How and Why is CANDU designed the way it is

Sub-title?

Reactor Type Selection

Summary:

The fundamental decision to use natural uranium and heavy water set the CANDU reactor on quite a separate course compared to the PWR design. Some of the key characteristics, such as diffusion length and neutron lifetime, determine key design features such as core size, the use of pressure tube vs pressure vessel, refuelling method, rod worth, possible reactivity insertions under accident conditions, reactivity coefficients of temp and void, and transient response.

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Introduction

1 An Accident of Birth

The only naturally occurring fuel of significant quantities is $_{235}$U, hence most reactors use this fuel. Naturally occurring uranium is composed of 0.7% $_{235}$U. The rest is $_{238}$U. This percentage is too low to sustain a chain reaction when combined with most practical moderators. Hence, to achieve criticality, either, the probability of fission must be enhanced or the moderator effectiveness must be enhanced. One group of reactor types (PWR, BWR, HTGR) enrich the fuel (a costly task) and use a cheap moderator (ordinary water or graphite). Alternatively, natural uranium (relatively cheap) is used with an excellent but expensive moderator (heavy water). This is the CANDU approach. The choice of which combination of fuel / moderator is used has as much to do with historical legacy and national infrastructure than anything else.

As illustrated in figure 1, the fundamental decision to use natural uranium and heavy water set the CANDU reactor on quite a separate course compared to the PWR design. Some of the key characteristics, such as diffusion length and neutron lifetime, determine key design features such as core size, the use of pressure tube vs pressure vessel, refuelling method, rod worth, possible reactivity insertions under accident conditions, reactivity coefficients of temp and void, and transient response.

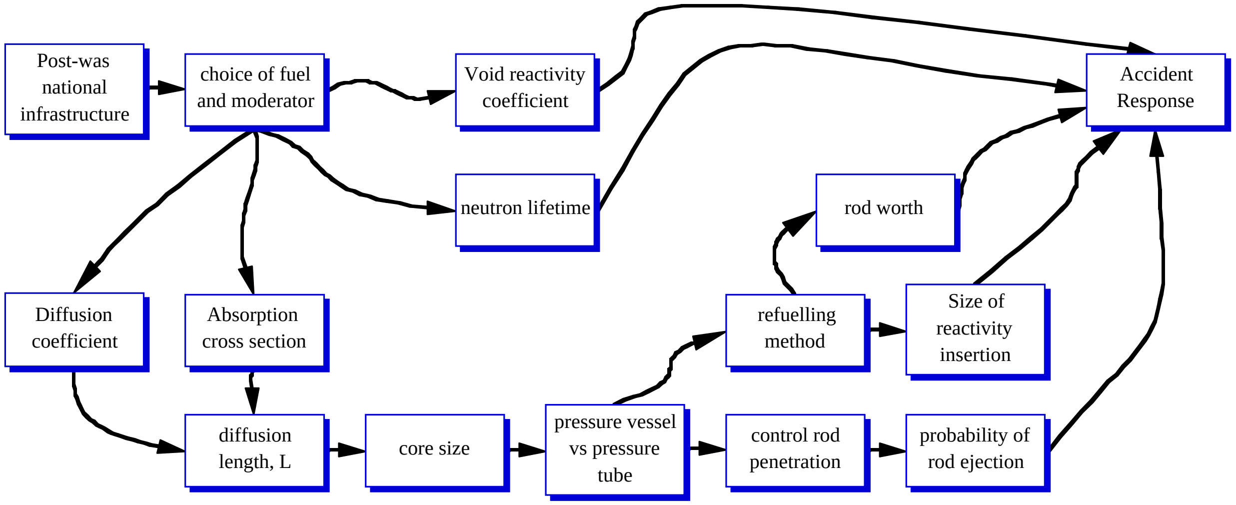

Figure 1 Influence diagram: a chain reaction of a different sort.

2 Post-war situation led to Canada choosing D2O and natural fuel.

CANDU is a natural U fuel, D2O moderated type reactor. The PWR is an enriched U fuel, H2O moderated type reactor. Development primarily in NA since far from war arena. US worked on

U235 enrichment, Canada worked on Pu production via U-238 which implied nat U and D2O. Thus it was natural that in the post-war era, when peaceful uses of nuclear were sought, that Canada when the heavy water / nat fuel route while the Us went the enriched fuel / H2O route.

3 L

This means that the diffusion length, L = sqrt(D/sigma a) is about 20 time longer for CANDU than PWR (show calcs).

4 Neutron lifetime

lifetime ~.0001 sec for CANDU, .00001 for PWR. Relate to inhour eqn; show the lifetime is impt for prompt critical events

5 Core size determines the use of pressure tubes

This means that the CANDU core is bigger than the PWR for comparable power (give sizes). HTS is water (say why) and must be pressurized (to prevent excessive boiling and raise t/d efficiency). The tight pitch of PWR requires a pressure vessel. CANDU can use pressure tubes. Limitations of hoop stress (show calc) limits the size of a practical pressure vessel. Wall of PWR about 12" thick - limit of technology. CANDU pressure tube thin (give thickness). Resulting core is +ve void coefficient

Use of pressure tubes possible because of Zr

The D2O moderator of CANDU means that the core is larger in physical size than a PWR (see the solution to question 5). Since the coolant (heavy and light water in these cases) must be pressurized (to about 100 atmospheres) to prevent too much boiling and to raise thermodynamic efficiency, pressure boundaries must be provided for the coolant. Pressure boundary wall thickness goes up in proportion to vessel diameter (a simple hoop stress calculation shows this), and for CANDU, the wall thickness would be prohibitive if a pressure vessel were used to surround the entire core. Hence pressure tubes are used in CANDU.

6 Re-fuelling

Even if there was no hoop stress problem, the use of natural fuel dictates that the core be refuelled frequently. So on-line refuelling is required.

The PWR has a smaller core and enriched fuel, so it can get away with a pressure vessel and batch refuelling, say once a year.

7 Void coefficients

The tight H2O core of the PWR means that the reactivity coefficient for void is negative, meaning that the core tends to shut itself down when the power goes up.

8 Rod worth

Just as well, too, because the control rods must penetrate the pressure vessel, making them subject to sudden ejection should the rod housing fail. The rods must have a high worth because they have to compensate for all the extra fuel that must be added to permit a reasonable time between shutdowns that are required to refuel.

CANDU, on the other hand, does not have, or need to have, a large reactivity inventory since it uses natural U fuel and can refuel continuously.

9 Transient response

So the control rods have far less worth than a PWR and the maximum reactivity insertion due to inadvertent rod withdrawal will be lower in magnitude, slower in occurring and less likely to occur than in the PWR. However, the void coefficient is positive in the D2O design. The CANDU also has an neutron lifetime 10 times longer than the PWR.

So, for normal transients, in which the inserted reactivities are small, the time constants are dominated by the delayed precurors. So one design is as good as the other - control is not a problem.

But for accident transients, the reactivity insertions can be large. The PWR is prone to much larger insertions in a shorter time. But the reactor tends to shut itself down. Of course, the flip side to that is that the PWR resists being shutdown! And, here=s the point of this discussion, the shorter neutron lifetimes make the resulting transients more rapid since it is the neutron lifetime that dictates the transient response times when insertions are greater than prompt critical.
The CANDU, on the other hand, has accident scenarios characterized by smaller reactivity insertions that occur less quickly, making them easier to manage and the runaway is slower since the neutron lifetime is 10 time longer in CANDU than in PWR. The positive reactivity coefficient increases the instability but makes it easier to detect a problem (the flux rate change is an easy signal to detect). In the PWR case, the negative feedback tends to mask the event that we need to detect. To compensate for the positive void coefficient, CANDU uses a second shutdown system as a backup. The PWR has only one system.

Both systems have unique characteristics that result from their design. Both have been engineered to be safe enough. In, short, safety coverage is more a function of system behaviour that it is of any single design characteristic.