

THE DESIGN AND PERFORMANCE FEATURES OF A SINGLE-FLUID MOLTEN-SALT BREEDER REACTOR

REACTORS

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A conceptual design has been made of a single-fluid 1000 MW(e) Molten-Salt Breeder Reactor (MSBR) power station based on the capabilities of present technology. The reactor vessel is ~22 ft in diameter × 20 ft high and is fabricated of Hastelloy-N with graphite as the moderator and reflector. The fuel is ^{233}U carried in a $\text{LiF}-\text{BeF}_2-\text{ThF}_4$ mixture which is molten above 930°F. Thorium is converted to ^{233}U in excess of fissile burnup so that bred material is a plant product. The estimated fuel yield is 3.3% per year.

The estimated construction cost of the station is comparable to PWR total construction costs. The power production cost, including fuel-cycle and graphite replacement costs, with private utility financing, is estimated to be 0.5 to 1 mill/kWh less than that for present-day light-water reactors, largely due to the low fuel-cycle cost and high plant thermal efficiency.

After engineering development of the fuel purification processes and large-scale components, a practical plant similar to the one described here appears to be feasible.

INTRODUCTION

The objective of this design study is to investigate the feasibility of attaining low-cost electric power, a low specific inventory of fissile material, and a reasonably high breeding gain in a molten-salt reactor. As discussed by Perry and Bauman¹ a molten-salt reactor can be designed as either a breeder, or, with relatively few major differences other than in fuel processing, as a converter. This particular design study is confined to the single-fluid Molten-Salt Breeder Reactor (MSBR).

The conceptual design of the MSBR plant was made on the basis that the technology required for fabrication, installation, and maintenance be generally within present-day capabilities. Major design considerations were keeping the fuel-salt inventory low, accommodating graphite dimensional changes, selection of conditions favoring graphite life, and providing for maintainability.

The facilities at an MSBR power station can be grouped into the following broad categories: (a) the reactor system which generates fission heat in a fuel salt circulated through primary heat exchangers; (b) an off-gas system for purging the fuel salt of fission-product gases and colloidal noble metal particulates; (c) a chemical processing facility for continuously removing fission products from the fuel salt, recovery of the bred ^{233}U , and replenishment of fertile material; (d) a storage tank for the fuel salt which has an after-heat removal system of assured reliability; (e) a coolant-salt circulating system, steam generators, and a turbine-generator plant for converting the thermal energy into electric power; and (f) general facilities at the site which include condensing water works, electrical switchyard, stacks, conventional buildings, and services. These categories are not always clearly defined and are closely interdependent, but it is convenient to discuss them separately. The reactor, and its related structures and maintenance system, the drain tank, the off-gas system, and the chemical processing equipment, are of primary interest. The steam turbine plant and the general facilities are more or less conventional and will be discussed only to the extent necessary to complete the overall picture as to feasibility and costs of an MSBR station.

In a single-fluid MSBR the nuclear fuel is ^{233}U (or other fissile material) carried in a lithium-7-fluoride, beryllium-fluoride, thorium-fluoride salt. The mixture is fluid above ~930°F and has good flow and heat transfer properties and very low

vapor pressure. This salt is pumped in a closed loop through a graphite-moderated and reflected core where it is heated to $\sim 1300^\circ\text{F}$ by fissioning of the fuel. It then flows through heat exchangers where the heat is transferred to a circulating heat transport salt. This fluid, in turn, supplies heat to steam generators and reheaters to power a conventional high-temperature, high-pressure steam turbine-generator plant. The thorium in the fluoride fuel-salt mixture is converted to ^{233}U at a rate in excess of the fuel burnup so that fissile material, as well as power, is a valuable product of the plant.

A low specific inventory is obtained by designing the MSBR to operate at a high reactor power density with a minimum of fuel salt in the circulating system. The concentration of fissile-fertile material in the salt results from a compromise between keeping the inventory low and achieving a higher breeding gain. High performance depends on keeping the neutron parasitic absorptions low and fuel losses to a minimum. The Li and Be in the fuel salt are good neutron moderators, but their concentrations are relatively low in fluoride salts and additional moderation is needed. Graphite is the most satisfactory moderator and reflector for the MSBR. However, radiation affects the graphite and its useful life varies nearly inversely as the maximum power density in the core. The radiation damage effect is also increased by higher temperatures. Selection of a power density is thus a balance between a low fuel inventory and the frequency with which the graphite must be replaced.

The optimization studies which equate the several factors mentioned above are described by Scott and Eatherly.²² These studies indicate that an average core power density of 22.2 kW/liter results in a useful graphite life of ~ 4 years, which is the operating condition used in this design study. Thus, the reactor design must provide for periodic replacement of the core graphite with minimal plant downtime and complexity of maintenance equipment.

To attain a high nuclear performance it is necessary to maintain low concentrations of Pa and ^{135}Xe in the high flux region of the core. The protactinium is kept low by processing a small side stream of the salt for removal of this nuclide and other fission products. By integral processing on-site a minimum inventory of fuel salt is involved in transport and storage. The xenon is removed by helium-sparging the fuel salt on a few-second cycle; the core graphite is also sealed to decrease the rate of diffusion of the Xe into the pores of the graphite. The plant design therefore includes the auxiliary systems to remove the nuclear poisons and the bred fissile ma-

terial from the salt, to purge the fission-product gases, and to store or dispose of the radioactive waste products; Whatley et al.,³ and Perry and Bauman¹ treat the subject of salt processing and estimate fuel-cycle costs.

Although the economic performance of a 2000 MW(e), or larger, MSBR station would be significantly better than that of smaller sizes, a plant with a net electrical output of 1000 MW(e) was chosen for this study because it permitted more direct comparison with the results of other studies. A steam-power cycle with 1000°F and 3500-psia turbine throttle conditions, with single reheat, was selected because this was representative of current practice and because it afforded a high overall plant thermal efficiency of $\sim 44\%$. The MSBR is adaptable to other steam conditions and to additional reheats if future developments lead in this direction.

All portions of the systems in contact with salts are fabricated of Hastelloy-N. When this material is modified with $\sim 1\%$ titanium or hafnium to improve resistance to radiation embrittlement, as described by McCoy et al.,⁴ it has good high-temperature strength and excellent resistance to corrosion. No exothermic reactions of concern result from mixing of the fuel and coolant salts with each other or with air or water. It is important to keep water and oxygen out of the salts in normal operation, however. The reactor graphite is a specially developed type having very low salt and gas permeability and good resistance to radiation damage. The salt composition is a compromise between the nuclear and physical properties, chemical stability, etc., as discussed by Grimes.⁵ Some selected physical properties of the materials important to the design study are shown in Tables I, II, and III.

The performance features of the plant, in terms of breeding gain, graphite life, thermal efficiency, and the net cost to produce electric power, are all reported here on the basis of normal full-load operation at 80% plant factor. Very preliminary review of the various modes of start-up and shut-down, partial-load operation, etc., has not disclosed any major problem areas, however.

PLANT DESCRIPTION

A simplified flow diagram of the primary and secondary-salt circulating systems is shown in Fig. 1. The fluoride fuel-salt mixture is circulated through the reactor core by four pumps operating in parallel.^a Each pump has a capacity of $\sim 14\ 000$

^a Flow sheet does not show duplicate equipment.

TABLE I

Properties of the Primary and Secondary Salts Used in Conceptual Design Study of MSBR 1000-MW(e) Station

	Primary Salt	Secondary Salt
Components	LiF-BeF ₂ -ThF ₄ -UF ₄	NaBF ₄ -NaF
Composition, mole%	71.6-16-12-0.4	92-8
Molecular weight, approximate	64	104
Liquidus temperature, °F	930	725
Density, lb/ft ³	205 (at 1300°F)	117 (at 988°F)
Viscosity, lb/(ft h)	16.4 (at 1300°F)	2.5 (at 900°F)
Thermal conductivity, Btu/(h ft °F)	0.7 to 0.8	0.27
Heat capacity, Btu/(lb °F)	0.32	0.36
Vapor pressure at 1150°F, Torr (mm Hg)	<0.1	252

gal/min and circulates the salt through one of four primary heat exchangers and returns it to a common plenum at the bottom of the reactor vessel. Use of four pumps and heat exchangers corresponds to a pump size which represents a reasonable extrapolation of the Molten-Salt Reactor Experiment (MSRE) experience.

Each of the four coolant-salt circuits has a pump of 22 000-gal/min capacity which circulates the coolant salt through a primary heat exchanger located in the reactor cell and then through steam generating equipment installed in an adjacent cell. The reactor can continue to operate although at reduced output, if not all of the coolant salt pumps are operative.

A plan of the reactor plant is shown in Fig. 2; an isometric view and a sectional elevation are presented in Figs. 3 and 4.

The reactor cell is ~62 ft in diameter and 35 ft deep. It houses the reactor vessel, the four primary heat exchangers, and four fuel-salt circulating pumps. The roof of the cell has removable plugs over all equipment which might require maintenance. The reactor cell is normally kept at a temperature of ~1000°F by electric heater thimbles to ensure that the salts will remain above their liquidus temperatures. The estimated maximum heating load is ~2500 kW. This "furnace" concept for heating is preferred over trace heating of lines and equipment because it ensures more even heating, heater elements can be replaced without reactor shutdown, there is no need for space coolers inside the cell, and bulky thermal insulation that would crowd the cell and require removal for maintenance and inspection is eliminated.

TABLE II

Nominal Values for Properties of MSBR Graphite

Density, lb/ft ³ at room temperature	115
Bending strength, psi	4000-6000
Young's modulus of elasticity, psi	1.7×10^9
Poisson's ratio	0.27
Thermal expansion, per °F	2.3×10^{-6}
Thermal conductivity, Btu/(hr ft °F) (1340°F)	35-42
Electrical resistivity, Ω-cm	$8.9-9.9 \times 10^{-4}$
Specific heat, Btu/(lb °F) at 600°F	0.33
Btu/(lb °F) at 1200°F	0.42

Biological shielding for the reactor cell is provided by reinforced concrete. The walls of the reactor cell also furnish double containment for the fuel-salt systems. Two thicknesses of carbon steel plate form inner and outer containment vessels, each designed for 50 psig, and also provide gamma shielding for the concrete. Nitrogen gas flows between the plates in a closed circulating loop to remove ~3 MW(th) of heat. Double bellows are used at all cell penetrations. The normal cell operating pressure is ~26 in. Hg abs.

High-temperature thermal insulation is attached to the inside of the containment membrane to limit heat losses from the reactor cell. The inside surface of the insulation is covered with a thin stainless-steel liner to protect the insulation from damage, to act as a radiant heat reflector,

TABLE III

Selected Physical Properties of Hastelloy-N

Nominal Chemical Composition of Modified Alloy for Use in MSBR ^a	Wt%	
	At 80°F	At 1300°F
Nickel	75	
Molybdenum	12	
Chromium	7	
Iron	4	
Titanium	1	
Other	1	
Density, lb/ft ³	~553	~553
Thermal conductivity, Btu/(h ft °F)	6.0	12.6
Specific heat, Btu/(lb °F)	0.098	0.136
Thermal expansion, per °F	5.7×10^{-6}	9.5×10^{-6}
Modulus of elasticity, psi	31×10^6	25×10^6
Electrical resistance, Ω-cm	120.5×10^{-6}	126.0×10^{-6}
Approximate tensile strength, psi	115 000	75 000
Maximum allowable design stress, psi	25 000	3 500
Maximum allowable design stress, bolts, psi	10 000	3 500
Melting temperature, °F	~2 500	~2 500

^aThe exact composition may be different from the nominal values given here, as discussed by McCoy et al.⁴

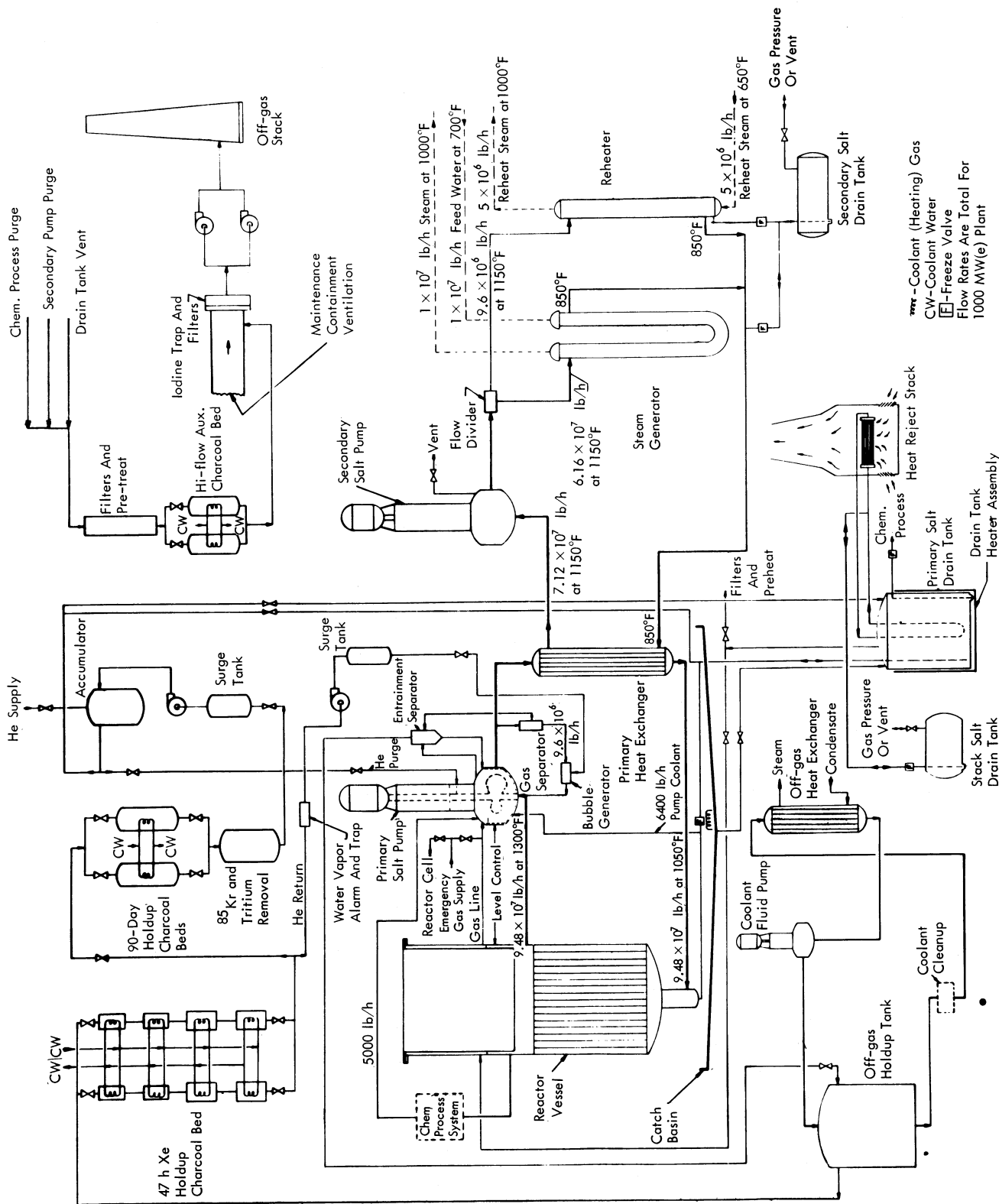


Fig. 1. Flow diagram of MSBR for 1000 MW(e) MSBR power station.