Baseload nuclear with variable electricity to the grid

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The fluoride-salt–cooled high-temperature reactor with a nuclear air-Brayton combined cycle is designed to meet the challenges of a changing electricity market.

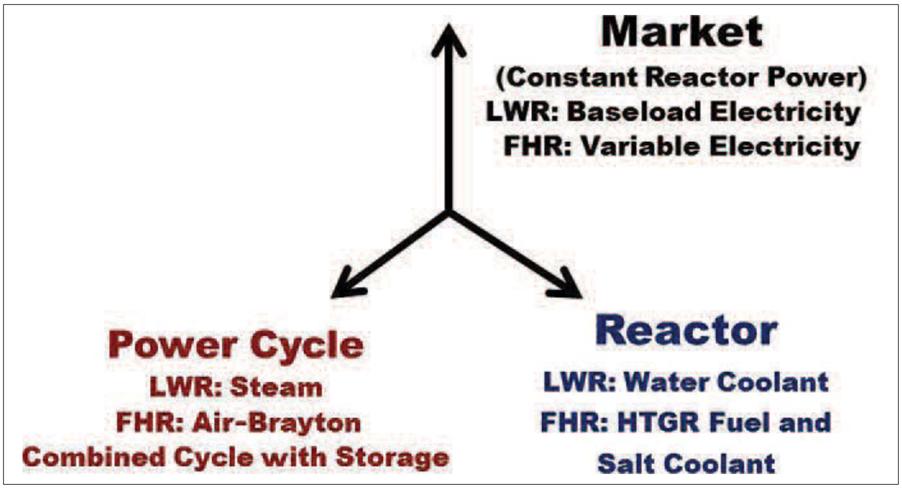

Fig. 1. Comparison of the light-water reactor and the fluoride-salt–cooled high-temperature reactor (FHR)

In this century, mankind will transition to a low-carbon energy future—either in the first half of the century because of concerns about global climate and ocean pH (acidity) changes, or in the second half of the century because of the depletion of fossil resources. Since the caveman first discovered fire, our energy policy has been to have a storable supply of a carbon fuel (wood, whale oil, coal, natural gas) that we light on fire to provide variable light and heat. The technology may have changed from the wood cooking fire to the natural gas–fired turbine, but the essentials have not: a storable carbon-based fuel coupled to a low-cost method to convert fuel to heat and light as needed.

In a low-carbon world, the energy sources are nuclear and renewables, primarily wind and solar. The defining characteristics of these technologies are (1) high capital costs and low operating costs, requiring full-capacity operation for economic energy production, and (2) output that does not match variable energy needs. This challenge suggests a need to develop new nuclear technologies that can meet the variable energy needs of a low-carbon world while improving economics.

To address the above challenge, a research group representing the Massachusetts Institute of Technology, the University of California at Berkeley, and the University of Wisconsin has been developing a fluoride-salt–cooled high-temperature reactor (FHR) with a nuclear air-Brayton combined cycle (NACC) and firebrick resistance-heated energy storage (FIRES). The goals of the research are to improve nuclear power plant economics by increasing plant revenue by at least 50 percent relative to a baseload nuclear power plant and to develop the enabling technology for a zero-carbon nuclear-renewables electricity grid by providing dispatchable power. The FHR generates baseload electricity, with peak electricity produced by a topping cycle that uses auxiliary natural gas or stored heat—or, farther into the future, hydrogen. The concept of the FHR is about a decade old [1]. Since its inception, there has been growing interest at universities and national laboratories [2], and a decision was made by the Chinese Academy of Science to build a 10-MWt test reactor by 2020.

FHR with NACC and FIRES

The FHR is a new class of reactors (Fig. 1). The fuel is the graphite-matrix coated-particle fuel used by high-temperature gas-cooled reactors (HTGR), resulting in similar reactor core and fuel cycle designs, except that the power density is higher because liquids are better coolants than gases. The coolant is a clean fluoride salt mixture. The salts were originally developed for the molten salt reactor, where the fuel was dissolved in the coolant. Current coolant-boundary materials limitations imply maximum coolant temperatures of about 700 °C. New materials are being developed that may allow exit coolant temperatures of 800 °C or more. The proposed power cycle is similar to that used in natural gas–fired plants.

The fluoride salt coolants were originally developed in the late 1950s for the U.S. Aircraft Nuclear Propulsion Program, the goal of which was to develop a nuclear-powered jet bomber. These fluoride salts have low nuclear cross sections with melting points of 350–500 °C and boiling points in excess of 1200 °C, properties for the efficient transfer of heat from a reactor to a jet engine. Since then, there have been two developments: high-temperature graphite-matrix coated-particle fuels for HTGRs that are compatible with liquid-salt coolants, and a half-century of improvements in utility gas turbines that now make it feasible to couple a nuclear reactor to an NACC. The

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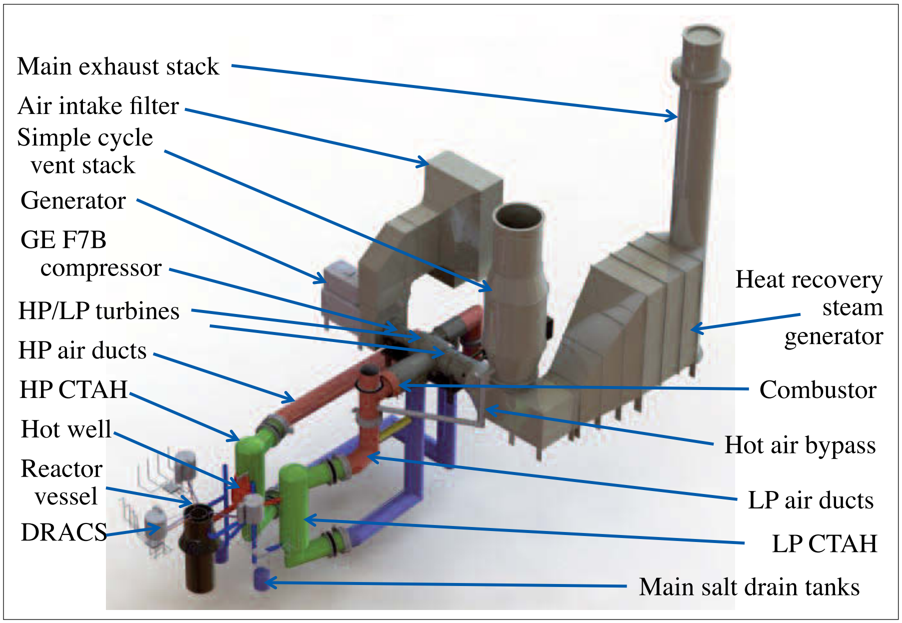

Fig. 2. The Mark-1 pebble-bed FHR (Mk1 PB-FHR) plant layout, showing coupling to NACC power conversion

gas turbine technology for a commercially viable FHR did not exist 15 years ago.

We have developed a path forward, including a commercialization strategy [3], an FHR preconceptual reactor plant design known as the Mark-1 pebble-bed FHR (Mk1 PB-FHR) [4], and a test reactor strategy [5]. Figure 2 shows the Mk1 PB-FHR and its NACC power conversion system, while Table 1 lists some of the design parameters. The pebble-bed fuel is similar to that originally developed in Germany and now used in China for its HTGRs, but the pebble size has been reduced to 3-cm-diameter spheres to enable a higher power density. Like the HTGR pebble bed reactors, the pebbles flow through the reactor core to allow on-line refueling. The coolant is FLiBe ($^{7}\text{Li}_2\text{BeF}_4$), the same coolant proposed for many molten salt reactors, except that in an FHR, clean salt is used to minimize corrosion and radiation levels in coolant piping. Fixed-fuel FHR designs are also options, and several different designs have been developed in multiple reactor sizes[2].

Table 1. Mk1 PB-FHR System Design

Parameter	Value
Power System	GE 7FB
Peak FHR Coolant Temperature (°C)	700
NACC Compressor Exit Temperature (°C)	418.7
Air Temperature After Nuclear Heat (°C)	670
Baseload Heat (MWt)	235.3
Baseload Electricity (MWe)	100.0
Baseload Efficiency (%)	42.5
Natural Gas Heat Input (MWt)	213.5
Natural Gas Electricity (MWe)	141.8
Natural Gas Efficiency (%)	66.4
Peak Electricity (MWe)	241.8

The Mk1 PB-FHR is coupled to an air-Brayton combined cycle, similar to natural gas combined-cycle plants. The power cycle is shown in Fig. 3. This specific NACC is based on General Electric's 7FB natural gas–fired combined-cycle plant. The GE 7FB compressor is unmodified, but the turbine is redesigned to introduce external air heating and reheating. Air is filtered, compressed, and heated by high-temperature salt using a coiled-tube air heater (CTAH) as shown in Fig. 4. In a CTAH, the one unique piece of equipment that is not found in other power reactors, the compressed air flows radially outward through tube sub-bundles, while the salt coolant flow spirals inward in counterflow. The high-pressure compressed-air exit temperature after nuclear heating is 670 °C. The hot compressed air is then expanded through a turbine to lower pressure, is reheated, and is sent through a second turbine. The warm, near atmospheric pressure exhaust gas from the air-Brayton cycle is sent to a heat recovery steam generator (HRSG), where the warm air is used to generate steam that can provide additional power via a steam Rankine bottoming cycle or be sold to off-site users. The baseload efficiency is 42.5 percent. The cooling water requirements are 40 percent per unit of electricity as compared to a light-water reactor because of the higher baseload efficiency and because all combined-cycle plants reject much of their heat as warm air from the HRSG.

The NACC enables the production of additional electricity by injecting supplemental natural gas, stored heat, biofuels, or hydrogen before the last set of turbine stages to raise the compressed air temperature. The NACC operates at significantly lower temperatures than traditional natural gas combined-cycle plants, so compressed nuclear-preheated air temperatures can be raised without exceeding existing gas turbine temperature limits. Because the natural gas acts as a peaking fuel above the "low-temperature" nuclear heat, the natural-gas-to-electricity efficiency is 66.4 percent, which is higher than the best stand-alone natural gas combined-cycle plants with 60 percent efficiency. The plant can operate in multiple modes, as follows, while the reactor remains at full power:

- *Baseload electricity (nuclear)*—The reactor runs at full power. No supplemental fuel is injected, and the Brayton and Rankine (HRSG) cycles produce electricity for sale.
- *Peak electricity (nuclear plus natural gas)*—The reactor runs at full power. Supplemental natural gas is injected after nuclear heating of air to maximize electricity production, and the natural gas provides an extra 142 MWe for every 100 MWe of baseload electricity.
- *Electricity and steam (nuclear)*—The Brayton cycle produces electricity for sale, and the HRSG steam is directed to the industrial steam distribution system for process heat sales.

There are differences between steam sales to industrial customers from an NACC and from other reactors. Because heat from the reactor is transferred to the HRSG via an air stream, there is no concern about contamination of the steam, and so, a steam isolation heat exchanger is not required, as it is for LWRs selling process steam. That implies no expensive steam isolation heat exchanger for off-site sales of steam or the associated temperature losses. Almost no cost is incurred for the capability to sell steam to industrial customers. There are two types of industrial steam sales:

- *Variable sales*—Many large industrial complexes that have their own steam boilers would turn them down if they could buy steam that costs less than the fuel for producing their own steam. This creates the option of selling steam to industrial customers at times of low electricity prices to boost reactor revenue while selling steam at prices below the cost of steam generated by industrial customers using natural gas.
- *Baseload sales*—There is the classic cogeneration strategy of selling electricity and steam. The historical limitation for using nuclear reactors to provide steam to industrial users was the need for backup sources of steam if the reactor was shut down for any reason. With an NACC, there is the option to add natural gas burners with fresh air to ensure that hot air is available for continued operation of the HRSG if the reactor and gas turbine shut down. This is a feature found in some existing natural gas– and

waste gas–fired combined-cycle plants used to provide electricity and steam in refineries and chemical plants. If the turbine has problems, steam generation continues.

The FHR with NACC can be used to provide spinning reserve and other grid services. Stand-alone natural gas–fired combined-cycle plants operating at part load have the ability to rapidly increase their power level if required to meet the demands of the electrical grid. The natural gas to electricity efficiency, however, is much lower. The alternative is a cold start, but it takes considerable time to start up a gas turbine and connect it to the grid. With an operating baseload FHR plant, these problems are avoided because the peaking power is on top of an operating baseload nuclear plant. The power maneuvering capabilities are also enhanced because unlike a natural gas–fired turbine, there is no need to control the air-to-fuel ratio to ensure combustion, as the temperature of the hot gas is higher than auto-ignition temperatures.

The properties of fluoride salt coolants are what enable coupling to an NACC. In modern gas turbines, the front-end compressor heats the air to between 350 and 500 °C. The temperatures of LWRs and sodium-cooled reactors are too low to couple to an NACC. Current HTGR designs can't couple to an NACC because the return helium gas temperature is typically 350 °C to enable cooling of the steel reactor pressure vessel, and this is below the outlet temperature of air from the compressor. In contrast, the temperature range of the FHR couples to a gas turbine, a consequence of these coolants' being explicitly designed to allow for a nuclear reactor to be coupled to a jet engine. If the economics favor larger FHRs, multiple turbines could be coupled to a single reactor, similar to some LWRs that have multiple steam turbines.

Economics

The economics of a reactor depends on costs versus revenue. Traditional nuclear power plants are designed for baseload operation, where there is no capability to increase revenue by increasing electricity production at times of high prices. The FHR with NACC enables baseload operation of the reactor with variable electricity to the grid, a capability that increases revenue relative to a traditional nuclear power plant.

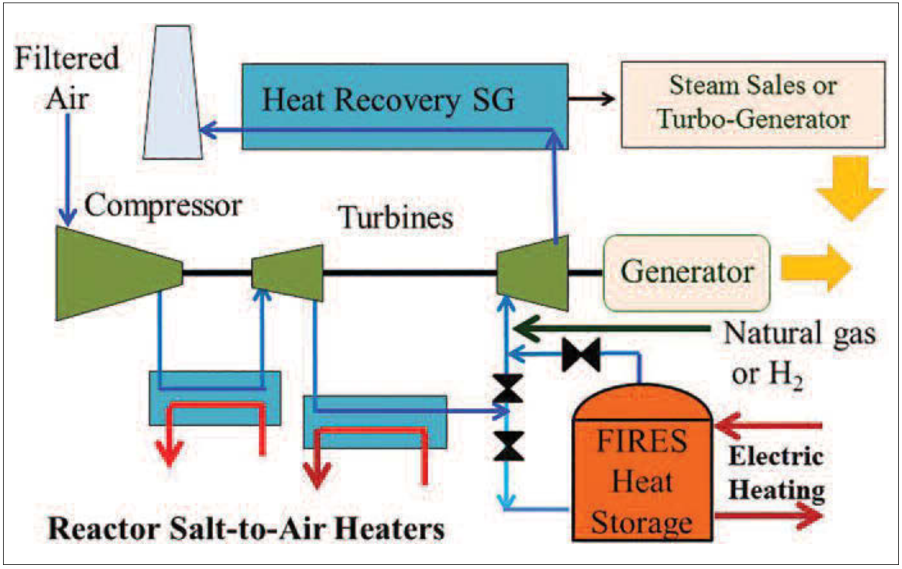

Fig. 3. A simplified schematic of a nuclear air-Brayton combined cycle (NACC) and firebrick resistance-heated energy storage (FIRES)

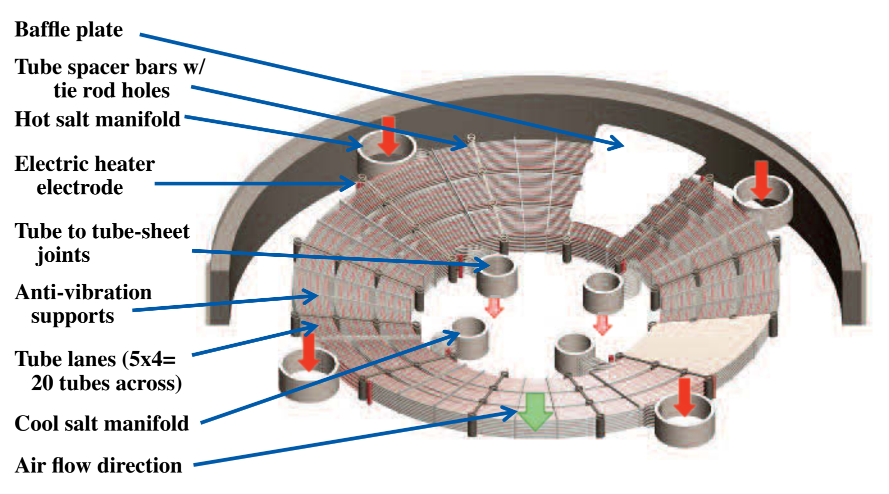

Fig. 4. An Mk1 coiled-tube air heater (CTAH) sub-bundle. Each CTAH uses 36 sub-bundles.

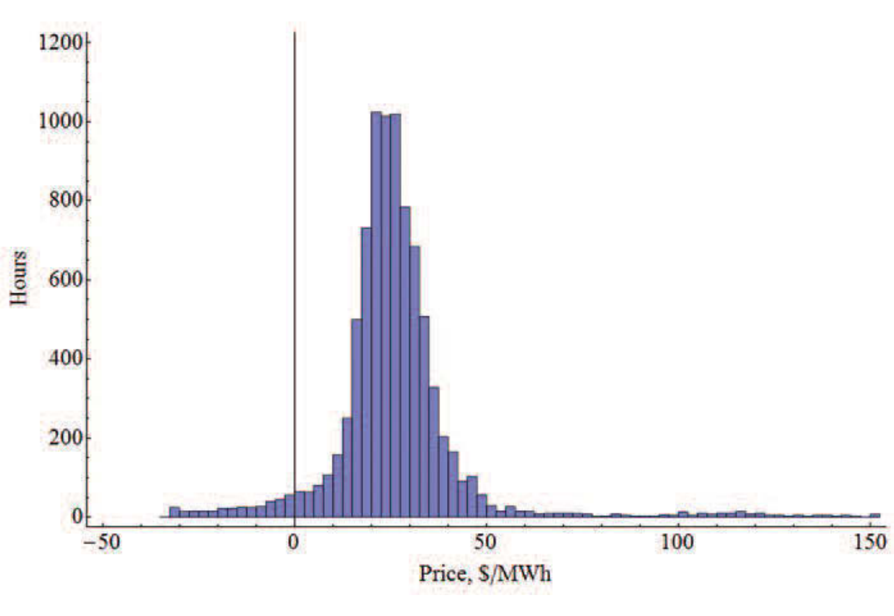

Fig. 5. California hourly wholesale electricity prices in 2012

In deregulated markets, the price of electricity varies with time. Figure 5 shows the 2012 California electricity prices in terms of the price of electricity versus the number of hours per year that electricity could have been bought at that price. The price of electricity ranges from negative to high. Negative prices occur at times of low demand. Nuclear and coal plants cannot shut down and start up quickly. They remain on line at times of negative prices and pay the grid to take their electricity to avoid shutting down

TABLE 2. 2012 NET REVENUE FOR MK1 NACC PLANT IN TEXAS OR CALIFORNIA: M$/Y (%)

Allowed Operating Modes	Texas	California
Baseload Electricity (Nuclear)	21.9 (100)	26.6 (100)
Baseload and Peak Electricity (Nuclear plus Natural Gas)	31.2 (142)	44.4 (167)

and being unable to produce electricity at times of high demand and high prices, which may occur a few hours later. FHR revenue can be maximized by increasing the production of electricity at times of high prices and minimizing electricity sales at times of low prices.

To estimate FHR revenue, we used the 2012 hourly wholesale prices of electricity on the Texas and California grids and average 2012 natural gas prices ($3.52/million Btu). With this price data, the revenue for both baseload electricity and peak electricity using nuclear heat and auxiliary natural gas were calculated for each hour of the year. Also for each hour of the year, the plant was assumed to be operated in the mode that would provide the most revenue for that hour. The revenue for the year was totaled, and after subtracting the cost of the natural gas, the result was the net revenue. Auxiliary natural gas was not used when its cost exceeded the additional revenue from peak power operations. It was assumed that the nuclear reactor would operate at full capacity. At times of high electricity prices, the plant would use natural gas to maximize electricity production, and thus also maximize revenue. At times of very low or negative prices, only baseload electricity would be produced. Table 2 shows the relative revenue as compared to baseload electricity production.

The results show dramatic increases in revenue for plants with multiple operating modes versus operating the reactor only to produce baseload electricity. For example, if the Mk1 plant operated in two modes (baseload and peak electricity with auxiliary natural gas), the plant's revenue in California in 2012, after subtracting natural gas costs, would have been 167 percent of a baseload nuclear plant. There is also the option to reduce power levels or vent hot air from the NACC when electricity prices are negative to reduce losses at these times. If there are industrial customers for steam, HRSG steam can be sold when the revenue from steam sales would be greater than from electricity sales.

Because an NACC is more efficient in converting natural gas to electricity than a stand-alone natural gas plant, it has the lowest operating costs in terms of converting natural gas to electricity. Consequently, it is dispatched in peak power mode before any stand-alone natural gas plant comes on line. In California and Texas, that implies operating, respectively, 77 percent and 80 percent of the time with auxiliary natural gas. After dispatch of an FHR with NACC, the next power plants that would be dispatched as electricity demand grows would be the combined-cycle plants, with 60 percent efficiency in the conversion of natural gas to electricity. Those plants would then determine the market price of electricity. As the electricity demand further increases, simple air-Brayton natural gas plants would come on line at 40 percent efficiency and set the prices of electricity. In a free market, the FHR and the gas plants are paid the same for their electricity and pay the same for natural gas. The higher efficiency results in more net revenue for the FHR. As the price of natural gas goes up, the net revenue climbs rapidly.

The other half of the economics is the reactor costs. Several groups have estimated FHR capital costs to be lower than those of LWRs based on higher efficiency, a low-pressure system, and the characteristics of the salt as a heat transfer fluid. No FHR has been built, however, and no regulatory review has been conducted. Others believe that costs will be higher. At this time, a reasonable conclusion is that costs will be similar to other types of nuclear power plants.

Future low-carbon grids

With the transition to a low-carbon grid, the FHR with NACC can be used to produce variable zero-carbon electricity from hydrogen, biofuels, or stored high-temperature heat. Hydrogen made from electrolysis or biofuels can substitute for natural gas. Alternatively, high-temperature stored heat may be used for peak electricity production using firebrick resistance-heated energy storage (FIRES).

The stored-heat option (Fig. 3) involves heating firebrick inside a prestressed concrete pressure vessel with electricity to very high temperatures at times of low electricity prices; that is, below the price of natural gas. When peak power is needed, compressed air after nuclear heating and before entering the second turbine would be routed through the firebrick, heated to higher temperatures, and sent to the second turbine. The efficiency of converting electricity to heat is 100 percent. The efficiency of converting auxiliary heat (natural gas or stored heat) to electricity in our current design is 66 percent. This results in a round-trip efficiency of electricity to heat to electricity of about 66 percent. Improvements in gas turbines in the next decade are expected to raise that efficiency to 70 percent, which is similar to that of many other electricity storage technologies as a result of improvements in gas turbine efficiency.

In the context of a zero-carbon nuclear-renewable electricity grid, the FHR with FIRES is fundamentally different from batteries or pumped storage. First, with traditional storage systems, the electricity charging rate is close to the discharge rate. In this system, low-capital-cost resistance heating enables buying large quantities of low-priced electricity when available, such as for two or three hours in the middle of the day in a grid with large photovoltaic output. We define low-priced electricity as electricity selling at less than the price of natural gas. Second, an FHR with FIRES addresses the capacity challenge. Storage (MWh) by itself does not enable the use of renewables. Electricity generating capacity (MW) is also needed because conventional storage systems will become fully discharged if there are multiple days of unfavorable solar or wind conditions. Heat storage embedded in an NACC provides both storage and backup generating capacity using natural gas, biofuels, or, ultimately, hydrogen.

Much of the FIRES heat storage technology is being developed by General Electric and its partners for an adiabatic compressed-air energy storage system called Adele (German abbreviation). The first prototype storage system is expected to be operational by 2018, with 90 MWe peak power and the capability to store 360 MWh. When the price of electricity is low, the air is adiabatically compressed to 70 bars with an exit temperature of 600 °C, cooled to 40 °C by flowing the hot compressed air through firebrick in a prestressed concrete pressure vessel, and stored as cool compressed air in underground salt caverns. At times of high electricity prices, the compressed air from the underground cavern passes through the firebrick, is reheated, and is sent through a turbine to produce electricity, with the air exhausted to the atmosphere. The expected round-trip storage efficiency is 70 percent. The Adele project is integrating firebrick heat storage into a gas turbine system. For an NACC using high-temperature stored heat for peak power, the differences are that (1) the peak pressure would be about one-third that of the Adele project, (2) the firebrick is heated to higher temperatures, and (3) electricity is used to heat the firebrick to higher temperatures at times of low electricity prices. The technology for heat storage integration into an NACC is partly under development.

Making the case

No new reactor will be developed unless there is a compelling case for its development. For the LWR, that compelling case was the need for a nuclear submarine that could stay underwater for months at a time. The technology was transferable to commercial power plants because submarines and utility fossil plants used steam power cycles. For the FHR, that compelling case is based on two goals: (1) increased net revenue relative to nuclear power plants that sell electricity at constant output to the grid (economics), and (2) the enabling technology for a zero-carbon nuclear-renewables grid by providing variable electricity on demand to replace traditional fossil power plants (environmental). In the near-term, the fuel for that peaking capability would be natural gas or, in some markets, stored heat. In the long-term, it could also include hydrogen and biofuels.

When the LWR was being developed, the United States had regulated utilities, and the competition was from fossil fuels, where costs were dominated by fuel operating costs. Evaluating nuclear plant economics using levelized electricity costs was the appropriate model, because nuclear power plants were to replace baseload power plants in electricity production. Today we have deregulated markets and an increased use of renewables, which are leading to increased daily swings in electricity prices. Future electricity prices are projected to drop significantly at times of favorable solar or wind conditions and increase significantly when there are unfavorable solar and wind conditions [6]. Changes in the electricity markets require that nuclear economics be evaluated on net revenue—that is, revenue minus costs. Market changes create large economic incentives for a different type of nuclear power system—one designed to provide variable power to the electricity grid. The FHR with NACC and FIRES is designed to meet those market demands.

Last, the technical viability of an FHR with NACC is a consequence of advances in natural gas–fired combined-cycle plants and HTGR coated-particle fuel. Neither of these technologies was sufficiently advanced 15 years ago for this reactor concept to have been viable. The case for the FHR with NACC and FIRES is not dependent upon the specific details of the FHR design except for the requirement of exit salt temperatures at 700 °C or higher and a cold salt temperature above 550 °C to couple to the power technology. Given the massive ongoing research and development on gas turbines, the power systems will be further improved by the time an FHR can be deployed.

Because no FHR has been built, there are significant uncertainties. The next major step is to build a test reactor to demonstrate viability. The earliest estimated commercialization date is about 2030.

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