2013 Annual Report[1]

High-Temperature Salt-Cooled Reactor For Power and Process Heat

Fluoride-Salt-Cooled Reactor (FHR)
With Nuclear Air-Brayton Combined Cycle (NAC) Power System

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[1] This paper includes the body of the annual report but does not include the detailed appendixes of laboratory and other results. It is to provide a top-level perspective of the path forward defined by the MIT/UCB/UW Integrated Research Project

SUMMARY

The U.S. Department of Energy in January 2012 awarded the Massachusetts Institute of Technology (MIT), the University of California at Berkeley (UCB) and the University of Wisconsin (UW) a Nuclear Energy University Program grant (NEUP11-3272) to investigate salt cooled reactors. As defined in the proposal: *The objective of this Integrated Research Project (IRP) is to develop a path forward to a commercially viable salt-cooled solid-fuel high-temperature reactor with superior economic, safety, waste, nonproliferation, and physical security characteristics compared to light water reactors for base-load electricity production and process heat applications.*

The development of a new reactor concept is a major undertaking that ultimately requires universities, national laboratories, vendors, and utilities. For that to occur a path forward must include three components:

- There must be confidence that a technically-viable and licensable reactor is possible.
- There must be a compelling case that this reactor should be developed. That case must include a strong economic case so vendors and utilities want to develop the reactor. There must also be a compelling national need. Realistically a new reactor will require government support thus there must be a case for national support of the development effort to meet specific national goals.
- A developmental pathway must be defined that provides reasonable confidence in defining the level of effort required to achieve goals.

This year a path forward to achieve these goals has been defined for a Fluoride-salt-cooled High-temperature Reactor (FHR) coupled to a Nuclear Air-Brayton Combined Cycle (NACC)—the topic of this report. While not complete, the pathway is now defined. The pathway includes both the reactor and the associated power cycle. It is the combination that creates the compelling economic case for development of this reactor and the strong national incentives to develop the reactor with power cycle. The power cycle is similar to that used in natural gas power plants. Within the NACC, air is compressed, heated with nuclear heat, goes through a turbine producing electricity, and the hot exhaust is sent to a heat recovery steam generator (HRSG). The HRSG produces added steam that can be used to produce electricity or sold to industrial customers. The FHR operates at base-load. NACC can produce peak power with addition of natural gas (NG) after nuclear heating to raise air temperatures and power output.

A first-generation FHR design coupled to a General Electric gas turbine has been developed at UCB. The MIT economic analysis using 2012 hourly electricity prices from the Texas and California grids indicates the ability to produce base load and peak power using auxiliary NG increases plant revenue by 50% relative to a base-load nuclear power plant—this is after subtracting the cost of the NG.

The ability to produce variable power enables an FHR with NACC to be the enabling technology for a nuclear-renewable grid with reduced greenhouse gas emissions. Electricity from solar and wind are not dispatchable. Other power generating units are required to provide variable electricity to match production with demand. An FHR with NACC can accomplish this with auxiliary NG and significantly lower greenhouse gas emissions than stand-alone NG plants. In the longer term there are the options to use hydrogen or biofuels to replace NG.

The FHR uses fuel developed for high-temperature reactors with failure temperatures near 1650°C. The coolant boiling point is above 1400°C. Unlike other reactor types, the accident failure modes are not in the reactor core. Preliminary analysis indicates the potential to prevent major fuel failure and large-scale radionuclide releases in a beyond design basis accident.

In the last two years major experimental facilities have been set up at the three universities to support the early development of the FHR. The first set of corrosion experiments of prototypical materials under prototypical conditions (700°C) in the coolant flibe ($^{7}Li_2BeF_4$) salt have been completed with out-of-reactor experiments at UW. Parallel experiments with prototypical materials in 700°C flibe coolant salt are now underway inside the MIT reactor core. Such capabilities to conduct realistic experiments using prototypical materials and high-temperature salts have not existed in the U.S. since the early 1970s.

Large-scale thermal hydraulic safety experiments will soon be underway at UCB. The unique characteristic of these experiments is the development of a strategy that may dramatically reduce the cost and time for such experiments. Historically thermal hydraulic experiments for new reactors have been extremely expensive: light water reactors require test rigs with high pressures, sodium cooled reactors require test rigs with high temperatures and chemically reactive sodium, and gas cooled reactors require test rigs with high pressures and high temperatures. In the case of the FHR, organic fluids (Dowtherm®) have almost identical properties at atmospheric pressure at temperatures slightly above 100°C as liquid salt coolants at 700°C. This coincidence has the potential to drastically reduce the required thermal hydraulic testing with high-temperature salts.

The requirements for a FHR test reactor have been developed. For the United States, the path forward would be for a general purpose 20 to 40 MWt test reactor. The most credible strategy to build such a test reactor in the United States at this time would be as an international project similar to DRAGON. DRAGON was the first high-temperature gas-cooled reactor—an international test reactor funded under the sponsorship of the OECD.

There are also ongoing activities at several other universities (Ohio State, Georgia Tech, University of New Mexico, etc.) and at national Laboratories (Oak Ridge National Laboratory and Idaho National Laboratory). Overseas there is a major program by the Chinese Academy of Science and smaller efforts in the United Kingdom and the Czech Republic.

1. Introduction

MIT, UCB, and UW have initiated a research program for a Fluoride-salt-cooled high-temperature reactor (FHR). The FHR is a new reactor concept that is about a decade old. It combines several existing technologies including high-temperature fuel developed for high-temperature gas-cooled reactors, liquid salt coolant technology from the molten salt reactor program where the fuel was dissolved in the coolant and air-Brayton combined cycle technology developed for natural-gas-fired power plants. A practical FHR has become possible because of advances in the last two decades in high-temperature reactor fuel and air-Brayton power cycles.

The objective of this Integrated Research Project (IRP) is to develop a path forward to a commercially viable salt-cooled solid-fuel high-temperature reactor with superior economic, safety, waste, nonproliferation, and physical security characteristics compared to light water reactors (LWRs) for base-load electricity production and process heat applications. The primary challenges are economics and safety. The FHR fuel is a modified high-temperature gas-cooled reactor fuel. Earlier studies on this fuel indicate it has superior waste, nonproliferation, and physical security characteristics relative to LWR fuels.

To develop a path forward for the FHR we adopted a top-down strategy (Fig.1) that defined goals that led to the commercial reactor concept. Because no FHR has ever been built, a test reactor will be required. The commercial design and test reactor requirements define the technology development program.

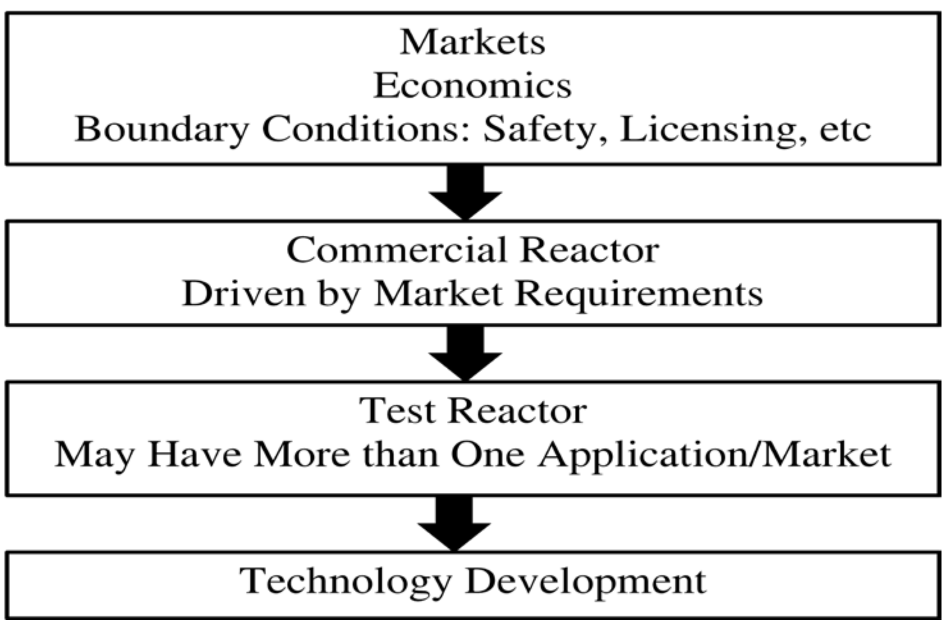


Fig. 1. Strategy to Develop a Path Forward for the FHR

The top-level goal for a commercial reactor is that it be economic and meet the requirements of the market. Because the FHR is a new reactor concept, the earliest deployment time is ~2030. Therefore the goal is to be competitive in the 2030 electricity market. That market is likely to be different than today's market with restrictions on greenhouse gas releases and significant deployment of non-dispatchable wind and solar resources.

The development of a new reactor concept is a major undertaking. It will require a test reactor to demonstrate key components—a large investment in time and resources. History and discussions with reactor vendors indicate that such a development will require major government funding at least through the test-reactor stage of development. The development times are too long and the risks are too high for private funding. This implies that the FHR must address national needs and goals for such support to be obtained.

Last, the Fukushima accident occurred shortly after the start of this program. It emphasized the need for safety. This is an economic goal and a social goal.

Within the last year, we have defined an FHR to meet these goals and a pathway forward to a test reactor and ultimately a commercial reactor. The body of this annual report summarizes those results at a high level to provide a broad integrated perspective of the reactor and path forward. The basis for major decisions is described. More specific details including detailed progress this quarter is included in the appendix. The following chapters include (1) a pre-conceptual reactor design, (2) the commercialization basis, (3) the basis for the test reactor, and (4) key components of the technology development program, and (5) conclusions.

2. Reactor Design

A pre-conceptual FHR commercial reactor design has been partly developed with definition of the major components and characteristics. A schematic of key components is shown in Fig. 2. Design parameters are summarized in Table 1. This description outlines key features and the basis for major design decisions.

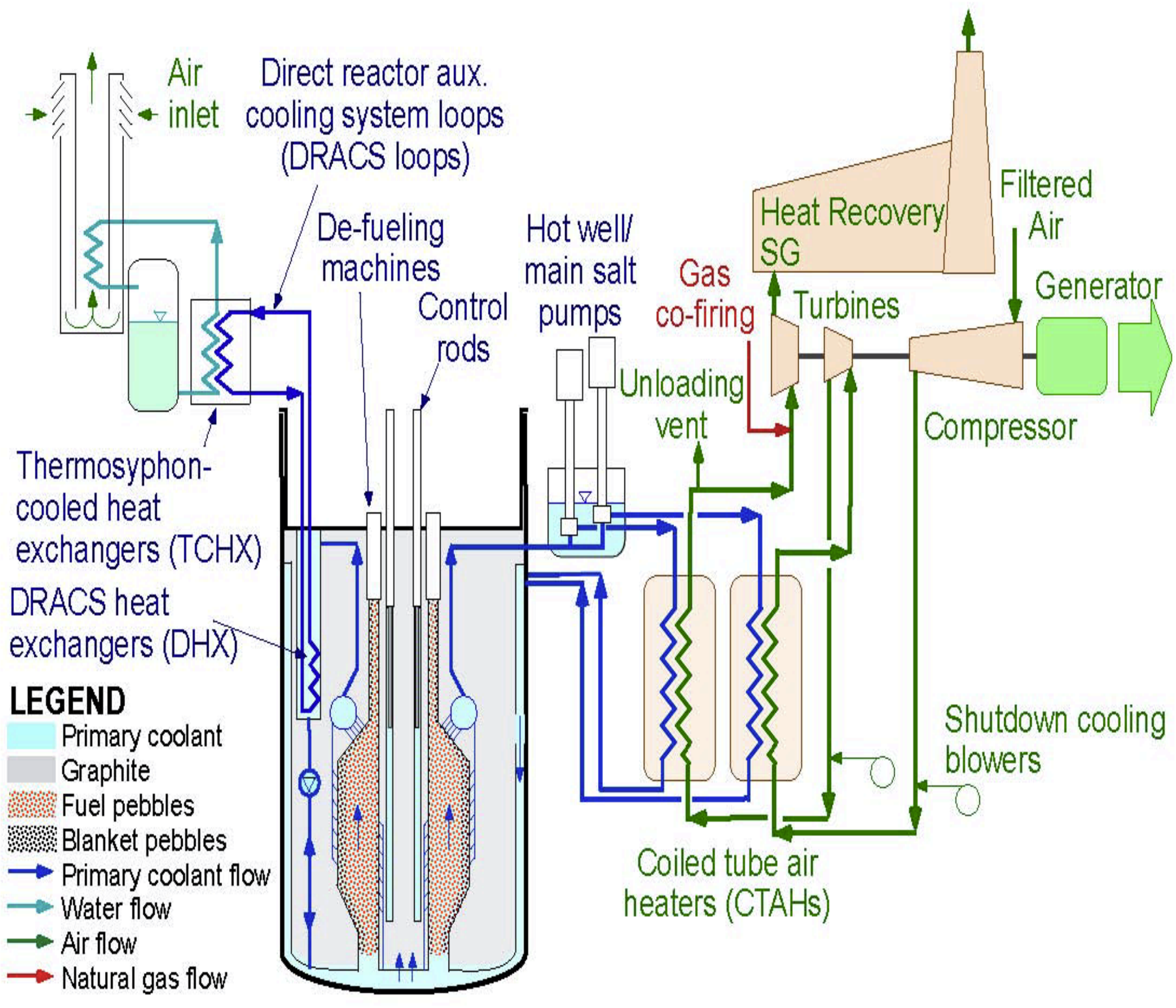


Fig. 2. Schematic of FHR with NACC

The FHR is coupled to a Nuclear Air-Brayton Combined Cycle (NACC) that is the basis for achieving commercialization goals as discussed in Chapter 3. Within NACC, air is filtered and compressed, heated with nuclear heat, goes through a turbine producing electricity, and the hot exhaust is sent to a heat recovery steam generator (HRSG). The HRSG produces added steam that can be used to produce electricity or sold to industrial customers. The FHR operates at base-load. However, NACC can produce additional peak power with added natural gas injected after nuclear heating to raise air temperatures and power output. There is the long-term option of producing peak power using hydrogen or biofuels rather than natural gas.

Table 1. Key Mk1 PB-FHR design parameters.

Reactor Design	
Thermal power	236 MWth
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	
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 (total flow is 440.4 kg/s; conventional 7FB design uses excess for turbine blade cooling)	418.5 kg/sec
CTAH 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 %

† The co-firing efficiency is the ratio of the increased power produced (total minus baseload) during peaking, to the energy input from combustion of natural gas, and represents the efficiency with which the natural gas combustion energy is converted into electricity. The efficiency (66.4%) is higher than a stand-alone natural gas plant (60%) because the natural gas acts as a high-temperature heat source with lower temperature heat provided by the FHR.

The development of air Brayton power systems is expensive and time consuming; thus, the FHR uses an existing air-Brayton power system with no changes in the front-end air compressor. General Electric, Siemens, and others manufacture appropriate power systems. The IRP base-line design uses an existing General Electric F7B gas turbine. The power cycle defines several key reactor characteristics.

- *Temperature*. Modern air-Brayton compressors raise inlet temperatures to between 450 and 550°C. The minimum return salt coolant temperature from the power cycle to the reactor must be significantly above this temperature. The baseline salt is a lithium-beryllium fluoride salt ($^7Li_2BeF_4$) with a melting point of ~460°C that results in minimum coolant-salt operating temperatures of ~600°C. Consequently the FHR can couple to NACC. Only salt-cooled reactors deliver their total heat at sufficiently high temperatures to couple with modern air-Brayton front-end compressors.[2]
- *Reactor size*. The reactor size is defined by available gas-turbine sizes. The largest gas turbines require about 500 MWt of heat. Large FHRs can be built but with multiple gas turbines. The baseline design uses a single GE F7B gas turbine.

A decision was made that the reactor should be a modular reactor that is rail transportable. This enables factory fabrication with manufacturing cost and learning curves. The size matches that of the largest commercial GE rail-transportable gas turbine with one reactor to one gas turbine. Last, the development of an FHR will require scale-up over time. The size matches the likely size of a pre-commercial demonstration plant.

A schematic of the reactor and vessel internals is shown in Figure 3. It has the following design features.

- *Fuel*. The fuel is a pebble-bed graphite-matrix coated-particle fuel originally developed for high-temperature gas-cooled reactors. The pebbles are 3 centimeters in diameter rather than the 6 centimeters in diameter used in gas-cooled reactors because the salt coolant has better cooling properties that allows higher power densities. The base-line power density is 23 kW/liter—4 to 5 times higher than an HTGR. The core is not fully optimized so the power density may increase. The pebble-bed fuel was chosen because it has been demonstrated in gas-cooled reactors and thus presents fewer developmental risks. Because the fuel is the same basic type as used in high-temperature gas-cooled reactors (HTGRs), the core and fuel cycle characteristics are similar to that of HTGRs.

[2] Salt-cooled reactors intrinsically couple to NACC because the high melting points of the salt coolant imply high inlet temperatures to the reactor that are above the exit air compressor temperatures. Current high-temperature gas-cooled reactors (HTGRs) have helium inlet temperatures near 250°C to cool the reactor vessel and thus can't couple to NACC. In principle a redesigned HTGR could couple to NACC. Current lead-cooled fast reactors (LFRs) have peak temperatures near 450°C. If new fuel cladding materials could be developed to 700°C, a LFR could be coupled to NACC.

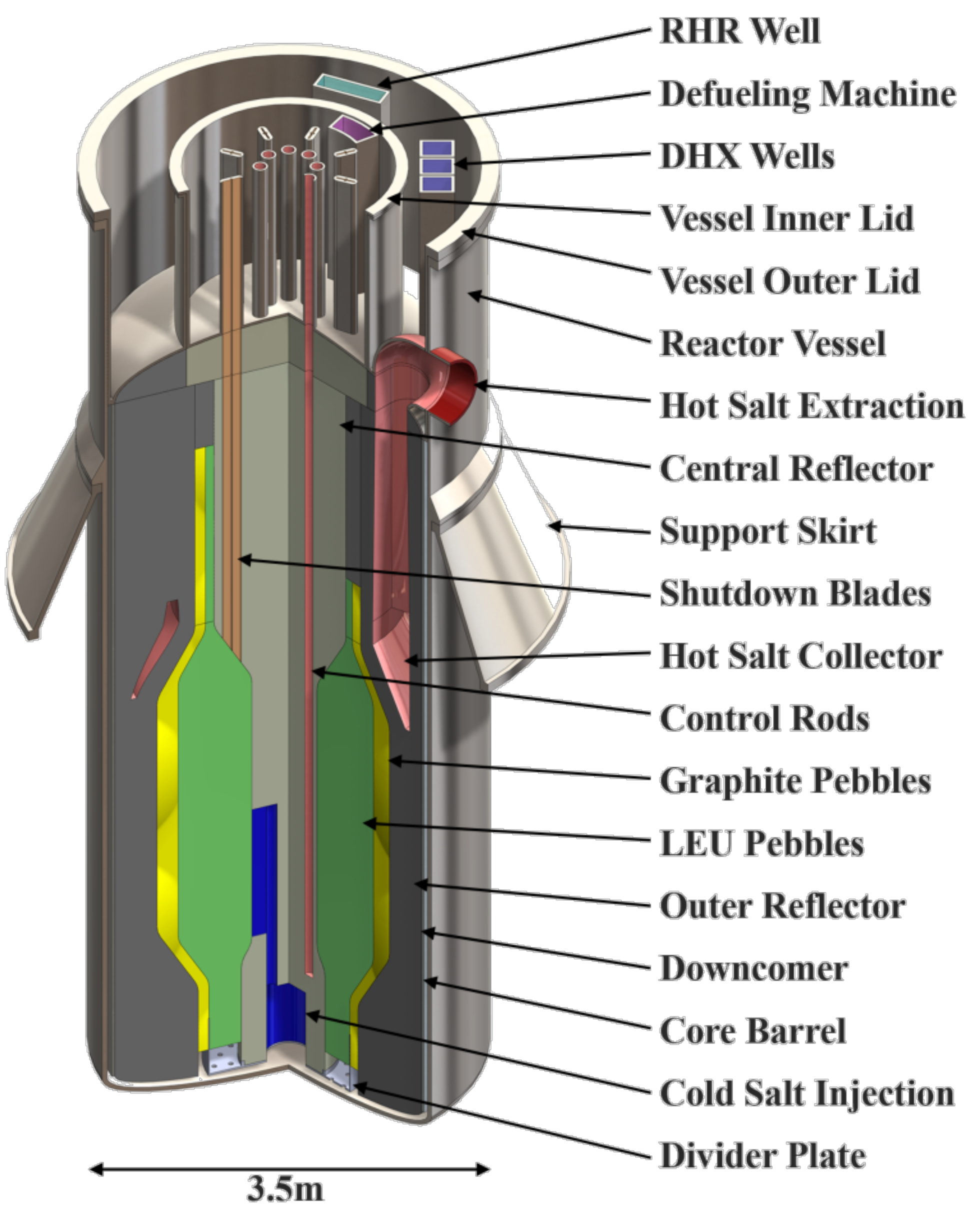


Fig. 3. Schematic of the FHR Reactor vessel and Its Internal Components

- *Core geometry*. An annular pebble bed was chosen with a graphite central zone. This allows (1) easy placement of control rods in the central zone and (2) maximizes cooling in the reactor core. There are no control rods in the core. The coolant flows upward in the core and outward from the central annular zone in a pattern designed to enable higher power densities and provide a more uniform exit temperature from the reactor core.
- *Coolant salt*. The salt is $^{7}Li_2BeF_4$ with a melting point of 459°C. This is the same salt that was developed for the molten salt reactor in the 1960s where the fuel is dissolved in the

salt. It was chosen because of (1) its excellent neutronic and thermal hydraulic properties and (2) the previous experience in the MSR program. The salt is chemically stable in high radiation fields and compatible with the graphite moderator and fuel. Its boiling point is above 1400°C. Based on experience using this salt in MSRs, the minimum coolant temperature has been chosen to be 600°C.

- *Materials of construction*. The vessel and heat exchangers are made of 316SS. This limits peak temperatures to ~700°C. The 316SS was chosen because it is a nuclear code-qualified material of construction. There is limited experimental evidence that the material is suitable for use in clean salt but added work to confirm this is required. The backup material is Hastelloy-N. This material has been demonstrated to be compatible with fluoride salts but is not fully code qualified. To minimize galvanic corrosion, the same metal is used for all surfaces exposed to salts.
- *Decay heat removal system*. The FHR uses a Direct Reactor Auxiliary Cooling System (DRACS). The intermediate loop contains a molten salt. The external loop uses a two-phase water thermosyphon loop similar to what was proposed for commercial MSRs in designs that were developed in the 1970s.

A building schematic is shown in Figure 4 of the major system components.

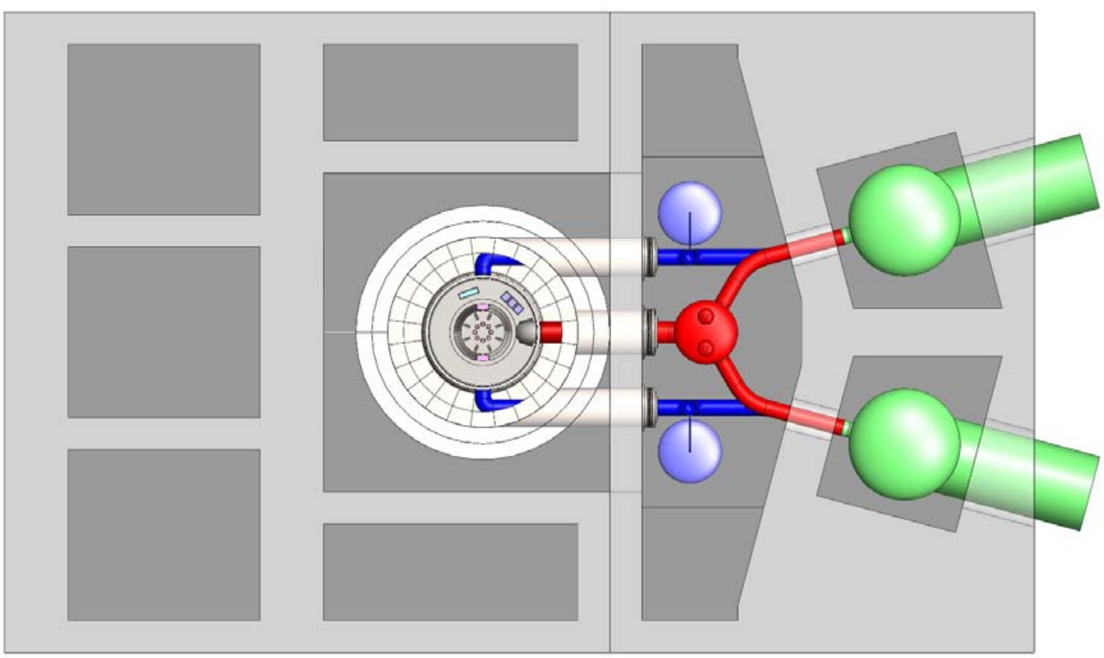


Figure 4. Building Schematic with Reactor vessel, pumps (red), and the air heat exchangers (Green)

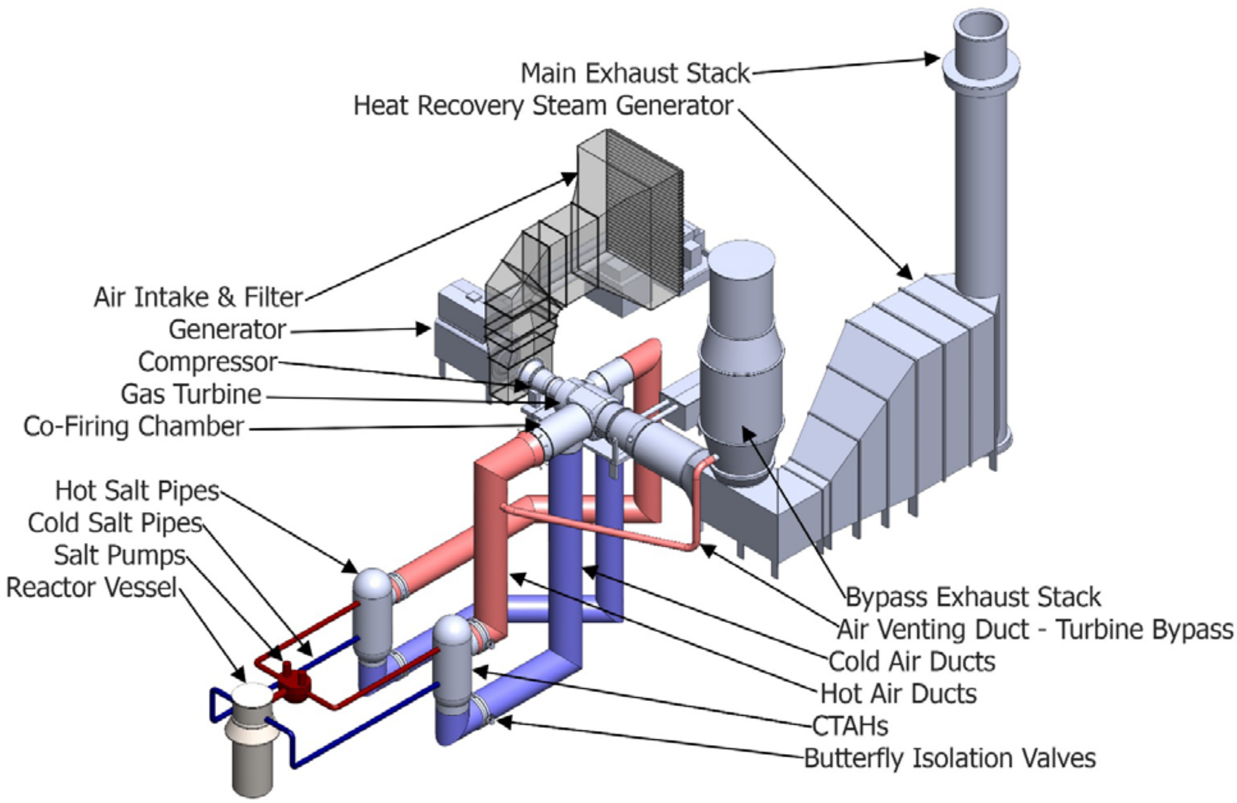


Figure 5. The Mk1 PB-FHR interface with the NACC power conversion system.

A schematic of the plant site is shown in Fig. 5. The layout is to allow a clear separation of the nuclear island from the NACC power systems. The layout would also allow multiple units on a single site with the nuclear island to the left and the common electrical switchyard with natural gas piping on right side of all units. There are multiple special features to assure plant safety relative to natural gas leaks.

Initial studies have been completed for Beyond Design Basis Accidents (BDBAs) with a BDBA workshop scheduled for next year. The FHR is unique with a fuel failure temperature of 1650°C and a liquid salt coolant with a boiling point above 1400°C. As a consequence, it appears possible to design an FHR where there are major systems failures (loss of all cooling systems, vessel failure) but where there is no major fuel failure and thus no major offsite release of radioactivity. Severe accidents would result in loss of the plant but no major offsite consequences. There are major uncertainties that must be addressed to confirm this. This conclusion is based on several considerations.

- The extreme temperature capabilities of the reactor core imply accidents do not start in the core. The metal heat exchangers or vessel will fail first.

- If the reactor vessel is in a silo, the coolant can't leak out. The coolant freezes at 460°C and thus self-seals any leaks.
- In BDBAs in most power reactors, the decay heat raises fuel temperatures until the fuel fails and radionuclides are released. If peak core temperatures are below fuel failure temperatures, the fuel will not fail. In an FHR the fuel and temperature efficiently transfer heat to the reactor vessel thus providing a 1000°C temperature drop to drive decay heat from the reactor core through any structures to the environment. The very high temperature drop implies one can have a large reactor and keep reactor core temperatures below fuel failure temperatures. No other reactor has such large temperature drops available for heat removal under BDBA conditions.
- There are a variety of design options to assure efficient heat conduction from the reactor vessel to the environment under the assumption of major structural failures.

3. Commercial Basis for FHR

The first requirement for any advanced reactor is that it be commercially viable. No FHR has been built; consequently, we estimate the earliest commercialization date to ~2030; thus, one must consider the future structure of the electricity grid. We analyzed current economics and expected future economics for commercial viability.

3.1. Electricity Markets and Implications for Future Reactors

Electricity demand varies by the hour, week, and season. There are large peaks in the summer due to air conditioning. The 5-day workweek has a higher power demand than the weekend. Imposed on these longer duration demand variations is the daily swing in electricity demand.

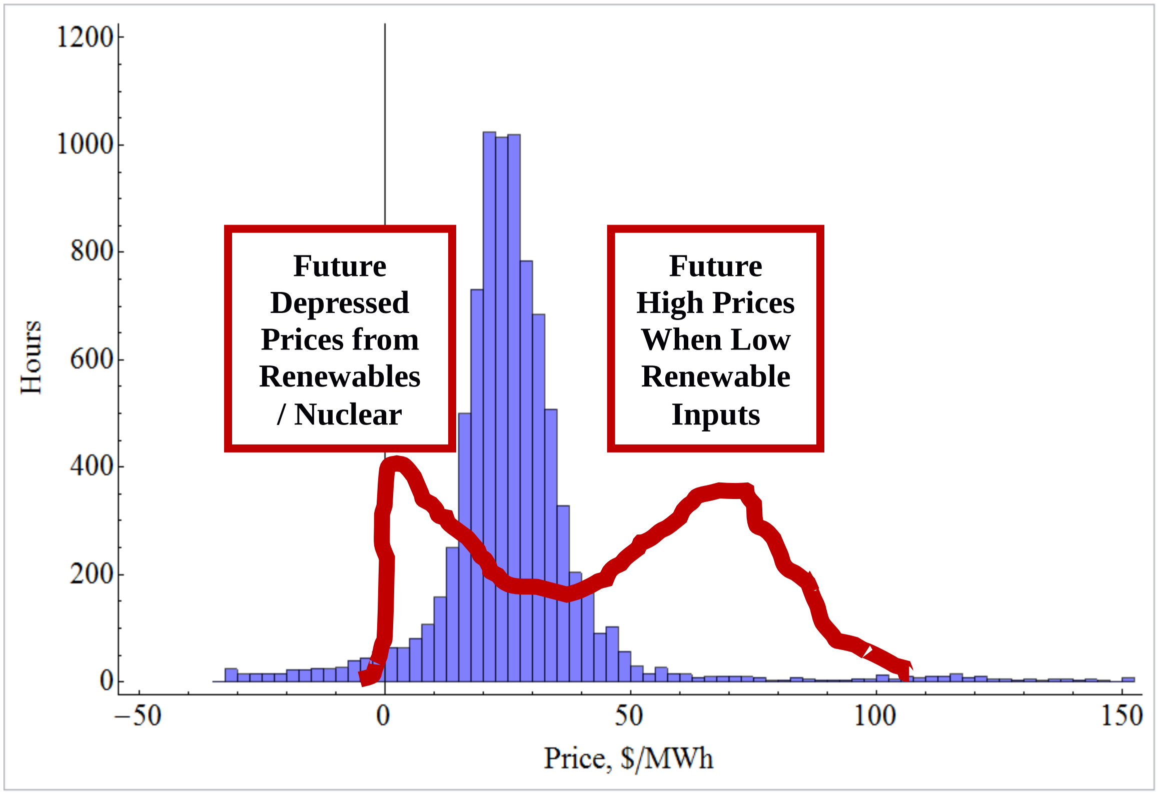


Fig 6. Distribution of Electrical Prices (Bar chart), by Duration, Averaged over CAISO (California) Hubs (July 2011-June 2012) and Potential Impact of Low-Carbon Grid (Red Curve).

About half of the United States have partly deregulated markets that have a free market component and various regulatory mandates such as a required fraction of renewables. In a free market the varying demand and varying supply result in the price of electricity changing with time. Figure 6 shows the market price of electricity versus the number of hours per year electricity can be bought in California. Note that there are negative prices for a significant number of hours per year when electricity generators pay the grid to take electricity. Nuclear and fossil plants can't instantly shut down and restart. They pay the grid at times of negative prices to accept electricity so as to be able to sell electricity a few hours later at high prices. At times of negative prices, the grid dumps electricity to other grids across long transmission lines—an inefficient process.

The economics of a nuclear power plant depend upon the cost of producing electricity and the price that electricity is sold for. Historically the goal of power reactor designers has been to minimize costs. We have chosen to improve economics by two strategies: (1) minimizing cost and (2) maximizing revenue. This decision was based on two considerations.

- *Minimizing costs*. Recent DOE economic studies have evaluated the costs of different types of reactors (LWRs, SFRs, HTGRs). For similar sized reactors, the cost difference was only about 20% from the lowest to highest cost per kWe. It suggests that the nuclear characteristics (quality assurance, safety, licensing, etc.) drive costs somewhat independent of the technology. This has two implications. First, much of the effort to reduce the costs of nuclear power plants is generic (licensing, modular construction, etc.), not specific to a particular reactor type. Second, it is unlikely that any new reactor type will have major improvements in economics relative to other types of nuclear reactors. While preliminary cost estimates of an FHR are less than LWRs, there are large uncertainties and there are real limits on the relative cost improvements that are possible for one type of reactor relative to other types of reactors.

- *Maximizing revenue*. The revenue stream of an FHR with a NACC is about 50% greater than for a base-load nuclear power plant based on the ability to produce both base-load and peak power. Revenue gains can be easily calculated based on market data.

We analyzed the revenue for an FHR with NACC with the modified combined cycle plant as shown in Figure 7. The plant has four operating modes.

- *Base-load*. Air is compressed, heated with nuclear heat, goes through a turbine producing electricity, and the hot exhaust is sent to a heat recovery steam generator (HRSG). The HRSG produces added steam that is used to produce electricity
- *Peak power*. Auxiliary natural gas (NG) can be added after nuclear heating of the compressed air to double plant output—with the long-term option of replacing NG with hydrogen or biofuels. The peaking capability is built on top of a base-load capability. Relative to a traditional stand-alone NG plant that implies: (1) no natural gas consumption when just using nuclear, (2) ability to add power to the grid faster than traditional stand-alone natural gas plants and (3) more efficient conversion of NG [66%], hydrogen or biofuels to electricity relative to traditional gas turbines [60%].

- *Bypass venting*. The plant can vent hot compressed air to the atmosphere to allow rapid decreases in power output to stabilize the grid or operate at full reactor power without full power to the grid. This capability enables the FHR to be used for grid frequency control or for black start of a downed grid.
- *Steam heat*. The plant HRSG produces steam heat that can be sold to industrial customers. This ability to sell steam is different than from traditional nuclear power plants. When an LWR provides steam to industrial customers (Switzerland, Russia, Japan, etc.) there is an isolation heat exchanger between the nuclear plant steam supply system and steam sent off site to assure no transport of radioactivity offsite. That adds to the capital cost and imposes inefficiencies—temperature drops across the isolation heat exchanger. In NACC there is hot air transport of heat to the HRSG assuring isolation of the steam system from the nuclear system. This implies no significant added capital cost to sell steam to industrial customers.

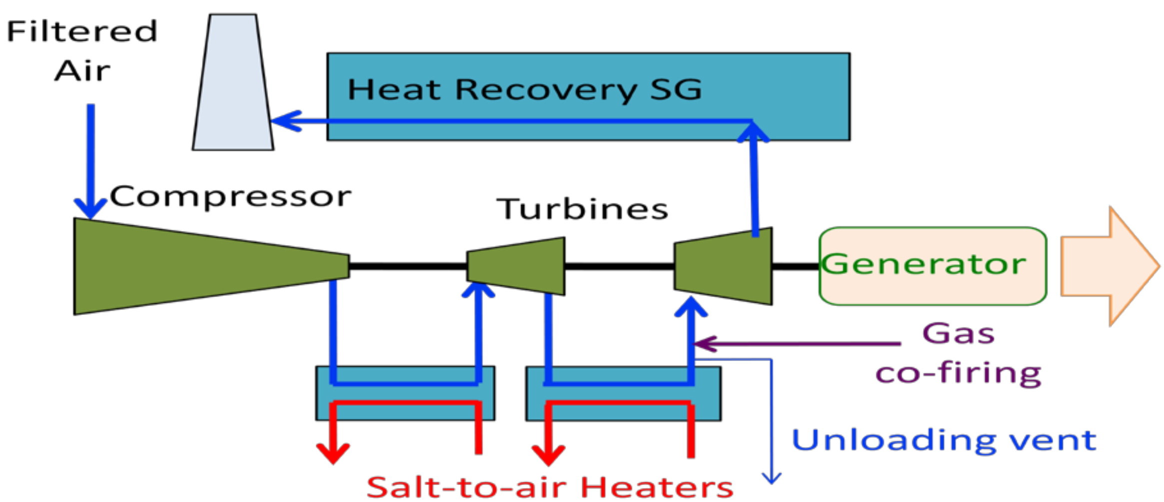


Fig.7. Nuclear Air-Brayton Combined Cycle

These gas-turbine capabilities exist in some existing combined cycle plants—particularly those used in chemical plants with (1) variable electricity and heat demand and (2) burning of variable quantities of waste hydrocarbons.

An economic analysis of the revenue gain from an FHR with NACC versus the traditional base-load nuclear plant was conducted using 2012 hourly electricity price data from Texas and California considering three operating modes.

- *Base-load electricity production*. The Brayton (gas turbine) and Rankine (steam turbine) systems produce electricity for the grid
- *Peak power production*. Auxiliary natural gas is used to boost electricity production

- *Electricity production and steam sales*. In this mode the Brayton cycle produces electricity for the grid and the heat recovery boiler produces steam for industrial customers. That steam is sold at 90% of the cost of natural gas. This provides an incentive for industrial customers to turn down industrial boilers and purchase steam when cheap steam is available.

The relative revenue of different operating modes is shown in Table 2 after subtracting the cost of natural gas. For example, if the plant sells only base-load and peak power, the operating mode for each hour is determined by which mode would produce the most revenue after subtracting natural gas costs. If prices are low, the plant operates in the base-load mode. If prices enable increased revenue after subtracting the cost of natural gas, the plant operates in peaking mode. In all cases the reactor operates with a steady state output.

TABLE 2. Relative Plant Revenue after Subtracting Cost of Auxiliary Natural Gas

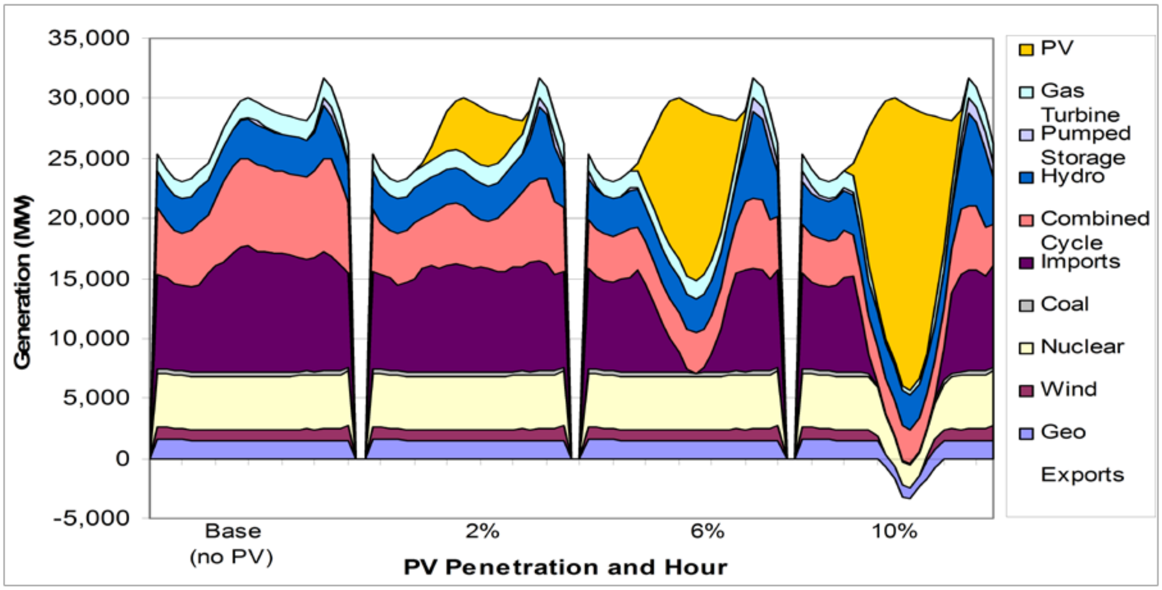
Allowed Operating Modes	Texas Grid	California Grid
	Percent	Percent
Base Load	100	100
Base Load + Peak	125	144
Base Load + Steam	146	134
Base Load + Peak + Steam	161	167

The ability to produce peak power or steam substantially increases revenue relative to base-load nuclear plants. This however is only one source of added revenue. In addition, the FHR with NACC can provide spinning reserve and frequency control because of its quick response capability. The value of these services may be up to $1000 per kilowatt of capacity—a quarter of the capital cost.

3.2. Future Electricity Markets

The future electricity market is likely to be very different than the existing market. Concerns about greenhouse gas emissions will restrict the use of fossil plants to meet variable electricity demand. At the same time there will be large additions of non-dispatchable wind and solar power systems.

The outputs of non-dispatchable renewables do not match electricity demand. Figure 8 shows the impact of adding non-dispatchable photovoltaic (PV) electricity generation to the California grid on a spring day—the time of year with low electricity demand. The far left figure shows the total electricity demand and how it is met today with a mixture of different types of electricity sources. The other figures show the impact of adding different quantities of PV where the percent PV is the fraction of total California electricity demand over a period of a year met by PV. Most of this electricity is generated in the late spring and early summer because of more hours of sunlight per day and the higher location of the sun in the sky.



California Daily Spring Electricity Demand and Production with Different Levels of Photovoltaic Electricity Generation

The addition of a small amount of solar (2 %) as shown is beneficial because the electricity is added at times of peak demand. However, as additional solar is added, it drives down the price of electricity. Each owner of a PV array will sell electricity at whatever price exists above zero. This implies that when somewhere between 10 to 20% of the total electricity demand is met by solar in California, the output from solar systems during midday for parts of the year will exceed demand and the price of electricity will collapse to near or below zero.

This also implies that the price of electricity at times of low renewable input will dramatically rise. If other types of power plants operate half the time because they do not generate electricity at times of high renewable inputs, replacement plants will not be built unless there is a dramatic rise in the prices of electricity when renewable energy sources are not producing electricity. In a low-carbon world, this effect may double electricity prices when there is not a large renewable output. Figure 6 shows with a hand-drawn line the expected impact of larger-scale use of renewables on electricity prices.

The implications for the grid are that there will be larger swings in electricity prices with time. There will be a greater demand for power systems that can deliver variable electricity and for power systems that can provide rapid-response spinning reserve. These expected changes in the electrical grid would dramatically improve the economics of an FHR with NACC relative to a base-load nuclear plant—beyond that shown for an FHR in the existing markets (previous section). All of these trends favor nuclear power plants with the capability for variable electricity output relative to nuclear power plants that produce base load electricity.

The implications go beyond economics. The likely future requirements for a low-carbon grid and the expanded use of non-dispatchable wind and solar demand the development of new low-carbon generating technologies with unique flexibility for variable power output. This may enable the FHR with a NACC to be the enabling technology for a future low-carbon nuclear-renewable grid. It meets a national goal.

3.3. FHR Goals

Based on the above analysis, two goals have been defined for the FHR.

- *Increase plant revenue by 50% relative to base-load nuclear power plants*. The expectation is that the FHR in terms of capital cost will be competitive to base-load LWRs.

- *Enabling technology for a low-carbon nuclear renewable electrical grid*. In a low-carbon grid, the need is for dispatchable electricity to match production with demand. The FHR with NACC is designed to meet this need while the reactor operates at base load.

These goals impose a series of technical requirements on the FHR. They require that all heat be delivered at temperatures that exceed the air-Brayton compressor exit temperature. In addition, this is an air-Brayton open cycle that requires controls of radionuclides to the power cycle—specifically tritium. Existing steam and other proposed power cycles (supercritical carbon dioxide, helium, etc.) provide the option of trapping radionuclides in the power cycle. That option does not exist with NACC.

The commercialization case does not depend upon the reactor size, the choice of high-temperature fuel, the choice of fluoride salt coolant, or many other plant parameters. We have chosen one specific set of FHR options but there are other choices. If future research indicates other design options are preferable, it does not change the commercialization basis for an FHR with NACC.

4. Test Reactor

No FHR has ever been built; thus, there is a requirement for a Fluoride-salt-cooled High-temperature Test Reactor (FHTR). There are two technical options.

- *Test (Pilot) Reactor for Commercial Prototype*. The FHTR would be designed to provide the necessary information for a specific pre-conceptual design of a commercial reactor. The goal would be to minimize time and resources. Such a reactor would be expected to operate for only a few years.
- *General Purpose Test Reactor*. The FHTR would be designed for broader test capabilities to enable providing required information for a variety of FHR concepts. It would be functionally similar to DRAGON—the first high-temperature gas-cooled reactor. This was a 20-MWt reactor built by the European Commission in the United Kingdom. Such general purpose machines have higher costs, are more versatile and keep design options open for a longer period of time. Our base-line design uses prismatic fuel assemblies because of the ability to provide three dimensional control of fuel loading and enrichment to provide the desired neutron flux for tests.

The test reactor choice depends upon the government and commercial structure of the country. Our analysis and discussions with vendors indicates that vendors would not be willing to finance a test reactor. For a commercial company, the time is too long and the risks are too great to start with a new concept and commercialize that reactor. Globally, all first-of-a-kind reactors have been built by governments. The implication is that an FHTR if built in the United States will be built by the U.S. Government. In that case one must consider government goals.

- *U.S. National goals*. The government interest in a commercial FHR is driven by national policy goals such as environment (low-carbon electrical grid), nonproliferation and safety—as well as competitive economic goals. A test reactor will have multiple goals.
- *Competitive vendors*. Historically the U.S. government has been unwilling to choose a vendor and support that vendor to develop a national product. That was true for the sodium-cooled fast reactor program, the high-temperature gas-cooled reactor program, and for the current DOE small modular reactor (SMR) program. This implies that a test reactor will need the capability to support multiple FHR design concepts.
- *U.S. Government markets*. The government interest will be driven by commercial and government needs such as the general purpose capability to undertake high-temperature irradiations for government missions. There are potential FHR government markets for an FHR with NACC where the reactor design would be significantly different than a commercial design. The federal government has a potential need and is examining the use of nuclear reactors to provide power to isolated facilities where it is very expensive to bring in fossil fuels. The FHR with NACC is potentially attractive because the reactor could be sized to meet the average needs of the facility with NACC using auxiliary fossil fuel to providing peak power. The reactor would not need to be sized for peak demand while the fuel logistics would be dramatically decreased.

Our analysis of goals leads to three FHTR missions.

- Demonstrate the technical viability of an FHR
- Provide the required information for design and licensing of a commercial demonstration FHR but provide options in the design features for such a reactor.
- Provide the test bed for different fuels, salt coolants, and materials.

Licensing analysis indicates that an FHTR would be licensed as a 104(c) reactor—not a commercial reactor. The power level would be between 20 and 40 MWt. This is similar to other first-of-a-kind reactors. No first-of-a-kind reactor has been built for over 40 years and thus there is no modern experience with building a new type of reactor. Four strategies have been identified for funding such a test reactor.

- *A U.S. centric program*. This would be similar to the U.S. strategy in the 1950s and 1960s where the U.S. government fully funds the test reactor and development program.
- *Joint program with the Chinese Academy of Science* (CAS). The first FHR will be built by the CAS. This will be a 2-MWth experimental reactor, the TMSR-SF1, using a fixed pebble bed core, which will operate at a power density around $1/10^{th}$ the value expected for commercial FHRs. FHR fuels and materials can be tested at prototypical power densities and temperatures in existing test reactors, as with the testing of U.S. Next Generation Nuclear Reactor fuel in the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL). This creates the option of a US-China partnership to reduce costs and risks for both partners for a larger test reactor. Data from the TMSR-SF1 would enable the U.S. to build a sophisticated FHTR on a shorter schedule at lower costs with lower risks.
- *International FHTR*. The first high-temperature gas-cooled reactor was DRAGON that was built in the United Kingdom. It was a European Commission project that paved the way for all later HTGRs. A FHTR could be organized in a similar fashion. There was a common understanding that DRAGON was a science project—not a commercial project. This allowed maximum sharing of information and simplified forming of partnerships.
- *Public private partnership with domestic and foreign partners*. This strategy would have a significant early commercial input. Based on expertise, likely partners could include Japan, China, and Westinghouse because of their high-temperature gas-cooled reactor programs. Candidate commercial partners include the vendors for natural-gas combined-cycle plants: General Electric, Toshiba, Ahlstrom, Siemens, etc.

The second and third options appear to be the most viable. The second option depends upon future U.S.-China relations. The third option with multiple partners reduces political risks. A test reactor program would cost ~2 billion dollars, less than several other international cooperative programs by National Aeronautics and Space Administration and DOE. The size and scope of the project, plus the blueprint provided by the DRAGON project, makes this an attractive option.

5. Test Program

A large experimental R&D program is required to develop a new reactor. The IRP project has emphasized two areas to begin to address the key technical challenges: materials corrosion and thermal hydraulics/safety. These areas have the longest lead times and are the two areas where advancing technology may enable major reductions in schedule and cost to test reactor.

The activity that requires the longest time in the development of a new reactor is development of appropriate corrosion-resistant materials for the reactor core with its high radiation fields. This is because it takes time for such tests to be conducted. The challenges for the FHR are somewhat less than for other reactors because the FHR and HTGRs use the same basic type of graphite-matrix coated-particle fuel. The United States Next Generation Nuclear Plant (NGNP) program has spent significant resources in improving this fuel in the last 10 years. This work is directly applicable to the FHR.

What is new and different is the use of clean salt coolants in the reactor core; thus, UW and MIT have initiated corrosion tests on prototypical materials. In the last two years significant experimental facilities have been set up at both universities that recreate some of the testing capability that Oak Ridge National Laboratory had in this area in the early 1970s for the molten salt reactor (MSR) with fuel dissolved in the coolant. Initial work was completed on corrosion and characterization of samples of Alloy N in KF-ZrF4 salt at 650 to 850^{o}C. This is a candidate intermediate heat transfer salt with the unexpected result that the corrosion rate of Alloy N is lower at 850^{o}C than at 700^{o}C. The reason is after Alloy N is exposed to 850^{o}C molten salt for more than 200 hrs, a significant amount of Mo-rich precipitates are formed at the grain boundaries and these grain Mo-rich phases mitigate the corrosion.

The base-line primary coolant salt is flibe. Wisconsin is testing materials in flibe salt in the laboratory at 700°C. Duplicate experiments are being conducted in the MIT reactor under identical conditions with flibe ($^{7}Li_2BeF_4$) salt. By conducting duplicate experiments in the laboratory (no neutron irradiation) and in a reactor (full neutron flux), it is possible to determine what corrosion effects are the result of chemical reactions and what corrosion effects are enhanced in the presence of radiation. In-reactor experiments are much more expensive and time consuming than experiments in the laboratory. By understanding where radiation has an impact, future experimental programs can minimize in-reactor testing and thus accelerate understanding of materials degradation in an FHR.

A second goal of the in-reactor experiments is to measure tritium production and partitioning in the components. Tritium is produced from the neutron irradiation of flibe and has impacts on both materials performance and radiological control. It diffuses through some materials (nickel) and is absorbed on other materials (graphite)

Table 3 shows the initial list of prototypic materials being tested at UW and MIT in the first set of capsule experiments. This includes (1) alternative metals of construction (Alloy N and 316SS), (2) nuclear-grade graphite, (3) different types of silicon carbide that may be used for control rods and other reactor internals and (4) triso particles. The triso particles are identical to the coated particle fuel proposed for the FHR except that the uranium has been replaced with zirconium dioxide. All the outer layers are identical.

The prototypic materials were provided by the Department of Energy through Oak Ridge National Laboratory and Idaho National Laboratory. The lithium-7 isotopically-separated flibe salt was provided by Oak Ridge National Laboratory. The salt was purified at Wisconsin.

This quarter the first set of tests of these materials were completed at Wisconsin. Preliminary examination indicated low corrosion rates. The parallel tests were started up in the MIT reactor core and are currently undergoing irradiation. Figure 9 shows the irradiation capsule before being loaded with salt and samples and placed inside the MIT reactor. A wide variety of other corrosion testing is being done.

Table 3. Corrosion testing matrix at UW and MIT test reactor

Compartment	**Container Material Combinations**
A	Graphite container – Alloy N sample (size: 0.5”x0.25”x0.05”, 2 pieces)
B	Graphite container – 316 SS sample (size: 0.5”x0.25”x0.05”, 2 pieces)
C	Graphite container – SiC samples (including SiC composites) R&H CVD SiC, 13mmx2mmx1.5mm, 2 pieces SiC/SiC Tyranno-SA3 CVI SiC composites, 25mmx2mmx1.5mm, 1 piece SiC/SiC Hi-Nicalon type-S CVI SiC composite, 4mm dia. x 4mm high
D	Graphite container –TRISO, 300 particles.
E	316 SS container (liner introduced) – 316 sample size: (0.5”x0.25”x0.05”, 2 pieces)
F	Alloy N container (liner introduced) – Alloy N sample size: (0.5”x0.25”x0.05”, 2 pieces)

These tests provide a starting point to narrow choice of materials for construction of a FHTR and define future tests. However, ultimately these tests must be followed by much larger-scale tests at the HFIR reactor at ORNL and the ATR at INL.

Figure 9. Components of the FS-1 in-core capsule. Left-to-right are the outer nickel capsule, the three sections of the graphite sample and flibe holder, and, top-to-bottom on the right, the bottom graphite support/spacer, the top cover plate, and the capsule lid. The combination of the bottom spacer, top cover plate, and the pins protruding from the bottom of the lid ensure that under in-core, nuclear heating conditions, the flibe melts from the top down. The pins protruding from the bottom of the lid also ensure that the graphite rotates when the lid is screwed onto the capsule bottom. Two of these pins are hollow and will have Inconel sheathed, type-K thermocouples brazed into them. The bottom plate has a threaded hole in its center so the graphite pieces can be pulled from the nickel capsule after irradiation.

The other major component of the testing program is a series of thermal hydraulic safety experiments UCB. A series of smaller-scale experiments have been undertaken while larger test facilities are being built. The unique characteristic of these experiments is the development of a strategy that may dramatically reduce the cost and time for such experiments in development of an FHR.

Historically thermal hydraulic experiments for new reactors have been extremely expensive and time consuming: light water reactors require test rigs with high pressures, sodium cooled reactors require test rigs with high temperatures and chemically reactive sodium, and gas cooled reactors require test rigs with high pressures and high temperatures. The tests are central for design and safety analysis—one of the critical aspects in the development of any new reactor.

In the case of the FHR, organic fluids (Dowtherm) have almost identical properties at atmospheric pressure at temperatures slightly above 100°C as liquid salt coolants at 700°C. This coincidence has the potential to drastically reduce the required thermal hydraulic testing with high-temperature salts using the low-temperature stimulant. Much of the required thermal hydraulic testing can be done in facilities of relatively modest size (10 meters high) at low pressures and temperatures compared to traditional reactor development strategies. It may enable better testing and shorter development schedules for a fraction of the cost of the traditional approach. Figure 10 shows part of the large scale (10 meter high) facility that is being constructed at UCB.

Figure 10. CAD model and current fabrication status of bottom of CIET primary loop (photograph taken on 9/27/2013).

6. Conclusions

The development of a new reactor is a substantial undertaking that requires collaboration efforts among universities, national laboratories, vendors, and utilities. The early development will require significant federal funding followed by large private investments. Our goal is to layout a pathway to a commercial FHR that provides the stepping stone for a larger cooperative program. That requires (1) a base-case design to assess technical viability, (2) a commercialization strategy that defines why such investments should be made by private industry and the U.S. government, and (3) a technological pathway that begins to define the time and resources required. The general outline for that pathway was defined in 2013 using workshops, design studies, analysis, and experiments.