Compatibility Study of Prismatic Core Single Loop Gas Turbine Very High Temperature Reactors

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Abstract

This is a compatibility study of VHTR's operating on a single loop gas turbine, and thus why they should be used instead of other reactor designs. The VTHR design alone has a number of benefits, the most important being higher outlet coolant temperatures. However, the VHTR with a single loop helium gas turbine is what could possibly be the future of nuclear power. The single loop helium gas turbine would dramatically decrease the cost of new reactor installations, due to smaller plant size and complexity. The thermal efficiency of a helium gas turbine is also significantly higher than any operational pressurized water reactor in use today, through improved turbine blade materials, and a recuperated Brayton cycle. This study aims to prove why single loop helium gas turbine VHTR's out class other reactor designs, and why they should be the new standard for nuclear power going forward.

Higher Outlet coolant Temperatures

One of the most important advantages of the single loop helium gas turbine is its extremely high outlet coolant temperatures. Outlet coolant temperatures for a prismatic core VHTR design typically reach at standard operating conditions temperatures of around 850 Celsius, or 1562 Fahrenheit [1]. However due to advances in prismatic core operation and inlet gas turbine blade materials temperatures of 950 Celsius, or 1742 Fahrenheit, are now achievable. This is compared to pressurized water reactors typically having outlet coolant temperatures around 325 Celsius, or 684 Fahrenheit [2]. For heavy water reactors like CANDU that use deuterium dioxide for moderation and coolant the outlet coolant temperatures typically only reach 295 Celsius or 563 Fahrenheit [2]. For Boiling water reactors (BWR) the outlet temperatures are even lower typically operating at 285 Celsius, or 545 Fahrenheit [2]. With higher outlet coolant temperatures increased thermal efficiencies are achievable.

Increased Thermal Efficiency

Due to the increased outlet coolant temperatures possible from the prismatic core VHTR design, as well as other advancements in reactor technology, higher thermal efficiencies are now possible. Thermal efficiency is the percentage of how much of the thermal energy produced by the reactor is converted to mechanical energy, that can then be used to create electricity. The single loop gas turbine VHTR has a proposed thermal efficiency between 45 to 50 percent depending on operational conditions [1]. A typical PWR is only able to achieve a thermal efficiency of 32 percent, most BWR type reactors can achieve efficiencies of around 35 percent, and heavy water reactors like CANDU, typically can only achieve thermal efficiencies of around 30% [3]. Improved blade materials utilizing nickel-based alloys allow the gas turbine blade to endure the high coolant temperature exiting the reactor core. The single loop VHTR operates on a thermodynamic cycle called a Brayton cycle, specifically a Brayton cycle utilizing inter cooling and recouperation sometimes called a regenerative Brayton cycle. The higher the outlet coolant temperatures from the reactor allow for a pressure ratio of two which is the ideal pressure ratio for that reactor design[1]. The Pressure ratio is the difference in pressure between the inlet and outlet of the compressor pumping the helium through the core. Two a certain pressure ratio point, typically the higher the pressure ratio the better the thermal efficiency. The use of a recuperator and inter cooler also boosts the thermal efficiency of the Brayton cycle. The regenerator uses the exhaust gases coming from the gas turbine and utilizes them for heating the incoming helium gas going into the turbine, allowing the turbine to operate at higher temperature, and thus increased efficiency. While the intercooler cools the incoming helium gas going into the compressor, decreasing the temperature of the compressor, and allowing for more efficient compressor operation.

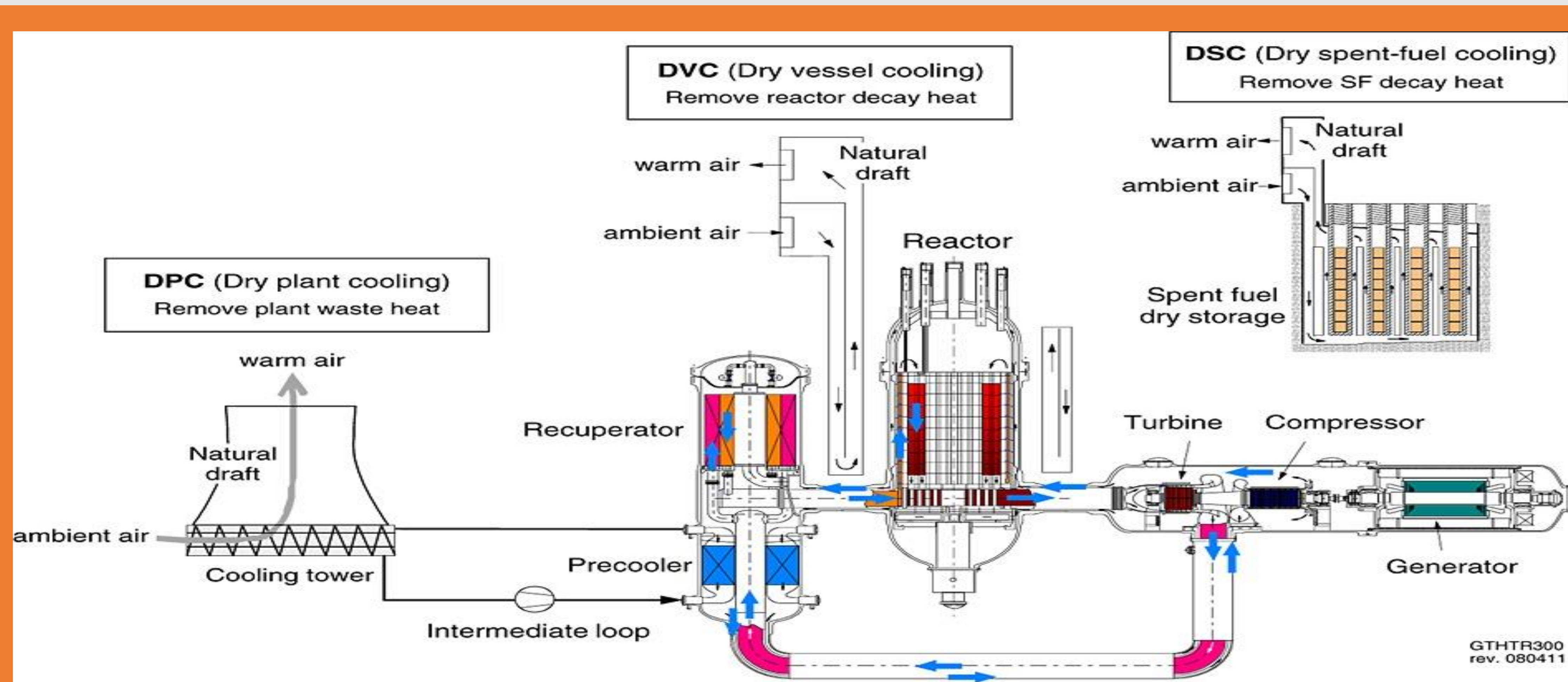

Figure 1 GTHTR300 with dry cooling overview schematic [6]

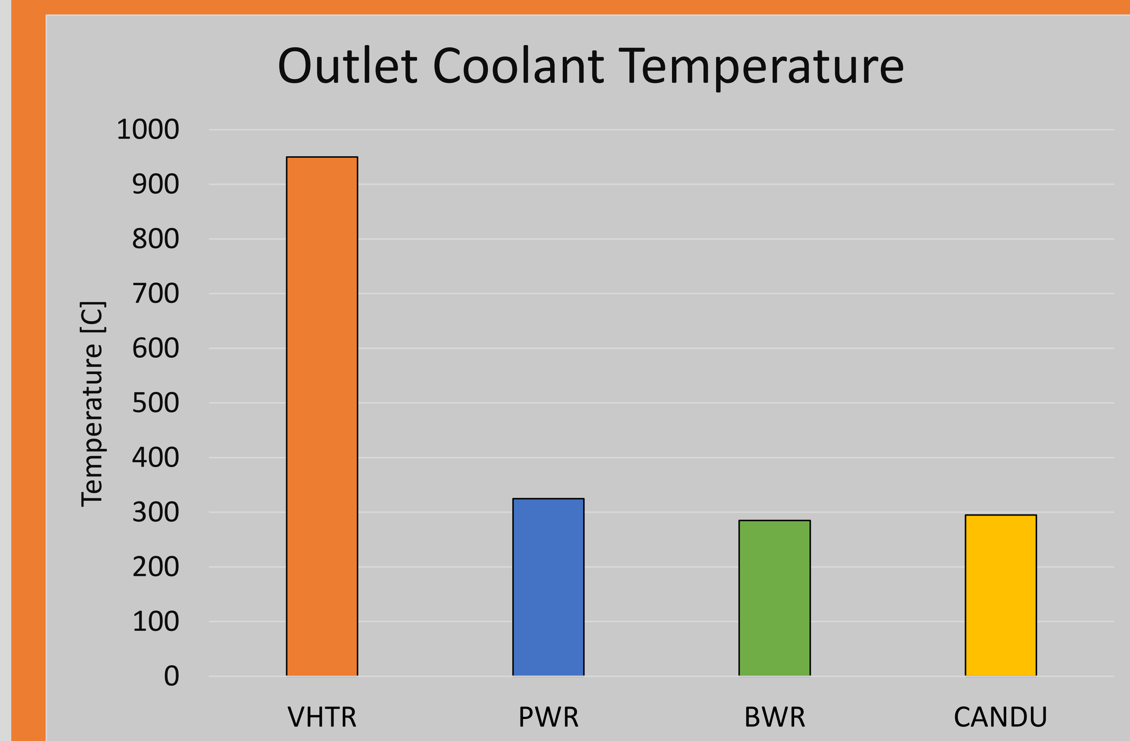

Table 1 Outlet Coolant temperatures

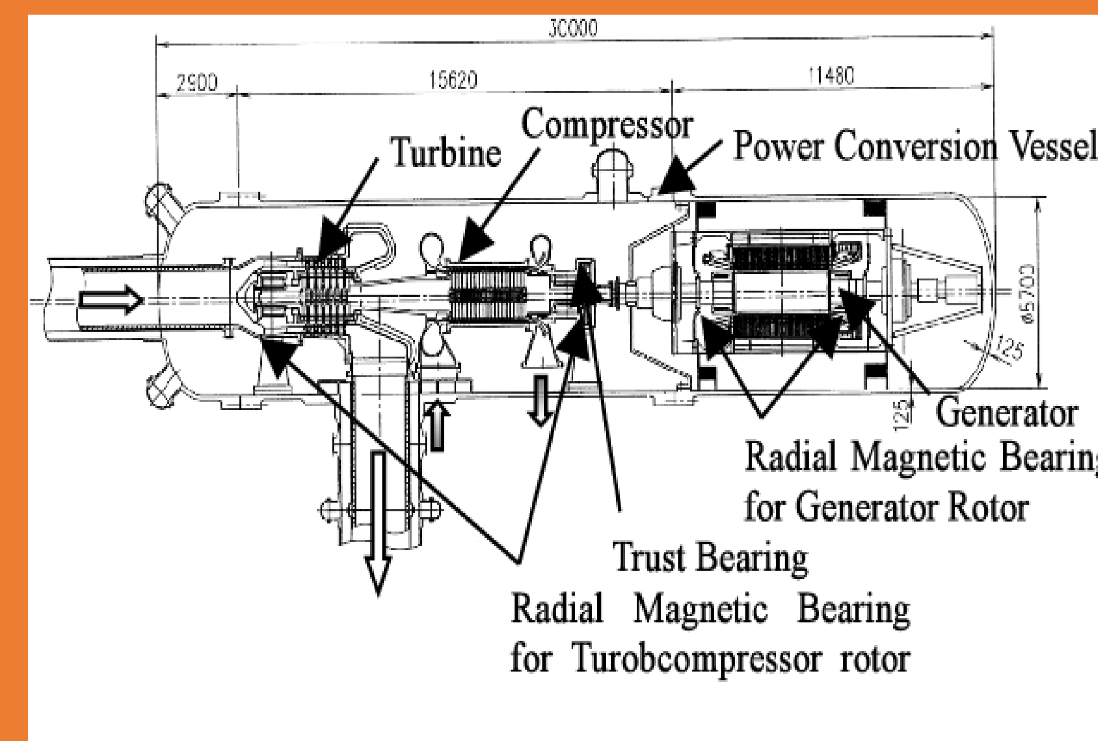

Figure 3 GTHTR300 helium gas turbine schematic [9]

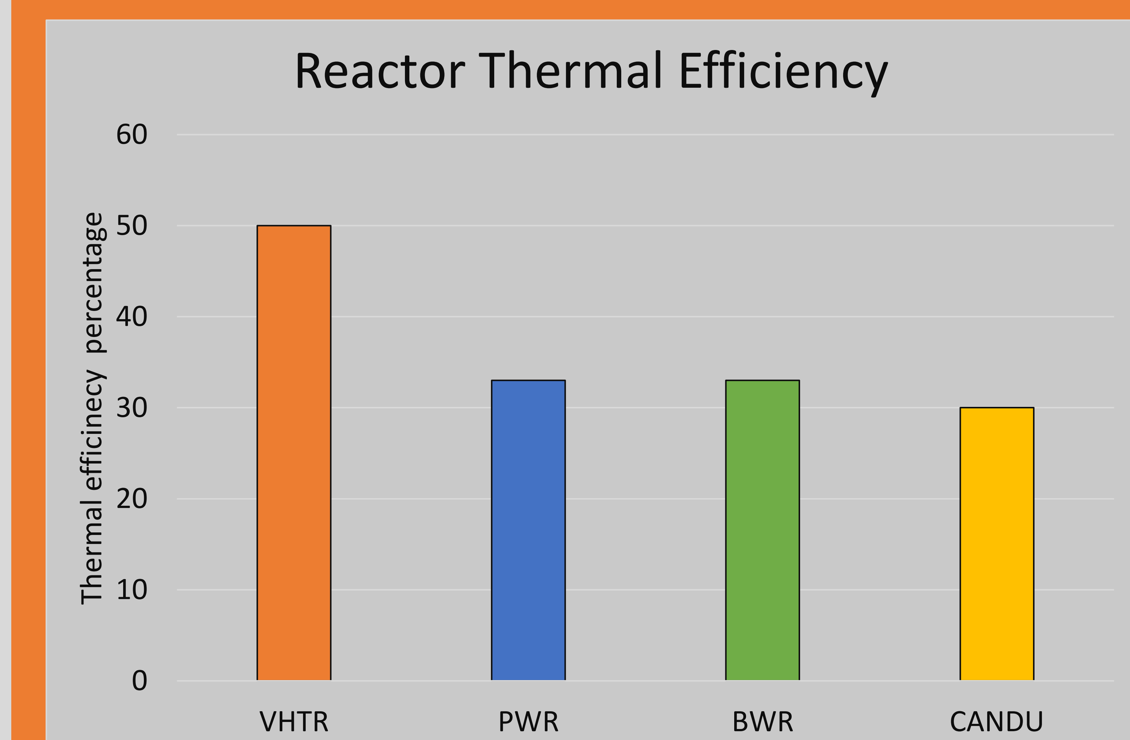

Table 2 Reactor Thermal Efficiency

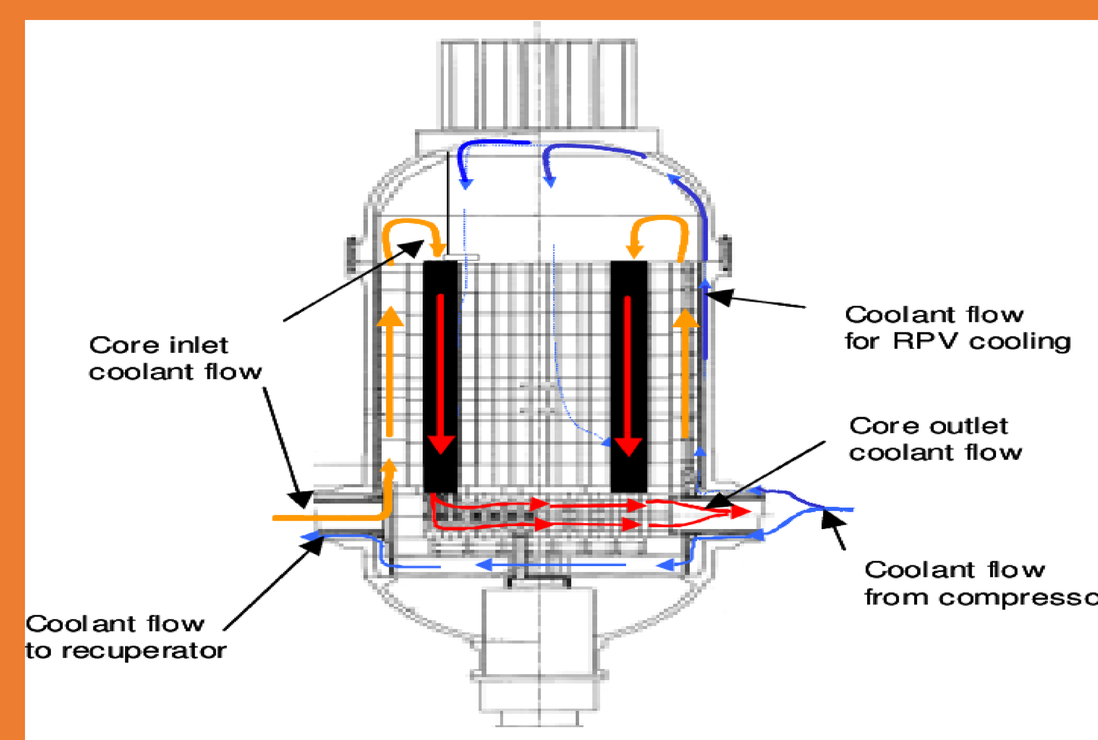

Figure 4 Prismatic reactor core diagram [10]

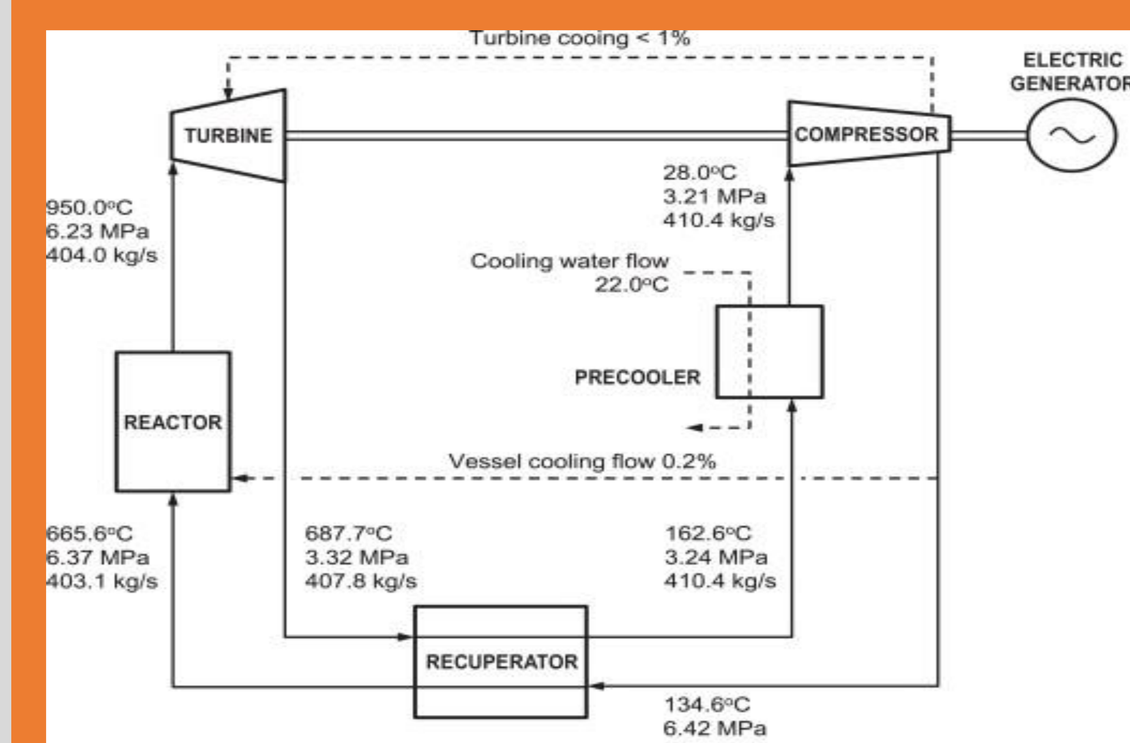

Figure 2 GTHTR300 thermofluidic system overview [8]

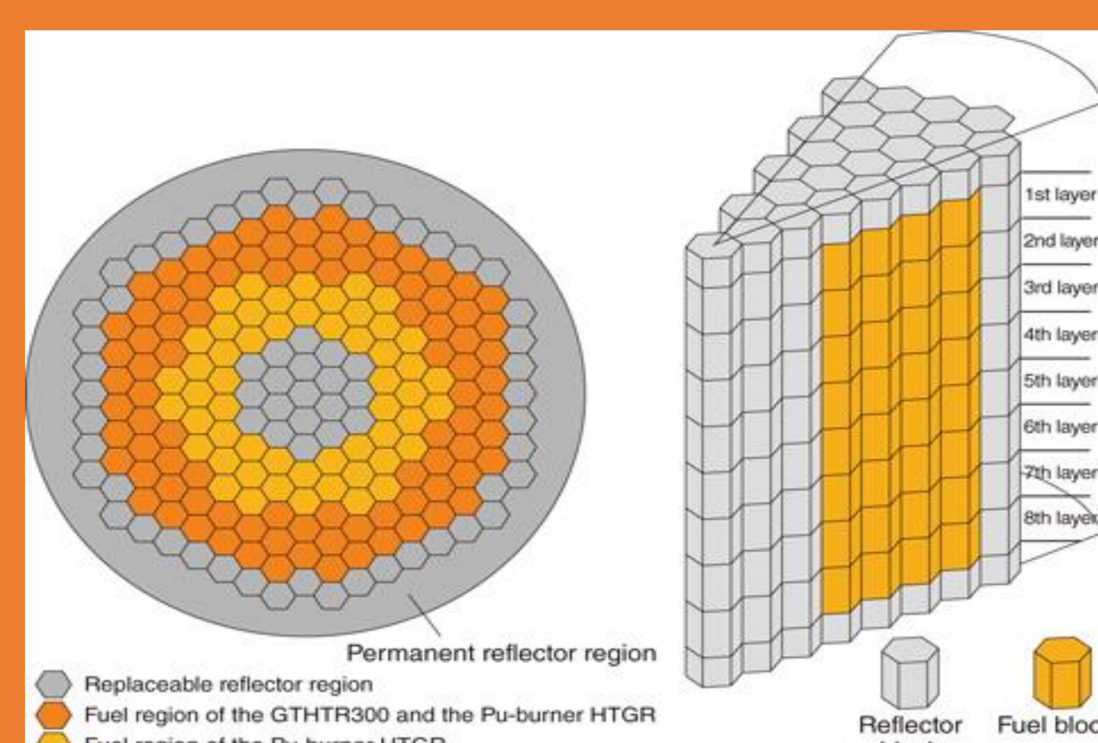

Figure 5 Prismatic reactor core cut-away cross section [11]

Reduced Power Plant Cost

The cost of new nuclear power plant installations has steadily begun to rise since the 1970's. A new 1,100 Mega-Watt nuclear plant can cost anywhere between six to nine billion dollars [4]. Because of this increasing price for new power plant installations, of the 99 Gigawatts of power that is sent to the electric grid from nuclear power, 95 Gigawatts of that power comes from nuclear power plants installed between 1970, and 1990 [5]. The prismatic core single loop gas turbine VHTR reactor design could help in decreasing the cost of new future power plant installations. One of the ways this could be achieved is through the compact plant design of the single loop gas turbine VHTR. In a standard light or heavy water reactor three coolant loops are required to transport the thermal energy coming from the reactor into steam for mechanical work. These reactors also require access to large quantities of water in order to meet the needs of their thermodynamic cycle, as well as ensure reactor safety. This also typically requires the use of very large conical cooling towers that require lots of land area and material. The turbines for the installations also typically must be housed in their own separate building requiring low- and high-pressure turbines. The single loop gas turbine VHTR operates on a single closed loop involving helium, and an incorporated gas turbine. This simplification requires less material to build the reactor and allows for a more compact power plant less encroaching on its environment. Because helium is used as a coolant instead of water or heavy water dry cooling towers can be utilized. These cooling towers are estimated to be half the height of current conical cooling towers and one eighth the diameter, this would again make these installations more compact and better blend in with the ambient environment, and less of an eye sore compared to standard cooling towers [6]. While the single loop gas turbine VHTR would still require some outside coolant water, it would require significantly less water input then standard light and heavy water reactor designs. The need for less coolant water is another advantage of this reactor allowing them to be deployed to less water abundant areas where nuclear power was not an option. Because of the compact nature of this reactor design, it has possible applications as small modular reactors (SMR). SMR's are reactors that are radically smaller than a normal nuclear plant, likely being used to service remote areas or operated in grids to fulfil larger power requirements. This and the ability to be manufactured in a central location, then shipped and assembled where they are needed, is another promising application. Another aspect of the single loop VHTR design that allows for greater economic viability is the efficient production of hydrogen. This could be done using a Cu-Cl thermochemical process, achievable because of the high outlet coolant temperatures a VHTR can offer, the produced hydrogen could then be used to help offset the operational costs of the VHTR [7].

References

1: Sato, Hiroyuki, et al. "GTHTR300—A nuclear power plant design with 50% generating efficiency." *Nuclear Engineering and Design* 275 (2014): 190-196.

2: Breeze, Paul. *Power generation technologies*. Newnes, 2019.

3: Other Designs of Nuclear Power Stations ." *Open Knowledge Wiki - Other Designs of Nuclear Power Stations*, International Atomic Energy Institute, 2012, nucleus.iaea.org.

4: David Schlissel, David, and Bruce Biewald . "Nuclear Power Plant Construction Costs." *Nuclear Power Plant Construction Costs* , Synapse Energy , 2008, www.synapse-energy.com/sites/default/files/SynapsePaper.2008-07.0.Nuclear-Plant-Construction-Costs.A0022_0.pdf.

5: "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." *Most U.S. Nuclear Power Plants Were Built between 1970 and 1990 - Today in Energy - U.S. Energy Information Administration (EIA)*, U.S. Energy Information Administration, www.eia.gov/todayinenergy/detail.php?id=30972.

6: Yan, Xing, et al. "Evaluation of GTHTR300A nuclear power plant design with dry cooling." *International journal of energy research* 38.11 (2014): 1467-1477.

7: Jaszczur, Marek, et al. "Hydrogen production using high temperature nuclear reactors: Efficiency analysis of a combined cycle." *International Journal of Hydrogen Energy* 41.19 (2016): 7861-7871.

8: Yan, Xing L., et al. "GTHTR300 cost reduction through design upgrade and cogeneration." *Nuclear Engineering and Design* 306 (2016): 215-220.

9: Kunitomi, K. et al. "Research and Development for Gas Turbine System in GTHTR 300 *." (2004).

10: Kunitomi, K. et al. "Design and Development of Gas Turbine High Temperature Reactor 300 (GTHTR 300)." (2003).