Innovative Fuel Elements with Enhanced Decay Heat Removal Capability for Passive, Pressure-Tube LWRs

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ABSTRACT

This paper focuses on the development of advanced fuel elements for innovative pressure tube LWRs. Considerations and constraints affecting the design process and various possible design options are discussed. The two most promising fuel designs, which can survive LOCA without primary coolant replenishment while having sufficient margins to fuel design limits, are proposed, described and evaluated. It is demonstrated that this key objective can be achieved provided that reliable SiC cladding/coating, which can withstand operating and accident conditions without failure, can be manufactured. Recent advances in ceramic coating technologies and experimental tests of coated specimens indicate that the attainment of this goal is feasible.

1. INTRODUCTION

Two conceptual designs of passive, light water cooled and moderated pressure-tube reactors have been developed at MIT. These concepts, described in a separate paper [Hejzlar, et al., ibid.] and designated the wet and dry calandria designs, were developed with the goal to ensure sufficient decay heat removal from the voided fuel bundle without the need for replenishing the primary coolant. The achievement of this key objective requires significant changes in the core geometry and in the fuel compared to a typical LWR core. The major changes include modularity of the fuel using pressure tubes in the same manner as in CANDU reactors and important modifications of traditional fuel pins or their replacement by a matrix** fuel with high thermal conductivity and high specific heat. Except for the fuel modularity all other changes apply to the fuel—a critical component of the proposed designs. This paper will focus on the evolution and evaluation of the various fuel configurations considered, which have the potential to satisfy this objective and draws extensively from the previously published paper by Hejzlar, et al. [1997a].

With respect to the design of fuel elements for the dry and wet calandria concepts, there are no critical differences between these two concepts, but various constraints governing the design process need to be considered. One major constraint is the maintenance of a negative coolant void coefficient. This necessitates fuel elements with high fuel loadings for the wet calandria concept, while the dry calandria design with only in-fuel-channel moderator, requires low fuel loadings. The dry calandria fuel elements favor a matrix-type fuel with high specific heat to accommodate excess heat generated in the matrix before the calandria is flooded, i.e., before the fuel channels become coupled to the heat sink. Considerations and constraints affecting the design of fuel elements will be discussed in the next several sections. Finally, it is noted that while the designs presented in this paper have been developed for pressure tube LWRs, some may also be applicable to CANDU reactors.

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** There are two basic types of fuel arrangement within a pressure tube. The first type consists of cladded fuel pins which are surrounded by coolant but do not employ any solid matrix, i.e., CANDU-like bundle-type fuel. The second type uses a solid matrix which contains the fuel and coolant channels. The fuel itself in both the bundle-type and matrix-type design can be either in the form of fuel pins, fuel compacts or dispersed fuel in the form of small particles.

2. CONSIDERATIONS AND CONSTRAINTS AFFECTING THE FUEL ELEMENT DESIGN PROCESS

The fuel arrangement within a pressure tube affects a broad spectrum of core characteristics relating to performance during normal operation as well as during accidents. It is essential that the fuel element parameters are chosen such that the reactor remains within the prescribed safety limits under all conditions. It is also desirable that the fuel element is designed to be economically competitive with current LWR fuel and to allow good uranium utilization. Basic factors having an impact on safety limits and economic aspects of the fuel element design can be divided into three categories:

- reactor physics,
- thermohydraulics,
- materials compatibility.

These factors will be presented next. The remainder of the paper will focus on thermal hydraulic and materials compatibility issues associated with the fuel element designs proposed for each reactor concept.

2.1 Reactor Physics Considerations

Desirable reactor physics characteristics include a negative and prompt Doppler coefficient, negative void coefficient, high reactivity for a given enrichment, low fast fluence, and high burnup.

The proposed pressure tube LWRs are thermal reactors with low-enriched UO_2 fuel, hence they exhibit a negative Doppler coefficient. To achieve prompt response of the fertile Doppler coefficient, all fuel elements under consideration in this study use a low-enriched fissile/fertile mixture fuel.

One of the key goals for the fuel element design is the achievement of a negative void reactivity coefficient. The main design parameter responsible for the magnitude and sign of the void coefficient is moderator/fuel volume ratio. Hence, the fuel loading and the amount of coolant inside the fuel channel must be adjusted such that the void coefficient remains negative for all operating conditions. The magnitude of the void coefficient also depends on soluble boron concentration and neutron leakage. Since the proposed PTLWRs do not require soluble boron for reactivity control, change of void coefficient due to this effect is eliminated. The proposed designs have a high-leakage core, which makes the void coefficient more negative. However, since leakage is primarily a consequence of the voided space in the calandria, changes in fuel arrangement inside the pressure tubes will have a small effect on this aspect.

A well-optimized fuel element should achieve high reactivity at low enrichment while keeping the void coefficient negative. In the dry calandria design this is achieved by adjusting the fuel loading and the amount of coolant inside the fuel channel. The disadvantage of the dry calandria design is the limited space in the fuel channel. Consequently, it is difficult to optimize the design for high fuel loading, where more moderator is needed. A wet calandria design offers the advantage of providing separate light water moderator outside the fuel channel, thus allowing the designer to better optimize the design, especially for high fuel loadings.

Low fast fluence is an important factor in pressure tube reactors because high fluence shortens the lifetime of the pressure tubes. Two main parameters decrease the fast fluence—high fuel loading and a well thermalized neutron spectrum. The limited space inside the pressure tubes restricts the attainable fuel loading. The introduction of a solid matrix significantly reduces the space left for the fuel. Use of particle fuel exacerbates this problem even more because of the low heavy metal densities achievable with particle fuels. The potential to lower fast fluence through neutron spectrum thermalization is limited since the best one can do with light water moderator is to achieve thermalization comparable to a CANDU heavy water moderated lattice. Therefore, achieving a fuel channel design which exhibits a low fast fluence poses a challenge.

Higher initial enrichment increases burnup, but leads to larger power peaking, and hence reduction of thermohydraulic margins. For the matrix-type fuel, neutron economy within the matrix can be improved by use of low-absorption matrix material and high fuel loading to increase the fraction of neutrons absorbed in the fuel. Higher conversion ratio could result in less enrichment, but it would require a harder neutron spectrum, and hence have adverse effects on fast fluence. Burnup in conventional LWR fuel pins is also restricted by mechanical limits arising from pellet-cladding interaction (PCI) mechanisms. This limit can be effectively eliminated by the use of the particle fuel typical of HTGRs.

2.2 Thermal hydraulics considerations

- *During normal operation*

Key desirable thermal hydraulic parameters involve large Departure from Nucleate Boiling Ratio (DNBR), low fuel centerline temperature and a small fuel channel pressure drop. The first two characteristics can be optimized by fuel arrangements having a large heat transfer surface exposed to coolant, high heat transfer coefficient, small peaking factor, low coolant quality and high mass flux. In addition, a short path length between fuel center and coolant, small contact resistance between the fuel and the matrix (or between fuel pellets and cladding, for fuel pins) and high thermal conductivity of the materials involved, to attain low fuel centerline temperature is desirable. The axial shape of the heat flux profile is also important with respect to DNBR. In the PTLWR concepts, peaking arises primarily from the higher content of fissile isotopes in fresh fuel bundles, and is controlled by on-line refueling. Peaking can be reduced by maximizing fuel loading. High fuel loading increases the fraction of neutrons absorbed in the fuel, which results in a lower initial enrichment requirement, and hence lower fission rates in fresh fuel elements.

Small pressure drop can be achieved by large flow area, large hydraulic diameter, low form losses, smooth surface, small coolant mass flux and one-phase flow. Unfortunately, all of these tactics lead to reduction of heat transfer and of critical heat flux margins. Hence a compromise between the pressure drop and heat transfer performance must be found. The approach adopted in this work is to set the maximum allowable fuel-channel pressure drop equal to that of the CE-CANDU reference design [Shapiro and Jesick,1977] and to maximize heat transfer capabilities by changing the design parameters of the fuel element.

- *During accident (without coolant)*

There are two key constraints for a fuel element in loss of coolant accidents—the temperature of the fuel and the temperature of the matrix/steam interface (or cladding, for fuel pin alternatives) must remain below the prescribed limits. It is desirable that the matrix (for matrix-type fuel) and fuel have high thermal conductivity and a short conduction path length. However, the conduction path is different than during normal operation because the heat sink is no longer coolant, but the pressure tube wall. A large heat capacity of the matrix decreases maximum matrix and fuel temperatures since it stores excess energy thereby reducing the fuel temperature excursion. Finally, since radiative heat transfer plays an important role, high matrix or cladding emissivity is a desirable characteristic.

2.3 Materials considerations

The choice of fuel element material is a difficult task, especially for the matrix-type fuel because it has to meet many stringent requirements. Fuel matrix materials requirements are discussed by Hejzlar [1993]. They include satisfactory nuclear characteristics, the compatibility of the material with light water coolant and good irradiation stability during normal operation, and good oxidation resistance in a steam/air atmosphere during high temperature excursions following LOCA accidents. Compliance of the fuel design with these requirements is affected by material selection which will be discussed in more detail in Section 5. In addition, the structural integrity of the fuel matrix must be ensured. Maintenance of this integrity depends on mechanical and thermal properties of the material, matrix temperature, temperature gradients and stresses. For a matrix with coolant holes, a minimum web thickness needs to be preserved to maintain the structural strength.

3. FUEL ELEMENTS FOR THE DRY AND WET CALANDRIA CONCEPTS

The foregoing discussion suggests that the requirements are many and the parameters affecting the desirable factors are closely interrelated. Moreover, many requirements are contradictory so that all cannot be satisfied. Hence a compromise needs to be made. Figure 1 shows a flow chart for various possible combinations of fuel arrangements in a fuel channel of the proposed passive pressure tube LWR concepts. There are two main categories—a bundle-type fuel arrangement and a matrix-type fuel arrangement. The bundle-type fuel uses the same geometry as CANDU fuel elements, with fuel pins surrounded by coolant, while the matrix-type fuel employs a matrix with separate coolant channels. Both fuel types can use either particle fuel or a traditional fuel pin configuration. The flow chart identifies reference fuel configurations selected for the dry and wet calandria versions.

The selection process involved exploration of all the paths on the flow chart, but not all the options sketched in Figure 1 appeared promising. Alternative **E** had to be discarded from both the dry and wet concept considerations because it leads to high fuel and clad temperatures during normal operation—a consequence of the long conduction path between the coolant and the pin. Option **D** eliminates this deficiency, but at the expense of placing contact lands between the clad and the matrix to increase heat transfer rate from the pin into the matrix during accidents without coolant. The small contact lands and intricate assembly necessary make the manufacture of this fuel element difficult. Therefore this design path was discarded from further considerations. Options **A**, **B**, **C**, **F** with particle fuel are not applicable to the wet calandria concept because their small fuel loading yields a positive coolant void coefficient. Consequently, the wet calandria concept is limited to design option **G**. Since the two-ring geometric configuration was found to give the best performance, it was chosen as a reference design. All the **A**,**B**,**C**,**F**,**G** options are feasible with the dry calandria concept. Preference was given to option **A**, primarily due to experience with manufacturing technology for this type of fuel element. More details on individual design options can be found in Mattingly [Mattingly, et al., 1995]. The reference fuel configurations—designs **A** and **G**, for the dry and wet calandria concepts respectively—will be described next.

3.1 A Fuel Matrix Design with Separate Fuel Compacts and Coolant Channels for the Dry Calandria Version [Option A]

The cross section of the fuel matrix design with separate fuel compacts and coolant channels is shown in Figure 2. The fuel elements are 0.5m long and slide inside the pressure tube on pads (not shown) to facilitate on-line refueling. The alignment of the two neighboring channels is ensured by a key/dowel coupling. The design makes use of the proven manufacturing technology developed for HTGR fuel elements [Melese and Katz, 1984] (albeit without SiC coating). Considerable experience has been accumulated with this type of fuel, but at different operating conditions and for a different environment than that experienced in the PTLWR. The fuel region consists of TRISO particle fuel in a graphite binder pressed into prefabricated holes in a graphite matrix. An alternative technology uses a molded graphite block fuel element instead of a machined block. It allows pressing the fuel region together with the matrix, thus forming a monolithic fuel element with increased heavy metal loading. This technology, developed by HOBEG/NUKEM [Hrovat, et al.,

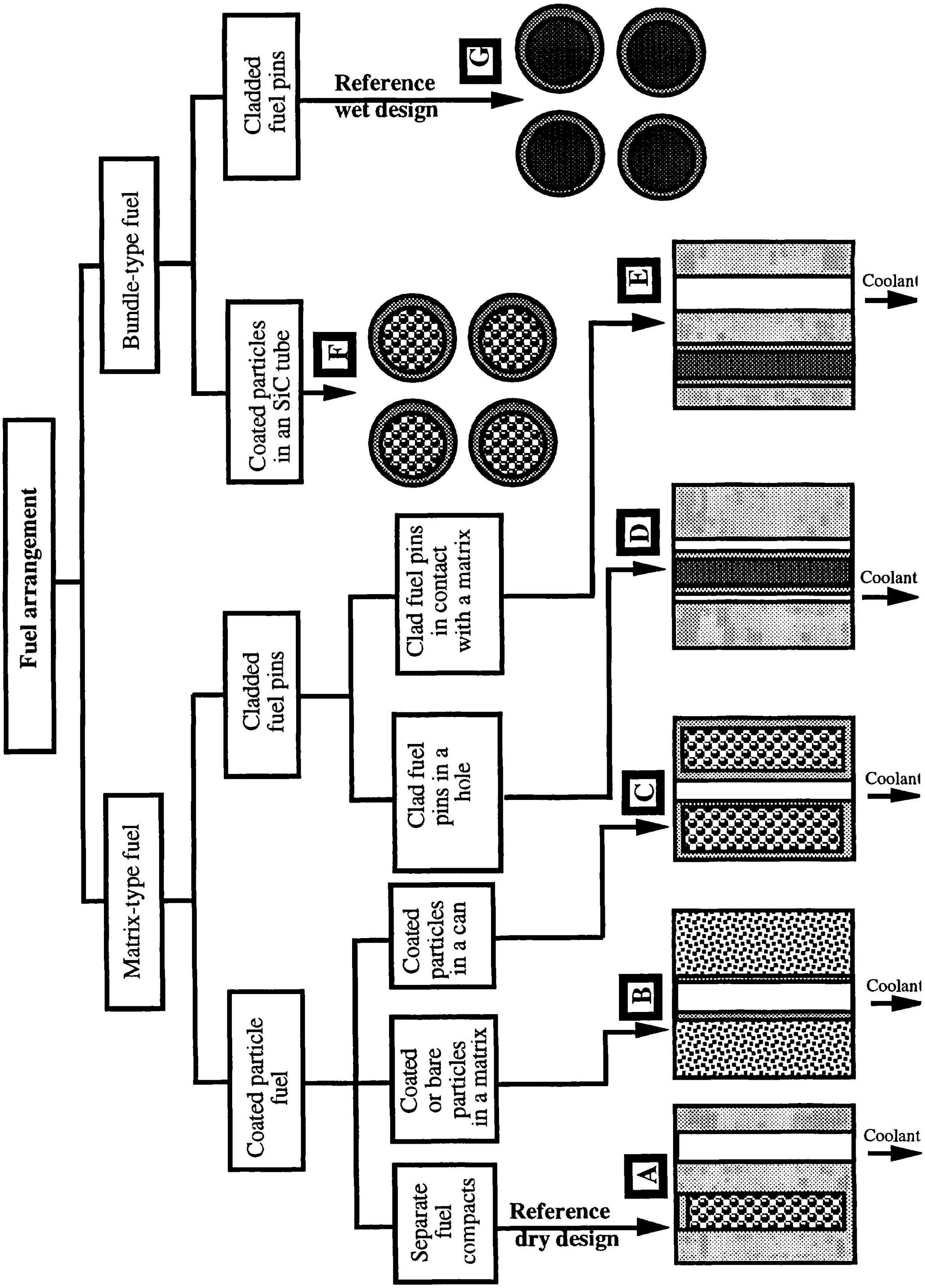
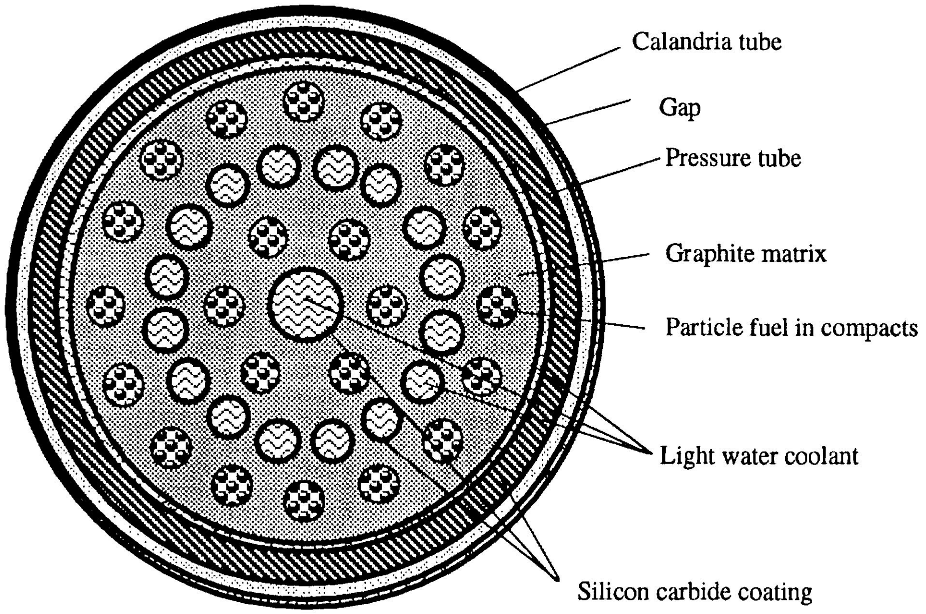


Figure 1. Flow Chart for PTLWR Fuel Options



matrix material	SiC-coated graphite
fuel matrix outer diameter	120.8 mm
fuel matrix element length	500 mm
number of fuel compacts	26
diameter of fuel compacts in inner fuel ring	12.4 mm
diameter of fuel compacts in the outer fuel ring	12.7 mm
number of coolant channels	19
diameter of central coolant channel (roughened)	22.7 mm
diameter of coolant channels in intermediate ring	8.4 mm
minimum web thickness	4.5 mm
fuel material	coated UO_2 kernels
alignment of coolant holes	key and dowel

Figure 2. Fuel Element with TRISO Fuel and Separate Coolant Channels for the Dry Calandria Version (Design A)

1975], also eliminates contact resistance between the fuel region and the matrix. Based on an extensive literature survey [Hejzlar, et al., 1993], SiC-coated graphite has been selected as a matrix material. The primary function of the silicon carbide coating is to provide protection against graphite oxidation at high temperatures in steam/air mixtures.

Reactor physics calculations showed that this matrix design in a voided calandria exhibits a very well thermalized spectrum comparable to heavy water moderated lattices, very long prompt neutron lifetime, negative void coefficient and flat thermal flux profile [Hejzlar, et al., 1995]. The disadvantages include low heavy metal loading and hence high fast fluence on the pressure tubes, as well as relatively high parasitic losses, and thus relatively high initial enrichment to attain the high burnups achievable with particle fuel.

In the thermal hydraulics area, the key advantage is good effective thermal conductivity and high specific heat capacity, which results in exceptionally good capability to dissipate decay heat without the coolant. On the other hand, the matrix thermohydraulic performance during normal operation poses a challenge for the following reasons:

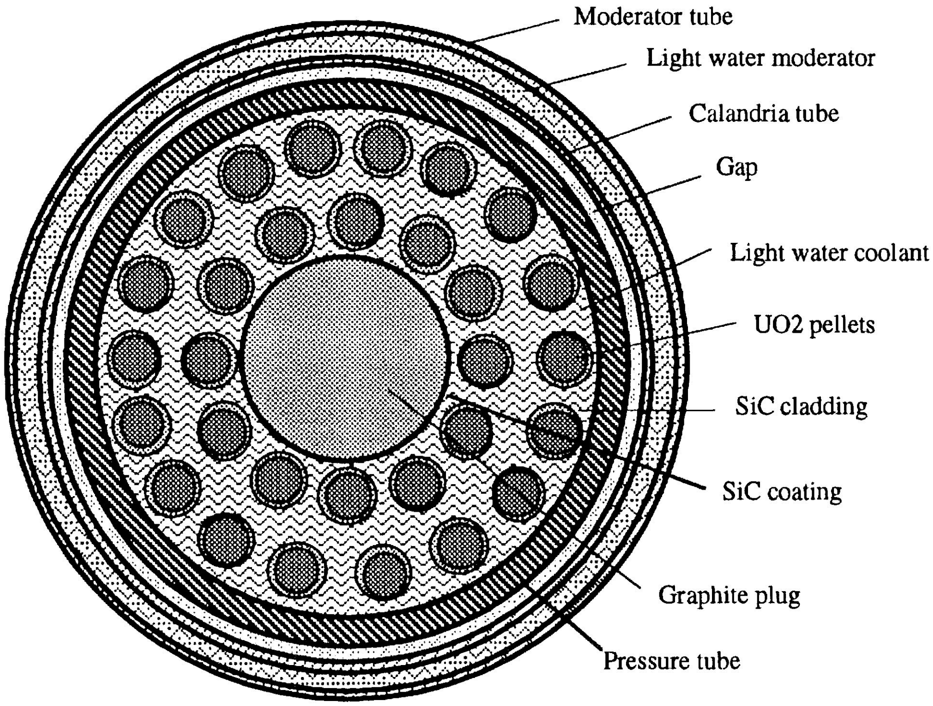
- The total heated perimeter is small as a result of limited space inside the fuel channel. This leads to a higher heat flux and lower CHF margins.

- The conduction path between the fuel centerline and coolant is relatively long. Compared to CANDU fuel pins, which are in direct contact with the coolant, the heat must be transferred through the matrix, thus increasing the temperature difference between the coolant and the fuel.
- The small number of fuel compacts results in a high pin linear heat rate (at fixed total reactor power).

These drawbacks are compensated for by smaller peaking and by the high thermal conductivity of fuel compacts. Heat transfer to coolant is improved by increasing the mass flux. Such an increase can be accomodated without compromising the pressure drop because the matrix does not need spacers, which are responsible for a significant portion of the pressure drop in bundle-type fuels.

3.2 A Two-Ring Bundle Design with SiC-Clad UO_2 Fuel Pins for the Wet Calandria Version [Option G]

The configuration of the two-ring design with SiC-clad UO_2 fuel is shown in Figure 3. It consists of a modified CANDU 37-pin bundle. The center pin and the inner ring of six pins have been removed and replaced by a SiC-coated graphite cylinder. This graphite cylinder channels the



number of fuel pins in inner ring	12
number of fuel pins in outer ring	18
clad outer diameter	13.08 mm
clad inner diameter	12.24 mm
fuel pin diameter	12.15 mm
graphite plug outer diameter	40.00 mm
moderator annulus thickness	8 mm
fuel material	UO_2 pellets

Figure 3. A Two-Ring Fuel Element with SiC-Clad UO_2 Fuel Pins for the Wet Calandria Version (Design G)

coolant to the pins during normal operation, and acts as a temporary heat sink during the initial stages of a LOCA. The removal of the innermost fuel pins in a CANDU fuel bundle was proposed first by AECL in 1977 [Roshd, et al., 1977] to reduce the positive coolant void coefficient. The reasons for removing the pins in the present design are to reduce the path length from the heat source to sink during a loss of coolant accident and to increase the heat capacity of the fuel bundle. The disadvantage of this approach is the slight reduction in bundle average power. This reduction can be recovered, however, due to the smaller peaking factor in the PTLWR compared to that of CANDU.

Use of a silicon carbide tube instead of Zircaloy cladding allows an increase in the temperature limit which can be withstood by cladding in LOCAs without damage. The drawbacks of bundle-type fuel are relatively low heat removal rates compared to matrix type configurations, moderate thermal storage capacities and low thermal conductivity of the fuel. Advantages include high heavy metal fuel loading compared to matrix-type fuel, and hence reduced fast fluence on the pressure tube.

4. THERMOHYDRAULIC PERFORMANCE

In compliance with the objective set for the PTLWR fuel to dissipate the decay heat from voided fuel elements without exceeding safe temperature limits, special attention will be paid to the thermohydraulic performance of the proposed fuel elements during LOCA without emergency coolant delivery. Since normal operation thermohydraulics of the wet calandria fuel bundles (OPTION G) does not differ significantly from the typical CANDU bundles due to the very similar geometry of the two-ring bundle, it will not be discussed here. On the other hand, the matrix-type fuel (OPTION A), which is very different from any LWR or HWR fuel elements necessitates thermohydraulic performance analysis, even at the conceptual design level.

4.1 Fuel Elements for the Dry Calandria Version [Option A]

During Normal Operation

The first objective of the thermohydraulic analysis is to confirm that the proposed fuel channel design satisfies the key thermal-hydraulic limits during normal operation. These include the maximum fuel centerline temperature and critical heat flux ratio. The TRISO particle fuel can withstand peak transient temperatures up to 1600°C. During normal operation, the limiting fuel temperature is lower, to reduce fission gas release into the primary circuit by diffusion. To ensure that the radiation dose resulting from accidental release of primary system inventory to the atmosphere remains within regulations, the limit on fuel particle center temperature is 1300 °C at 100% power [Todreas and Kazimi, 1990]. PWR reactor designers use for the critical heat flux limit the Minimum Departure from Nucleate Boiling Ratio (MDNBR), MDNBR>1.3. In BWR reactors the comparable limit is the Minimum Critical Power Ratio (MCPR), MCPR>1.2. For CANDU units a CHF correlation formulated in terms of critical quality is used to determine the onset of intermittent fuel dryout—an approach similar to that used in BWRs. In this work, the CPR estimator will be employed.

Exact solution of heat transfer from fuel compacts to coolant is more complex than for traditional LWR fuel pins because it involves 3-dimensional heat conduction from the fuel compacts through the matrix, coupled to fluid flow in the channels. Since the heat flux in the radial direction is several orders of magnitude larger than that in the axial direction, the 3-D heat transfer problem can be simplified into a 2-D problem by solving the 2-D conduction equation at selected planes (perpendicular to the fuel channel centerline) of the fuel matrix, typically at the location of maximum power density. This task can be accomplished using a standard finite element code, such as ALGOR [ALGOR, 1990], provided that the boundary conditions—heat generation in fuel compacts and coolant parameters are known. The power density in the fuel compacts, as a function of position, was obtained from the Monte Carlo code MCNP [Briesmeister, 1991].

The boundary conditions at the coolant interface involve the heat transfer coefficient to the coolant, and the fluid bulk temperature. These parameters were obtained from a separate code, PARCHANL (PARallel CHANneLs), developed for this purpose [Hejzlar, 1994]. The PARCHANL code calculates the flow split in parallel noncommunicating channels and the bulk fluid properties, as well as the wall temperature and the heat transfer coefficient as a function of axial position. PARCHANL solves 1-D transport equations of mass, momentum and energy using the HEM model. Heat transfer in the subcooled boiling region is modeled using Bowring's [Bowring, 1962] approach; the heat transfer coefficient in the central roughened channel is calculated from the Dipprey-Sabersky correlation [Dipprey and Sabersky, 1963]. The boundary conditions for PARCHANL include total mass flow rate, inlet pressure, inlet coolant temperature, and the heat flux distribution to individual coolant channels. The last one is obtained from ALGOR. Since the heat transfer coefficient and coolant bulk temperature depend on the incident heat flux to coolant, which in turn depends on both these variables, iterations between ALGOR and PARCHANL are necessary.

There are three types of coolant channels—central channel, intermediate channels and outer annular channel, designated #1 through #3, as shown on the sketch of the cross section of the ALGOR 2-D model in Figure 4. The matrix temperature profile in the plane at the axial position of the highest power density is plotted in Figure 5. The maximum centerline temperature is well below the steady state limit of 1300°C. Because of the contact resistance of the fuel compact-matrix interface there is a large temperature jump across this interface. An alternative fuel element fabrication technique [Hrovat, et al., 1975] can eliminate this jump, resulting in a significant decrease of fuel centerline temperature by about 300°C [Hejzlar, 1994].

The average channel exit quality was calculated to be 0.5%, which is less than the average exit quality for CANDU of 2%. The total channel pressure drop of 0.7 MPa is less than the pressure drop of the reference CE-CANDU design by about 0.3 MPa. CHF margins were calculated using the AECL lookup tables by the heat balance method [Groeneveld, et al., 1986; Hejzlar and Todreas, 1996]. Since the PTLWR coolant channels are isolated subchannels with no mixing, the

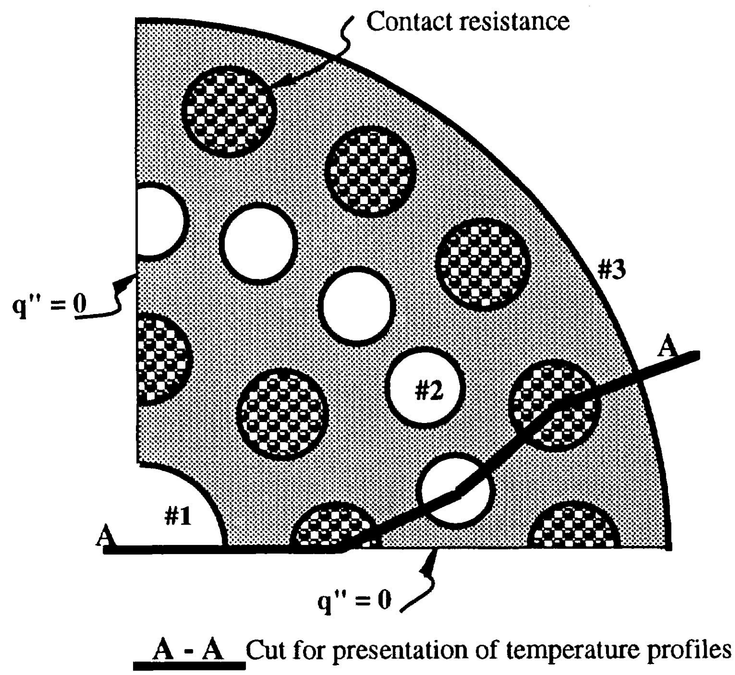


Figure 4. Sketch of the Fuel Matrix Cross Section for an ALGOR 2-D Model

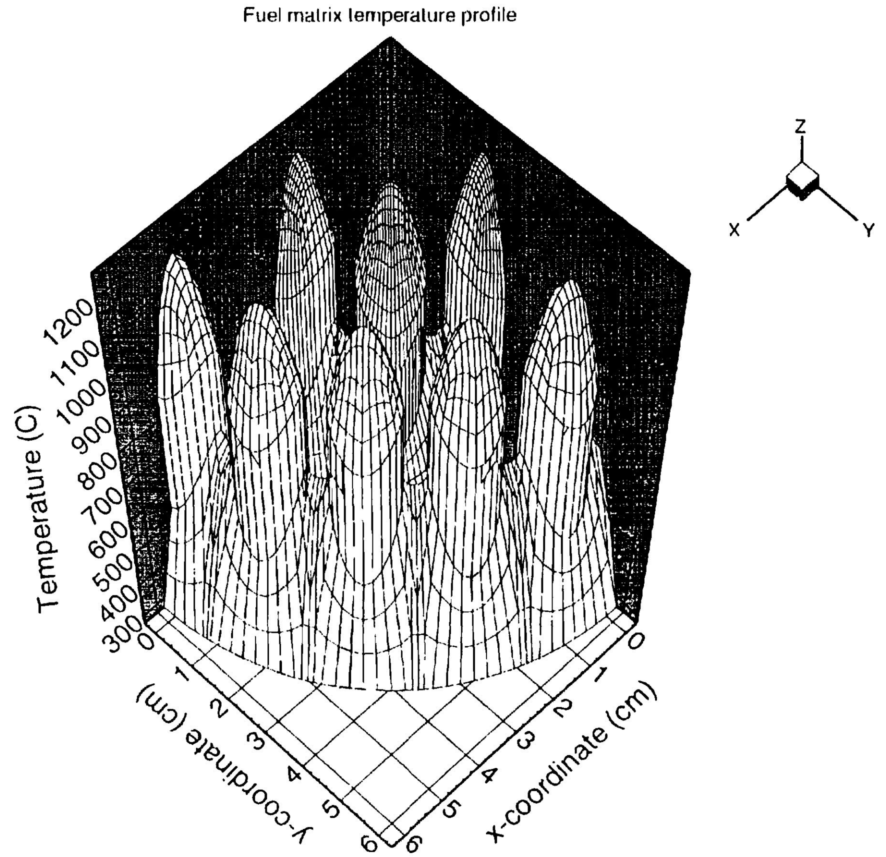


Figure 5. Maximum Fuel Matrix Temperature Profile for the Equilibrium Core

CHF margins calculated in this manner correspond to critical power ratio (CPR). Figure 6 plots the CPR along the central coolant channel (channel with the lowest CPR) for the fresh and equilibrium cores. The curve shape differs from that of typical LWRs due to the different power density profile. The CHF is reached at a fuel channel power of about 150%, which is comparable to the CANDU typical value of 156%. Furthermore, the traditional CPR limit of 1.2 is of much less importance in the dry calandria design because the proposed fuel matrix is capable of operating in the post-CHF regime without exceeding fuel design limits*. Achievement of these satisfactory fuel temperature characteristics was confirmed for the fresh core at channel conditions of 50% full flow and 100% power. These conditions lead to establishment of film boiling at the end of the channels (location of highest power density). The location of the sudden transition to the post-CHF regime can be observed on Figure 7, showing the development of the heat transfer coefficient along each channel. The resulting temperature profile along the cut plane A-A, shown in Figure 4, is plotted on Figure 8. The temperature increase is only about 200°C, giving a maximum matrix surface temperature of 500°C, which is far below the design limit of 1300°C. The increase in fuel centerline temperature is also modest and the temperature remains well below the 1600°C limit.

Parallel channels with two-phase flow may be susceptible to various instability phenomena. Density wave oscillations are especially of concern in systems consisting of combined sections of

* The CPR limit is determined from maximum allowed cladding temperatures which are relatively low for the Zircaloy cladding of LWR fuel. The SiC coating of the matrix surface can withstand temperatures up to 1300°C, which is still significantly above the surface temperatures achieved after the transition to post-CHF heat transfer regimes. However, it is noted that the coating integrity during possible matrix surface temperature oscillations, resulting from such transitions, needs to be experimentally verified.

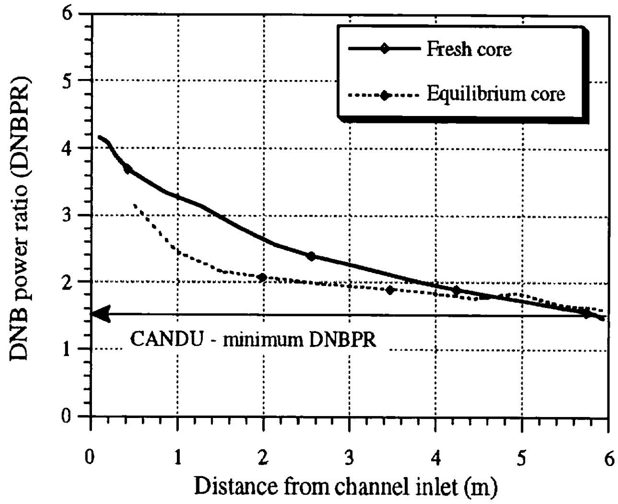


Figure 6. DNB Power Ratio Along the Central Coolant Channel

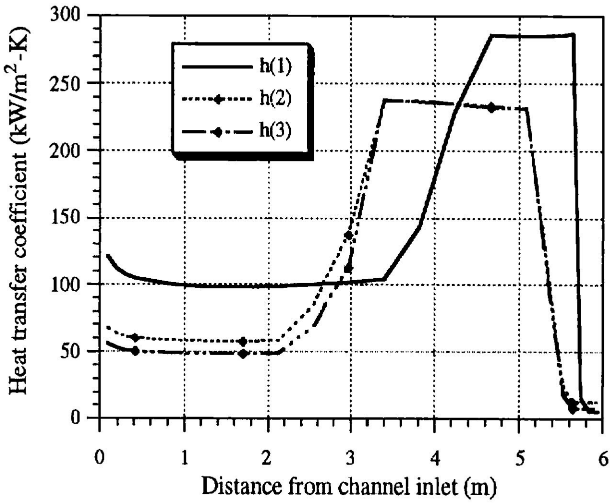


Figure 7. Transition of Heat Transfer Coefficient to the Post-CHF Regime

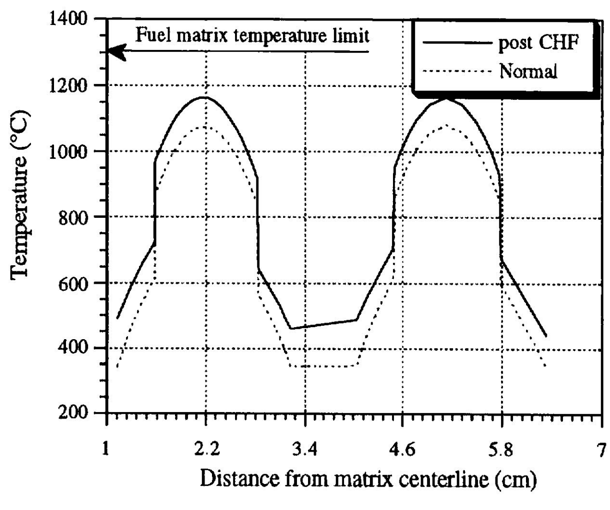


Figure 8. Fuel Matrix Performance During Normal Operation and in the Post-CHF Regime

single-phase and two-phase flow, such as the PTLWR fuel channels. The dry calandria coolant channels are relatively long and operate at high heat flux, which favors instability. On the other hand, they possess stabilizing factors since they operate at high inlet velocity, large inlet subcooling and high pressure. Also, the two-phase flow section is very short (about 15 cm compared to a 580 cm-long single-phase section). Hence it is not expected that the PTLWR parallel channels will be susceptible to density wave oscillations. To confirm this hypothesis the simplified stability criterion of Saha [Saha, et al., 1976] has been applied. Saha recommends construction of a stability map in an equilibrium phase change number-subcooling number space where the equilibrium phase change number and the subcooling number are defined as

$$N_{pch,eq} = \frac{\rho_f - \rho_g}{\rho_g} \frac{q'' P_h L}{\dot{m}\, h_{fg}}, \tag{1}$$

$$N_{sub} = \frac{\rho_f - \rho_g}{\rho_g} \frac{h_f - h_{in}}{h_{fg}} \tag{2}$$

The complete stability map generated per the Saha recommendations is calculated for the intermediate coolant channels (there are 16 intermediate coolant channels per bundle) since these channels reach instability first. This map is shown in Figure 9. As expected, the operating point lies well within the stable region.

Overall, it can be stated that the normal-operation thermohydraulic performance of the fuel elements proposed for the dry calandria version is satisfactory. There are sufficient margins to the key limits and the thermohydraulic parameters fall within the range of the reference CE-CANDU design. Dryout is expected to occur at power levels of 160% of nominal power for the equilibrium core and 146% for the fresh core. However, it is to be appreciated that the fuel matrix can operate in the post-CHF regime, while the temperatures of both the fuel and matrix-coolant interface remain substantially below safe limits. Hence, the traditional CHF limits are of less importance in the matrix fuel, and concerns of burnout-related problems during pump coast down or pump seizure are practically eliminated.

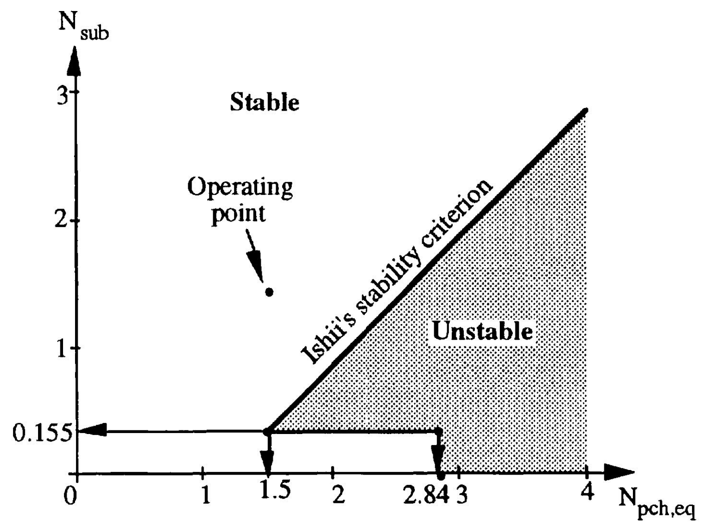


Figure 9. Simplified Stability Criterion for Thermally Induced Flow Oscillations in Intermediate Coolant Channel

During LOCA without Emergency Coolant Delivery

During LOCA, the fuel channel needs to dissipate decay heat by conduction, radiation and convection in steam/air mixtures to the heat sink without exceeding safe temperature limits. These limits are 1600°C for TRISO particle fuel to avoid increased fission product release, 1300°C for the SiC coating to avoid excessive oxidation, and 500°C for the pressure and calandria tubes to assure their reusability. The transient history of these limiting temperatures has been obtained by analysis of the heat transfer from the fuel matrix to the flooding water coupled to the neutron point kinetics equation [Hejzlar, 1994]. The 2-D heat transfer conduction problem was transformed into a simplified 1-D model using geometry factors and effective thermal conductivity from Selengut's formula [Han, et al., 1992]. Heat transfer across the gap between the fuel matrix and the pressure tube involves radiation, conduction and natural convection in horizontal annuli. The latter two phenomena were evaluated from the Kuehn and Goldstein correlation [Kuehn and Goldstein, 1976]. The gap between the pressure tube and calandria tube which provides protection of the pressure tube from thermal shock during flooding must retain some thermal conductivity to allow sufficient decay heat removal. The value of 2W/m-K, which was selected for the analysis, can be attained using a packed bed of graphite pebbles in the gap [Tang, et al., 1994] or other technology. The heat transfer phenomena at the calandria tube-flood water interface during the flooding process has been discussed by Hejzlar [Hejzlar, et al., 1997b].

The scenario selected is a 100% break of the inlet header in both loops without scram. All heat transfer coefficients in all coolant channels were set to zero at the same time as the break occurs, thus neglecting the energy carried away by the coolant during blowdown. The calandria flooding process was assumed to be delayed by about 10 seconds. Another conservatism was introduced in the analysis by setting the temperature of the flood water to saturation, i.e., the subcooling was neglected. The analysis results are presented for the equilibrium core at the location of maximum power density. The reactor is shut down upon loss of coolant due to the negative coolant void coefficient and rendered deeply subcritical (by about -200 β) shortly later by calandria flooding. Figure 10 shows the temperature traces of the inner fuel ring, matrix surface at the central coolant channel, the pressure tube, and the calandria tube for the channel at the top row, i.e., the last channel flooded. Figure 11 plots the steady state temperature profile at 0 seconds and at 200 seconds, i.e., the time when maximum fuel matrix temperature is reached. At the time

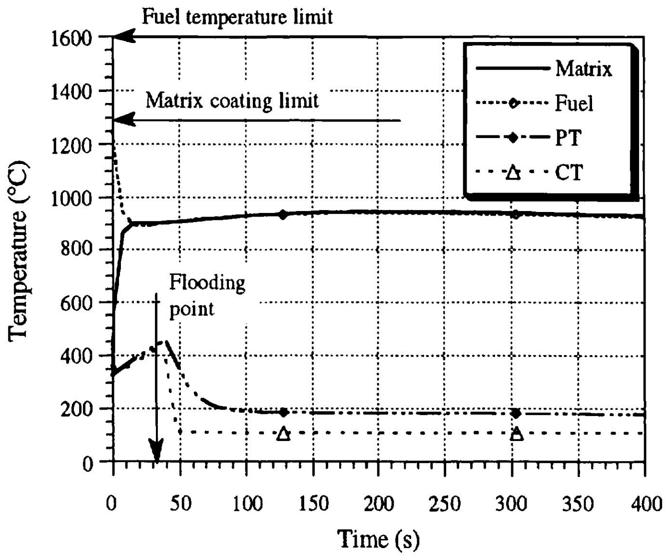


Figure 10. Time Development of Limiting Temperatures for the Equilibrium Core following LOCA

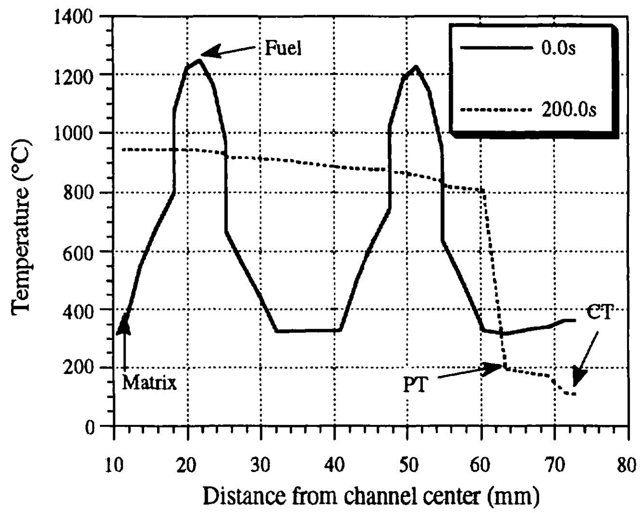


Figure 11. Temperature Profiles Across the Fuel Channel for Equilibrium Core at Outset of the Most Limiting Stage of LOCA

flooding water reaches the uppermost row of fuel channels (35 seconds) the calandria tube surface temperature is slightly higher than the Leidenfrost point. Hence, the initial cooldown through the film boiling regime (after about 5 seconds) reduces the calandria wall temperature below the Leidenfrost point. Consequently, the calandria tube is rapidly quenched and its temperature drops close to the saturation temperature of flood water and is then maintained at this level until the end of the transient. The temperature of the pressure tube quickly follows that of the calandria tube, and the channel slowly cools down. All peak temperatures remain below their design limits. Note that even if the calandria would not quench below the Leidenfrost point, the heat load could still be removed in the film boiling regime at an only slightly higher fuel matrix temperature (by about 20°C) and a pressure tube temperature of about 500°C [Hejzlar, et al., 1997b].

In summary it has been demonstrated that the decay heat in a LOCA without scram scenario can be removed without exceeding safe limits on the fuel, matrix and pressure tube, and without an emergency cooling system. This capability is primarily due to:

- the arrangement of the fuel in small modules distributed in a heat sink, having a very short conduction path between the fuel and the heat sink,
- the introduction of the fuel matrix which
  - retains high effective thermal conductivity in the absence of coolant,
  - reduces initial energy stored in the fuel, and
  - provides for additional energy storage,
- a relatively flat power density profile throughout the entire core, which decreases thermal limits imposed by the hot spot,
- a large flooding water-to-fuel matrix mass ratio, responsible for the deposition of a substantial portion of the gamma decay heat directly in the heat sink, hence reducing the decay heat load on the fuel matrix, and
- a large negative void coefficient, responsible for rapid reactor shutdown following LOCA.

4.2 Fuel Elements for the Wet Calandria Version [Option G]

During Normal Operation

As mentioned earlier, a detailed hydraulic analysis during normal operation was not performed on the two-ring wet calandria fuel design. The flow area is decreased by 17% from a normal CANDU 37-pin bundle and the wetted perimeter is decreased by 8%. These changes are not substantial. In terms of pressure drop the design is expected to perform close to a normal CANDU bundle. The peak heat flux to coolant is less (by 25%) for the two-ring design than that for the CE-CANDU, thus the two-ring design is deemed to perform adequately during normal operation.

During LOCA without Emergency Coolant Delivery

Since the bundle-type fuel exhibits reduced heat transport capabilities compared to the matrix-type fuel, this design will be limited by decay heat removal during an accident. To prove the ability of the bundle to transfer decay heat from the fuel to the heat sink without exceeding critical temperature limits, an analysis was performed using the finite element computer code ADINA-T [ADINA, undated]. This code was chosen for its radiation heat transfer capabilities. Based on Tang's evaluation of the moderator system [Tang, et al., 1994], the analysis assumed that the calandria tube outer surface is maintained at 90°C throughout the transient. The effective thermal conductivity of the gap between the pressure tube and the calandria tube was maintained in the range 2 to 4 W/m^2-K, based on Novak's [Novak, 1995] extensive testing of thermal switches. The details of the thermal model are given by Mattingly [Mattingly, 1995].

Figure 12 plots several temperature traces during a loss of coolant accident for a peaking factor of 1.42 and a gap conductivity of 2 W/m-K. The temperatures shown are for the cladding on the inward and outward facing sides of both of the rings of fuel rods, the graphite surface temperature immediately adjacent to one of the fuel rods, and the temperature on the inner surface of the pressure tube. The benefit of the graphite slug in the center of the fuel channel can be observed for the first 250 seconds of the transient, where the inner surface of the cladding on the inner ring of fuel pins is at a lower temperature than the cladding facing outward. This indicates that most of the heat generated in the inner ring of pins during the first 200 seconds is being absorbed in the graphite slug. The peak cladding temperature of 1204°C is reached on the inner ring near the graphite slug at 700 seconds into the LOCA. This temperature is within the range of operability for

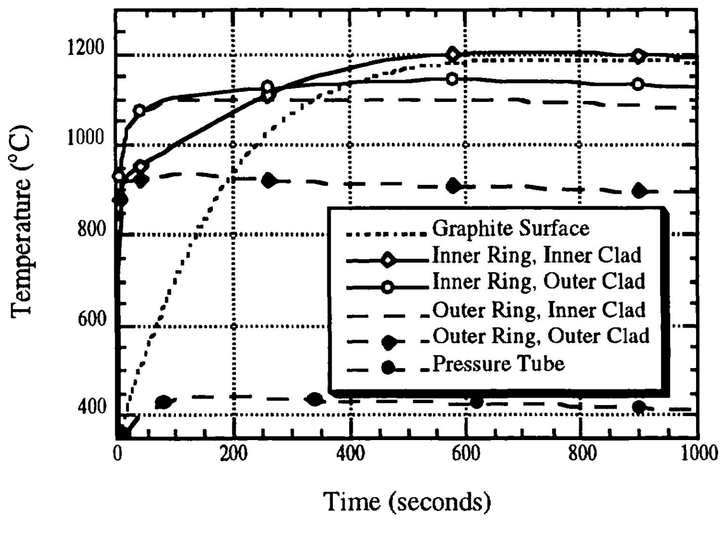


Figure 12. LOCA Temperature Traces for the Two-Ring Fuel Element

the SiC cladding and the SiC coating on the graphite slug. Similar calculations performed for Zircaloy cladding and the upper gap conductivity limit show that the maximum temperature would reach about 1196°C, which exceeds the 1000°C temperature limit for Zircaloy.

The temperature profiles in the two-ring fuel corresponding to the time when the absolute maximum cladding temperature is reached and during normal operation (initial state at t=0s) using the gap conductivities of 4 and 2 W/m-K are plotted in Figure 13. It can be observed that decreasing the gap conductivity has negligible effect on the clad maximum temperature (increase by about 20°C) but significant effect on the pressure tube temperature (increase from 350°C to 474°C).

The above temperatures are conservative because the ADINA-T thermal model did not take into account convective heat transfer involving the steam/air mixture present in the pressure tube. To quantify the contribution of steam convection, a 2-D model of the fuel element using the computer code FLUENT [FLUENT, 1996] was developed. The boundary conditions — volumetric heat flux and the temperature of the pressure tube wall at the time of 700s — for this steady-state model were obtained from ADINA. The code was run for two cases, first one with pure radiative heat transfer and the second with combined radiative and convective heat transfer. The latter run yielded a maximum temperature only 13°C [Rumlar, 1997] less than the pure-radiation case indicating a relatively small effect of free convection in steam. Figure 14, which depicts velocity vectors, shows that the most intensive convection occurs in the recirculation zones between the outer fuel ring and pressure tube wall, while the hotter inner fuel ring is exposed to very small convective cooling. Hence, the effect of convective heat transfer on the maximum clad temperature is insignificant and radiation is by far the dominant heat transfer mode at such high temperature levels.

The analysis shows that the decay heat in a LOCA can be dissipated without exceeding safe limits on the fuel elements and pressure tubes, and without an emergency cooling system. This favorable fuel performance is primarily due to the short distance between the heat source and the heat sink and the employment of ceramic cladding.

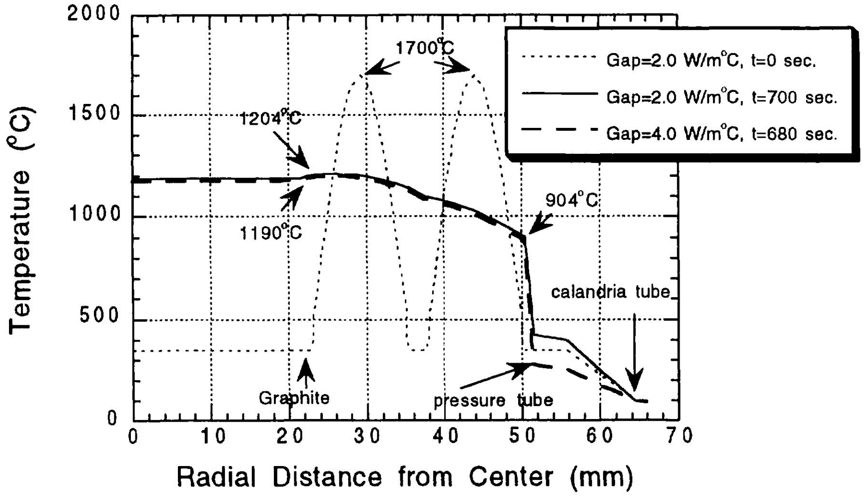


Figure 13. LOCA Radial Temperature Distribution in the Two-Ring Fuel Element

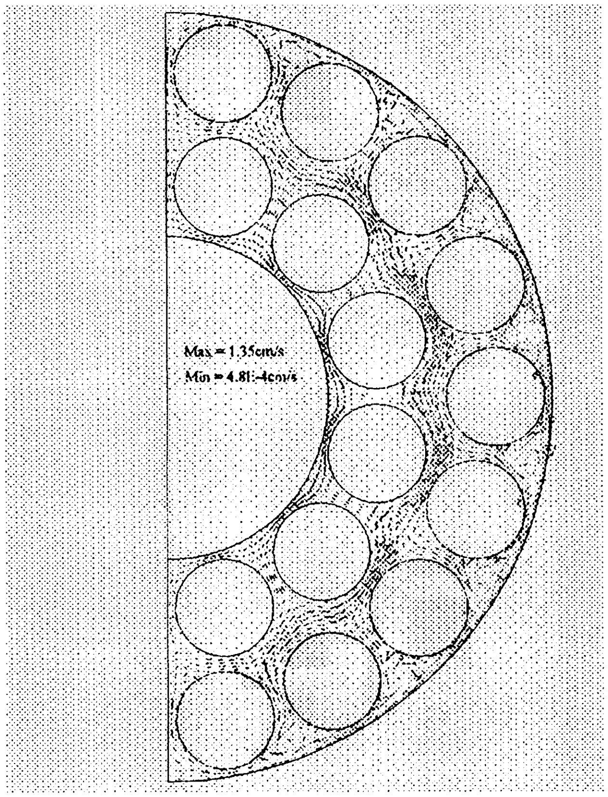


Figure 14. Velocity Vectors in the Two-Ring Fuel Element for Passive Cooling Mode

5. MATERIALS COMPATIBILITY ISSUES

Key requirements for the fuel matrix material have been summarized in Section 2.3. An extensive search [Hejzlar, et al., 1993] for a matrix material which can satisfy these requirements resulted in the selection of silicon carbide. It has good resistance to irradiation damage, it is compatible with high temperature light water coolant [Hyrayama, et al., 1989; Ono, et al., 1991], and primarily it is resistant to oxidation in steam and air up to temperatures of 1300°C [Horn, et al., 1979; Maeda, et al., 1988]. However, the matrix type fuel, characterized by a relatively large volume of material in the core, would result in high parasitic absorptions due to the relatively high absorption cross section of SiC, and consequently in higher enrichment and fuel cycle cost. Thus a graphite matrix with silicon carbide coating has been selected for the dry calandria matrix-type fuel. For the wet calandria pin-type fuel with small-volume cladding, SiC cladding was chosen.

The SiC-coated graphite matrix combines the excellent nuclear properties of graphite with the protective function of silicon carbide. A large body of experience has been assembled regarding silicon carbide coating of graphite. The key problem is the assurance of SiC coating integrity during normal operation and during rapid temperature changes following a LOCA. The experience with the behavior of large SiC-coated graphite blocks under irradiation and thermal cycles is rather limited, and requires more research.

Recently, increased attention has been paid to SiC-coated graphite for applications in HTGRs [Kugeler, 1992] and for plasma facing components in fusion facilities [Eto and Shindo, 1992]. To mitigate thermal stresses induced at the interface between the coated SiC layer and graphite substrate during rapid temperature changes, it is important to choose a compatible graphite grade with appropriate thermal expansion coefficient and to eliminate the abrupt coating-substrate interface. Progress in these areas has been achieved by introducing a "functionally gradient" material of silicon carbide and carbon [Fujii, et al., 1992], slip coating methods [Hurtado, et al., 1994a] and a direct infiltration process [Hurtado, et al., 1994a, 1994b]. The "functionally gradient" applied coating proved successful for thermal cycling tests and in tests of quenching the 1000°C hot specimens in cold water [Fujii, et al., 1992] (repeated quenching ultimately produced coating failure). The slip coated samples were found to provide superior corrosion protection to direct infiltration-coated specimens. Moreover multiple thermal shock experiments involving water quenching of slip-coated spheres (3 cm OD) from 800°C to 20°C did not degrade the protective function of the coating. Thus the technology for coating the graphite structures, which are corrosion resistant in air and steam up to temperatures above 1000°C, is available. However more tests need to be performed to confirm the stability of the coating-substrate interface under neutron irradiation.

To confirm the compatibility of SiC-coated graphite with the PTLWR conditions, a small-scale experimental program has been carried out at MIT [Mattingly, 1995]. Limited results indicate that an intact SiC coating can protect graphite from oxidation in a steam atmosphere at 1000°C for several hours. Microcracks in SiC coatings, caused by quench cooling of the SiC coated graphite, reduce the oxidation protection offered by SiC layers. However, some protection from rapid graphite oxidation is provided by a partially intact SiC layer. These results are similar to the results mentioned previously. However, the more challenging issue was identified as the performance of SiC coated graphite during normal reactor operation. The specific water chemistry in a nuclear reactor during normal operation, if not chosen carefully, is detrimental to SiC coatings. Good corrosion performance of SiC under normal conditions appears feasible if lithium is avoided in the primary chemistry. The most important issue identified was that of water infiltration into graphite through SiC coating defects. During rapid power changes, or the initial stages of an accident, water that has penetrated the graphite can flash to steam. This can cause the SiC coating to crack and spall, thus exposing graphite surfaces to an oxidizing environment. It must be shown that this issue can be overcome through manufacturing control, quality assurance inspections, and the selection of an appropriate coating technology that will withstand in-service conditions.

Large-scale production of SiC cladding, proposed for the wet calandria design, has been successfully demonstrated [Kennedy and Shennan, 1974]. SiC-clad UO_2 pellets, were tested by British investigators, although only for modest power density [Kennedy and Shennan, 1974]. Fuel performance was found to be determined primarily by the ability of the silicon carbide tube to withstand stresses. To alleviate the stress on the SiC tube, interaction of the fuel pellets with the cladding from fission-product-induced swelling needs to be avoided. This may limit burnup to low values or require more research into how to design a conducting gap which would provide some free volume for fuel expansion without strong mechanical interaction with the cladding.

Another attractive option for future high-temperature cladding material appears to be filament wound composites consisting of zirconia alumina fibers in a zirconia or alumina matrix [Feinroth, 1990]. The recent advances in the development of such materials for aerospace structural applications make it possible to manufacture tubes from filament wound composites, which retain their high yield strength and are inert in H_2O vapor environment up to temperatures of 1900°C. The tubes from these materials can be fabricated up to lengths of 30 inches, which is compatible with the short CANDU fuel elements. Although zirconia and alumina matrials have significantly lower emissivities in comparison with silicon carbide (between 0.45 and 0.6 compared to 0.8) FLUENT calculations indicate that at such a high temperature limit decay heat up to 4% rated power can be transferred from the 37-pin CANDU bundle through radiation and steam convection to the pressure tube wall at a temperature of 400°C (yielding maximum cladding temperature of 1870°C). This allows passive cooling of the full 37-pin bundle without the need of removing central pins at temperatures that do not lead to any exothermic reaction or hydrogen generation, unacceptably accelerated corrosion or loss of strength. However, more research is necessary to answer questions on the long term corrosion performance of these materials in 340°C primary coolant water, issues of their radiation stability and compatibility with UO_2 pellets.

6. CONCLUSIONS

Innovative fuel element designs for light water cooled and moderated pressure tube reactors have been described. The fuel design has been tailored for pressure tube LWRs in the dry and wet calandria versions. However, many of the features and advances suggested are also applicable to other pressure-tube-type reactors. The key characteristic of the proposed fuel elements which distinguishes these designs from current fuel bundles for water-cooled reactors is their capability of dissipating the decay heat in the absence of primary coolant. This ability is primarily due to a short heat transport path between the source and the heat sink afforded by the pressure tube concept and also due to the employment of ceramic cladding/coating which can withstand high temperatures in an oxidizing environment. The analysis has confirmed that the key objective of sufficient cooling of the fuel elements in the absence of primary coolant can be achieved without exceeding safe temperature limits. Moreover, the study indicates that the matrix-type fuel elements for the dry calandria design can operate in the post-CHF condition even at full power without exceeding fuel design limits. Notwithstanding, these attractive characteristics necessitate the availability of reliable SiC cladding/coating which can withstand operating and accident conditions without failure. Recent advances in ceramic coating technologies and experimental tests of coated specimens indicate that the attainment of this objective is feasible. Large scale production of reliable SiC coating/cladding, however, needs to be investigated further and confirmed. Another option requiring further development, but offering very attractive features for decay heat removal from dry fuel elements is provided by cladding fabricated from filament wound composites in the form of zirconia or alumina.

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