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# Converging Fission and Fusion Systems toward High-Temperature Liquid-Salt Coolants: Implications for Research and Development Strategies

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*Recent technology advances are creating growing interests in three nuclear technologies that require high-temperature salt coolants: (1) Fluoride-salt-cooled High-Temperature Reactors (FHRs) with solid fuel and liquid salt coolants, (2) Molten Salt Reactors (MSRs) with fuel dissolved in the salt coolant, and (3) high-magnetic-field fusion machines with immersion salt coolant blankets. The FHR is enabled by improved graphite-matrix coated-particle fuel developed for high-temperature gas-cooled reactors (HTGRs). Multiple technological advances primarily from outside nuclear engineering are improving MSR viability. A new superconductor that enables doubling magnetic fields in fusion machines may reduce fusion machine size by a factor or ten or more that, in turn, improves fusion viability and creates large incentives to use liquid salt immersion blankets for cooling, shielding and tritium production.*

*Salt coolants were originally developed for the Aircraft Nuclear Propulsion Program in the 1950s with the goal of coupling a nuclear reactor to aircraft jet engines. They can transfer heat from the reactor to the power cycle at between 600 and 700°C. Recent advances in utility natural-gas combined-cycle technologies now enable coupling these reactors to a Nuclear Air-Brayton Combined Cycle (NACC) or potentially a Nuclear Helium Combined Cycle (NHCC). NACC can provide base-load electricity with additional variable peak electricity produced by using auxiliary natural gas, biofuels, hydrogen, or stored heat to (1) increase nuclear plant net revenue by 50 to 100% relative to base-load nuclear plants and (2) enable a low-carbon nuclear renewable electricity system.*

*These developments create large incentives for cooperative research and development programs on salt coolants (corrosion, heat transfer, tritium control, etc.) and the associated power systems to advance and commercialize these three technologies.*

## I. INTRODUCTION

Two sets of developments are creating a new and rapidly growing interest in salt-cooled fission and fusion systems. The first set of developments is associated with power cycles that may enable salt-cooled reactors to provide variable electricity to the grid with base-load reactor operation—and much improved economics. The second set of developments is associated with the separate reactor developments.

In the 1950s the United States initiated the Nuclear Aircraft Propulsion program to couple a nuclear reactor to a jet engine to create a nuclear-powered bomber with unlimited range. The program resulted in the initial development of the MSR at Oak Ridge National Laboratory (ORNL). The salt coolants were designed to deliver high-temperature nuclear heat to the jet engines. The program was cancelled with the development of intercontinental ballistic missiles (ICBMs). The MSR development continued for another decade to create a nuclear power plant coupled to a steam power cycle because at that time gas turbine technology was not sufficiently developed to be practical power system for utility applications.

In the last 50 years there have been extraordinary developments in utility gas turbine combined cycle plants burning natural gas[1]. About 15 years ago the technology had advanced sufficiently to enable coupling salt-cooled reactors to nuclear air-Brayton combined cycles (NACC). Because of advances in gas turbine technology, this power cycle enables base-load nuclear electricity production with additional peak electricity produced by using auxiliary natural gas or stored heat with incremental heat-to-electricity efficiencies of 66 to 70%. When using natural gas for incremental heat, that capability increases net plant revenue by 50 to 100% after subtracting the cost of natural gas relative to a base-load nuclear plant. It potentially enables a salt-cooled reactor coupled to NACC to compete with stand-alone low-price natural gas plants and subsidized renewables. Because of the high exit temperatures from the front-end compressor of utility gas turbines, NACC requires delivery of all heat from the reactor above 500°C and thus only reactors using salt coolants efficiently couple to NACC.

In addition to the potential to couple salt-cooled reactors to NACC, a separate set of developments is increasing interest in salt-cooled reactors.

- *Fluoride-salt-cooled High-Temperature Reactor*. The FHR uses salt coolant and the graphite-matrix coated-particle fuel developed for HTGRs. Advances in the fuel are enabling the development of the FHR. Because this reactor uses a proven fuel and a clean salt coolant, it is the near-term commercialization option for a salt-cooled reactor.
- *Molten-salt-reactor*. Recent advances in chemistry, materials and neutronics have improved the capabilities and viability of reactors that use liquid salt coolants with fuel dissolved in the coolant. The liquid fuel enables a variety of different open and closed fuel cycles. Recent advances in materials may enable simplified salt processing via distillation and other techniques that (1) may simplify the salt processing associated with the fuel and (2) allow selected removal of fission products such as cesium to reduce the reactor accident source term relative to solid-fuel reactors and thus the risk of land contamination in an accident.
- *High-Magnetic Field Fusion*. In the last five years a new superconductor has become available: Rare-Earth Barium Copper Oxide (REBCO). This new superconductor enables magnetic fields in electromagnets over 20 Tesla—more than twice the capability of older superconductors. The size of magnetic fusion machines for any power level scales as one over the magnetic field to the fourth power. REBCO should enable reducing the size of fusion systems by an order of magnitude so the radius of a 500 MW plasma system is about 3 meters. It is potentially a revolution in fusion; however, increasing the power density by an order of magnitude drives the fusion machine design to a liquid blanket to generate tritium fuel because of the high power density and the need for highly efficient neutron shielding at small size. A low-electrical-conducting liquid lithium salt, rather than liquid lithium metal, is preferred to ease magneto hydrodynamic issues such as coolant pumping and plasma control.

The NACC power cycle and the three salt-cooled reactor technologies are described (Fig. 1). The implications in terms of development of pathways for liquid salt coolant technology are discussed as well as the differences in requirements for the salt cooling technologies between the different applications.

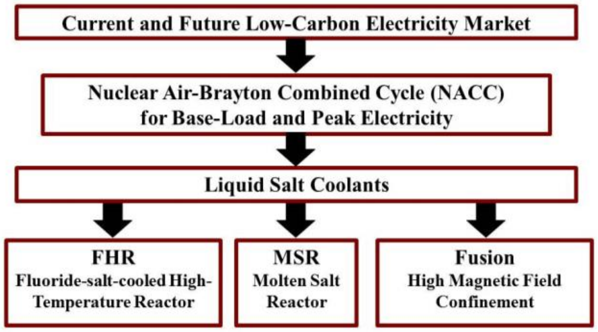

Fig.1. Basis for Liquid Salt Technology Development

## II. NUCLEAR AIR-BRAYTON COMBINED CYCLE (NACC)

Advances in gas turbine technology now enable coupling a high temperature reactor to a nuclear air-Brayton combined cycle (NACC).[2, 3, 4, 5] Such a power system can operate in two modes: base-load and peak electricity (Fig. 2). Nuclear heat is used for base-load electricity production. Additional heat for peak electricity production can be provided by natural gas (near-term), stored heat, or ultimately hydrogen. During base-load operation of a NACC, atmospheric air is filtered, the air is compressed, heat is added from the reactor through a coiled-tube heat exchanger (CTHX), the hot compressed air goes through turbines to produce electricity, the warm air exiting the gas turbine goes through a heat recovery steam generator to generate steam that is used to produce added electricity, and the air is exhausted to the stack. Depending upon the specific design, there may be one or more stages of nuclear reheating of the compressed gas followed by a power turbine before exiting to the steam generator. This is the same basic power cycle as used in natural gas combined-cycle plants. If coupled to a salt-cooled reactor delivering heat between 600 and 700°C, heat-to-electricity efficiency is 42%. This specific example uses a modified General Electric 7FB gas turbine.

The base-load NACC temperatures, determined by heat-exchanger materials constraints, are far below allowable peak gas turbine temperatures. Thus, there is the option of adding heat after the nuclear heating to further raise compressed gas temperatures before entering a power turbine—a topping cycle. The incremental heat-to-electricity efficiency depends upon the design, ranging from 66 to 70%. This is the most efficient system known to convert heat to electricity based on existing technology.

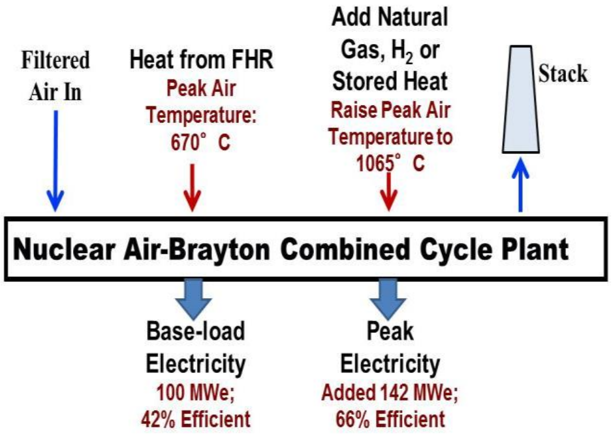

Fig. 2. Nuclear Air-Brayton Combined Cycle (NACC)

An economic analysis[6] was done of the performance of an FHR with NACC in California and Texas using natural gas to produce peak electricity. These states have deregulated electricity markets. The peaking capability increased the plant yearly revenue by about 50% after subtracting the cost of the natural gas compared to a base-load nuclear plant. Because NACC is more efficient than a stand-alone natural-gas combined cycle plant in converting natural gas to electricity (uses less natural gas), its electricity production costs for peak electricity are less than a stand-alone natural gas plant; thus, it earns large profits when electricity prices are set by natural gas plants in competition with stand-alone natural gas plants.

The addition of wind and solar in some electricity grids has resulted in significant hours per year with very low electricity prices—near zero at times of high wind or solar input.[7, 8, 9] In such utility systems it is proposed that a Firebrick Resistance-Heated Energy Storage (FIRES) system replace the use of natural gas for providing heat to produce peak electricity. FIRES consists of high-temperature firebrick heated to high temperatures with electricity at times of low or negative electric prices. 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 hot firebrick and 66% efficiency in conversion of incremental heat to electricity within NACC. FIRES enables the reactor to operate at base-load at all times while the station buys electricity from the grid at times of low prices (electricity prices less than natural gas) to charge FIRES and sells electricity at times of high prices.

The rapid advances in gas turbine technology indicate NACC will have peak incremental heat-to-electricity efficiencies above 70% within a decade. The new "H-Class" natural gas combined cycle plants are just beginning to be introduced with outputs above 500 MWe—thus the ability to design NACC to couple to large reactors if desired. The water cooling requirements for combined cycle plants are ~40% of a light-water reactor (LWR) because much of the heat rejection is by warm air versus cooling towers from the steam cycle.

There is a second potential power cycle—a Nuclear Helium Brayton Combined Cycle (NHCC). Very little work has been done on this option. The potential attraction is that the closed power cycle provides an additional barrier for isolation of radionuclides (primarily tritium) from the environment. It could incorporate FIRES for peak electricity but not natural gas.

## III. SALT-COOLED FISSION AND FUSION REACTOR OPTIONS

There are three salt-cooled fission and fusion reactor options capable of delivering the high-temperature heat required by NACC—and thus the potential for improved economics based on increased power plant revenue.

### III.A. Fluoride-salt-cooled High-temperature Reactors (FHRs)

There are many proposed FHR designs but all have two defining features: fuel and coolant. The fuel consists of tri-structural isotropic (TRISO) coated-particle fuel embedded in a graphite matrix—the same fuel used in high-temperature gas-cooled reactors (HTGRs). The power densities in the salt-cooled FHR are higher than in HTGRs because liquids are better coolants than gases. Like the HTGR, FHRs are thermal neutron spectrum reactors. Three different fuel designs are proposed by different groups (Fig. 3).

- *Pebble bed*. The pebble-bed FHR[10] uses 3-cm diameter graphite pebbles with embedded coated-particle fuel—the same basic fuel that was used in the German HTGRs and will be used in the Chinese HTGRs that are under construction. The pebbles are 3-cm rather than the traditional 6-cm diameters used in HTGRs to increase surface area per unit volume of the core to allow higher power densities. The pebble-bed FHR design is the most developed. The Chinese Academy of Sciences plans to complete a 10 MWt pebble-bed FHR test reactor by 2020. Like pebble bed HTGRs, this design allows online refueling. It is the near-term option.
- *Plate fuel*. Oak Ridge National Laboratory[11] is developing a plate fuel where the hexagonal fuel assembly is similar in shape to a sodium-cooled reactor fuel assembly. The fuel plates are made of a carbon composite with the coated-particle fuel on the plate surfaces. It is a "traditional" type fuel assembly with a refueling strategy similar to a sodium fast reactor—another low-pressure reactor.
- *Fuel Inside Radial Moderator (FIRM).*[12] This FHR core design is somewhat similar to the operating British Advanced Gas-Cooled Reactors (AGRs) except for use of salt coolant, higher power densities and the details of the fuel design. The AGRs are graphite-moderated carbon-dioxide-cooled high-temperature reactors with exit gas temperatures of 650°C. The AGR fuel consists of $UO_2$ pellets in stainless steel pins with an assembly consisting of a circular array of pins inside an annular graphite shell. Fourteen AGRs have been operating for several decades. The FHR FIRM assembly replaces the AGR fuel assembly with a graphite cylinder containing liquid-salt cooling channels and fuel channels filled with coated-particle fuel in carbon-matrix pellets—a cylindrical variant of the prismatic fuel blocks used in some HTGRs. FIRM assemblies would be refueled using the same refueling strategies used by the AGR, pulling assemblies straight up through the vessel cover. AGRs refuel on-line at about 650°C, similar to FHR temperatures.

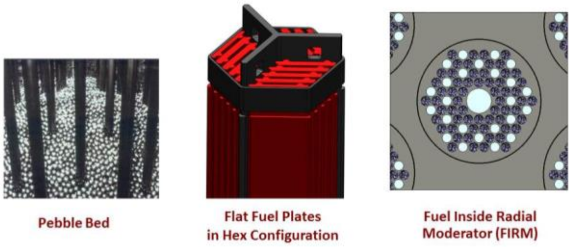

Fig. 3. Alternative FHR Fuel Designs

The base-line coolant is a lithium-beryllium-fluoride salt known as flibe ($^7Li_2BeF_4$). The characteristics of the flibe as well as other potential salts are listed in Table 1. The primary coolant system is a closed loop that operates at atmospheric pressure with nominal core coolant inlet and outlet temperatures of 600°C and 700°C respectively.

TABLE I. FHR Coolant Options[1]

| **Coolant** | **$T_{melt}$ (°C)** | **$T_{boil}$ (°C)** | **ρ (kg/m$^3$)** | **ρ$C_p$ (kJ/m$^3$ °C)** |
|---|---|---|---|---|
| **66.7 $^7$LiF-33.3BeF$_2$** | **459** | **1430** | **1940** | **4670** |
| 59.5 NaF-40.5 ZrF$_4$ | 500 | 1290 | 3140 | 3670 |
| 26 $^7$LiF-37 NaF-37 ZrF$_4$ | 436 | | 2790 | 3500 |
| 51 $^7$LiF-49 ZrF$_4$ | 509 | | 3090 | 3750 |
| Water (7.5 MPa) | 0 | 290 | 732 | 4040 |

[1] Compositions in mole percent. Salt properties at 700°C and 1 atmosphere. Pressurized water data shown at 290°C for comparison

Figure 4 shows a schematic of a pebble-bed FHR. The FHR would have the traditional safety systems of a sodium fast reactor: active decay heat cooling systems and a decay heat reactor auxiliary cooling system (DRACS). Work is underway to develop a beyond-design-basis-accident (BDBA) system[13] that assures no major fuel failures in extreme accidents including accidents with reactor vessel failure. It is based on the very high-temperature fuel performance of fuel and coolant. The peak fuel temperature is ~800°C with a fuel failure temperature above 1650°C. The nominal peak coolant temperature is 700°C, and the coolant boils above 1400°C. The BDBA system is based on driving decay heat in a severe accident from the reactor core to the environment while keeping peak fuel temperatures below fuel failure temperatures.

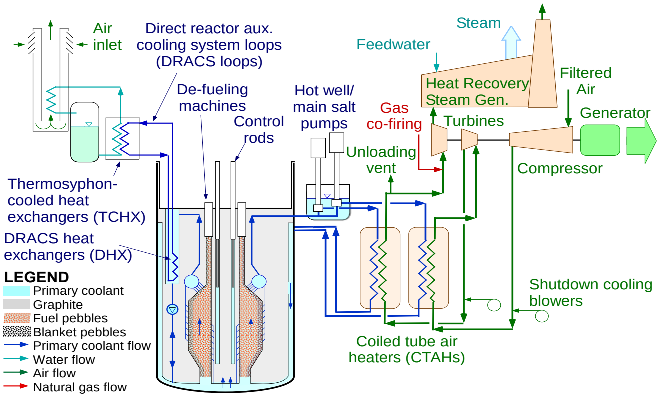

Fig. 4 Pebble-bed FHR Process Schematic Coupled to NACC

A recent study examined fuel cycle options.[14] The base-case fuel cycle is a once-through fuel cycle similar to HTGRs. The graphite-matrix coated-particle SNF has outstanding performance in repository environments and better proliferation-resistance characteristics than other types of SNF. There are options to recycle FHR SNF but these are more challenging than for other types of SNF because the chemical and physical characteristics of the fuel that enable high-temperature operations and accident tolerance also make recycle more difficult.

### III.B. Molten Salt Reactors (MSRs)

Molten salt reactors were first developed as part of the nuclear aircraft propulsion program in the 1950s and then as a thermal-neutron-spectrum breeder reactor using the thorium fuel cycle in the 1960s. The Molten Salt Reactor Experiment (MSRE), an 8-MWt reactor (Fig. 5), successfully demonstrated the technology in the late 1960s. This reactor used flibe ($^{7}Li_2BeF_4$) salt with fuel and fission products dissolved in the salt. The reactor used bare graphite as the neutron moderator. The program was cancelled in the early 1970s when the United States decided to focus its breeder reactor program on sodium-cooled fast reactors (SFRs). In the last decade[15, 16] there has been a renewed interest in MSRs by companies such as Terrapower and Hatch for several reasons.

Fig. 5. Molten Salt Reactor Experiment

- *Advancing technology*. Many of the technology challenges of the 1960s have been reduced or eliminated thanks to advances in other fields. Better high-temperature carbon composites may provide better materials for reactor internals and enable high-temperature (>1000°C) distillation to simplify removal of fission products from the liquid fuel salt. The development of high-temperature additive manufacturing enables fabrication of complex components including control rods, distillation columns, and other items out of molybdenum and other salt-compatible high-temperature materials. Advanced carbon and metal absorbers may enable efficient removal of noble metal fission products from the molten salt. Unless removed, these fission-product metals plate out on heat exchanger surfaces, are a major source of short-term decay heat, and cause multiple challenges. Last, advances in metallurgy may enable development of more corrosion resistant materials in an environment that includes most of the periodic table.
- *Fast-spectrum MSRs*. The last decade has seen the development of fast-spectrum MSRs using new salts containing (1) primarily lithium and thorium or uranium fluoride [no beryllium] or (2) chloride salts. These reactors can use traditional fast reactor plutonium fuel cycles. Figure 6 shows a schematic of the European SAMOFAR fast reactor concept.

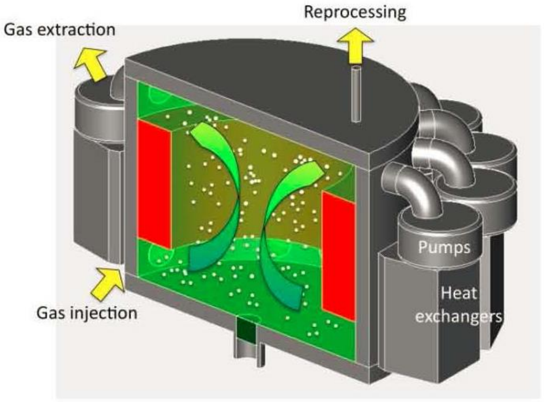

Fig. 6. Fast Spectrum Molten Salt Reactor: European SAMOFAR Concept

The safety strategies of MSRs are different than solid fuel reactors. First, in most designs if the fuel salt overheats, solid fuse plugs melt and the liquid salt drains to critically safe, passively-cooled dump tanks. Second, depending upon the design, selected fission products can be removed continuously that reduces the reactor radionuclide source term—an alternative safety strategy. This may include the option to remove cesium and other radionuclides that in severe accidents are the primarily responsible for land contamination. The separated radionuclides must be converted into a stable waste form and sent to a passively-cooled storage facility—otherwise one is only transferring the accident source term from the reactor to the chemical processing facility. This possibility is enabled by new separation options such as high-temperature distillation of the fuel salts enabled by high-temperature materials of construction.

MSRs provide a wide choice of fuel cycles, including the possibility of burning actinides as part of a waste management strategy. In the last several decades various options to convert the various wastes into acceptable waste forms have been developed.

### III.C. High Magnetic-field Fusion Reactors

The size of magnetic fusion devices for any given fusion power level is determined by the maximum feasible magnetic field with the size proportional to one over the magnetic field to the fourth power. Practical fusion machines require superconducting wire or tape to generate the magnetic fields to minimize electrical consumption by the magnets. However, standard superconductors lose their superconducting properties in high magnetic fields. In the last five years a new superconductor has been developed: Rare-Earth Barium Copper Oxide (REBCO). This new superconductor enables magnetic fields at the coil over 22 Tesla—more than twice the capability of older superconductors. It eliminates magnetic field strength as the primary design constraint in magnetic confinement fusion devices with the new limit being magnetic field induced stress in the coils. The REBCO is in the form of a steel tape that enables addressing the high stresses.

REBCO superconductors may enable doubling the practical peak magnetic field in a fusion machine and thus reduce the volume of fusion systems by an order of magnitude. The radius of a 500 MW plasma fusion system would be about 3 meters—the size of several existing magnetic fusion devices. Figure 7 shows JET (an existing fusion experimental device in the United Kingdom) and the proposed high magnetic field fusion system based on REBCO superconductors.[17] It is potentially a revolution in fusion.

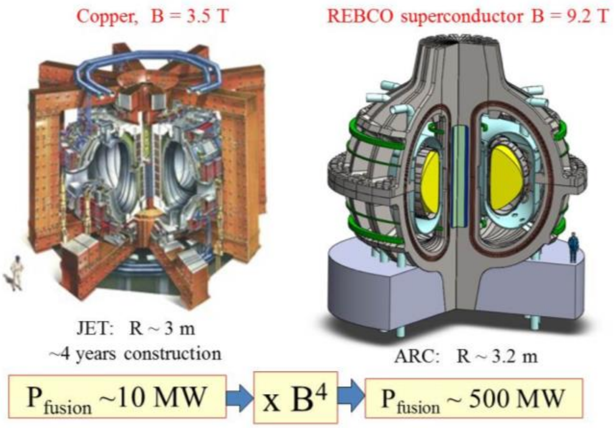

Fig. 7. Impact of Higher-Field Superconductors on the Size of Magnetic Fusion System

Increasing fusion power density by an order of magnitude dramatically improves the potential long-term economic viability. However, it imposes major changes in fusion blanket design because of the much higher power densities. Historically proposed blankets have been solid lithium-containing materials. The higher power densities may require changing to a liquid blanket containing lithium—most likely flibe (66.7$^6$LiF-33.3BeF$_2$).

- *Radiation shielding*. A liquid blanket is needed for highly efficient neutron shielding with such high plasma fusion power densities. There must be no leaks (cracks) in the blanket because the higher radiation levels would quickly destroy the superconductors. Liquids have no cracks.

- *Tritium production*. The fuel in fusion is tritium. To generate the tritium the fusion machine has a lithium-6 blanket. Historically the proposed blankets have been solid lithium-containing materials. Increasing power density by a factor of ten increases radiation damage to such solids by a factor of ten. Ionic liquid salts do not undergo radiation damage. The fusion neutrons must be slowed down to convert lithium-6 in the blanket to produce the required tritium fuel. The low-Z uniform composition in a liquid salt blanket aids neutron thermalization. These considerations support the use of a liquid salt (flibe) blanket for tritium production.
- *Cooling*. Fusion generates about 17 MeV per fusion of tritium and deuterium—most of this energy is in the form of 14 MeV neutrons. Liquid shielding enables efficient cooling as 14 MeV neutrons slow down and deposit their energy as heat in the liquid.

The liquid coolant must contain lithium-6 that is converted into tritium, the fuel for the fusion machine. The coolant choices are (1) fluoride coolant salts—most likely flibe or (2) a liquid metal coolant containing lithium (lithium, lead-lithium, etc.). A low-electrical-conducting liquid salt rather than liquid lithium or a lead-lithium eutectic is preferred to ease magneto hydrodynamic issues such as coolant pumping and plasma control because the magnetic fields produced by external coils more rapidly penetrate through the blanket. The liquid immersion blanket also has highly favorable safety properties in that the activated material/tritium boundary becomes a simple, atmospheric-pressure containment vessel. This stands in stark contrast to standard solid fusion blanket designs, where the vacuum vessel serves as both the vacuum and safety boundary while simultaneously providing the mechanical support for the blanket modules.

## IV. IMPLICATIONS FOR SALT TECHNOLOGY DEVELOPMENT

There are common requirements for the salt coolants for all of the reactor concepts. If these reactors are coupled to NACC, there are an additional set of common requirements. These common requirements create large incentives for synergistic cooperative development programs for liquid salt coolants in nuclear systems.

In terms of the NACC power cycle, the gas turbine would be a derivative of one of the commercial combined cycle plants at the time the reactor is commercialized. The major new component within NACC is the liquid salt/compressed-air heat exchanger that is located after the main compressor. There was a major experimental program to develop such heat exchangers as part of the Aircraft Nuclear Propulsion Program. However there are some important differences between an aircraft jet engine and NACC: (1) a commercial NACC and associated heat exchanger will be far larger than what was developed for the ANP program, (2) weight and size are not major constraints for NACC, and (3) there will be large incentives to improve efficiency because NACC will operate with a high capacity factor relative to an aircraft jet engine.

Table II summarizes some of the differences and similarities in salt coolant requirements between the different reactor concepts. Carbon in the system can have a large impact on system behavior because carbon can absorb tritium and other impurities in the salt and has other chemical impacts.

Table II. Salt Characteristics of Different Systems

| Property | FHR | MSR | Fusion |
|---|---|---|---|
| Salt | Fluoride | Fluoride or Chloride (fast spectrum only) | Fluoride |
| Impurities | Corrosion impurities and possible fission product impurities | High concentrations of fission products and actinides | Corrosion impurities |
| Use lithium salts | Optional | Depends upon goals | Required |
| Tritium production | Small ($^7$Li in Coolant) | Small ($^7$Li in Coolant) | High ($^6$Li in Coolant) |
| Tritium value | Waste | Waste | Fuel |
| Carbon in system | Yes | Depends upon option | No |
| Redox control | $Ce^{+2}/Ce^{+3}$, other | $U^{+3}/U^{+4}$ | $Ce^{+2}/Ce^{+3}$, Be, other |

The different reactors impose different constraints on the salt. In MSRs one must assure high solubility of fission products and actinides. Because nuclear absorption cross sections are less in fast neutron spectrums than thermal neutron spectrums, a fast-spectrum MSR may use chloride salts. Fusion has the requirement to breed tritium, the fuel. This requires salt with a high lithium content and makes flibe the preferred salt. There are multiple salt choices for the FHR (Table I)

There are common challenges for all salt-cooled nuclear systems that define a common research and development agenda.

- *Thermal hydraulic testing*. Developing and understanding thermal hydraulic behavior of high temperature salts is central for all reactor concepts. There are two differences relative to other reactor coolants. First, about a decade ago it was discovered that certain organics (Dowtherm A®, etc.) have thermal hydraulic behavior at less than 100°C that almost exactly duplicates high temperature salts near 700°C. This coincidence enables low-temperature low-cost thermal hydraulic studies using these fluids to provide much of the experimental thermohydraulic data that previously would have required high-temperature test loops. Second, high-temperature salts are transparent over much of the thermal spectrum. Radiation heat transfer becomes important above 600°C. Because radiation heat transfer increases as the fourth power of the absolute temperature, this enhanced heat transfer mechanism becomes important at higher temperatures—something not important with other reactor coolants. Furthermore, the emissivities of component surfaces change as a function of temperature. Historically only glass melters had semi-transparent fluids where radiation heat transfer was important. This requires measuring optical properties of the salts and development of heat transfer codes that fully account for radiation heat transfer.
- *Corrosion control*. The corrosion potential of liquid salts is dependent upon redox control and thus the need to control redox potential—a similar challenge for all salt-cooled systems. This requires methods to accurately measure redox on line, adjust redox, and hold a particular redox potential in the liquid salt—the equivalent to pH and oxidation potential control in light water reactors. New methods have been recently developed for redox measurement in high-temperature salts. Redox control for MSRs is usually done by control of the ratio of $U^{+3}/U^{+4}$ that assures uranium and other actinides remain in solution. In the FHR and fusion machines, other redox control strategies are required such as use of $Ce^{+2}/Ce^{+3}$, hydrogen or beryllium. The choice of redox agent is dependent upon the materials in the system. Beryllium creates highly reducing conditions that may be used in fusion machines[18, 19] but there are unanswered questions on whether it is viable with systems containing carbon because of the potential of creating carbides.
- *Mechanical equipment*. All of the reactor concepts have similar requirements for mechanical equipment such as pumps and valves. The FHR and MSR require control rods. High-temperature carbon composites may provide better materials for reactor internals, valve packings and seals. Valves have been a challenge because these salts dissolve oxide coatings and at high temperatures there is the potential for clean metal surfaces to diffusion weld if compressed together—as in a closed valve. The development of carbon-based seals for the chemical industry may be directly applicable to salt systems but development requires significant test programs and development of industrial supply chains.
- *Instrumentation*. The unique feature of salt coolants versus other reactor coolants is that the pure coolants (FHR and fusion) are nearly transparent and MSR coolants with dissolved fission products are semi-transparent. Those properties enable monitoring the chemical properties (redox, impurity levels, etc.) using on-line spectrometry. Laser measuring technologies may enable measuring fluid velocities as well as inspection of surfaces through the hot salt. Temperature can be measured remotely by the light signal. It may also be possible to measure power levels by light emission from the salt under neutron and gamma ray radiation. All of these options require a much better understanding of the optical properties of the salts as a function of frequency and temperature.

- *Lithium isotopic separation*. Many of the salt coolants being considered for the FHR and MSR contain lithium to reduce the melting points of the salts. For these applications one uses isotopically-separated $^{7}$Li to avoid the high parasitic neutron capture by $^{6}$Li, subsequent generation of $^{3}$HF and generating radioactive tritium gas that can escape from the reactor. For fusion one wants to use isotopically-separated $^{6}$Li to maximize tritium production. There have major advances in the isotopic separation of lithium isotopes that may dramatically reduce isotopic separation costs. Furthermore, lithium isotopic separation may be commercialized to produce lithium-6 on an industrial scale for high-performance lithium batteries for aerospace applications. Such scale up in production would reduce lithium isotopic separation costs by one to two orders of magnitude. The power output of a lithium ion battery depends upon the chemical diffusion rate of the lithium ion. The diffusion rate is significantly higher for $^{6}$Li than $^{7}$Li implying higher-performance light-weight batteries. This is an area of both R&D and development of industrial supply chains for multiple industrial customers.
- *Tritium control*. Any salt-cooled reactor with lithium or beryllium in the salt will generate tritium. This must be removed to prevent escape to the environment or in the case of fusion machines, efficiently recovered to use as fuel. It is a common challenge for all salt-cooled systems. Recent studies[20] have developed full system models for tritium in FHRs. Some of the tritium removal options such as carbon beds may remove fission product gases (Kr/Xe) and noble metals in a MSR system.
- *Low-pressure operation*. The great advantage of these systems is the low pressure—avoiding the difficult engineering challenge of high-temperatures and high mechanical stresses. This does require pressure relieve valves or other mechanisms to avoid over pressurization of the primary circuit—like sodium fast reactors. NACC has the lowest operating pressure of any proposed power conversion system that reduces these challenges.

There is also an overlap in liquid salt technologies for nuclear reactors and several advanced solar power technologies—particularly a system called Concentrated Solar Power on Demand (CSPonD). In this system, hundreds of hillside heliostats shine light down through a single ~3-meter-diameter hole in the roof of an insulated tank filled with liquid salt. The light is absorbed as it travels through the salt with hot salt sent to the power cycle that could be a gas turbine. The salt temperatures may exceed 700°C. The high temperatures and efficiencies relative to other solar thermal systems are possible because the sunlight effectively enters through a 3-meter diameter pin hole that minimizes radiation losses to the sky relative to conventional solar power towers. Many of the salt handling and instrumentation challenges are similar to those faced in salt-cooled nuclear systems.

## V. CONCLUSIONS

The electrical market is changing with large incentives to develop base-load nuclear reactors with variable electricity to the grid to (1) improve economics and (2) enable a low-carbon electricity grid. Technological advances have created a pathway to such systems that combine nuclear air-Brayton combined cycles with high-temperature salt-cooled high-temperature reactors. Because natural-gas combined-cycle technology is improving rapidly, the economics of high-temperature reactors coupled to NACC is improving rapidly. NACC nuclear-heat-input temperature requirements drive the decision to use liquid salt coolants—the coolants that were designed originally to couple nuclear reactors to jet engines. The near-term reactor option is the FHR with longer-term MSR and fusion options. There have been major advances in FHR, MSR, and high-magnetic-field fusion reactors in the last several years—a fortunate coincidence. The combination of advancing gas turbine and reactor technologies creates large incentives to accelerate development of the common salt coolant technologies.

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