Reactor, Boiler & Auxiliaries - Course 233

FUEL - DESIGN AND MANUFACTURING FEATURES

GENERAL DESIGN

The basic requirements of CANDU fuel are to:

- allow efficient removal of fission heat and also to
- contain the highly active fission products.

Additional requirements of a fuel bundle are:

- ability to withstand high temperatures, stresses and strain as a result of the above requirements,
- adequate strength for handling and withstanding heat transport fluid pressures, flow rates and fuelling operations,
- low cost,
- neutron economy.

The typical fuel bundle design meeting these requirements is illustrated for Bruce in Figure 1. In this case 37 elements make up the bundle, adequate space being allowed between for heat transfer. Thin Zircaloy-4 end plates are welded to the end of each element. Sintered UO_2 pellets are sealed in Zircaloy-4 sheaths with welded end plugs. Induction heating is used to braze small pads (spacers) to the elements to provide spacing between the elements and between the bundle and the pressure tube (bearing pads). The two basic materials then are UO_2 fuel (natural) and Zircaloy-4 sheathing.

FUEL MATERIAL

Fuel material must have the following properties:

(a) Sufficient U-235 (or fissile content) to maintain a chain reaction.

(b) Chemical compatibility with the sheath and heat transport fluid.

(c) Dimensional stability at operating conditions.

(d) High thermal conductivity.

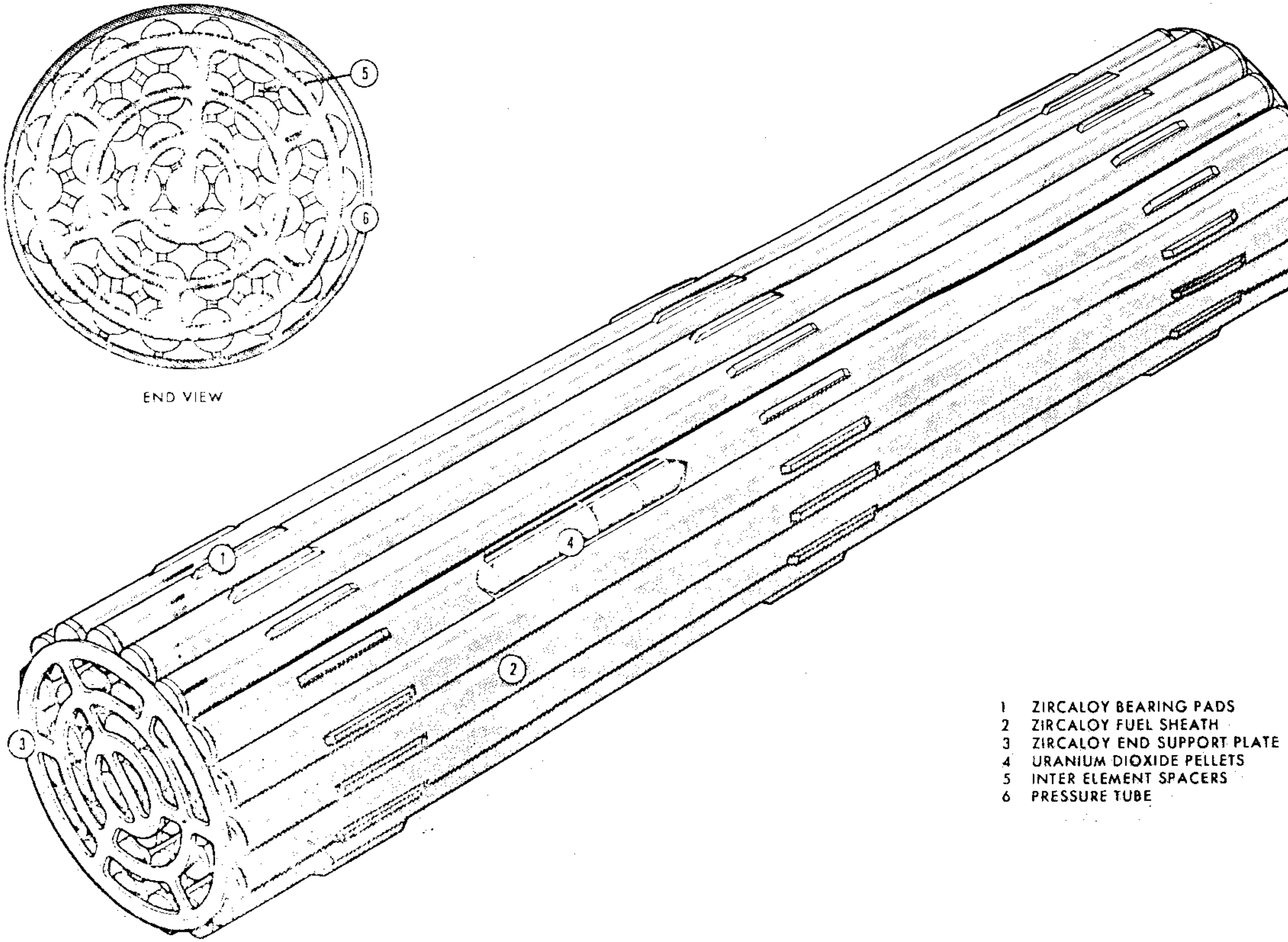

Figure 1

Bruce 37-Element Fuel Bundle

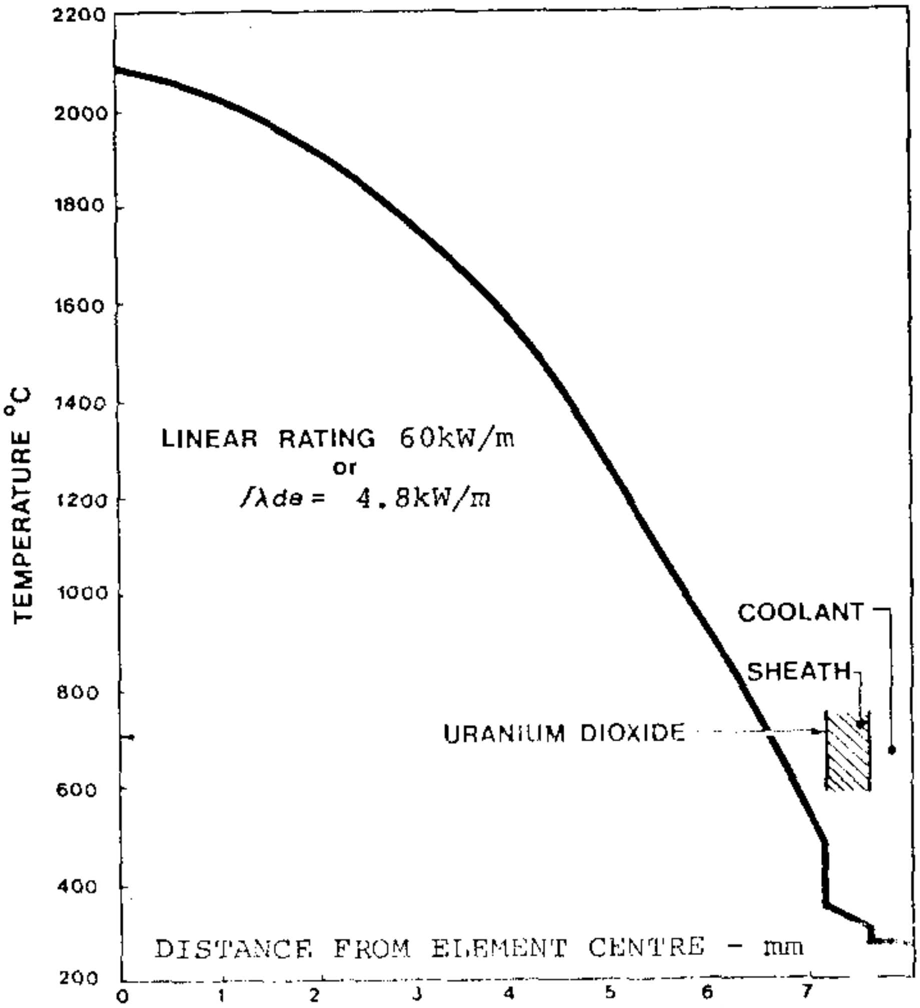

Figure 2: Radial Fuel Pellet Temperature

(e) High melting temperature.

(f) Low manufacturing costs.

(g) Minimum personnel hazards while handling.

Solid uranium metal would appear to be the first choice as it has a high density, high thermal conductivity and is compatible with common sheathing materials. However, it is highly corrosive in hot water, which it would contact in the event of a sheath defect, and it elongates an undesirable amount under conditions of irradiation and thermal cycling. These last two effects prevent the use of uranium metal in CANDU.

Uranium dioxide on the other hand is chemically compatible with cladding materials and with hot water. It can be manufactured easily and handling presents no personnel hazard. However, the concentration of fissile U-235 in UO_2 is approximately 50% that of uranium metal, and the low thermal conductivity of UO_2 results in high fuel temperatures. High temperatures can be tolerated however, since UO_2 has a melting temperature of 2750°C ± 400°C and is dimensionally stable. Figure 2 shows the temperature distribution through a maximum rated (outer ring) element at full power for a Pickering 28-element bundle. The resulting temperature gradient across the element illustrates well the stringent conditions under which our fuel has to operate. Figure 3 shows an actual photograph of a fuel element (pencil) cross section. UO_2 then, has been chosen for all the world's water cooled reactors and, in natural form, for CANDU.

SHEATHING MATERIAL

Sheathing material must have the following properties:

(a) Low neutron absorption.

(b) Adequate strength and ductility to support the fuel.

(c) Chemical compatibility with both the fuel material and the heat transport fluid.

(d) Adequate heat conductivity.

The most essential property is that of low neutron absorption and of the elements with sufficiently low absorption only zirconium and aluminum have satisfactory corrosion properties in water. Aluminum, however, loses its strength at fuel sheath operating temperature and only zirconium metal is considered at all suitable.

All our reactor fuels today use Zircaloy-4 sheaths (98% Zirconium + 1.7% Tin).

FUEL MANUFACTURE

Fuel Material

Uranium is found in abundance in various areas of Canada. After removal from the ground, the ore is processed at the mine to extract the uranium in the form of sodium di-uranate or 'yellowcake'. At a refinery the yellowcake is then converted into UO_2.

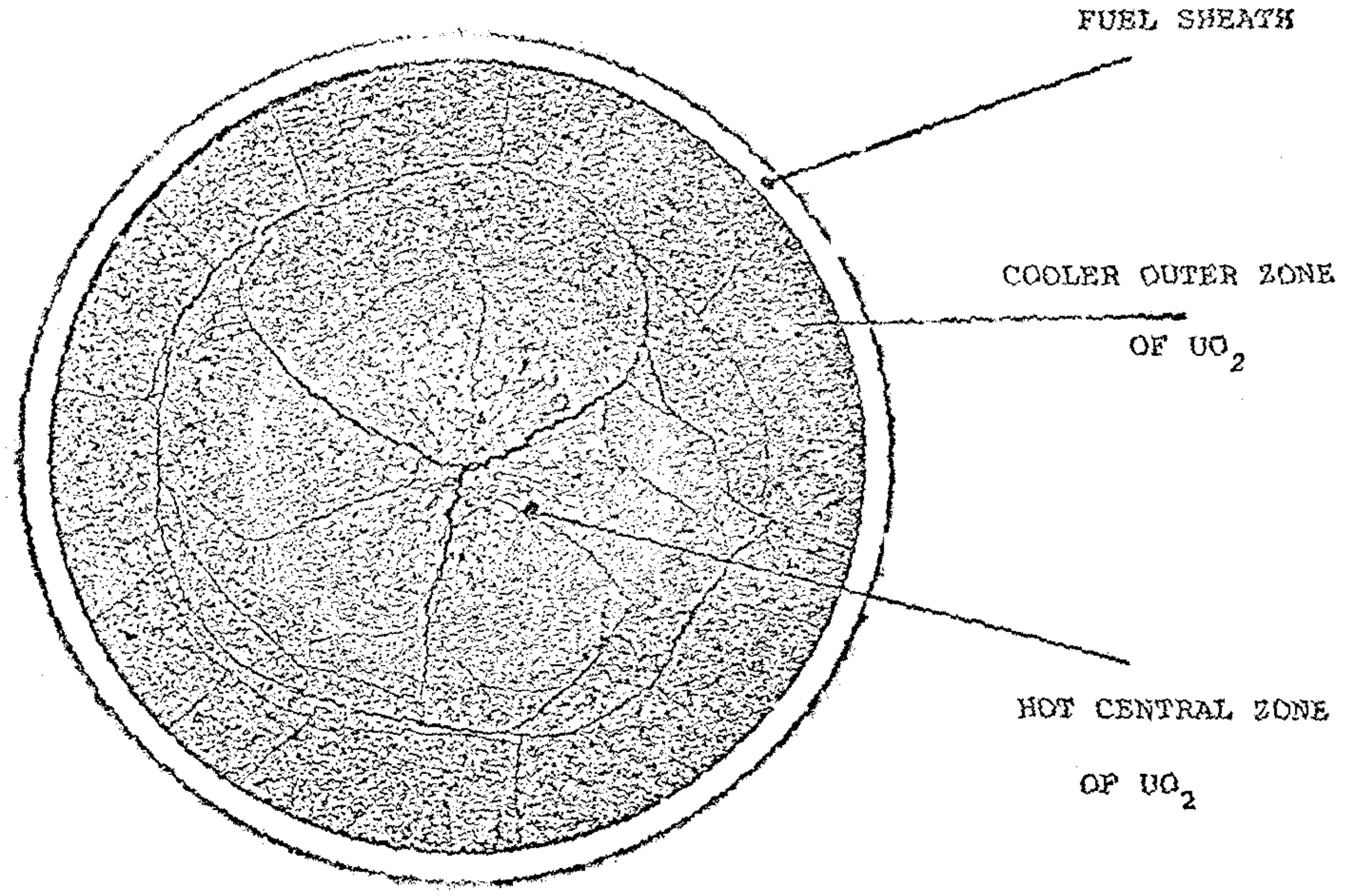

Figure 3: Cross Section Through CANDU Fuel Pencil

The UO_2 is sent to one of three fuel fabricators (CGE, Combustion Engineering and Westinghouse) where it is pressed and sintered in a hydrogen atmosphere at ∿1600"C to form a hard, dense pellet. The pellets are then ground to size and finished with a shallow spherical dish at one end, the purpose of which is to allow for pellet expansion and also for space in the element to accommodate fission product gases.

Zircaloy

Zirconium ore is processed to form a zirconium alloy ingot from which tube, strip and bar is produced. The fuel manufacturer currently obtains this material outside Canada, since the ore has not been found in Canada in economical quantities.

Bundle Fabrication

At the fuel fabricating shop the Zircaloy strip is made into bearing pads and spacers which are brazed to the fuel sheaths. End plugs machined from the Zircaloy bar are welded to both ends of the sheaths which are previously filled with fuel pellets in an inert atmosphere. Elements are then assembled with two end supports and welded to form the fuel bundle. When Ontario Hydro receives these bundles they are ready to load directly into the reactors.

GENERAL CANDU FUEL DESIGN

The basic design concept just described and illustrated for Bruce in Figure 1 has changed little since the original fuel charge for NPD in 1962. However, fuel development and improvement is still continuing and the changes made (and still being made) up to the present time are worth looking at to illustrate the experience that has been gained over the years.

Table I summarizes the most important design and operating data for the fuel of all our stations.

Pickering A and B fuel is 28-element fuel which fits the now standardized ID of pressure tubes (103.4 mm). This enabled the maximum bundle power to be increased by ∿50% over the smaller Douglas Point 19-element bundles (Table I).

At Bruce A and B the number of elements/bundle has been increased to 37 providing a larger surface area for heat removal than the Pickering bundles and hence a larger power than Pickering.

TABLE I

Canadian Power Reactor Fuel: Design and Operating Data

REACTOR		NPD	NPD	DOUGLAS POINT	GENTILLY-1 BLW	PICKERING A	BRUCE A	600 MW
NUMBER OF ELEMENTS PER BUNDLE		7	19	19	18	28	37	37
PELLETS (Sintered UO_2)								
Density	Mg/m^3	10.3	10.3	10.55	10.55	10.6	10.6	10.6
O/U Ratio		2-2.015	2-2.015	2-2.015	2-2.015	2-2.015	2-2.015	2-2.015
Length (approximate)	mm	22.4	19.9	20.07	24.0	22.99	15.3	16.4
Length/Diameter Ratio (Approximate)		0.9	1.39	1.4	1.3	1.56	1.35	1.35
ELEMENTS								
Material		Zircaloy-2	Zircaloy-4	Zircaloy-4	Zircaloy-4	Zircaloy-4	Zircaloy-4	Zircaloy-4
Nominal Outside Diameter	mm	25.4	15.25	15.22	19.74	15.19	13.08	13.08
Minimum Cladding Thickness	mm	0.64	0.38	0.38	0.49	0.38	0.38	0.38
BUNDLES								
Nominal Length	mm	495	495	495.30	500.00	495.30	495.30	495.30
Maximum Diameter	mm	82.04	82.04	81.74	102.41	102.49	102.49	102.49
Number per channel		9	9	12	10	12	13	12
Number per channel in Reactive Zone		9	9	10.1	10	12	12	12
Number per Core in Reactive Zone		1188	1188	3090.6	3080	4680	5760	4560
Minimum Element to Coolant Tube Spacing	mm	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Nominal Bundle Weight	kg	16.70	16.72	16.72	26.7	24.8	23.7	23.35
Nominal Weight U/bundle	kg	13.39	13.41	13.412	20.71	19.86	18.8	18.5
PRESSURE TUBE								
Nominal Minimum Inside Diameter	mm	82.55	82.55	82.55	103.56	103.38	103.38	103.38
OPERATING CONDITIONS								
Coolant		D_2O	D_2O	D_2O	H_2O	D_2O	D_2O	D_2O
Nominal Inlet Pressure	MPa	7.9	7.9	10.16	6.32	9.6	9.18	11.09
Fuel Pressure Drop/Channel (Crud Free)	kPa	241	241	738	799.8	551.6	765.	758
Nominal Maximum Channel Power	MW	0.985	0.985	2.752	3.18	5.125	6.53	6.5
Inlet Temperature	°C	251.6	251.6	249	267	249	250.5/264.9*	266.4
Outlet Temperature	°C	276.6	276.6	293	270	293	303.9	312.3
Steam Quality at Fuel Exit	%	-	-	-	16.5	-	~0.8/4.0+	~2.55
Nominal Maximum Mass Flow/Channel	kg/sec	6.6	6.6	12.6	11.2	23.88	23.88	23.94
Nominal Maximum Mass Velocity	kg/m^2,sec	3988.	3711.	6630.	4349.	6687.	6957.	6998
Nominal Maximum Sheath Temperature (outside)	°C	288.	288.	301.	290.	304.	326.	326.
Nominal Maximum Heat Rating $\int \lambda\, d\theta$	kW/m	3.45	2.08	4.0	4.8	4.2	4.1145□	4.3
Nominal Maximum Linear Bundle Power	kW/m	298.	447.	871.	968.	1325.	1670.	1676.
**Nominal Maximum Linear Element Power $\frac{4\pi \int \lambda\, d\theta}{F}$	kW/m	43.4	24.9	50.3	61.2	52.8	51.70□	54.08
Approximate Average Discharge Bundle Burnup	MWh/kg	156.	156.	190.	168.	170/185$^\Delta$	251/165*	180
Maximum Nominal Surface Heat Flux $\frac{\frac{4\pi}{F}\int \lambda\, d\theta}{\pi d}$	kW/m^2	560.7	514.1	1070.	986.5	1120.	1258.3□	1315.5
Nominal Maximum Bundle Power	kw	221.	221.	420.	484.	636.	827.	830.

* Inner zone/outer zone

** From "$\int k\, d\theta$ in Fuel Irradiations", J.A.L. Robertson, AECL 807, January 1969

\+ Based on cold nominal dimensions and hot fluid properties

□ Based on element power distribution at 240 MWd/kgU burnup

$^\Delta$ Pickering 1 and 2: 170
Pickering 3 and 4: 185
± 2 MWh/kgU

The cross-sectional areas of our fuel bundles are illustrated for comparison in Figure 4.

A layer of graphite is also incorporated between pellet and sheath and has been shown to be effetive in preventing sheath defects due to bundle power increases which would likely have occurred under similar conditions without the graphite layer. Fuel which uses graphite is called CANLUB fuel.

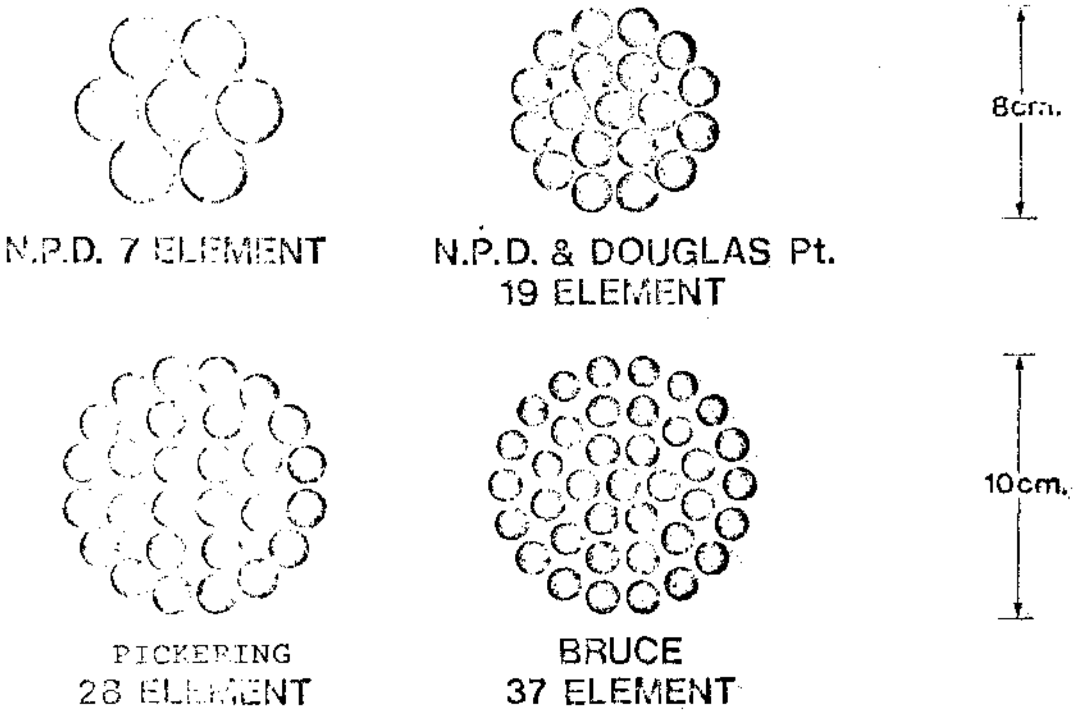

Figure 4: Fuel Bundle Cross-Sections

Specifically the graphite has the following effects:

(a) It limits pellet/sheath friction, hence reducing sheath strain due to pellet movement.

(b) It provides a physical barrier to corrosive fission products (eg, iodine) for reaching the sheathing.

Most fuel in our plants is now CANLUB and costs around 2200$/bundle in 1979. (In addition to fuel utilizing a graphite layer between pellet and sheath, some CANLUB experimental fuel has graphite discs between fuel pellets in an attempt to improve heat transfer. Other tests are being made on a different coating, siloxane, as a possible alternative to graphite.)

SPECIAL PURPOSE FUELS

The fuel design described above can be considered the standard natural uranium CANDU fuel. Variations of this design are used in our stations for special purposes which are now discussed.

Depleted Fuel

For the initial fuel charge of units using boosters rather than adjusters (NPD, Douglas Point, Bruce A) a number of bundles containing depleted uranium (∿0.4% U-235) have been used in the central region of the core to provide flux flattening until equilibrium fuel burn up has been reached. Apart from the isotopic variation, these bundles are identical to those containing natural uranium.

Occasionally depleted fuel may also be used in a station which has had some channels defuelled. Examples of this would be (a) in a pressure tube replacement program and (b) refuelling a channel which contains defective fuel. In either case the refuelled channel will contain some depleted fuel bundles, in locations chosen by the station fuel engineer, so that the new reactivity and new channel power simulate the reactivity and channel power of the irradiated fuel removed from the channel. The irradiated fuel from a replaced channel, or non-defective irradiated fuel from a channel containing defect fuel, would not be replaced in the channel because of the risk of fuel damage during the removal and subsequent replacement operations.

Enriched Fuel

For experimental purposes, some fuel now being used at NPD and Douglas Point is slightly enriched (∿2%) in U-235 or Pu-239. Apart from the isotopic change, this fuel is identical to the natural uranium bundles. In the long term, AECL is proposing to use an alternative fuel cycle with fuel slightly enriched with plutonium extracted from the currently accumulating irradiated fuel in our storage bays. This fuel will probably be used in combination with natural UO_2 and/or THO_2 fuel. A pilot fuel fabrication plant has been set up at Chalk River to begin work on the production of PuO_2 and UO_2/ThO_2 bundles.

Booster Fuel

To provide Xe poison override at Douglas Point and Bruce A, booster rods containing highly enriched (90%) U-235 fuel are used. These particular rods consist of six bundles strung together vertically on a Zircaloy-4 support tube passing through the central space of the 19-element bundle configuration (Figure 5). The 18 booster elements are made up of cylindrical Zircaloy tubes allowing internal and external cooling. The tubes are filled with fuel of a uranium-zirconium alloy. This composition was chosen to enable the booster operating temperature to be relatively low (75°C maximum), the thermal conductivity of this alloy being much larger than that of UO_2. As a result of this the coolant is low pressure and is supplied directly from the moderator circulating system itself.

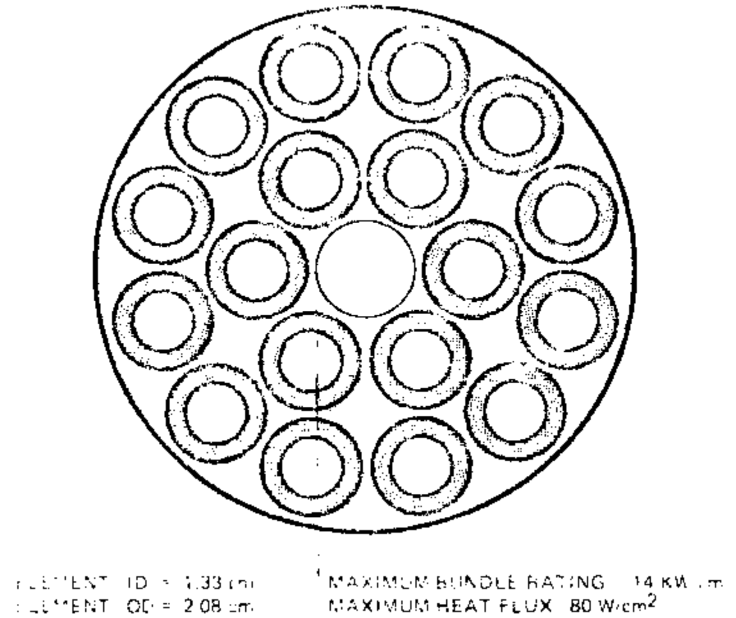

Figure 5: Bruce Booster Fuel Cross-Section

HANDLING OF NEW FUEL

Ontario Hydro nuclear stations receive the completed fuel bundles from the manufacturers and store them in the stations. Handling precautions before loading them into the fuelling machines are as follows:

(a) The palletized containers (usually containing 36 bundles) should not be jarred or shaken during transit in the plant.

(b) The bundles should be handled with clean cotton gloves to prevent contamination from body sweat (chlorides in particular as these will chemically attack the HT system materials).

(c) Visible dirt should be removed with a clean cloth.

(d) Bundle diameter gauging must be done to ensure a fit into the fuelling machine and reactor channel.

(e) Bundles should be handled horizontally to avoid possible pellet compression or chipping.

HANDLING OF ENRICHED FUEL

The storage and handling of enriched fuel - in particular the highly enriched booster fuel - requires special precautions to avoid the possibility of a criticality accident of theft.

For the criticality problem these precautions will include having separate storage areas for new booster bundles, each containing no more bundles than a specified number in any one area. In addition, the storing of D_2O or H_2O (or any type of good moderating material) close to the booster storage areas should be prohibited. Even the location of irradiated bundles in the fuel bay is carefully specified by the fuel engineer to avoid accidental criticalities, as the bundles will still contain more than the natural abundance of U-235.

Movement in the plant of new and irradiated enriched fuel also has restrictions on how much may be moved at any time. Again this is to ensure that accidental criticality during transit of the fuel cannot occur.

ASSIGNMENT

1. Compare the bundle design data for the reactors of Table 1 and explain any differences or similarities in the operating conditions given below, for each reactor. (Read 70-2 before you do this.)

   (a) fuel pressure drop/channel
   (b) nominal maximum channel power
   (c) inlet/outlet temperature
   (d) average discharge bundle burnup
   (e) nominal maximum bundle power

2. List some of the precautions taken in inspecting/ handling fresh fuel bundles in a station.

3. State a reason for using depleted fuel in our stations.

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