CONSIDERATIONS FOR THE DEVELOPMENT OF A DEVICE FOR THE DECOMMISSIONING OF THE HORIZONTAL FUEL CHANNELS IN THE CANDU 6 NUCLEAR REACTOR
PART 2 - FUEL CHANNEL PRESENTATION

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Abstract: As many nuclear power plants are reaching their end of lifecycle, the decommissioning of these installations has become one of the 21st century’s great challenges. Each project may be managed differently, depending on the country, development policies, financial considerations, and the availability of qualified engineers or specialized companies to handle such projects. The principle objective of decommissioning is to place a facility into such a condition that there is no unacceptable risk from the decommissioned facility to public health and safety of the environment. In order to ensure that at the end of its life the risk from a facility is within acceptable bounds, action is normally required. The overall decommissioning strategy is to deliver a timely, cost-effective program while maintaining high standards of safety, security and environmental protection. If facilities were not decommissioned, they could degrade and potentially present an environmental radiological hazard in the future. Simply abandoning or leaving a facility after ceasing operations is not considered to be an acceptable alternative to decommissioning. The final aim of decommissioning is to recover the geographic site to its original condition.

Key words: calandria tube, fuel channel, pressure tube, fuel bundle, end fitting, feeder coupling,

1. INTRODUCTION

Nuclear reactors are designed and manufactured with respect of the specific requirements of codes and standards for the manufacture of components, equipment and systems required for the construction and operation of CANDU nuclear power plant.

The requirements for CANDU reactor design must comply with the codes of Canada Standards Association (CSA), Atomic Energy Control Board (AECB) of Canada and International Energy Agency (IAEA) which specify the specific and regulatory requirements.

The CSA standards (Canadian Standards Association) applicable to the design and implementation of a nuclear power plant are the following:
- N285 - Systems and Components;
- N286 - Quality Assurance;
- N287 - Concrete Containment Structures;
- N288 - Environmental Radiation Protection;
- N289 - Seismic Design;
- N290 - Control Systems, Safety Systems, and Instrumentation;
- N291 - Safety Related Concrete Structures;
- N292 - Waste Management;
- N293 - Fire Protection;

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2. EVOLUTION OF CANDU FUEL CHANNEL DESIGN

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.

This evolution of the fuel channel design is illustrated in Figure 1, which shows the essential features of the NPD, Douglas Point, Pickering, and Bruce designs.

The evolution of the fuel channels design for CANDU reactors is the following:

1) NPD reactor (20MW), the first reactor with fuel channel, entered into service in 1962, with the following characteristics of channels:
   - 132 fuel channels;
   - pressure tube made of Zircaloy 2, diameter 82.6 mm, thickness 4.20 mm;
   - calandria tube made of Aluminium, diameter 101.9 mm, thickness 1.27 mm;
   - annulus spacers made of IncX750, coil diameter 4.75 mm, 1 piece;

2) Douglas Point reactor (200MW) entered into service in 1967, with the following characteristics of channels:
   - 306 fuel channels;
   - pressure tube made of Zircaloy 2, diameter 82.6 mm, thickness 3.94 mm;
   - calandria tube made of Zircaloy 2, diameter 107.7 mm, thickness 1.24 mm;
   - annulus spacers made of htZrNbCu, coil diameter 7.52 mm, 2 pieces;

3) Pickering A, Cernavoda reactor (>500MW), first commercial reactor with 2 units, entered into service in 1971 and 1973, with the following characteristics of channels:
   - 380 fuel channels;
   - 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;

Fig. 1 - Schematic illustration of a CANDU fuel channel design evolution [5]
4) Bruce A reactor (>500MW), first commercial reactor with 4 units, entered into service in 1977 and 1979, with the following characteristics of channels:
- 480 fuel channels;
- pressure tube made of Zi 2,5% NB, diameter 103,4 mm, thickness 4,06 mm;
- calandria tube made of Zircaloy 2, diameter 129,0 mm, thickness 1,37 mm;
- annulus spacers made of Incon.X750, coil diameter 6,81 mm, 2 pieces;

3. CONDITIONS RELATING TO THE DESIGN OF THE FUEL CHANNELS CANDU REACTOR

The main purpose of the fuel channels in a CANDU reactor is to support and locate the fuel inside the reactor. The fuel channels are designed to resist the flow of coolant, temperature, pressure and conditions imposed by the heat transport system. The time life of the fuel channel is for 30 years at 80% of its capacity and 24 years for full capacity functioning. The fuel channels must satisfy all conditions that are imposed by their design.

3.1. Fuel channel functional requirements

The functional requirements of the fuel channel are to:
- support and bound the reactor fuel;
- share of the cooling fluid for removing efficiency of heat released from fuel;
- allow the passage of fuel through the reactor core during refuelling with fuel;
- represent a part and parcel of the primary heat transport through fiders coupling system;
- provide information for detecting leaks in pressure tube and calandria tube;
- ensure the thermal insulation so that heat transfer to the primary cooling agent for the moderator to be carried out in normal operation at the reactor;
- reduce of the neutron absorption;
- ensure protection to mitigate radiation through the stopper of the isolation and locking channel;
- allow the elimination with the fuel loading/unloading machine;
- ensure ease replacement.

3.2. Fuel channel performance requirements

Leakage Requirements

All joints in the fuel channel are designed and built to minimize leakage. Rolled joints are used to connect the pressure tube to the end fittings as well as the calandria tube to the calandria tubesheet. All welded joints (e.g. the lattice tube to end shield joint) must have no detectable leakage.

Shielding Requirements

Fuel channels must incorporate radiation shielding where they pass through the calandria end shields, so that maintenance and periodically inspection to be carried out in low radiation fields during reactor shutdowns. The objective of the shielding design is to ensure a maximum dose rate value of 1.0 mSv/h at the feeder cabinet after 24 hours shutdown of the reactor.
Leak Detection Requirements

The gas annuli between the outside of the pressure tubes and the inside of the calandria tubes must be monitored in order to detect a leak from a pressure tube crack in time and to shutdown the reactor before the crack reaches an unstable length, and also to detect any leakage from either the moderator or the end shields.

3.3. Seismic requirements

The Canadian seismic requirements are documented in the CAN3-N289 series of standards. Seismic qualification of the fuel channel is performed by analysis as required by ASME, Section III, using the Design Basis Earthquake (DBE) as a level C condition.

An analysis is done for the fuel channels as part of the whole reactor assembly to determine the seismic loading on the fuel channels. The magnitude of seismic loads and number of cycles is then provided as input to the fuel channel stress analysis.

Seismic qualification is done to "Category A", which means that the fuel channel must allow HTS coolant to continue to flow through it after a DBE. The fuel channel is analyzed to confirm the integrity of its pressure boundary as part of the seismic analysis.

3.4. Safety requirements

The pressure boundary integrity of the fuel channel assembly has to be maintained during all postulated emergency cases, as well as during all normal and upset operating conditions, as postulated in the station specific safety reports. The rupture of any one fuel channel must not lead to rupture of any other channel. Also, under certain postulated accident conditions, the design must provide for effective heat transfer from the fuel channel to the moderator. There have been two historical cases of channel rupture to date. One on-power event at Pickering in which a pressure tube ruptured and its moderator tube remained intact. A second event at Bruce was the off-power rupture of one pressure tube plus its calandria tube.

3.5. Reliability and maintainability requirements

The original design objective for fuel channel components was to achieve high reliability and no channel failures during their design life. It was anticipated, however, that replacement of pressure tubes would be required in a reactor after 30 years operation. Fuel channel design is therefore intended to minimize the cost and radiation exposure associated with this retubing. Downtime associated with retubing is not expected to reduce unit lifetime capacity factor below its designed value. Retubing of Pickering A has taken one to two years per unit.

3.6. Inspection and testing requirements

In-service inspection of the fuel channel is performed in accordance with the requirements of the Periodic Inspection of CANDU Nuclear Power Plant Components, CSA Standard N285.4. Besides mandatory inspections, utilities may institute additional inspections for reasons of maintenance, operational reliability, etc. These may include sampling of pressure tube material using scrapings from the inside of tubes or periodic single channel replacement.
3.7. Material requirements

The effect of environmental conditions on fuel channel material properties must be taken into account. The effects of stress, irradiation, temperature, hydrogen absorption and any other significant environmental factors on material properties must be accounted for. It must be demonstrated that no significant reduction in the initial stress margins will occur in-service, and that protection against non-ductile failure is provided in accordance with ASME Section III paragraph NB-3211(d).

4. FUEL CHANNEL COMPONENTS

4.1. Fuel channel

Fuel channels are one of the major distinguishing features of a CANDU reactor, and their reliability is crucial to the performance of the reactor. The components of the fuel channel design are illustrated in Figure 2.

![Fig. 2 - Schematic illustration of a CANDU fuel channel](image)


4.2. Calandria tubes

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.
These tubes provide access through the calandria for the pressure tube/end fitting assemblies. The calandria tubes help to support the fuel channel pressure tubes by means of four spacers per channel, as is illustrated in Figure 4.

Calandria tubes are made of seam-welded, annealed and stress relieved zirconium alloy (Zircaloy 2). This material was chosen for its low neutron absorption cross-section and corrosion resistance.

### 4.3. Pressure tubes

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 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 5.

One of the main requirements of the pressure tube design is to optimize wall thickness and to minimize neutron absorption.

The fabrication process for cold-worked Zr-2.5% Nb pressure tubes, which is illustrated in Figure 6.
The product specification requires that the following tests and examinations also be carried out on each pressure tube before it can be accepted: hydrostatic pressure test, chemical analysis, tensile testing and corrosion testing.

4.4. End fittings

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 7.

The outboard end contains a removable closure 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, which is illustrated in Figure 8.

4.5. Annulus spacers

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 a pressure tube to contact the calandria tube. That is illustrated in Figure 9. The spacers are made by forming Inconel wire into a close coiled helical spring, which is illustrated in Figure 10.
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.

4.6. 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, as is illustrated in Figure 11.

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.
4.7. 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 12.

![Fig. 12 - Schematic illustration of position assembly](image)

4.8. Annulus bellows
The annulus bellows, which is illustrated in Figure 13, 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.

![Fig. 13 - Schematic illustration of annulus bellows](image)

4.9. Channel closures
Channel closures, illustrated in Figure 14, 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. Channel closures can be remotely removed by a fuelling machine.

![Fig. 14 - Schematic illustration of channel closures](image)
4.10. Shield plugs

The shield plugs, which provide shielding where the fuel channels pass through the reactor end shield, are latched into the end fitting, which is illustrated in Figure 15. They are also removed by the fuelling machine before the refuelling of a channel can occur.

![Fig. 15 - Schematic illustration of shield plugs](image)

5. CONCLUSIONS

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

The fuel channels in 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 refuelling.

REFERENCES


[8] CNCAN, "Rules for the decommissioning of objectives and nuclear installations", 2002;
