Reactor, Boiler & Auxiliaries - Course 133

FUEL - DESIGN & MANUFACTURING FEATURES

GENERAL DESIGN

The basic requirements of CANDU fuel are to

- allow efficient removal of fission product 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 and flow rates,
- 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) Figure 2. 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

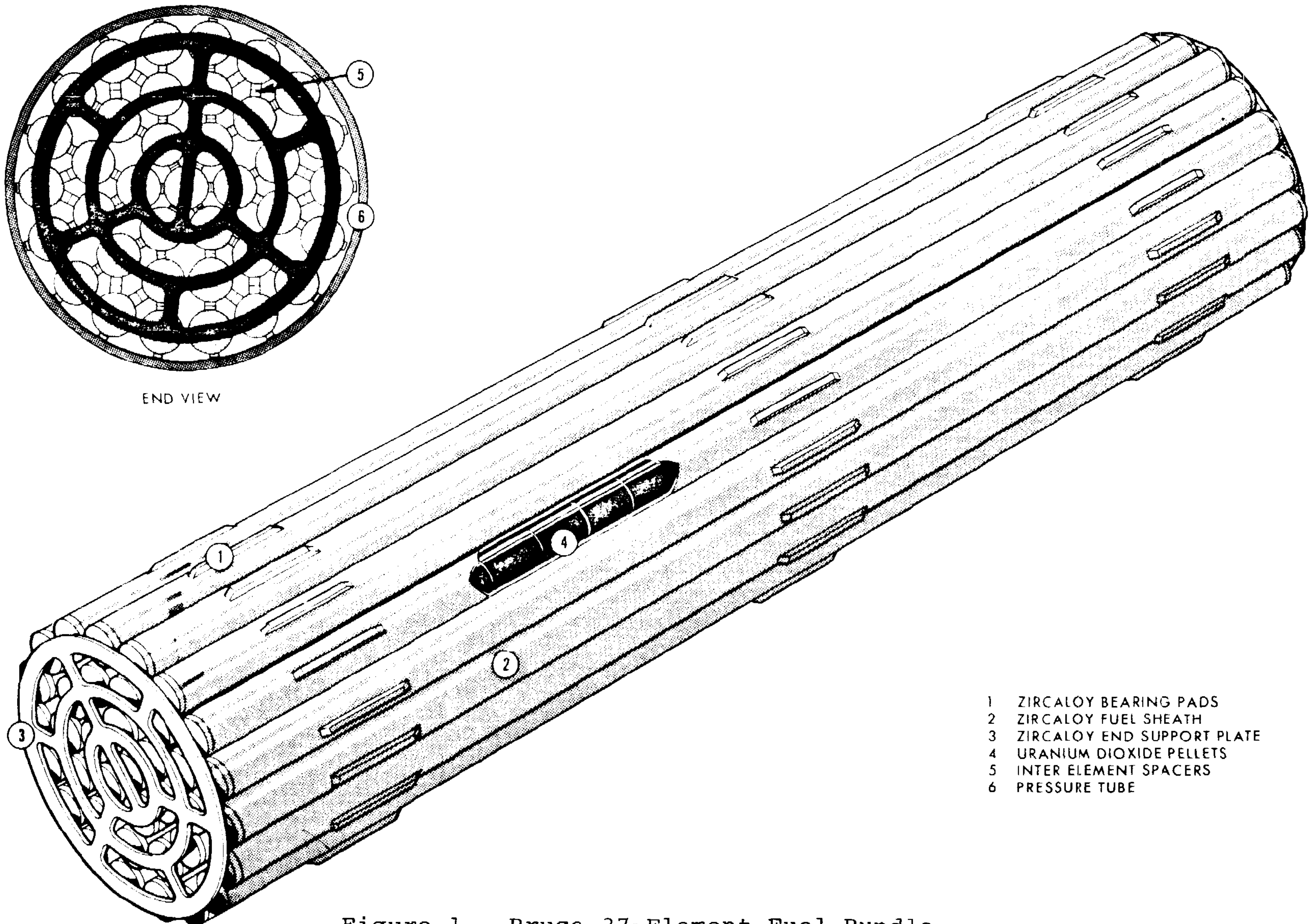


Figure 1 Bruce 37-Element Fuel Bundle

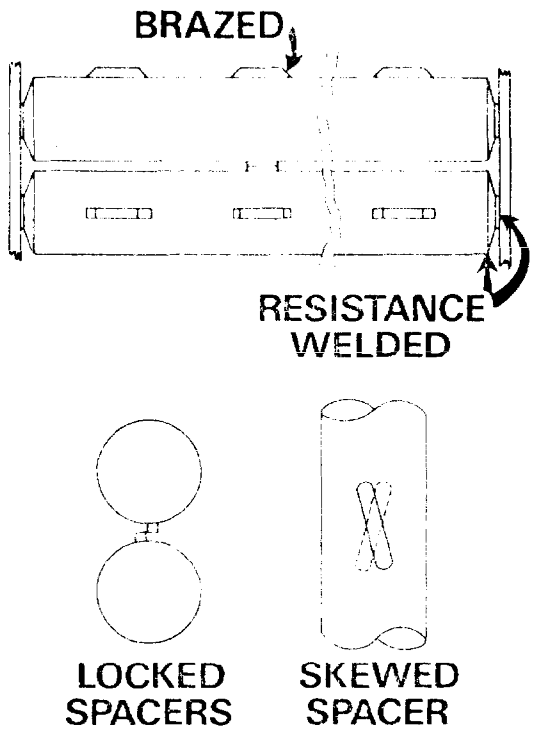


Figure 2 Spacer Pads and Bearing Pads

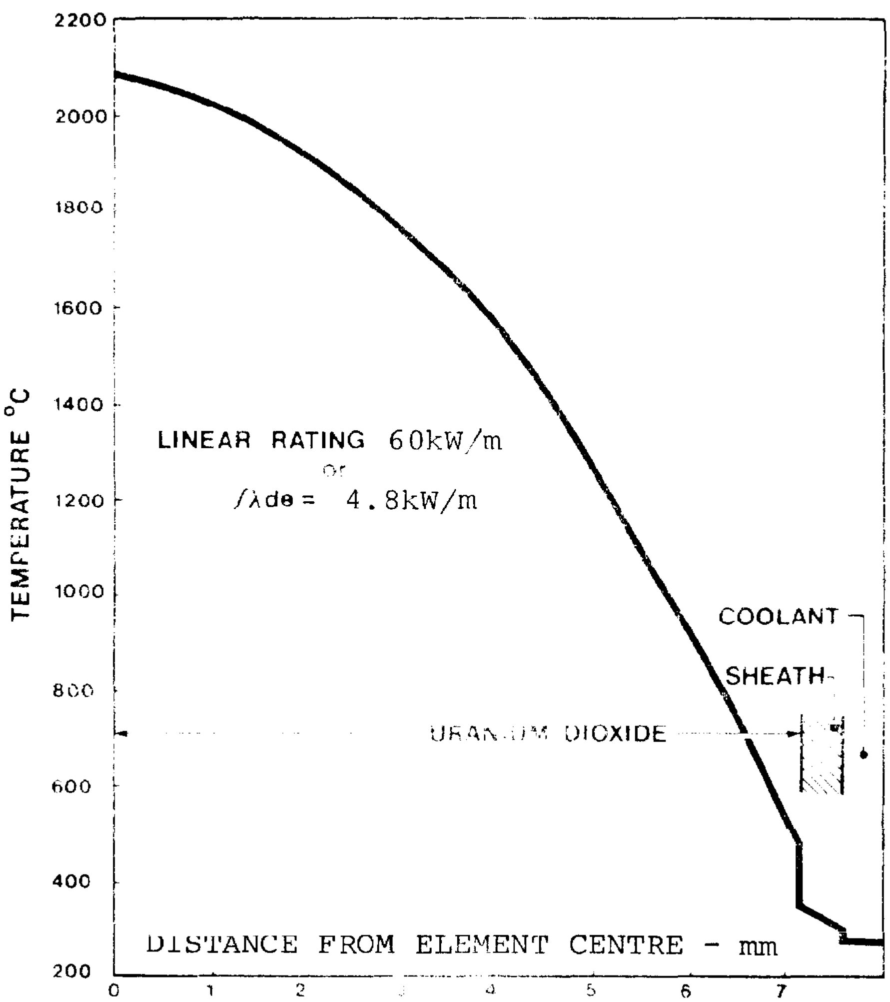


Figure 3 Radial Fuel Pellet Temperature

(e) high melting temperature

(f) low manufacturing costs, and

(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 is not dimensionally stable 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 2800°C and is dimensionally stable. Figure 3 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.

UO_2 then, in ceramic form, has been chosen for all the worlds 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, and

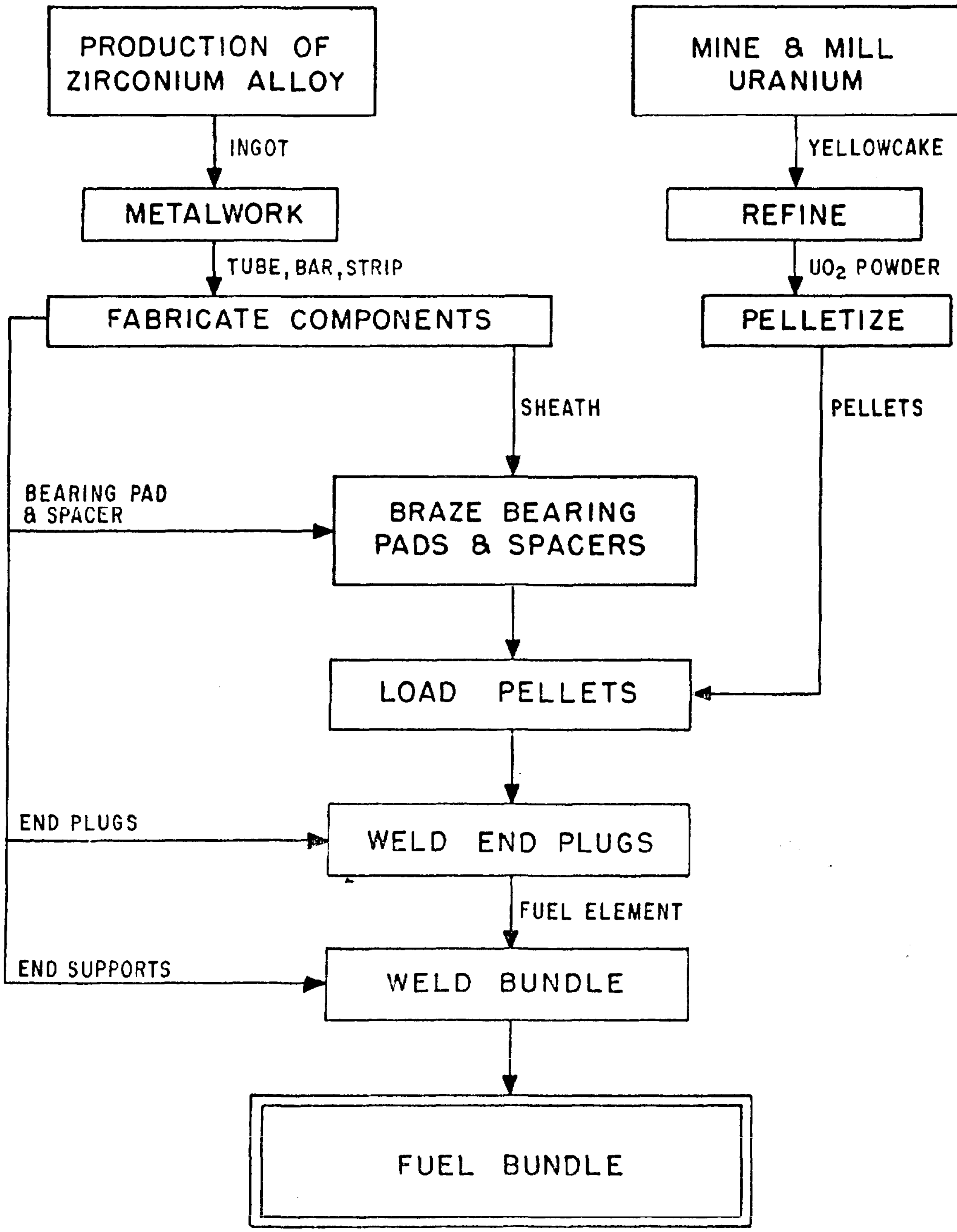
(d) adequate heat conductivity.

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% Zr + 1.7% Sn).

Figure 4

FUEL BUNDLE MANUFACTURE



Earlier fuel used Zircaloy-2, the difference being the depletion of nickel content and increase of iron content in Zircaloy-4 which leads to performance advantages with respect to

(a) corrosion

(b) deuterium pick up.

FUEL MANUFACTURE (Figure 4)

Fuel Material

Uranium is found in Canada in the form of uranium oxides. 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'. In the refinery the yellowcake is converted to ceramic grade UO_2, a black powder.

The UO_2 is then sent to the fuel fabricators (CGE and Westinghouse) where it is pressed and sintered in a hydrogen atmosphere ≈ 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 to allow 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, 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. Ontario Hydro then receives these bundles ready to load directly into the reactors.

SPECIFIC STATION DESIGNS

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

Table I Canadian Power Reactor Fuel: Design and Operating Data

REACTOR		NPD	NPD	DOUGLAS POINT	GENTILLY-I 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^Δ	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

Δ Pickering 1 and 2: 170
Pickering 3 and 4: 185
± 2 MWh/kgU

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

The original fuel charge for NPD contained wire wrapped 7-element bundles for the outer zone and 19-element wire wrap bundles for the central zone. The 7-element bundles are no longer in use.

At Douglas Point the initial fuel charge was all 19-element fuel (wire wrapped) similar to the NPD design. However, the replacement Douglas Point and NPD fuel abandoned the wire wrap design in favour of element spacing by spacer pads (Figure 2), the spacers being at an angle of 30° to each other to prevent interlocking of mating spacers. Also the bundle/pressure tube spacing is now achieved using three planes of bearing pads (Figure 2). These changes were made for two reasons.

- Significant fretting of the sheath by the wire wrap could occur at the coolant velocities obtained at Douglas Point and would have been more significant for Pickering.
- The wire wrap was found not necessary to provide coolant mixing to avoid local boiling, as was expected.

Pickering fuel uses the same length, element diameter and fabrication technique but the number of elements has been increased to 28 in order to fill the larger and now standardized ID of pressure tubes (103.4 mm). This then enabled the maximum bundle power to be increased by 50% over the Douglas Point bundles (Table 1).

At Bruce the number of elements/bundle has been increased to 37 elements providing a larger bundle power than Pickering with a similar element rating (Table I).

The cross sections of our fuel bundles are illustrated in Figure 5. The Gentilly (G1) fuel shown uses a 18-element bundle with a major change from CANDU fuel as all the fuel bundles are connected together to permit on-power refuelling from the bottom end of the reactor. To satisfy this requirement the central element was removed from the 18-element configuration and the vacant site used for a tubular tie rod which holds the bundles together in a string.

SPECIAL PURPOSE FUELS

The fuel design described above can be considered the basic natural uranium CANDU fuel. Other variations of our 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 (0.45% 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.

Enriched Fuel

For experimental purposes some fuel now being used at NPD and Douglas Point, has slightly enriched (~1 - 2%) U-235. Apart from the isotopic change this fuel is identical to the natural uranium bundles. In the long term AECL are proposing to use an alternative fuel cycle with fuel slightly enriched with plutonium extracted from the currently accumulating spent fuel in our storage bays. For this purpose AECL are considering setting up a Pu fuel fabrication plant at Chalk River.

Booster Fuel

To provide Xe poison override at NPD, Douglas Point and Bruce A booster rods containing highly enriched (90%) U-235 fuel are used. An example of the Bruce A booster rods is shown in the section on reactivity mechanisms. These particular rods consist of 6 bundles strung together vertically on a Zircaloy-4 support tube passing through the central space of the 19-element bundle configuration (Figure 6). 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 cooling circuit itself.

CANLUB Fuel

An improved fuel performance on the standard fuel is now being achieved for all new fuel at Douglas Point and Pickering called CANLUB fuel. This design incorporates a layer of graphite between pellet and sheath and has been shown to be effective in preventing defects due to power increases, which would likely have occurred under similar conditions with the non-CANLUB fuel. The purpose of the graphite layer is to reduce the friction between the sheath and the pellet to limit the sheath strain produced over cracks in the pellets. The layer also provides a barrier for vaporized iodine, possibly reducing the chance of iodine stress corrosion cracking of the sheath.

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 an organic lubricant, siloxane, as a possible alternative to graphite.

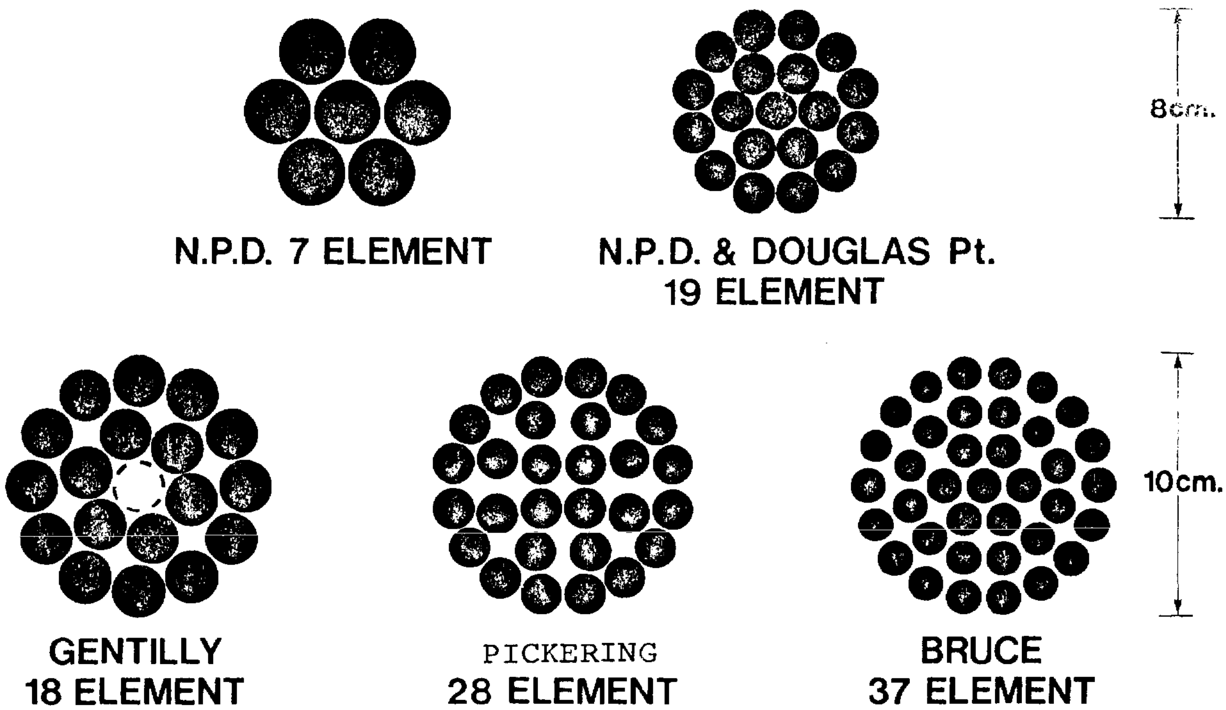


Figure 5 Fuel Bundle Cross-Sections

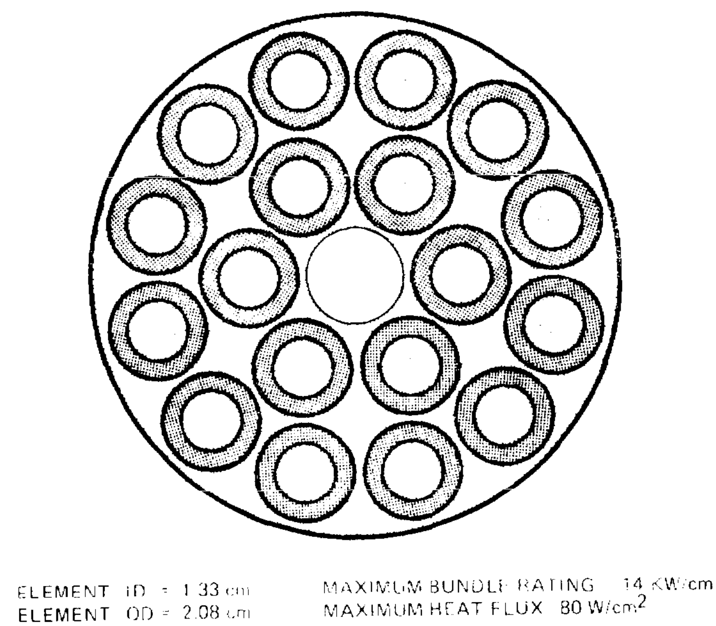


Figure 6 Bruce Booster Fuel Cross-Section

ASSIGNMENT

1. Referring to the data of Table 1 why was the original NPD fuel charge not all 7-bundle type?

2. Compare the fuel bundle design data for the reactors listed in Table 1 and explain the differences or similarities in the various specifications for each reactor.

D. Winfield