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CONCEPTUAL DESIGN OF A WATER COOLED REACTOR WITH PASSIVE DECAY HEAT REMOVAL

FINAL PERFORMANCE TECHNICAL REPORT

for Period September 30, 1992 – October 31, 1995

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CONCEPTUAL DESIGN OF A WATER COOLED REACTOR WITH PASSIVE DECAY HEAT REMOVAL

**N.E. Todreas, M.J. Driscoll,
P. Hejzlar, B. Mattingly and G. Dalporto**

ABSTRACT

A conceptual design was performed of a light water moderated reactor with power output in the range of 1000 MWe, which allows passive decay heat removal (i.e., the heat path to the ultimate heat sink, ambient air, is provided by natural heat transfer mechanisms such as conduction, radiation and free convection). This eliminates the reliance on the availability of emergency pumped cooling. The design ensures that the fuel remains within safety limits even in the total absence of coolant in the primary system. The challenge met was the achievement of this passive cooling capability while simultaneously achieving a high, 1000 MWe power rating.

INTRODUCTION

To further enhance the passive safety features of light water reactors, new approaches have been explored at MIT, which would allow the reactor to withstand the total loss of primary coolant without core damage. Various options for passive decay heat removal from a voided reactor core were investigated before the start of this DOE project with the concurrent goal of achieving a high reactor power rating during normal operation. As a result, a pressure tube geometry with a solid matrix was identified as the most promising configuration [Hejzlar, et al., 1991]. The feasibility of such a design was evaluated primarily from the point of view of decay heat removal from the fuel to the pressure tube boundary. This work [Hejzlar, et al., 1991; Tang, 1992] created a reactor concept named the Passive Pressure Tube Light Water Cooled and Moderated Reactor (PTLWR), which had two embodiments—a wet and a dry calandria design. A conceptual design of the wet calandria scheme was performed by Tang [Tang, 1992].

SCOPE OF THIS PROJECT

This project was initiated to execute a conceptual design of the PTLWR concept created prior to the start of this project. The design work is focused on the dry calandria scheme, but extensive fuel concept design effort for both calandria schemes was accomplished. In executing the design, the goals of Table 1 were stressed.

The PTLWR was designed using the CE-CANDU [Shapiro & Jesick, 1979] study as the reference point. The CE-CANDU was a Combustion Engineering conceptual design of a large heavy water reactor specifically developed for siting in the United States. The reactor is similar to the Canadian heavy water reactors (CANDU) in many ways with only slight changes made in design specifications and some systems to accommodate the U.S. manufacturing and regulatory standards.

Table 1: Goals for the Passive Pressure Tube Light Water Reactor

• Survive loss of primary coolant with no core damage• Prevent fast reactivity excursions• Operate at a high power rating• Achieve inherent reactor shutdown during accidents• Minimize technological and economic risk• Produce electricity at a competitive cost

The PTLWR uses the CE-CANDU as a reference design, and any changes are measured relative to the CE-CANDU performance. The basic philosophy adhered to in the PTLWR is to keep all of the ex-core systems exactly the same as in the CE design. The largest innovation in the PTLWR design is in the core layout and materials selection. Two of the most obvious changes are that the PTLWR has a calandria tank filled with gas (CO_2 or N_2) and uses light water as the coolant. The PTLWR core has 740 pressure tubes, each surrounded by a thin calandria tube (same as CE-CANDU), but the fuel arrangement inside the pressure tube is radically different from current pressure tube reactors, due in part to the use of light water coolant. The fuel configurations and materials were developed with primary emphasis placed on:

- achieving a minimum total plant power output of 1000 MWe during normal operation;
- storing appreciable decay heat during initial heat up in an accident; and
- transferring the decay heat from the fuel to the pressure tube surface in the absence of primary coolant without exceeding fuel, clad, or pressure tube thermal limits.

Except for the fuel modularity, which is achieved by using pressure tubes dispersed in a heat sink, all other changes apply to the fuel bundle itself. Thus the fuel matrix is a critical component of the proposed design which deserves special attention.

For technical completeness, both the dry and the wet calandria designs will be discussed next.

Wet and Dry Calandria Forms and Function

Two fundamentally different moderator schemes were originally conceived to remove decay heat from the core during a loss of coolant accident. Designs were executed in this project for each scheme. Both designs incorporate the previously mentioned voided calandria. The first design removes decay heat from the core by flooding the calandria with water. This results in boiling of the flooding water and in transferring the decay heat by the steam to the containment. The flooding water also introduces sufficient neutron capture into the core to result in reactor shutdown even if no other shutdown mechanisms were previously initiated. This design is designated the **Dry Calandria** because the calandria tube is maintained dry during normal operation.

The second design utilizes a thin water annulus outside the calandria tube. This is accomplished by the addition of another tube surrounding the calandria tube. This water annulus is part of a separate low pressure moderator system which, during a loss of coolant accident, acts as a heat sink. This design is designated the **Wet Calandria** because the calandria tube is maintained wet during normal operation. Both the wet and dry calandria reactor designs have been developed in detail in earlier reports and will only be summarized here.

A schematic of the dry calandria design is shown in Figure 1. This design is developed in detail by Hejzlar [Hejzlar, 1994]. The pressure tube employs a solid matrix within which fuel and coolant can be arranged in a variety of ways. The fuel matrix shown here is only one of several possible designs that have been developed. A calandria surrounded by a solid neutron reflector is submerged in a tank of light water which serves to both cool the reflector and act as a biological shield. The tank and the calandria are both submerged in a large amount of in-containment water. During normal operation this water is kept out of the calandria space by a gas lock. The gas pressure is maintained sufficient to balance the water column outside the calandria. Any disturbance in the primary cooling system (such as loss of coolant or heat sink) beyond the pre-defined envelope of safety limits results in the flooding of the entire calandria space. The flood water serves as an effective heat sink, which transfers the decay heat from the submerged calandria tubes, by boiling/condensing, to the containment walls.

A schematic of the wet calandria design is shown in Figure 2. This design was developed in detail by Tang [Tang, 1992]. The pressure tube can again employ a solid matrix with varying configurations of fuel and coolant. The fuel design shown in Figure 2 is a two-ring design which is only one of the possibilities. The pressure tube is surrounded by a calandria tube, which in turn is enclosed by a light water moderator annulus confined by an outer moderator tube. The gap between the calandria tube and the pressure tube may be equipped with a thermal switch. The thermal switch is a device specifically designed to have an increasing thermal conductivity with increasing temperature. During normal operation the thermal switch conducts a relatively small amount of heat from the pressure tube to the moderator tube. During a LOCA, when the pressure tube temperature is considerably higher, the conductivity of the thermal switch increases substantially to remove a much larger amount of heat from the pressure tube. Two thermal switch designs are presented in Tang [Tang, 1992]. Additional thermal switch designs have been developed and experimentally tested in a parallel EPRI-sponsored project by Novak [Novak, 1995]. An alternative to a complex thermal switch is to tailor the gap conductivity to remove the appropriate amount of energy on a continuous basis. The moderator system is designed to be capable of transferring the desired level of decay heat to the ultimate heat sink by natural circulation during accidents, but can also be tailored to provide heat to a chain of feedwater heaters during normal operation, thus reducing the amount of heat lost. Note that in current CANDU designs all moderator heat (~5% of total from fission) is discarded.

There are some inherent advantages and disadvantages associated with each of these designs. The dry calandria design has inherent shutdown provided by the flooding water regardless of whether other scram systems have caused reactor shutdown. The flooding system is also simple to develop and maintain. However, the critical component of the system is the valve or other mechanism that activates to initiate the flooding process. Failure of this redundant/diverse system

Figure 1: Dry Calandria Design Configuration

Figure 2: Wet Calandria Design Configuration

can cause failure of the decay heat removal process. During normal operation the calandria tubes in the dry design are at a relatively uniform high temperature which helps to reduce the buildup and localization of zirconium hydrides, which cause tube embrittlement.

The wet calandria design benefits from the presence of decay heat removal water at all times, in the moderator annulus outside the calandria tube. Thus there is no need for the flooding system and the vulnerability to operation of the flood initiating valve. (Flooding can also be used in this design as an added safety measure.) This added water annulus significantly increases the moderating capability and allows for a heavier fuel loading in the core. The increased fuel loading causes a decrease in the fast flux and consequently reduces neutron damage to the pressure tubes. However, the present configuration of this low pressure moderating system is vulnerable to failure if it suffers a pipe break, especially since the system removes heat via a natural convection circulation loop.

The factors mentioned above are the primary determinants of whether to use a wet calandria or a dry calandria design. Table 2 summarizes the points mentioned above.

Table 2: Advantages and Disadvantages of Wet and Dry Calandria Variants

	<i>Dry Calandria</i>	<i>Wet Calandria</i>
Advantages	Flooding provides inherent shutdown High, uniform tube temp reduces localization of Zirc-hydrides Simple ultimate heat sink system	Decay heat sink always present More moderating water, allows higher fuel loading Flooding is optional, not required
Disadvantages	Must initiate flooding with some action	Decay heat system is complex and vulnerable to failure Thermal switch may be complex and costly

The fuel configurations for the wet calandria (WC) and dry calandria (DC) reactors depend on which variant they are to be used in. The basic reason for the split between WC and DC fuel configurations is the neutron physics of the fuel: undermoderation is required to insure negative coolant temperature and void coefficients. The dry calandria has a limited amount of water present for neutron moderation and therefore can not support a large fuel loading based upon criticality requirements. However, the low fuel loading achieved with the TRISO particles does not require more moderation than is provided by the coolant water in the channel in order to operate at the

optimum moderator/fuel ratio. (TRISO particle fuel also provides superior thermal performance during a LOCA.) This low fuel loading results in a high neutron fluence. To reduce the fluence, a higher fuel loading (achieved by using UO_2 fuel pins) can be used, which in turn requires a substantial addition of moderator outside the fuel channel to operate at the optimum moderator/fuel ratio. This increase in the amount of moderator can be provided in the dry calandria design by using additional pressure tubes in the lattice which only carry water. On the other hand, the wet calandria design provides this increase in moderator by the water annulus surrounding the pressure tube. In general all of the WC fuel matrix designs developed by Tang [Tang, 1992] can operate in either the wet or dry calandria configurations (based on the neutron physics), but the same is NOT true for all of the DC fuel matrices designed by Hejzlar [Hejzlar, 1994]. However, the optimum performance of the WC matrices can only be achieved by operating these matrices in the presence of sufficient moderator.

For an overview of all fuel designs, see [Mattingly, et al., 1995]. Figures 3 through 12 present the fuel designs from Mattingly's work. Hejzlar developed the dry calandria variant in detail [Hejzlar, 1994]. Tang developed the wet calandria variant in detail [Tang, 1992].

The subject concept has been published through a series of papers in the archival literature (the last one on Fuel Elements will be in the December 1996 issue of *Nuclear Engineering and Design*). The principal papers, which are in the archival literature, are.

- J-R. Tang, N.E. Todreas and M.J. Driscoll, "Conceptual Design of the Passive Light Water Pressure Tube Reactor (PLPTR)," *Proceedings ANP '92*, Intl Conf on Design and Safety of Advanced Nuclear Power Plants, Vol. 1-4.2, Tokyo, October 25-29, 1992; *Nuclear Technology*, Vol. 107, No. 1, pp. 49-62, 1994.
- G. Dalporto and N.E. Todreas, "Achieving Higher Capacity Factors through Longer Cycle Lengths," presented at ANS 1995 Annual Meeting, Philadelphia, PA, *ANS Transactions*, Vol. 72, June 25-29, 1995.
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- P. Hejzlar, B.T. Mattingly, N.E. Todreas and M.J. Driscoll, "Advanced Fuel Elements for Passive, Pressure-Tube LWRs," December 1996 issue of *Nuclear Engineering and Design*, 1996.

This innovative concept work stimulated a short exploration of the potential for more economic plant operation through achieving higher capacity factors by longer operating cycle

Fuel Arrangement WC-1

Advantages	Disadvantages
<ul style="list-style-type: none"> • Uses high conductivity TRISO fuel • Matrix takes most of the mechanical loading • No water contacting particle • Annular cooling improves heat transfer 	<ul style="list-style-type: none"> • Small heat transfer area • High fuel temperature during normal operation • Long conduction path between fuel centerline and coolant

Figure 3 (from Tang)
WC-1, Graphite Matrix with an Annular TRISO Fuel Ring

Fuel Arrangement WC-2

Advantages	Disadvantages
<ul style="list-style-type: none"> • Uses easily attainable UO_2 fuel pins and Zircaloy cladding • Matrix takes most of the mechanical loading • No water contacting cladding material 	<ul style="list-style-type: none"> • Low conductivity of fuel along with long conduction path through graphite lead to a high centerline temperature of 2660°C during normal operation • High cladding temperature of 835°C during normal operation • Difficult to maintain good contact conductance between the Zy cladding and the matrix • Small heated perimeter, thus difficult to provide sufficient cooling during normal operation

Figure 4 (from Tang)
WC-2, Graphite Matrix with Zircaloy-Clad UO_2 Fuel Pins

Fuel Arrangement WC-3

Advantages	Disadvantages
<ul style="list-style-type: none"> • Uses standard UO_2 fuel pins and Zircaloy cladding • Fuel maximum temperature of 1960°C and clad maximum temperature of 385°C are both within CANDU experience • Heat passes directly from fuel to coolant in normal operation, but conducts through graphite in accident conditions 	<ul style="list-style-type: none"> • Small web thickness, stress becomes a critical concern • Difficult to manufacture precise fit of fuel into coolant hole • Contact resistance between pin cladding and matrix lands can not be well bounded • Crevice assisted corrosion between the pins and matrix may become a problem

Figure 5 (from Tang)
WC-3, Graphite Matrix with UO_2 Fuel in Coolant Channels

Fuel Arrangement WC-4, 36 Pins

Advantages	Disadvantages
<ul style="list-style-type: none"> • Uses standard UO₂ fuel pins and Zircaloy cladding • Direct contact between fuel and coolant, no conduction through graphite for normal operation • 36 pins instead of 24, more wetted surface for the same core power as the WC-3 design 	<ul style="list-style-type: none"> • Relies on contact between pins and matrix at all times to insure satisfactory thermal performance in an accident (spring needed) • Cladding temperature borderline on 1000°C limit during accident condition • Complex design and the structural integrity of relatively narrow graphite spokes during irradiation is questionable • Continuous runner contact between pressure tube and matrix for conduction is problematic because of pressure tube sagging. Matrix may get stuck during refueling.

Figure 6
WC-4, Mini-Bundles Contained within a Graphite Matrix

Fuel Arrangement WC-5

Advantages	Disadvantages
<ul style="list-style-type: none"> • Uses similar geometry to CANDU, thus the thermal hydraulics are similar • Flatter power density profiles (peaking of 1.42) compensates for removed inner rings, and allows operation at a higher average heat flux than CE-CANDU (74.35 vs. 59.7 W/cm²) • Allows radiation of all decay heat to pressure tube, no conduction path is needed 	<ul style="list-style-type: none"> • Low heat removal rate from voided bundle compared to matrix type configurations • Moderate storage capacity, temperature may exceed critical limits for Zircaloy before decay heat generation decreases enough to match the heat removal via radiation to the pressure tube • PCI exerts stress on SiC cladding and limits power rating and burnup • Low thermal conductivity of fuel, thus high stored energy

Figure 7
WC-5, Two-Ring Design with SiC-Clad UO₂ Fuel Pins

Fuel Arrangement DC-1

Advantages	Disadvantages
<ul style="list-style-type: none"> • Uses SiC-clad fuel technology developed in UK for CO₂ cooled reactors which was extensively tested and showed good performance • Uses similar geometry to CANDU, hence the thermal hydraulics are similar • Flatter power density profile allows recovery of power lost by removing inner fuel rods; there is a potential to operate at an even higher power rating • High fuel thermal conductivity, hence low operating fuel temperature and low stored energy 	<ul style="list-style-type: none"> • Low heavy metal loading, hence high fluence on pressure tube (but less than for matrix-type with particle fuel) • Low heat removal rates from voided bundles compared to matrix type configuration • Low heat storage capability, hence the temperature of the matrix and pressure tube may exceed limits before the upper row of pressure tubes is flooded, establishing the decay heat removal path

Figure 8 (from Hejzlar)
DC-1, Two-Ring Design with SiC-Clad TRISO Fuel

Fuel Arrangement DC-2

Advantages	Disadvantages
<ul style="list-style-type: none"> • Uses SiC-clad fuel technology developed in UK for CO₂ cooled reactors • Uses similar geometry to CANDU, thus the thermal hydraulics are similar • Flatter power density profile allows recovery of power lost by removing inner fuel rods • High heavy metal loading, hence lower fast fluence on pressure tubes than matrix fuel • High conversion ratio 	<ul style="list-style-type: none"> • Low thermal conductivity of fuel, hence high stored energy • Pellet-clad interaction exerts stress on SiC cladding and limits power rating and burnup • Low heat removal rates from voided bundles compared to matrix type configuration • Low heat storage capability, thus limiting temperatures may be exceeded in an accident before the upper row of tubes is flooded

Figure 9 (from Hejzlar)
DC-2, Two-Ring Design with SiC-Clad UO₂ Fuel Pins

Fuel Arrangement DC-3

Advantages	Disadvantages
<ul style="list-style-type: none"> • Uses proven manufacturing technology of MHTGR fuel or HOBEQ molded fuel blocks • High thermal conductivity and storage capability, hence very good performance during LOCA • Heterogeneous arrangement of fuel and coolant combined with voided space outside pressure tubes results in the longest prompt neutron lifetime, and flattest power profile compared with all other DC matrices 	<ul style="list-style-type: none"> • Small number of fuel compacts results in relatively high linear heat rate • Small heavy metal loading results in high fast fluence on pressure tubes • Small heated perimeter, hence difficult to provide sufficient cooling during normal operation

Figure 10 (from Hejzlar)
DC-3, Graphite Matrix with TRISO Fuel and Coolant Channels

Fuel Arrangement DC-4

Advantages	Disadvantages
<ul style="list-style-type: none"> • Based on all ceramic fuel technology developed in UK for CO₂ cooled reactors which showed good fuel performance • High thermal conductivity and storage capacity, thus good performance during LOCA • Large heated perimeter, hence easy to cool during normal operation - large DNBR • Small distance between fuel and coolant and high thermal conductivity, hence low operating fuel temperature 	<ul style="list-style-type: none"> • Low heavy metal loading, hence high fluence on pressure tubes • Requires higher enrichment to overcome parasitic absorption in SiC • Structural integrity of irradiated SiC matrix may be a problem due to decreased thermal conductivity and high thermal gradients

Figure 11 (from Hejzlar)
DC-4, SiC Matrix with UC Fuel Dispersed Throughout

Fuel Arrangement DC-5

Advantages	Disadvantages
<ul style="list-style-type: none"> • High thermal conductivity and storage capacity, hence good performance during LOCA • Large heated perimeter, hence easy to cool during normal operation - Large DNBR • Small distance between fuel and coolant and high thermal conductivity, hence low operating temperature • Higher heavy metal loading than for DC-4, hence lower fluence, also requires slightly less enrichment 	<ul style="list-style-type: none"> • Non-proven fuel, may be difficult to manufacture with a high quality assurance • Difficult to ensure the SiC closure plugs remain tight during operation • Difficult to provide good key and dowel coupling between two neighboring elements

Figure 12 (from Hejzlar)
DC-5, TRISO/Graphite Matrix Surrounded by an SiC Structure

lengths. The benefits of this strategy appeared to be promising as detailed in the report [Dalporto and Todreas, 1995] and summarized in the ANS Conference Summary [Dalporto & Todreas, 1995].

All Theses, Reports and Papers prepared under this contract are listed in the Table on Page i of this report.

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