System Design of a Refitable Supercritical Heavy Water Primary Heat Transport System for Pressurized Heavy Water Reactors

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Abstract

Current Pressurized Heavy Water Reactors (PHWRs) have thermal efficiencies of about 30%. A significant increase in thermal efficiency can be obtained by operating at higher temperatures using supercritical water coolant. Supercritical water cycles have not been used in nuclear power plants due in part to the in-core high neutron absorption and material degradation of high temperature alloys typically used in thermal plants. This paper examines the replacement of the primary heat transport system (PHTS) and fuel channels in an existing PHWR with a supercritical heavy water PHTS. The in-core materials, thermal hydraulics and passive safety heat transfer are described. The out of core main heat transport loop is described including integration of the primary side high pressure turbine and interfacing with the plant main steam system. A benchmark application is examined resulting in a 100% increase in electrical output.

1. Introduction

The global push to reduce carbon emissions that are responsible for global warming is leading to greater electrification of energy uses and the need for green hydrogen. This, in turn, leads to the prospect of increased future electrical generation capacity for electrified transport, electric heat pump heating and cooling and electrolytic hydrogen production. Nuclear is well positioned to fulfill this need as one of the few non emitting electrical generation options with high power density that is well suited to the intense electrical demand in dense urban and industrial centres.

While the opportunities for new nuclear generation are significant, there remain hurdles. Recent experience with modernised large nuclear power plant construction in western industrial countries has resulted in long construction and commissioning times and cost overruns, particularly for first-of-a-kind units. These appear to result from project management and supply chain challenges after a long period of relatively little new nuclear construction. The track record of long construction times and cost overruns is a significant impediment to the economics and financing of new large nuclear generation in western countries. This situation exists in spite of the sound economics of many currently operating large nuclear generating stations.

One response to the challenges facing large nuclear new build projects is the development of small modular reactors (SMRs). SMRs are smaller, making them easier to finance, and they are built mostly in factories averting some of the project management and supply chain challenges of larger plants. While SMRs hold the promise of accessing new markets for nuclear and expanding the options for existing markets, they do not functionally replace the compact concentrated generation of large nuclear plants. There is likely to continue to be a need for large concentrated power sources particularly to feed large industrial and urban centres.

One option to achieve additional large scale nuclear power generation, is by renovating existing plants to increase electrical output. This option is feasible for Pressurised Heavy Water Reactors (PHWRs) of the pressure tube type where thermal efficiency and output can be increased by refitting the primary heat transport system (PHTS). Thermal cycles exist that allow a higher temperature and pressure PHTS to be interfaced to the main steam system with additional generation on the primary side. Space constraints of the existing plant can be accommodated by increases in steam generator heat transfer efficiency using primary side condensing operation.

A PHWR power upgrade through refitted PHTS has some distinct advantages in the current power demand environment. The project management challenges facing large scale nuclear new build are partially averted by relying on the extensive project management experience for PHWR refurbishment. Refurbishments already involve replacing many of the same fuel channel and PHTS components as will be required for refit. The difference, is rather than replacing components with like-for-like, they are replaced with new higher temperature and pressure components. Refit projects can also be executed on a shorter time frame than new builds with refit taking slightly longer than the existing refurbishments. Refits will be lower cost than large new builds. The ability to extend the useful life of existing nuclear plants will improve life-cycle economics. Land use is improved by generating power on an existing site that could otherwise become moribund under decommissioning.

While future electrification will inevitably increase electrical demand, there remains considerable uncertainty on when this demand will materialize. The shorter build time of PHWR refits, and the use of an existing plant and site, make PHWR refits a relatively nimble way to respond to approaching increases in electrical demand. The remainder of this paper will elaborate the refit concept and describe a benchmark application for obtaining a 100% increase in electrical output from Pickering A generating station.

2. PHWR refit design concept

The principal concept for the refit is to achieve greater output and efficiency through a modular replacement of the PHTS main circuit and fuel channels. In this context, modular replacement means that changes to the reactor and plant are confined, in so far as practical, to the PHTS and fuel channels. In practice, some changes will also be required to interfacing systems but these are kept to a minimum. The purpose of this approach is to avoid cascading changes to many systems that would complicate the refit and to also make the refit as similar to the existing refurbishments as possible.

The increased power output comes from two components, increased average fuel channel power and increased thermal efficiency. The increased fuel channel power is enabled by higher temperature fuel cladding and the thermalhydraulics of supercritical heavy water. The higher thermal efficiency results from increased fuel channel coolant exit temperature, 625 °C, compared to 293 °C to 310 °C for existing pressure tube type PHWRs. The higher coolant temperature is enabled by the high temperature fuel cladding and a high temperature 'cold pressure tube' fuel channel.

The increased power is converted to electricity through two supercritical heavy water primary side turbine generators and higher main steam turbine output through steam superheat.

Another aspect of modularity is the ability to fit the refitted PHTS into the same dimensional-envelope as the existing PHTS. This is plant specific, since pressure tube type PHWRs have a variety of different PHTS configurations. The main concept used to achieve envelope interchangeability is to compensate for the additional space required for the two primary side turbine generators by reducing the steam generator heat transfer space. A reduction in heat transfer space is enabled by the improved efficiency of condensing heavy water heat transfer compared to the near single phase liquid heavy water heat transfer in existing PHWRs.

3. Refit requirements and constraints

One principal requirement is economic, being that the capital cost of the refurbishment, including financing, must be more than compensated by the additional revenue from increased power and plant life to provide a desirable return on investment (ROI). A refit configuration with main steam superheat and 625 °C channel outlet temperature can double the power output with only a small increase in operating costs. This provides a good prospect for desirable ROI, but since each plant will have unique refit implementation costs, including life extension costs for systems that are not refit, the ROI analysis must be made on a case-by-case basis for each plant.

The second principal requirement relates to safety. Since a refit implies an extended service life for the plant it must meet 'at time of refit' safety expectations including any increased safety that might be warranted from increased population density surrounding the plant. This indicates that the refit should provide for safety that is enhanced in comparison to the original plant. This is enabled by augmented passive safety for decay heat management and shutdown system instrumentation that provides augmented coverage for accidents. The augmented shutdown system coverage for trips includes individual channel trips and accident specific trips such as seismic trips.

The primary constraint is the existing plant layout and interfaces with the refit systems. The refit must be configured so as to fit within the existing plant layout. Each plant will need to have its refit adapted to the plant specific layout constraints.

4. Materials and system design

The use of new materials is a key enabling feature for high temperature supercritical operation of the PHTS. This section will describe the new materials and their roles in PHTS components. The description of the system design will focus on the new refit systems and the modifications required to existing systems. The components and systems will require extensive development testing which is not described in this paper.

4.1 Fuel and Fuel Channel

The fuel and fuel channel need considerable changes from existing PHWRs to enable operation at the higher temperatures and pressures of super critical heavy water. The approach has been to adopt changes where necessary while maintaining compatibility with current reactor dimensions and physics. Where new materials are necessary, the approach is to select materials that can provide the capability for substantially higher temperature operation (e.g. ultra supercritical – 650 °C to 1000 °C) to allow for future enhanced designs using the same fuel and fuel channel technology.

The fuel design approach is to make best use of the existing PHWR fuel experience by keeping to known fuel operating conditions to the extent possible. The overall bundle geometry is a CANFLEX [1] type geometry. The external diameters of the fuel elements are identical to those of CANFLEX bundles that have been tested in Point Lepreau Generating Station [2]. This allows the refit to benefit from tested thermal hydraulics [3] for sub-critical heavy water conditions that will exist during plant start-up and shutdown and some accident conditions.

The fuel itself is composed of uranium dioxide fuel in a combination of natural and slightly enriched fuel pellets. The enrichment is ~0.9% which has been studied as a higher burn-up fuel for existing PHWRs [4]. The fuel can be manufactured similarly to existing PHWR fuel with the exception that some dimensional tolerances will need to be tightened. In the pellet, most temperatures, power density and burn-up are within the range of existing PHWR experience.

The major divergence from the existing PHWR fuel is that the existing zircalloy-4 fuel sheath, end plates and appendages are replaced with single crystal sapphire fuel cladding, endplates and appendages. The term cladding is used because the single crystal sapphire will not thermally creep and collapse on the fuel pellets as with existing PHWR fuel but retain its geometry in a manner similar to LWR fuels. The use of a ceramic single crystal sapphire fuel cladding, different from any existing reactors, naturally brings about concerns of new and enhanced failure mechanisms that are not present in existing reactors. These have been systematically studied and are reported in a separate paper [5]. The difference in material properties and characteristics can be handled by modest modifications to the systems design while maintaining adequate normal operation and accident margins.

Single crystal sapphire has been selected for the fuel cladding primarily due to its very desirable mechanical and chemical properties. It has very high mechanical strength maintained over a large temperature range and very high oxidation corrosion resistance [5]. It also has very good thermal and irradiation expansion compatibility with the fuel. Its melting temperature is 2053 °C and thermal creep does not activate in the principal stress axes until 1150 °C [4]. While it has much lower fracture toughness than unirradiated zircalloy-4, its unirradiated and irradiated fracture toughness is only slightly lower than that of irradiated zircalloy-4 [5]. The fracture toughness can be accommodated by features in fuel bundle design and fuel handling.

Another rationale for selecting single crystal sapphire is its high transparency to thermal radiation [8]. This characteristic allows the efficient transfer of heat when the fuel is at high temperature such as during accident conditions. When combined with features of the fuel channel, it permits the transfer of fuel decay heat to the moderator soon after shutdown while maintaining fuel cladding well below the melting temperature and within the lower ranges of thermal creep temperatures. The fuel pressure boundary is predicted to remain intact following accidents that lead to a dry fuel channel such as LLOCA with no ECC. Once the reactor is shutdown, it is expected to remain safe in the absence of external energy sources, even with a damaged PHTS.

The in-core section of the fuel channel is based on the ‘cold’ pressure tube concept where the pressure tube is in contact with the moderator and there is an insulator inside the pressure tube. A cross-section of the in-core fuel channel with fuel is shown in Figure 1.

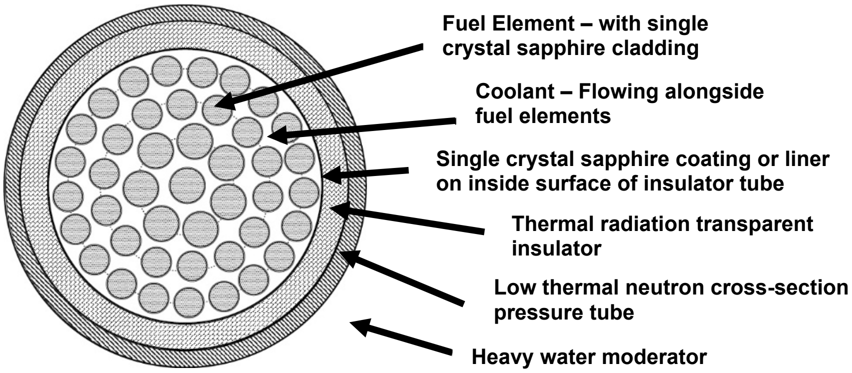


Figure 1: Cross-section of Fuel Channel in Reactor Core

The in-core fuel channel materials are SiC-SiC fibre composite for the pressure tube, sapphire coated fused silica for the insulator and Excel zirconium alloy for the pressure tube to end fitting transition piece.

The selection of SiC-SiC fibre composite for the pressure tube is based on a combination of strength and neutron economy. The rolled joint used to join current PHWR pressure tubes to the end fittings is not possible with the SiC-SiC fibre composite because it does not plastically deform under stress. The approach to joining the SiC-SiC fibre composite pressure tube is to first roll in an Excel transition piece into a hub in the pressure tube and then roll the transition piece into the end fitting.

The selection of fused silica for the insulator is based on a combination of low thermal conductivity, high thermal radiation transparency and good dimensional stability under irradiation. The low thermal conductivity prevents normal operation heat loss to the moderator. The high thermal radiation transparency provides an efficient means of transferring heat from high temperature fuel during accident conditions to the pressure tube. The good dimensional stability under irradiation ensures a constant cross-sectional flow profile to provide consistent thermalhydraulics over the life of the fuel channel.

4.2. PHTS Main Loop

The PHTS has several new components that are not present in current PHWR PHTSs. These are two primary side turbine generators and superheater-desuperheaters. In addition to the extra components, there are configuration differences that do not exist in existing PHWR PHTSs. These are the coupling of fuel channels in pairs and the coupling of the loops at the turbine generator. A simplified system configuration is illustrated in Figure 2 and the full coupled loop main piping is illustrated in Figure 3.

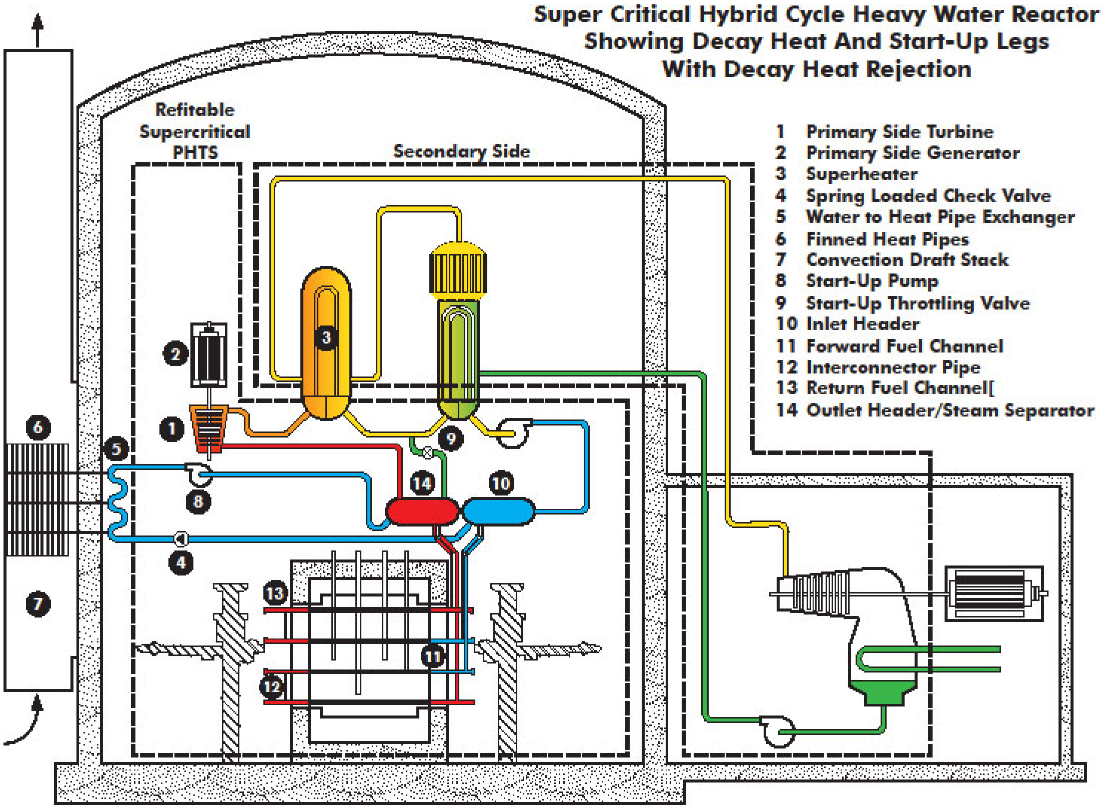


Figure 2: Simplified System Configuration of Refit

The coupled loop flowsheet also shows two secondary flow paths. One is for start-up and shutdown, to bypass the primary side turbine, and the second is for decay heat removal when the primary pump is shutdown. There are also accumulators connected to the inlet headers and outlet endfittings. These provide short term cooling for LOCA accidents and pump or power failures.

The temperatures in the PHTS between the steam generator outlet and the fuel channel inlet are similar to the current PHTS but the pressure is much higher. While carbon steel used in current PHWRs would be suitable from a strength perspective, stainless steel would be preferable to reduce corrosion products. The use of single crystal sapphire clad fuel in the core to achieve good accident heat transfer means there is a low tolerance for impurities that might foul the fuel with films and reduce thermal radiation heat transfer.

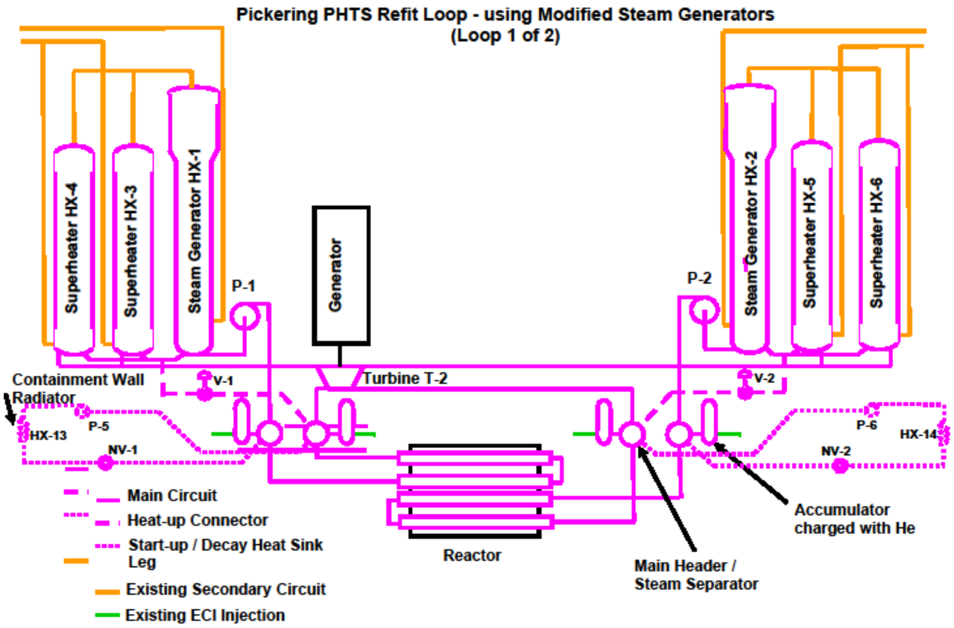


Figure 3: One of Two Coupled PHTS Loops in Refit

The primary coolant pump is oriented in a horizontal axis similar to thermal supercritical water plant pumps. This differs from existing PHWRs that have vertically oriented pumps and will have an impact on the pump dimensional and maintenance envelope. The pump is also variable flow, with flow being varied to maintain constant channel outlet conditions with changes in reactor power. The pump may need to include features to regulate outlet pressure to maintain it sufficiently constant over the full flow range.

The outlet feeders will pose the greatest material challenge due to a combination of high temperature, irradiated supercritical heavy water corrosion and the need for high strength to limit feeder tube wall thickness. It is expected that alloys used in ultra supercritical water thermal plants will provide the best material solution for the feeders. These materials will need to be tested in the presence of irradiated supercritical heavy water to make the best material selection. The outlet headers and piping leading to the primary turbine inlet will more closely approximate the conditions in existing supercritical water thermal plants and the use of similar materials is expected to be adequate.

The primary side turbine is similar to the high-pressure stage of current thermal plant turbines except that it is vertically oriented and designed to minimize heavy water leakage. The vertical orientation requires different bearings and a different approach to rotor and stator removal for maintenance. The turbine will be located in an in-floor silo to protect other components inside containment from damage in the event of rotor failure. The generator is an air-cooled generator similar to existing models but modified for vertical orientation and with control located remotely outside of containment.

The superheater-desuperheater is a new PHTS component. Its function is to remove superheat from the heavy water steam exiting the primary turbine and superheat the secondary side steam exiting the steam generator. No specific design has been selected at this stage of concept development; however, an assessment of required heat transfer area suggests the volume of the equipment can be considerably less than the existing steam generators.

The steam generators are expected to be similar in design to existing PHWR steam generators. A big difference is the boiling rate relative to steam generator tube area. The condensing heavy water steam has a much higher heat transfer rate that will lead to greater boiling. This may affect the optimal tube spacing. recirculation rate and tube vibration. This will need to be considered in the detailed design of new or modified steam generators. The increased steam generation rate will also affect the steam drum likely leading to greater moisture carryover. An increase in exit steam moisture can be addressed by drying in the superheater desuperheater.

4.3. Other System Interfaces and Modifications

The design concept is to focus refit modifications on the PHTS and fuel channels while keeping other systems the same insofar as practical. Some modifications to other systems have been identified as necessary for a refit. The affected systems are described below.

The interfaces with the main steam system are at the steam generator and the superheater desuperheater. A new steam generator will likely be needed due to the higher steam generation rate although modification or re-use of the existing steam generator can be studied. The superheater desuperheater is a new component that will be located close to the steam generator and will need to be piped into the main steam system.

The generator will need to be uprated or replaced to accommodate additional power from the main turbine. The switchyard will need to accommodate the power from the primary side turbine generators and any increase in power from the main generator. The control and regulation of the generators will need to be modified to accommodate multiple power sources.

The moderator cooling system needs to be modified to provide a syphon break to prevent draining of the moderator in the event of a cooling system fault. This is to maintain the calandria full under accident conditions given its passive decay heat removal role. The moderator also needs a passive back-up cooling capability to remove fuel decay heat. This is expected to be a flash driven natural circulation system [6] delivering heat to heat pipes connected to natural circulation air cooled radiators outside of containment.

The reactor regulating system interfaces with the refit at the PHTS instrumentation. While changing the RRS PHTS instrumentation and the RRS Digital Control Computer (DCC) algorithm could be sufficient for the refit, larger changes may provide a more optimal result.

The fueling machine interfaces with the refit at the channel closure. A completely new fueling machine will be required due to the new grappling and sealing at the closure and the higher temperature and pressures of heavy water and the greater frequency of fueling machine visits. The fuel handling system interfaces with the new fueling machine that is described above. The fuel handling system will need to be modified to better cushion fuel movement and avoid mechanical shocks that could damage the sapphire fuel cladding.

The shutdown systems interface with the refit at the PHTS shutdown system instrumentation. The shutdown systems will need new PHTS instrumentation and new PHTS trips that will need to be programmed into the shutdown system control modules. The ECI/ECC system interfaces with the refit at the PHTS piping. New accumulators will be required, connected at the headers and end fittings. The ECC will have a reduced role with passive decay heat removal and could be eliminated following extensive validation and testing of the passive decay heat removal via the moderator.

The containment interfaces with the refit at the penetrations for the primary turbine generator electrical and control connections, other wiring connections such as for the RRS and shutdown system, and the piping for passive decay heat removal. The modifications to containments are new penetrations for these interfaces.

5. Benchmark Study

The refit design concept described in the forgoing sections has been applied to a specific reactor design to define the operating parameters for a specific refit configuration. The Pickering A reactors have been selected for this benchmark study, in part, because Pickering Units 2 and 3 were laid up with little prospect for restart at the time that the study was commenced.

The Pickering A units are the oldest commercial PHWR units and have a relatively high moisture, low efficiency main turbine. These units were anticipated to gain significant economic benefit from a refit. The key refit parameters are a maximum channel outlet temperature of 625 °C with superheat on the secondary side. This permits an increase in electrical output of over 100% as indicated below. The passive decay heat removal features of the refit are also considered appropriate for a site with increasing surrounding population density.

The fuel channels are coupled such that the colder ‘forward’ channel is near the centre of the core and the hotter ‘return’ channel is near the periphery of the core. The forward and return channels are in a ‘checkerboard’ configuration with adjacent channels having opposite flow directions. This configuration provides several advantages: radial flux flattening since the colder, denser, channels are more neutron absorbing, colder coolant providing improved cooling for the highest power channels, and a more inlet skewed axial power profile for the highest power channels. The forward and return channels are connected by an interconnector pipe.

The coolant temperature averaged across the bundle cross-section and the highest element heat flux are shown in Figures 4 – 7 for the average and highest power forward and return channels. The return channel outlet temperature for the highest power channel is significantly lower than that for the average power channel (487 °C versus 625 °C). The reason for this is that the highest power channels are overcooled to improve margins.

As can be seen from Figures 4 and 6, the coolant passes through the pseudo-supercritical temperature of 382.6 °C near the outlet end of the forward channels. At the location of the pseudocritical coolant temperature of the high-power channel pair the heat flux for the high power element is 491,000 W/m^2 compared to the peak of 1,282,000 W/m^2 further upstream in the forward channel. Reduced heat flux in the zone of supercritical transition is beneficial in reducing the heat transfer degradation phenomenon that manifests in supercritical water transition at high heat fluxes.

The coupling of fuel channels results in two heat transfer benefits, a doubling of coolant mass flux per channel, and pseudo-supercritical water transition at low heat fluxes. The doubling of coolant mass flux per channel increases the coolant velocity, which increases the convection heat transfer coefficient, resulting in improved cooling of the fuel. It also results in lower coolant temperatures in the forward channels, which have higher power than the return channels, resulting in improved cooling of the higher power channels. When the coolant passes through the pseudo supercritical temperature at lower heat flux, there is a benefit in that the heat transfer degradation is lower than it would have been at higher heat fluxes. Also, the impact on fuel temperature from heat transfer degradation is less since the heat flux is less.

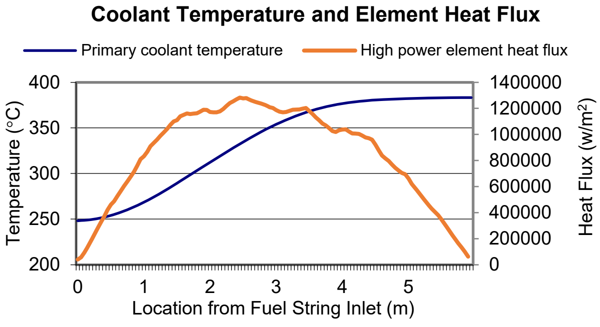


Figure 4: Forward channel – high power pair

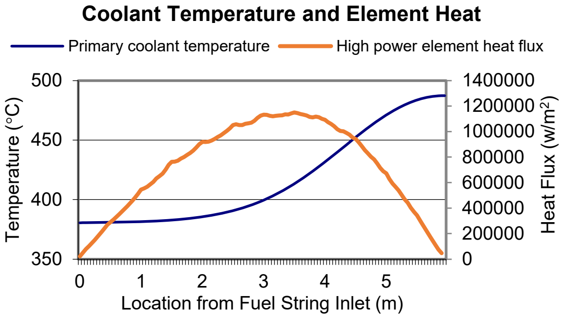


Figure 5: Return channel - high power pair

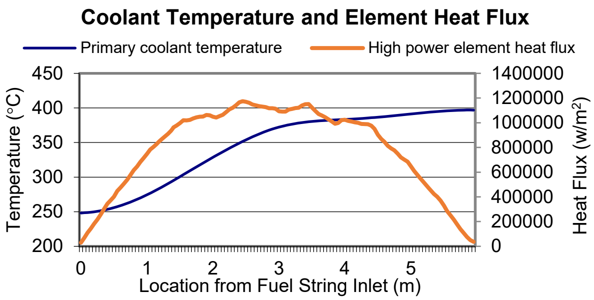


Figure 6: Forward channel - average power pair

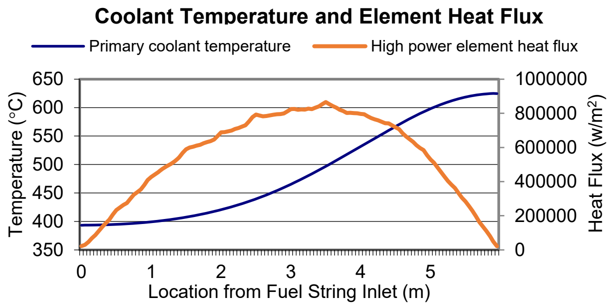


Figure 7: Return channel - average power pair

The fuel outer surface, centreline and average temperatures for the highest power elements are shown in Figures 8 – 11. As can be seen from Figures 8 and 10, the peak centre line and average fuel temperatures are 2201 °C and 1474 °C respectively. One of the consequences of higher fuel operating temperature is greater fission gas migration and release to the fuel pellet to cladding free volume. This increase in fission gas can be accommodated due to the high strength of single crystal sapphire and the significant irradiation growth of the cladding that provides increased free volume with irradiation.

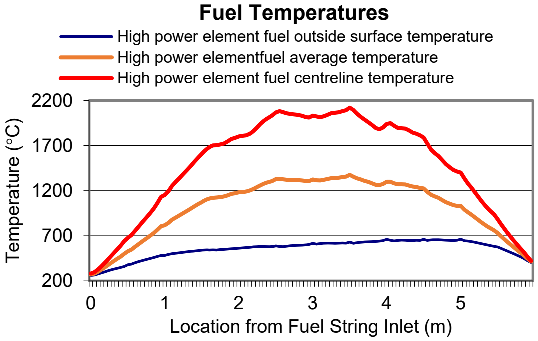


Figure 8: Forward channel - high power pair

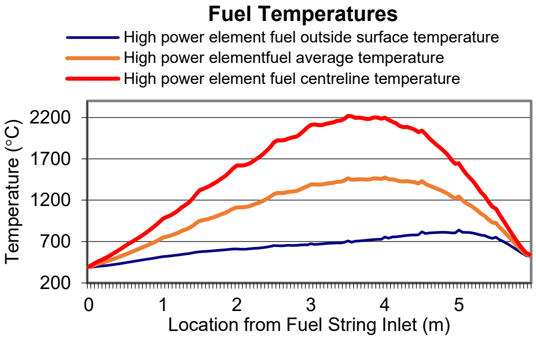
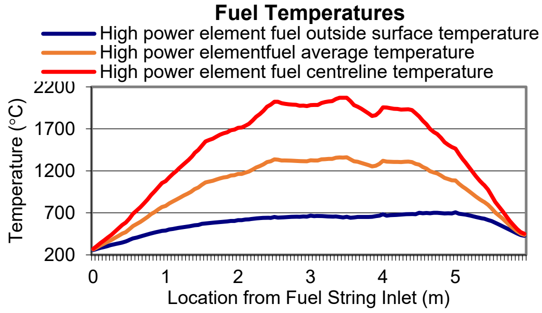


Figure 9: Return channel - high power pair



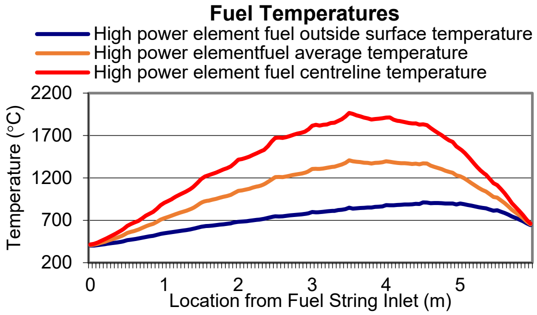


Figure 10: Forward chan. - average power pair Figure 11: Return chan. - average power pair

The fuel power deposited in the coolant is 2320 MW of which 380 MW is transferred to the primary turbines for electricity production, 316 MW is transferred to the secondary side to superheat the main steam to 383 °C, 1644MW is transferred to the secondary side to heat and boil water and 10 MW is lost through the pressure tubes heating the moderator. 30 MW is added by the main primary coolant pumps. With the increased secondary side steam temperature, and thermal efficiency, 826 MW is utilized by the main turbine to generate electricity. The overall unit heating rate / power balance is shown in Table 1

TABLE 1: Unit Heating Rate / Power Balance

Heat / Work component	Energy Generated (MW)	Energy consumed (MW)
Primary side turbines (2)	380	
Main turbine (1 – secondary side)	826	
Primary coolant pumps (4)		30
Main boiler feed pumps (4)		24
Other plant loads		8
Net electrical output	1144	

6. Conclusions

The use of non-traditional in-core materials can enable PHWR operation at much higher coolant temperatures in the supercritical fluid domain. The increase in coolant temperature and fuel power can enable a 100% increase in electrical output. This increased power output is achieved through refitting an existing PHWR using modular replacement of the PHTS and fuel channels. The refit builds on existing project management experience from refurbishment and can be accomplished on similar time frames. This provides an opportunity to increase the economic life of existing units while generating new electrical supply at considerably shorter lead time than large new build projects.

The author thanks Geoffrey Dimmick, Mukesh Tayal and Kevin Britton for their insightful and thoughtful suggestions during the preparation of this paper.

6. References

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