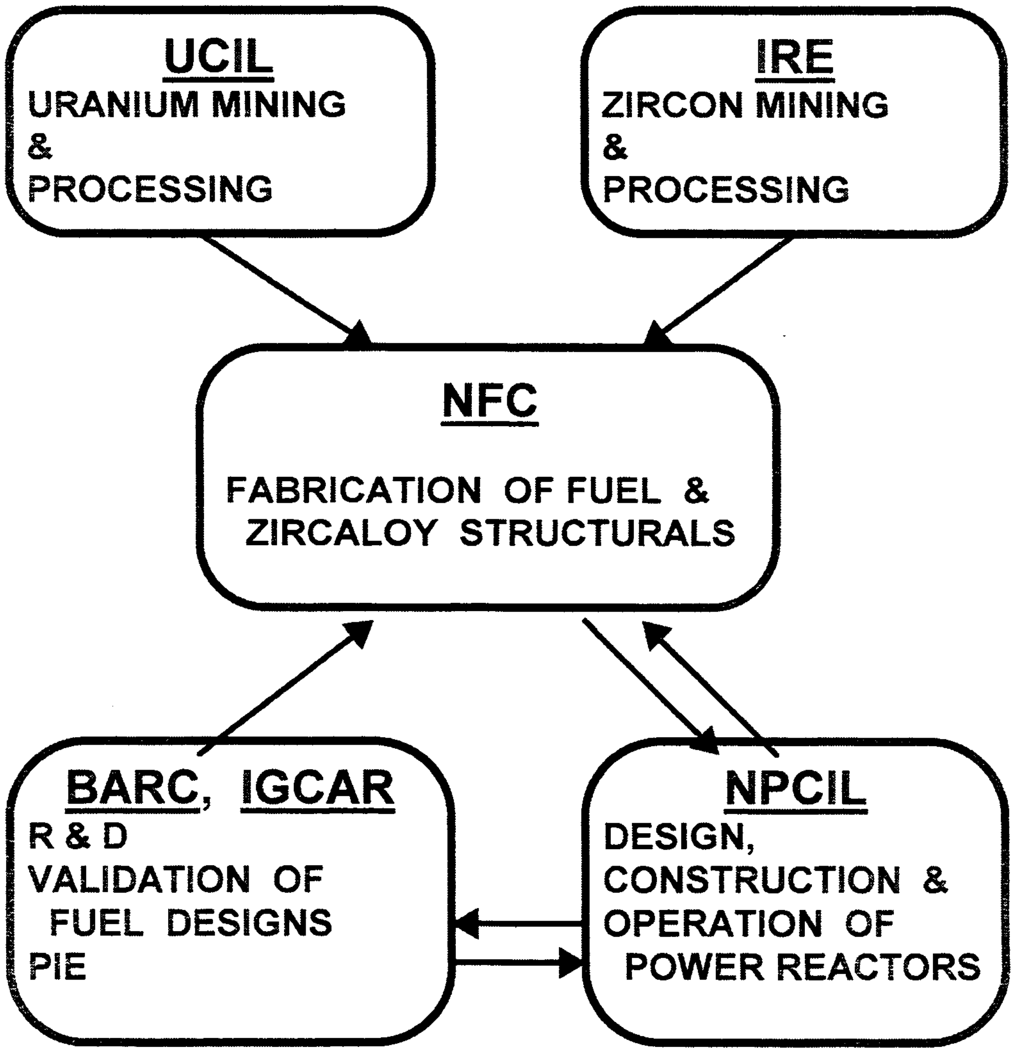
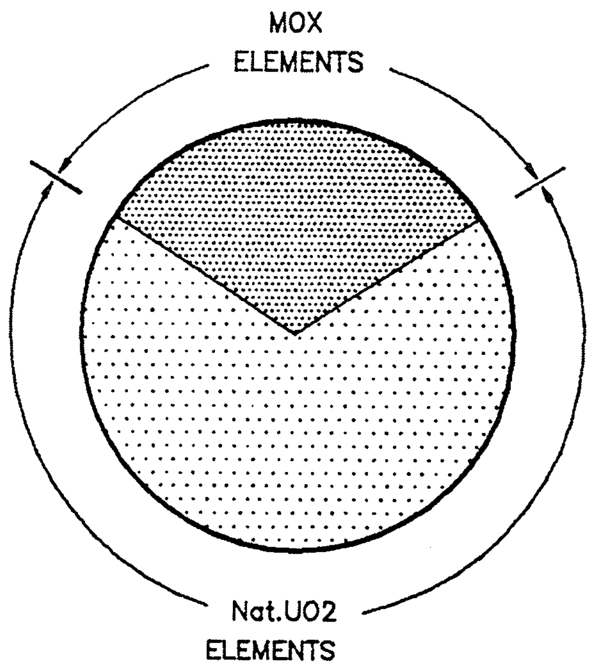
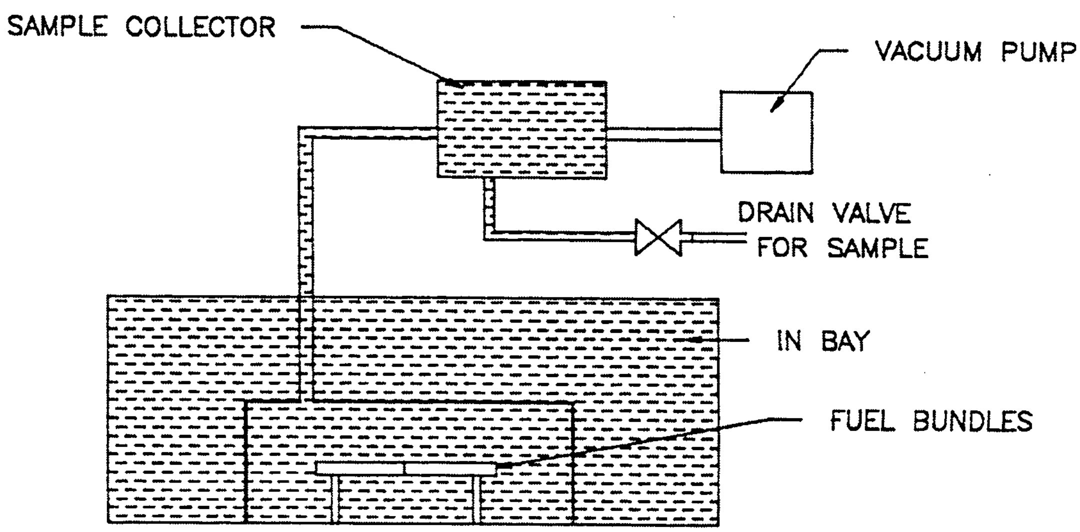



FIG-1: FUEL RELATED FACILITIES IN INDIA




FIG—2: PHWR CORE COMPOSITION
WITH MOX FUEL




FIG—3: SCHEMATIC DIAGRAM OF
FAILED FUEL DETECTION SYSTEM