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Achieving Salt-Cooled Reactor Goals: Economics, Variable Electricity, No Major Fuel Failures

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Abstract –The Fluoride-salt-cooled High-temperature Reactor (FHR) with a Nuclear air-Brayton Combined Cycle (NACC) and Firebrick Resistance-Heated Energy Storage (FIRES) is a new reactor concept. The FHR uses High-Temperature Gas-cooled Reactor (HTGR) coated-particle fuel and liquid-salt coolants originally developed for molten salt reactors (MSRs) where the fuel was dissolved in the coolant. For a modular FHR operating with a base-load 100 MWe output, the station output can vary from -242 MWe to +242 MWe. The FHR can be built in different sizes.

The reactor concept was developed using a top-down approach: markets, requirements, reactor design. The goals are: (1) increase plant revenue by 50 to 100% relative to base-load nuclear plants with capital costs similar to light-water reactors, (2) enable a zero-carbon nuclear renewable electricity grid, and (3) no potential for major fuel failure and thus no potential for major radionuclide offsite releases in a beyond-design-basis accident (BDBA). The basis for the goals and how they may be achieved is described.

I. INTRODUCTION

Since the development and initial deployment of light-water reactors (LWRs) there have major changes: (1) introduction of renewables and restrictions on greenhouse gas emissions that are changing the electricity market with a growing need for low-carbon dispatchable variable electricity production, (2) renewed concerns about land contamination associated with reactor accidents, and (3) major technological advances—particularly associated with gas turbines. These factors suggest the need to rethink reactor goals and technologies. We describe herein an FHR where design goals are driven by expected 2030 electricity market conditions[1]. The design is enabled by advances in combined-cycle gas turbines. This technology option could not have existed 20 years ago because the gas-turbine technology was not sufficiently developed.

II. FHR REACTOR DESCRIPTION

The FHR is a new reactor concept (Fig. 1) that combines (1) a liquid salt coolant, (2) graphite-matrix coated-particle fuel originally developed for High Temperature Gas-cooled Reactors (HTGRs), (3) a NACC power cycle adapted from natural gas combined-cycle plants and (4) FIRES. The FHR concept is a little over a decade old and has been enabled by advances in gas turbine technology. The liquid salt coolant was originally developed for use in molten salt reactors (MSRs) where the fuel is dissolved in the salt. The original MSR program was part of the Aircraft Nuclear Propulsion Program of the 1950s to develop a jet-powered nuclear bomber. Consequently, the fluoride salt coolant ($^7Li_2BeF_4$) was developed to transfer high-temperature heat from a nuclear reactor to a gas turbine. Advances in utility gas turbines over 50 years have now reached the point where it is practical to couple a salt-cooled reactor to a commercial utility combined-cycle gas turbine. It is this combination that enables the FHR to potentially have the transformational capabilities as described herein.

A point design (Mk-1 PB-FHR) for a commercial FHR was developed with a base-load output of 100 MWe.[2] This specific design uses 3-cm pebble fuel. The power output was chosen to match the capabilities of the GE 7FB gas turbine—the largest rail transportable gas turbine made by General Electric. FHRs with higher output could be built by coupling multiple gas turbines to a single reactor or using larger gas turbines. The development of an FHR will require construction of a test reactor—this size commercial machine would be a logical next step after a test reactor.

This point design describes the smallest practical FHR for stationary utility power generation. The market would ultimately determine the preferred reactor size or sizes. There are many FHR design variants under study including alternative geometries for the coated particle fuel, fluoride salt coolants, and plant designs.

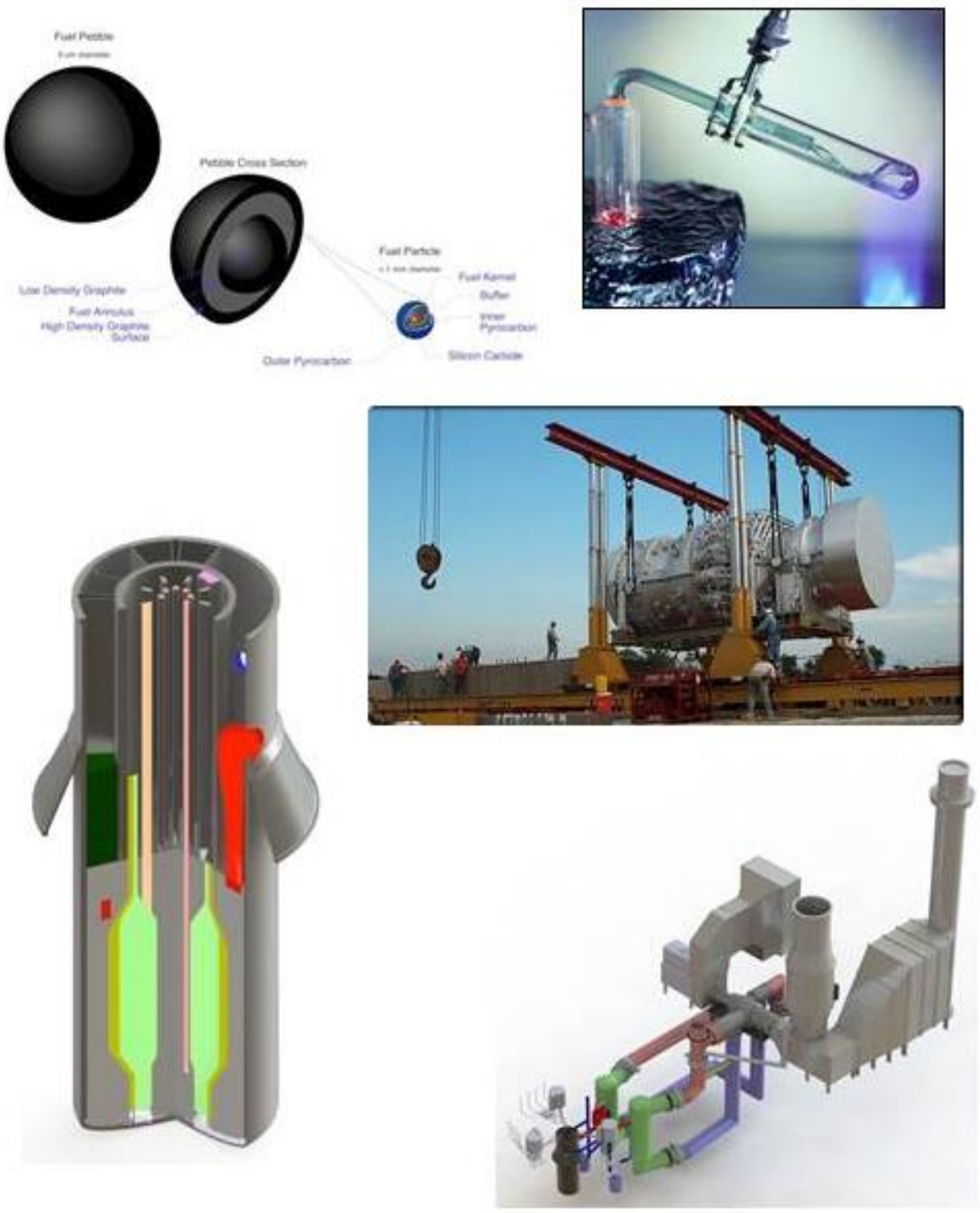

Fig. 1. FHR Features. From top to bottom: fuel, coolant, GE gas turbine, reactor vessel and plant layout (bottom right) where the reactor vessel is black and the salt-to-air heat exchangers are green

The FHR is coupled to a NACC (Fig. 2; Fig. 3) with the option of including FIRES. In the power cycle external air is filtered, compressed, heated by hot salt from the FHR while going through a coiled-tube air heat exchanger (CTAH) to 670°C, sent through a turbine producing electricity, reheated in a second CTAH to 670°C, and sent through a second turbine producing added electricity. Warm low-pressure air flow from the gas turbine system exhaust drives a Heat Recovery Steam Generator (HRSG), which provides steam to either an industrial steam distribution system for process heat sales or a Rankine cycle for additional electricity production. The air from the HRSG is exhausted up the stack to the atmosphere. Added electricity can be produced by injecting fuel (natural gas, hydrogen, etc.) or adding stored heat after nuclear heating after the second CTAH. This boosts temperatures in the compressed gas stream going to the second turbine and to the HRSG.

The use of an open-air Brayton combined cycle enables peak electricity production using auxiliary fuels (natural gas, hydrogen, etc.) that substantially improves the economics.

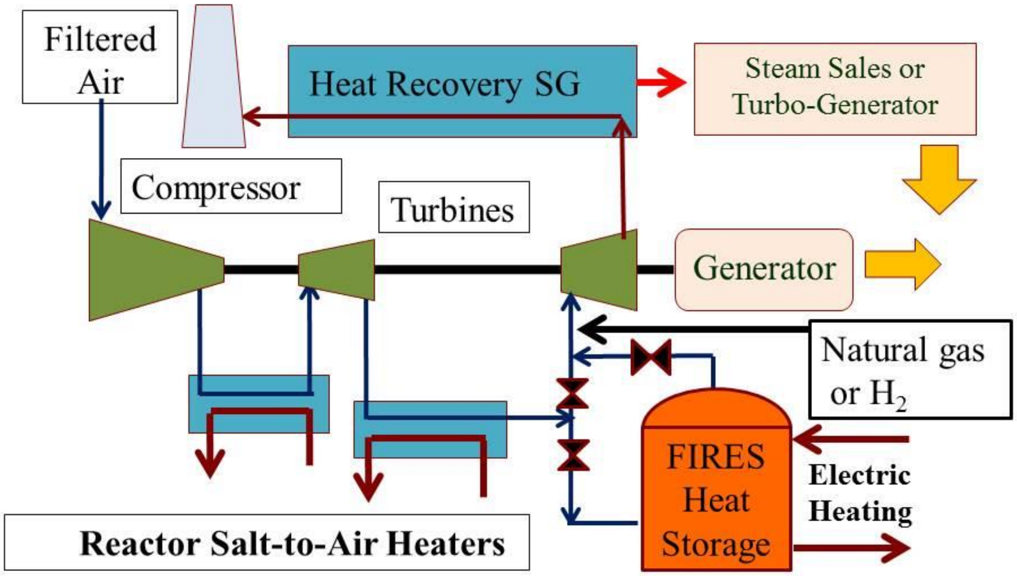

Fig. 2. Nuclear Air-Brayton Combined Cycle (NACC)

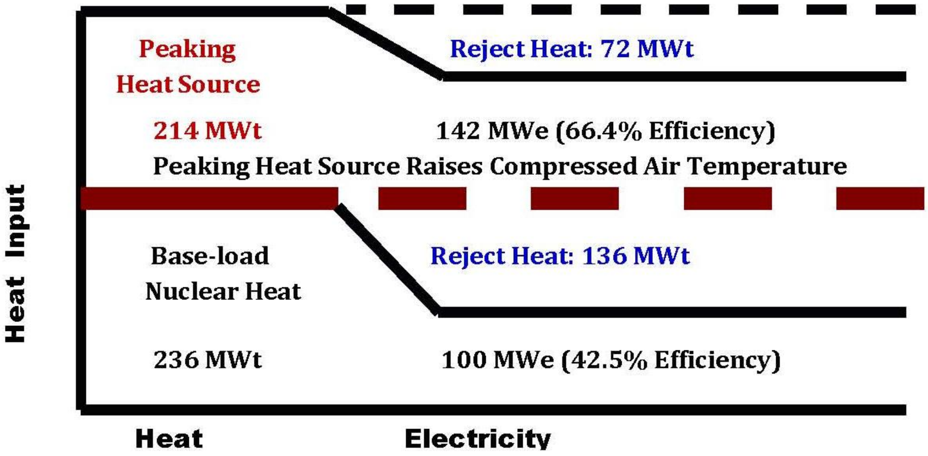

Fig. 3. Heat and Electricity Balance for NACC

The incremental natural gas, hydrogen, or stored heat-to-electricity efficiency is 66.4%--far above the best stand-alone natural gas plants. For comparison, the same GE 7FB combined cycle plant running on natural gas has a rated efficiency of 56.9%. The reason for these high incremental natural gas or stored heat-to-electricity efficiencies is that this high temperature heat is added on top of "low-temperature" 700°C nuclear heat (Fig. 3) resulting in 1065°C hot compressed air in the power cycle. For a modular 100 MWe FHR coupled to a GE 7FB modified gas turbine that added natural gas or stored heat produces an additional 142 MWe of peak electricity.

The heat storage system consists of high-temperature firebrick heated to high temperatures with electricity at times of low or negative electric prices. The hot firebrick is an alternative to heating with natural gas. The firebrick, insulation systems, and most other storage system components are similar to high-temperature industrial recuperators. The round-trip storage efficiency from electricity to heat to electricity is ~66%, based on ~100% efficiency in resistance electric conversion of electricity to heat and 66% efficiency in conversion of heat to electricity. That efficiency will be near 70% by 2030 with improving combined-cycle gas turbines, such as increasing the HRSG peak temperature with a radiant heat boiler section.

Table 1. Mk1 PB-FHR System Design

Parameter	**Value**
Reactor Design	
Thermal power[1]	236 MWt
Core inlet temperature	600°C
Core bulk-average outlet temperature	700°C
Primary coolant mass flow rate (100%power)	976 kg/sec
Primary coolant volumetric flow rate (100% power)	0.54 m^3/sec
Power Conversion	
Gas turbine model number	GE 7FB
Nominal ambient temperature	15°C
Elevation	Sea level
Compression ratio	18.52
Compressor outlet pressure	18.58 bar
Compressor outlet temperature	418.7°C
Compressor outlet mass flow[2]	418.5 kg/sec
Coiled tube air heater outlet temperature	670°C
Base load net electrical power output	100 MWe
Base load thermal efficiency	42.5 %
Co-firing turbine inlet temperature	1065°C
Co-firing net electrical power output	241.8 MWe
Co-firing efficiency (gas-to-peak-power)	66.4 %

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[1] Power output chosen to couple to GE-7FB gas turbine and first reactor size of commercial interest above FHR test reactor. The power plant would contain up to 12 modular reactors built in groups of four.

[2] Total flow is 440.4 kg/s; GE-7FB design uses excess for turbine blade cooling

The coupling of an open-air power cycle requires several special features to assure no escape of radionuclides during normal or accident conditions. Tritium is generated in the salt. To prevent release of significant tritium there are two systems. First, a carbon absorber or gas stripping system is used to efficiently remove tritium from the salt. Second, the heat exchangers have oxide coatings on the outside to reduce the permeability of tritium through hot metal. The system contains valves to isolate the air flow from the salt-air heat exchangers if required.

III GOALS

The commercialization of a new reactor requires transformational goals. Otherwise the incentives to develop such a reactor will not be sufficient to obtain the required resources over a multi-decade time frame. Because the commercialization date is ~2030, the goals must be defined in terms of the expected future conditions, not the current environment. The basis for those goals is described and how those goals are met: improved economics, enabling a zero-carbon electricity grid, and no major fuel failures in severe accidents.

III.A Superior Economics

The traditional nuclear-reactor economic figure of merit has been levelized cost of base-load electricity (LCOE)—an appropriate metric if comparing two base-load electricity generating technologies. However changes in the market (deregulation, renewables, etc.) have resulted in large variations in the price of electricity with time. This creates large economic incentives to produce variable electricity with higher production at times of higher prices. The FHR with NACC and FIRES produces variable power while the reactor operates steadily at full power. Figure 4 shows the plant as a black box and indicates its capabilities, assuming that the base-load electricity production is 100 MWe. The reactor can be built in different sizes. This capability implies that economic analysis must be based on return on investment that accounts for both the production costs and added revenue made possible by variable electricity production.

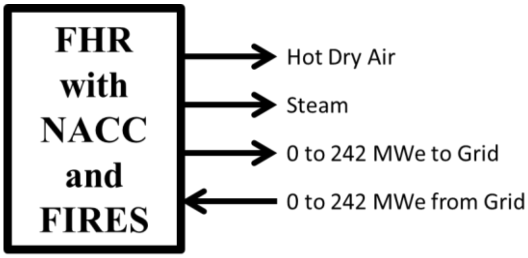

Fig. 4. Inputs and Outputs of a Modular FHR with a Base-load Power Output of 100 MWe

The base-load FHR electricity output is 100 MWe with a thermal-to-electricity efficiency of 42%. An additional 142 MWe of peaking power can be generated by using auxiliary natural gas or stored heat to increase total power to the grid to 242 MWe. If the price of electricity is less than the price of natural gas per unit of heat, up to 242 MWe of electricity can be bought from the grid to go into FIRES thermal storage system. If the price of electricity is low, the 100 MWe base-load output will also go into the FIRES thermal storage system to produce peak power later at times of high prices.

The decision to include FIRES in an FHR facility depends upon whether the specific electricity market has a significant number of hours with electricity prices below natural gas prices (or other suitable future peaking fuels, possibly including hydrogen) with the incentive to use stored heat to replace the burning of more expensive fuels for peak power. The design of FIRES depends upon the local market that determines how much heat should be stored. About a half a megawatt-hour can be stored per cubic meter of firebrick. FIRES is heated with electricity for several reasons.

- *Technical limits*. Production of peak power implies peak gas temperatures to 1065°C—far above reactor peak temperatures. The reactor can't produce heat for peak electricity production
- *FIRES capital costs*. There are large economic incentives to maximize FIRES firebrick temperatures to minimize FIRES volume and thus capital costs. Firebrick can be heated electrically to ~1800°C. Steam from the HRSG can then be used to cool the hot gas down to the turbine temperature limits.
- *Markets.* The addition of wind or solar in significant quantities causes electricity price collapse[3-4] at times of peak wind or solar conditions. By the time solar provides 10% of all electricity over a year, the price of electricity at the mid-day at times of maximum solar production will exceed demand and drive the price to near zero. Near-zero prices will occur for 2-3 hours per day with a large peak in production Resistance heating is cheap; thus, FIRES can be designed to maximize electricity purchases at the times of lowest prices. Unlike batteries or pumped storage, energy storage into the system can be many times electricity out of the system. The same type of revenue collapse occurs with wind at about 20% of total electricity production by wind.

The price of electricity varies with the time of day. We examined deployment of the FHR in the California and Texas electricity markets using the NACC power cycle with natural gas peaking but without FIRES. Based on using 2012 hourly wholesale rates in those states and the corresponding average natural gas price ($3.52/MBTU), the net revenue for base-load and peak electricity was ~50% higher than a base-load-only nuclear plant of equivalent performance. Net revenue is total revenue minus the cost of natural gas used to produce peak power. The incremental natural gas to electricity efficiency is 66% versus 60% for a stand-alone natural gas plant. Because an FHR with NACC is more efficient in converting natural gas to peak power, it is dispatched before any natural gas plant. This also implies that as stand-alone natural gas plants come on-line, they set the market prices for electricity. Because the FHR with NACC is more efficient, this increases FHR revenue after accounting for the cost of the natural gas.

Increasing natural gas prices increase electricity prices with two effects: (1) increased revenue for all nuclear plants and (2) relative increases in revenue for the FHR with NACC versus base-load nuclear plants. When the FHR is producing peak power and electricity prices are set by stand-alone natural gas plants, the net revenue from FHR peak electricity production increases with natural gas prices. This is because of the higher efficiency in turning natural gas into electricity than stand-alone natural gas plants. If U.S. natural gas prices were to triple from their historical lows, the FHR revenue from base and peak electricity production would be double a base-load nuclear plant. Natural gas prices in Europe and Asia are about three times those in the United States and thus one would expect much larger advantages for the FHR with NACC versus a base-load nuclear plant in those markets.

If industrial markets are available for steam sales from the HRSG, the net plant revenue is about double that of a base-load nuclear plant. This assumes sales of steam at 90% of the cost of natural gas heat to industrial customers at times of low electricity prices with varying electricity and steam sales to maximize revenue. It also assumes that the industrial customer has his own boilers that burn natural gas and turns those boilers down and buys steam when available to reduce his total cost of steam. The revenue gains are larger if there are increases in natural gas prices or any limits on carbon dioxide emissions.

Limited analysis indicates FHR capital costs are similar to LWRs per kWe—implying significantly better economics because of the higher revenue from peak power sales. The economics are helped by intrinsic characteristics of the reactor: low-pressure operation, high-temperature operation with high thermal-to-electricity efficiency, high reactor-vessel power density (slightly less than a boiling water reactor), coupling to a gas turbine power conversion system, and modularization.

III.B. Providing the Enabling Technology for a Zero-Carbon Nuclear Electricity Grid

The FHR with NACC and FIRES potentially enables a zero-carbon nuclear-renewable grid. Fig. 5 shows the power demand in New England (part of the U.S.) by hour over a year and the capability of FHR plants to meet variable electricity demand with the reactors operating at continuous full power.

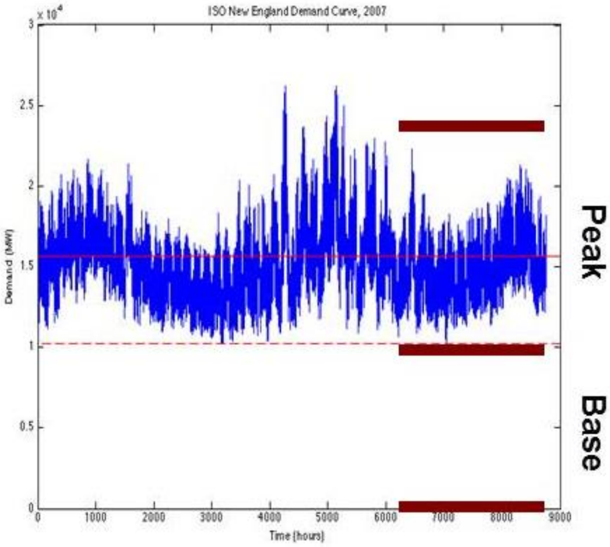

Fig. 5. New England Power Demand (Vertical axis in 10s of GWe) vs. Time over a Year (Hours) Showing FHR Capabilities to Meet that Demand

In a zero-carbon world, one would not use natural gas to produce peak electricity. Peaking power would use stored heat or hydrogen as the fuel. The characteristics of this system have major implications in terms of a zero-carbon electricity grid where natural gas is not available.

- *Enabling zero-carbon nuclear renewable grid*. Large scale use of wind or solar imply low prices and excess electricity capacity[3-4] at times of high wind or solar output. The FHR with NACC and FIRES can store excess electricity as heat when available from renewables that do not have their own built-in storage capacity (like nearly all present renewable facilities other than hydro). Existing storage technologies (hydro pumped storage, batteries, etc.) have a major weakness when coupled to renewables. If there is a multi-day period of no wind or solar, these storage systems are depleted. As a consequence, renewables require backup generating capacity such as gas turbines for reliable electricity. The FHR with NACC and FIRES has that capacity built-in to a single facility that also earns revenue from base-load electricity production and possible heat sales, and has the highest efficiency in converting gaseous or liquid fuels to electricity—better than stand-alone natural-gas turbines. This results in major capital cost and operating cost savings relative to other electricity storage systems.

- *Minimizing electricity storage costs*. The two methods to cheaply store energy are heat and hydrogen because the energy storage media are cheap, firebrick for heat storage and underground caverns and permeable geologies for hydrogen storage similar to those used for natural gas. There is a difference. In the FHR the round trip electricity-to-heat-to-electricity efficiency is ~66%. The efficiency of electricity-to-hydrogen-to-electricity efficiency in all technologies identified to date is below 50%. While hydrogen storage is cheap, hydrogen is expensive and thus hydrogen is a more expensive method for electricity storage because of the low round-trip efficiency of electricity-to-hydrogen-to-electricity. Hydrogen can be stored seasonally underground like natural gas at low costs whereas FIRES would be expensive for long-term heat storage because the firebrick is inside a pre-stressed concrete pressure vessel of much more limited volume. This implies that the optimum FHR system for a zero-carbon grid would store energy in FIRES for daily swings in electricity demand but use hydrogen for longer-term seasonal variations in electricity demand. In practice, maintenance and refueling outages for FHRs would be at times of year with low electricity demand that would reduce the need for seasonal storage using more expensive hydrogen.
- *Alternative to Hydro Pumped Storage and Batteries*. The storage system is built on firebrick with the potential that the total system cost will be less than other energy storage systems. The integration of firebrick heat storage with gas turbines is being developed by General Electric and KWU for another storage technology—adiabatic compressed air storage (Adele project in Germany). Much of this technology development program is directly applicable for NACC with FIRES.

These capabilities may result in the FHR with NACC and FIRES becoming the enabling technology for a zero-carbon electricity grid and for the larger scale use of renewables by addressing the central challenges of renewables—their non-dispatchability and lack of cost-effective storage technologies.

III.C. Assure No Major Fuel Failures in Beyond Design Basis Accidents (BDBAs)

The FHR has the traditional safety systems to prevent accidents and thus protect the public and plant investment: (1) active decay-heat cooling systems and (2) Direct Reactor Auxiliary Cooling Systems (DRACS)—a passive decay heat cooling system developed for sodium fast reactors. Several intrinsic characteristics of the FHR improve safety and economics: (1) low pressure coolant, (2) excellent coolant heat transfer properties, (3) a high-temperature fuel, and (4) high heat capacity in the reactor core.

In addition, the FHR combination of fuel and coolant characteristics has the potential to prevent major fuel failures with large FHRs (thermal outputs significantly greater than 1000 MWt) in BDBAs. The BDBA events could include reactor vessel, containment, and other such failures. The larger the thermal output of the reactor, the more difficult it is to prevent fuel failure in a severe accident. As a consequence, LWRs use reactor containments to contain radioactivity if there is an accident with large-scale fuel failures. The largest reactor today that can be built without large-scale fuel failure in a severe accident is a HTGR with an output of ~600 MWt. Because the FHR uses the same fuel as the HTGR, an FHR of similar output could be built with this characteristic. A series of studies[5], including modeling of severe accidents, was undertaken to develop a pre-conceptual design of an FHR BDBA system for larger FHRs with these capabilities.

When a reactor shuts down, it continues to generate decay heat at a decreasing rate. If this decay heat is not removed, fuel temperatures ultimately increase until the fuel fails and radionuclides are released. It follows that fuel failure can be prevented by finding a way to remove decay heat to keep fuel temperatures below failure temperatures in an accident. The potential to avoid major fuel failures under extreme accident conditions in large FHRs is a consequence of the unique combination of the high-temperature properties of the fuel and coolant. The FHR uses HTGR graphite-matrix coated-particle fuel with failure temperatures of >1650°C. The coolants are clean fluoride salts that have melting points above 350°C and boiling points above 1400°C. These high temperature limits relative to other nuclear fuels and coolants may enable systems to be designed to prevent major fuel failures in large FHRs in severe accidents. There are five features of this system.

- *Core heat capacity*. The reactor core has a large heat capacity and there is a 700°C margin between the nominal peak coolant operating temperature and its boiling point. The combination provides the ability to absorb large quantities of decay heat and thus provides time for the decay heat rate to decrease and reducing the BDBA decay heat removal rate system requirements.
- *Temperature driving force for decay heat removal*. The rate of decay heat transfer from the fuel to the environment (atmosphere) in an accident is

proportional to the temperature difference. There is a 1400°C temperature drop between the coolant boiling point and the environment and 1700°C difference between fuel failure and the environment. The temperature driving forces for decay heat removal before fuel failure or coolant boiling are larger in an FHR than in any other reactor.

- *Removal of heat transfer barriers*. Normally the FHR is highly insulated to prevent heat loses. If decay heat in a BDBA is to be removed, these barriers to heat transfer must be eliminated. There is a 700°C temperature difference between normal FHR operating temperatures and the boiling point of the salt that would remove the coolant salt from the reactor core and allow higher reactor accident temperatures. In an accident the salt coolant temperature will rise. The temperature rise in an accident before fuel failure and coolant boiling can be used to degrade the insulation system—reducing the resistance for heat transfer from the fuel to the environment that, in turn, rapidly increase heat loses from the fuel to the environment. Unlike other reactor coolants, there is sufficient temperature margin that this can be done before coolant boiling.
- *Silo cooling system*. The silo has a passive silo cooling system that removes decay heat during normal operations and more efficiently in a BDBA once there is insulation failure. It is similar to some HTGR silo cooling systems and uses natural circulation of water through pipes in the silo wall to remove decay heat. It is the first accident stop point in the BDBA system.
- *Ultimate silo cooling system*. If the normal passive silo system fails, there is a backup cooling system. The silo contains a low-cost BDBA salt. In an accident the silo temperatures increase, causing this salt to melt and partly flood the silo. The melting of the BDBA salt absorbs decay heat reducing vessel and fuel temperatures. It thermally couples the reactor vessel to the silo wall to reduce the temperature drop between the fuel and silo wall. This provides over 1000°C in temperature drop to drive decay heat from the silo to the environment in a BDBA by conduction through the silo structure with no major insulation barriers. The activation of this system may occur before or after vessel failure. Cements designed for high temperatures (such as alumina cements) are required so the temperature transient does not result in the cement releasing large quantities of gases

The combination of mechanisms enables decay heat to move sufficiently fast from fuel to the environment in an accident to prevent exceeding temperatures at which major fuel failures occur. *The BDBA safety system is not dependent upon mechanical system design features or maintaining geometry except the physical properties of the fuel, coolant, and materials near the reactor core*. Significant research will be required to develop and confirm this unique capability to assure that severe accidents will not result in large-scale fuel failures.

Separate from the above mechanisms, if fuel damage were to occur, in fluoride salts most significant radionuclides are soluble as fluorides. This includes cesium and strontium. It has been shown the iodine largely remains in the salt as I^- ion or as an iodide compound such as CsI. Noble gases such as Xe and Kr are not soluble in the salt. This is not unexpected. The fluoride salts come from the MSR program and were chosen partly because of their capability to dissolve fission products and actinides.

Table 2. Mapping of Technologies and Goals

Project Goals → Required technologies ↓	Improved Economic Performance	Zero-Carbon Electricity Grid	Accident Resistance	Fuel Cycle Performance
High-temperature fuel	X	X	X	X
Liquid salt coolant	X	X	X	
NACC	X	X		
FIRES	X	X		

IV. Goals and Technology

Fuel, coolant, and power cycle choices enable meeting the goals as summarized in Table 2. Meeting the economic and zero-carbon electricity grid goals require NACC and FIRES. NACC defines the top-level reactor requirements and thus drives the choice of fuel and coolant. In modern gas turbines the exit temperature from the air compressor is between 400 and 500°C. That implies any reactor coupled to a utility gas turbine must deliver heat above those temperatures. Neither LWRs nor SFRs have that capability. The capability to be the enabling technology for a zero-carbon grid requires the addition of FIRES heat storage to NACC—a storage technology partly being developed elsewhere for gas turbines. The accident resistance capability of the FHR is a consequence of a high-temperature fuel and a high-temperature coolant. The fuel cycle characteristics are consequences of fuel choices.

V. CONCLUSIONS

A new type of reactor will not be developed unless there are compelling needs. Needs must drive reactor requirements. The LWR was developed to match the needs of the 1960s and the need for base-load electricity but there are economic challenges in markets with significant renewables. Another paper[6] at this conference addresses adding heat storage to existing and future LWRs to enable storing energy at times of low prices to produce peak electricity at times of high prices to improve their economics. However, there is the need for power systems with additional capabilities.

- *Markets*. Today the utility concern is how to provide economic dispatchable electricity to the grid because of (1) the increase need for economic dispatchable electricity output to an electrical grid that contains significant quantities of non-dispatchable renewables with times of electricity price collapse and (2) potential limitations on burning fossil fuels—the primary method we use to produce variable dispatchable electricity. Studies by the State of California[7] and Google[8] show that strategies based only on renewables lock in natural gas or other fossil fuels to provide variable dispatchable electricity. A low-carbon economic dispatchable electricity generating source is the missing link for a zero-carbon electricity grid—what the FHR with NACC and FIRES is designed to provide.
- *Technology*. When the LWR was developed, steam turbines were the primary utility power cycle and helped the utility transition to nuclear power. Today the combined-cycle gas turbine is replacing pure steam cycles in utility applications because of higher efficiency, lower water cooling requirements (FHR water cooling requirements are 40% of an LWR), and other unique capabilities. That experience lays the foundation for utilities to consider a nuclear power plant coupled to a gas turbine. Most of the world's research on utility-scale power conversion systems is associated with gas turbines; thus there is the expectation of continued improvements in gas turbine technology relative to other power cycle technologies. Gas turbine advances has made possible an FHR with NACC.
- *Safety*. The nuclear accident in Japan and previous accidents indicate that nuclear technology is remarkably safe with respect to protecting human health. However, the disruptive consequences of land contamination have large social, economic, and political consequences. This provides incentives to develop safety systems more dependent upon materials than human decision making to provide higher assurances of protecting human health and avoid land contamination in severe accidents. Combining high-temperature fuels with high-temperature coolants makes that possible.

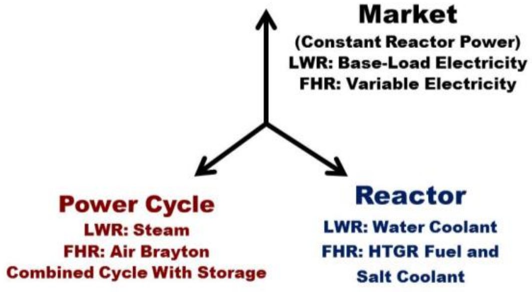

Fig. 6. Comparison of LWR and FHR

The technical, financial and institutional challenges to develop an FHR with NACC and FIRES should not be underestimated[9]. The required component technologies exist but it requires a large development program that will have significant challenges to develop and integrate those technologies into a practical power plant. The financial challenge is to provide the required funding over the multi-decade development time before a commercial product is developed, built, installed and begins to operate to generate revenue. The earliest commercialization date is ~2030. Work is underway in the United States and other countries. The Chinese Academy of Sciences plans to build the first FHR test reactor by 2020.

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The results herein were from a three year project lead by the Massachusetts Institute of Technology (MIT) with the University of California at Berkeley (UCB) and the University of Wisconsin (UW). MIT was responsible for

defining goals, market analysis, BDBA assessments, and test reactor design. UCB was responsible for the reactor point design. The parallel experimental program included thermal hydraulics test loops using simulants at UCB, materials testing in 700°C salt at UW, and materials irradiations in 700°C salt at MIT. The major FHR project reports (References 1, 2, and 9) and other FHR reports can be downloaded at two web sites: http://web.mit.edu/nse/people/research/forsberg.html and http://fhr.nuc.berkeley.edu/

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