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An Advanced Molten Salt Reactor Using High-Temperature Reactor Technology

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Abstract—*Molten salt reactors (MSRs) are liquid-fueled reactors that can be used for burning actinides, producing electricity, producing hydrogen, and producing fissile fuels (breeding). Fissile, fertile, and fission products are dissolved in a high-temperature, molten fluoride salt with a very high boiling temperature (~1400ºC). Two reactors were successfully built and operated in the 1950s and 1960s. A detailed conceptual design of a 1000 MW(e) reactor was developed. There is renewed interest in MSRs because of changing goals and new technologies. Three technologies, partly or fully developed since the 1970s, have been identified that may dramatically improve the economics and viability of MSRs: Brayton helium power cycles, compact heat exchangers, and carbon–carbon composites. All three technologies are being developed for high-temperature reactors. This paper describes how each of these technologies may remove major technical challenges, improve the performance, expand the potential missions, and improve the fundamental economics of the MSR. The new technologies become the enabling technologies for an Advanced Molten Salt Reactor (AMSR).*

1. INTRODUCTION

Molten Salt Reactors (MSRs) were first developed in the late 1940s and the 1950s in the United States for military jet aircraft propulsion.[1] In 1954, the 2.5-MW(t) Aircraft Reactor Experiment (ARE) demonstrated high-temperature operation and established benchmarks in performance for a circulating fluoride molten salt ($NaF-ZrF_4$) system with the uranium dissolved in the salt.

Although a nuclear aircraft was never deployed, the ARE was followed in the 1960s by a program[2] to develop a molten salt breeder reactor. The MSR Experiment, an 8-MW(t) reactor, demonstrated many of the features required for a power-generating reactor: (1) a $^7LiF-BeF_2$ salt suitable for breeding applications; (2) graphite moderator compatibility with the fluoride salt; (3) stable performance; (4) removal of xenon and krypton from the fuel and subsequent trapping in the off-gas systems; and (5) the use of different fuels, including ^{235}U, ^{233}U, and plutonium. The MSR Experiment successfully operated for 13,000 equivalent full-power hours between 1965 and 1968. A detailed 1000-MW(e) engineering conceptual design of a molten salt breeder reactor was developed. The programs of the1950s and 1960s demonstrated the key technical features of these concepts. The MSR program was later canceled when the United States decided to concentrate its reactor development program on the sodium fast reactor (SFR). Work to develop pyro-reprocessing methods for the SFR further developed methods for dissolving and transporting fuel in high-temperature molten salts, and addressed many of the safety and nonproliferation issues for handling fuel in a liquid, molten-salt form.

A schematic of an MSR is shown in Fig. 1. The fluoride molten salt with dissolved fissile, fertile, and fission isotopes flows through a reactor core moderated by unclad graphite to a primary heat exchanger, where the heat is transferred to a secondary molten salt coolant. The fuel salt then flows back to the reactor core. The fission heat is deposited directly in the molten fuel. In traditional MSR designs, the liquid fuel salt enters the reactor vessel at 565EC and exits at 705EC and -1 atmosphere (coolant boiling point: -1400EC). The reactor and primary system are constructed of modified Hastelloy-N or a similar alloy to provide corrosion resistance to the molten salt. Volatile fission products (e.g., krypton and xenon) are continuously removed from the fuel salt. Fission products may be removed with on-line processing of the salt, or the salt may be sent off site for processing. A secondary coolant loop transfers the heat to the power cycle. In any type of accident scenario, the fuel is drained to passively cooled, critically safe fuel storage tanks. Typically, the drain valves are freeze valves (actively cooled) that open if the salt temperature exceeds its operational limit.

MSRs have several unusual characteristics[3]: (1) the wastes have very low levels of long-lived actinides, (2) the inventories of fissile materials per unit of energy are lower than those of any other reactor system, (3) the dispersible inventory [source term] of radionuclides in the reactor can be made less than that of any other reactor, (4) fuel costs are very low compared to solid-fuel reactors, and (5) there are large economics-of-scale with the potential to build very large reactors with low per-megawatt capital costs. These intrinsic reactor characteristics address current concerns about waste management, fissile resources, safety, and economics.

New developments in technology have reduced or eliminated some of the technical challenges, improved the performance, and improved the economics. As a consequence of changing goals and potentially major improvements in the technology, the MSR is one of the six advanced reactor concepts identified by the Generation IV International Forum as a candidate for cooperative development.

This paper describes some of the key technical challenges of the MSR and how the newly developing technologies that may dramatically improve both economics and viability of the MSR. A more detailed description of each new technology is then provided.

II. TECHNICAL CHALLENGES

By the 1970s, the MSR was a workable concept that could be built; however, there were major complications. Three technologies, now being developed for high-temperature reactors[4,5] have the potential to dramatically improve the viability of MSRs. The implications of these technologies to MSR design are described herein.

II.A Brayton Power Cycles

The 1970s designs of the MSRs used the Rankine (steam) cycle. This was the only technology available at the time. There were multiple complications.

- *Tritium*. As a liquid-fuel reactor, tritium from fission remains in the salt. Additional tritium is produced by neutron irradiation of the fuel salt. This tritium can diffuse through high-temperature heat exchangers into the steam cycle, resulting in tritium-contaminated water that presents an exposure issue for workers and a waste management issue. No easy way exists to manage steam with tritium. This tritium contamination created complications similar to those associated with managing tritium in heavy water reactors.

- *Temperature mismatch*. To obtain good salt physical properties for operations, MSRs operate above 500EC. At low temperatures, the salt may freeze. At the high temperatures preferred by molten salt systems, steam is highly corrosive. While designers were able to develop a workable steam cycle for the MSR, the cycle was complex and the power plant efficiency was less than would be expected for a reactor with coolant exit temperatures in excess of 700EC. High-temperature heat was not efficiently utilized.

- *Chemical reactions*. Salts slowly react with steam.

The use of closed Brayton power cycles with MSRs reduces or eliminates all of these issues. Tritium is easily removed from the nitrogen or helium Brayton cycle in the cold parts of the cycle. The desired operating temperatures of molten salt systems match the temperatures preferred by Brayton cycles. No chemical reactions occur between nitrogen or helium and molten salts.

II.B Compact Heat Exchangers

The 1970s designs of MSRs used tube intermediate heat exchangers. This was the only technology available at the time, and it resulted in two complications.

- *Fuel inventory*. In an MSR, the fuel is dissolved in the salt that goes from the reactor core to the intermediate heat exchangers and back. The fuel inventory depends upon the salt volume in the reactor core and the heat exchanger. Typically, for those early designs, half of the fuel salt was in the heat exchangers and pumps. The cost of the fuel, the cost of processing the fuel salt inventory, the size of salt storage tanks, and many other plant characteristics are directly proportional to the inventory of fuel salt. Big heat exchangers resulted in large inventories of fuel salt.

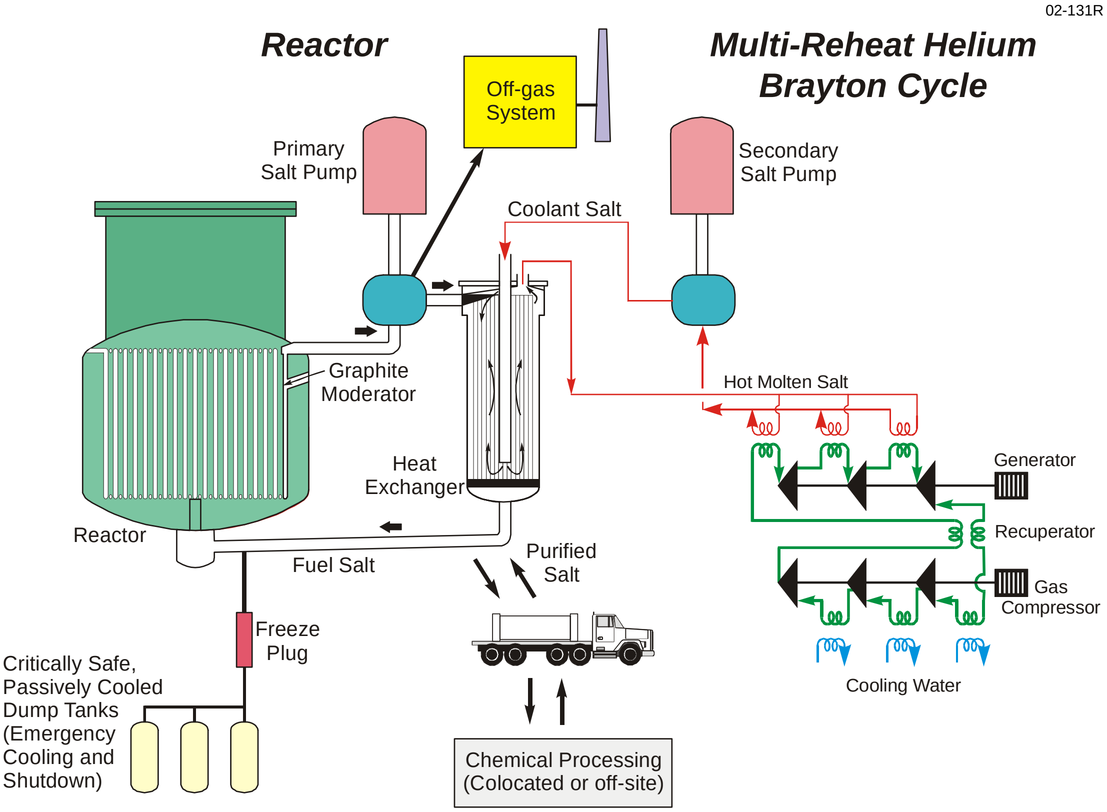

Fig. 1. Molten salt reactor.

- *Size*. Unlike solid-fuel reactors, the primary heat exchangers are in contact with highly radioactive fluids. The heat exchangers are located in the equivalent of a hot cell. Large heat exchangers have a major cost penalty in addition to that associated directly with the cost of the heat exchanger.

The development of compact heat exchangers may reduce the total fuel salt inventory to 60% or less of traditional MSR designs. The heat exchanger volume shrinks by a factor of 5 or more. Major improvements in plant layout are possible. This technology has been developed for severe operations such as those associated with offshore oil production. Compact heat exchangers can be built of metals (www.heatric.com) or carbon-carbon composites.

II.C Carbon-Carbon Heat Exchangers

The metals of construction for the MSRs were high-nickel alloys. There were corrosion issues that were ultimately addressed successfully by the development of a modified Hastelloy-N alloy. There are two limitations.

- *Operating temperatures.* Hastelloy-N can operate up to ~750EC. The alloy’s strength is insufficient for higher temperatures. The reactor core and system performance improve with higher temperatures. For hydrogen production and similar missions, higher temperatures are needed.

- *Noble metal plate out.* The fission products include noble metals that form multiatom clusters in the molten salt. Unlike other elements, noble metals are not soluble in the molten salt.

> Ultimately, these noble metals plate out on metal surfaces such as those of heat exchangers. The noble metals produce significant decay heat. If the plate out of noble metals is excessive, the decay heat from the noble metals may damage the heat exchangers by overheating them if a loss of cooling occurs. This type of accident is not likely to be a major safety concern because the heat exchanger and noble metals can reach very high temperatures without releasing radioactivity. However, plate out is a major design and operational issue. Systems are proposed to remove the noble metals from the molten salts, but to keep the noble metal plate out low on metal heat exchangers (with their massive surface area), the salt processing rates must be high.

The development of carbon-carbon heat exchangers may eliminate both of these constraints. Industrial experience shows that graphite-based materials are compatible with molten salts at 1000EC for periods of decades. Short-term tests have demonstrated that molten salts are compatible with graphite at 1400EC. Molten fluoride salts do not easily wet graphite; thus, plate out of noble metals is expected to be significantly reduced, allowing trapping systems to remove most of the noble metals. Carbon-carbon composite heat exchangers are a new technology, but this type of heat exchanger would be an enabling technology to allow operating temperatures in excess of a 1000EC, bringing about major improvements in plant efficiency.

Higher temperature operation has one other advantage. The solubility of various actinides increases with temperature. This provides greater safety margins against precipitation of solids in the salt under accident conditions. For example, recent measurements[6] indicate that the solubility of PuF_3 in FLIBE increases from 0.35% at 525ºC to 1.22% at 675ºC.

III. BRAYTON CYCLES

For an AMSR, a 2400 MW(t) reference point design[7] of a multi-reheat helium Brayton cycle[8] was developed. It was derived from the current power conversion unit (PCU) design for the General Atomics gas-turbine modular helium reactor (GT-MHR). As shown in Fig. 1, the high-pressure helium is heated to its peak temperature, flows through a turbine to reduce its pressure by a third, reheated again to its peak temperature, flows through a second turbine to reduce its pressure by another third, reheated again to its peak temperature, and flows through the last turbine. It is then compressed through three stages of compression with inter-stage cooling.

Figure 2 shows a schematic representation of the Brayton cycle flow configuration with the system compartmentalized into three turbine-compressor modules and separate recuperator module. This configuration allows for a 2400 MW(t) high-temperature Brayton cycle that uses three PCUs similar in size and configuration to those proposed for the General Atomics GT-MHR, a 600 MW(t) modular gas-cooled reactor. In this specific example, the turbine inlet temperature is 900°C, resulting in a thermal efficiency of 54% [1300 MW(e)]. The General Atomics GT-MHR PCU is used as the basis for the design because it has turbo machinery that is large enough to extrapolate to a >1000 MW(e) power conversion system for a MSR.

Analysis shows that, with relatively small engineering modifications, multiple GT-MHR PCUs can be connected to create a Brayton power conversion system in the >1000 MW(e) class. To do this, compact, intermediate salt-to-helium heat exchangers (power densities from 80 to 120 MW/m^3) are inserted into the annular space around the turbines (currently occupied by the upper set of recuperator heat exchangers in the GT-MHR design) and the Brayton-cycle recuperator is moved to a separate pressure vessel. The resulting configuration is quite compact, resulting in what is probably the minimum helium duct volume possible for a multiple-reheat, closed Brayton-cycle system.

Table I shows the resulting design parameters for two MSR systems and reference parameters for the GT-MHR system. The GT-MHR PCU produces 285 MW(e) with an 850°C turbine inlet temperature and a PCU power density of 230 kW(e)/m^3. Based on the same turbo machinery parameters, the high-temperature helium MSR Brayton cycle is predicted to achieve a power density of 360 kW(e)/m^3. Because the MSR power conversion system can be located in conventional structures instead of within the nuclear safety envelope, the MSR PCU capital cost per kW(e) will be about half that of the GT-MHR PCU. Parallel studies were conducted on a system with a peak Brayton-cycle temperature of 600ºC with the same molten fuel salt temperatures (705ºC peak temperature) in traditional designs of MSRs. For the lower-temperature system, the power density was 250 kW(e)/m^3 (vs 360 kW(e)/m^3,and the overall plant efficiency was 44% (vs 54%).

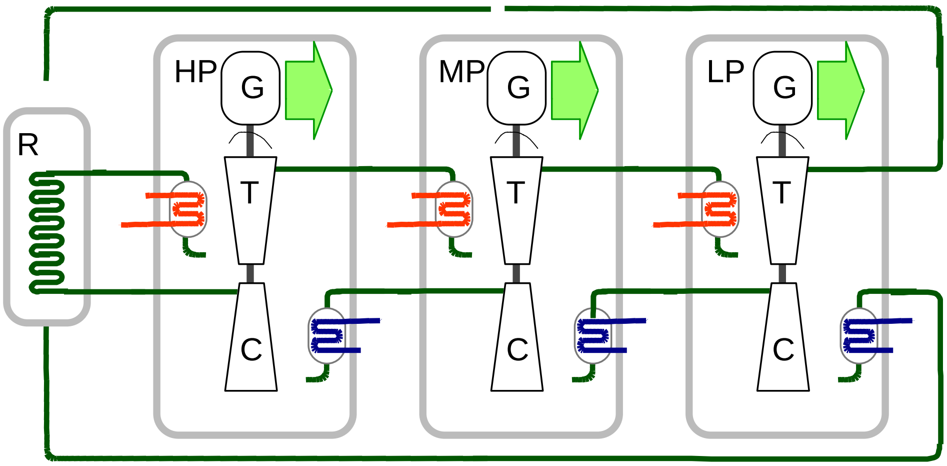

Fig. 2. Schematic flow diagram for the reference three-expansion-stage Brayton cycle, using three PCU modules (HP, MP, and LP) each containing a generator (G), turbine (T), compressor (C), and heater and cooler heat exchangers, with a recuperator (R) located in a fourth vessel.

Figure 3 compares the size of a high-temperate helium Brayton cycle (900°C turbine inlet temperature, 1300 MW(e) output) to a 1380 MW(e) steam Rankine cycle of a modern light water reactor. The Brayton system is clearly more compact, thus providing potential for major reductions in the turbine building volume and power conversion system capital cost for high-temperature MSRs. The much smaller size is primarily a consequence of two factors: (1) higher efficiency that reduces the size of heat rejection equipment as well as the size of many other components and (2) much higher power densities that are a consequence of the higher pressures in the Brayton cycle (minimum ~7 atm) compared to steam turbines (sub-atmospheric).

IV. COMPACT HEAT EXCHANGERS

Compact plate heat exchangers are already commonly used for heat transfer at lower temperatures. Of great interest for MSRs is the potential to fabricate compact plate type heat exchangers that would provide very high surface area to volume ratios and very small fluid inventories while operating at high temperatures. Both metal and non-metal heat exchangers are being investigated for high-temperature, gas-cooled reactors for temperatures to 1000ºC.

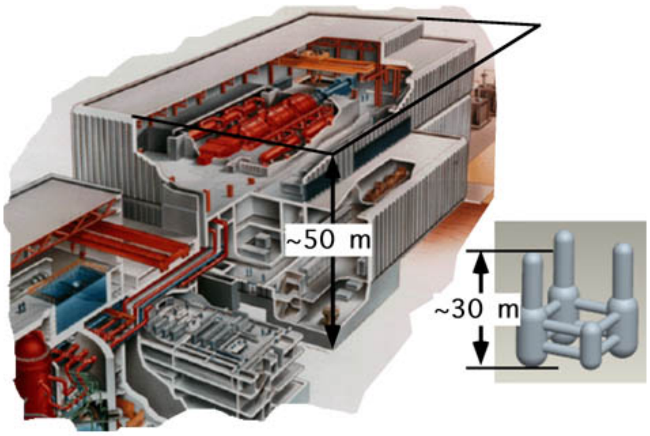

Fig. 3. Size comparison between the power conversion units of a high-temperature, 1300 MW(e) AMSR, and a 1380 MW(e) turbine for an advanced boiling water reactor. The Brayton cycle also requires space for a crane, turbine lay-down, cooling-water circulation equipment, and high-pressure gas storage.

TABLE I. MSR Brayton Cycle Design Parameters.

	MSR Cycle (High-Temp. System/ Low-Temp. System)	Reference GT-MHR
Number of PCUs	3 / 4	1
Gas Mass Flow Rate (kg/s)	596/818	317
Turbine Inlet Temp.	900°C/600ºC	848°C
Turbine Outlet Temp.	650°C/463ºC	508°C
Compressor Inlet Temp.	35°C/35°C	26.4°C
System Pres.	10 MPa/10 MPa	7.24MPa
Cycle Pressure Ratio	7.04/6.32	2.69
Turbine Efficiency	0.93/0.93	0.93
Compressor Efficiency	0.88/0.88	0.88
Recuperator Effectiveness	0.95/0.95	0.95
Generator Efficiency	0.98/0.98	0.98
Pressure Loss Fraction	0.04/0.06	0.013
Overall Cycle Efficiency	0.54/0.44	0.46
Power Density (kW(e)/m^3)	360/250	230

Recent design work has suggested that chopped fiber carbon-carbon preformed material[9,10] potentially could be used to fabricate plates a few to several millimeters thick. Figure 4 illustrate discontinuous fin geometry for molten salt-to-helium compact heat exchangers. The cross-sectional area of the fins and the thickness of the remaining plate below the machined channels would be adjusted to provide sufficient strength to resist thermal and mechanical stresses. For the fuel-to-intermediate salt heat exchanger, thermal and mechanical stresses are small. For the intermediate salt-to-helium heat exchangers in the power conversion system, mechanical stresses are substantially larger. For the case in which the heat exchanger is immersed into a helium environment; however, detailed stress analysis has shown that the stresses are dominantly compressive and can be accommodated with relative ease.

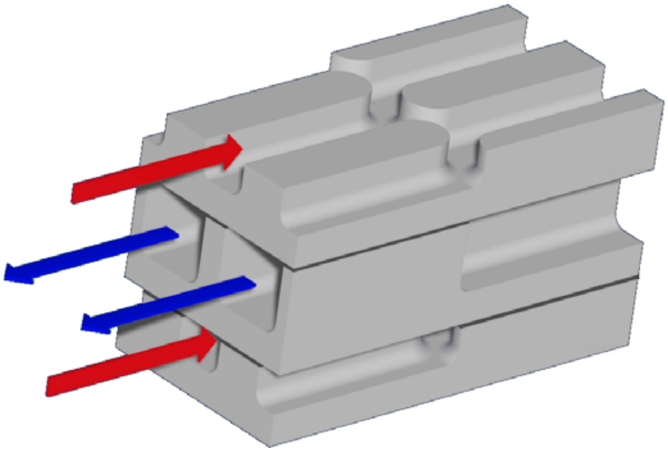

Fig. 4. Cut away view through a plate showing alternating molten salt (top and bottom arrows) and helium (middle arrows) flow channels. Dark bands at the top of each fin indicate the location of reaction-bonded joints between each plate (*Source:* R. Abbott, Lawrence Livermore National Laboratory).

An intermediate heat exchanger loop, using clean molten salt, transfers the heat from the molten fuel salt to a Brayton cycle that produced electricity. Table II shows the parameters for a reference intermediate heat exchanger design. The heat exchanger uses a compact offset-fin plate configuration with 1-mm-thick plates and 1-mm-high molten-salt fins. Table II shows the total volume and fuel inventory in the heat exchanger for both a high-temperature and lower temperature MSR system. It is notable that the intermediate heat exchanger and molten fuel salt volumes are exceptionally small for a 2400 MW(t) reactor (high temperature system: 9.6 m^3 and 1.6 m^3, respectively). These features can dramatically decrease the MSR fuel inventory and hot cell volume.

Table II. MSR Intermediate Heat Exchanger Parameters for two Reference Designs

	High Temp. System	Low Temp. System
Primary Fuel Salt	Flibe	Flibe
Intermediate Salt	LiF, NaF and ZrF_4 (42-29-29)	LiF, NaF and ZrF_4 (42-29-29)
Primary Fuel Inlet/Outlet Temp. (°C)	1000/955	705/670
Intermediate Salt Inlet/Outlet Temp. (°C)	860/920	570/620
Logarithmic Mean Temp. Difference (°C)	87	92
Primary/Intermediate Salt Flow Rate (m^3/s)	12/10	15/11
IHX Core Volume (m^3)	9.6	9.8
IHX Fuel-Salt Volume (m^3)	1.6	1.6
Flow Length (m)	0.3	0.3
Total Frontal Area (m^2)	36	36
Primary/Inter. Fin Heights (mm)	1.0/1.0	1.0/1.0
Primary/Intermediate Pressure Loss (kPa)	81/86	154/171
Thermal Density (MW/m^3)	250	250

Considerable flexibility exists to trade off all of these design parameters. For example, the logarithmic mean temperature difference can be adjusted to increase or decrease the total heat transfer area, accordingly affecting the total volume of the heat exchanger. Increasing the total front area will decrease flow-path length and the pressure losses through the heat exchanger and also affect the arrangement of the heat exchanger in the MSR hot cell. Depending on the purpose of the reactor (breeding or actinide burning) different fuel salts can be chosen. For the purpose of heat transfer analysis and pumping power, our calculations show that the results are not too sensitive to the salt type. Therefore, we use the pure salt properties of the solvent salt instead of the actual fuel salt properties in the calculations reported in Table II.

V. CARBON-CARBON COMPOSITE HEAT EXCHANGERS

Liquid silicon infiltrated carbon-carbon composites provide a potentially very attractive construction material for high-temperature heat exchangers, piping, pumps, and vessels for MSRs, because of their ability to maintain nearly full mechanical strength at high temperatures (up to 1400°C), the simplicity of their fabrication, their low residual porosity, their capability of operating with high-pressure helium and molten fluoride salts, and their low cost.[10]

Chopped carbon fiber can provide a particularly attractive material that can be readily formed by pressing with dies, machined using standard milling tools, and assembled into complex parts. To fabricate compact plate-type heat exchangers, one side of each plate would be die-embossed or milled, to provide appropriate flow channels, leaving behind fins or ribs that would provide enhanced heat transfer, as well as the mechanical connection to the smooth side of the next plate. For green carbon-carbon material, milling can be performed readily with standard numerically controlled milling machines. Alternatively, plates can be molded with flow channels, as has been demonstrated for carbon-carbon composite plates fabricated at Oak Ridge National Laboratory (ORNL) for fuel cells.[11] For assembly, the ends of the fins and other remaining unmachined surfaces of around the machined flow channels would be coated with phenolic adhesive, the plate stack assembled, header pipes bonded and reinforced, and the resulting monolith pyrolysed under compression. Then liquid silicon would be infiltrated to reaction bond the plates and headers together, forming a compact heat exchanger monolith.

Surfaces to be exposed to molten salts would be coated with carbon, using chemical vapor infiltration (CVI). Such methods have been developed at ORNL for coating carbon-carbon composite plates for fuel cells.[11] Figure 5 shows a carbon-carbon composite plate coated at ORNL using the CVI method. From the perspective of protecting the substrate material from the molten salt, some porosity of the carbon layer could be acceptable, as is found for nuclear graphites.[12] ORNL has also subjected samples treated by CVI of carbon to 100 MPa stresses in bi-directional bending of plates.[11] These samples were then tested for hermeticity by pressurizing one side with 206 kPa of hydrogen and measuring the through-thickness gas leakage rate, and it was found that excellent permeation resistance could be achieved.

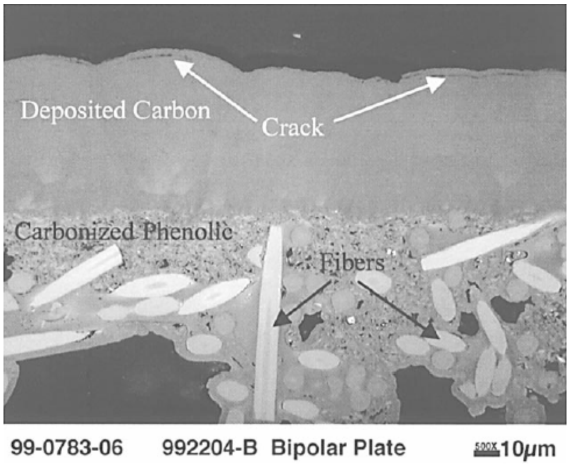

Fig. 5. Photo of CVI-deposited carbon layer on a carbon-carbon composite plate.[10]

VI. CONCLUSIONS

By the early 1970s, a relatively detailed design of a 1000 MW(e) MSR had been developed based on test reactor experience. A good understanding of strengths and weaknesses had been developed. Work stopped for several decades. MSRs are now being reexamined. Three technological developments since then (Brayton power cycles, compact heat exchangers, and carbon-carbon composites) have (1) eliminated or significantly reduced several major technical issues associated with MSRs, (2) created the potential for major improvements in performance, and (3) significantly reduced costs. These major technological advances and changing goals for nuclear reactors strongly support a major investigation and assessment of MSRs as future GenIV reactors for deployment.

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