16 Reactor Fuel

16.1 Introduction

This module shows how fuel materials are selected and assembled to make a fuel bundle that is safe and economic. It also introduces some fuel performance and operating features.

Economic fuel operation requires a bundle to generate heat energy continuously for a long time. It does this routinely in the hostile reactor environment. Good fuel design allows energy extraction without fission product releases during normal plant operation.

Good fuel design also should prevent or limit fission product releases during accidents. No fuel design can prevent all releases in all circumstances. Fuel design and performance features combine with safe operating practices to prevent releases.

Sometimes a fuel bundle fails during normal operation. Failed fuel is fuel that releases fission products through a defect into the heat transport system. Defects vary from small holes in a poorly made bundle to large splits.

Figure 16.1 shows the design chosen for a CANDU fuel bundle. This bundle, used in all routine fuelling of CANDU reactors, is called CANLUB fuel. Many years of successful operating experience prove the safe and economic use of this fuel in normal operation.

To date, no serious accident has subjected CANDU fuel to extreme stress. Tests and analysis suggest it will contain most fission products effectively in these situations too.

The bundle in figure 16.1 is mostly uranium dioxide (UO_2), sheathed and held together by zircaloy. Zircaloy 4, the specific alloy used for this purpose, is 98% zirconium and 1.7% tin. The UO_2 is in the form of high-density pellets. Each fuel element is a thin zircaloy tube, the fuel sheath, filled with fuel pellets. A thin lubricating layer of graphite between the pellet and the sheath is what gives the fuel the proprietary name CANLUB.

Welded end caps seal the ends of each tube. End plates hold the elements in the required arrangement. Spacers brazed to the fuel elements keep them properly spaced. Bearing pads brazed to the outer elements keep the bundle centered in the fuel channel

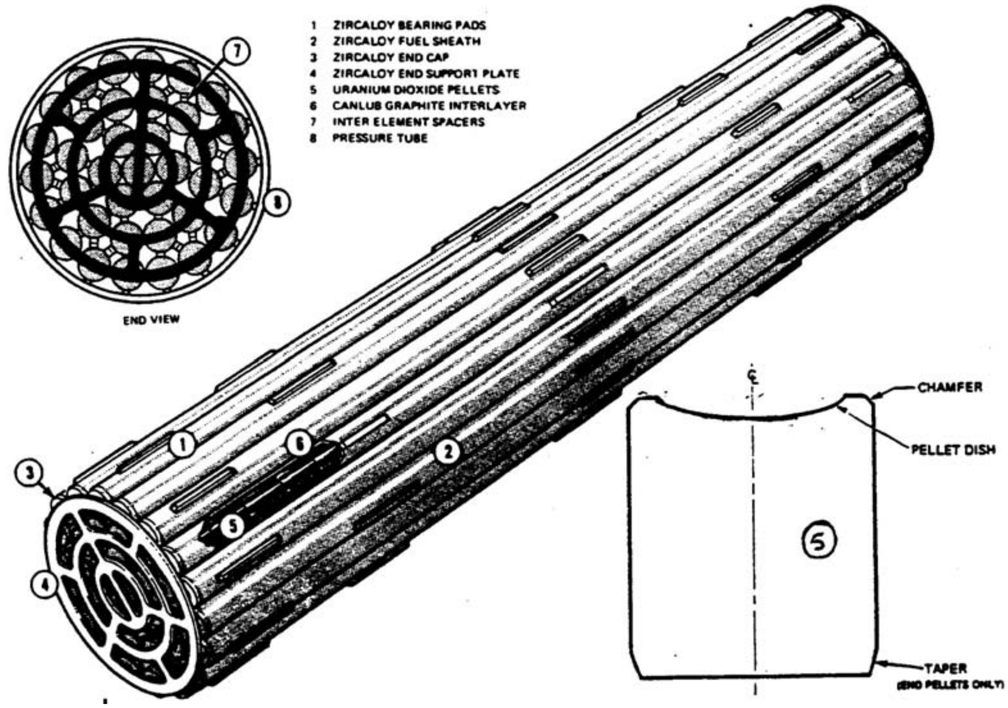

Figure 16.1
37-Element CANLUB Fuel Bundle & Fuel Pellet

The37 element bundle shown in figure 16.1 is used in the majority of CANDUs. Pickering bundles have 28,thicker fuel elements. The overall bundle dimensions are the same and both bundles contain about the same amount of uranium.

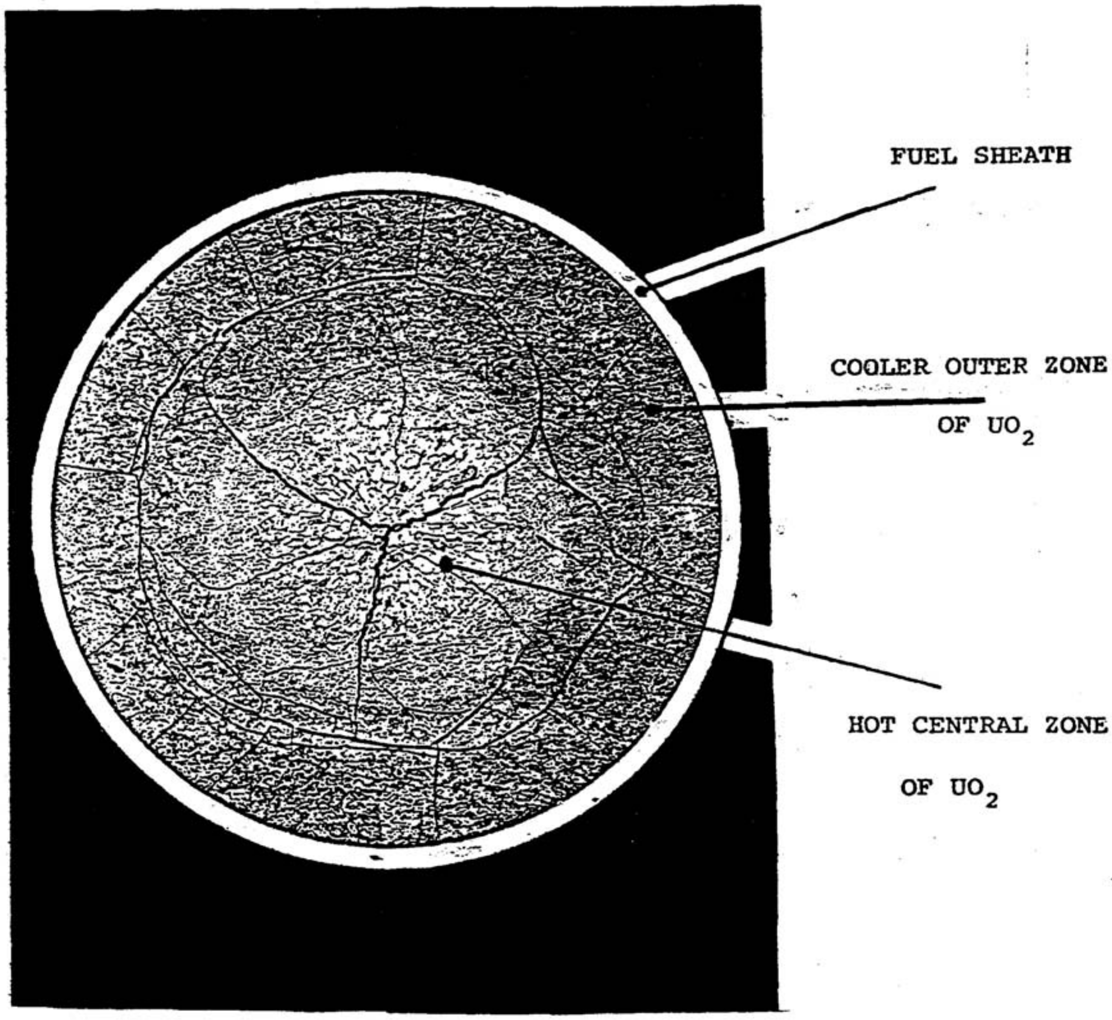

Figure 16.2
Cross Section through a CANDU Fuel Element

16.2 Summary Of Key Ideas

- Failed fuel is fuel that releases radioactive material. Good fuel design and construction produce fuel bundles that operate safely and economically.

- Safe operation implies that fuel does not release radioactive fission products during normal use or during accidents or upsets. Design and operating features combine to limit or prevent releases.

- Economic operation requires each bundle to supply its share of thermal power over a long period. Economics also requires safe reactor operation.

- Fuel elements are assembled to make fuel bundles. The elements are natural UO_2 sheathed in sealed zircaloy tubes. Zircaloy end plates, spacers and bearing pads keep the elements spaced properly.

- CANLUB fuel has a thin layer of graphite between the fuel pellet and the sheath.

16.3 Material and Fabrication

Uranium metal, uranium alloys and uranium compounds have been suggested or tried as reactor fuel. The combination of uranium dioxide (UO_2) for fissile material and zircaloy for sheathing and structural parts is the most common choice for commercial power reactors world wide.

16.3.1 The Fissile Material

There are several characteristics the fissile material should have:

High Fissile Content

High density uranium dioxide pellets contain only half as much uranium as the same volume of pure uranium metal. Natural uranium (0.7% U-235) nevertheless provides enough fissile U-235 to make a critical reactor using natural uranium dioxide fuel and a heavy water moderator.

Other moderators require fuel enrichment of UO_2 to between 2% and 5% U-235. Natural uranium metal can be used with a less expensive graphite moderator, but uranium metal is a troublesome fuel in other ways. This will be seen as we compare its properties with UO_2.

Separation and removal of U-238 increases the concentration of U-235 from the 0.7% found in nature. A CANDU would produce more energy per gram of U-235 using enriched fuel with enrichment between 1% and 2%.

Better use of uranium might not be worth the cost of enrichment. Even without enrichment, a CANDU reactor uses 15% less uranium than an equivalent light water reactor.

Efficient Heat Transfer

Poor thermal conductivity is the main disadvantage of uranium dioxide. Because of it, the fuel pellet interior is much hotter than the exterior. The hottest elements in the core have central temperatures near 1800 ºC for a 37 element bundle and 2200ºC for a 28 element one.

The manufacturer makes a dish shaped end in each fuel pellet to allow for thermal expansion. The hot interior of the pellet expands more than the exterior. The dish shape, shown in figure 16.1, also provides space for fission product gases to collect.

Hot uranium dioxide is not brittle. Shading in figure 16.2 marks the inner and outer regions of the pellet. During operation there are no cracks in the soft inner region. Thermal stress causes permanent radial cracks in the brittle outer region. These cracks may strain the surrounding sheath, but are not likely to cause fuel failures in normal operation.

Fission Product Containment

Uranium dioxide holds 95% of the fission products within its structure. Most of the fission products released come from the hot inner part of the pellet. These migrate to cracks in the cooler part of the pellet and escape into the spaces between the pellets. Some of this free inventory escapes if the fuel element ruptures.

The pellet is the first barrier to the release of fission products to the public. Even a 5% release is not acceptable. For example, in the Chernobyl reactor explosion, between 5% and 10% of the fission products in the core escaped to the atmosphere.

Chemical Compatibility with the Surroundings

Uranium dioxide resists corrosion better than most materials. In contrast, hot uranium metal is very corrosive in hot water. Commercial reactors with metal fuel use gas cooling and a graphite moderator. It does not react with the sheathing material. If the sheathing fails, UO_2 reacts weakly with water. Corrosion is not a problem in normal operation.

Uranium dioxide reacts with oxygen. This could be a problem after a reactor accident if, for example, air contacts the fuel pellets. Breakdown of the UO_2 would result in fission product release.

High Melting Temperature

Uranium dioxide melts at a very high temperature, higher than 2700ºC. This partly offsets the disadvantage of poor thermal conductivity. Even though the central temperature is very high, there is a large margin to melting in normal operation.

Under accident conditions the surface of the bundle may become covered with steam. This causes poor heat transfer and uranium dioxide in the centre of the pellet may melt. Two mechanisms can cause fuel element failure under these conditions: thermal expansion of molten UO_2 stresses the sheath; hot, molten UO_2 may contact the sheath and melt a hole in it. It is important to keep the fuel wet because water cooling will usually prevent fuel failure.

Stability in the Reactor Core

Uranium dioxide is stable under wide temperature variations and intense neutron and gamma radiation. Some materials behave badly when irradiated.

The main disadvantage of uranium metal, for example, is that it changes shape and size during exposure in the core. Uranium metal was used in the world's first commercial power reactor, the British Calder Hall reactor. The fuel was made from natural uranium metal castings, clad with a magnesium alloy. Fuel was routinely removed before it had time to distort. This limits time in the reactor and makes uranium metal fuel uneconomic.

Ease of Fabrication

Uranium dioxide is a chemically inert black powder. A punch and die operation forms compacted UO_2 pellets. These pellets are too big and not dense enough or strong enough for reactor fuel. Sintering the pellets at high temperature in a hydrogen atmosphere reduces their volume by 25%. This makes them into hard, dense ceramic pellets. Grinding them to size polishes the surface. This improves the thermal contact with the sheath.

The expensive difficulties that can be faced in making fuel are illustrated by uranium metal fuel. Uranium metal can be machined, however, the turnings spontaneously combust in air. Fine machinings and dust are hazardous, both because uranium metal is chemically toxic and because it is radioactive.

16.3.2 The Sheath Material

The fuel sheath is the second barrier to the release of fission products. Zircaloy satisfies the requirements for a good fuel sheathing material.

Low Neutron Absorption
Zircaloy absorbs very few neutrons. High neutron absorption rules out most other materials. For example, steel has good structural properties but absorbs too many neutrons. More fuel is needed if neutron absorption is too high.

Mechanical Strength
Zircaloy has good structural rigidity and ductility under operating conditions. Aluminum satisfies the other requirements for a good sheathing material. This less expensive choice has inadequate high temperature strength.

When the fuel temperature changes, the fuel and sheathing do not expand or contract at the same rate. Friction between fuel and sheath can stretch and weaken the sheath. In CANLUB fuel, a thin layer of graphite between the pellet and sheath reduces friction and sheath strain.

Zircaloy loses strength at high temperature. It melts above 1800ºC, but begins to weaken above 1000ºC. At low temperature, below about 1500ºC, zircaloy becomes brittle. This is especially true for irradiated bundles. Fuel should not be moved in a cold core.

Adequate Thermal Conductivity
The zircaloy sheath has good thermal conductivity, but the gap between pellet and sheath hampers heat removal. In normal operation the heat transport system pressure forces the sheath against the smoothly ground surfaces of the pellets. The CANLUB graphite layer may improve the thermal contact.

Accident conditions impair heat removal from some fuel elements. When the heat transport pressure is low, gas pressure inside the element may lift the sheath away from the pellet. Only old bundles contain enough fission product gas for this. Accident conditions produce high temperatures that expand the gas and strain the sheath.

Mechanical stress will cause some fuel failures during a large loss of coolant accident. Stress may come from internal gas pressure or thermal expansion of UO_2. In an accident, this mechanical stress combines with sheath weakness at high temperature to cause failures.

Chemical Compatibility with Fuel and Coolant
Zircaloy has good corrosion resistance in water at the normal operating temperature. It is chemically compatible with uranium dioxide, but some fission products attack it The CANLUB graphite layer, by

holding on to some of the more corrosive fission products, helps protect the sheath from chemical attack.

In an accident, high temperature steam quickly oxidizes the zircaloy sheath. Oxidation makes the sheath brittle. Oxidation will cause some fuel failures in a large loss of coolant accident

16.4 Summary Of Key Ideas

- Uranium dioxide (UO_2) is a black ceramic material that is easy to fabricate.
- UO_2 remains intact under intense heat and radiation in the reactor core.
- UO_2 is chemically compatible with fuel sheathing material and with hot coolant.
- The fuel pellet is the first barrier to fission product release. The ceramic matrix of UO_2 holds about 95% of the fission products.
- Natural UO_2 contains about half as much uranium as does pure uranium metal. This is enough to build a heavy water moderated reactor without fuel enrichment.
- The low thermal conductivity of UO_2 results in high fuel temperatures. Low thermal conductivity is acceptable because UO_2 has a very high melting temperature.
- The fuel sheath is the second barrier to fission product release. Zircaloy has the best combination of properties to fill this role.
- Zircaloy has low neutron absorption combined with good mechanical strength and good thermal conductivity.
- Zircaloy resists corrosion in normal operation.
- A thin graphite layer between pellet and sheath reduces destructive chemical and mechanical interactions between the pellet and sheath.
- Zircaloy is brittle at low temperatures. Fuel could crack if moved in a cold core.

- Zircaloy weakens at high temperature and hot steam oxidizes it, making it brittle.

16.5 Fuel Handling

16.5.1 New Fuel Handling

The ceramic UO_2 is brittle and may chip if fuel bundles receive rough handling. These chips or the sharp edges they leave may puncture the sheath.

The new fuel should not introduce contaminants to the heat transport system. These could increase corrosion or cause erosion damage to the fuel or heat transport system. In the turbulent flow of the fuel channel small pieces of debris have punctured fuel sheaths.

To satisfy the preceding requirements, several precautions are taken in handling new fuel:

a) Bundles are kept in their original containers on the shipping pallets until needed for fuelling. Devices (accelerometers) attached to the shipping containers indicate any severe jolts the bundles might have received during handling prior to fuelling.

b) The bundles are unpacked by band and inspected. Bundles are handled horizontally as the pellets rattle and may chip when the bundle is turned end over end.

c) During fuelling, there is a time limit on how long a bundle may sit in the coolant cross flow in the end fitting. A bundle exposed to excessive vibration is not fuelled.

d) Before a bundle is selected for fuelling, its size is carefully checked for dimensional accuracy. If the outer diameter is too small, the coolant flow will make it vibrate in the fuel channel This could chip the uranium dioxide or cause fretting damage to the sheath or pressure tube. If the outer diameter is too large, excessive force is needed to move it. The pressure tube sags slightly and an oversized bundle will bind as it slides.

e) Visible dirt is removed with a clean cloth to make sure contaminants are not introduced to the heat transport system.

f) Bundles are handled with clean cotton gloves to prevent contamination from sweat.

g) New fuel is loaded by hand into the new fuel transfer system. The transfer system then loads it into a fuelling machine through a shielded port.

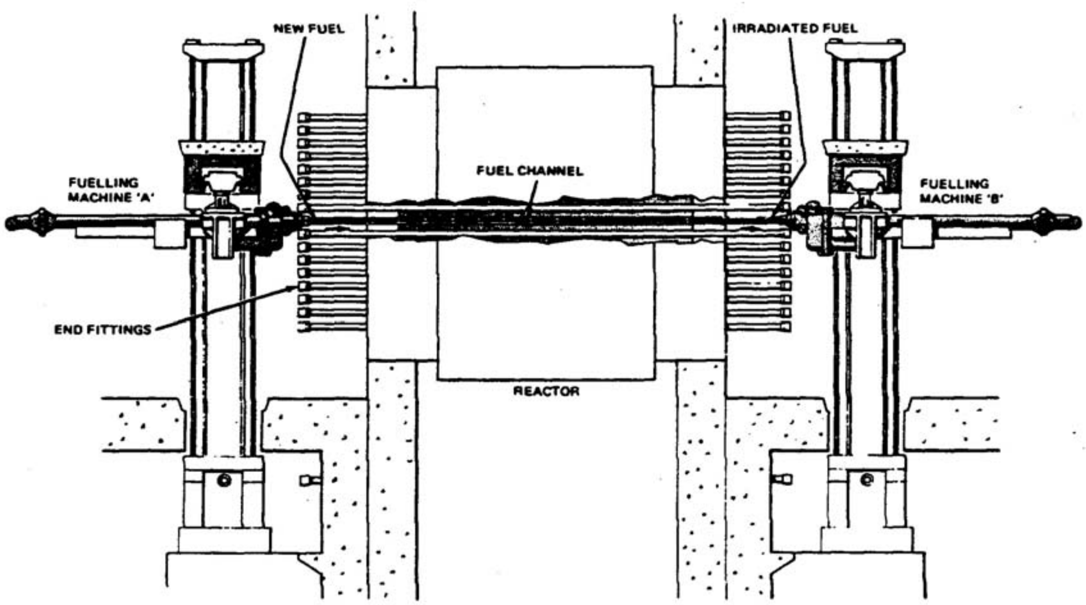

Figure 16.3
The Fuelling Machines in Action

16.5.2 Fuelling
In a CANDU reactor, fuelling is a routine operation. A pair of remotely controlled fuelling machines insert new fuel and remove old fuel while the reactor is running. Figure 16.3 shows the machines aligned with a fuel channel.

The two machines move into alignment at opposite ends of the reactor. Each fuelling machine has a snout that locks on to the end fitting of the channel to be fuelled. When the seal is tight, pressure in the fuelling machines increases to the pressure of the heat transport system.

Behind the fuelling machine snout is a rotating magazine, much like a revolver barrel. A tool in each fuelling machine, the ram assembly, removes the closure plug and the shield plug before fuelling starts. The magazine stores the plugs during fuelling.

Several magazine chambers in one fuelling machine contain pairs of new fuel bundles. The corresponding chambers in the second machine are empty. The ram inserts new bundles two at a time, displacing irradiated bundles into the empty chambers of the second machine.

After fuelling, the ram replaces the shield and closure plugs and the fuelling machines release from the channel.

Either machine can load or receive fuel They insert fuel in the opposite direction in adjacent channels. At some stations, fuelling is in the same direction as coolant flow. In others, fuelling machines insert fuel against the flow.

The fuelling machines usually replace four or eight bundles in a channel on each visit. The fuelling engineer works out details of the fuelling strategy. Fuelling of a channel typically takes two to three hours. Steady operation at full power requires about 100 to 140 bundles (a dozen or so channels) per week.

16.5.3 Handling Spent Fuel

Fission product decay generates heat in spent fuel. The amount of heat is large when the fuel is first removed. Water cooling continues during removal and transfer. Even a few minutes of air exposure may be enough to cause a bundle defect. Cooling continues during storage.

Fuel from the reactor is lethally radioactive. It must be handled remotely and shielded. The fuelling machine discharges spent fuel to remotely controlled equipment. The irradiated fuel transfer system then moves it to the shielded spent fuel storage location. Underwater storage provides both shielding and cooling.

Irradiated fuel is brittle when cool. Handling is reduced by transferring and storing the irradiated bundles on trays.

Defective fuel should be removed from the reactor. Most defects get worse if they are left in. These defects can have several serious consequences: Fission products released into the coolant increase the radiation dose to plant staff. High radiation levels can limit the time workers are allowed to spend in the plant. This increases the cost of routine work at the station.

High concentration of fission products in the coolant increases the risk of release to the public. High iodine 131 concentration requires that the plant be shut down.

Contamination of the coolant and heat transport system piping increases background radiation and makes it hard to detect or locate the next defect.

Once removed, a defective fuel bundle is canned in a sealed water filled container. It, like the intact bundles, is stored under water for cooling and shielding.

The operating license limits the amount of radioactive fission products in the coolant.

16.6 Depleted Fuel and Flux Flattening

In addition to normal CANLUB fuel, depleted fuel is sometimes used for special purposes. Depleted fuel bundles are the same as standard bundles, except they contain about 0.4% or 0.5% U-235, compared to 0.7% for the natural uranium bundles.

During normal, long-term operation, the exposure of the fuel to neutrons varies from place to place in the reactor. The fuelling engineer selects fuel replacement times and places to even out the availability of neutrons across the core. This is known as neutron flux flattening. The oldest fuel, which absorbs many neutrons uselessly, is left longer in areas of the core where the neutron flux tends to be high. Fresh fuel, which gives a higher rate of fission per neutron, is inserted into regions where the neutron flux is lower.

Depleted fuel is used to help flatten flux in a freshly fuelled reactor. In a new or a retubed reactor, all the fuel is new fuel. During the first month or two of operation the uranium content is high. Neutron absorbing fission products take time to build, but the fissile plutonium content increases rapidly at first. The flux flattening effect of high burnup fuel is missing. Typically, one depleted bundle, near the middle of each central core channel, helps flatten the flux.

Depleted bundles are often used to flatten flux when defective fuel is removed from a channel. Replacing fuel ahead of schedule often causes a local hot spot. The fuelling engineer selects locations for depleted bundles. Depleted bundles are placed in the channel to keep the power output similar to before.

Used fuel that is removed to get the defective bundle out is not replaced in the channel. Too much handling of irradiated fuel will likely damage it.

16.7 Summary Of The Key Ideas

- New fuel is handled horizontally with cotton gloves. Visible dirt is removed with a dean cloth. Careful handling reduces fuel pellet chipping and sheath damage and prevents chemical contamination.

- There is a limit on the time a new bundle may sit in coolant cross flow. Bundle vibration in the cross flow could chip the pellets.

- Accurate bundle dimensions are important to prevent damage to the bundle and pressure tube. Bundles that fit loosely in the channel vibrate. Bundles that are too tight require excessive force to move them.

- Identical fuelling machines lock on opposite ends of a fuel channel to refuel it. One machine inserts new fuel and the other accepts spent fuel.

- The fuelling machine includes a snout, a revolving magazine and a ram tool. The snout connects the fuelling machine to the channel. The ram inserts and removes plugs and fuel bundles and stores them in the magazine.

- Spent fuel requires cooling and shielding. Handling is kept to a minimum because the irradiated fuel is brittle. Spent fuel is stored underwater on trays. Defective fuel is placed in sealed canisters for underwater storage.

- Fission products from failed fuel increase the radiation dose to plant staff and makes later defect detection and location difficult. High concentrations could require a shutdown to reduce public risk.

- The fuelling engineer uses depleted fuel, with 0.4% or 0.5% U-235 content instead of 0.7%, to flatten flux. This is necessary in a fresh core where all the fuel is new fuel. It is often required when a channel is refuelled prematurely to remove defective fuel

16.8 Assignment

1. The text lists desirable properties of fuel materials, both for the fissile content of the fuel and for the fuel sheath. For each property listed, state if it is important for economic operation of the fuel or for safety in normal operation.

2. For each of the properties in question 1 that you listed as affecting safe operation, describe how the fuel could behave in an accident.

3. How does the CANLUB graphite layer help prevent fuel defects in the normal operation of CANDU fuel?

4. Give two reasons for using depleted fuel.

5. What are the three operational results of not refueling a channel containing failed fuel?

6. Describe how refueling of a channel is done. Include the removal of old fuel in your description.

7. Compare the handling of fresh and spent fuel.