Chapter 6

FOURTH GENERATION REACTOR CONCEPTS

3/11/2014

6.1 INTRODUCTION

Nuclear power plants across the globe are producing about 16 percent of the world's electricity. With the depletion of the world liquid hydrocarbons and the concerns about greenhouse gases emissions, the world is moving towards a hydrogen economy. Hydrogen being just an energy carrier, nuclear energy can provide the energy to dissociate water into hydrogen and oxygen. Synthetic fuel from coal gasification and liquefaction can also be used for transportation fuels.

The hydrogen can be used as transportation fuel with water as the product of an electrochemical reaction producing electricity in fuel cell engines. Looming shortages in fresh water supplies can be averted with the use of nuclear reactors for fresh water desalination. The introduction of breeder reactors would turn nuclear energy from a depletable energy supply into an expandable practically limitless supply.

6.2 NUCLEAR REACTOR GENERATIONS

Concerns over energy resource availability, climate change, air quality, and energy security suggest an important role for nuclear energy in future energy supplies. So far, nuclear energy use for the production of electricity has evolved through three generations and is still evolving into a new generation that is being extensively studied.

Figure 1. Depiction of AP1000 system showing its cooled containment structure.

First generation: The first power reactors generation was introduced during the period 1950-1970 and included early prototype reactors such as Shippingport, Dresden, Fermi I in the USA and the Magnox reactors in the UK.

Second Generation: The second generation included commercial power reactors built during the period 1970-1990 such the Light Water cooled Reactors LWRs with enriched uranium including the Pressurized Water Reactor, (PWR) and the Boiling Water Reactor (BWR). In Canada it includes the Canadian Deuterium Uranium heavy water moderated and natural uranium fuelled CANDU reactors. In Russia this was the era of pressurized water reactor VVER-1000 and the RBMK-1000 of Chernobyl accident notoriety.

Third generation: The third generation started being deployed in the 1990s and is composed of the Advanced Light Water Reactors (ALWRs) including the Advanced Boiling Water Reactor, (ABWR), and the System 80+. These were primarily built in East Asian countries. New designs that are expected to be deployed by 2010-2030 include the Advanced Passive AP600 and AP1000 (Figs. 1, 2). These are considered as evolutionary designs offering improved safety and economics.

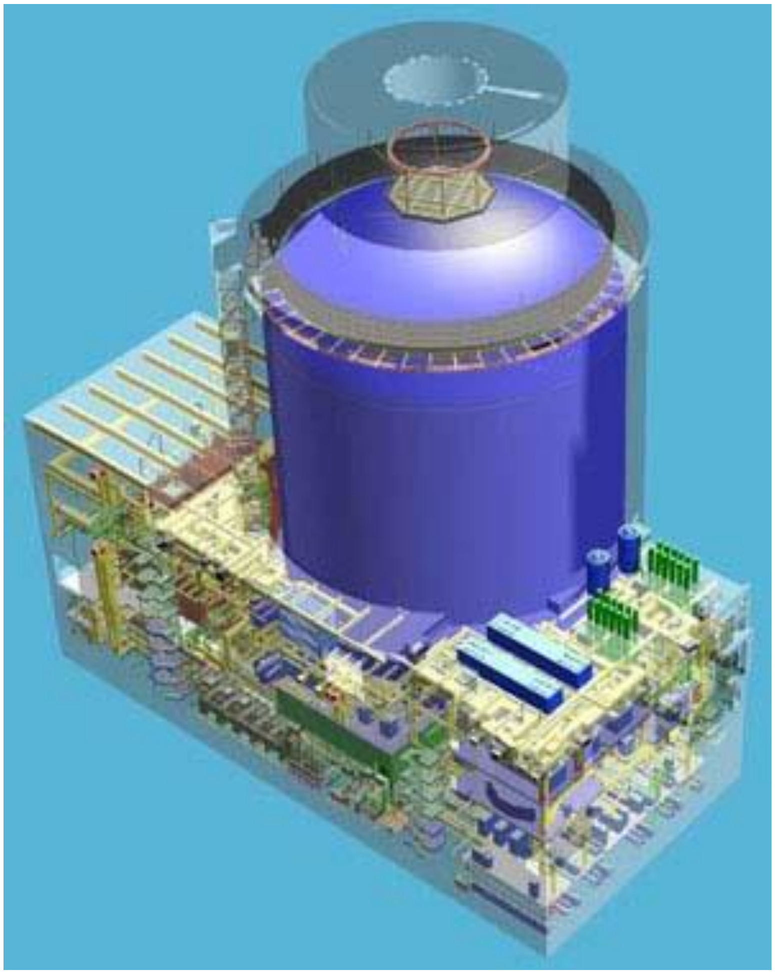

Figure 2. Cutout of the AP1000 showing its chimney concrete containment structure surrounding its steel shell containment.

Fourth generation: While the current second and third generation nuclear power plant designs provide an economically, technically, and publicly acceptable electricity supply in many markets, further advances in nuclear energy system design can broaden the opportunities for the use of nuclear energy. The fourth generation of nuclear reactors is expected to start being deployed by 2030. These new reactors are designed with the following objectives in mind:

1. Economic competitiveness
2. Enhanced safety,
3. Minimal radioactive waste generation,
4. Proliferation resistance.

6.3 GENERATION IV INITIATIVE

The Generation IV initiative has as a goal to have one or more reactor designs certified by 2030, in time to replace aging reactors built in the USA country during the 1970s and 1980s.

An international forum has been composed of ten countries to lead the effort. These are: the USA, the UK, France, Japan, Canada, Argentina, South Korea, Republic of South Africa, Switzerland, and Brazil.

The ten Generation IV International Forum (GIF) countries have selected six concepts to develop in order to meet the technology goals for new nuclear systems. These nations believe that developing these concepts will achieve long-term benefits so nuclear energy can play an essential role worldwide. Generation IV systems are intended to be responsive to the needs of a broad range of nations and users.

6.4 INITIATIVE GOALS AND CRITERIA

The goals of the generation IV initiative cover the areas of sustainability, econpmic competitiveness, safety and reliability and security against weapons proliferation.

Sustainability: Concerning sustainability, the main concern was the management of the environment through clean air restrictions, waste management restrictions and conservation of resources. Four general classes of nuclear fuel cycles were considered:

1. The once through fuel cycle.
2. A fuel cycle with partial recycling of the bred fissile Pu.
3. Full plutonium recycle.
4. A cycle with the recycle of the transuranic elements.

It appears that waste management is a major concern with the existing once through cycle because of the limited availability of repository space worldwide. Closed fuel cycles or recycling reactors allow some of the fuel to be reused so less of it has to be placed in a repository. Improvement in reactor performance can be achieved if thermal and fast reactors are operated in a coupled mode. An increase in the fuel burnup of gas cooled and water cooled thermal reactors can improve the management of the produced actinides by burning them in situ (Fig. 3).

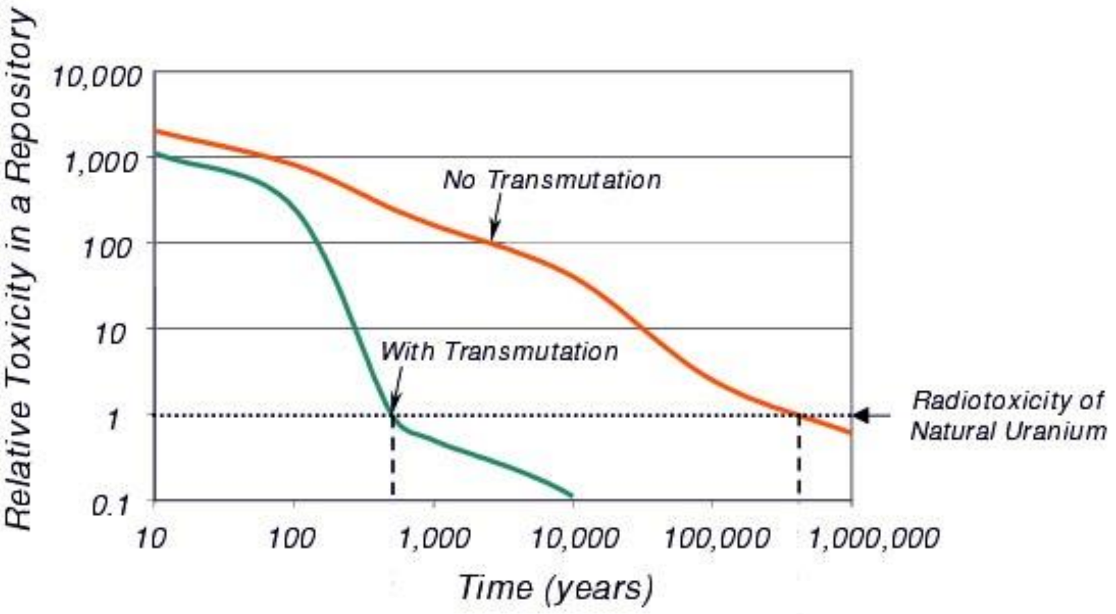

Figure 3. With transmutations, the relative toxicity of the transuranics is considerably decreased.

Economics: New reactors must be competitive in a changing market place of energy demand. There exists a possibility of privately owned nuclear facilities as opposed to publicly owned ones. Private ownership would create a need for larger or smaller unit sizes depending on location worldwide. Plants need to be modular or with standardized technical specifications so that plant parts can be duplicated and replaced. This would be more economical than if each plant is uniquely designed as is currently the case.

Safety and reliability: Active and passive safeguards features against accidents are to be carefully considered. International safeguards and regulations for the handling of fissile materials in place are to be strictly enforced. To reduce the probability of radioactive elements leaking to the atmosphere or damage to the plants, there must be an emphasis on the human factors pertaining to plant operations.

Proliferation Resistance: Plants are designed to cope with natural disasters such as earthquakes. Attention is to be devoted to the possibility sabotage or acts of fissile material theft or dispersal by individuals or non-national groups.

These considerations resulted in the consideration of six concepts for research and development.

6.5 VERY-HIGH-TEMPERATURE REACTOR: VHTR

The USA energy bill contains a provision for a new Generation IV innovative reactor design. An amount of $1.1 billion is budgeted for its construction until 2010. The reactor would be ready for demonstration by 2015.

The core would be He cooled using fuel similar to that of the Gas Turbine Modular Helium Reactor (GT-MHR) or a Pebble bed Modular Reactor (PBMR).

TheVery High Temperature Reactor or VHTR is a fourth generation gas cooled reactor design that would produce both electricity and hydrogen (Fig. 4). The Idaho National Engineering and Environmental Laboratory (INEEL) is sponsoring the development of the project.

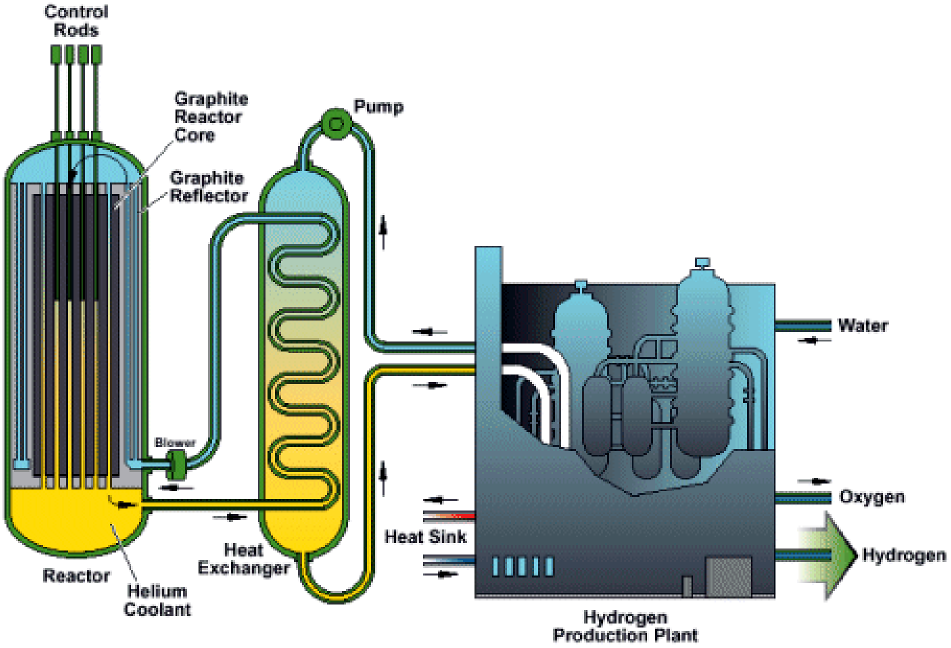

Figure 4. Very High Temperature Hydrogen and Electricity (VHTR) design.

It is a graphite-moderated, He cooled reactor with a once-through uranium fuel cycle intended for the dual purpose production of electricity and hydrogen. Hydrogen as a nuclear energy carrier is considered for a future nonpolluting energy economy with fuel cells directly producing electricity from hydrogen and releasing steam and water as a product.

The VHTR supplies heat with a He coolant core outlet temperature of 1,000 ^{o}C, which enables applications such as hydrogen production, synthetic fuel production from coal or process heat for the petrochemical industry. The reference pilot reactor is a 600 MWth core connected to an intermediate heat exchanger to deliver process heat. The reactor core can either be a prismatic block core such as the previous USA Fort Saint-Vrain, or the operating Japanese HTTR, or a pebble-bed core such as the operating Chinese HTR-10. For hydrogen production, the system supplies heat that could be used efficiently by a thermochemical iodine-sulfur process.

A safety feature is the reactor heat can be passively radiated through its steel vessel away from the high thermal inertia graphite moderator core without damage to the graphite encased fuel and release of fission products radioactivity. The reactor would be built underground with the earth becoming its ultimate heat sink.

The main circuit releases heat to a steam reformer/steam generator. It is capable to use a U/Pu fuel cycle to manage the actinides waste.

Several goals are aimed at: economical operation, high efficiency comparable to that of combined cycle natural gas plants, minimum waste generation, walk away safety and a proliferation resistant fuel cycle.

The VHTR offers a broad range of process heat applications and an option for high-efficiency electricity production, while retaining the desirable safety characteristics offered by modular high-temperature gas-cooled reactors.

There is a need for developing carbo n-carbon composites for control rod sheaths. The core internals would need up to ten years of testing for oxidation, post irradiation heat up and fracture behavior of the high temperature materials. Testing for the safety of valves and internal heat exchanger modules will be needed.

The VHTR can be rapidly developed in the years ahead for hydrogen production, or alternatively. It can be used for coal gasification and synthetic fuel production for transportation as a replacement to the depleting liquid hydrocarbon supplies.

Nuclear utilities like Exelon Corp., Dominion Resources Inc. and Entergy Corp., as well as equipment manufacturers like General Electric Co., The Westinghouse Nuclear unit of British Nuclear Fuels Ltd., and the Framatome unit of France’s Areva have shown interest i the VHTR project.

6.6 THE GAS COOLED FAST REACTOR: GFR

This concept features a fast-neutron-spectrum, a He gas cooled reactor and a closed fuel cycle. A fast spectrum would efficiently convert fertile uranium into fissile fuel and mange the actinides by burning them for energy.

The high outlet temperature of the helium coolant makes it possible to deliver electricity, hydrogen, or process heat with high efficiency. The reference design is a 600 MWth, 288 MWe helium-cooled system operating with an outlet temperature of 850 ^{o}C using a direct Brayton cycle gas turbine for high thermal efficiency (Fig. 5).

Several fuel forms are candidates that hold the potential to operate at very high temperatures and to ensure an excellent retention of fission products: composite ceramic fuel, advanced fuel particles, or ceramic clad elements of actinide compounds.

The core configurations may be based on prismatic blocks, pin or plate-based assemblies. The GFR reference design has an integrated, on site spent fuel treatment and refabrication plant.

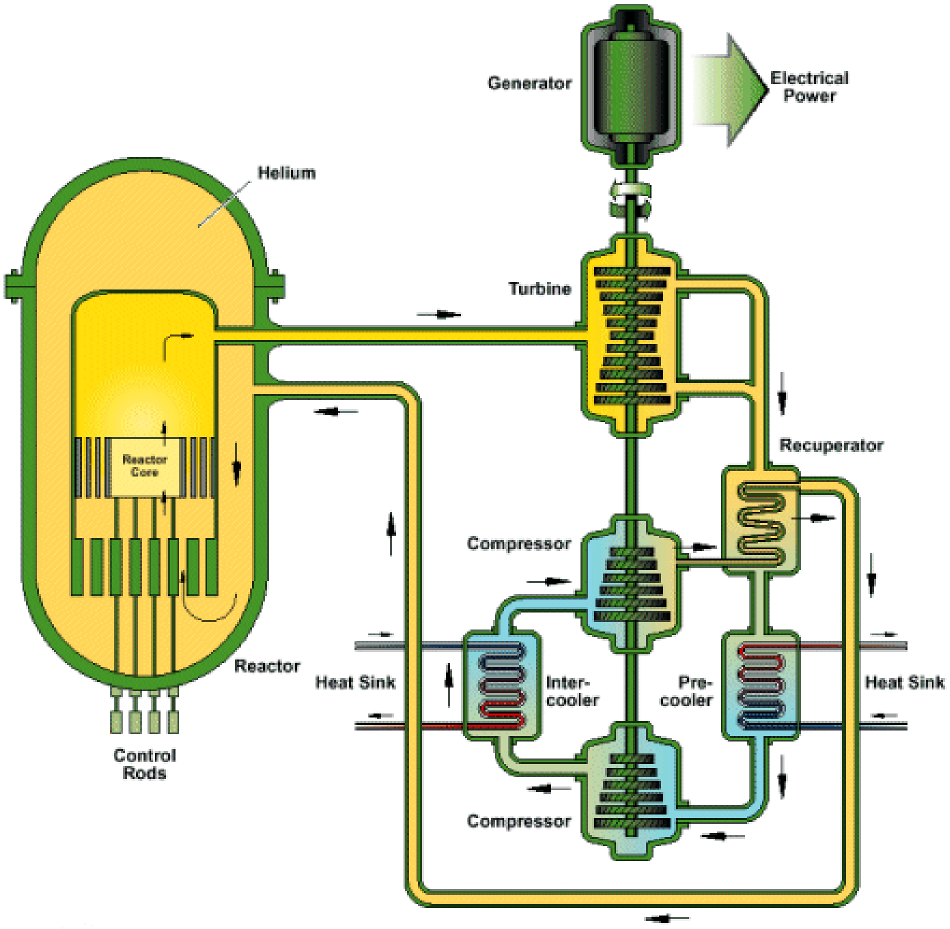

Figure 5. Brayton or Joule gas turbine Gas cooled Fast Reactor, GFR.

It uses a direct-cycle helium turbine for electricity generation, or can optionally use its process heat for thermochemical production of hydrogen. Through the combination of a fast spectrum and full recycle of actinides, the GFR minimizes the production of long-lived radioactive waste. The GFR's fast spectrum also makes it possible to use available fissile and fertile materials including depleted uranium considerably more efficiently than thermal spectrum gas cooled reactors using the once-through fuel cycle.

Testing the structure for resiliency during radiation under temperatures up to 1,400 degrees C needs to be tested. The fast spectrum has a drawback in in poor heat removal at low pressures of the He coolant in case of leakage, and low thermal inertia. Passive approaches of natural convection cooling and the development of semi-passive heavy gas injectors and conduction paths need to be studied.

6.7 THE SODIUM COOLED FAST REACTOR: SFR

The Sodium-Cooled Fast Reactor (SFR) system features a fast neutron spectrum, Na cooled reactor and a closed fuel cycle for efficient management of actinides and conversion of fertile U^{238} into fissile Pu^{239} (Fig. 6).

The fuel cycle employs a full actinide recycle with two major options: One is an intermediate size of 150 to 500 MWe, Na cooled reactor with uranium-plutonium-minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in facilities integrated with the reactor. The second is a medium to large of 500 to 1,500 MWe sodium-cooled reactor with mixed uranium-plutonium oxide fuel, supported by a fuel cycle based upon advanced aqueous processing at a central location serving a number of reactors. The outlet temperature is approximately 550 degrees Celsius for both.

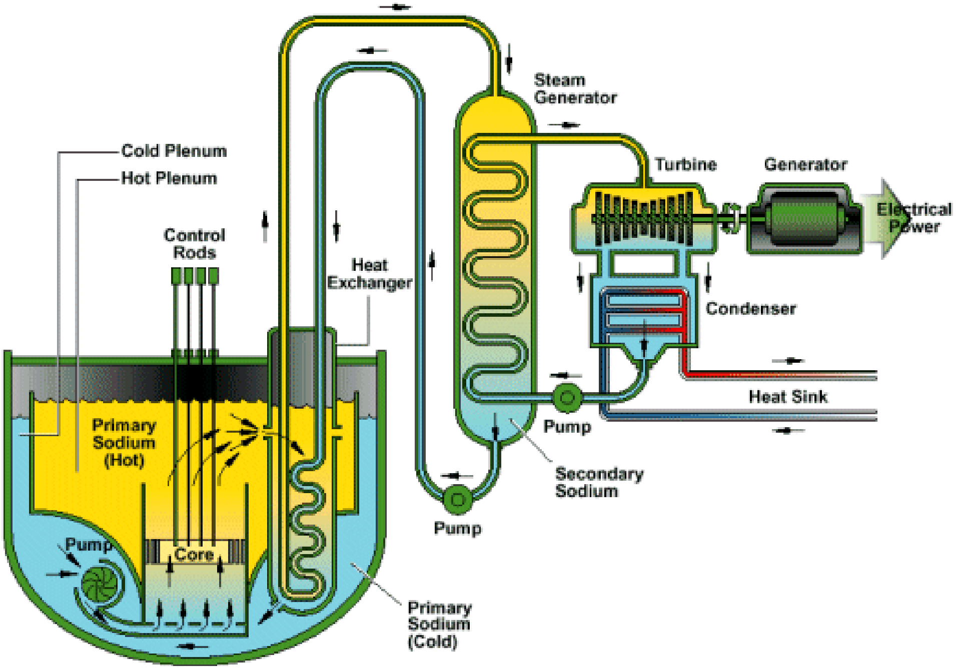

Figure 6. The Sodium cooled Fast Reactor (SFR).

The SFR is designed for management of high-level wastes and, in particular, management of Pu and other actinides. Important safety features of the system include a long thermal response time, a large margin to coolant boiling, a primary system that operates near atmospheric pressure, and intermediate sodium system between the radioactive sodium in the primary system and the water and steam in the power plant.

With innovations to reduce capital cost, the SFR can competitively serve markets for electricity. Research must decide a choice between a metal alloy or a metal oxide fuel. An economic consideration is the choice of structural components for tubes and pipes. Ferritic steels with 12 percen t Cr could be considered since they possess better strength at high temperatures than austenitic steels.

The SFR's fast spectrum also makes it possible to use available fissile and fertile materials, including depleted uranium, more efficiently than thermal spectrum reactors with once-through fuel cycles. A good management of the actinides is expected as well as a good resource life.

6.8 LEAD COOLED FAST RREACTOR: LFR

The Lead-Cooled Fast Reactor (LFR) system features a fast-spectrum Pb or Pb-Bi eutectic liquid metal-cooled reactor and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides (Fig. 7). The fuel is composed of fertile uranium and transuranics, and is metal or nitride based. The plant can be large and monolithic with a factory manufactured battery of 1,200 MWe or it could be a modular system with 300-400 MWe or it could be a small battery of 50-150 MWe that would be more difficult to refuel.

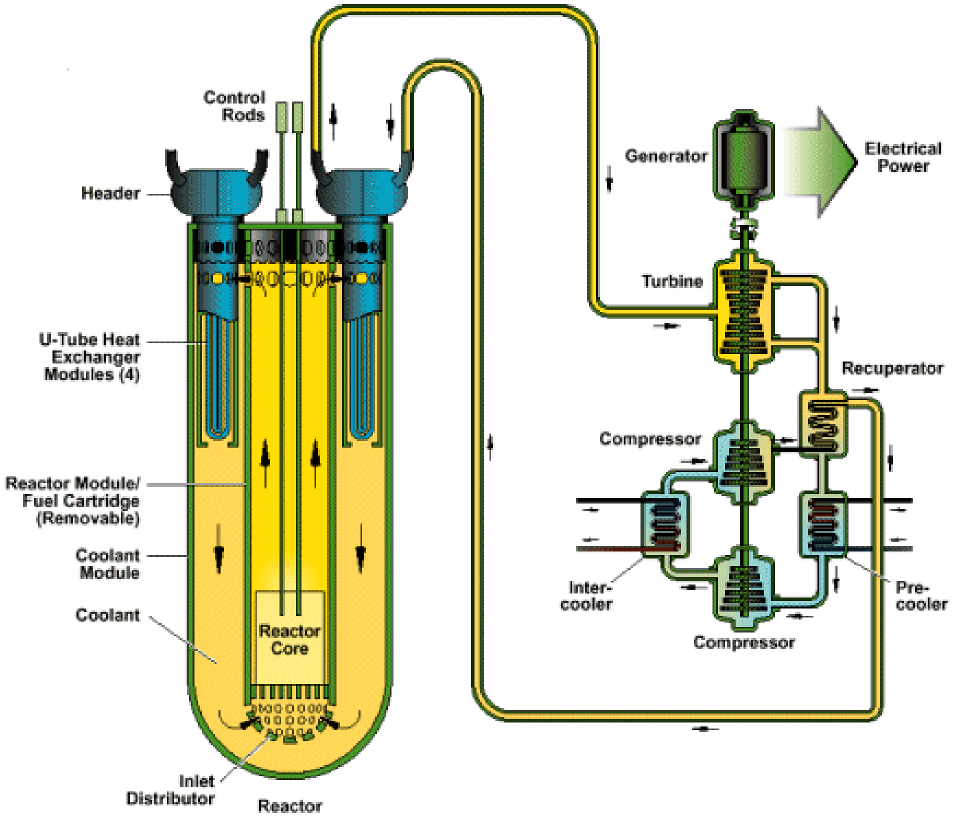

Figure 7. Lead cooled Fast Reactor with Brayton, Joule gas turbine cycle.

It has a fast neutron spectrum with a closed full actinide recycle fuel cycle with central or regional fuel cycle facilities. The fuel is metal or nitride-based, containing fertile uranium and transuranics. The LFR is cooled by natural convection with a reactor outlet coolant temperature of 550 ^{o}C, possibly ranging up to 800 ^{o}C with advanced materials. The higher temperature enables the production of hydrogen by thermochemical processes. The ractor is cooled with natural convection .

The small size LFR is designated as a nuclear battery. It is a small factory-built turnkey plant operating on a closed fuel cycle with very long refueling interval of 15 to 20 years cassette core or replaceable reactor module. Its features are designed to meet market opportunities for electricity production on small grids, and for developing countries that may not wish to deploy an indigenous fuel cycle infrastructure to support their nuclear energy systems. The battery system is designed for distributed generation of electricity and other energy products, including hydrogen and fresh water obtained through sea water desalination.

Issues to be addressed are the development of a viable nitride based fuel, evaluation of lead and bismuth cross sections, and oxygen control to protect against corrosion.

6.9 SUPERCRITICAL WATER COOLED REACTOR: SCWR

The Supercritical-Water-Cooled Reactor (SCWR) system is a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water at 374 ^{o}C, 22.1 MPa, or 705 ^{o}F, 3,208 psia (Fig. 8).

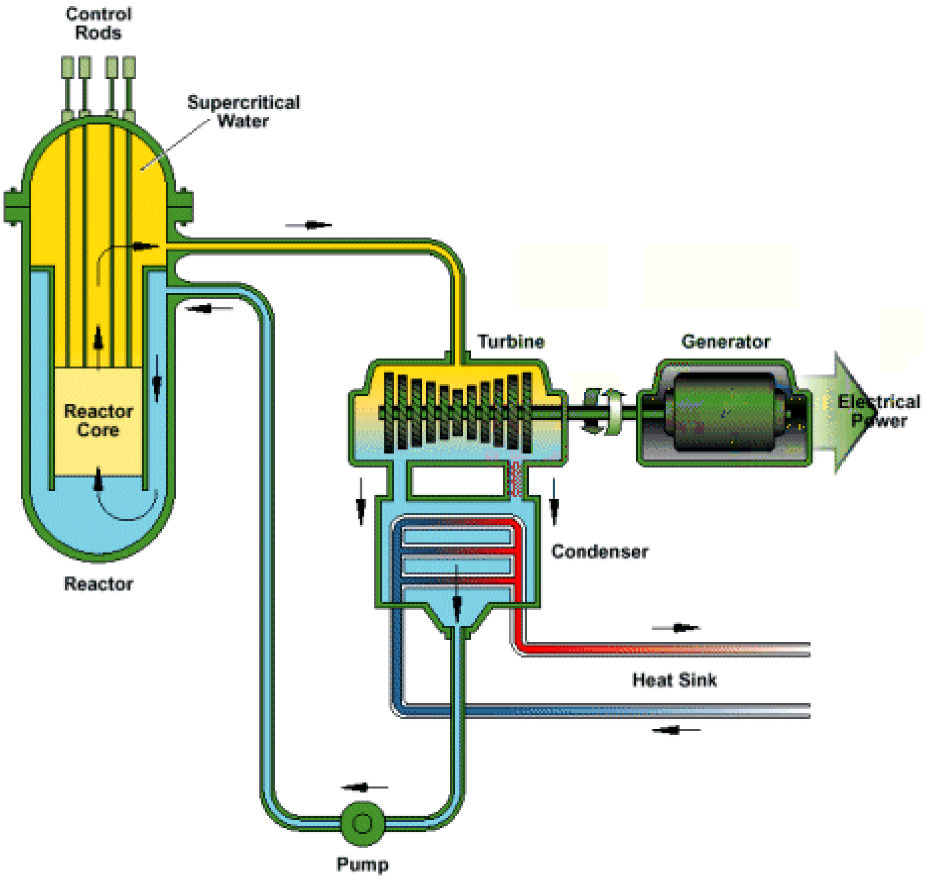

Figure 8. Supercritical Water Cooled Reactor (SWCR) using the Rankine steam cycle.

The supercritical water coolant enables a thermal efficiency about one-third higher than current light-water reactors, as well as simplification in the balance of plant. The balance of plant is considerably simplified because the coolant does not change phase in the reactor and is directly coupled to the energy conversion equipment. However, steam above the critical point is highly corrosive and requires special materials design. The reference system is 1,700 MWe with an operating pressure of 25 MPa, and a reactor outlet temperature of 510 ^oC, possibly increasing up to 550 ^oC. The fuel is UO_2. Passive safety features are incorporated similar to those of simplified boiling water reactors (SBRs).

The SCWR system is primarily designed for efficient electricity production, with an option for actinide management based on two options in the core design: the SCWR may have a thermal or fast-spectrum reactor; the second is a closed cycle with a fast-spectrum reactor and full actinide recycle based on advanced aqueous processing at a central location.

Issues for development include corrosion and stress corrosion cracking (SCC), radiolysis as a function of temperature and fluid density, and water chemistry, dimensional and micro-structural stability and strength, embrittlement and creep resistance. The effects of neutrons, gamma radiation and impurities introduced into the primary system on water radiolysis needs to be studied. Water flow could affect the criticality safety of the system, since cold water would have a higher moderating ability possibly leading to a power surge.

6.10 MOLTEN SALT REACTOR: MSR

The Molten Salt Reactor (MSR) system produces fission power in a circulating molten salt fuel mixture with an epithermal neutron spectrum reactor with graphite core channels, and a full actinide recycle fuel cycle (Fig. 9). The MSR can be designed to be a thermal breeder using the Th^{232} to U^{233} fuel cycle.

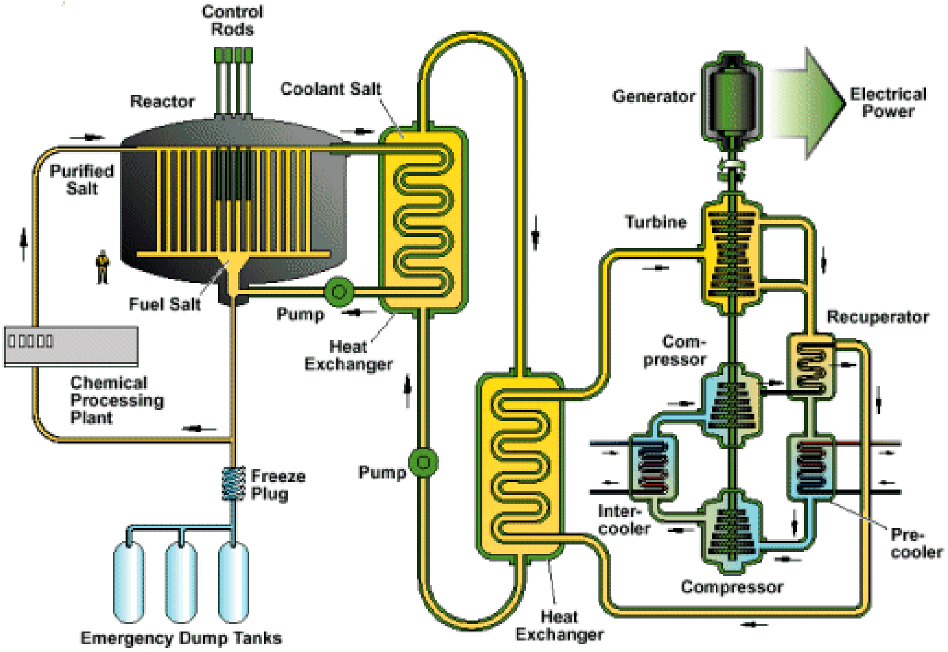

Figure 9. Molten Salt Reactor, MSR using a Brayton, Joule gas turbine cycle.

In the MSR system, the fuel is a circulating liquid mixture of sodium, zirconium, and uranium fluorides. The molten salt fuel flows through graphite core channels, producing an epithermal spectrum. The heat generated in the molten salt is transferred to a secondary coolant system through an intermediate heat exchanger, and then through a tertiary heat exchanger to the power conversion system. The reference plant has a power level of 1,000 MWe. The system has a coolant outlet temperature of 700 ^oC, possibly ranging up to 800 ^oC, affording improved thermal efficiency.

The closed fuel cycle can be tailored to the efficient burn up of plutonium and minor actinides. The MSR's liquid fuel allows addition of actinides such as plutonium and avoids the need for fuel fabrication. Actinides - and most fission products - form fluorinides in the liquid coolant. Molten fluoride salts have excellent heat transfer characteristics and a very low vapor pressure, which reduce stresses on the vessel and piping.

An Engineered Safety Feature, ESF involves a Freeze Plug where the coolant is cooled into a frozen state. Upon an unforeseen increase in temperature, this plug would melt leading to the dumping of the coolant into emergency dump tanks. In the absence of moderation by the graphite, the coolant would be in a subcritical safe state.

Research and development would address the selection of a fuel salt with small neutron cross section of the fuel solvent, radiation stability, and a negative temperature coefficient of reactivity. It needs a low melting point good thermal stability, low vapor pressure and adequate heat transfer and viscosity coolant. The secondary salt must be corrosion resistant to the primary salt. Graphite as a moderator would have to be replaced every four years due to radiation damage to its matrix.

6.10 CONCLUSION

These systems would each need a dedicated effort in research and development for issues specific to each design. Some considerations for the fuel and recycling technology are common and can be shared. The common areas encompass: fuel cycles, fuels and material choices, energy products, risk and safety, economics and proliferation and physical protection concerns.