SESSION 5 - Design of Fuel Channels

The CANDU fuel channel is essentially the same in all CANDUs, and is considered a fundamental building block in the CANDU system. Its design is the result of continual, intensive development of its components, reflecting a very large amount of operational experience in over 10,000 operating channels, totalling more than one billion hours of operation. The development is aimed at maximizing its durability and longevity while maintaining the optimal thickness of neutron absorbing pressure tube material in the core. Excessive in-core material would cause excessive burn-up penalty on the fuel, with significant negative effect on operating costs. Accordingly, the basic design of the fuel channel is fairly simple and functional, but its components have been extensively refined through optimization and continued development. Accordingly, this session focuses on the special aspects of functional requirements, operating conditions and service factors and their influence on the present configuration and construction of the fuel channel components, including use of specialized materials.

5.1 Functional Description

The fuel channels support and locate the fuel in the reactor core and allow the pressurized Primary Heat Transport (PHT) coolant to flow through it to remove the heat generated in the fuel by the nuclear fission process. The channels also allow refuelling while the reactor is operating at full power. This is performed by two fuelling machines that can each latch onto one end of a channel, as illustrated in **Figure 1-1**.

5.2 Basis for Design

Current CANDU 6 reactors have a design life of 40 years at an average 85% capacity. The pressure tube design life is 25 years at the reactor's 85% capacity factor. As the pressure retaining items enclosing the fissioning fuel, the fuel channels and its components are designed to meet the specified service requirements, and to meet applicable standards. However, the fuel channel design is highly optimized because excess thickness of material causes significant operating cost penalties, owing to excessive fuel burn-up penalties due to unwanted neutron absorption. The design of the CANDU fuel channel is accordingly the result of continuing intensive engineering development. Discussion of the process of its design necessarily revolves around a very detailed review of the highly refined details of its major components.

The design of the channel meets the following requirements:

a)   Supports the weight of the fuel, as well as that of the HT coolant, contained within the

channel and locates the fuel within the reactor core. This requires restraining the fuel string against the drag force due to the coolant flow.

b)   Forms part of the PHT system pressure boundary. This requires that the integrity of the channel's pressure retaining components be demonstrated for all service conditions. This is achieved by satisfying the Class 1C requirements of CSA Standards N285.0, and N285.2. These standards also refer the designer to the ASME, Section III, Class 1 requirements for design rules.

c)   Contains the heavy water PHT coolant with very small leak rates. The end fitting-to-feeder pipe bolted connection leakage does not exceed 0.045 gm/hr per connection

d)   Permits the PHT coolant to efficiently remove heat from the fuel with low pressure drop and a low level of turbulence, etc., to minimize fuel vibration.

e)   Operates reliably for all temperature and pressure conditions that it may experience. Key operating parameters are listed in **Section 5.7**, below.

f)   Allows the fuelling machines to make leak-tight connections onto the ends of the channels, and provides removable internal end fitting components (closure plug and shield plug) so that refuelling can be efficiently performed while operating at full power. This also provides ready access to permit pressure tube inspections to be performed, during shutdowns.

g)   Provides clearance and allowance for axial and diametral pressure tube dimensional changes due to thermal- and flux-induced creep and growth.

h)   Uses low neutron absorbing materials for components in the core of the reactor. Zircaloy and Zircaloy-2.5% Ni alloys are used almost entirely.

I)   Includes provision for corrosion and wear allowances. A 0.2 mm allowance is added to the pressure tube wall thickness beyond that which stress analysis indicates is required.

j)   Provides shielding to attenuate radiation streaming where the channel passes through the end shields. The fields near the outboard ends of the end fittings, at full power, do not exceed a fast neutron flux of $2 (10^9)$ n/m²/sec and the gamma radiation does not exceed 30 rads/hour. Shutdown fields are much less, and permit controlled maintainer access 24 hours after shutdown.

k)   Provides an axial clearance between the shield plug inboard faces and the fuel string to accommodate irradiation elongation and differential thermal expansion of the fuel and fuel channel components. The hydraulic drag of the PHT flow keeps the fuel firmly seated

against the downstream shield plug.

l)   Minimizes thermal losses to the moderator and end shield cooling system during normal operation. The low-pressure gas-filled annular gap between the pressure tube and calandria tube provide effective thermal insulation.

m)   Monitors the humidity of the gas in the annulus between the pressure and calandria tube so that any leakage from them can be detected very soon after it starts.

n)   Allows fuel removal with one fuelling machine disabled, utilizing the hydraulic drag of the PHT flow to push the fuel from the channel into the machine.

o)   Allows replacement of pressure tubes. Key joints are relatively accessible and designed to permit unbolting and re-assembling or cutting and re-welding, using simple manually operated, long-handled tools, operated from the fuelling machine vault, at the end fitting end.

5.3   Fuel Channel Assembly Structural Description

The core of a CANDU 6 reactor is enclosed and supported by the horizontal cylindrical calandria vessel, whose ends are closed by the end shields, which are joined by the horizontal calandria tubes. A fuel channel assembly passes through each calandria tube, with its end fittings supported in bearings in the end shields, as illustrated schematically in **Figure 1-2.** A detailed cross–section of the fuel channel assembly is shown in **Figure 5-1**, and a pictorial view is shown in **Figure 1-5.**

5.3.1   Pressure Boundary Components

At each end of the fuel channel a PHT feeder pipe is attached by a bolted connection onto a side port in the end fitting, and some of the channel components form part of the PHT pressure boundary. These components are the pressure tube, two end fittings, their two closure plugs and the two feeder pipe connections.

The pressure tube, which supports and locates the fuel inside the reactor core, is the major component of the fuel channel. It is a straight tube with an inside diameter of about 104 mm, a wall thickness of about 4 mm and a length of about 6.3 metres. The pressure tube material, Zr–2.5%Nb, was selected because it has low neutron absorption, good corrosion resistance, good creep and growth resistance, good creep ductility and high strength to permit thin tube walls, so as to obtain good fuel economy. It also has excellent consistency in producing these properties as well good manufacturability and inspectability characteristics, which are extremely important for this key component in the CANDU design.

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An end fitting is connected to each end of the pressure tube using a high integrity roll–expanded joint, as shown in **Figure 5-2**, which AECL has qualified for in–reactor use by an extensive testing program. Each end fitting passes through a lattice tube in a reactor end shield and extends outboard of the reactor end shield. End fittings are about 2.4 metres long and about 160 mm in diameter, with a varying cross–section. **See Figure 5-3.**

Near the outboard end of each end fitting, there is a bolted Tee- connection to a feeder pipe of the PHT system. Each feeder to end fitting connection consists of a metallic seal ring, a hub on the feeder pipe, a flange, four cap screws, a lock plate and a lock wire. **See Figure 5-4.**

A channel closure is held in position at the outboard end of each end fitting by retractable jaws which engage in a groove in the end fitting bore. See **Figure 5-5.** Its inboard end seals against the seal insert ring in the bore of the end fitting to provide the HT pressure boundary at the outboard ends of the fuel channel. During refuelling, a fuelling machine clamps and seals itself onto the end of the end fitting, engaging on grooves and faces provided there. It then removes the closure plug from the channel and temporarily stores it inside itself, while the fuel is being changed.

5.3.2 Non–Pressure Boundary Components

The non–pressure boundary fuel channel components are the annulus spacers, liner tubes, bearing sleeves, journals rings, shielding sleeves, bellows assemblies and positioning assemblies.

Four annulus spacers, spaced about a metre apart along the pressure tube, ensure that an insulating annulus is maintained between it and the calandria tube surrounding it. The circulation of dry, low-pressure CO_2 through this annulus provides thermal insulation and also allows pressure tube leakage to be quickly detected, if it ever occurs. The calandria tube provides support for the pressure tube contained inside it through these four annulus spacers.

Each spacer is made by forming Inconel wire into a coiled helical spring whose coils are 4.8 mm in diameter, slightly less than the gap between the two tubes. It is stretched around the pressure tube and its ends are hooked together so each spacer is a tight fit around a pressure tube. See **Figure 5-6.** The spacer clearance in the annular gap between each pressure and calandria tube accommodates up to 5% increase in pressure tube diameter due to creep. Axial movement of the pressure tube relative to the calandria tube surrounding it is accommodated by rolling of the spacers, which results in almost no wear of either the pressure or calandria tube.

A liner tube extends through each end fitting, as shown on **Figure 5-7**, to provide a continuation of the pressure tube bore. (The free end of the end fitting is on the left). This allows free movement of fuel into and out of the pressure tube. The liner tube is held in the inboard bore of the end fitting by a roll–expanded joint. The PHT coolant passes through the end fitting in the

annulus between the liner tube and the end fitting bore. This coolant enters or exits the pressure tube via flow holes in the inboard region of the liner tube and shield plug.

A shield plug is located inside the liner tube of all end fittings to provide radiation shielding where the end fitting passes through the reactor end shield, as shown on **Figure 5-7**. It is latched into a groove in the bore of the liner tube. The shield plug at the outlet end of the channel axially supports the fuel bundles against the hydraulic force of the coolant flow, and holds them in position in the reactor core. During refuelling, a fuelling machine removes the shield plug from the channel and temporarily stores it inside itself. The inboard end of the shield plug is designed to reduce the flow turbulence of the coolant before it enters the fuel.

Two sets of bearing sleeves and journal rings support each end fitting in the lattice tube of the reactor end shield. The journal rings are held in position by retaining rings. One set of bearings and journals are located near the middle of the end fitting and the other set is located near its inboard end. See **Figures 5-2** (inboard end) and **5-8** (outboard end). The bearings are designed to accommodate at least 153 mm of pressure tube elongation. The maximum pressure tube elongation predicted for 25 years at 85% capacity factor is less than this value.

A shielding sleeve fits around the outside diameter of each end fitting and overlaps a step in the lattice tube to prevent radiation streaming through the gap between the end fitting and bore of the lattice tube, as shown on **Figure 5-7**.

A bellows assembly as shown on **Figure 5-9** is attached to each end fitting just outboard of a reactor end shield, as shown on **Figure 5-8**. This assembly closes the annular gap between the end fitting and lattice tube while allowing relative movement between the channel and the calandria due to thermal effects and pressure tube elongation. The assembly consists of a bellows ferrule at one end of the bellows and a flange at the other end. The flange is welded to an attachment ring that is shrunk fit on the end fitting body. The bellows ferrule is welded to the outboard end of a lattice tube. The ferrule portion of the assembly has a tube connection for the Annulus Gas System that provides very sensitive leak detection instrumentation to detect pressure or calandria tube leakage, should it ever occur.

A positioning assembly is attached to each end fitting just outboard of the bellows assembly as shown on **Figure 5-10.** This assembly is used to locate the fuel channel assembly axially in the reactor. It consists principally of a yoke and a stud, and a nut that connects them. The yoke fits in a groove on the outside of the end fitting. The stud is threaded into the reactor end shield and locked with a pin. The stud extends through the yoke and is attached to it by the nut. The nut and the stud's outboard end both have intermittent threads so a 90 degree rotation of the nut disengages that assembly, to determine which end of the channel is attached to the reactor. A locking spring holds the nut in the desired location. To avoiding restraint of pressure tube thermal expansion and creep elongation, only one end of each channel is restrained at any time. After about 15 years service, the assembly at the original end is released and the one at the other end is

engaged, so that half of the channel's lifetime elongation is taken up at each end.

The calandria tube functions as a part of the calandria vessel from a structural viewpoint, and is not considered a part of the fuel channel assembly, but is a major interface component. A calandria tube surrounds each pressure tube and is separated from it by the four annulus spacers located in the insulating annulus between these two tubes. These spacers transmit some of the weight of the pressure tube, fuel and HT coolant to the calandria tube. In fact, they act as coupled beams, both having distributed vertical loads, and both having their ends built in against end rotation, but the pressure tube is free of axial fixing loads. The calandria tube has axial thermal restraint due its being built into the end shields. The pressure tube has external tension load applied due to its internal pressure. As the calandria tube is much cooler than the pressure tube, it provides much of the sag resistance for the fuel channel and restricts its sag to about 80 mm. This ensures that there will not be interference to fuel passage and that the channels will not sag into contact with the horizontal mechanisms located below them.

5.4   Manufacturing Requirements

The following is a description of the materials used to manufacture the fuel channel components, and a brief summary of the manufacturing steps for the key fuel channel components.

5.4.1 Pressure Tube

The pressure tubes are fabricated from extruded, cold worked and stress relieved Zirconium 2.5 wt% Niobium seamless tubing to the requirements of AECL specifications that comply with CSA Standards N285.6.1 and N285.6.7. This material is not used for pressure retaining items in light water reactors, so is not included in lists of code materials in the ASME code. AECL has qualified this material for in-reactor use by an extensive testing program, which has the following minimum mechanical properties at 300°C:

-    ultimate tensile strength of 480 MPa

-    0.2% yield strength of 330 MPa

-    12% elongation.

The principal steps in the manufacture of the pressure tubes are:

a)   production of Zirconium metal sponge from sand

b)   making of sponge into electrodes for vacuum arc furnaces

c)   multiple melting in vacuum arc furnaces

d)   ingot sampling and inspection

e)   ingot cutting and hot forging (using press and rotary forges)

f)   machining of forged logs into hollow billets

g)   inspection of billets

h)   beta heat treatment and quenching of billets

I)   hot extrusion of billets

j)   cold drawing of the extruded billets

k)   inspection of cold drawn tubes, including ultrasonics in longitudinal and transverse
        directions, eddy current and dimensions check

l)   corrosion and tensile tests and hardness measurements on off-cuts

m)   hydrostatic pressure test to a hoop stress of at least 330 MPa at 20°C

n)   autoclaving to produce an oxide on the surfaces.

5.4.2   End Fittings

The end fittings are manufactured from a modified AISI 403 stainless steel to the requirements of
AECL specifications that comply with CSA Standard N285.6.8. This material was selected for
end fittings because it has good corrosion resistance and high strength. This material has the
following minimum mechanical properties at 21°C:

-   ultimate tensile strength of 725 MPa

-   yield strength of 585 MPa

-   12% elongation.

The principal steps in the manufacture of the end fittings are:

•   air melt steel and produce ingots for forging

•   forge to rough dimensions and press straighten as required (cold)

•   rough turn and bore a 9.5 cm hole through the forging

•   quench and temper the forging

•   perform mechanical, chemical and physical tests on off-cuts

•   clean forging blanks and perform ultrasonic inspection

•   rough machine forging

•   stress relieve and perform final machining.

After final machining, the end fitting bodies are hydrostatically tested to 15.2 MPa at 21°C and
the outside surfaces of the fuelling snout region are hard chrome plated to Specification AMS

2406. The liner tube, bellows attachment ring and closure seal insert are installed by the end fitting manufacturer before the end fittings are shipped to site.

5.4.3 Liner Tube

The liner tube is fabricated from stainless steel seamless tube, ASTM A–268, Grade TP–410. The material is hardened and tempered to give the following minimum mechanical properties at 21°C:

-       ultimate yield strength of 691 MPa
-       0.2% yield strength of 518 MPa.

5.4.4 Closure Seal Insert

The closure seal insert, which is located in the bore of the end fitting near its outboard end, is manufactured from stainless steel forging or bar stock, ASME SA–564, Type XM–16, H1000. The material is rough machined in the annealed condition, and then aged prior to finish machining. Following aging, the material hardness is RC 40–50. The outside of the seal insert is gold plated to Specification MIL–G–45204.

5.4.5 Feeder to End Fitting Connection Assembly

a)   Hub - Manufactured to AECL specifications from carbon steel forgings to meet the requirements of ASME Specification SA–105.

b)   Seal Ring - Manufactured to AECL specifications from a modified type 410 stainless steel material.

c)   Flange - Manufactured to AECL specifications from alloy steel, ASME SA–541, Class 1C material.

d)   Capscrews - Manufactured to AECL specifications from ASME SB–637, Grade UNS N07718 precipitation–hardened nickel alloy material.

e)   Lock plates - Manufactured from ASTM A–619, cold rolled, drawing quality, 24 gauge strip.

f)   Lock wire - Manufactured from stainless steel, Type 302, spring tempered.

5.4.6 Annulus Spacers

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The annulus spacer that separates the pressure tube from the calandria tube surrounding it is a coiled spring, with a girdle wire passing through the centre of the coils. **See Figure 5-3.** The coiled spring is made from 0.76 mm square Inconel X–750, AMS 5698D wire. The girdle wire is made from 1.27 mm diameter cold drawn reactor grade Zirconium alloy, ASTM B351, Grade R60802 material. The coiled spring is formed, then the wire at each end is formed into a hook and the two ends of the spring are hooked together to form a torus. The girdle wire is then threaded inside the coils and the spacer is precipitation heat treated at 732°C for 16 hours in a vacuum.

5.4.7 Bellows Assembly Components

The bellows material is nickel–chromium–iron alloy UNS N06600 (Inconel 600) strip, ASTM Specification B–168, cold rolled, annealed, deep drawing quality. The ferrule is machined from austenitic stainless steel type 304L seamless pipe, ASTM Specification A–312. The flange is machined from seamless carbon steel pipe, ASTM Specification A–106, Grade C.

The bellows is manufactured, tested and inspected to the requirements of AECL specifications which generally follow the intent of ASME Section III for Class 3 components. The key manufacturing steps for the bellows are:

a)   Inconel strips are formed into cylinders by rolling;

b)   longitudinal edges of the cylinders are welded;

c)   3 concentric cylinders are used to form a 3 ply wall;

d)   convolutions are formed by hydraulic pressure;

e)   the ferrule and flange are welded to the bellows ends;

f)   1 in 10 sampling of the bellows longitudinal welds for liquid penetrant examination;

g)   circumferential welds between bellows plies and the flange and ferrule are liquid penetrant examined;

h)   bellows are leak tested at 0.24 Mpa.

5.4.8 Bellows Attachment Ring on End Fitting

The shrunk fit ring on the end fitting body for attaching the bellows is fabricated from high strength steel centrifugal casting material to the requirements of AECL specifications, which generally meet the requirements of ASTM A–148.

5.4.9 Positioning Assembly Components

The positioning assembly components are manufactured using the following materials:

a) Stud   - alloy steel, ASTM Specification A–193–B7

b) Nut   - alloy steel, ASTM Specification A–194–G7 or G7B

c) Yoke   - structural steel, ASTM Specification A–36

d) Locking Spring   - type 302 stainless steel, ASTM Specification A–666.

5.4.10 Bearing Sleeves, Journal Rings, Retaining Rings and Shielding Sleeves

The bearing sleeves and journal rings are fabricated to the requirements of AECL specifications. The bearing sleeve material is AISI Type A–2 tool steel. The journal ring material is AISI Type D–2 tool steel. The retaining rings are manufactured from Type 302 stainless steel, cold–worked to give a minimum tensile strength of 1034 MPa. The shielding sleeves are manufactured from ASTM A–519, Grade 1025 material, except that the cobalt content is limited to 0.05%. The shielding sleeves are nickel plated for corrosion resistance.

5.4.11 Channel Closure

The body of the closure plug and many of its mechanical components are machined from ASTM Type A564 630 stainless steel, Malcomized to reduce wear and galling. There are coil springs made of Inconel X–750, and parts machined from type 410 stainless steel. The closure disk has a layer of soft nickel plated on the sealing area. Precision machining is required on this component because of the many tight tolerances.

5.4.12 Shield Plug

The shield plug body is made from type 410 stainless steel, and components in the latching mechanism from ASTM A564 grade 630 stainless steel. Surfaces with sliding wear are Malcomized. As with the channel closure, tight tolerances in the mechanism require precise machining.

5.5 Stress Analysis

Stress analyses are performed to demonstrate the structural integrity of the fuel channel pressure boundary components. Finite element methods are generally used to calculate the stress intensities for various operating conditions in accordance with the ASME code requirements.

5.5.1 Code Requirements

The stress analyses for the pressure retaining items comply with the detailed rules of the ASME Code, Section III, Subsection NB–3200, 'Design by Analysis' for Class 1 components, as required by CSA Standard N285.0. Calculated stress intensities are compared with the ASME Code allowable limits for all loading conditions specified in the Design Specification.

5.5.2 Loading Conditions

The loading conditions specified in the Design Specification document are classified as Design, Level A, B, C or D Service conditions or Test conditions in accordance with the requirements of standard CSA N285.0. These Design, Service and Test conditions are defined by appropriate combination of internal pressure, thermal loads (steady state and transient temperatures), interaction loads from interfacing systems and mechanical loads. The mechanical loads include feeder load, fuelling machine load, annulus spacer load, bearing reaction and friction, bellows load, component weights, coolant drag force, bellows attachment ring shrink–fit load, etc.

5.5.3 Dimensions

The dimensions used in the stress analysis of the pressure tube take into account the applicable allowances due to manufacturing tolerances, corrosion, wear and irradiation creep and growth. A worst combination of dimensions, along with minimum material strength, is used to assess both beginning–of–life and end–of–life conditions to obtain the maximum stress intensities. The stress analysis conservatively accounts for only 15% irradiation strengthening in calculating the stress limits for the pressure tube to assess its structural integrity at the end–of–life condition. This practice has been approved by the Canadian regulatory authorities although it is not explicitly referred to in the CSA Standards. The actual irradiation strengthening has been measured to be much larger.

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5.5.4 Analysis

Thermal, stress, seismic and fatigue analyses are generally carried out by the finite element method. Post–processing of the stress analysis results is performed by linearizing stresses at selected sections to obtain maximum stress intensities for various stress categories, as per the ASME Code, para NB–3213. The stress categories are primary membrane, local primary membrane, primary bending, secondary and peak, as well as triaxial stress intensities. The computed stress intensities are compared with the limits established by the ASME Code.

Creep and growth analysis is carried out for the pressure tube to predict the axial elongation, diametral increase, wall thinning and sag at the end of the design life. These predictions are calculated with deformation equations developed by AECL using measurements from operating reactors and many small specimen tests.

5.6 Testing of Fuel Channel Components

Extensive development testing was done to establish the design used for fuel channel components. Prototype fuel channels have been subjected to flow endurance testing and are used in the acceptance tests performed for fuelling machines. As essentially the same fuel channel design is used for all CANDU reactors, its reliability has been demonstrated by the more than 10,000 operating channels, incurring over $1(10^9)$ hrs of operation. After installation in a reactor, all channels are hydrostatically tested to 1.25 times the heat transport system design pressure and commissioned as part of the HT system.

Individual fuel channel components are subjected to testing during their manufacture. In addition, prototype components have been subjected to the testing indicated in the following to show that they satisfy their design basis.

5.6.1 Pressure Tube

Pressure tubes have been installed and used in research reactors to demonstrate that they operate reliably. In addition, an extensive program of research and development testing has studied the in–reactor behaviour (deformation, Delayed Hydride Cracking behaviour, etc.) of pressure tube material to define analytical models for predicting this behaviour. These models are used in fuel channel design to ensure that pressure tubes will operate reliably throughout their design life. As described in **Section 5.8.2**, below, pressure tube performance is monitored in each operating unit

to verify that these tubes are behaving as anticipated.

5.6.2   Pressure Tube to End Fitting Rolled Joint

Rolled joints have been pull tested to show they have the strength required by CSA Standard N285.2. The residual stresses of typical joints have also been determined to show that they do not exceed the allowables of this Standard. Typical joints have also been subjected to cyclic thermal and load testing to show that their integrity is retained in such conditions. In addition, after each production rolled joint is made, its leak tightness is checked using highly sensitive helium leak detection equipment to verify that the joint is acceptable.

5.6.3   Annulus Spacers

Annulus spacers have been subjected to conservative life cycle tests involving at least twice their design loading for at least four times their design cycling. These tests have subjected spacers to at least a 400 pound load during 3000 simulated startup/shutdown cycles, to demonstrate their durability and endurance.

5.6.4   Feeder Connection

Feeder connection assemblies have been subjected to cyclic thermal and load testing to demonstrate that they satisfy their design leak tightness requirements when subjected to the maximum design loading.

5.6.5   Positioning Assembly

Positioning assemblies have been functionally tested and load tested to failure to demonstrate their load capacity, for the yoke remaining engaged on the end fitting and for the stud pulling out of the end shield.

5.6.6   Bellows

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Bellows have been functionally tested for proper elongation and been pressure tested at 0.41 MPa differential pressure to demonstrate that they perform adequately. It is considered that the bellows functional testing has involved sufficient cycles to cover the plant life to 40 years at 85% capacity.

5.6.7   Channel Closure

The closure plug design was subjected to qualification tests including repeated insertions and removals under hot, pressurized conditions, using the fuelling machines in the test facility at AECL. It has been proven by many years of operational service in over 20,000 end fittings, enduring over $1(10^9)$ hrs of service, and encompassing over $40(10^6)$ opening and closing cycles. The first four closures of each production batch are similarly tested during the fuelling machine acceptance tests.

5.7   Significant Developments Derived from Operating Experience and Research

5.7.1 Experience with Hydriding and Creep Elongation in Pressure Tubes

All of the fuel channels (but not the calandria tubes) that were initially installed in the four earliest commercial CANDU reactors, Pickering A units 1, 2, 3 and 4, have been replaced ("retubed") after between 20 and 25 years' service, at more than 75% lifetime capacity factor. This has extended the anticipated operating life for these reactors to more than 40 years. These tubes were replaced before their original 30 year target design life, for two reasons. Both are related to insufficient service experience accumulated at the time they were designed, which lead to innaccurate forecasts of material behaviour under those operating conditions. That experience provided a wealth of better understanding, from which all subsequent CANDU designs have benefitted. All the subsequent plants built since 1980, including all CANDU 6's and the four Pickering B plants continue to demonstrate the improved life expected of these later pressure tubes. The two main lessons learned from the Pickering A experience are:

1) The deuterium content of the Zircaloy-2 pressure tubes initially installed in Pickering units 1 and 2 significantly exceeded the solubility limit at which hydrides start to form. Later tubes of Zirconium-2.5% Nb exhibit better resistance to this phenomenon. Also, some simple but effective changes to PHT operating procedures have been implemented as a result of the the improved understanding of the Hydriding process, which greatly reduce the potential for it being a concern.

2) The allowances for pressure tube creep elongation provided in the fuel channels

initially installed in Pickering A units 1, 2, 3 and 4 were inadequate, because it was not then recognized that the rate creep and elongation caused by is not constant, but increases after a period of initial irradiation at operating fluxes. Subsequent CANDUs incorporate appropriate allowances, such as longer bearings, which preclude this problem.

5.7.2 Experimental Work and Design Forecasts

The material property changes for Zr–2.5%Nb pressure tubes and Zircaloy 2 calandria tubes during operation have been studied in laboratory testing, including irradiation tests, as well as by examining surveillance tubes removed from operating reactors. This work has shown that the effect of irradiation generally saturates during the first few years of operation, with material property values remaining constant during further operation.

Delayed Hydride Cracking (DHC) is a potential failure mechanism for zirconium alloy if the material contains enough dissolved hydrogen or deuterium so hydrides can form. The fabrication processes for CANDU pressure tubes and calandria tubes ensure that they contain very low levels of hydrogen. The subsequent ingress of deuterium into calandria tubes in service is very low, because of the low operating temperature, so DHC is not a concern for them, until after many more than 40 years of operation. The ingress of deuterium into Zr–2.5%Nb pressure tubes is low enough that DHC is not a concern during at least 25 years of normal operation at 85% capacity.

Rather than DHC or creep elongation, it is the accumulated deformation which is expected to be the limiting factor for the allowable operating life for pressure tubes and calandria tubes, as finite allowances are provided for deformation. Predictions for fuel channel deformatiom during service are based on deformation equations that have been developed by AECL in an extensive research and development program that started more than 20 years ago. The formulation of these equations has been based on combinations of the results of tests on representative pressure tube and calandria tube material specimens subjected to fluence in fast flux facilities and test reactors, and measurements of pressure tube and calandria tube dimensions during and after service, and after subsequent irradiation in high flux facilities. The derived deformation equations account for the functional relationships between temperature, stress, flux and microstructural parameters of the pressure tube and calandria tube materials. The validity of these equations has been established by comparing the analytical predictions to a large database of in–reactor measurements of deformation in CANDU operating reactors. These allowances are discussed below:

a) Pressure Tube Elongation

The prediction for the maximum pressure tube elongation during 25 years of operation at85% capacity is 150 mm, which is less than the 153 mm available bearing travel (3 mm total margin in

addition to the most conservative prediction). This is accomodated by simply designing longer bearings.

b)　Pressure Tube Diameter Change

This is predicted to be less than 4% which is less than the 5% minimum available allowance. The main concern here is that, beyond 5% increase, the PHT coolant will by-pass the fuel bundle interior passages, flowing more through the increased annular gap between the outside of the bundle and the tube bore. This can be ovecome by supplying oversize fuel later in the plant life, but this can cause logistics problems in fuelling operations since, if only a few pressure tubes have been replaced, they will have original gaps and will not accept oversize fuel.

c)　Fuel Channel Sag

The predictions for the maximum fuel channel sag after 25 and 40 years of operation at 85% capacity is 56 mm and 83 mm, respectively. The 25 year sag value is less than the initial 78 mm clearance that will exist between calandria tubes and LIN, so these components will not contact before pressure tubes are replaced at 25 years. In the event of creep sag being slightly higher than predicted, before retubing, the LIN tensioning load can be adjusted (by access on the outside of the vault) to increase the clearance. Alternatively, a replacement offset LIN design is available to increase this clearance by about 30 mm, if needed. This offset LIN design can be installed at any shutdown, but would be preferably done at the time of retubing.

The existing pressure tube replacement tooling has been qualified for use in fuel channels that have sagged up to 60 mm.

Fuel passage is not a concern for the initial pressure tubes, as their diameter increase compensates for the fuel passage difficulty introduced by sag. Assessments have been performed showing that there will not be a fuel passage problem following a pressure tube replacement if it is performed at 25 years of operation for a CANDU 6 reactor.

5.8　Maintenance and In–service Inspection

5.8.1　Maintenance

Fuel channels for CANDU 6 units are designed to operate for 25 years without maintenance, other than a mid–life reconfiguration of their positioning assemblies.

Each channel has two positioning assemblies, one at each end of the channel. At any time, only one of these positioning assemblies attaches the channel to a reactor end shield, while the positioning assembly at the other end is left disconnected. During a shutdown after 10 to 15 years of operation, positioning assembly reconfiguration will be performed for each channel, to free the positioning assembly that had been previously attached to a reactor end shield and attach the

previously free positioning assembly at the other end. This is performed using a simple tool to rotate the nut of each positioning assembly by 90 degrees.

5.8.2   In–Service Inspection

Fuel channel inspections are performed while the reactor is operating or during normal maintenance outages.

5.8.2.1   Elongation Monitoring

The elongation of each pressure tube is monitored to verify that this deformation is occurring as anticipated and to optimize the time at which positioning assembly reconfiguration is done. This timing depends on the available bearing travel, clearances between feeder pipes and clearances between the outboard ends of end fittings and the fuelling machine snouts. These clearances are determined by both the total amount of pressure tube elongation and the differences between the elongation for adjacent tubes. The simplest technique for monitoring pressure tube elongation is simply to record the position of the outboard end of end fittings each time a fuelling machine attaches to them.

5.8.2.2   Periodic Inspection Program

Fuel channel inspections are periodically performed in accordance with the requirements of CSA Standard N285.4. This Standard requires volumetric/dimensional measurements and material surveillance to measure the hydrogen/deuterium content of a few pressure tubes.

a)   Volumetric and Dimensional Inspection

Baseline measurements are required to be performed during a 2 year period after 7000 Equivalent Full-Power Hours (EFPH), based on the requirements of CSA–N285.4. Baseline volumetric and dimensional measurements have only been done by a special system of equipment known as Channel Inspection Gauging Apparatus for Reactors (CIGAR), developed by Ontario Hydro.

Based on the requirements of CSA–N285.4, baseline volumetric and dimensional measurements are required for 12 pressure tubes in the reactor unit. The baseline measurements will consist of the following:

- full–length ultrasonic inspection,
- dimensional gauging (internal diameter and wall thickness measurements),
- garter spring location and/or pressure tube to calandria tube gap measurements, and pressure tube sag measurement.

A minimum of five pressure tubes, selected from the twelve tubes having the baseline inspection, must be designated for periodic inspection during operation. A complete periodic inspection must be performed within a three–year period starting four years after the first generation of power. Subsequent periodic inspection intervals must not exceed six years, or 1/5 of the component

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design life (whichever is less).

b)   Hydrogen/Deuterium Concentration Measurements

Baseline measurements of hydrogen/deuterium concentration are performed on six pressure tubes in the reactor. These baseline measurements must be performed between nine and eleven years after generation of first power.

Periodic hydrogen/deuterium concentration measurements are performed on three of the six pressure tubes for which baseline measurements were performed. The measurement intervals are three years ±1 year, for the remainder of the operating life of the reactor.

5.8.2.3 Periodic Inspection Equipment/Tools

The inspection equipment/tools used to perform the periodic non-destructive inspections required by CSA Standard N285.4 are the Channel Inspection Gauging Apparatus for Reactors (CIGAR) tool and the Scrape tool. The CIGAR tool is used to perform volumetric and dimensional inspections to measure pressure tube sag, diameter, wall thickness, flaw size, and to measure the gap between the pressure tube and calandria tube. The Scrape tool is used to remove a small sliver of pressure tube material to measure its hydrogen/deuterium concentration.

The feeder pipe freezing process used to temporarily isolate a fuel channel from the rest of the heat transport system is fast, economical process that AECL has developed in an extensive testing program. In order to form an ice plug in a feeder pipe, a freezing jacket (consisting of a hinged double walled stainless steel tube with vent holes at one end) is clamped around the target feeder pipe in a convenient vertical location. The jacket is then filled with liquid nitrogen which cools the pipe locally and the D_2O in the pipe to form the ice plug. To form an ice plug, the heat transport system must be shut down and allowed to cool off to less then 150°F, and its flow rate less than two litres/minute.