ENHANCING THE SEISMIC CAPABILITY OF THE ON-POWER REFUELING SYSTEM OF THE CANDU REACTOR

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ABSTRACT

The CANDU reactor assembly includes several hundred horizontal fuel channels, each containing twelve fuel bundles, arranged in a square lattice, and supported by the reactor structures. CANDU operates on natural uranium or other low fissile content fuel, and is refueled on-power, with either four or eight fuel bundles in a channel being replaced during each refueling operation. The fueling machines clamp onto the opposite ends of the fuel channel to be refueled. The seismic capacity of this refueling system is evaluated in terms of its dynamic response during an earthquake.

This paper describes the approach adopted to enhance the seismic capability of the fueling machine and calandria assembly for earthquakes of 0.3g ground acceleration covering a broad range of soil conditions ranging from soft to hard. A detailed, 3-D finite element seismic model of the fueling machine and calandria assembly system is developed to calculate the seismic responses of the structure.

Some relatively simple hardware design changes have been considered to increase the seismic capacity of the CANDU 6 reactor. These changes in the fueling machine and calandria assembly of the CANDU 6 reactor are briefly described. They have been incorporated into the finite element seismic model of the system. Most of these design changes have already been considered and implemented in other CANDU reactor projects.

The current CANDU 6 reactor design fully meets the requirements of seismic qualification for sites with potential for 0.2g ground acceleration where the seismic loads need to be combined with the other design loads for the support and pressure boundary components to demonstrate compliance with the applicable Code requirements. In the present study it is demonstrated that, with relatively simple hardware changes, the fueling machine and calandria assembly of the CANDU 6 reactor can withstand earthquakes of 0.3g ground acceleration. Based on the current study and some preliminary analysis of the CANDU 6 reactor and its fuel handling system, it is envisaged that there is still further potential to increase the seismic capacity beyond a level of 0.3g ground acceleration.

SYSTEM DESCRIPTION

A CANDU reactor assembly consists of a heavy-water-filled, horizontal, cylindrical tank, called the calandria, which is closed at each end by an endshield. An array of horizontal fuel channels span the calandria and are supported by the end shields. Each channel contains twelve fuel bundles, which are cooled by recirculated D_2O coolant. One of the principal features of the CANDU reactor is the ability for on-power refueling, which is performed by two fueling machines, one located at each end of the reactor, that can access any fuel channel.

The reactor, as shown in Figure 1, is comprised of a cylindrical stainless steel calandria, closed at each end by an endshield, that is housed within a light-water-filled, steel lined, concrete vault which provides the thermal shielding and cooling. The calandria contains heavy water moderator and several hundred fuel channels with pressurized D_2O coolant flowing through the fuel bundles inside the pressure tubes.

The refueling operation is carried out by two fueling machines that are operated remotely. The fueling machines move to the ends of the fuel channel, to be refueled, as shown in Figure 2.

The fuel handling system shown in Figure 2. The fueling machine consists of three major components; namely: the head, the gimbals and the carriage.

The head is basically a pressure containment vessel designed to ASME Code[1], Section III, Class 1 requirement. It consists of a magazine, ram, gear box, drives and other components for refueling operation.

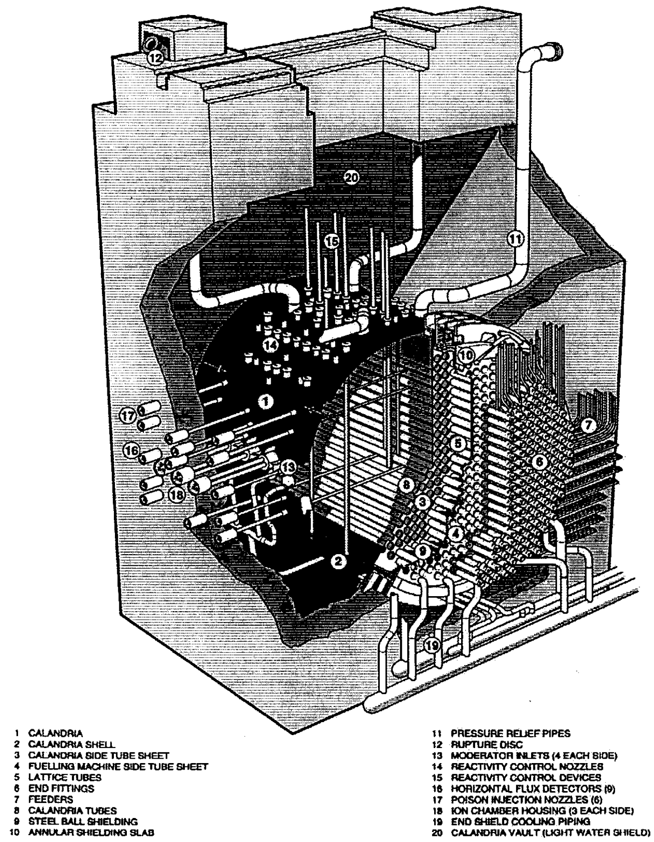

Figure 1 CANDU 6 Reactor Assembly

The complete head, which is resting on the cradle, is supported in a suspension through a pair of trunnions mounted approximately at the center of the assembly. However, counter balanced weights are often required to ensure that a proper balance is maintained after manufacture and assembly. The combination of the lower and upper gimbals, together with the carriage, provides the mechanical support for the head and particularly for the fine X (horizontal transverse), Y (vertical) and Z (channel axial) motions for homing onto the fuel channel end fitting. The movement of the carriage trolley along the bridge in the X direction, together with the bridge moving up and down along the column in the Y direction, provides the access to all the channel locations for refueling.

SEISMIC ANALYSIS

The approach adopted to seismically qualify the CANDU reactor, fuel handling structures and components is based on the analytical methods that are permitted by the CSA Standard. The seismic analysis of the Reactor & Fuel Handling (R & FH) system is carried out by adopting the direct-integration time history method using the DYNRE6 routine in the STARDYNE[3] computer code. The advantages of using this real-time method are that it is least conservative and at the same time provides a reasonably good prediction of the seismic responses for the non-linearly behaving, complex structures.

The seismic model consists of the reactor and vault model, the fuel channel model and the fueling machine models on both A and C sides (the free and fixed end shield sides, respectively). A typical model for attachment at a selected channel location is shown in Figure 3.

SEISMIC QUALIFICATION REQUIREMENTS

In CANDU reactors, one of the design requirements for the safety-related systems is that they should be seismically qualified to the specified site ground acceleration per CSA Standard CAN3-N289.3[2] rules. Therefore, measures are taken in the design to ensure that all these safety-related structures and components maintain their structural integrity and function during and after a Design Basis Earthquake (DBE) to Category A requirements. The main purpose is to ensure that the reactor can be shut down and maintained indefinitely in. that state so that decay heat can be removed from the fuel during the shutdown period.

The reactor and vault model is shown in Figure 4, in which the concrete vault is represented by two beams, the lower beam fixed at the base slab. The middle node represents the vault centre line, where the reactor model is connected. The node at the top of the reactor vault is considered free. The reactor structures are represented by the lumped mass system in which appropriate mass and stiffness constants are used to represent the dynamic behaviour of the various components of the reactor assembly. The single fuel channel, which consists of the pressure tube along with the calandria tube and the end fittings, is attached to the fueling machines at each

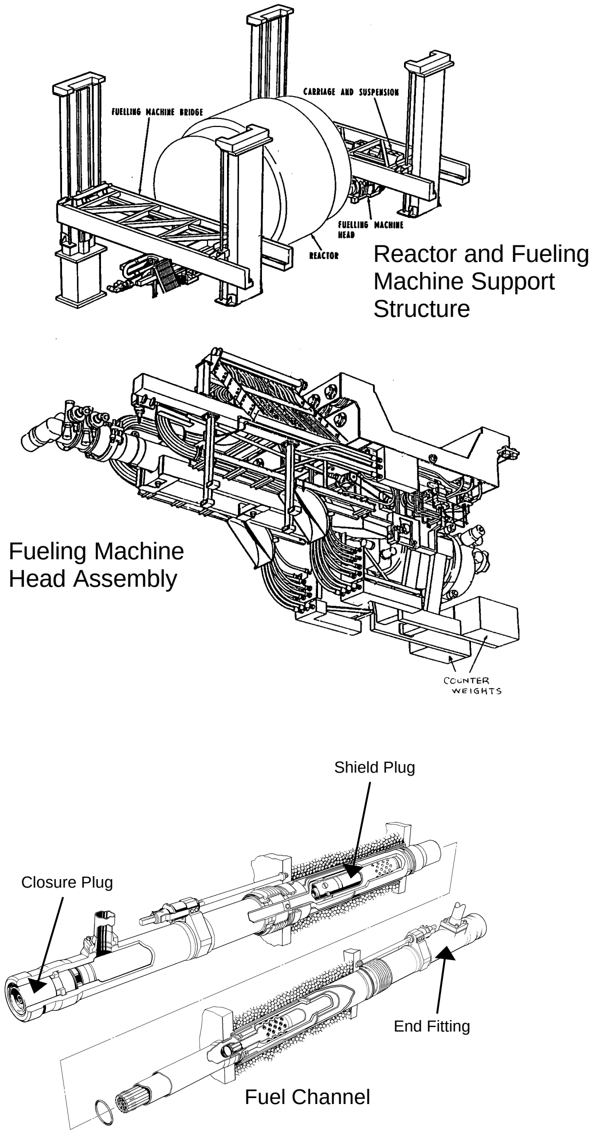

Figure 2 Reactor and Fuel Handling System

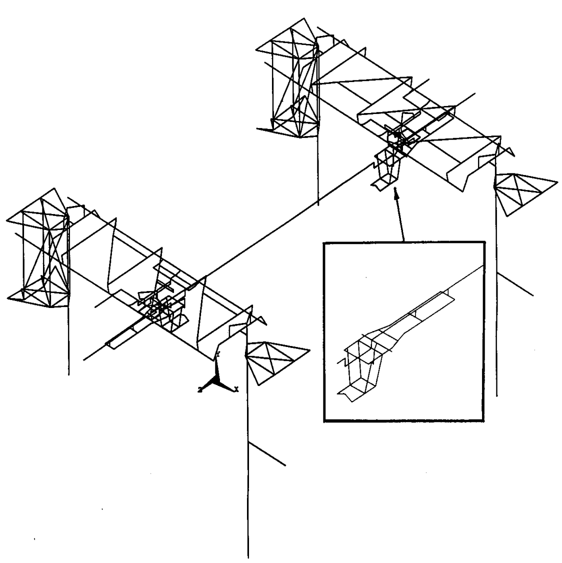

Figure 3 Fuel Handling System Seismic Model

end. The pressure tube is supported by the bearings in the end shields and by the garter springs in the calandria tubes.

As input, time histories, based on particular site soil conditions and other earthquake parameters, are applied at the fueling machine support points. The soil conditions can vary from soft to hard. For the seismic analysis, the time-scale variation of plus and minus 15% is considered to take into account the effects of the possible frequency variation of the structures. For this feasibility study, a total of 70 cases were considered in the seismic analysis to capture the worst loads due to fuel channel location, soil variations and positioning assembly on the A and C sides.

DESIGN CHANGES FOR HIGHER SEISMICITY

The current CANDU 6 reactor design of the R & FH system is seismically qualified for 0.2g ground acceleration. In order to further increase the seismic capability of the R & FH system to higher acceleration levels such as 0.3g, simple design modifications in the reactor and fueling machine structures and components are considered. Based on the parametric studies of the system, the following design modifications to the existing reactor design are considered to be feasible:

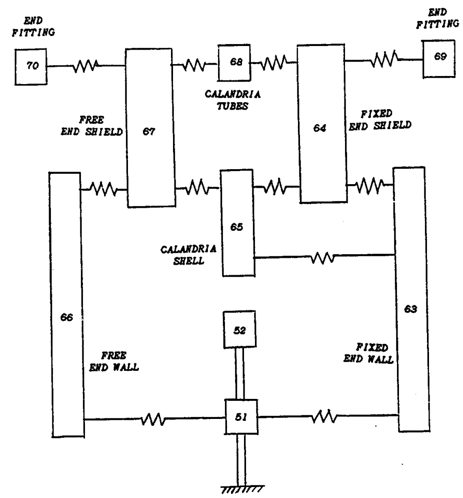

Figure 4 Reactor Lumped Mass Model

1. End Shield Support Stiffening;
2. Fueling Machine Counter Weight Reduction;
3. Stronger Fuel Channel Positioning Assembly;
4. Z-spring Stiffness Optimization;
5. Bridge Stiffening;
6. Short Column Free End Support;
7. Pitch & Yaw Spring Stiffening.

This list of design modifications are discussed in the following.

1. End Shield Support Stiffening

The end shield support plate and shell in the reactor structure provide support to the calandria and end shields assembly. In the current calandria design for a CANDU 6 reactor, one side of the support plate has 80 bolts anchored to the embedment ring to provide axial stiffness to the end shield, thus called the fixed end shield. The other side with no bolts, known as the free end shield, allows the relative thermal movement between the calandria and the end shield assembly during steady state and thermal transient conditions. Considering both the end shields as symmetrical (i.e., restraining the axial movement of the free end shield, Figure 5), tends to decrease significantly the seismic responses of the reactor structures, thus reducing the seismic interaction between the reactor and the fueling machines. However, the increase in the thermal loads due to the restraining of the free end shield is well within the acceptable values.

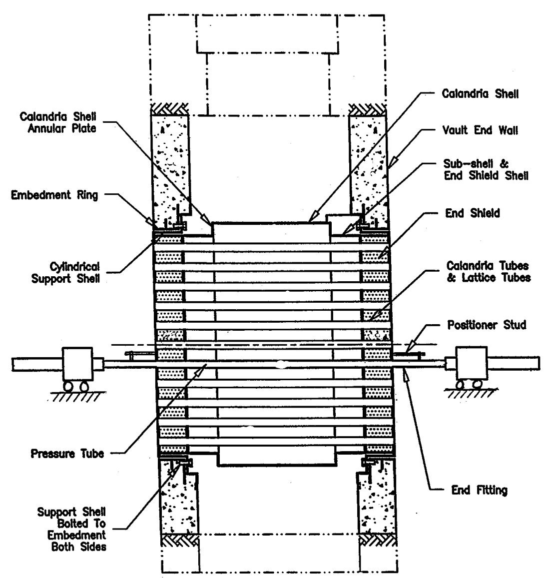

Figure 5 Reactor End Shield Symmetry Design

2. Fueling Machine Counter Weight Reduction

The fueling machine counter balance weight, as shown in Figure 2, is designed to balance the fueling machine head about the trunnion support points during reactor operation. Currently this counter weight has been increased to about 15.57 kN (3,500 lbf.) due to the addition of components such as bulkhead, drain pipes, etc. From a design point of view, the fueling machine support has been relocated to significantly reduce the counter balance weight. In order to achieve this goal, it is estimated that the trunnions need to be shifted by about 178 mm (7 inches).

Due to the need for various configurations of the fueling machine, the counter weight may not be reduced to zero; therefore, for the analysis a maximum of 4.45 kN (1,000 lbf.) counter weight is considered as a reasonable target weight for balancing.

3. Stronger Fuel Channel Positioning Assembly

The positioning assembly in each fuel channel is designed so that the fuel channel can be locked at one side of the reactor while the other side is allowed to expand axially. The seismic loads between the reactor and the fuel channel, with fueling machines attached at both ends, are transferred through the positioning assembly. For higher seismic capacity, the seismic loads acting on this component increase substantially, which requires the design of a strengthened positioning assembly.

A new, stronger positioning assembly with a wrap-around yoke and increased component stiffness that will have a seismic load carrying capacity of 356 kN (80,000 lbf.) is currently under development.

4. Fueling Machine Z-spring Stiffness Optimization

During a seismic condition the FM Z-springs between the lower and upper gimbals connection serve as an important link between the fueling machine head on the one side and the carriage, bridge and column on the other side. In the current CANDU 6 reactor design, both soft and stiff Z-springs, as shown in Figure 6, are used. Selection of the soft or stiff Z-springs mounted on both fueling machines depends on the soil conditions and other system variables.

Based on the feasibility study, a combination involving the use of both soft and stiff Z-springs appears to be the most important design modification for achieving a higher seismic. The findings indicate that the soft Z-spring should be used for the side with the positioning assembly locked at the channel (i.e., the fixed end of the channel), whereas the stiff Z-spring should be used on the other side of the fuel channel with the unlocked positioning assembly. The Z-springs will be interchanged when the positioning assembly's locking-unlocking is interchanged at the pressure tube's half life.

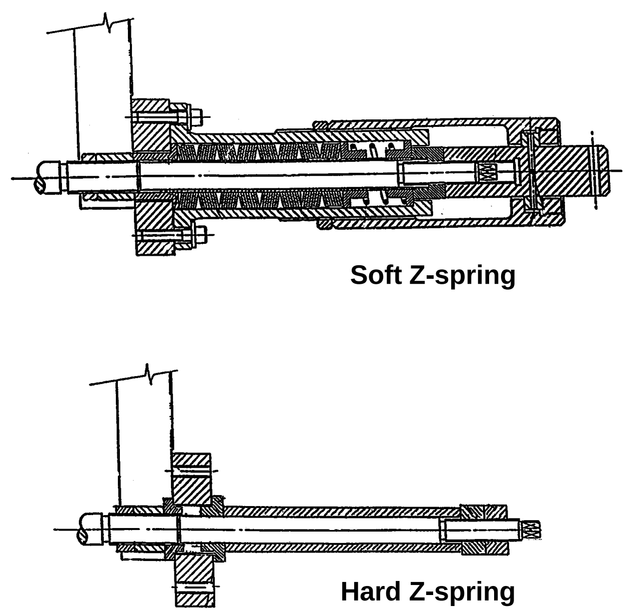

Figure 6 Soft & Stiff Z-Springs

5. Bridge Stiffening

Stiffening of the bridge and columns in the axial direction reduces the seismic motion of the fueling machines, particularly in the axial direction.

The bridge design is modified by adding three more cross bracing at the top instead of a single bracing as shown in Figure 7. This helps to further increase the stiffness in the axial direction.

As the seismic loads tend to increase due to a higher seismic response capability, the transverse-direction (along the bridge) seismic clamps on the FM carriage also need to be strengthened.

6. Short Column Free End Support

Based on the seismic analysis results, it is assessed that the maximum loads acting on the fuel channel, especially in the axial direction, come from the configuration where the fueling machine is attached to the bottom-most channel, e.g. the W11 location. These loads are about 15% higher than those compared to the middle channel locations. This is due to the fact that the axial stiffness, provided by the un-supported part of the short column, is reduced at the lower-most location, thus further amplifying the seismic responses. Figure 7 shows the location of the axial bracing on the unsupported column, which increases the axial stiffness, thus reducing the seismic loads.

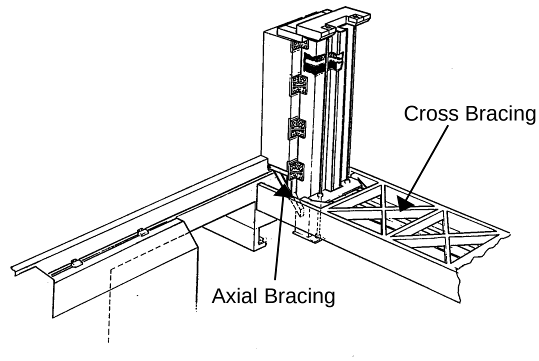

Figure 7 Bridge & Column Stiffening

7. Pitch and Yaw Spring Stiffening

Pitch and yaw springs are designed with a low spring stiffness for the X and Y fine motion of the fueling machine head during the clamping of the snout to the fuel channel end fitting. The calculated linearized spring stiffness for both pitch and yaw springs is about 525 to 700 kN/m (3,000 to 4,000 lbf./in.). As a result of these soft springs, the X and Y seismic response of the fueling machine head will impose significant bending moments onto the end fitting under a seismic condition. In order to further cut down the bending moments, stiffening the pitch and yaw springs provide another effective solution. This can be accomplished by simply locking the X and Y motion of the fueling machine after the fueling machine is properly aligned and attached to the end fitting.

COMPARISON OF SEISMIC ANALYSIS RESULTS

Incorporating the above recommended and relatively simple design changes in the reactor and fuel handing seismic model, the seismic loads acting on the fuel channel are evaluated and listed in Table 1. The results are summarized for the fuel channel critical components, in terms of seismic equivalent axial loads and compared to their maximum allowable limits.

Table 1 Summary of Fuel Channel Seismic Loads For 0.3g Ground Acceleration

Fuel Channel Critical Component / Region	Max. Allowable Equivalent Axial Load lbf. (kN)	Calculated Max. Equivalent Axial Load Under 0.3g lbf. (kN)	Seismic Qualification ‘g’ Levels based on 80% of Code Allowable Limits
Pressure Tube	61,000 (271)	47,910 (213)	0.32 g
Rolled Joint	61,200 (272)	45,440 (202)	0.34 g
End Fitting Bellows Attachment Ring Region	330,000 (1468)	236,630 (1053)	0.35 g
End Fitting At Snout Region	500,000 (2224)	407,350 (1812)	0.31 g
Positioning Assembly Stud	80,000 (336)	58,930 (262)	0.34 g

For the pressure boundary components the seismic inertia loads are combined with other loads for the Design Basis Earthquake condition, and the results are compared with allowables as per ASME Level C service limits. This determines the acceptability of the seismic loads for higher seismic response levels.

CONCLUSIONS

Based on the results of the seismic analysis with all the design changes incorporated in the R & FH system, it has been demonstrated that with simple design modifications, the R & FH system of the CANDU 6 reactor can withstand earthquakes up to 0.3g ground acceleration.

FUTURE WORK

In addition to the above simple design changes, it is believed that there is still some potential to increase the seismic capability of the CANDU 6 Reactor and Fuel Handling system beyond 0.3g ground acceleration level. One possible way would be to do a soft de-coupling of the reactor assembly from the fueling machines by using a soft positioning assembly.

The design of the fuel channel positioning assembly would be optimized in the axial stiffness direction to provide a soft connection so that it would have sufficient load carrying capability for normal operation. With this design, the seismic interaction between the reactor assembly and the fueling machines would be minimized, thus further enhancing the seismic capacity of the CANDU reactor on-power refueling system.

REFERENCES

[1] ASME Boiler and Pressure Vessel Code, Section III, The American Society of Mechanical Engineers.

[2] Canadian Standards Association, “Design Procedures For Seismic Qualification of CANDU Nuclear Power Plants”, CAN3-N289.3-M81.

[3] STARDYNE computer code, Supercomputing Solutions, Inc.