

EXPERIENCE WITH THE MOLTEN-SALT REACTOR EXPERIMENT

REACTORS

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The MSRE is an 8-MW(th) reactor in which molten fluoride salt at 1200°F circulates through a core of graphite bars. Its purpose was to demonstrate the practicality of the key features of molten-salt power reactors.

Operation with ^{235}U (33% enrichment) in the fuel salt began in June 1965, and by March 1968 nuclear operation amounted to 9000 equivalent full-power hours. The goal of demonstrating reliability had been attained—over the last 15 months of ^{235}U operation the reactor had been critical 80% of the time. At the end of a 6-month run which climaxed this demonstration, the reactor was shut down and the 0.9 mole% uranium in the fuel was stripped very efficiently in an on-site fluorination facility. Uranium-233 was then added to the carrier salt, making the MSRE the world's first reactor to be fueled with this fissile material. Nuclear operation was resumed in October 1968, and over 2500 equivalent full-power hours have now been produced with ^{233}U .

The MSRE has shown that salt handling in an operating reactor is quite practical, the salt chemistry is well behaved, there is practically no corrosion, the nuclear characteristics are very close to predictions, and the system is dynamically stable. Containment of fission products has been excellent and maintenance of radioactive components has been accomplished without unreasonable delay and with very little radiation exposure.

The successful operation of the MSRE is an achievement that should strengthen confidence in the practicality of the molten-salt reactor concept.

INTRODUCTION

The paper by Rosenthal et al.¹ describes the origin of the molten-salt reactor concept and how the encouraging results of the aircraft reactor program led to recognition of the potential of molten-salt reactors for economical production of electricity. The role of the Molten-Salt Reactor Experiment (MSRE) was to demonstrate the practicality of this high-temperature fluid-fuel concept which seemed so promising on the basis of materials compatibility information and calculated fuel cycle costs. When design of the MSRE was initiated in 1960, therefore, a primary objective was to make the reactor safe, reliable, and maintainable. How well these efforts succeeded is told in this paper.

DESCRIPTION OF THE MSRE

The MSRE was designed² to use essentially the same materials as the proposed molten-salt breeders but, for economy and simplicity, there was no attempt to make the reactor actually breed. The core is small (54 in. in diam \times 64 in. high) so that the neutron leakage is high, and there is no blanket of fertile material. The fuel salt contains no thorium because at the time the reactor was being designed we were thinking in terms of the two-fluid breeder and we made the MSRE salt similar to the anticipated breeder fuel salt. The power level was to be limited to 10 MW(th) or less, but we wanted to try fairly large molten-salt pumps. As a result, the temperature rise of the salt as it passes through the core is $<50^\circ\text{F}$. The average temperature of the fuel salt was to be 1200°F in the range proposed for the power breeders. Even at this temperature, the vapor pressure of the salt is <0.1 mm Hg, so the pressure of the gas blanket over the salt was set

at only 5 psig. The flowsheet of the MSRE (Fig. 1) shows the normal operating conditions at 8 MW, the maximum heat removal capability of the air-cooled secondary heat exchanger. The special materials used in this reactor system are listed in Table I.

The physical arrangement of the salt systems is shown in Fig. 2. The building housing the reactor is the one in which the Aircraft Reactor Experiment was operated in 1954. The cylindrical reactor cell was added for the Aircraft Reactor Test (which was never built) and was adapted for MSRE use.

Details of the MSRE core and reactor vessel are shown in Fig. 3. The 54-in.-diam core is made up of graphite bars, 2 in. square and 64 in. tall, exposed directly to fuel which flows in passages machined into the faces of the bars. The graphite was especially produced³ to have low permeability, and, since salt does not wet the graphite, very high pressure would be required to force any significant amount of salt into the graphite. Some cracks developed in the manufacture of the graphite, but cracked bars were accepted when tests showed effects attending heating and salt intrusion into cracks were inconsequential.

All metal components in contact with molten salt are made of Hastelloy-N (formerly called INOR-8). Metal corrosion by salt mixtures consists of oxidation of metal constituents to their fluoride salts, which do not form protective films.⁴ Attack is therefore limited only by the

thermodynamic potential for the oxidation reaction, and is selective, removing the least-noble constituent, which in the case of Hastelloy-N is chromium. However, the diffusion coefficient of the chromium in the metal is such that there is practically no chromium leaching at temperatures below 1500°F. Impurities in the salt, such as FeF_2 , react with Hastelloy-N, but this is a limited effect which goes to completion soon after the salts are loaded. The metallurgy and technology of Hastelloy-N have been thoroughly developed⁵ and it has been approved for construction under ASME Unfired Pressure Vessel and Nuclear Vessel Codes. Hastelloy-N is stronger than austenitic stainless steel and most nickel-base alloys but, like these metals it is subject to deterioration of high-temperature ductility and stress-rupture life by neutron irradiation. (These effects are due to accumulation in grain boundaries of helium produced by n, α reactions.) In the MSRE neutron spectrum the fast neutron reactions with nickel are insignificant compared to the slow neutron reactions with impurity boron. Careful analysis of stresses and neutron fluxes in the MSRE⁶ led to the conclusion that the service life of the reactor vessel would extend at least 20 000 h beyond the point at which the properties of the metal began to be seriously affected by the neutron exposure.

The control rods are flexible, consisting of hollow cylinders of $\text{Gd}_2\text{O}_3\text{-Al}_2\text{O}_3$ ceramic, canned in Inconel and threaded on a stainless-steel hose which also serves as a cooling-air conduit. An endless-chain mechanism, driven through a

TABLE I
MSRE Materials

Fuel Salt	⁷ LiF-BeF ₂ -ZrF ₄ -UF ₄ (65.0-29.1-5.0-0.9 mole%)	
Composition:		
Properties at 1200°F (650°C)		
Density	141 lb/ft ³	2.3 g/cm ³
Specific heat	0.47 Btu/lb-°F	2.0×10^3 J/kg-°C
Thermal conductivity	0.83 Btu/h-ft-°F	1.43 W/m-°C
Viscosity	19 lb/h-ft	29 kg/h-m
Vapor pressure	<0.1 mm Hg	$<1 \times 10^{-4}$ bar
Liquidus temperature	813°F	434°C
Coolant salt ^a	⁷ LiF-BeF ₂ (66-34 mole%)	
Moderator	Grade CGB graphite	
Salt containers	Hastelloy-N (68 Ni-17 Mo-7 Cr-5 Fe)	
Cover gas	Helium	

^aAnother batch of salt of this composition is used to flush the fuel system before it is opened to minimize fission product escape and again after it is resealed to pick up moisture that may have entered.

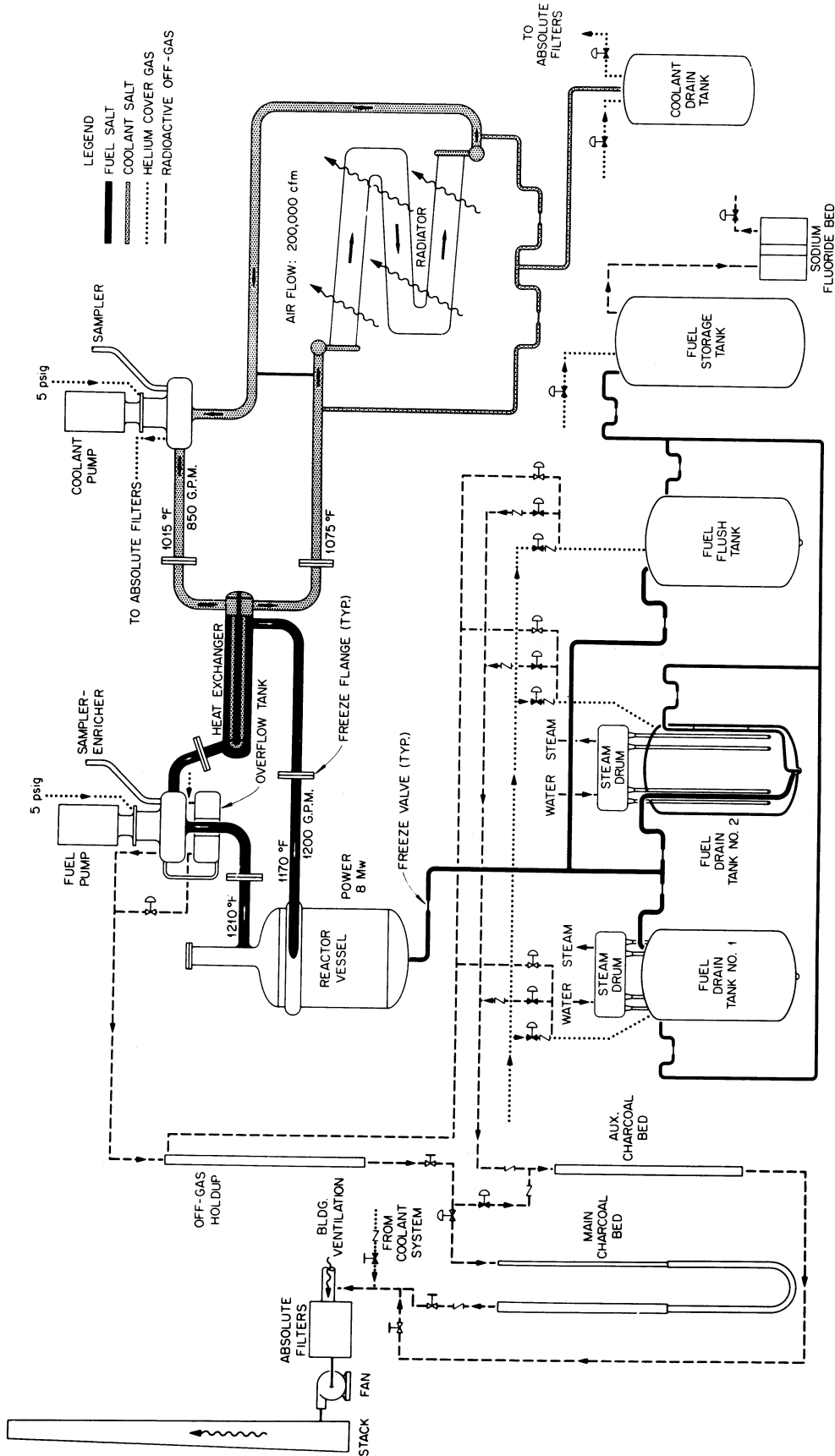


Fig. 1. Design flow sheet of the MSRE.

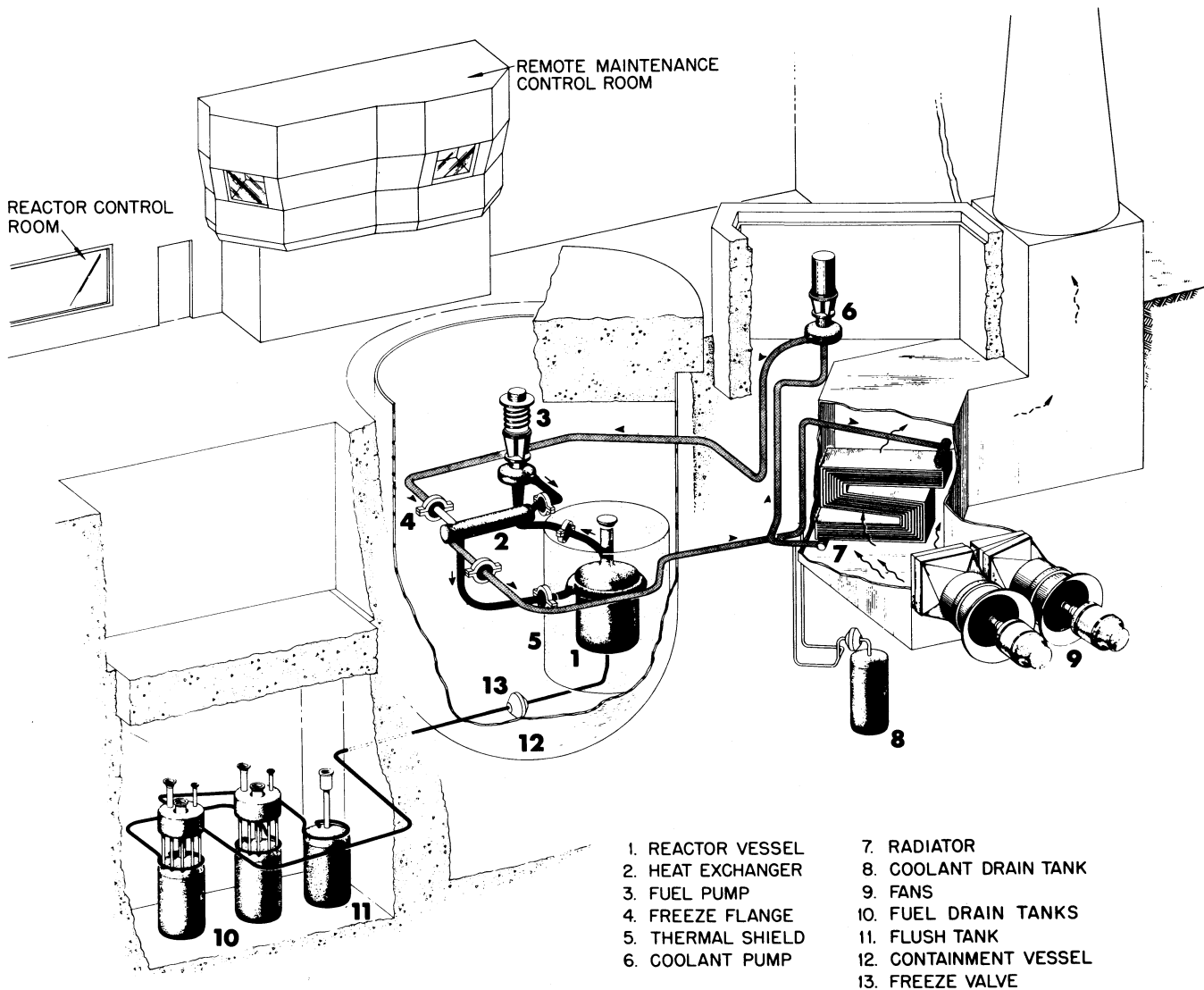


Fig. 2. Layout of the MSRE.

clutch, raises and lowers the rods at 0.5 in./sec. When scrammed, the rods fall with an acceleration of ~ 12 ft/sec².

The bowl of the fuel pump is the surge space for the circulating loop. Dry, deoxygenated helium at 5 psig blankets the salt in the pump bowl. About 50 of the 120 gal/min discharged by the pump is sprayed into the gas space to provide contact between salt and cover gas to allow ¹³⁵Xe to escape from the salt. (The solubility of xenon and krypton in the salt is very low.) A flow of 4 liters/min STP of helium carries the xenon and krypton out of the pump bowl, through a holdup volume providing ~ 40 -min delay, a filter station, and a pressure-control valve to charcoal beds. The charcoal beds consist of pipes filled with charcoal, submerged in a water-filled pit at

$\sim 90^\circ\text{F}$. The beds are operated on a continuous-flow basis and delay xenon for ~ 90 days and krypton for ~ 7 days. Thus, only stable or long-lived gaseous nuclides are present in the helium which is discharged through a stack after passing through the beds.

All salt piping and vessels are electrically heated to prepare for salt filling and to keep the salt molten when there is no nuclear power.⁷ In the reactor and drain-tank cells, where radiation levels make remote maintenance necessary, heater elements and reflective metal insulation are combined in removable units. Thermocouples under each heater monitor temperatures to avoid overheating the empty pipe. The radiator is equipped with doors that drop to block the air duct and seal the radiator enclosure if the coolant salt

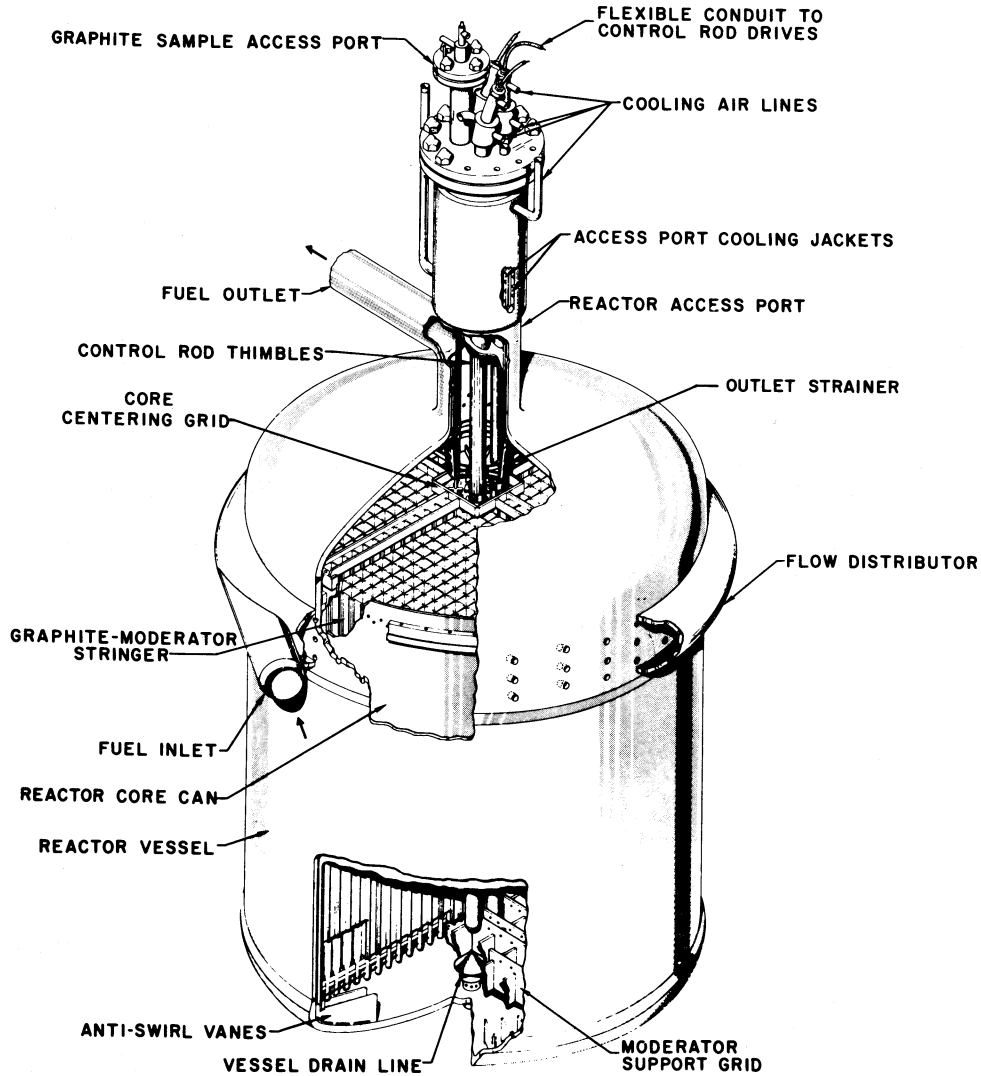


Fig. 3. Details of the MSRE core and reactor vessel.

circulation stops and there is danger of freezing salt in the tubes.

Around the reactor-vessel furnace is a shield, 16 in. thick consisting of a tank of stainless steel filled with steel balls and circulating water. The shield absorbs most of the energy of neutrons and gammas escaping the reactor vessel (20 kW/MW of reactor power). It also cuts down on neutron activation of components in the reactor cell, facilitating maintenance. The cooling-water supply for the shield is deaerated to remove radioactive gas.

Neutron chambers are located in tubes in a 36-in.-diam water-filled shaft that slopes down through the reactor cell to the inner surface of the thermal shield. Included are 3 uncompensated ion chambers driving safety channels, 2 compensated chambers, and 2 servo-driven fission chambers

that provide a 10-decade power indication. The compensated chambers are connected to multiple-range ammeters and a flux- or power-servo system. Any one of the three rods can be connected as a regulating rod to the servo system. The fuel salt, which is a mixture containing both alpha emitters and beryllium, is itself a strong neutron source, but there is also an Am-Cm-Be start-up source in a thimble in the thermal shield.

There are no mechanical valves in the salt piping. Instead, flow is blocked by plugs of salt frozen in flattened sections of the lines. Temperatures in the "freeze valves" in the fuel and coolant drain lines are controlled so they will thaw in 10 to 15 min when a drain is requested. A power failure of longer duration also results in a drain because the cooling air required to keep the valves frozen is interrupted.