FABRICATION, CHARACTERISATION, QUALITY COANTROL AND NON-DESTRUCTIVE TESTING OF PHWR FUEL

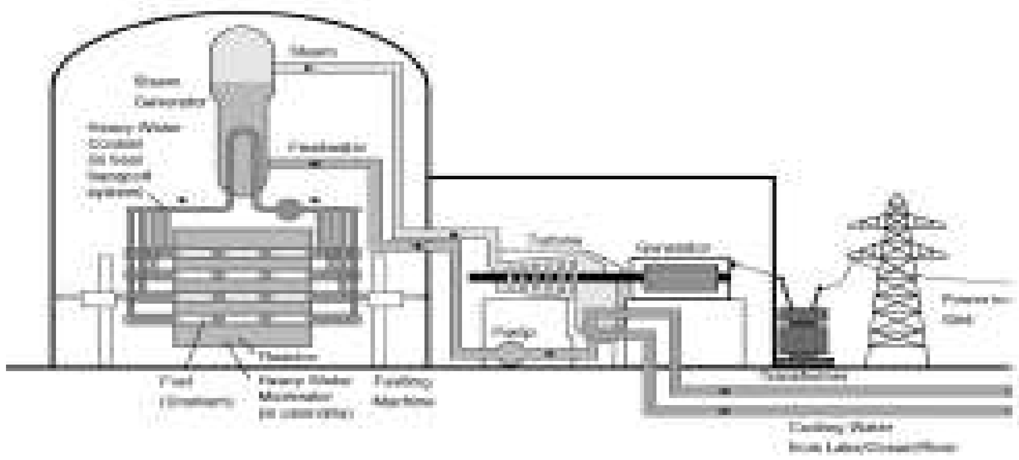
Lecture Notes for workshop
on
"Modelling and Quality Control for Advanced and Innovative Fuel Technologies"
14-25 November 2005
ICTP, Miramare –Trieste, Italy

(G.V.S.Hemantha Rao, Nuclear Fuel Complex, Hyderabad, India)

A. INTRODUCTION:

Since the inception of Nuclear Power Reactors in early 1950s many designs have been conceived. Quite a few of these designs were actually built and a handful have been successful. The types of reactors are distinguished mainly by design of fuel, coolant and moderator. Pressurised Heavy Water Reactor (PHWR) uses natural uranium as fuel, high pressure heavy water as coolant in pressure tubes and low pressure heavy water as moderator. PHWRs have been built in Argentina, Canada, China, India, Pakistan , Romania and South Korea.

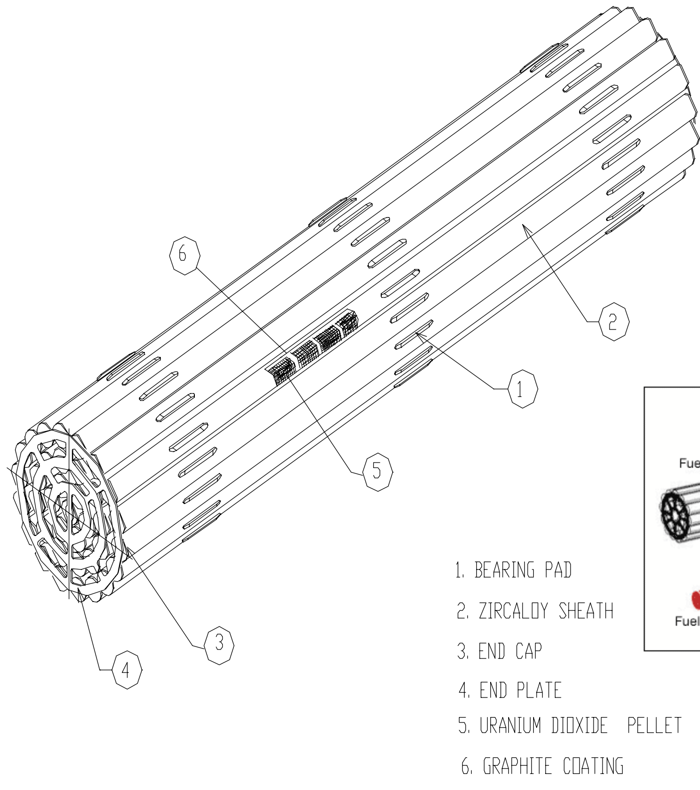
At the heart of the PHWR is the reactor core containing fuel and moderator. Heat generated is transported away by the coolant system to the conventional side of the

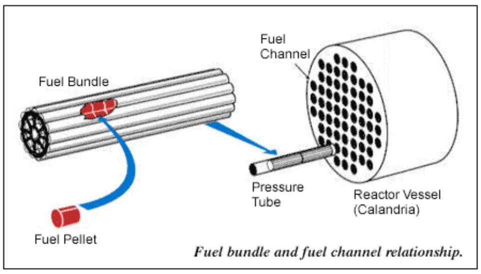


plant (steam generator, turbine and electrical generator). The layered defence-in-depth approaches wherein the radioactive products are kept away from the environment by multiple protection barriers, culminating in the outer containment shell. One of the recognized strengths of PHWRs is the excellent performance of its fuel. The low defect rate of fuel is attributed to the fuel element and bundle design. Equally important factors are the specialized manufacturing process and systems that have been developed to produce fuel within the designed specifications under good quality assurance programme.

B. DESIGN CONSIDERATION FOR FUEL ELEMENT & BUNDLE COMPONENTS AND CHARACTERISATION:

A typical fuel bundle is about half a meter long and consists of a number of cylindrical fuel elements arranged in concentric rings. The elements are held together in a circular geometry by end plates welded at both ends of the fuel elements. Split spacers are provided to give necessary inter-element spacing. Bearing pads are provided to maintain necessary gap between the pressure tube





Fuel bundle and fuel channel relationship.

and the outer fuel elements. A fuel element consists of sintered cylindrical UO_2 pellets contained in a thin zircaloy cladding, which is collapsible under coolant pressure. The element is filled with helium gas at atmospheric pressure and the sheath is sealed at both ends by welding end caps. Inside surface of the cladding is coated with graphite. Each UO_2 pellet is spherically dished at both the ends. The various types of production and development bundles are: 7-element, 19-element (wire wrap and split spacer), 22-element, 28-element, 37-element and 43-element.

Fuel element and bundle components are pellets, sheath, spacers & bearing pads, end caps and end plates.

Material properties and geometric parameters of the fuel pellet are chosen and controlled to

a) Maximize the amount of fissile material present in the fuel element,
b) Minimize the pellet volumetric changes during fuel in-reactor life
c) Ensure that fission gas release is within acceptable limits,
d) Ensure that the pellet design meets the requirements imposed by production capability and economy, and
e) Minimize circumferential ridging of the sheath

A thorough database on material properties is generated by detailed characterisaton of powder and pellet. The characterisaton of PHWR fuel & pellet can be divided into following categories. For establishing a fabrication route, the fuel requires to be characterized for all these aspects. Once the route is established meeting the design requirements, the properties of the material to be evaluated by characterisation are fixed. Some of these are monitored on regular basis to get a consistent quality.

Physico-chemical: Purity, isotopic content, O/U ratio, density, morphology of powder, size & distribution of powder and defects (macro)
Thermo-mechanical: Expansion, conductivity/diffusivity and creep
Metallurgical: Microstructure, size & distribution of pores and shrinkage characteristics

The UO_2 properties that bear the strongest influence on the pellet thermal behaviour are density and oxygen-to-uranium ratio. These characteristics determine the thermal conductivity of the oxide and are maintained with the specified ranges to ensure acceptable UO_2 temperatures and, hence fission gas release. Pellet ends are designed with dishes to accommodate thermal volumetric expansion of the plastic core of the pellet and fission gases. The pellet ends are chamfered on the corners of the flat pellet surfaces to minimize pellet chipping during loading and subsequent element handling. Chamfering also reduces sheath strain at pellet interfaces.

Zircaloy-4 is used for fuel sheath production because of its low neutron absorption. It also has good corrosion resistance and low hydrogen or deuterium pickup performance under severe coolant conditions. Material properties and heat treatments are specified so that the material will retain required ductility at high irradiation levels. The sheathing is designed to collapse into contact with the UO_2 pellets at reactor coolant conditions. The thin sheath provides fission product containment while ensuring minimum neutron absorption and resistance to heat transfer. The as-fabricated diametrical clearance between the UO_2 pellet stack and the sheath is chosen and controlled within in the appropriate range to

a) Prevent the formation of longitudinal ridges in the sheath
b) Facilitate pellet loading during fuel element manufacturing, and
c) Accommodate part of the pellet diametrical expansion and minimize sheath strain.

Before pellet loading, a thin layer of graphite is applied to the inner surface of the fuel sheaths to reduce pellet-sheath interaction. The void within the fuel elements is filled (unpressurized) with a He/air or He/inert gas mixture prior to endcap welding. The presence of helium in the fuel element allows leak detection during fabrication and provides some improvement in the pellet-to sheath heat transfer. Fuel element closure is provided by two end caps that are resistance welded to the ends of the sheath.

The fuel element and bundle are characterized for integrity, susceptibility to handling damage, tolerance to in-reactor thermo-mechanical environment. A number of non-destructive tests are carried out to ensure the suitability of the assembly towards these requirements. The assessment is carried out at cap, appendage and end plate welding stages as described below.

The endcap material is specified and inspected to ensure adequate strength and lack of porosity, which is needed for fission product containment. The weld joint to tube is complete without lack of fusion.

The spacers maintain separation of elements of the bundle at midplane. The spacers are rectangular with an aspect ratio of about 3.5. They are brazed/resistance welded to the sheath with their major axis slightly angled (skewed) with respect to the element axis such that the spacers on any two adjacent elements are skewed in the opposite direction. This skewing decreases the area of possible contact between spacer pairs and decreases the probability of spacer interlocking.

The bearing pads, brazed/resistance welded to the outer element sheaths near the element end and at the midplane support the bundle inside the fuel channel and fuel handling systems. They protect the fuel sheaths from any mechanical damage throughout the fuel bundle lifetime. The pads are profiled to minimize pressure tube surface damage during the in-reactor residence time of a fuel bundle and during refueling operations. The pads must also be designed to minimize local corrosion of the pressure tube.

The endplates hold the fuel elements together in a bundle configuration. They have to be strong enough to maintain the bundle configuration and to allow axial loads to be distributed among many elements rather than being concentrated on a few. Simultaneously, they should be flexible enough to allow differential axial expansion among the elements and to permit bending and skewing of the bundle. The endplates should also be thin to minimize the quantity of neutron absorption material and to minimize axial separation between the fuel pellets in adjacent bundles.

C. FABRICATION:

A typical 37 element fuel bundle and the component details are given below.

37 element PHWR fuel bundle

ONE FUEL BUNDLE CONTAINS

FUEL TUBES	485.80 1 X 13.08 od X 0.4 t	37 Nos
END CAPS	13.24 od X 5.3 t	74 Nos
SPACER PADS	8.6 1 X 2.5 w X 0.82 t	144 Nos
	8.6 1 X 2.5 w X 3.17 t	12 Nos
BEARING PADS	33.00 1 X 2.5 w X 1.22 t	36 Nos
	33.00 1 X 2.5 w X 0.94 t	18 Nos
END PLATES	90.98 od X 1.63 t	2 Nos

NATURAL URANIUM DIOXIDE

PELLETS	12.2 od X 14.00 1	1295 Nos
WEIGHT OF PELLETS		21 Kg

TYPICAL 700 MWe PHWR CORE CONTAINS

FUEL ASSEMBLY	5096 Nos
URANIUM DIOXIDE	107 Te
FUEL ASSEMBLY WELD JOINTS	31,49,328

The flow sheet followed for the production of natural UO2 powder pellets and final assembling of PHWR bundles are shown in the following figures.

Nat UO2 Powder

- Precompaction
- Granulation
- Admixing of Lubricant
- Final Compaction

↓

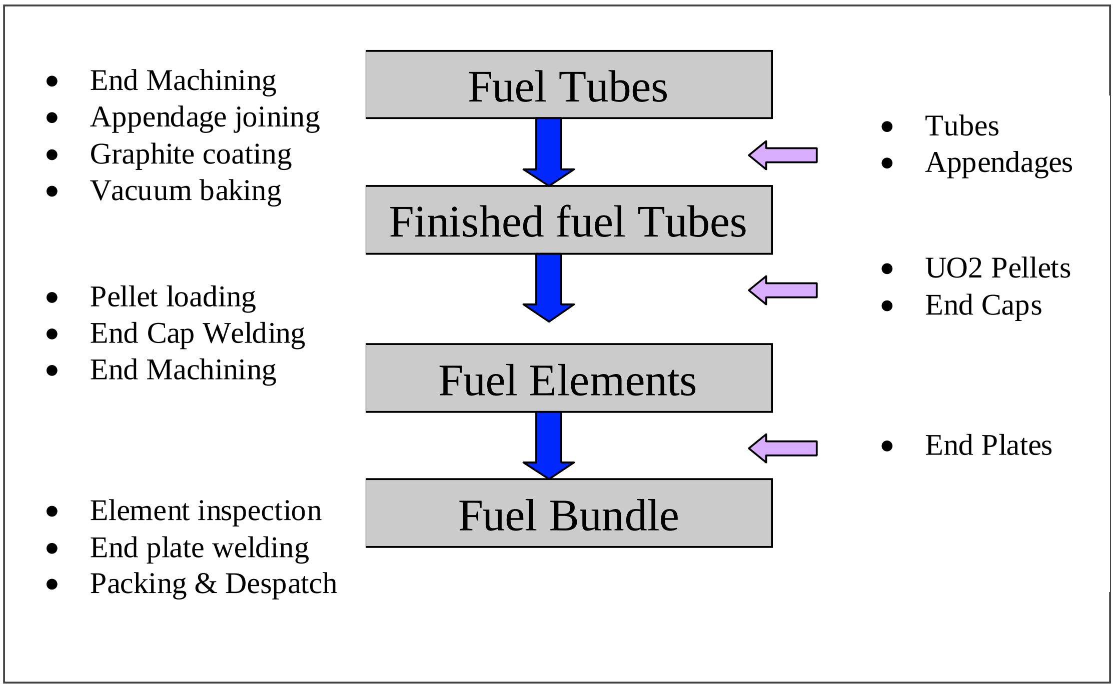
Green Pellet

- Sintering
- Grinding
- Washing
- Stacking

↓

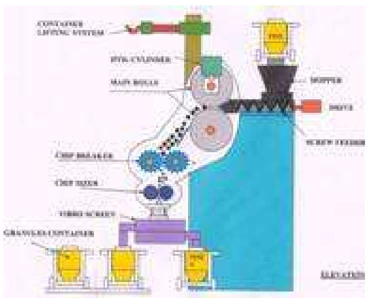
Finished Pellet

Starting with Magnesium di-uranate (MDU), Ammonium di-uranate is produced through a series of chemical operations like HNO_3 dissolution, solvent extraction and addition of ammonium hydroxide and precipitation. By further steps of calcination, hydrogen reduction and stabilization, nuclear grade uranium di-oxide powder is produced. By following standard powder metallurgy techniques, involving pre-compaction, granulation, final compaction and sintering the green pellets at high temperature (about 1700^{0}C) in hydrogen atmosphere, high density UO_2 pellets are produced.



The basic flow-sheet in assembly shop involves end preparation of fuel tubes by carrying out end machining and joining of spacers and bearing pads (appendages). A special operation – graphite coating of inner surface of fuel tube followed by vacuum backing is carried out for PHWR fuel to mitigate Pellet-Clad Mechanical and Chemical Interaction. The centreless ground UO_2 pellets are then loaded into the fuel tubes and the loaded tubes are filled with helium and resistance welded at both ends with zircaloy end caps to obtain fuel elements. Welded elements are machined to correct length, get specific profile to end cap and remove radial weld flash. Such thirty seven fuel elements of specified configuration are assembled and joined together by welding them onto end plates at either end to form an integral fuel bundle for PHWRs.

1. Nat.UO2 Pellet fabrication:



Qualified powder lots are taken for production. Pre-compaction is done in hydraulic press/Roll compacting press. The compact is broken in granulator (in hydraulic press) / chip breaker (in Roll compactor). The product is screened in the Vibro-screen. The +60# / -100# fraction is collected and admixed with solid lubricant by blending. The -60# / +100# fraction is collected in a separate container and recycled in the press.

The blended powder is poured in a special conical container attached to the final compacting press for facilitating automatic transfer of powder to the dies via feed shoe. The press is either a multi cavity hydraulic press or a rotary press. The powder is pressed into pellets to obtain a green density in the range of 5.5 to 5.9 gm/cc.

Sintering of UO_2 green pellets is done under reducing atmosphere at high temperature to attain specified high density pellets with required O/U ratio. The furnace is operated with a desired temperature profile for gradual heating of the charge, soaking at sintering temperature of 1650-1720^{o} C for a predetermined period and cooling of the charge before its exit from the furnace. The sintering atmosphere is cracked ammonia or pure Hydrogen. The charge is prepared by assembling moly sheets loaded with pellets vertically, keeping one sheet above the other using moly spacers. Here, the stack over the thick moly base plate is covered by a moly shroud. The charge thus prepared is pushed into the furnace at regular intervals. Each time, a charge is pushed inside, a charge is discharged from cooling end of the furnace.

QC cleared sintered pellets are taken for centreless grinding operation. Grinding is done to get uniform diameter. The grinding operating is either dry or wet. After grinding these pellets are washed online with hot D.M.Water (around 80^{o} C) and dried around 150^{o} C. The pellets are automatically arranged in rod trays.

The ground, washed and dried pellets from centreless grinder are inspected for visual defects. After inspection, accepted pellets are kept in the same tray. These trays are taken for stacking operation. Pellets are stacked to specified length. After stacking, these trays are cleaned ultrasonically in D.M.Water and passed through a drying unit (around 150^{o} C) to remove moisture from the pellets.

2. Zircaloy-4 tube preparation:

Zircaloy blank tubes are machined at both the ends on a special purpose machine. This operation is carried out to provide 60^{0} chamfer at both OD & ID and to get specified length. The chamfer should be within 0.10 mm and machined tube length should be within 0.10 mm.

Machined tubes are received for joining spacer / bearing pads after cleaning. Either resistance welding technique or brazing is used to join spacers on the machined tubes as per predefined configuration to make five types of elements for 37 element PHWR fuel bundle. Spacers are joined on each tube at a helix angle of 15^{o} with respect to the axis of tube in a predefined orientation. To make outer elements curved bearing pads are joined on empty tube by

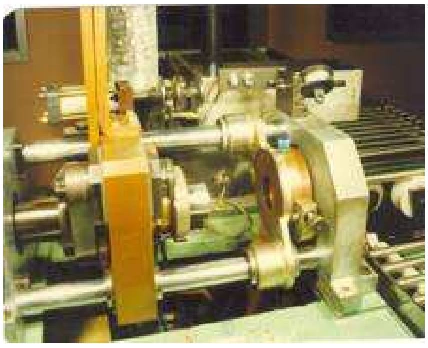
brazing/resistance welding technique. Curved bearing pads are joined only on those tubes on which three / four spacers are already joined at the centre, as per predefined configuration. For carrying out brazing the spacers and bearing pads are coated with beryllium and initially tack welded for positioning before brazing. For resistance welding, the spacers and bearing pads are provided with projections.

After spacer pad and bearing pad joining operations on empty tubes graphite coating operation is carried out. Thin layer (3 to 8 micron meters) of graphite is coated on the inner surface of the tubes. Both the ends are kept uncoated up to approximately 5mm.

Graphite Coated Tubes are pre-dried at about 120°C before baking to remove traces of alcohol. These tubes are finally baked in a vacuum oven at a vacuum level of 10^{-4}m bar or better and 350ºC for three hours.

3. Fuel element fabrication:

Stacked pellets are loaded in zircaloy tubes and weights are taken and noted on the loading sheets for each tray. The tray is routed with an element card which contains details about lot no., tare weight, and net weight of UO_2.



The loaded tubes are endclosed at both the ends with end caps by resistance welding. The purpose of this operation is to hermetically seal appendage welded loaded tubes at both the ends under helium atmosphere. Special purpose resistance-welding machine is used to weld end caps at both the ends of loaded tubes. The loaded tube is transferred into welding chamber. End caps are positioned at the end with pneumatic squeeze force. Helium is filled and welding is carried out by passing low voltage, high current under helium gas atmosphere. Additional electromagnetic force can be superimposed while welding.

End cap welded elements will have variable length and radial upset. These elements are machined at both the ends to remove radial upset, provide conical profile and achieve specified length. The specified length and profile are required for welding of end plate to the element. This profile increases the current density during end plate welding.

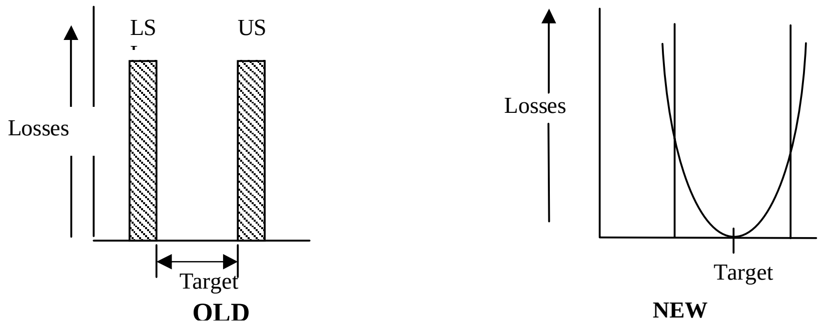
4. Bundle assembly:

One central, six inner I, twelve inner II, six outer I and twelve outer II elements are welded with end plates at both the ends using resistance welding technique to make 37 element PHWR fuel bundle. Specially designed jigs and fixtures are used for keeping the element in specific orientation and position.

Each fuel bundle which is cleared after final visual inspection contains a QC clear tag. The tag contains fuel bundle number with date and signature of QC inspector. All the QC cleared and QS cleared bundles are sleeved in a polythene tube / wrapped in a paper and packed in a packing box. A typical packing box is made of sheet steel. Fuel bundles are placed in preformed thermocole sheets kept in the box.

D. QUALITY CONTROL:

Production is what we count; quality is what we count on. Quality has been synonymous with nuclear fuel production right from the inception as the cost of failure is very high when compared to cost of attaining quality. However the role of the quality and means to attain it has been dynamic. In the past, emphasis was laid on product. Process was considered stable and good as long as components produced "conformed to specification". Quality was attained essentially through inspection. This approach could not predict process deterioration and often led to large number of rejects and reworks. Changes in the market conditions and economic factors have lead to paradigm shift in manufacturing philosophy. The new philosophy emphasis that manufacturing costs can be lowered if the deviations during manufacturing are minimal from the process target-that is, by centering the process around the target / mean. .



The changing economic scenario and market conditions have been pressurising various fuel manufacturer's to attain "Zero defects" during manufacturing. This has led to adoption of newer quality strategies like "Total Quality Management" and "Six Sigma" by fuel manufacturers through out the world. These strategies emphasise involvement of every individual in the organisation for quality improvement. In simple words, quality becomes everybody's job. They also emphasise on application of statistics to study the process behaviour and trends so as to predict and prevent defect occurrence.

The quality systems consists all those activities that are essential for an organisation to attain quality related objectives. Quality related activities are broadly classified into System related activities and Product related activities. For effective functioning it is essential that both system and product related activities are complementary and mutually supporting.

System related activities provide necessary administrative framework for quality related activities in an organisation. These involve preparation, implementation and control of various procedures like design, development, documentation, external and internal quality audits, customer feedback etc. These activities provide assurance, that all measures essential for attaining quality are intact and effective.

Product related activities / Quality Control cover all those activities that are essential for maintaining and improving the product quality. These activities can be broadly classified as Offline Quality Control and Online Quality Control.

Off line quality control involves ‘planning for quality’ – deciding when, what, who, where and how to inspect / test and the supporting infrastructure, resources including human. In a nutshell, all that proceeds before actual QC / Inspection. Off line quality control activities are those that are undertaken to make manufacturing process robust enough so that it can withstand fluctuations in the input conditions without affecting the product quality. Off line quality control involves determining optimum process parameters that are required to attain desired quality levels. Designed experiments are carried out to determine optimum process parameters. Process capability (Cp) studies are carried for determining the ability of a process to produce goods of desired quality. Production is allowed to carry out only after Cp attains a value of 1.67. Apart from the process optimisation, it is also essential to qualify men carrying out production and inspection to ensure quality. Operators are subjected to various qualification tests depending on the job. Example welders are subjected to qualification and inspectors carrying out non – destructive evaluation are trained in their field through the courses conducted by ASNT or ISNT.

Whereas online quality control activities are those that are traditional quality related operations like, inspection, statistical quality control and documentation. These operations are carried out encompassing all operations during pellet production and fuel assembly.

1. Pellet Production

PHWR fuel pellets are characterised by high sintered density (95–98 % of theoretical density) and chemical purity. Quality control operations commence with incoming material inspection viz. Uranium Oxide powder, consumables like lubricants, dies, plungers and sleeves. Uranium oxide powder is subjected to various tests to determine its physical and chemical characteristics. Physical attributes like surface area, O/U ratio, particle size and morphology play a significant role in attainment of sintered density. The powder is taken up for production if it meets acceptance criteria with respect to physical and chemical attributes.

Uranium oxide powder from a new source is subjected to an additional test viz. sinterability test. It involves production of small quantity of pellets from representative sample of UO_2. The test is carried out to ensure that desired sintered densities and high recoveries are obtained under normal pelletising operation. During production process control is carried out at pre-compaction, final compaction, sintering and grinding operations.

The determination of metallic impurities in fuel is usually carried out by ICP-AES and AAS after removal of matrix by the usual solvent extraction step.While the determination of the non-metallic impurities such as F and Cl are carried out by potentiometry, N is carried out by spectrophotometry after the separation by Kjeldahl distillation. The determination of O/U atomic ratio in pellets is carried out by spectrophotometry which involves the dissolution of crushed sample pellet in a non-oxidising dil. Sulphuric acid medium containing a few drops of HF on a water bath and under inert atmosphere. The absorbance measurement is carried out at 285 nm and 535 nm where hexavalent and tetravalent uranium absorb respectively. The isotopic assay of fuel is determined by Mass spectrometry. The sample after dissolution is converted to ions by thermal ionization method using TIMS. The ions are then subjected to a magnetic field where it gets dispersed according to its mass to charged ratio. The ion intensity is directly proportional to concentration.

Table below gives the list of tests that are carried out at each of these stages.

Operation	Tests.	Controls
Pre-compaction	Granule bulk density and flowability.	Control charts
Blending	Lubricant purity & Homogeneity test	Sampling
Final Compaction	Die sets	100 % inspection
	Parameter monitoring	Sampling
	Green density and Physical integrity	Control charts
Sintering	Parameter monitoring	Conformance to limits /Range
	Sintered density	Sampling
	Microstructure	Sampling
Grinding	Metrology checks	Control charts
Stacking & Loading	Moisture content, Chemical purity	Conformance to limits.
	Stack length, Stack weight	Control charts

Sintered pellets are subjected to density evaluation, metallography and purity analysis on sampling basis for each batch. The density measurement is done either by geometric or hydrostatic means. Metallographic evaluation is carried out to determine grain size, inhomogeniety in matrix and tear outs.

Pellets that meet these criteria are ground to desired size. The ground pellets are subjected to visual inspection to remove pellets with surface defects. Pellets may be subjected to 100 % visual inspection or cleared by acceptance sampling depending on process average and customer requirements. Accepted pellets are stacked and loaded into zircaloy tubes. At this stage moisture content, stack weight and stack length measurements are carried out on sampling basis. The determination of Hydrogen in UO_2 pellet is carried out by inert gas hot extraction method. The sample is heated at about 2000° C and evolved gases are passed through the preliminary chemical traps and the hydrogen is measured by Gas Chromatograph using thermal conductivity cell.

The latest trends in quality control during pelletising include assessment of green compacts by UT, application of lasers for gauging & measurements and application of machine vision systems for inspection of finished pellets.

2. Tube preparation

Table below gives the list of quality control operations carried out during the tube preparation stages.

Operations	Tests	Controls
Tube machining	Length & chamfer measurement	Control charts
Spacer Pad & Bearing pad welding	Machine & operator qualification Set up trials Parameter monitoring Shear strength testing	MIL –6858 – D & ASTM Control Charts
Graphite coating	Purity and specific gravity Weight gain, adherence, wear, Hydrogen content, Coating thickness	Acceptance sampling
Surface and metrology checks	Visual and metrology	100 % inspection.

Zircaloy tubes are machined to desired length. The ends of the tubes are provided with a profile so as to facilitate end closure welding operation. Machine is cleared for production after checking the initial setup of tubes machined at the start of the day.

Spacer pads and bearing pads are joined on these machined tubes by using resistance welding / beryllium brazing. Stringent quality checks are carried out at this stage. All the components like bearing pads and spacer pads are subjected to sampling inspection.

For resistance welding operations set-up trials are taken on the machine everyday before commencing production. Welds are subjected to visual examination and subsequently shear strength is evaluated. Production is allowed, if the trial welds are free from defects like sparking, metal flow etc and weld strength meets prescribed values of mean and standard deviation. During production, weld parameters like current, squeeze force, resistance are monitored by data acquisition system. Control charts are used to monitor the trends. For brazing operations, the adherence is checked by metallographic examination and strict process control is adopted during the process

After joining spacer and bearing pads, the inner surfaces of the tubes are coated with graphite. Quality checks involve checking of purity and specific gravity of graphite suspension. Coated and baked tubes are tested on sampling basis for graphite adherence, wear resistance, coating thickness and Hydrogen content. These tubes are subjected to 100 % inspection for length, inner diameter and surface defects prior to loading.

The latest trends involve application of lasers and vision system for measurement of tube length, evaluating tube chamfer and inspection of spacer and bearing pads. Studies are being carried out to develop non-destructive methods for weld strength evaluation. Acoustic emission and ultrasonic testing using lamb waves hold lot of promise in this direction.

3. Element and Assembly operations:

Table below gives the quality control operations and the tests carried out during element and assembly operations.

Operation	Tests	Controls
End closure welding	Machine and operator qualification Set up trials Parameter monitoring Ultrasonic testing, Metallography, Helium and Hydrogen content.	MIL –6858 – D & ASTM Acceptance sampling. Acceptance sampling.
Ends machining	Set up trials Metrology checks Helium leak testing and Visual inspection,	 Acceptance sampling. 100 %. inspection
Bundle assembly	Machine and operator qualification Set up trials Parameter monitoring Torque strength testing	MIL –6858 – D & ASTM Control Charts
Final inspection of Bundles	Metrology checks, weight, Helium leak testing and visual inspection	100 %. inspection

End closure welding is the most critical operation in PHWR fuel fabrication process. Apart from covering a circumference of around 45 mm, the welds experience thermal stresses due to expansion of pellet stack. Quality checks commence with set-up trials on each machine prior to production everyday. The set up welds are subjected to visual examination and the weld quality is assessed by Ultrasonic testing, followed by metallographic evaluation. Helium that is used as cover gas in fuel element is subjected to purity test. End caps are subjected to visual inspection. Production is allowed to commence, if there are no visual defects and weld fusion values are within the limits. The fusion values are calculated by the formula: % of fusion = (Projected weld length / Nominal tube wall thickness) X 100.

During regular production, parameters like weld current, voltage, frequency dynamic resistance, weld upset are continuously monitored through data acquisition system. If any of the parameters deviate from pre-set operation band, the production is stopped. Welds are sampled at periodic intervals for ultrasonic evaluation. The fuel elements produced are tested for Helium content and Hydrogen content on sampling basis. Acoustic emission and thermography based techniques are being developed for evaluating weld quality. The determination of helium content of the fuel element is carried out by puncturing the fuel element under vacuum (less than 100 micron) and the evolved gas is collected and passed through a Gas Chromatograph which gives the impurity as oxygen and nitrogen and the difference is arrived as helium content. The determination of moisture content in helium gas is carried out by puncturing another fuel element under vacuum and evolved moisture is estimated by low pressure manometric method.

Inspection of the pre-formed tool bit forms the first step in the sequence of quality control checks that are performed during welded element machining stage. Every day prior commencement of production set up samples are taken. These include checking of length and profile as specified in drawing. During production control charts are used for various controlling various dimensions. Machined fuel elements produced are subjected to 100 % visual inspection followed by Helium back filling and leak testing. The accepted fuel elements are released for bundle assembly.

Quality checks at bundle assembly operations commence with 100 % inspection of jigs and fixtures used during bundle assembly operations. Every day prior to commencement of production set up samples are taken. These include checking for torque strength of the welds. The production is allowed to commence only if weld strength meets pre-set average and standard deviation.

Final inspection of fuel bundles involves carrying out metrology checks, helium leak testing and visual inspection. Fuel bundles are checked for height, weight, diameter, inter element spacing and their flexibility to pass through a kinked tube. Fuel bundles are also subjected to Helium leak testing after backfilling with helium. The bundles are accepted if the leak rate is lesser than a specified value. Finally, fuel bundles are subjected to visual inspection, for checking any surface defects and inter element spacers. Latest trends involve application of special purpose inspection systems using lasers and displacement transducers for metrology checks.

4. Documentation:

Documentation is essential for trend analysis and for correlating fuel performance with manufacturing conditions. The test reports at each inspection station are fed into the respective terminals. The data generated is transferred to main system to generate "integrated quality data management system". The quality data management system provides assurance to the customer that all the stated and implied actions are taken at various stages of fuel manufacture to ensure quality.

Analysis & Improvement:

Improvement and innovation are the need of the day to survive in business. Measurement of current quality level is the first step for improvement. Conventional indices like scrap rate, first pass yield indicate the percentage of non-conformance with respect to specifications. They do not take into consideration the shift in process mean. Farther, the process mean from the target value, higher the losses. These losses can be customer dissatisfaction, warranty costs etc. Capability indices, like Capability potential index (Cp) and Capability performance index (Cpk) take into consideration shift in the process means and are better quality performance indicators.

Choice of the quality improvement strategy depends on the existing quality level. When quality level is high, continual improvement can be attained easily by using simple tools. Cause and effect analysis is used for identifying causes for poor quality. Pareto analysis is used for prioritising the causes. The root cause could be in any of the 4 M's viz. Men, Machine, Methods or Materials. Solving the root cause and monitoring the quality by using control charts help in sustaining the improved quality levels.

Break through strategies are adopted to attain quantum jumps. These strategies advocate determination of relationship between customer's requirements and product characteristics. Evaluation of product characteristics are made and critical to quality characteristics (CTQs) are identified using Pareto analysis. Alternatively, Failure Mode Effect and Criticality Analysis (FMECA) can be used to identify CTQs. Suitable metric is defined for measurement of these CTQs. The improvements can be attained by providing innovative solutions for quality improvements. These innovations can be either in the product design or process or material. Once the breakthrough improvement is attained, it is sustained by using above mentioned simple tools.

E. NON-DESTRUCTIVE TESTING:

It is mandatory to maintain highest quality level during fuel fabrication. A wide variety of testing methods are employed so as to ensure that the desired levels of quality are met. Several destructive and non-destructive testing techniques are employed during various stages of production and on finished products. Different NDT methods employed are Ultrasonic Testing (UT), Radiographic Testing (RT), Helium Leak Testing (HLT), Gamma scanning, Eddy current Testing (ET), Penetrant Testing (PT) and Visual Testing (VT).

1. Zirconium alloy products: Products in the form of tubes, sheets and bars of different sizes are required for PHWR & BWR fuel fabrication. The operations involved are melting and casting of ingots, hot extrusion, cold pilgering for seamless tubes, swaging for bar stock, hot & cold rolling for sheet and intermittent vacuum annealing. Due to the critical role played by these products, higher degree of confidence is essential regarding their integrity and properties during manufacture. Selection of right NDT technique is essential based on the design requirement of final product. NDT techniques employed on different zircaloy products are given below.

Product	NDT Technique	Type of defects detected
Ingot/billet/slab	VT, UT	Shrinkage, cavity, blow holes, folds, laminations
Fuel tube	VT, UT	Cracks, folds, dents & dimensional variations
Rods	VT, UT, ET	Piping, laminations, folds, cracks, centre bursts
Sheet	VT, UT	Cracks, surface defects, laminations

UT standard for 150 mm diameter machined billet is 1.5 mm diameter FBH and 12.5 mm radial depth. The technique employed is pulse echo contact method. The test is carried out as per ASME-E-114 with longitudinal beam transducer of 4 MHz with suitable couplant. For fuel tubes, 'V' notches of 10% wall thickness (0.038 mm depth X 0.75mm long in longitudinal direction and 0.038 mm depth X 0.37 mm long in transverse direction) are used. High speed computerized UT machine is used for testing of fuel tubes. The technique employed is angle beam pulse echo and the probe (rotating) is a line focus of EBW 3 mm and operates at a frequency of 15 MHz.

The sizes of the zircaloy sheet for various fuel components are: thickness 0.8-1.7 mm, width 10-100 mm and length 200-800 mm. These sheets are tested by UT. The longitudinal and transverse reference notch standard is 3% of thickness x 12.5 mm long x 1.6 mm wide. The technique employed is angle beam immersion type and the probe used is 12.5 mm diameter flat probe of 4 MHz.

.

Zirconium alloy bars are produced by hot extrusion and multiple swaging to get finished size. The diameter of the bar is 13.5 mm. The UT reference standards are 0.04mm deep X 1 mm long & 0.083 mm deep X 1 mm long for longitudinal and 0.2

mm diameter X 12 mm long centre & off center hole are used. The type of probe used is line focus 10/15 MHz. Eddy current testing is also employed for detecting the surface / near surface defects. Eddy current probe of frequency 28 KHz is used for this purpose. The reference standard is 0.2 / 0.3 mm diameter radial hole X 3 mm deep.

2. PHWR fuel production: In addition to various tests carried out during fuel fabrication, non-destructive testing occupies a special place as they facilitate 100% online and offline assessment of the product. NDT techniques employed during fuel fabrication are given below.

Product	NDT Technique	Type of defects detected
PHWR		
Pellet	VT	Cracks, pits, end-capping, chips
Fuel tubes	VT	Visual defects and end chamfer
End cap weld	UT	Fusion, internal sparking
Fuel element	HLT,VT	Integrity of weld, visual defects, dimensional
Fuel bundle	HLT,VT	Integrity of bundle, visual defects, dimensional
BWR		
End cap weld	RT	Porosity, non-fusion, inclusions
Fuel element	HLT,VT	Weld integrity, visual defects, dimensional
Fuel assembly	VT	Integrity of bundle, visual defects, dimensional
Tie plates	PT, RT	Cracks, shrinkages, inclusions, porosities
Spacer s	VT, PT	Cracks, pitting, deep scratches

UO_2 pellets are subjected to 100% visual inspection for various surface defects like cracks, chips, end-capping and pits. To minimize the operator strain, vision based system is also used. The system consists of a light source, camera, photo grabbing system and a computer. Software is written for identifying different types of defects.

Visual inspection of end chamfer of tube and possible defects in the inner side of the tube occurring during spacer and bearing pad welding is carried out on sampling basis. In case of doubt for carrying out 100% inspection, vision based systems are also developed. The system is also similar to pellet inspection system.

End closure weld of PHWR fuel element is critical and the process control of the welding operation is generally carried out by metallographic evaluation of setup welds. Due to its complex shape and dimensions, evaluation by RT like in BWR is not possible due to sensitivity limitations. In the recent past pulse-echo immersion type UT method is being adopted. A typical system uses 0.2 mm spot focused probe of 30 MHz. A motorized system provides both rotary and linear movement of the fuel element thereby subjecting the entire weld area. Defects are characterized based on the signal shape and amplitude. Calibration is carried out using a natural standard of leaky fuel element and fuel element with 0.04 mm deep, 60^0 'V' notch on ID and OD of the fuel tube.

In order to ensure leak tightness of the fuel elements, mass spectrometer based Helium Leak detectors operating on contra flow principle are adopted. Fuel elements are tested for leaks by pressure vacuum testing, as per ASME section 5, article 10. Fuel elements are kept in a chamber which is connected to the detector. The leak rate specified is 1x 10^{-8} STD cc /Sec. All the operations are controlled through a computer which maintains a database and gives reports in desired format. Fuel bundles are also subjected to HLT just before final QC clearance.

3. BWR fuel production: The BWR fuel is a mechanical assembly of 36 fuel elements of four meter long approximately. These are arranged in a 6x 6 matrix. The NDT techniques carried out are VT of UO2 pellets, elements and assemblies, RT of the end cap welds, gamma scanning and HLT of fuel elements. TIG welded end closure welds of BWR fuel elements are subjected to RT to ensure their soundness. The radiography of these welds is quite complex as the ratio of the wall thickness to the diameter of the tube including the weld bead is very less, restricting the sensitivity limit. Double wall, double image technique with zirconium alloy correction block is used to get a radiographic sensitivity of 1.4% Radiographic exposure is carried out at three different positions, each 120 degree apart. As a supplement to RT, evaluation by UT is generally practiced. In BWR fuel assembly three different U^{235} enrichments 1.6%, 2.1% and 2.66% are used. The fuel design requires that all the fuel pellets in a fuel element must be of same enrichment. The amount of gamma radiation emitted by the fuel pellets depends on its enrichment level and this forms the principle for operation of gamma scanner. Entire fuel element is scanned with a computerized gamma scanner. The scanner consists of Thallium activated NaI crystal based scintillation counter.

.