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SUMMARY OF MOLTEN-SALT BREEDER REACTOR DESIGN STUDIES

Paul R. Kasten

E. S. Bettis	W. B. McDonald
H. F. Bauman	R. C. Robertson
W. L. Carter	J. H. Westsik

Abstract

Design and evaluation studies were made of thermal molten-salt breeder reactors (MSBR) in order to assess their economic and nuclear potential and to identify important design and development problems. The MSBR reference design concept is a two-region, two-fluid system with fuel salt separated from the blanket salt by graphite tubes. The energy produced in the reactor fluid is transferred to a secondary coolant-salt circuit, which couples the reactor to a supercritical steam cycle. On-site fluoride volatility processing is employed, which leads to low unit processing costs and economic reactor operation as a thermal breeder. The resulting power cost is estimated to be 2.7 mills/kwhr for investor-owned utilities; the associated fuel cycle cost is 0.45 mill/kwhr(e), the specific fissile inventory is 0.8 kg/Mw(e), and the fuel doubling time is 21 years. Development of a Pa-removal scheme for the blanket region of the MSBR could lead to power costs of 2.6 mills/kwhr(e), a fuel cycle cost of 0.33 mill/kwhr(e), a specific fissile inventory of 0.7 kg/Mw(e), and a fuel doubling time of 13 years.

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Author(s): P.R. Kasten, E.S. Bettis, H.F. Bauman, W.L. Carter, et al.

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FOREWORD

This memorandum is a partial summary of the molten-salt breeder reactor studies which will be presented in a forthcoming ORNL report. The purpose of the present memo is to provide results of these studies prior to issue of the complete report.

In utilizing these studies, it should be emphasized that the cost estimates tacitly assume the existence of an established industry.

CONTENTS

INTRODUCTION

Design and evaluation studies have been made of thermal molten-salt breeder reactors (MSBR) in order to assess their economic and nuclear potential and to identify the important design and development problems. The reference reactor design presented here contains design problems related to molten-salt reactors in general.

The MSBR reference design concept is a two-region, two-fluid system, with fuel salt separated from the blanket salt by graphite tubes. The fuel salt consists of uranium fluoride dissolved in a mixture of lithium-beryllium fluorides, while the blanket salt is a thorium-lithium fluoride of eutectic composition (about 27 mole % thorium fluoride). The energy generated in the reactor fluid is transferred to a secondary coolant-salt circuit, which couples the reactor to a supercritical steam cycle. On-site fluoride volatility processing is employed, leading to low unit processing costs and economic operation as a thermal breeder reactor.

MSBR PLANT DESIGN

Flowsheet

Figure 1 gives the flowsheet of the 1000-Mw(e) MSBR power plant. Fuel flows through the reactor at a rate of about 44,000 gpm (velocity of about 15 ft/sec), entering the core at 1000°F and leaving at 1300°F. The primary fuel circuit has four loops, each loop having a pump and a primary heat exchanger. Each of these pumps has a capacity of about 11,000 gpm. The four blanket pumps and heat exchangers, although smaller, are similar to corresponding components in the fuel system. The blanket salt enters the reactor vessel at 1150°F and leaves at 1250°F. The blanket salt pumps have a capacity of about 2000 gpm.

Four 14,000-gpm coolant pumps circulate the sodium fluoroborate coolant salt, which enters the shell side of the primary heat exchanger at 850°F and leaves at 1112°F. After leaving the primary heat exchanger, the coolant salt is further heated to 1125°F on the shell side of the blanket heat exchangers. The coolant then circulates through the shell side of 16 once-through superheaters (four superheaters per pump). In addition, four 2000-gpm pumps circulate a portion of the coolant through eight reheaters.

The steam system flowsheet is essentially that of the new TVA Bull Run plant, with modifications to increase the rating to 1000 Mw(e) and to preheat the working fluid to 700°F prior to entering the heat exchanger-superheater unit. A supercritical power conversion system is used, which is appropriate for molten-salt application and takes advantage of the high-strength structural alloy employed. Use of a supercritical fluid system results in an overall plant thermal efficiency of about 45%.

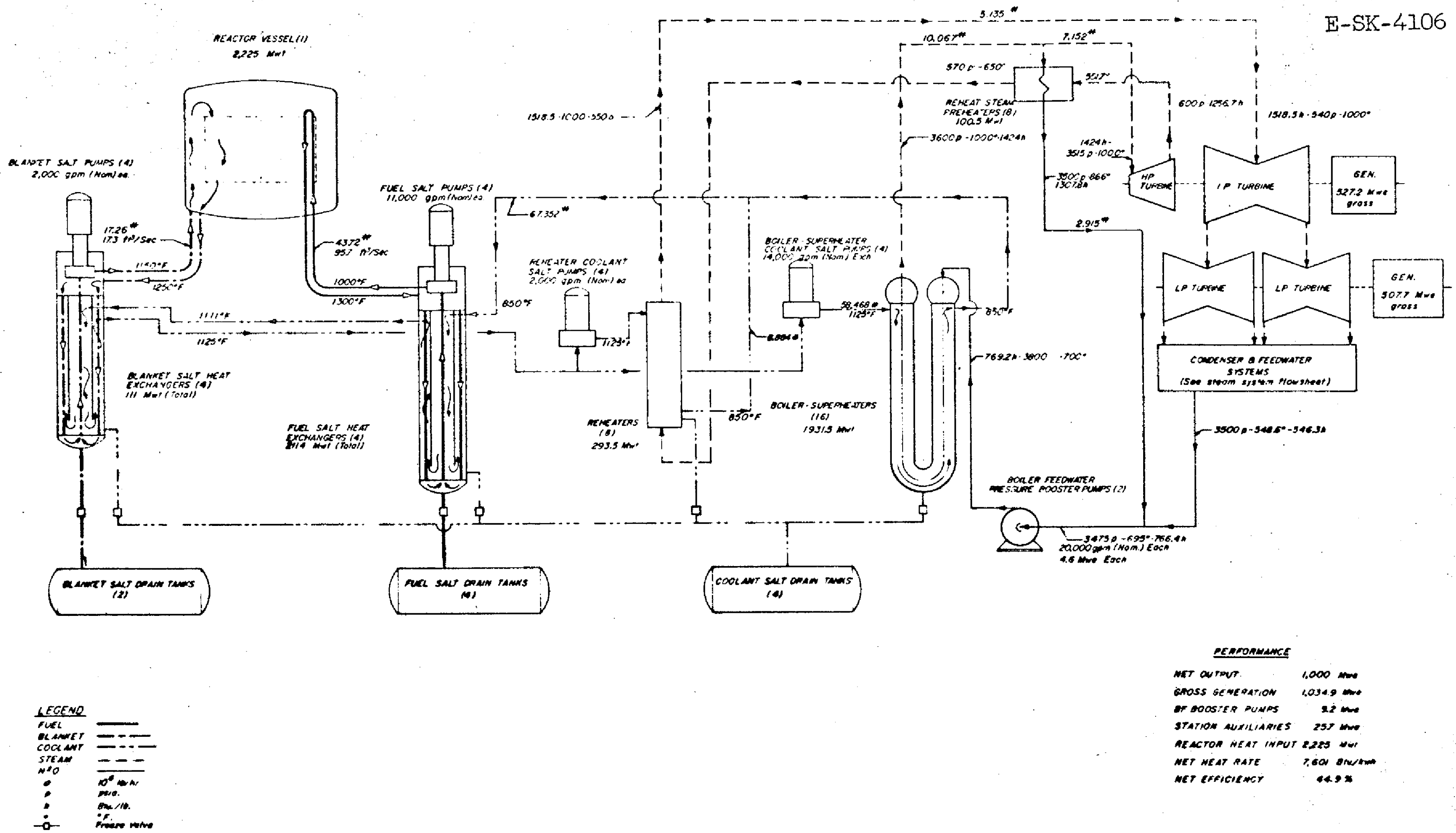

Fig. 1. Molten Salt Breeder Reactor Flow Diagram (700°F Feedwater).

Reactor Design

Figure 2 shows a plan view of the MSBR cell arrangement. The reactor cell is surrounded by four shielded cells containing the superheaters and reheater units; these cells can be individually isolated for maintenance. The processing cell, located adjacent to the reactor, is divided into a high-level and a low-level activity area.

Figure 3 shows an elevation view of the reactor and indicates the position of equipment in the various cells. Figure 4, a plan view of the reactor cell, shows the location of the reactor, pumps, and fuel and blanket heat exchangers. Figure 5 is an elevation of the reactor cell. The Hastelloy N reactor vessel has a side wall thickness of about 1-1/4-in. and a head thickness of about 2-1/4 in.; it is designed to operate at 1200°F and 150 psi. The plenum chambers, with 1/4-in.-thick walls, communicate with the external heat exchangers by concentric inlet-outlet piping. The inner pipe has slip joints to accommodate thermal expansion. Bypass flow through these slip joints is about 1% of the total flow. As indicated in Fig. 5, the heat exchangers are suspended from the top of the cell and are located below the reactor. Each fuel pump has a free fluid surface and a storage volume which permit rapid drainage of fuel fluid from the core upon loss of flow. In addition, the fuel salt can be drained to the dump tanks when the reactor is shut down for an extended time. The entire reactor cell is kept at high temperature, while cold "fingers" and thermal insulation surround structural support members and all special equipment which must be kept at relatively low temperatures. The control rod drives are located above the core, and the control rods are inserted into the central region of the core.

The reactor vessel, about 14 ft in diameter by about 15 ft high, contains a 10-ft-diam core assembly composed of reentry-type graphite fuel cells. The graphite tubes are attached to the two plenum chambers at the bottom of the reactor with graphite-to-metal transition sleeves. Fuel from the entrance plenum flows up fuel passages in the outer region of the fuel cell and down through a single central passage to the exit plenum. The fuel flows from the exit plenum to the heat exchangers, then to the pump and back to the reactor. A 1-1/2-ft-thick molten-salt blanket plus a 1/4-ft-thick graphite reflector surround the core. The blanket salt also permeates the interstices of the core lattice so fertile material flows through the core without mixing with the fissile fuel salt.

The MSBR requires structural integrity of the graphite fuel cell. In order to reduce the effect of radiation damage, the fuel cells have been made small to reduce the fast flux gradient across the graphite wall. Also, the cells are anchored only at one end to permit axial movement. The core volume has been made large in order to reduce the flux level in the core. In addition, the reactor is designed to permit replacement of the entire graphite core by remote means if required.

Figure 6 shows a cross section of a fuel cell. Fuel fluid flows upward through the small passages and downward through the large central

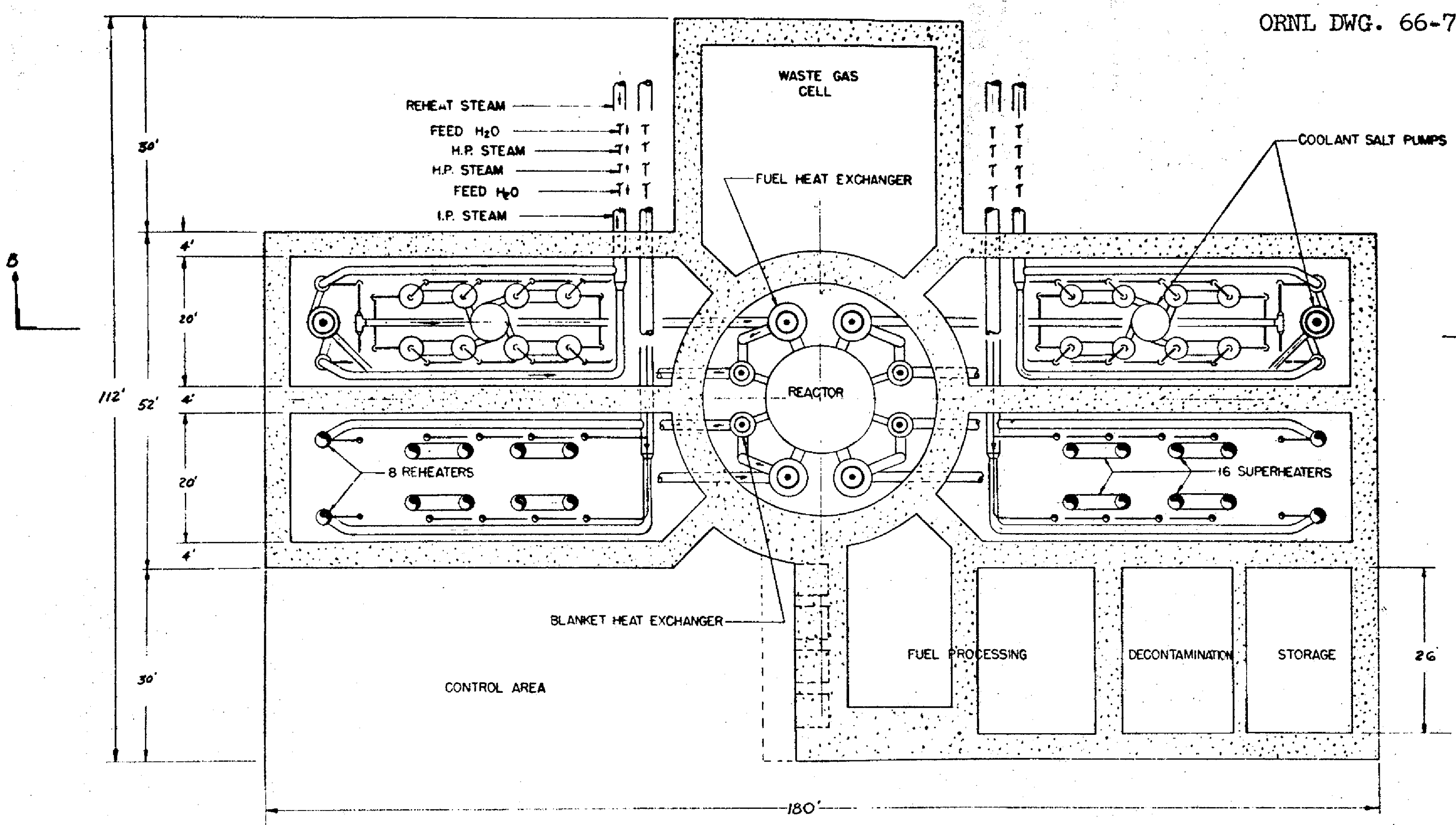

Fig. 2. Molten Salt Breeder Reactor – Reactor and Steam Cells-Plan.

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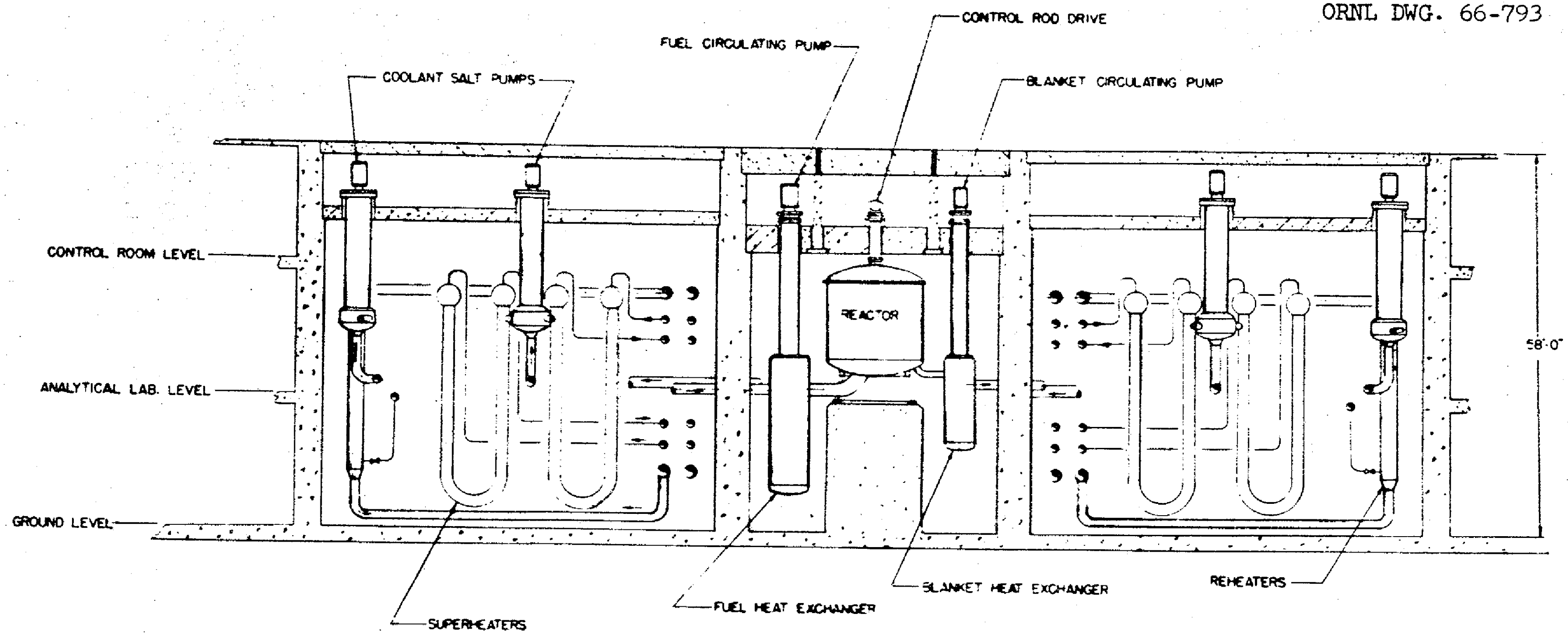

Fig. 3. Molten Salt Breeder Reactor — Reactor and Steam Cells-Elevation.

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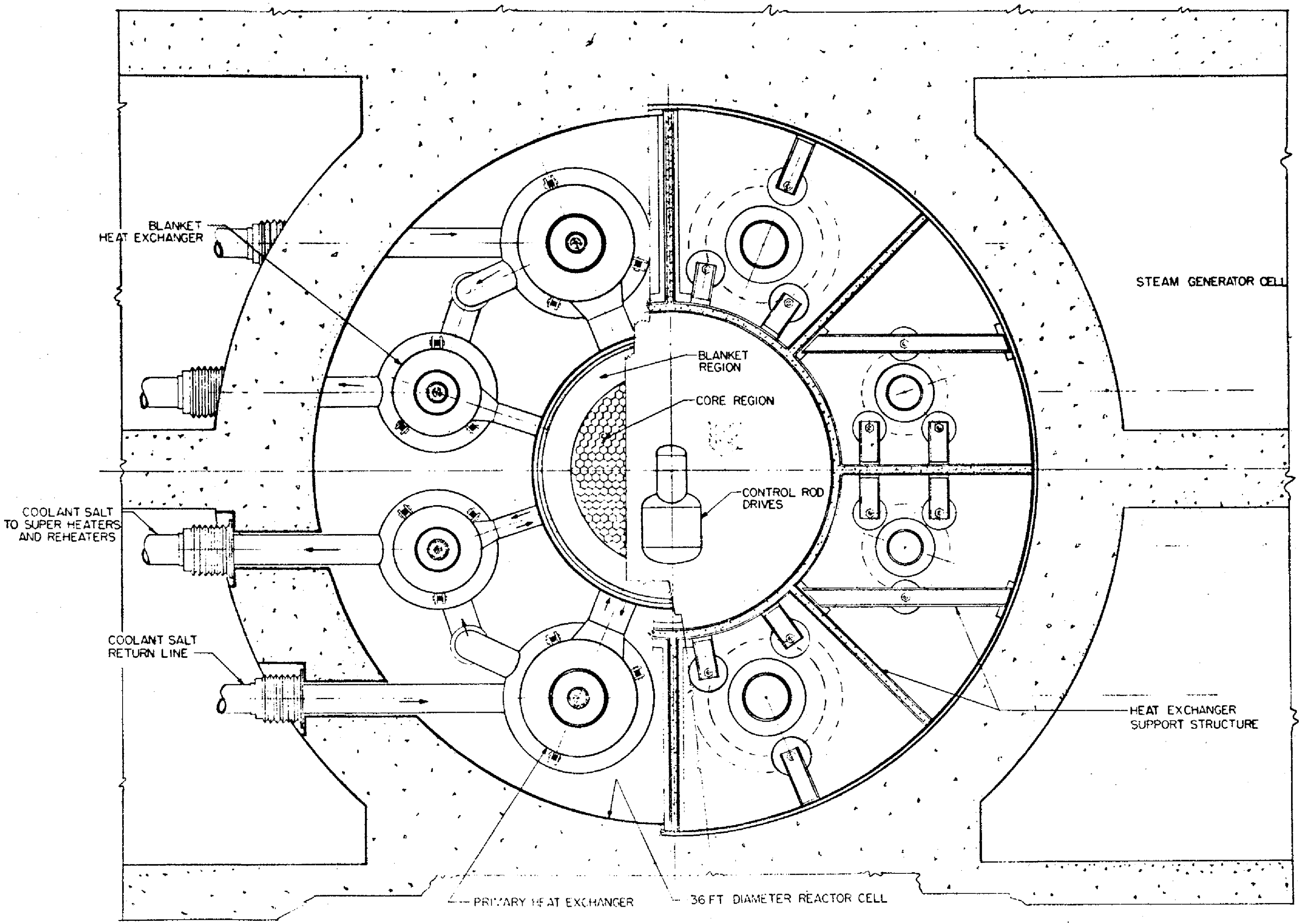

Fig. 4. Molten Salt Breeder Reactor – Reactor Cell-Plan View.

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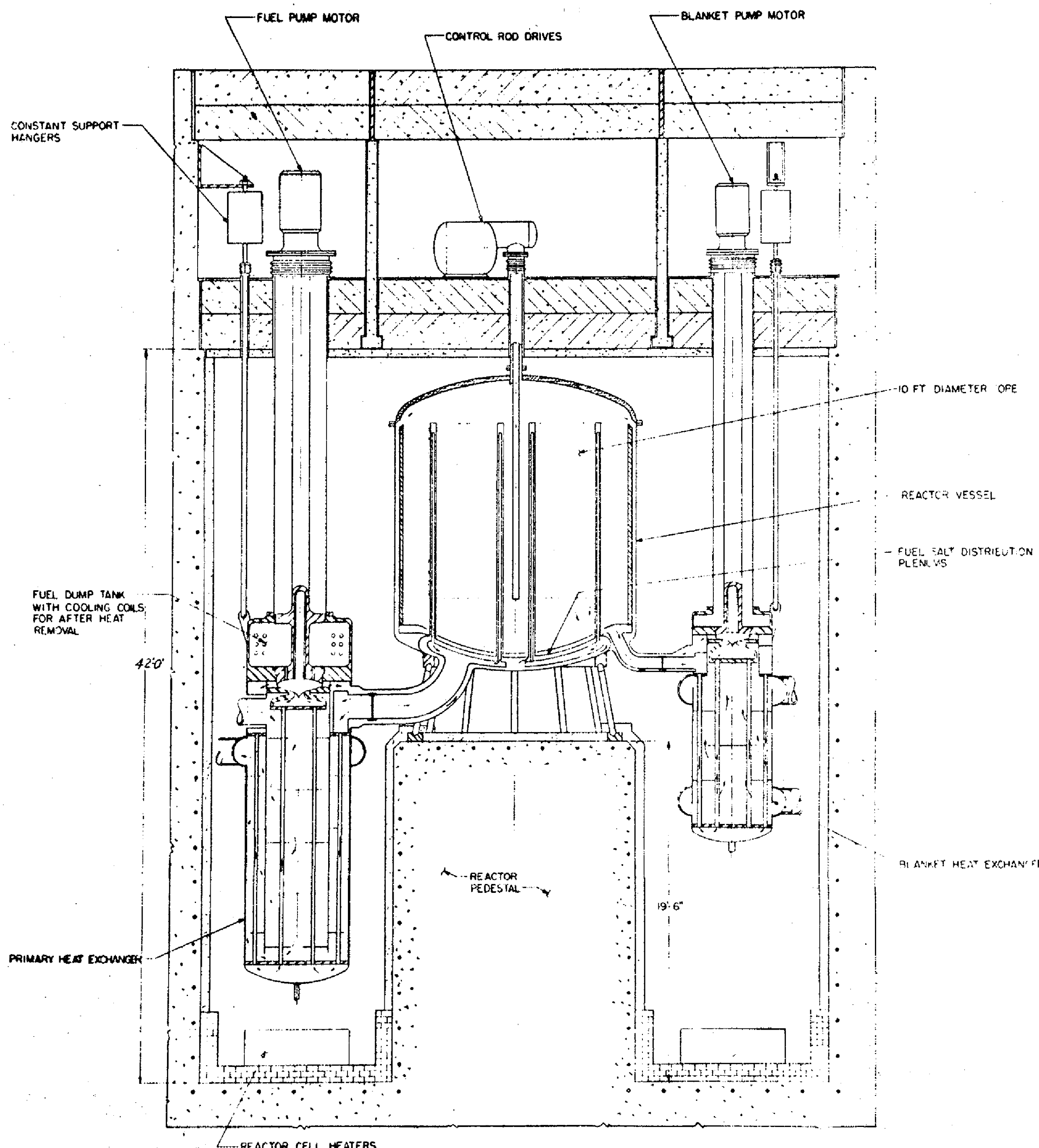

Fig. 5. Molten Salt Breeder Reactor — Reactor Cell-Elevation.

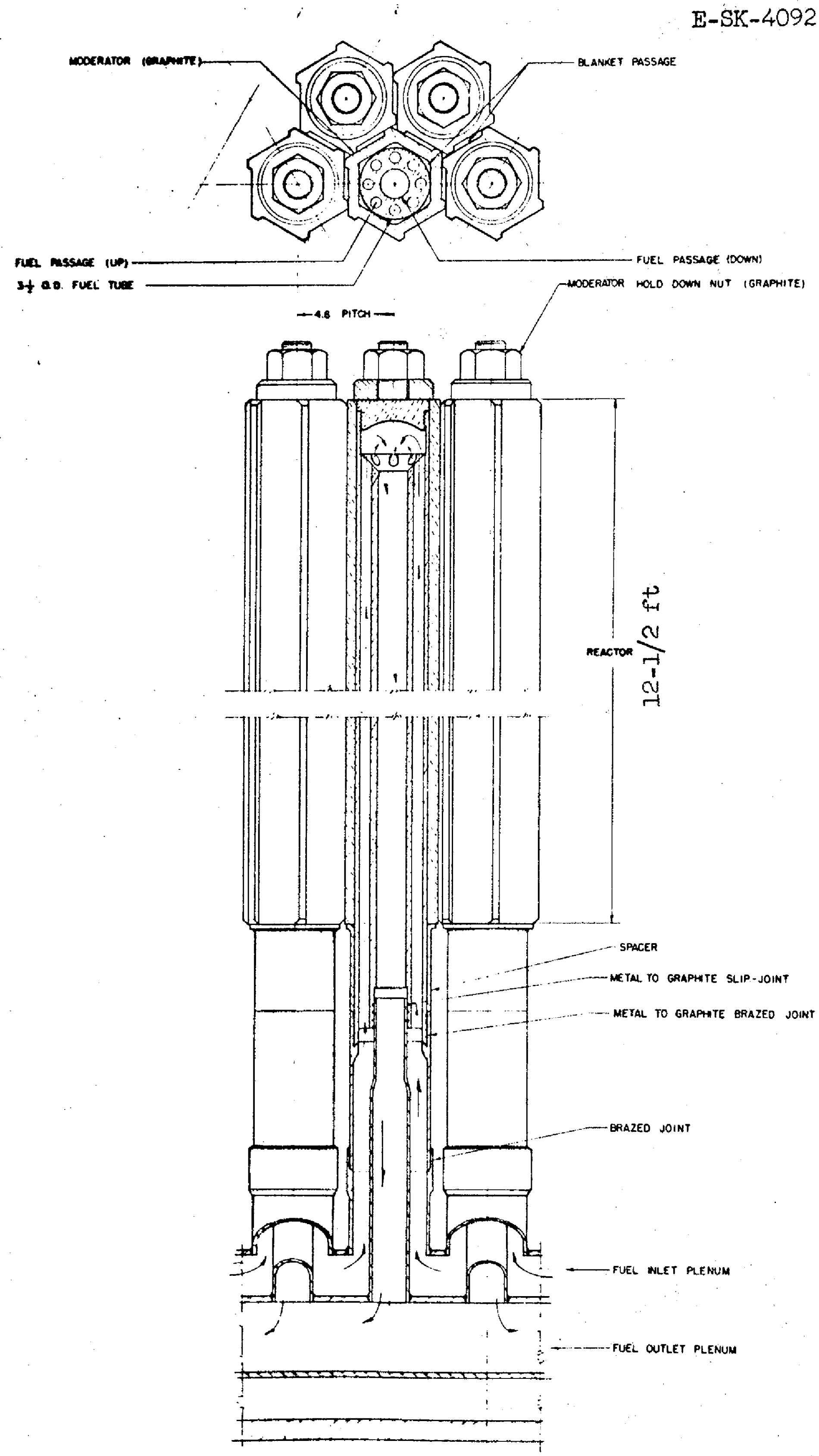

Fig. 6. Molten Salt Breeder Reactor Core Cell.

passage. The outside diameter of a fuel cell tube is 3.5 in.; there are 534 of these tubes spaced on a 4.8-in. triangular pitch. The tube assemblies are surrounded by hexagonal blocks of moderator graphite with blanket salt filling the interstices. The nominal core composition is 75% graphite, 18% fuel salt, and 7% blanket salt by volume.

A summary of parameter values chosen for the MSBR design is given in Table 1.

Fuel Processing

The primary objectives of fuel processing are to purify and recycle fissile and carrier components, and minimize fissile inventory while holding losses to a low value. The fluoride volatility-vacuum distillation process fulfills these objectives through simple operations.

The core fuel is conveniently processed by fluoride volatility and vacuum distillation. Blanket processing is accomplished by fluoride volatility alone, and the processing cycle time is short enough to maintain a very low concentration of fissile material. The effluent UF_6 is absorbed by fuel salt and reduced to UF_4 by treatment with hydrogen to reconstitute a fuel-salt mixture of the desired composition.

Molten-salt reactors are inherently suited to the design of processing facilities integral with the reactor plant; these facilities require only a small amount of cell space adjacent to the reactor cell. Because all services and equipment available to the reactor are available to the processing plant and shipping and storage charges are eliminated, integral processing facilities permit significant savings in capital and operating costs. Also, the processing plant inventory of fissile material is greatly reduced, resulting in low fuel inventory charges and improved fuel utilization characteristics for the reactor.

The principal steps in core and blanket stream processing of the MSBR are shown in Fig. 7. A small side stream of each fluid is continuously withdrawn from the fuel and blanket circulating loops and circulated through the processing system. After processing, the decontaminated fluids are returned to the reactor at some convenient point--for example, via the fuel and fertile stream storage tanks.

Fuel inventories retained in the processing plant are estimated to be about 10% of the reactor system inventory for core processing, and less than 1% for blanket processing.

Heat Exchange and Steam Systems

The structural material for all components contacted by molten salt in the fuel, blanket, and coolant systems, including the reactor vessel, pumps, heat exchangers, piping and storage tanks, is Hastelloy N.

The primary heat exchangers are of the tube-and-shell type. Each shell contains two concentric tube bundles connected in series and

Table 1. Parameter Values of MSBR Design

Power, Mw		
Thermal	2220	
Electrical	1000	
Thermal efficiency	0.45	
Plant factor	0.80	
Dimensions, ft		
Core height	12.5	
Core diameter	10.0	
Blanket thickness		
Radial	1.5	
Axial	2.0	
Reflector thickness	0.25	
Volumes, ft^3		
Core	982	
Blanket	1120	
Volume fractions		
Core		
Fuel salt	0.169	
Fertile salt	0.0735	
Moderator	0.7575	
Blanket		
Fertile salt	1.0	
Salt volumes, ft^3		
Fuel		
Core	166	
Blanket	26	
Plena	147	
Heat exchanger and piping	345	
Processing	33	
Total	717	
Fertile		
Core	72	
Blanket	1121	
Heat exchanger and piping	100	
Storage (Pa decay)	2066	
Processing	24	
Total	3383	
Salt compositions, mole %		
Fuel		
LiF	63.6	
BeF_2	36.2	
UF_4 (fissile)	0.22	
Fertile		
LiF	71.0	
BeF_2	2.0	
ThF_4	27.0	
UF_4 (fissile)	0.0005	
Core atom ratios		
Th/U	41.7	
C/U	5800	
Fissile inventory, kg	769	
Fertile inventory, 1000 kg	260	
Processing	Fuel Stream	Fertile Stream
Cycle time, days		
Volatility process	47	23
Rate, ft^3/day		
Volatility process	14.5	144
Unit processing cost, $/$ft^3$	183	6.85

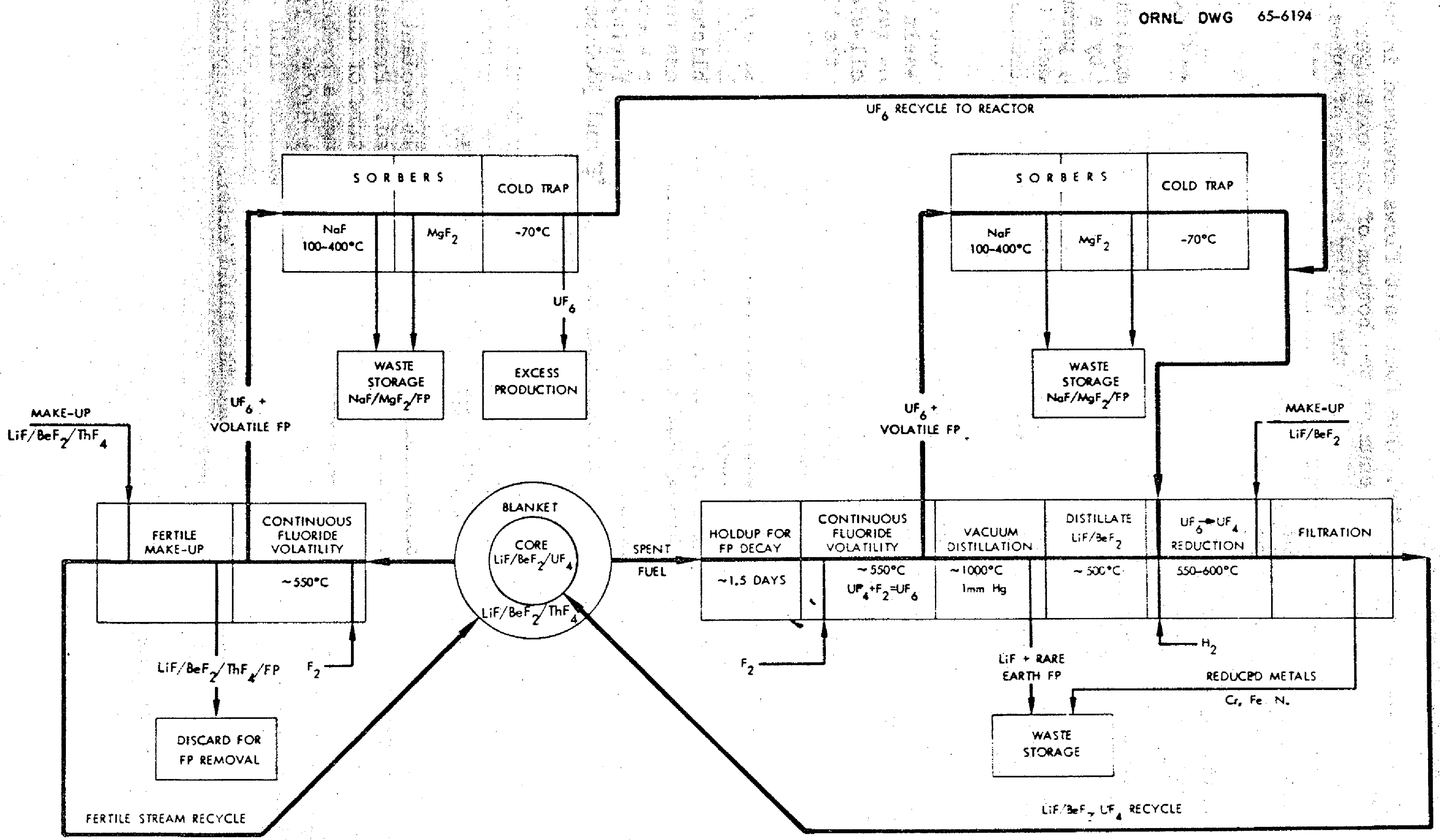

Fig. 7. Fuel and Fertile Stream Processing for the MSBR.

attached to fixed tube sheets. The fuel salt flows downward in the outer section of tubes, enters a plenum at the bottom of the exchanger, and then flows upward to the pump through the center section of tubes. Entering at the top, the coolant salt flows on the baffled shell-side of the exchanger down the central core, under the barrier that separates the two sections, and up the outer annular section.

Since a large temperature difference exists in the two tube sections, the tube sheets at the bottom of the exchanger are not attached to the shell. The design permits differential tube growth between the two sections without creating troublesome stress problems. To accomplish this, the tube sheets are connected at the bottom of the exchanger by a bellows-type joint. This arrangement, essentially a floating plenum, permits enough relative motion between the central and outer tube sheets to compensate for difference in tube growth without creating intolerable stresses in either the joint, the tubes, or in the pump.

The blanket heat exchangers increase the temperature of the coolant leaving the primary core heat exchangers. Since the coolant-salt temperature rise through the blanket exchangers is small and the flow rate is relatively high, the exchangers are designed for a single shell-side pass for the coolant salt, although two-pass flow is retained for the blanket salt in the tubes. Straight tubes with two tube sheets are used.

The superheater is a U-tube, U-shell exchanger using disc and doughnut baffles with varying spacing. It is a long, slender exchanger having relatively large baffle spacing. The baffle spacing is established by the shell-side pressure drop and by the temperature gradient across the tube wall, and is greatest in the central portion of the exchanger where the temperature difference between the fluids is high. The supercritical fluid enters the tube side of the superheater at 700°F and 3800 psi and leaves at 1000°F and 3600 psi.

The reheaters transfer energy from the coolant salt to the working fluid before its use in the intermediate pressure turbine. A shell-tube exchanger is used, producing steam at 1000°F and 540 psi.

Since the freezing temperature of the secondary salt coolant is about 700°F, a high working fluid inlet temperature is required. Preheaters, along with prime fluid, are used in raising the temperature of the working fluid entering the superheaters. Prime fluid goes through a preheater exchanger and leaves at a pressure of 3550 psi and about 870°F. It is then injected into the feedwater in a mixing tee, producing fluid at 700°F and 3500 psi. The pressure is then increased to about 3800 psi by a pressurizer (feedwater pump) before the fluid enters the superheater.

CAPITAL COST ESTIMATES

Reactor Power Plant

Preliminary estimates of the capital cost of a 1000-Mw(e) molten-salt breeder reactor power station indicate a direct construction cost of about $80.4 million. After supplying the indirect cost factors used in the advanced converter evaluation,[1] an estimated total plant cost of $113.6 million is obtained. A summary of plant costs is given in Table 2. The conceptual design was not sufficiently detailed to permit a completely reliable estimate; however, the design and estimates were studied thoroughly enough to make meaningful comparisons with previous converter reactor plant cost studies. The relatively low capital cost estimate obtained results from the small physical size of the MSBR and the simple control requirements. The results of the study encourage the belief that the cost of an MSBR power station will be as low as for stations utilizing other reactor concepts.

The operating and maintenance costs of the MSBR were not estimated. Based on the ground rules used in reference 1, these costs would be about 0.3 mill/kwhr(e).

Fuel Recycle Plant

The capital costs associated with fuel recycle equipment were obtained by itemizing and costing the major process equipment required, and estimating the costs of site, buildings, instrumentation, waste disposal, and building services associated with fuel recycle.

Table 3 summarizes the direct construction costs, the indirect costs, and total costs associated with the integrated processing facility having approximately the required capacity.

The operating and maintenance costs for the fuel recycle facility include labor, labor overhead, chemicals, utilities, and maintenance materials. The total annual cost for the capacity considered here (15 ft^3 of fuel salt per day and 105 ft^3 of fertile salt per day) is estimated to be $721,230, which is equivalent to about 0.1 mill/kwhr(e).[2] A breakdown of these charges is given in Table 4.

NUCLEAR PERFORMANCE AND FUEL CYCLE ANALYSES

The fuel cycle cost and the fuel yield are closely related, yet independent in the sense that two nuclear designs can have similar costs but significantly different yields. The objective of the nuclear design calculations was primarily to find the conditions that gave the lowest fuel cycle cost, and then, without appreciably increasing this cost, the highest fuel yield.

Table 2. Preliminary Cost-Estimate Summary[a]
1000-Mw(e) Molten-Salt Breeder Reactor Power Station

Federal Power Commission Account			Costs ($1000)
20	Land and Land Rights[b]		360
21	Structures and Improvements		
	211	Ground Improvements	866
	212	Buildings and Structures	
	.1	Reactor building[c]	4,181
	.2	Turbine building, auxiliary building, and feedwater heater space	2,832
	.3	Offices, shops, and laboratories	1,160
	.4	Waste disposal building	150
	.5	Stack	76
	.6	Warehouse	40
	.7	Miscellaneous	30
		Subtotal Account 212	8,469
		Total Account 21	9,335
22	Reactor Plant Equipment		
	221	Reactor Equipment	
	.1	Reactor vessel	1,610
	.2	Control rods	250
	.3	Shielding and containment	1,477
	.4	Heating-cooling systems and vapor-suppression system	1,200
	.5	Moderator and reflector	1,089
	.6	Reactor plant crane	265
		Subtotal Account 221	5,891
	222	Heat Transfer Systems	
	.1	Reactor coolant system	6,732
	.2	Intermediate cooling system	1,947
	.3	Steam generator and reheaters	9,853
	.4	Coolant supply and treatment[d]	300
	.5	Coolant salt inventory	354
		Subtotal Account 222	19,186
	223	Nuclear Fuel Handling and Storage (Drain Tanks)	1,700
	224	Nuclear Fuel Processing and Fabrication (included in Fuel Cycle Costs)	*
	225	Radioactive Waste Treatment and Disposal (Off-Gas System)	450
	226	Instrumentation and Controls	4,500
	227	Feedwater Supply and Treatment	4,051
	228	Steam, Condensate, and FW Piping	4,069
	229	Other Reactor Plant Equipment (Remote Maintenance)	5,000[e]
		Total Account 22	44,847

*See Table 3 for these costs, which are not included here.

Continued

Table 2 (continued)

	Federal Power Commission Account	Costs ($1000)
23	Turbine-Generator Units	
	231 Turbine-Generator Units	19,174
	232 Circulating Water System	1,243
	233 Condensers and Auxiliaries	1,690
	234 Central Lube Oil System	80
	235 Turbine Plant Instrumentation	25
	236 Turbine Plant Piping	220[f]
	237 Auxiliary Equipment for Generator	66
	238 Other Turbine Plant Equipment	25
	Total Account 23	22,523
24	Accessory Electrical	
	241 Switchgear, Main and Station Service	500
	242 Switchboards	128
	243 Station Service Transformers	169
	244 Auxiliary Generator	50
	245 Distributed Items	2,000
	Total Account 24	2,897
25	Miscellaneous	800
	Total Direct Construction Cost[g]	80,402
	Total Indirect Cost	33,181
	Total Plant Cost	113,583

[a]Estimates are based on 1966 costs, assuming an established molten-salt nuclear power plant industry.

[b]Land costs are not included in total direct construction costs.

[c]MSBR containment cost is included in Account 221.3.

[d]Assumed as $300,000 on the basis of MSRE experience.

[e]The ample MSBR allowance for remote maintenance may be too high, and some of the included replacement equipment allowances could more logically be classified as operating expenses rather than first capital costs.

[f]Based on Bull Run plant cost of $160,000 plus ~37% for uncertainties.

[g]Does not include Account 20, Land Costs. This is included in the indirect costs.

Table 3. Summary of Processing-Plant Costs for 1000-Mw(e) MSBR

Installed process equipment		$ 853,760
Structures and improvements		556,770
Waste storage		387,970
Process piping		155,800
Process instrumentation		272,100
Electrical auxiliaries		84,300
Sampling connections		20,000
Service and utility piping		128,060
Insulation		50,510
Radiation monitoring		100,000
	Total direct cost	$ 2,609,270
Construction overhead (30% of direct costs)		782,780
	Total construction cost	$ 3,392,050
Engineering and inspection (25% of total construction cost)		848,010
	Subtotal plant cost	$ 4,240,060
Contingency (25% of subtotal plant cost)		1,060,020
	Total plant cost	$ 5,300,080

Table 4. Summary of Operating and Maintenance Charges for Fuel Recycle in a 1000-Mw(e) MSBR ($/year)

Direct labor	$ 222,000
Labor overhead	177,600
Chemicals	14,640
Waste containers	28,270
Utilities	80,300
Maintenance materials	
Site	2,500
Services and utilities	35,880
Process equipment	160,040
Total annual charges	$ 721,230

Analysis Procedures

Calculation Method. The calculations were performed with OPTIMERC, a combination of an optimization code with the MERC multigroup, diffusion, equilibrium reactor code. MERC[3] calculates the nuclear performance, the equilibrium concentrations of the various nuclides, including fission products, and the fuel cycle cost for a given set of conditions. OPTIMERC permits up to twenty reactor parameters to be varied, within limits, in order to determine an optimum, by the method of steepest ascent. The designs were optimized essentially for minimum fuel cycle cost, with lesser weight given to maximizing the annual fuel yield. Typical parameters varied were the reactor dimensions, blanket thickness, fractions of fuel and fertile salts in the core, and fuel and fertile stream processing rates.

Several equations were included in the code for approximating certain capital and operating costs that vary with the design parameters (for example, capital cost of the reactor vessel, which varies with the reactor dimensions). These costs were automatically added to the fuel cycle cost in the optimization routine so that the optimization search would take into account all known economic factors. However, only the fuel cycle cost itself is reported in the results.

Modified GAM-1 — THERMOS cross-section libraries were used to compute the broad group cross sections for these calculations. It was assumed that all nuclides in the reactor system are at their equilibrium concentrations. To check this assumption, a typical reactor design was examined to determine the operating time required for the various uranium isotopes to approach their equilibrium concentrations from a startup with ^{235}U. It was found that ^{233}U and ^{235}U were within 95% of their equilibrium concentrations in less than two years. Uranium-234 was within 95% of equilibrium after eight years, while ^{236}U was within 80% after 10 years. Since the breeding performance depends mainly on the ratio of ^{233}U to ^{235}U in the fuel, the equilibrium calculation appears to be a good representation of the lifetime performance of these reactors, even for startup on ^{235}U.

Basic Assumptions

Economic. The basic economic assumptions employed in the calculations are given in Table 5. The values of the fissile isotopes were taken from the current AEC price schedule.

The processing costs are based on these given in the section entitled "Capital Cost Estimates" and are included in the fuel cycle costs. The capital and operating costs were estimated separately for each stream as a function of plant throughput, based on the volume of salt processed. The total processing cost is assumed to be a function of the throughput to some fractional power called the scale factor.

Table 5. Basic Economic Assumptions

Reactor power, Mw(e)	1000
Thermal efficiency, %	45
Load factor	0.80
Cost assumptions	
Value of ^{233}U and ^{233}Pa, \$/g	14
Value of ^{235}U, \$/g	12
Value of thorium, \$/kg	12
Value of carrier salt, \$/kg	26
Capital charge, annual rate, %	
Plant	12
Nondepreciating capital, including fissile inventory	10
Processing cost, \$/ft^3 salt	
Fuel (at 10 ft^3/day processing rate)	228
Blanket (at 100 ft^3/day processing rate)	8.47
Processing cost scale factor (exponent)	0.4

Processing. The processing scheme is that indicated in Fig. 7. A fissile material loss of 0.1% per pass through processing was assumed.

In addition to the basic processing scheme employed, results were also obtained for the case that Pa can be removed directly from the blanket stream. The improvement in performance under these circumstances is a measure of the incentive to develop Pa removal ability.

Fission Product Behavior. The disposition of the various fission products was assumed as shown in Table 6. The behavior of ^{135}Xe and other fission gases has a significant influence on nuclear performance. A gas-stripping system is provided to remove these gases from the fuel salt. However, part of the xenon could diffuse into the moderator graphite. In the calculations reported here, a ^{135}Xe poison fraction of 0.005 was assumed.

Corrosion Product Behavior. The control of corrosion products in molten-salt fuels does not appear to be a significant problem, and the effect of corrosion products was neglected in the nuclear calculations. The processing method considered here can control corrosion product buildup in the fuel.

Table 6. Disposition of Fission Products in MSBR Reactor and Processing Systems

Elements present as gases; assumed to be partly absorbed by graphite and partly removed by gas stripping (1/2% poisoning assumed):	Kr, Xe
Elements that plate out on metal surfaces; assumed to be removed instantaneously:	Ru, Rh, Pd, Ag, In
Elements that form volatile fluorides; assumed to be removed in the fluoride volatility process:	Se, Br, Nb, Mo, Tc, Te, I
Elements that form stable fluorides less volatile than LiF; assumed to be separated by vacuum distillation:	Sr, Y, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb
Elements that are not separated from the carrier salt; assumed to be removed only by salt discard:	Rb, Cd, Sn, Cs, Zr

Nuclear Design Analysis

The important parameters describing the MSBR design are given in Table 1. Many of the parameters were basically fixed by the ground rules for the evaluation or by the engineering design. These include the thermal efficiency, plant factor, capital charge rate, maximum fuel velocity, size of fuel tubes, processing costs and fissile loss rate, and the out-of-core fuel inventory. The parameters which were optimized by OPTIMERC were the reactor dimensions, power density, the core composition including the C/U and Th/U ratios, and the processing rates.

Nuclear Performance. The results of the calculations for the MSBR design are given in Table 7, and the neutron balance in Table 8. The basic design has the inherent advantage of no neutron losses to structural materials other than the moderator. Except for some unavoidable loss of delayed neutrons in the external fuel circuit, there is almost zero neutron leakage from the reactor because of the thick blanket. The neutron losses to fission products are minimized by the availability of rapid and inexpensive integrated processing.

Fuel Cycle Cost. The components of the fuel cycle cost for the MSBR are given in Table 9. The main components are the fissile inventory and processing costs. The inventory costs are rather rigid for a given reactor design, since they are largely determined by the assumed external fuel volume. The processing costs are, of course, a function of the processing cycle times, one of the chief parameters optimized in this study.

Table 7. MSBR Performance

Fuel yield, % per annum	4.86
Breeding ratio	1.0491
Fissile losses in processing, atoms/fissile absorption	0.0057
Neutron production per fissile absorption ($\eta \epsilon$)	2.221
Specific inventory, kg fissile/Mw(e)	0.769
Specific power, Mw(t)/kg fissile	2.89
Power density, core average, kw/liter	
Gross	80
In fuel salt	473
Neutron flux, core average, 10^{14} neutrons cm^{-2} sec^{-1}	
Thermal	6.7
Fast	12.1
Fast over 100 kev	3.1
Thermal flux factors, core, peak/mean	
Radial	2.22
Axial	1.37
Fraction of fissions in fuel stream	0.987
Fraction of fissions in thermal neutron group	0.806
Mean η of ^{233}U	2.221
Mean η of ^{235}U	1.958

Table 8. MSBR Neutron Balance

Material	Neutrons per Fissile Absorption: Absorbed Total	Absorbed by Fission	Produced
^{232}Th	0.9710	0.0025	0.0059
^{233}Pa	0.0079		
^{233}U	0.9119	0.8090	2.0233
^{234}U	0.0936	0.0004	0.0010
^{235}U	0.0881	0.0708	0.1721
^{236}U	0.0115	0.0001	0.0001
^{237}Np	0.0014		
^{238}U	0.0009		
Carrier salt (except ^{6}Li)	0.0623		0.0185
^{6}Li	0.0030		
Graphite	0.0300		
^{135}Xe	0.0050		
^{149}Sm	0.0069		
^{151}Sm	0.0018		
Other fission products	0.0196		
Delayed neutrons lost[a]	0.0050		
Leakage[b]	0.0012		
Total	2.2209	0.8828	2.2209

[a]Delayed neutrons emitted outside the core.

[b]Leakage, including neutrons absorbed in the reflector.

Table 9. Fuel Cycle Cost for MSBR

	Costs, mills/kwhr(e)			
	Fuel Stream	Fertile Stream	Total	Grand Total
Fissile inventory[a]	0.1180	0.0324	0.1504	
Fertile inventory	0.0000	0.0459	0.0459	
Salt inventory	0.0146	0.0580	0.0726	
Total inventory				0.2690
Fertile replacement	0.0000	0.0185	0.0185	
Salt replacement	0.0565	0.0217	0.0782	
Total replacement				0.0967
Processing	0.1102	0.0411	0.1513	
Total processing				0.1513
Production credit				0.0718
Net fuel cycle cost				0.4452

[a]Including ^{233}Pa, ^{233}U, and ^{235}U.

<u>MSBR Performance with Pa-Removal Scheme</u>. The ability to remove Pa directly from the blanket of the MSBR has a marked effect on fuel yield and fuel cycle cost. This is due primarily to the marked decrease in Pa neutron absorptions when Pa is removed from the blanket region. A simple and inexpensive blanket Pa-removal scheme would give the MSBR the performance indicated under MSBR (Pa) in Table 10; for comparison, the results without Pa removal are also given in the table.

POWER COST AND FUEL UTILIZATION CHARACTERISTICS

Based on the above, the power cost, specific fissile inventory, and fuel doubling time for the MSBR and MSBR (Pa) are summarized in Table 11.

Table 11 illustrates the economic advantage of MSBR's as nuclear power plants. Also, the fuel utilization characteristics as measured by the product of the specific inventory and the square of the doubling time[4] are excellent. On this basis the MSBR is comparable to a fast breeder with a specific inventory of 3 kg/Mw(e) and a doubling time of 10.5 years, while the MSBR (Pa) is comparable to the same fast breeder with a doubling time of 6 years.

Table 10. Comparison of MSBR Performance With and Without Pa Removal

	MSBR (Without Pa Process)	MSBR (Pa) (With Pa Removal)
Fuel yield, % per annum	4.86	7.95
Breeding ratio	1.0491	1.0713
Fuel cycle cost, mills/kwhr	0.45	0.33
Specific inventory, kg/Mw(e)	0.769	0.681
Specific power, Mw(t)/kg	2.89	3.26
Neutron production per fissile absorption ($\eta\epsilon$)	2.221	2.227
Volume fractions, core		
Fuel	0.169	0.169
Fertile	0.0745	0.0735
Moderator	0.7565	0.7575
Salt volumes, ft^3		
Fuel		
Core	166	166
External	547	551
Total	713	717
Fertile		
Total	3383	1317
Core atom ratios		
Th/U	39.7	41.7
C/U	5440	5800

Table 11. Power Cost and Fuel Utilization Characteristics of the MSBR and the MSBR (Pa)

	Cost, mills/kwhr(e)	
Reactor:	MSBR	MSBR (Pa)
Capital cost[a]	1.95	1.95
Operating and maintenance cost[b]	0.30	0.30
Fuel cycle cost[c]	0.45	0.33
Total power cost	2.70	2.58
Specific fissile inventory, kg/Mw(e)	0.77	0.68
Fuel doubling time, years	20.6	12.6

[a]Twelve per cent fixed charge rate, 80% load factor, 1000-Mw(e) plant.

[b]Nominal value used in advanced converter evaluation.[1]

[c]Costs of on-site integrated processing plant are included in this value.

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