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

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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.**

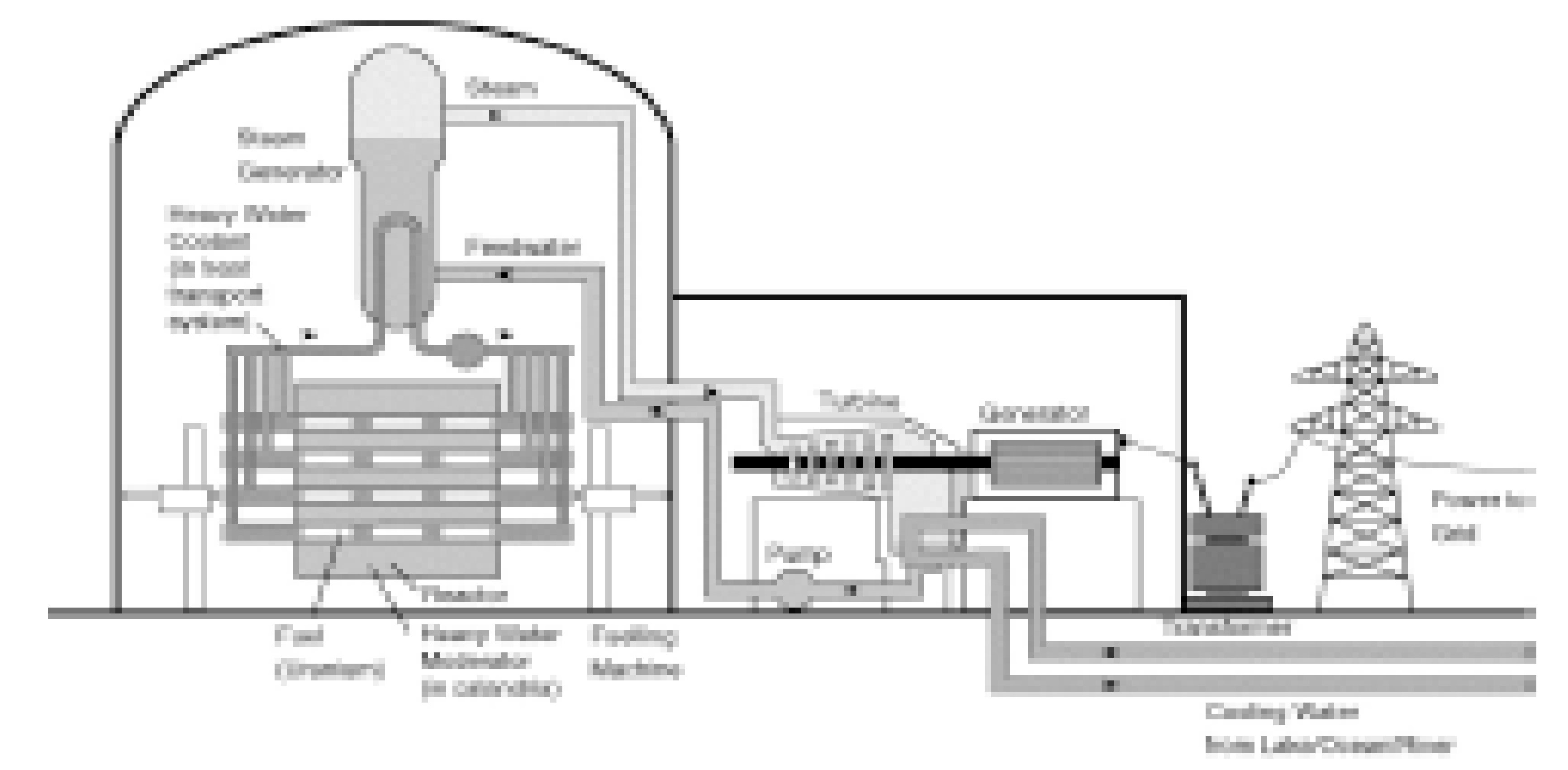
- **The types of reactors are distinguished by major designs of fuel, coolant and moderator.**

- **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.

PHWR - schematic

- 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).

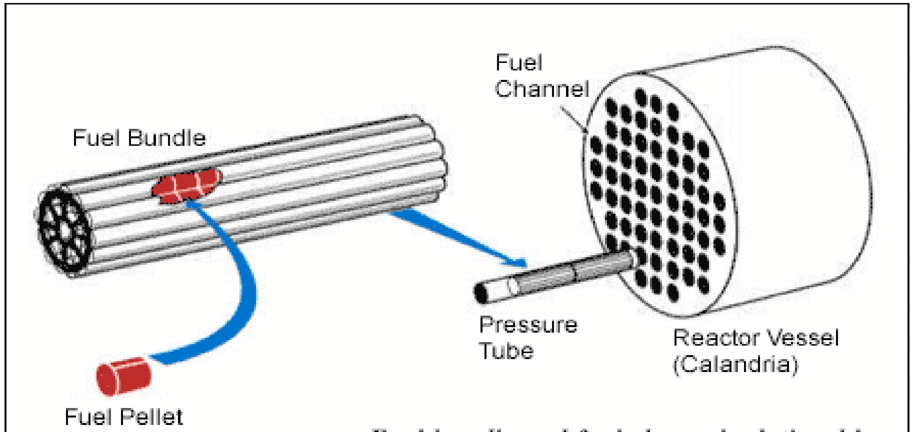


Strength of PHWR

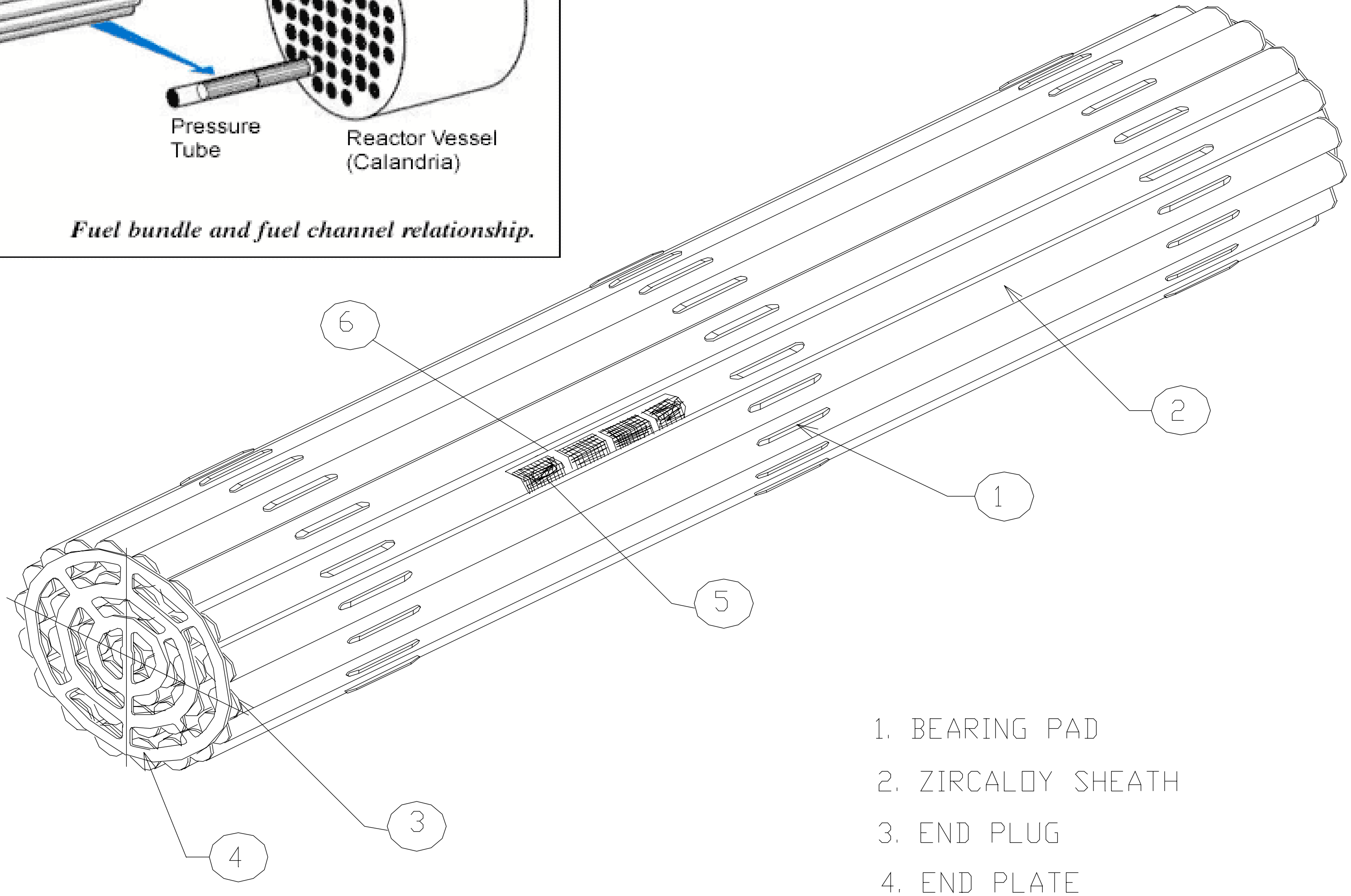
- One of the recognized strengths of PHWRs is the excellent performance of its fuel.

- 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.



Fuel bundle and fuel channel relationship.



1. BEARING PAD
2. ZIRCALOY SHEATH
3. END PLUG
4. END PLATE
5. URANIUM DIOXIDE PELLET
6. GRAPHITE COATING

Fuel bundle duty & environment

- Designed to generate heat as per the overall core design
- Must be able to withstand the power output of the reactor (quantified by bundle power vs burnup)
- Designed with sufficient strength to allow on power refueling and the fuel handling conditions
- Fuel bundle is contained coolant channels of nominal ID 103.6 mm

- **The coolant for primary system is Heavy water maintained at pH between 10.0 and 10.4**
- **Design flow in maximum rated channel is 26 Kg/sec equivalent to an average flow velocity of 9.35 m/sec**
- **The nominal coolant inlet temperature is 260 ^{0}C And the outlet temperature is 312 ^{0}C at an outlet header pressure of 115kg/cm^{2}**
- **Fuel element design provides sufficient strength to fuel element to contain the radioactive fission products during normal reactor operations**

Bundle power envelopes

- During the life of the bundle, its material constituents as well as interacting neutron flux values changes due to:

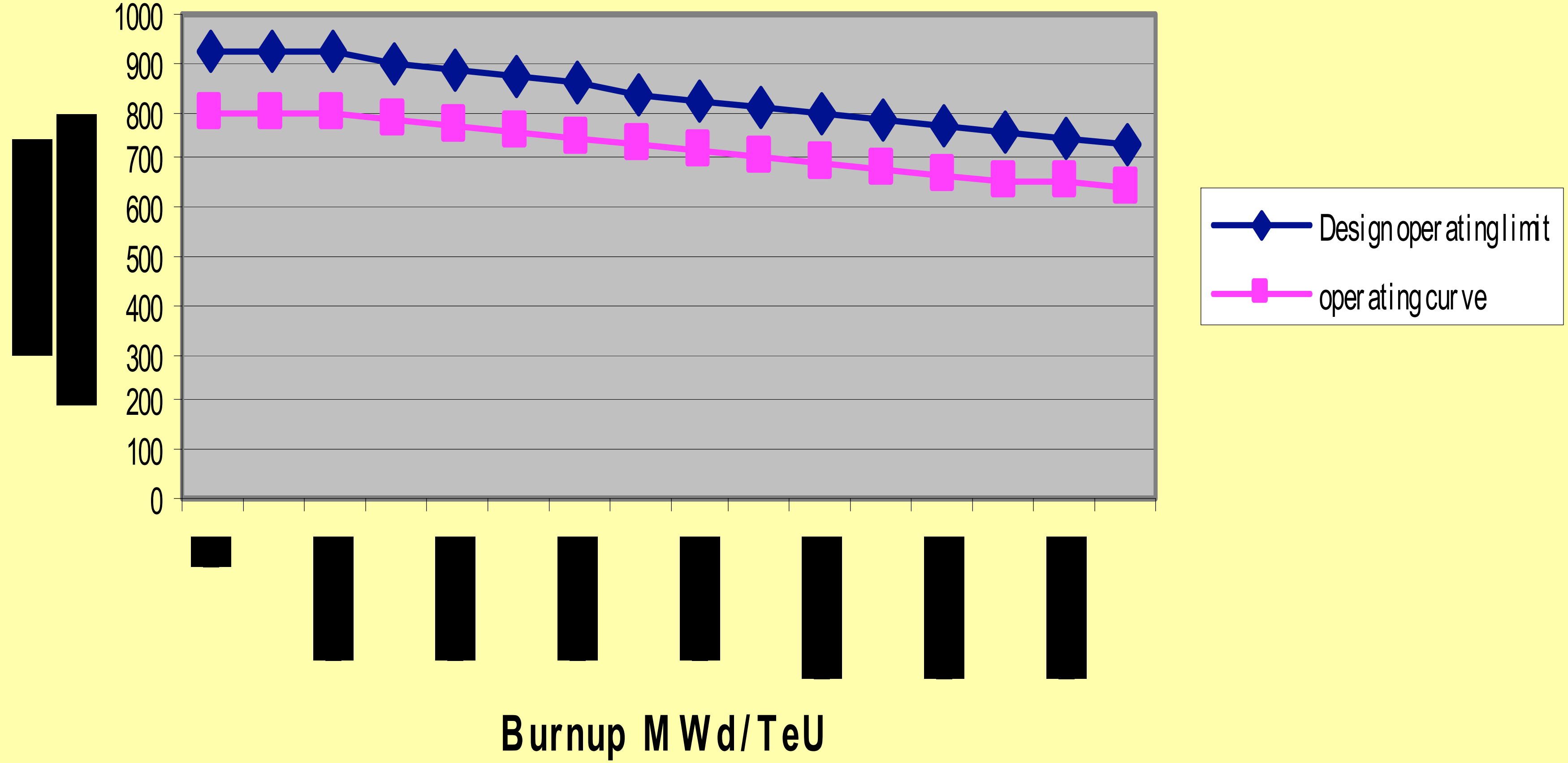
  - Changes in fuel composition (depletion) and generation of fission products
  - Initial location
  - Changes in location after refuelling
  - Movement of reactivity devices
  - Refueling in neighboring channels

- For design considerations average parameters are used for physics and are called time integrated values

Operating power limits

- The fuel bundle operating limit based on fuel bundle design has been worked out based on two considerations
  - Total plastic sheath strain shall not exceed 1%
  - Fission gas pressure shall not be more than the coolant pressure
- Fission gas pressure dictates 963 kW, a 5% margin it comes to 917 kW
- The corresponding equivalent LHR 580 W/cm and ∫kdt of 46 W/m

Fuel Bundle power operating limits



Bundle performance requirements

- The maximum power output of an element will never exceed 578 W/cm during the life of the bundle
- The maximum discharge burnup for central channels is assumed to be about 10,000 MWd/TeU in physics design as per the power envelopes
- The nominal maximum temperature on the outside surface of the sheath is 312 ^{0}C which is below 354 ^{0}C the upper limit derived from corrosion and strength considerations of sheath
- The pressure drop per bundle will not exceed 0.062 MN/m^2
- The average residence time for a fuel bundle in a reactor coolant tube is about 520 EFPDs for 100% capacity factor and a burnup of 6500 MWD/TeU. Average residence time is 2 years for 70% capacity factor.

Fuel bundle configuration design

- **Selection of number of elements in a bundle involves a number of following variables**
  - **Physics: Material buckling (maximum value of Bm^2 with minimum Vm/Vu, radial flux depression, fuel center temperature, fission gas release**
  - **Thermal hydraulics: Heat transfer coefficient, sheath temperature, Sub channel analysis and burnout**
  - **Element spacing**

Element design

- Cladding/sheath design
- Zirconium alloy properties: Chemical composition, Mechanical properties, Corrosion & hydriding and manufacturing process
- UO_2 pellet design: dimensional requirement, surface finish, chemical composition, density, O/U ratio, microstructure and visual standard
- End cap design

Properties of pellet

- Material properties and geometric parameters of the fuel pellet are chosen and controlled to
  - **Maximize the amount of fissile material present in the fuel element**
  - **Minimize the pellet volumetric changes during fuel in-reactor life**
  - **Ensure that fission gas release is within acceptable limits**
  - **Ensure that the pellet design meets the requirements imposed by production capability and economy**
  - **Minimize circumferential ridging of the sheath**

Pellet characteristics

- 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

Powder Requirements

Physical Requirement

Particle Size: All the uranium dioxide shall pass through a 10 - mesh U.S. Standard sieve using the procedure of ASTM-B-214.

Bulk Density: Bulk Density as determined by a Scott Volumeter shall be 1.00 ± 0.25 g/cc by procedure ASTM-B-329.

Sinterability: Test pellets shall be produced and measured in accordance with an approved sintering performance test.

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Chemical Requirements

Uranium Content: The uranium content shall be a minimum of 87.7 weight % on a dry weight basis Dry weight is the sample weight minus the moisture content.

Moisture Content: The moisture content shall be 0.4% maximum by weight of uranium.

Impurity Content: The impurity content shall not exceed the individual limit, on a uranium weight basis. Any one of the impurity elements (except Hydrogen, Nitrogen, Chlorine, Flourine and Thorium) can be upto twice the specified limit. Provided the specification on Equivalent Boron Content (EBC) being satisfied

Nuclear Requirements

- **The isotopic content of the uranium in the UO_2 powder shall be determined and the 234U, 235U, 236U and 238U content of uranium shall be reported on mass percent basis.**

- **The total equivalent boron content shall not exceed 1.1 ppm on an uranium weight basis. The total EBC is the sum of the individual EBC values. Cross sections of the elements is measured at neutron velocity of 2200 m/s.**

$$\text{EBC factor of impurity} = \frac{\sigma\ \text{Impurity}}{\text{At. Wt. of Impurity}} \times \frac{\text{At. Wt. of Boron}}{\sigma\ \text{Boron}}$$

EBC of impurity = (EBC factor of impurity) x PPM of impurity.

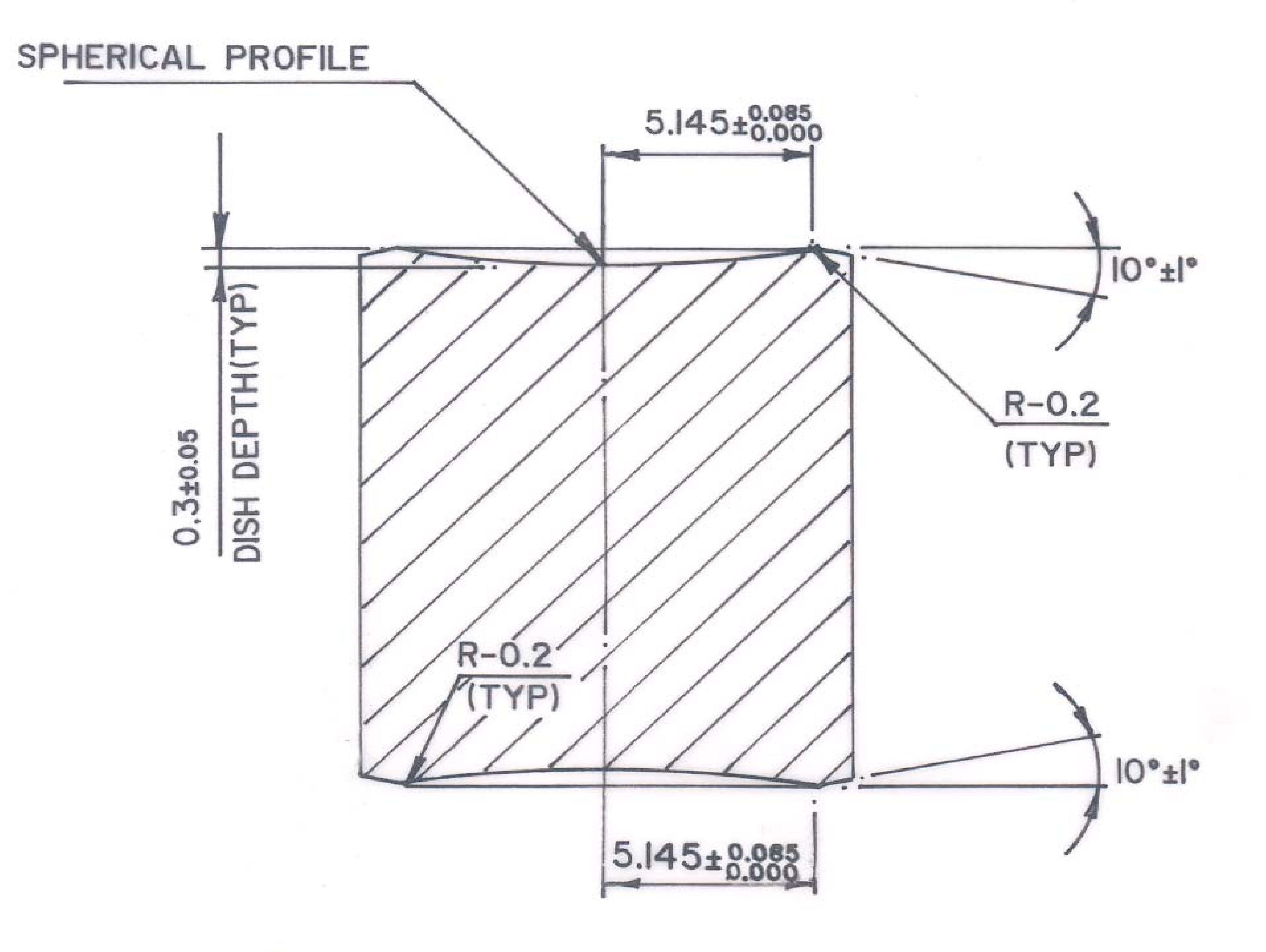
UO_2 pellet

- 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.

Specification of Natural Uranium Oxide Pellet



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- **Surface finish on long. surface : 1.6 microns Ra or better**
- **Diameter (D) : 12.08 - 12.24**
- **L/D ratio : 1.00 to 1.20**
- **Hydrostatic density : 10.60 to 10.80 g/cm3**
- **End squareness with reference to cylindrical surface : 0.15 mm Max. for both ends 0.10 mm Max per end**
- **Ovality : 0.012 mm maximum**
- **Dish depth and dish radius dimensions are applicable for lowest point of dish to highest point of pellet surface.**
- **Pellets shall be free from surface defects (eg. chips, cracks and flaking, etc.) and inclusions greater in size and number than the standards as defined**

Clad/Sheath requiements

- **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 better heat transfer.**

Chemical Composition of Nuclear Grade Zr-2 & Zr-4

Elements	Zr-2	Zr-4
Tin	1.20-1.70	1.20-1.70
Iron	0.07-0.20	0.18-0.24
Chromium	0.05-0.15	0.07-0.13
Nickel	0.03-0.08	-
Niobium	-	-
Total Fe+Cr+Ni	0.18-0.38	-
Total Fe+Cr	-	0.28-0.37
Carbon (ppm)	150-400	150-400
Oxygen (ppm)	900-1400	900-1400
Copper	-	-
Zr + permitted impurities	Balance	Balance

Impurities in Nuclear Grade Zr-4 & Zr-2

Elements	Zr-4	Elements	Zr-4
Alumunium	75	Manganese	50
Boron	0.5	Molybdnum	50
Cadmium	0.5	Nickel	70
Carbon	-	Niobium	100
Chlorine	-	Nitrogen	80
Cobalt	20	Phosphorus	-
Copper	50	Silicon	120
Chromium	-	Tantalum	200
Hafnium	100	Tin	-
Hydrogen	25	Titanium	50
Iron	-	Tungsten	100
Lead	130	Uranium	3.5
Magnesium	20	Vanadiun	50

SURFACE FINISH 32 Micro inch RMS

MECHANICAL PROPERTIES
(Room Temperature)

UTS	70 Ksi(min)
0.2% YS (x-3σ)	57 Ksi(min)
% EL	20 (min)

CLOSED END BURST TEST
(Room Temperature)

Hoop Stress	90 Ksi min.
% TCE (x-2 σ)	10 (min)

CORROSION TEST: At 400°C, 1500 Psi for 72 hours
Weight gain 22 mg/dm^{2}maximum
Lustrous black oxide surface

GRAIN SIZE: Average -10 microns, no grains shall exceed 25 microns

HYDRIDE FRACTION: 0.35 max.

- **The zircaloy sheath of the fuel element shall have a minimum material thickness of 0.38mm. The thickness of sound non-porous metal shall be not less than 0.34mm. This requirement applies to such points as the welds between end cap and tube as well as to points where scores, arc pits or similar imperfections may exist on the sheath.**

- **The external and internal surfaces of the zircaloy tubes in the finished bundle shall have a finish of 1.6 microns RMS or better**

The as-fabricated diametrical clearance between the UO_2 pellet stack and the sheath is chosen and controlled within in the appropriate range to

- **Prevent the formation of longitudinal ridges in the sheath**
- **Facilitate pellet loading during fuel element manufacturing, and**
- **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 (un-pressurized) with a He/air or He/inert gas mixture prior to end cap 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**.

- Weld shear strength of spacer welds and bearing pad welds shall have for each spot weld a minimum strength of 60 Kg and 80 Kg respectively when tested in transverse direction.

- Elements shall possess on assembly a total internal longitudinal clearance between element inside free-length and pellet stack length of 1.20 to 3.80 mm

- The diametrical clearance between the pellets and the zircaloy sheath on assembly shall be between 0.05 to 0.13mm.

- **All end cap to sheath or element closure welds shall have an amount of sound non-porous metal of any line in any direction which is not less than 90% of the nominal material thickness in that direction and no single defect shall exceed 0.13mm in any direction.**

- **Sealed fuel elements shall contain helium of slightly above atmospheric pressure at normal room temperature. The air inclusion in this gas shall be minimum, not exceeding 10% in any case.**

- **The total hydrogen gas content of a sealed fuel element whether derived from moisture, helium gas filling, hydrocarbon or other source picked up during manufacture shall be less than 1 mg of hydrogen.**

- **All sealed fuel elements shall be checked for leaks, after the end caps have been machined to their final shape, not later than seven days after the second end closure weld. Any fuel element found to have leaks through the cladding greater than 1.0 E-08 atmospheric cubic centimeters per second shall be unacceptable.**

End cap

The end cap material is specified and inspected to ensure adequate strength and lack of porosity, which is needed for fission product containment.

MECHANICAL PROPERTIES

Properties (min)	Room Temperature
UTS(ksi)	60
0.2% YS(ksi)	35
% EL	14

GRAIN SIZE: Average -35 microns (maximum), no grains shall exceed 50 microns

CORROSION TEST: At 400ºC, 1500 Psi for 72 hours
Weight gain: 22 mg/dm^2, maximum
Lustrous black oxide surface

Assembly design

The fuel bundle is characterized for integrity, susceptibility to handling damage, tolerance to in-reactor thermo-mechanical environment

- **End plate design:**
  - Compatability with fuelling machine, bundle assembly joint strength,
  - structural strength, Differential expansion of elements
  - Flexible enough to allow distribution of axial loads to all elements
  - flow resistance,
  - manufacturing requirements

- **Spacer & bearing pad joining:**

- **Bundle droop:**

Spacer pads

- The spacers maintain separation of elements of the bundle at mid plane.
- 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.
- Skewing increase the width of possible contact between spacer pairs and decreases the probability of spacer interlocking.

Bearing pads

- **The bearing pads, brazed/resistance welded to the outer element sheaths near the element end and at the mid plane.**
- **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 are also be designed to minimize local corrosion of the pressure tube.**

End plates

- **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.**
- **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.**

SURFACE FINISH 63 Micro inch RMS

MECHANICAL PROPERTIES

(Room Temperature)

Properties (min)	Longitudinal	Transverse
UTS	60 ksi	57 Ksi
0.2% YS	35	44
% EL	20	20

GRAIN SIZE:

Average -35 microns, no grains shall exceed 50 microns

CORROSION TEST:

At 400^{o}C, 1500 Psi for 72 hours Weight gain 22 mg/dm^2 maximum

Lustrous black oxide surface

Fuel bundle requirements

- The natural uranium fuel bundles shall contain an average of not less than 20.50 Kg of uranium. The neutron absorption, in a thermal neutron flux, of all material in the bundles, exclusive of the UO_2 shall not exceed the equivalent of 2.45 Kg of zircaloy per bundle
- The inter element spacing
  - **Outer to outer: 1.96 mm**
  - **Type 2 outer ring to 2nd ring: 4.15 mm**
  - **Other areas: 1.80**
- Rectangular profile of spacers 4.30 X 9.80
- Distance between endplate to sheath envelope: 4.24 mm
- Bundle length: 495.3±0.50 mm
- Bundle diameter
  - **Outer bearing pads: 102.36±0.13 mm**
  - **Central bearing pads: max 101.94 mm**


Thank you

Pellet Requirements

Density

The density of pellets shall be 10.45 to 10.75 g/cm3, when determined on finished pellets by accurate geometric measurements and weight.

Microstructure:

A longitudinal cross section on the diameter of the pellets, prepared and examined

Freedom from segregated porosity delineating the boundaries of any granules persisting from the powder.

No areas of grouped porosity, material torn out in sample preparation groups of abnormally fine grains, shall be in total greater than 10% of the area of the section.

The average grain size shall be measured and reported.

The pore morphology of a typical pellet shall be recorded for reference.

Chips or Pits

In this specification chips (or pits) refer to an imperfection having a major dimension greater than 0.4mm in the plane of the dished end, flat end or the circumferential surface and depth not greater than 0.38mm at the pellet surface. The bottom fo the pit shall be clearly visible. Pellets with chips or pits greater than 3.18mm in major dimension shall be unacceptable (Fig.1).

Chips or Pits at the Dished and Flat Ends

Pellets with chips on either end within the plane surface or extending to the periphery shall have a total are of circumference affected by such chips not greater than 6mm (fig.2).

Circumferential Chips or Pits

Not more than two chips of the limiting size or an aggregate of smaller chips of equivalent area in the circumferential plane shall be permitted (fig.3)

Note: Chipping of the circumferential surface is of concern because of the increased resistance to heat transfer and the loss of sheath support in the area over the defect. So distributed chips are better compared to grouped at a single place.

Circumferential Cracks

The following conditions shall apply only to cracks located further than 3mm from wither end of the pellet. Cracks located close than 3mm to either end of the pellet or in the end surfaces of the pellet shall conform to the requirements of Section-4.3(fig.4)

a) Fine cracks upto 0.05mm width

The maximum individual length of such a crack shall not exceed 6mm and any number of such cracks are acceptable provided they are not longitudinal or branching type. However, body crazing is not permissible

b) Cracks between 0.05mm – 0.13mm width

The maximum acceptable length of such a crack or aggregate length of shorter cracks of this type shall be 40% of circumference of the pellet. Longitudinal cracks and branching of cracks are not acceptable.

c) Pellets with any one or more cracks with a width more than 0.13 mm shall be rejected.

End-capping or End-flaking

This section concerns the presence of circumferential cracks within 3mm of either end of the pellet or in the case of end ground pellet of circular cracks on the end surface. These cracks may extend to the pellet axis and may result in the end of the pellet flaking off when subject to even mild shock. This condition is described as end-capping or end flaking, following conditions should be met.

a) The total circumferential length of end capping shall not be more than 25% of the circumference of the pellet (Fig.6)

b) Loose end capping is not acceptable.

c) Pellets shall also be free of cracks in the end surfaces.

d) End crazing and body crazing is not permitted (Fig.5 & 7).

Inclusions

Pellets with more than two inclusions of foreign material, in any location on the pellet surface, discernible to the unaided eye shall be unacceptable. The maximum permissible size of any inclusion shall be 0.6mm in major dimension. Where an inclusion has been partly or fully removed from the pellet, the limits for acceptance of pits shall also apply.

FIG. 1

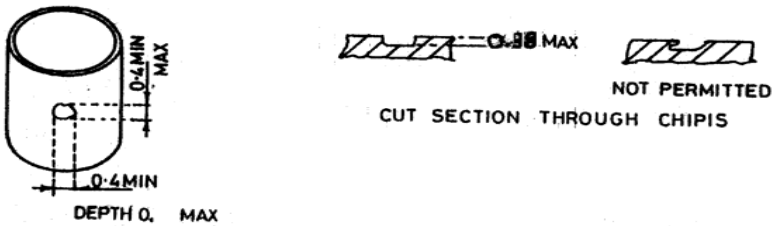

FIG. 2

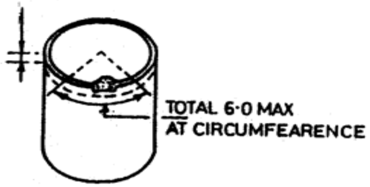

FIG. 3

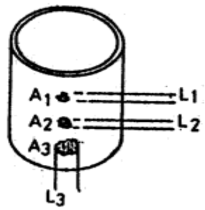

FIG. 4

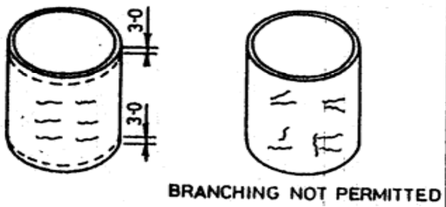

FIG. 5

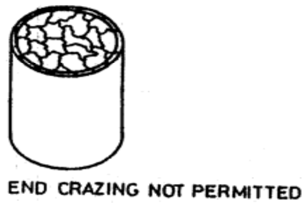

FIG. 6

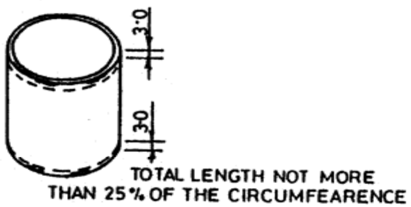

FIG. 7

NOTE : DIMENSIONS ARE IN mm

Pellet characteristic cause & effect

Characteristic	Cause	Effect
Specific surface area		
Low	•Coarse ADU grains •High temperatures during heat treatment	• Low sintered density.
High	•Coarse ADU grains • Low temperatures during heat treatment	• Inconsistent sintered density values. • Cracks on pellet surface • Bulging in sintered pellets
O/U ratio		
	•Air ingress during stabilisation. •Storage for long period.	•Inconsistent sintered density values. •Cracks on pellet surface •Bulging in sintered pellets

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Characteristic	Cause	Effect
Particle size.		
Small	•High U conc in UNPS. •Fast rate of ammonia addition. •High impeller speed during precipitation. •Impurity particles in UNPS	•Inconsistent sintered density values. •Cracks on pellet surface •Bulging in sintered pellets
Large	•Low U conc in UNPS. •Slow rate of ammonia addition. •High impeller speed during precipitation.	•Low sintered density . •Cracks on pellet surface •Bulging in sintered pellets
Morphology		
Shape and structure	• Route adopted • Preciptation tank design, • impeller design	• Inconsistency in sintered density and recovery.