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CONSIDERATIONS REGARDING THE HORIZONTAL FUEL CHANNELS NUCLEAR REACTOR. PART 1 - PRESENTATION AND INSTALATION REFERENCE PLANS OF THE FUEL CHANNEL

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Abstract: *The aim of this study is to identify the reference plans and the fuel channel components based on which is made the installation into calandria of CANDU 6 nuclear reactor. The fuel channel is designed to ensure a radiation exposure protection of workers and public, during the reactor operation. The reactor assembly of the CANDU 6 nuclear reactor consists of the horizontal, cylindrical, low-pressure calandria and the end-shield assembly. This enclosed assembly contains the heavy water moderator, the 380 fuel channels assemblies and the reactivity mechanisms. Each fuel channel consists of four major components: the pressure tube, the calandria tube, the annulus spacers and the end fittings. Fuel bundles are enclosed in the fuel channels that pass through the calandria and the end-shield assembly. The fuel channel assembly is made according with the specific requirements of reference planes definition, reference planes measurements, tools and equipments, installation procedures and the quality assurance program. Defining reference plans, measurements reported to reference plans and installation procedures to a new fuel channel in the calandria CANDU nuclear reactor comply the requirements described in the AECL (Atomic Energy of Canada Limited) specified documents.*
Keywords: *Candu reactor, Zirconium alloy, calandria tube, fuel channel, pressure tube, fuel bundle, end fitting, annulus spacer.*

1. GENERAL CONSIDERATIONS

The reactor assembly of the CANDU 6 nuclear reactor consists of the horizontal, cylindrical, low-pressure calandria and the end-shield assembly. This enclosed assembly contains the heavy water moderator, the 380 fuel channels assemblies , and the reactivity mechanisms. The CANDU reactor design shall respect of the specific requirements of codes and standards of Canada Standards Association (CSA), Atomic Energy Control Board (AECB) of Canada and International Energy Agency (IAEA).
All the 380 fuel channels, pressure tubes made of zirconium-niobium alloy, located inside the calandria tubes, chuck in the end fitting, are connected by the network pipes to the cooling system. Each fuel channel is composed of four major components: the pressure tube, the calandria tube, the annulus spacers and the end fittings. Fuel bundles are enclosed in the fuel channels that pass through the calandria and the end-shield assembly.
Defining reference plans, measurements reported to reference plans and install operations to a new fuel channel in the calandria CANDU nuclear reactor comply the requirements described in the AECL (Atomic Energy of Canada Limited) specified documents.

2. COMPONENTS OF THE FUEL CHANNEL

The CANDU reactor design is based on the experience derived from preceding CANDU reactors and virtually every design feature of the latest CANDU reactor is identical to, or is an evolutionary improvement of, an earlier proven design. The time life of the fuel channel is for 30 years at 80% of its capacity and 24 years for full capacity functioning. The CANDU reactor consists of a large, thin wall, low pressure cylindrical tank (the calandria) whose axis is horizontal. Its vertical ends (the end shields) are joined by a few hundred horizontal calandria tubes having a lattice pitch of 28.5 cm, as is illustrated in Figure 1.

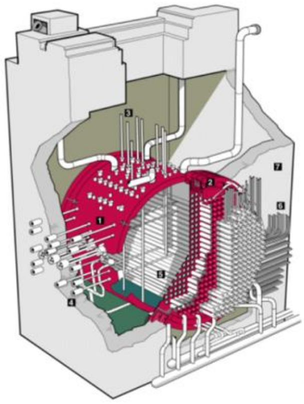

Figure 1: Calandria and End Shield Assembly in the Reactor Vault

1. Calandria; 2. Calandria end shield; 3. Shut-off and control rods; 4. Poison injection; 5. Fuel channel assemblies; 6. Feeder pipes; 7. Vault.

The CANDU 6 reactors are the following general features of the fuel channels:
- fuel channels in number of 380;
- pressure tube made of Zi 2,5% NB, diameter 103,4 mm, thickness 4,19 mm;
- calandria tube made of Zircaloy 2, diameter 129,0 mm, thickness 1,37 mm;
- annulus spacers made of Incon.X750, coil diameter 4,83 mm, 4 pieces;

2.1. General presentation

The fuel channels are one of the major distinguishing features of a CANDU reactor, and their reliability is crucial to the performance of the reactor. A pressure tube is located inside each calandria tube and is separated from it by spacers in the annular gap. The components of the fuel channel design are illustrated in Figure 2.

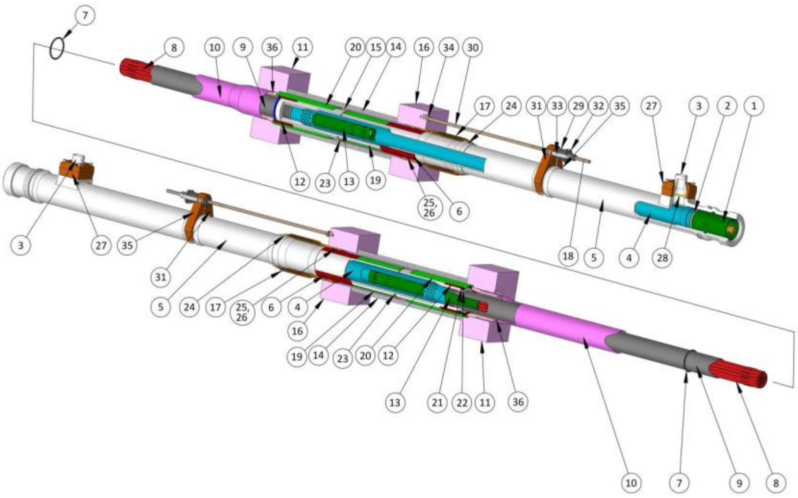

Figure 2: Representation of a CANDU fuel channel

1. Channel closure; 2. Closure seal insert; 3. Feeder coupling; 4. Liner tube; 5. End fitting body; 6. Outboard bearings; 7. Annulus spacer; 8. Fuel bundle; 9. Pressure tube; 10. Calandria tube; 11. Calandria tubesheet; 12. Inboard bearings; 13. Shield plug; 14. Endshield shielding balls; 15. Endshield lattice tube; 16. Fuelling tubesheet; 17. Channel annulus bellows; 18. Positioning assembly; 19. End fitting shielding sleeve; 20. Lattice tube shielding sleeve; 21. End fitting inner ring seal; 22. Elastic safety lock for end fitting inner ring seal; 23. Elastic safety lock for end fitting shielding sleeve; 24. Support ring for annulus bellows; 25. Annulus bellows outer ring seal; 26. Elastic safety lock for Annulus bellows outer ring seal; 27. Feeder coupling attachment; 28. Feeder gasket; 29. Rod positioning threaded part; 30. Rod positioning; 31. Right fastening piece for rod positioning; 32. Counter nut locking; 33. Safety lock for counter nut; 34. Lock pin for rod positioning; 35. Left fastening piece for rod positioning; 36. Crimping ring for calandria tube;

2.2. Calandria tube presentation

A calandria tube surrounds each pressure tube. Calandria tubes have an internal diameter of about 129 mm and span the calandria vessel between the two end shields. The calandria tube is illustrated in Figure 3.

Figure 3: Representation of the calandria tube

These tubes provide access through the calandria for the pressure tube and the end fitting assemblies. The calandria tubes help to support the pressure tubes by means of four spacers per channel.

2.3. Pressure tube presentation

The pressure tubes are the most important part of the fuel channel as they pass through the calandria and contain the fuel bundles. They are zirconium alloy tubes (Zr-2.5% Nb) that are about 6 meters long, about 11 cm in diameter and have a wall thickness of about 4 mm.
The design of the pressure tube consists primarily of the determination of the length, the inside diameter and the wall thickness of a simple thin-walled cylinder which is illustrated in Figure 4.

Figure 4: Representation of pressure tube

One of the main requirements of the pressure tube design is to optimize wall thickness and to minimize neutron absorption for radiation exposure protection of workers.
Each pressure tube is separated from a calandria tube by means of four spacers. These spacers are positioned so that pressure tube sag will not allow the contact with the calandria tube. The spacers are made by forming Inconel wire into a close coiled helical spring. That is illustrated in Figure 5.

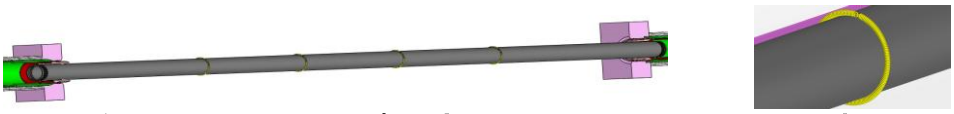

Figure 5: Representation of annulus spacers positioning on pressure tube

The axial movement of the pressure tubes is allowed by a rolling motion of the annulus spacers, which results in almost no wear on the pressure and calandria tubes where they contract the spacers.

2.4. End fitting presentation

The end fitting, manufactured from a modified AISI 403 stainless steel, is an out of core extension of the pressure tube that provides the connection for on power fuelling, the connection to the feeders coupling and the connection with the pressure tube, which is illustrated in Figure 5.
The outboard end contains a removable closure plug and provides facilities on which a fuelling machine can clamp and make a high pressure seal to allow on-power refuelling. Near the outer end of each end fitting is a side port for connection of a feeder pipe connection.
The inboard end of each end fitting is connected to one end of a pressure tube by a rolled joint, as is illustrated in Figure 6.

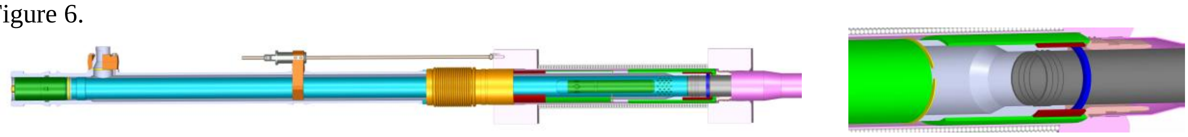

Figure 6: Representation of end fitting and pressure tube rolled joint

2.5. Channel closure plugs presentation

The channel closures, illustrated in Figure 7, are located in each end fitting of a fuel channel to seal the primary coolant and to permit on-power access to the fuel channel by the fuelling machines. he channel closures can be remotely removed by a fuelling machine.
The shield plugs, which provide shielding where the fuel channels pass through the reactor end shield, are latched into the end fitting. They are also removed by the fuelling machine before the refueling of a channel can occur.

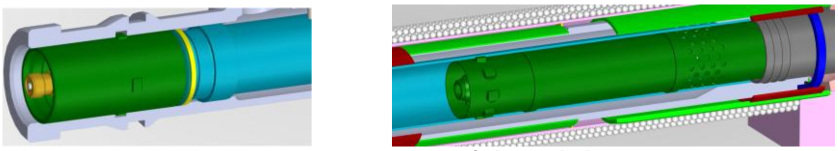

Figure 7: Representation of channel closures

2.6. Annulus bellows

The annulus bellows, which is illustrated in Figure 8, connects between an end fitting and the reactor end shield, allows axial motion of the channels and also limits the torque imparted to the end fitting by the feeder piping. Each end of the bellows is welded to an end ring. One end ring is attached to the lattice tube/calandria tubesheet by welding and another is a shrink-fit onto the end fitting.

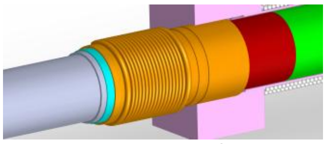

Figure 8: Representation of annulus bellows

2.7. Positioning assembly

Each fuel channel is located axially within the reactor by a positioning assembly which is connected to one end shield, as is illustrated in Figure 9. A second positioning assembly is installed at the other end of the fuel channel but it is not attached to the end shield so axial motion resulting from thermal expansion, so that the pressure tube elongation to be permitted.

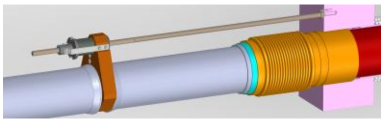

Figure 9: Representation of position assembly

2.8. Feeder coupling

The feeder pipe connection located on the side of each end fitting is necessary for cooling system connection. The bolted feeder pipe connection has a metallic seal. Four bolts pass thorough a flange into holes tapped into the end fitting body to tighten this connection. The flange holds a hub welded to each feeder pipe tightly against the metal seal ring, as is illustrated in Figure 10.

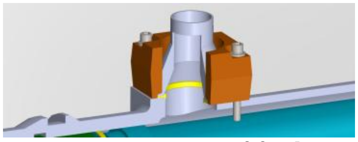

Figure 10: Representation of feeder coupling

3. CALANDRIA REFERINCE PLANS

For a new installation of the fuel channel into the calandria CANDU nuclear reactor, shall defining reference plans, measurements reported to reference plans which to comply the requirements described in the AECL (Atomic Energy of Canada Limited) specified documents.
Registration documents, check documents and relating reports to the installation of the fuel channel are part of the processes register of the assembly technique reactor.

3.1. Reference plans definition

The Calandria reference plans are carried out between R and R' plans. These are defined as reference planes for front and rear part of the calandria and are illustrated in Figure 11.

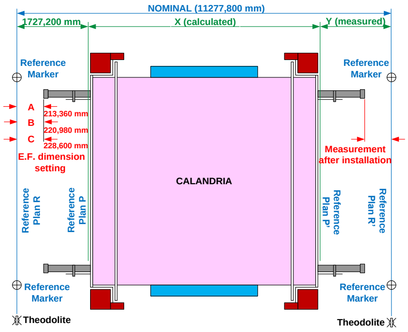

Figure 11: Representation of the reference plans for measurements making at fuel channel installation

The plans determination operations are as follows:
- preliminary determination of the R plan;
- preliminary determination of the R' plan;
- establishing of the R plan reference and markers reference;
- distance determining between P and P' plans reference, front and back calandria plane;
- establishing of the R' plan reference and markers reference.

3.2. The fuel channel measurements reported to the reference plans

The registration document of the reference plans measurements contains entries for used instruments to measurements, measured temperatures at different calandria points, measurements to the R and to R' reference plan, A, B, C and A', B', C' measured distance to the R and to R' calandria reference plans, X measured distance between P and P' plan and Y measured distance between the P' plan reference and the R' plan reference.
The record document of measurements for fuel channel length calculation and distance measurements from the plan R or R' to end fitting for fuel channel type, provides three fuel channels category:
- A channel category - nominal length = 10,850 mm, distance R-A / R'-A' = 213,36 mm;
- B channel category - nominal length = 10 836 mm, distance R-B / R'-B' = 220,98 mm
- C channel category - nominal length = 10,820 mm, distance R-C / R'-C' = 228,60 mm
The registration document of the fuel channel length calculation for each channel type contains information about channel elements length, shown in table 1.

Table 1: Channel elements length

Channel category	PT length (mm)	EF-PT length (mm)	Final length of FC (mm)
A	X-1496,57	X+765,61	X+3027,68
B	X-1511,81	X+730,37	X+3012,44
C	X-1527,05	X+735,13	X+2997,20

Notations: EF = End Fitting, PT = Pressure Tube, FC = Fuel Channel and X = measured distance between P and P' plane.
The general registration document for fuel channel installing contains entries for pressure tube, outer diameter and thickness, the measured distance from the end fitting face, annulus spacer no.1 position, annulus spacer no.2 position, annulus spacer no.3 position, annulus spacer no.4 position, end fitting, power feeder angle, gap between pressure tube and the liner tube before and after the rolling phase, the total length of the final sub-assembly, the distance between end fitting and the reference plan before and after rolling, the final overall length of the fuel channel, the data relating to test calibration, the data relating to pressure, welds checking and identifying, identification bulletin control, welder identification.
The general registration document and identification of each fuel channel in report of the calandria zone contains entries for: zone no., the end fitting serial number from R plan, the end fitting serial number from R' plan, the identification code of the pressure tube, mounting position and the end fitting orientation to the end of each fuel channel contains entries for: area no., line, column and front or rear of calandria, input / output feeder type, mounting position of the end fitting at 0°, left 32°, 58°, 90°, 32° right, 58° and 90° (see Figure 12).

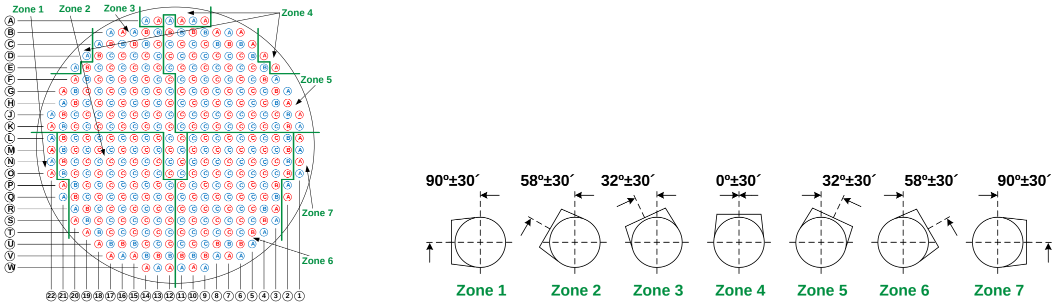

Figure 12: Representation of the cooling zone in relation to end fitting orientation for feeder pipe connection

4. CONCLUSIONS

The current CANDU 6 reactors have a design life of 40 years at an average of 85% capacity. The pressure tube design life is 25 years at the reactor's 85% capacity factor.

The design and the configuration characteristics of the fuel channel from the CANDU nuclear reactor are essentially in the design of device components. The fuel channel design has increased margins with extended operating life and is considered a fundamental part in the CANDU system.

The fuel channels from CANDU reactors, which use thin-walled zirconium alloy pressure tubes, represent a specialized application of pressure vessel design.

The fuel channels have made a significant contribution to the very high capacity factors attained in CANDU reactors since they allow on-power refueling.

The install operations to a new fuel channel must comply with the described requirements from the specified documents by AECL.

The reference plan for a new fuel channel install operations must comply with the described requirements from the specified documents by AECL.

All measurements according to reference procedures are recorded in the reference documents for fuel channel installation.

Documents registration, verification documents and reports of the fuel channel installation will be archived to take anytime a sequential picture of each fuel channel.

REFERENCES

[1] Cheadle B.A., Price E.G., *"Operating performance of CANDU pressure tubes"*, presented at IAEA Techn. Comm. Mtg on the Exchange of Operational Safety Experience of Heavy Water Reactors, Vienna, 1989.

[2] Cheadle, B.A., Price, E.G. - *Advance in fuel channel technology for CANDU reactors*, IAEA Techn. Comm. Mtg on Advances in Heavy Water Reactors, Toronto, 1993;

[3] Chun K. Chow, Hussam F. Khartabil - *Conceptual fuel channel designs for CANDU - SCWR*, Atomic Energy of Canada Ltd, 2007;

[4] Roger G. Steed, *"Nuclear Power in Canada and Beyond"*, Ontario, Canada, 2003.

[5] AECB, *"Fundamentals of Power Reactors"*, Training Center, Canada.

[6] AECL, *"CANDU Nuclear Generating Station"*, Engineering Company, Canada.

[7] CANDU, *"EC6 Enhanced CANDU 6 - Technical Summary"*, 1003/05.2012.

[8] CNCAN, *"Law no. 111/1996 on the safe deployment, regulation, authorization and control of nuclear activities"*, 1996.

[9] IAEA, *"Assessment and management of ageing of major nuclear power plant components important to safety: CANDU pressure tube"*, IAEA-TEDOC-1037, Vienna 1998.

[10] IAEA, *"Assessment and management of ageing of major nuclear power plant components important to safety: CANDU reactor assemblies"*, IAEA-TEDOC-1197, Vienna 2001.

[11] IAEA, *"Nuclear Power Plant Design Characteristics, Structure of Power Plant Design Characteristics in the IAEA Power Reactor Information System (PRIS)"*, IAEA-TECDOC-1544, Vienna 2007.

[12] IAEA, *"Water channel reactor fuels and fuel channels: Design, performance, research and development"*, IAEA-TEDOC-997, Vienna 1996.

[13] IAEA, *"Heavy Water Reactor: Status and Projected Development"*, IAEA-TEREP-407, Vienna 1996.

[14] Nuclearelectrica SA, *"Cernavoda NPP Unit 1&2, Safety features of Candu 6 design and stress test summary report"*, 2012.

[15] UNENE, Basma A. Shalaby, *"AECL and HWR Experience"*, 2010;