Concepts of Passive, Light Water Pressure-Tube Reactors

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ABSTRACT

High-power-rating, (≥1000MWe) passive pressure tube light water-cooled reactors are described that have the ability to reliably discharge decay heat to the ultimate heat sink, without the need to replenish primary coolant in loss of coolant accidents, while ensuring the integrity of the fuel and reusability of major reactor components. It is shown that pressure tube reactors have the attractive potential to dissipate the decay heat from voided fuel elements of large-power-rating cores without exceeding safe temperature limits. Two basic versions of a pressure tube, light water cooled and moderated reactor—the dry calandria and wet calandria concepts—are proposed and their advantages and limitations are pointed out.

1. INTRODUCTION

In the late eighties, a study was initiated at MIT to develop a conceptual design of an advanced LWR that would build on excellent experience with light water coolant while simultaneously improving safety. The key results of this study, which continued under the sponsorship of the US. Department of Energy, are summarized in this paper. The summary draws from the previously published set of articles related to this topic [Hejzlar, et al., 1993a], [Tang, et al., 1994], [Hejzlar, et al., 1995], [Hejzlar, et al., 1996a,b], [Hejzlar, et al., 1997]. More recently, reactors of this type have been evaluated in Korea [Kim and Yoon, 1997].

Three major objectives set for the MIT concept development involved the following:

a) **Ability to dissipate the decay heat from voided fuel elements.** The advanced LWR concepts [Frisch et. al., 1993] incorporate passive safety features at various levels, but all have one feature in common—the need to replenish the lost primary coolant in voided fuel bundles to assure removal of the decay heat from the fuel. In contrast, our objective is to ensure sufficient decay heat removal from the voided fuel bundle without the need for replenishing the primary coolant. This goal is partially motivated by the Modular High Temperature Gas Cooled Reactor (MHTGR), being developed by General Atomics, which has the capability to survive the absence of primary coolant without fuel damage.

b) **Large unit power rating of at least 1000 MWe.** Although small sized reactors can meet a large rating requirement by employing multiple modules, it is unlikely that they will be deployed in numbers sufficient to offset the economies of scale offered by large size units. Also many utilities in Europe and Asia prefer to employ the current size range of about 1000 MWe or larger because of the difficulty in securing suitable plant sites. Consequently, the target rating of the passive LWR was set to at least 1000 MWe. The trend of large power ratings is confirmed through current developments of passive LWR plants [Arnold, et al., 1996], [Oyarzabal and Noviello, 1996] and future BWR concepts [Tanaka, et al., 1997].

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c) **Retain conventional defense in depth**. With the introduction of new advanced concepts with inherent safety features, some opinions have been expressed that these may eliminate the need for multiple barriers, e.g., containment. For example, the above-mentioned MHTGR concept has been proposed without a conventional containment building, and it was argued that its function could be achieved by a high quality particle fuel coating. Nevertheless, one has to keep in mind that whatever the level of safety, any nuclear power plant contains radioactive material and involves a certain amount of risk. Since one cannot rule out what is physically possible, the objective of the design should be to reduce the risk of severe accidents to extremely low values comparable to other commonly accepted risks. Therefore, the present study retains the current defense in depth philosophy with multiple barriers to fission product release, including the final barrier–containment of the reactor.

The achievable power rating of nuclear reactors is limited by their coolant's capability to remove generated power at the location of highest power density without exceeding safe temperature limits on the cladding and the fuel. The traditional approach is to establish a nominal power such that these safe limits are not exceeded, both during steady state operation and plant transients. To stay within the safe limits in loss of coolant accident scenarios, the practice is to replenish primary inventory rapidly with emergency coolant (either by active or by passive means). The approach presented here is based on the objective that the fuel elements should safely survive the total loss of primary coolant, hence eliminating the necessity of primary coolant replenishment. Consequently, besides the traditional constraints stemming from thermal hydraulics and reactor physics limitations during normal operation and transients, an additional constraint on the achievable reactor power output arises. This constraint ensues from the requirement that voided fuel elements must be capable of dissipating the decay heat by natural phenomena such as conduction, radiation, and convection in steam/air mixtures, without exceeding safe temperature limits. The rated core power which would satisfy this requirement depends primarily on the following factors:

- maximum temperature limit of cladding or fuel,
- effective thermal conductivity of voided fuel elements,
- peaking factor,
- heat storage capabilities of the fuel, and
- the distance between the fuel centerline and the heat sink, and geometrical arrangement of the fuel element.

Enhancement of the maximum limiting temperature, T_{max}, under decay heat removal conditions can be achieved by replacing the conventional Zircaloy cladding with ceramic cladding or by using high temperature fuel in the form of particles with ceramic coating. The effective conductivity due to conduction, radiation and convection, k_{eff}, which is marginal for voided LWR fuel bundles, can be considerably increased by introducing a solid matrix with dispersed fuel and coolant channels. The large heat storage capability of the solid fuel matrix effectively delays the time at which the heat removal rate must equal the heat generation rate by storing a substantial amount of decay energy. Reducing the total peaking factor results in lower peak parameters at the locations where the limits are reached first. A considerable decrease in peaking factor can be achieved by introducing voided regions inside the core to increase the neutron mean free path, and consequently, to flatten the thermal flux profile.

The length of heat transfer path from the fuel centerline to the heat sink is of prime importance. The study of various core geometry configurations [Hejzlar, et al., 1993a] has shown significant benefits of arrangements of fuel modules dispersed in a low pressure heat sink—see Figure 1. Power **Q**, shown in Figure 1, is the core nominal power allowed by the decay heat removal constraint in case the fuel elements are voided, i.e., the maximum temperature limit on cladding

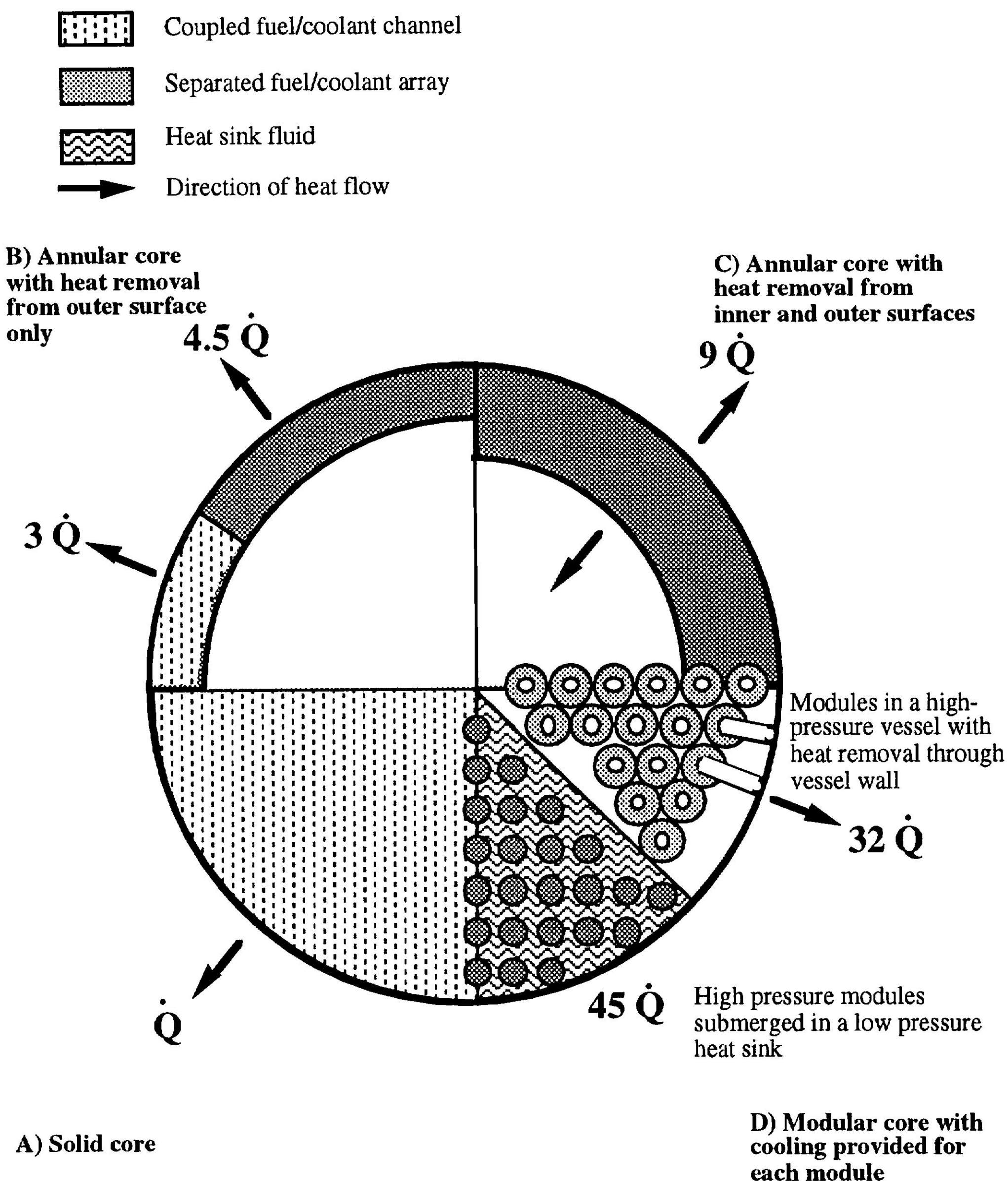

Figure 1. Various Fuel Matrix Configurations in an LWR Core—The Road to Fuel Modularity

cannot be exceeded. The transition from a solid core to an annular core configuration yields a power increase from **1Q** to **3Q**. The arrangements of fuel and coolant channels in the matrix have been assessed in two alternatives (note that all geometric configurations employ a fuel matrix). The first arrangement uses coupled fuel/coolant channels with clad fuel pins inserted in the center of coolant channels and the coolant flows around the rods. The second configuration uses separate fuel/coolant channels, where the fuel is in a set of fuel holes and coolant flows through separate coolant channels. Although some increase in achievable power can be attained by rearranging fuel/coolant channels within a matrix, this enhancement is not significant as can be observed from the modest increase: from **3Q** to **4.5Q**. Better gains can be achieved through changes of the core geometry. By far the largest increase can be achieved by going to a modular core. The first version of modules in a high pressure vessel (**32Q**) is rather impractical since it requires provisions to transfer the decay heat from the modules to the vessel wall. The highest decay-heat-limited power rating (**45Q**) is attained using high-pressure modules submerged in a low-pressure heat sink. The practical application of this fuel modularization principle, based on conventional technology and experience provided by CANDU reactors, is a pressure tube reactor having the low-pressure calandria as a heat sink.

Taking into consideration all these principles in combination with the available technology experience base, results in a new production line of CANDU-like, passive pressure tube light water reactors (PTLWRs). CANDU reactors are heavy water-cooled pressure tube reactors with separate low-pressure heavy water moderator. Similar to CANDU units, the fuel channel in a PTLWR consists of a pressure tube which provides the pressure boundary, a thin calandria tube surrounding the pressure tube and the fuel elements inside the pressure tube. Like all pressure tube concepts any break of the primary system boundary, including the catastrophic failure of the core region pressure boundary can be shown to be tolerated. The typical Zr-clad 37-pin CANDU fuel elements, however, are replaced by a matrix-type fuel. Ceramic-clad fuel bundles in a two-ring arrangement are also shown to be adequate.

2. DESIGN OPTIONS OF PRESSURE-TUBE LWRS

Consistent with the premises, light water is used as both the moderator and coolant. The minimum fuel channel pitch in pressure tube reactors is restricted by the space requirements associated with header plumbing and on-line refueling. This restriction is compatible with D_2O or graphite moderator which have relatively small slowing down powers. Using H_2O moderator, with its much larger slowing down power, maintenance of a relatively large channel pitch requires changes in the moderating properties of the H_2O-filled region. This can be attained by reduction of the moderator-to-fuel volume ratio through a mixture of H_2O and solid materials or a mixture of H_2O and voids in the calandria space, i.e., outside the fuel channels. The former approach is being explored by Russian investigators [Belousov and Naumov, 1993] who proposed filling the interchannel space with a low-absorbing, low-moderating, metal-oxide ceramic, such as magnesium oxide, cooled by circulating liquid moderator, e.g., H_2O. The latter approach has been adopted for a high-converting pressure-tube light water cooled reactor without any interchannel moderator, proposed for the purpose of plutonium breeding [Ronen,1990]. From the standpoint of decay heat removal from voided fuel elements, the latter approach is preferable since it allows placing more[a] light water moderator, which serves also as a heat sink, into the interchannel space. Therefore, this study is focused on the class of pressure tube LWRs having a mixture of H_2O and voids in the calandria space.

Figure 2 shows the two basic types of arrangement of the light water moderator in the calandria. In the first arrangement, no external H_2O moderator is in permanent contact with the fuel channels. The calandria tubes are dry during normal operation, hence the designation as the *dry calandria design.* A large, light-water pool, which is kept outside the calandria space by a gas lock has the designated function of a heat sink. The dry calandria design has two versions. The first version employs Zircaloy tubes containing low-pressure light water moderator in the calandria region, i.e., out-of-channel moderator, while the second version does not have any out-of-channel moderator. The out-of-channel moderator (in addition to the inside-the-channel moderator) allows good optimization of moderator-to-fuel ratio for fuel arrangements with high heavy metal loading. The second version is applicable to a fuel matrix with TRISO[b] particle fuel, since the heavy metal loading achievable with particle fuel is low, and no additional out-of-channel moderator is needed. The latter version has been analyzed by Hejzlar [1994].

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[a] Note that the voided space has virtually zero neutron absorption and slowing down power, hence more moderation can be achieved in the H_2O present in the calandria space than can be achieved in an equal volume of a mixture of weakly moderating solid material and H_2O in this region.

[b] Three-layer coating consisting of a composite structural coating, made up of two relatively dense PyC layers encased by a SiC layer over a buffer coating.

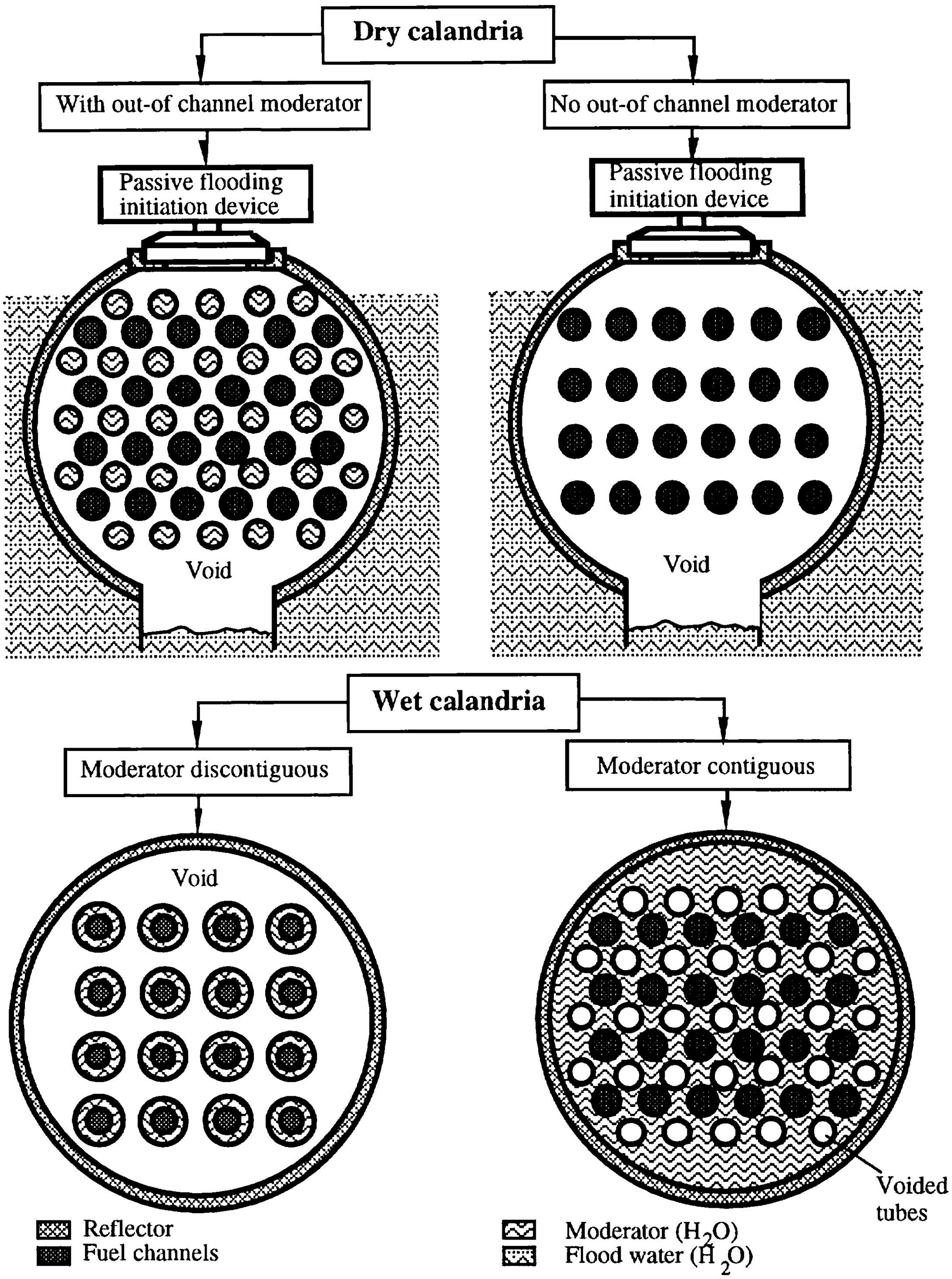

Figure 2. Configurations of Light Water Moderator in a Pressure-Tube LWR.

In the second arrangement type, designated as the *wet calandria design*, low-pressure H_2O moderator is in permanent contact with the fuel channel, wetting the outer surface of the fuel channel, typically, the calandria tube. There are two possible versions of the wet calandria design. In the first version, the moderator is discontiguous, separated by voids. One such possible arrangement, shown in Figure 2, employs a moderator annulus contained in a Zircaloy tube (designated henceforth as the moderator tube) surrounding the calandria tube. In the second version, moderator fills the calandria as a contiguous medium. To provide the optimum moderator-to-fuel ratio, voided Zircaloy tubes are introduced. The low pressure, low temperature moderator also serves as a passive heat sink in a loss of coolant or loss of heat sink accidents. The wet calandria design in the arrangement of the first version has been investigated by Tang, et al. [1994].

3. THE DRY AND WET CALANDRIA CONCEPTS

Overall arrangements of one of the dry and one of the wet calandria concepts are shown in Figures 3 and 4. To build on proven technology to the largest extent possible, both designs are based on CANDU reactors. They consist of fuel channels, calandria vessel, shield tank and the entire primary system (except for the Emergency Core Cooling System (ECCS), which has been eliminated) very similar to those of CANDU units.

3.1 Dry Calandria Version

The proposed dry calandria concept has no moderator outside the fuel channels. Under normal operation, the dry calandria space, surrounded by a graphite reflector with an inner liner, is filled with a gas under pressure slightly above atmospheric. The gas pressure is in balance with the water column in the containment and maintains containment water level outside the calandria space, as shown in Figure 3. During loss of coolant or loss of heat sink accidents the gas is released from the calandria upon a pre-defined disturbance of the primary system conditions, resulting in calandria flooding. Calandria flooding initiation, i.e., gas release, can be accomplished using a passive fluid-operated valve working on primary system pressure or a normally operating electrically powered blower designed to lose power and hence depressurize the gas space upon predefined disturbances in primary system parameters. Calandria flooding has four important purposes:

- it ensures the removal of decay heat from the calandria tubes by boiling, evaporation and subsequent condensation on containment walls during an accident,
- it provides a large amount of water, which stores a considerable amount of decay energy, thus substantially reducing the heat rate transported through the containment walls early in the accident,
- it shuts down the reactor (if still operating) and renders it deeply subcritical by excessive neutron absorption (even in the boiling mode)[c], and
- it considerably reduces the decay heat load on the fuel matrix (more than 20%) by absorbing a large portion of gamma heating which would have been otherwise deposited in the fuel matrix.

Note that since the normal operating gas pressure is only about 0.15 MPa above atmospheric, gas release is not accompanied by the large dynamic forces typical of the depressurization of normal LWR primary systems. Also, note that no primary system depressurization is necessary to couple the passive calandria heat sink to the core. Heat removal to the ultimate heat sink is accomplished via steam evaporation from the calandria and condensation on containment walls, cooled by buoyancy-induced air flow, as shown in Figure 4.

The dry calandria version, shown in Figure 3 employs a SiC-coated graphite matrix with coolant channels and TRISO particles in fuel compacts. The silicon carbide coating of the fuel matrix is required to prevent excessive graphite oxidation at high temperatures in the absence of coolant. During normal operation, cooling is accomplished by light water coolant flowing through coolant channels, while during accidents decay heat is conducted and radiated to the fuel channel outer boundary, and deposited in the flooding water. The calandria tube protects the pressure tube during flooding from excessive thermal stresses.

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[c] Note that the flooding water is non-borated, and still provides a negative reactivity of about 250 β, once all pressure tubes are fully covered.

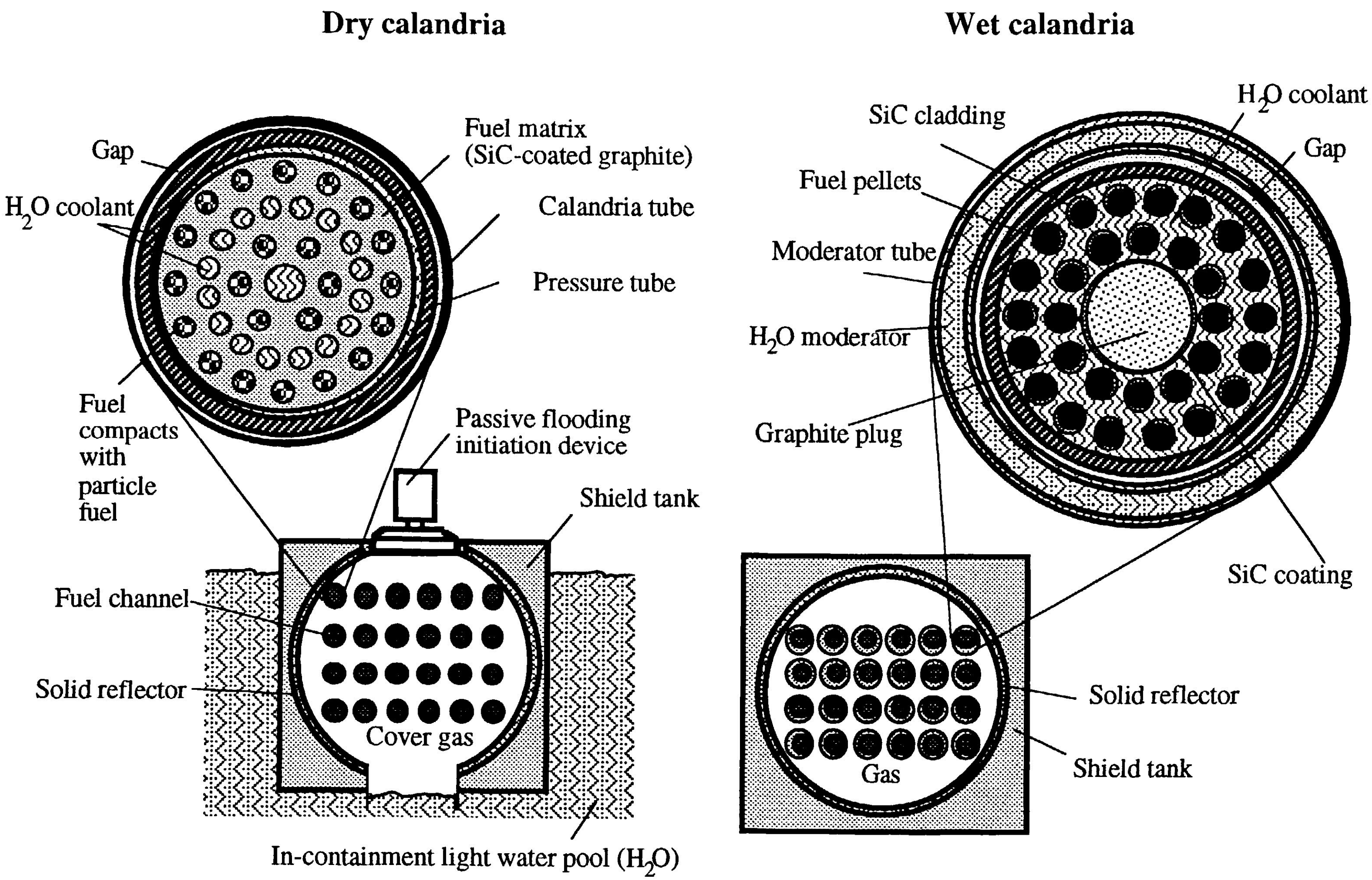

Figure 3. Passive Pressure-Tube LWR in Dry and Wet Calandria Versions.

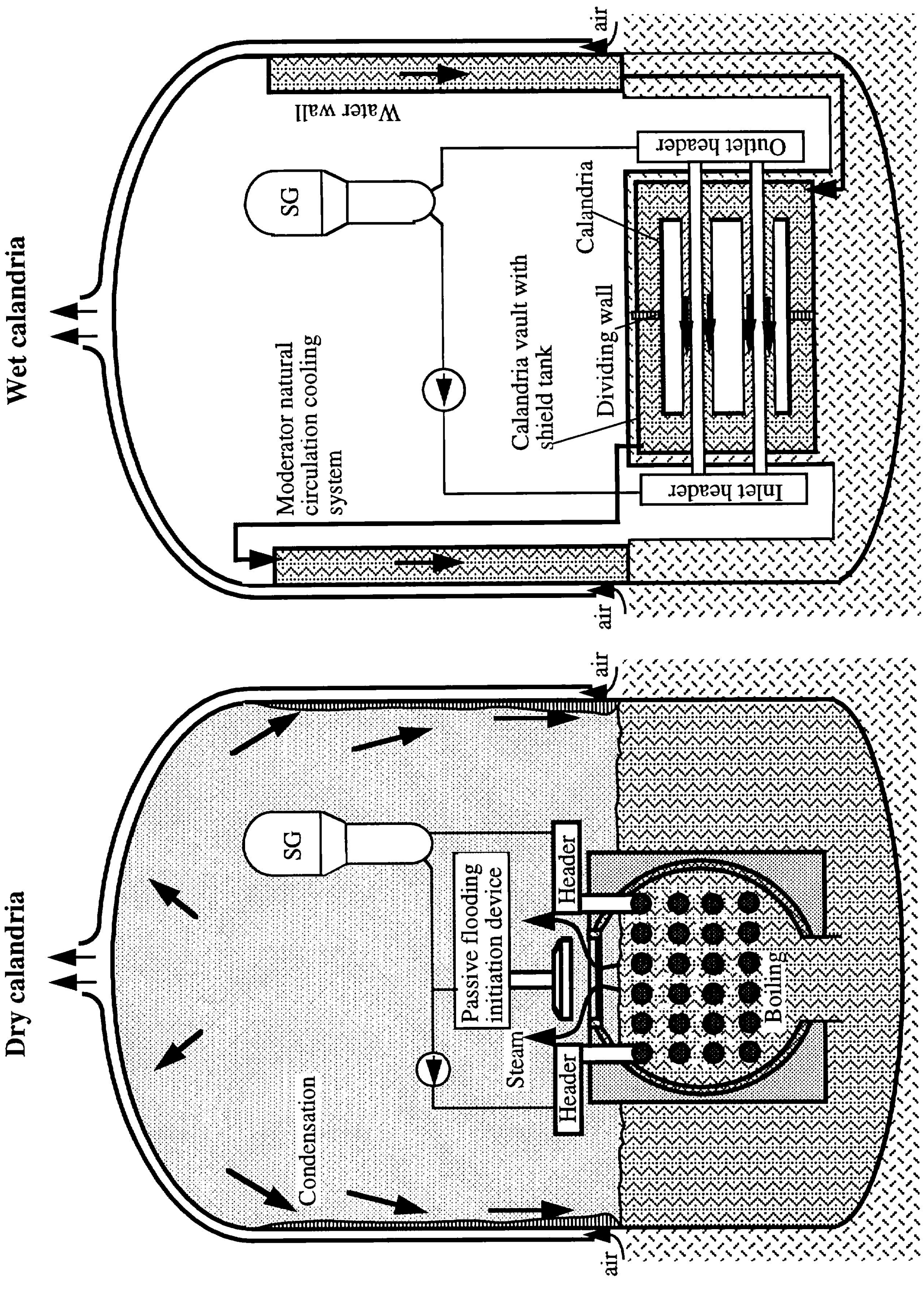

Figure 4. Ultimate Heat Removal Path for the Dry and Wet Calandria Versions.

The analysis of the dry calandria concept [Hejzlar, 1994] in the arrangement shown in Figures 3 and 4 shows favorable reactor physics and thermal hydraulics characteristics. Replacement of CANDU D_2O moderator with gas in the calandria region leads to significant changes in reactor neutronic behavior. The reactor physics features, obtained through analyses by the rigorous Monte Carlo neutron transport method encoded in the MCNP code [Briesmeister, et al., 1991], involve long prompt neutron lifetime comparable to that of the typical CANDU heavy water lattice, flat thermal flux profile with power peaking less than 1.2 for the fresh core and less than 1.35 for the equilibrium core, extremely tight neutronic coupling resulting in inherent stability against xenon spatial oscillations and providing the possibility to control the reactor from outside the core region, large negative Doppler coefficient contributing significantly to inherent reactor shutdown in ATWS scenarios, well thermalized neutron spectrum comparable to the spectra of heavy water lattices, and negative coolant void coefficient throughout the whole cycle [Hejzlar, et al., 1995]. On the other hand, the low heavy metal loading achievable with particle fuel in a matrix results in relatively high absolute values of neutron flux, and thus larger fast fluence on pressure tubes than that in the CANDU reference design. Less efficient neutron economy than in a typical LWR because of higher parasitic losses in thick pressure tubes and fuel matrix is compensated by on-line refueling and high burnup (about 70,000MWd/t) achievable with particle fuel.

Matrix-type fuel elements of the dry calandria version have smaller heated perimeter, smaller number of fuel pins and less available flow area than the traditional CANDU fuel bundles. Nevertheless, the thermohydraulic analyses have shown that during normal operation adequate cooling can be achieved with sufficiently high CHFR and fuel maximum centerline temperatures of 1200°C. This is primarily due to the small peaking factor, and hence decreased maximum linear heat rate, and relatively high thermal conductivity of fuel compacts. Simulation of LOCA without scram and without primary coolant replenishment confirmed that the PTLWR is capable of dissipating excess heat from voided fuel elements without exceeding the design limits. Thermohydraulic characteristics of the proposed fuel arrangements are described in more detail in an accompanying paper [Hejzlar, et al., 1998].

3.2 Wet Calandria Version

Similar to the dry calandria concept, the wet calandria concept employs a low pressure calandria vessel filled with gas and surrounded by a solid reflector. Each fuel channel is enclosed by a thin-wall Zircaloy tube which creates an annular space around the calandria tube that is filled with low-pressure, low-temperature moderator. In addition to performing its moderating function during normal operation, the moderator serves as a heat sink during loss of coolant or loss of heat sink accidents. Since the moderator is in permanent contact with the outer surface of the fuel channels, there is no need for flooding.

Heat deposited in the moderator needs to be transferred to the ultimate heat sink, without reliance on ac power sources. One possible arrangement of passive moderator cooling is shown in Figure 4. The calandria vault which surrounds the calandria contains the light water shield tank which also serves as a moderator reservoir and is in direct communication with the annular space between the calandria tube and the moderator tube. The dividing wall separates the shield tank into two subregions to form the inlet and outlet plena. Moderator recirculation and cooling can be established in a similar manner to that suggested by Spinks [1993] for advanced passive CANDU units using a containment water wall. As shown in Figure 4, hot moderator proceeds to the top of the water wall where it transfers its energy through the containment wall to a buoyancy-induced air flow and returns by gravity to the inlet plenum of the shield tank.

The most promising arrangement of the fuel channel for the wet calandria concept is shown in Figure 3. Fuel bundles have the same geometry as for CANDU units except for the centerline fuel pin and the innermost fuel ring, which are replaced by an SiC-coated graphite plug. This arrangement without the innermost fuel pins allows transfer of the decay heat from the voided fuel channel by radiation, conduction and convection to the moderator heat sink without exceeding safe temperature limits on the cladding. The graphite plug serves to divert the coolant flow to the fuel pins during normal operation and provide a temporary heat sink for the portion of decay heat generated in the inner fuel ring during loss of coolant accidents. Finally, the traditional Zircaloy cladding of the fuel pins is replaced by silicon carbide cladding to increase the maximum temperature the cladding can withstand without damage.

The wet calandria design, although with an alternate fuel element arrangement and moderator cooling system, has been investigated by Tang, et al. [1994]. Similarly as for the dry calandria design, the wet calandria version exhibits a relatively flat thermal flux profile, negative coolant and moderator void coefficients and tight neutronic coupling. In comparison with the dry calandria design, fast fluence is smaller due to higher heavy metal loading in pin-type fuel. Also, lower parasitic losses require low enrichment comparable to that of typical LWRs. Thermohydraulic performace of fuel bundles during normal operation is comparable to that of CANDU. Fuel bundle thermohydraulic analyses show [Hejzlar, et al., ibid.] that the decay heat can be dissipated from the voided fuel elements at temperatures below the acceptable limit.

4. EVALUATION OF THE MERITS OF DRY AND WET CALANDRIA VERSIONS

4.1 Merits Evaluation - General Issues

Both the dry and wet calandria concepts can survive loss of coolant accidents without the need for replenishment of lost primary coolant by conducting and radiating the decay heat from voided fuel elements to the heat sink at the outer boundary of the fuel channel. The key difference is that for the wet calandria version, the low pressure heat sink is in place at all times while for the dry calandria concept the heat sink is passively put in place when needed. Coupling of the heat sink to the calandria requires a reliable, fail-safe device for initiation of this process. Although it is possible to design such an initiating device, the need for reliable flooding initiation is a disadvantage compared to the wet calandria concept where the heat sink is always in place. In contrast to passive PWR designs, the dry calandria flooding system does not have to deliver primary coolant water makeup at high pressure, and accordingly permits simplification since high pressure injection and the associated equipment is eliminated. It also does not require for its function the depressurization of the primary system. However, addition of coolant to serve as a low-pressure heat sink is required, although this heat sink does not need to be delivered directly onto the fuel elements and cannot be interfered with by the steam escaping from the break.

Calandria flooding provides a diverse and redundant reactor shutdown mechanism, which plays an important role in ATWS. Because of the core geometry with large fuel channel spacing, nonborated light water entering the calandria behaves like a neutron trap and renders the reactor deeply subcritical even if the flooding water is in bulk boiling [Hejzlar, et al., 1995] There is no need for soluble boron and an associated chemical system. This diverse shutdown could be also compared to moderator dumping in CANDU systems (or in the wet calandria concept), except for the difference that the dumping of the CANDU moderator results also in the undesirable loss of heat sink, while in the dry calandria design flooding provides both the heat sink and shutdown. Relative to current passive PWR designs which face potentially extensive cleanup as a result of inadvertent primary system depressurization, the inadvertent flooding of the calandria has less adverse effects, since this heat sink is independent of the primary system and does not contain any radioactive contaminants. The recovery can be accomplished by essentially repressurizing the calandria with gas and draining of condensate from the steam released to the containment from boiling of the heat sink.

Since the calandria tubes of the dry calandria concept are not in contact with cold moderator during normal operation, they operate at high temperatures (around 340°C). The higher operating temperature can lead to increased sagging of fuel channels and poses mechanical difficulties in designing joints between the calandria tube and the calandria wall. During flooding, the calandria tubes are exposed to increased thermal stress. However, since the calandria tube operates at slightly higher temperature than the pressure tube, no large thermal gradients which are the primary driving force for hydrogen transport can develop. Hence, the concern of an increased concentration of zirconium hydrides, responsible for pressure tube failure in the CANDU Pickering No. 2 unit at the points of contact between the hot pressure tube and the cold calandria tube, is of much less importance than in the wet calandria concept or CANDU.

The permanent presence of the low-temperature moderator in the core of the wet calandria design results in an inevitable heat loss during normal operation. However, because the mass of out-of-fuel-channel light water moderator is much less than the mass of D_2O moderator in CANDUs, gamma and neutron heating deposited directly in the out-of-fuel-channel moderator is also much less. To ensure a sufficient heat removal rate to the heat sink during an accident, the gap between the pressure tube and the calandria tube needs to be designed to have higher thermal conductivity than that in current CANDU units. Therefore, the heat loss to cold moderator by conduction across this gap is increased. This heat loss could be minimized using a "thermal switch" between the pressure tube and the calandria tube which acts as an insulator during normal operation and as a good heat conductor during an accident. Such a switch is difficult to design and adds mechanical complexity. Several thermal switches have been proposed by Novak [1995]. The wet calandria design could operate without a thermal switch if a heat loss of about 5% is deemed to be acceptable—which is about what current CANDU units lose to their D_2O moderator.

Another disadvantage of the wet calandria concept is a more complicated decay heat removal path to the ultimate heat sink. The dry calandria version uses the most effective heat transfer modes—boiling and condensation—to transport the heat from the core to the containment wall and does not require any piping to accomplish this purpose. The wet calandria design employs natural circulation of the moderator in the liquid phase at atmospheric pressure. To avoid moderator boiling and concerns with two-phase flow instabilities and associated reactivity feedbacks, the temperature of the moderator in the core will be less than the saturation temperature in the dry calandria version. Moreover, to establish natural circulation in the loop, a temperature difference between thermal centers is required. For these reasons, the effective temperature of the containment wall is less than in the case of the dry calandria design. Since the power removable by buoyancy-induced air flow is proportional to the containment wall temperature, the wet calandria concept poses a far greater challenge for the design of containment cooling than the dry calandria concept. Tang proposed and confirmed the feasibility of a different moderator cooling system than that shown in Figure 4, using air coolers, but at the expense of containment penetrations. The moderator cooling system also requires piping to transport the fluid from the core to the containment wall. Since this piping accommodates low pressure, it is less susceptible to failure. Nevertheless it needs to be safety grade and protected against damage from missiles, jets or seismic events.

The main disadvantage of the wet calandria concept is its susceptibility to moderator tube failure and subsequent loss of low pressure heat sink, in case of pressure tube rupture. Although pressure tube rupture may not result in the simultaneous damage of the calandria tube, as the Pickering accident has demonstrated, the failure of the calandria tube and the surrounding moderator tube cannot be excluded. A gravity-driven accumulator tank having a mass of light water equal to the calandria free volume could solve this problem by replenishing the moderator which escaped through the break. Alternatively, the wet concept could be equipped with the calandria flooding system used in the dry design. Another challenging scenario would be pressure tube rupture and simultaneous failure of the calandria tube without the failure of the moderator tube, resulting in the subsequent pressurization of the moderator cooling system. Hence, safety relief valves must be provided to avoid moderator system overpressurization and damage.

Both the dry and wet calandria concepts are feasible, but in view of the above discussion the dry calandria version is deemed to be preferable, primarily due to its simple and more rugged heat removal system to the ultimate heat sink and due to the provision of diverse and redundant reactor shutdown by flooding the calandria space with light water.

4.2 Technical and Feasibility Issues

While the main purpose of this paper is to introduce a new class of LWRs with very good potential of passive decay heat removal rather than the detailed discussion of technical issues, some topics deserve to be briefly mentioned. This section will focus primarily on the technical solutions which differ from CANDU practice and on economic viability.

Technical issues

As mentioned earlier, the proposed PTLWRs are based on CANDU reactors. CANDU units have demonstrated very good reliability and safety [Expert group, 1989]. To underscore their high level of performance capability it is noted that in 1994 six of the 25 commercial reactors in the world having the highest capacity factors were of CANDU design even though CANDU reactors constitute only ~7% of all water cooled reactors. Except for different fuel, different operating conditions of fuel channels and the solid reflector, the PTLWR design is almost the same as that of CANDU, hence most of the CANDU technology experience is directly applicable to the PTLWR as well. The main differences will be discussed next.

1. Fuel Matrix Issues

Replacement of the traditional fuel bundles with Zircaloy-clad fuel pins by the solid matrix fuel is the major departure of the dry calandria design from CANDU practice. Graphite machined blocks having fuel compacts with particle fuel and separate coolant channels is proven technology for gas cooled reactors. U.S. and German tests of millions of TRISO coated particles have shown that the particles can retain fission products up to temperatures of 1600°C [Schleicher and Wistrom, 1992] An alternative to machined blocks are the molded block fuel elements developed by HOBEG [Hrovat, et al., 1975] which consist of an isotropic highly crystalline graphite matrix with coolant channels and fuel regions with TRISO particles embedded in a graphite matrix. The major departure from current experience with this type of fuel is the use of SiC-coated graphite in a light water environment. Moreover, during LOCA these fuel blocks must withstand temperatures around 1000°C in highly oxidizing steam/air mixtures. An extensive literature survey [Hejzlar et. al., 1993b] shows that silicon carbide is compatible with light water at LWR coolant conditions and can withstand temperatures up to 1300°C in air or steam. The key issue which needs to be confirmed is the reliability of SiC coating during long-term operation and during rapid temperature excursions.

Tests of SiC-coated graphite specimens in ten thermal cycling tests involving heating at a rate of 20°C/s up to 1000°C and cooling down to 170°C in 549 seconds, performed by Japanese researchers [Eto and Shindo, 1992], have shown no degradation of coating integrity and no weight loss. Severe quench tests from 1000°C to room temperature, performed by Mattingly [1995], caused microcracks in the coating. Subsequent exposure of these specimens to a steam environment at a temperature of 1000°C for five hours yielded only 2% weight loss. Hence there is some evidence that a coating with small cracks still retains some protective capability. However, these microcracks may result in undesirable water uptake by the graphite substrate during long-term normal operation. This has been shown by Matttingly [1995] who tested such specimens at reactor conditions for 500 hours. Very encouraging results have been obtained by German researchers [Hurtado, et al., 1994] who developed an SiC-infiltration/slip-coating method where the SiC layer is tightly embodied in graphite substrate and resists mechanical stresses. Several severe quench tests of specimens prepared by this method from 800°C to 20°C and subsequent tests in air for 24 hours at a temperature of 800°C did not degrade the protective quality of the coating even though some microscopic cracks appeared.

These results together with other efforts [Schulten, 1993] indicate that the silicon carbide coated graphite matrix is a viable option for use in a light water environment. There is also the ongoing research for even more strenuous applications such as the first wall liner and divertor in fusion technology, the progress of which can be directly applied for the PTLWR concept. More details on the material compatibility issues are provided in an accompanying paper [Hejzlar, et al., 1998].

2. Fuel Channel and Solid Reflector Issues

Fuel channels consisting of pressure tube, calandria tube, annulus spacers and end fittings are basically the same as those of CANDU units but work at different conditions. These different conditions involve higher operating temperature and pressure, and higher fast neutron flux. Higher coolant temperature and pressure to achieve thermal efficiency comparable to that of PWRs can be accommodated by increasing the wall thickness of the pressure tube, as discussed and evaluated by Shapiro and Jesick [1979]. The higher fast fluence on pressure tubes of the dry calandria version is of prime importance since it has detrimental effects on dimensional and property changes. In particular, the increased rate of axial elongation would require design changes to allow for a larger travel allowance. Nevertheless, it is not anticipated under these conditions that the fuel channel life could reach the target plant lifetime of 60 years, projected for advanced LWR plants. The plant would have to be designed, similarly as CANDU 3, to allow fast replacement of fuel channels once in a lifetime. CANDU 3 fuel channels employ a single-ended refueling scheme and integral design of the pressure tube and calandria tube into a single module which can be easily and quickly removed and installed as a unit into its lattice position.

The graphite reflector surrounding the calandria space requires cooling. The end reflectors are cooled by the coolant running through the fuel channels while cooling of the radial reflector can be accomplished by additional nonfueled channels placed in the reflector wall. Calculations showed [Hejzlar, 1994] that sufficient cooling of the reflector can be attained using 32 additional nonfueled channels. Detailed design of the calandria tube-graphite interface needs to consider dimensional changes of graphite due to irradiation as well as due to thermal expansion, and to provide for fuel channel replacement while having small heat transfer resistance. One possible solution, based on extensive RBMK experience, is an array of inner and outer graphite rings, located between the tube wall and graphite blocks.

Economic Viability Assessment

To establish a baseline for the PTLWR performance and compare it with other operating reactors, an approximate economic assessment has been performed [Hejzlar, 1994]. Fuel cycle cost analysis indicates that the PTLWR fuel for the dry calandria version is comparable to current PWR fuels. The fuel cycle cost for the wet calandria concept is expected to be less than that of the dry calandria fuel because of lower fabrication cost and lower enrichment.

With respect to the capital cost, only a qualitative estimate has been made based on an economic study of a large HWR for U.S. siting [Shapiro and Jesick, 1979]. This study reported 8% higher overnight capital cost of a 1260 MWe HWR than a 1256 MWe PWR plant. This higher capital cost was attributed primarily to the complicated primary system piping, refueling machines, large moderator heat rejection system, D_2O upgrader and lower net efficiency. Among these, the moderator heat rejection system and D_2O upgrader (indeed, the D_2O itself—a large savings) are eliminated in the PTLWR concept and the thermodynamic efficiency is increased to PWR levels. However, there is an additional cost for the large graphite reflector, plus the safety-grade passive flooding system or passive heat removal system for the dry and wet calandria versions, respectively. Hence, it is expected that the capital cost of the PTLWRs would remain slightly higher than for a PWR. The elimination of diesel generators, emergency core cooling system trains and associated safety-grade equipment in the PTLWR should lead to cost reduction. Also, advances realized in designing CANDU 3 where emphasis is put on plant simplification and cost reduction could be applied to PTLWR. However, since similar trends can be observed in advanced PWR designs, it is not expected that this would lead to significant cost benefits over PWRs.

5. CONCLUSIONS

A new family of pressure-tube light water cooled and moderated reactors with the ability to survive LOCA without the need to replenish primary coolant has been proposed. Two basic configurations—the dry calandria and the wet calandria designs—have been identified and briefly described. Both versions are distinguished from other typical LWRs by relatively large voided space in the core region and the option of partially or fully separate coolant and moderator. Decoupling the moderator from the cooling function relaxes the limits imposed by reactor physics and thermal hydraulics constraints, and hence introduces additional degrees of freedom into the design process. Currently operating thermal reactors, as well as advanced evolutionary and revolutionary reactors under development use fuel elements heterogeneously distributed in a homogeneous moderator. However, the useful range of fuel/moderator ratios in such arrangements (note that fuel/moderator ratio strongly affects many important reactor physics parameters, e.g., void coefficient) is limited because changes in this ratio to achieve desirable reactor physics characteristics are strongly coupled to thermohydraulics limits. For example, if one strives for a harder neutron spectrum by squeezing out as much light water as possible from the standard LWR lattice, cooling capabilities are affected, and impose a limit on the minimum practical pitch. This is not necessarily the case with the proposed concept, which allows changing the mass of heterogeneously distributed moderator in a voided calandria space (either in the dry or wet calandria version) without affecting the cooling capabilities of the channel. Hence, the designer has the additional variable—separate moderator—to work with. Using various fuel arrangements inside the fuel channel and a separate light water moderator outside the fuel channel to shift the neutron spectrum in the desired direction, a range of design alternatives can be demonstrated which emphasize specific missions; for example dry calandria versions for either plutonium production or plutonium burning.

The magnitude of neutron fluence on the pressure tubes is a parameter which can be reduced by increasing the fuel loading. In the wet calandria version, high heavy metal loading can be introduced; whereas in the dry calandria version with particle fuel, the loading is more limited, leading to the necessity of considering alternate means to ameliorate or accomodate the effect of neutron fluence on pressure tube mechanical conditions.

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