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SUBJECT: Evaluation of External Holdup of Circulating Fuel Thermal Breeders
as Related to Cost and Feasibility

TO: L. G. Alexander

FROM: I. Spiewak
L. F. ParslyABSTRACT

The holdup of expensive materials in the heat removal systems of fluid fuel breeders was determined. The aqueous homogeneous and molten salt breeders were found to contain substantially less uranium holdup external to the core than the liquid metal fueled breeder.

Cost of heat removal and turbogenerator plant equipment for the three systems was compared.

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1. Scope of Evaluation

This memorandum contains our opinions regarding the external holdup and associated capital costs for the power removal circuits of a number of 1000 MwE breeder stations. These quantities are estimated at two levels of conservatism, corresponding to typical first and second generation plants.

No attempt was made in this study to "optimize" the cost or external holdup of the stations.

2. General Procedures Used in Study

It was hoped, at first, to evaluate the holdup of fuel and blanket materials of Aqueous Homogeneous Reactor, Molten Salt Reactor and Liquid Metal Fuel Reactor breeders as a function of pumping power. However, the technological uncertainties in designing heat exchangers, surge volumes, pumps and piping (from the standpoint of minimum holdup) were so great as to completely overshadow any possible benefits obtainable from increased pumping power.

Therefore, following discussions with people who had worked on the fluid fuel reactors and the reading of many reports, ground rules were established for designing power components for the three reactor systems on a comparable basis. The first generation plants were designed to use current technology as far as possible, with attention devoted to minimizing holdup only where conservative practices could be retained. The second generation plants assumed that some technological improvements were made (note that no new scientific or technological breakthroughs were assumed), which permitted equipment designs with lower holdup and cost.

As far as possible, component design and pricing was conducted by one person for all systems considered. For example, C. H. Gabbard sized and priced all pumps.

3. Design of AHR Plants

The first generation AHR breeder station is assumed to contain 7 reactors, each of which supplies steam to a 148 Mw turbogenerator. The net output of the station is 1000 Mw when all 7 reactors are operating at design conditions. In the second generation plant, it is assumed that five reactor vessels will supply the required amount of steam for the production of 1000 MwE.

3.1 First Generation AHR Plant

The overall layout approximates that of the TBR study, (15) as shown in Fig. 1. Fuel solution, containing 1.5 g $U_{233} + U_{235}$ sulfate in D_2O , leaves the reactor vessel at $290^\circ C$ in a vertical pipe 25.3 in. inside diameter. The stream splits into two parallel circuits contained in 17.9 in. inside diameter pipe, each circuit containing one 19,550 gpm pump

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Fig. 1. Aqueous Homogeneous Breeder Reactor - First Generation Plant.

and a steam generator. Steam is generated in the shell of the generators at 400 psia saturated. Fuel leaving the steam generators enters the reactor vessel in a double-intake volute at 245°C. The piping system is believed to be adequate from the standpoint of thermal expansion, which was reviewed thoroughly by Kormsmeier et al in the TBR design.

The blanket circuit, which consists of D₂O, is similar to the fuel circuit, except that 18-in. pipe is used throughout.

Design pressure is 2000 psi. Design temperature is 650°F.

The circulating pumps are of canned-rotor type similar to those used in FWR plants. Basic pump materials and design are similar to present pumps, and the size is comparable. Special features are: a) Cast Zircaloy hydraulic parts now commercially available at prices comparable to machined stainless steel, b) aluminum oxide hydrodynamic bearings, c) a special shaft seal to minimize motor irradiation and d) a special seal-weld adaptable to remote machining and welding. It is expected that AHR pumps will be about 30 per cent more expensive than FWR pumps.

The fuel steam generators are of U-tube and shell type with natural circulation risers and downcomers from separate steam drums.(10,11) Shell side design pressure is 1200 psi. In principle, such steam generators are standard in FWR plants. Special features are: a) Composite tubing of stainless steel-carbon steel to eliminate stress corrosion cracking problems, b) unusually high quality control standards to reduce failures to the vanishing point and c) provision for in-place tube plugging in a manner resembling the Pennsylvania Advanced Reactor philosophy.(22,23) Blanket steam generators are straight through bent-tube type.

The piping is cast 347 or other cast stainless steel. Elbows are forged or mitred. The piping holdup was assumed to be that of the TBR design,(15) corrected for 25 ft/sec in the present study compared to the earlier 32, corrected for the relative flow rates (39,100 gpm vs 24,000) and with a 20 per cent contingency.

The pressurizer contains a D₂O vapor space generated from purge-D₂O. Uranium is excluded from the surge volume by purge in a manner similar to that used in the ERE-2.

Steam goes from the steam generator to a 400 psi saturated turbo-generator plant.

3.2 Second Generation AHR Reactor Plant

The second generation plant is similar to the first-generation plant with the following modifications:

- a) The equipment is more closely coupled, as shown in Fig. 2. A single pump is directly above the reactor vessel with a pipe-line gas separator between them. The pump contains a double-discharge volute.

Fig. 3. Superheater-Recombiner.

- b) Instead of using internal recombination for the radiolytic gases produced in the core, $D_2 + 1/2 O_2$ with some steam is removed in the gas separator and recombined in a high pressure sub system shown in Fig. 3. The heat of reaction is used to superheat the steam leaving the main steam generators. The amount of the reactor's heat transmitted in the superheater is 4.2 per cent.
- c) The heat exchangers contain 3/8-in. tubes instead of 1/2-in. tubes, which increase the difficulty of fabrication and repair to the high standards needed. Less fouling is assumed than in the first generation plant.

3.3 Enumeration of AHR Technical Problems and Design Uncertainties

Known problems which affect the feasibility of the aqueous heat removal system are the following:

- a) The 347 stainless steel system must be designed to minimize stress corrosion cracking. Failure of main pipe-lines and components in AHR service from this cause has not created serious difficulties to date. However, it might be desirable to switch to a more crack-resistant alloy such as cast CD4MCu stainless steel.
- b) The heat exchanger tubes are subject to fouling by corrosion-fission products. In the HRE-2, the scale coefficient of the fuel steam generator has leveled out at about 2400 Btu/hr-ft²°F. There is at present no good method to predict the amount of fouling as related to chem plant operation and other process variables. Some progress was made by Chemical Technology and Reactor Experimental Engineering Division in developing descaling methods, but additional experience is needed to demonstrate that the scale can be controlled at a reasonable level.
- c) The consequences of failed heat exchanger tubes must be overcome in an economic fashion. This implies that failures will be infrequent (none have occurred to date in the HRE-2), that a leak will be contained adequately and economically (the HRE-2 has a steam stop valve which has been tested only on nonradioactive steam to date), and that tubes can be repaired (the Pennsylvania Advanced Reactor personnel showed the feasibility of this, but a radioactive heat exchanger has not been repaired).

Some uncertainties which may affect the cost or holdup of the systems are the following:

- a) Development of maintenance equipment and procedures is needed in order to support a proposed plant layout and design. Some information on this has been gained by the HRE-2 program, the MSR program, the Pennsylvania Advanced Reactor program and equipment vendors.

Fig. 2. Aqueous Homogeneous Reactor -
2nd. Generation Plant Section.

- b) Detailed design and stress analyses are needed to support holdup volume estimates.
- c) Detailed component design requires further experimental development and demonstration. For example, flow tests are needed to define the pressurizer-piping geometry for minimum holdup. Large alumina bearings, and seals need to be developed for pumps. Numerous other minor difficulties can influence component cost and holdup. No equipment problems which may be unsolvable are known.
- d) The permissible fluid velocity in the external piping, which influences the cost and holdup of the piping, was assumed to be 25 ft/sec. This is a conservative specification based on corrosion tests in in-pile and out-of-pile loops. It is believed likely that the velocities can be increased.

3.4 Third Generation Plants

Substantial improvements in external specific power may be achieved in several ways, some of which might be economic:

- a) The Dutch propose to use an aqueous slurry of UO_2 as a fuel. Activated charcoal is circulated with the UO_2 to adsorb fission products. In principle, it is possible to circulate only D_2O through the heat exchangers if solid-liquid separators are used at the core discharge. Charcoal is removed continuously with its load of fission products.
- b) The reactor heat could be removed by boiling or flashing, reducing external holdup of uranium.
- c) A limited reduction of external holdup might be obtained in a "package" design using circulating uranyl sulfate fuel.
- d) The external system capitalization could be improved substantially by higher operating temperatures.

Considerable investigation of the above concepts would be needed prior to design of a third generation power breeder.

4. Design of MSR Plants

The MSR breeder station is assumed to contain 2 reactors, each of which supplies steam to a single 526 Mw turbogenerator. The net output of the station is 1000 Mw when both reactors are operating at design conditions.

4.1 First Generation MSR Reactor Plant

The entire fuel circulating system is a very compact arrangement contained within the reactor vessel, (17) shown in Fig. 4. Fuel salt 63 mol per cent LiF and 37 mol per cent BeF_2 , containing 9.8 g $U_{233} + U_{235}$ per liter as UF_4 , leaves the core at 1300°F. Fuel salt flows up 15 ft into the pump suction, which discharges fluid directly into the intermediate

Fig. 4. Molten Salt Breeder Reactor

heat exchanger head. The tubes of the heat exchanger, containing fuel, spiral down at a 45° angle in an annulus surrounding the pump suction line. The discharge header empties into the core at 1125°F. Surge volume is provided in the pump, which is a sump type.

The blanket circuit was not laid out in detail, but the principle is the same as that of the fuel circuit. The blanket salt is LiF-BeF₂ carrier containing 1.16 g U-233 + Pa-233 per liter and 1550 g Th per liter as ThF₄.

The intermediate coolant is LiF-BeF₂ at a pressure slightly above fuel pressure. This coolant has the great advantage of complete compatibility with both core and blanket fluids so that small heat exchanger leaks are tolerable. It is also reasonably compatible with water (compared to sodium-water compatibility). Its disadvantages are high cost, and high melting point.

The design pressure of salt components used in this study was 250 psi.

The fuel salt circulating pumps are sump-type. (16,20) The motor is a conventional water-cooled type with a pressure can around it, containing inert helium gas. Beryllium shielding is provided to limit radiation damage to motor insulation. Pumps are bayonet-mounted into the primary reactor shield for easy maintenance. (16) Either pump or stator may be replaced, but the casing is permanently installed. The pump size and design is not unusual for liquid metal pump suppliers, and much successful small pump operation is cited by Reactor Projects Division. Fission product gases are removed in the pump sump. A special feature of the pump is a lower sleeve bearing operating in salt.

The intermediate heat exchanger requires considerable additional design and development work. This is a removable unit just above the reactor core physically, about 15 ft long and 6 ft in diameter. Coolant salt flows in the shell, but no practical means of baffling the shell fluid has been proposed. Using more optimistic design assumptions than used in the present study, Kinyon proposed a more compact unit. (17) The unit is made entirely of INOR.

The coolant salt leaves the reactor vessel, enters a pump room, passes through pumps similar to the reactor fuel pump but without shielding, goes to steam generator-superheaters and reheaters, another pump and back to the reactor. The layout is similar to that proposed for the LMTBR by B and W. (6)

The only special item in the coolant salt system is the steam generator-superheater proposed by B. Kinyon. This features bayonet tubes in which steam passes through an annulus in which it is superheated and gives up heat to boiling water in a second internal annulus. The cost of this type of unit is believed to be competitive with other high temperature liquid metal-to-water heat exchangers, and it is believed that the Kinyon design might be superior from the stress standpoint. A boiler recirculating pump is needed to recycle water.

Steam is sent through a plant similar, in all respects except size, to the TVA John Sevier Plant. (18) The condenser cooling water is assumed to be available at 63°F (typical of northern U.S.) compared to 72°F in Tennessee.

4.2 Second Generation MSR Plant

The second generation plant is similar to the first generation plant with the following modifications:

- a) Sodium is used as intermediate coolant. It is realized that sodium is incompatible with fuel salt and water, but if heat exchangers don't leak, incompatibility is immaterial. The sodium viscosity and thermal conductivity insure adequate performance of a compact intermediate heat exchanger. Sodium has a low melting point. Sodium is cheap. On the other hand, sodium has well known disadvantages.
- b) Material selection is changed to conform to sodium practice. Composite tubing is needed in some cases.

4.3 Enumeration of MSR Technical Problems and Design Uncertainties

Known problems which affect the feasibility of the MSR heat removal system are:

- a) The design of liquid-metal (and presumably molten salt) steam generator-superheaters is very difficult because of mechanical problems.(2,8,13) There is no strikingly successful industrial experience in the field. On the other hand, MSR will get the benefit of technological improvements made in the SGR and fast breeder 10-year programs of the USAEC.
- b) The fuel and blanket pumps and heat exchangers will be required to operate reliably for long periods of time in the temperature range where creep is important. Some replacements will need to be executed, possibly of parts which have changed slightly in dimensions. Long-term operating experience with equipment run at 1300°F is needed to show whether this is a serious problem.
- c) In the second generation plant using sodium coolant, the consequences of failed heat exchanger tubes must be overcome in an economic fashion. This implies that sodium-steam and sodium-salt interchange can be controlled, and that heat exchangers can be repaired or replaced afterward. This problem is present to a much lesser degree in the first generation plant using a salt coolant.
- d) It is presumed, on the basis of several in-pile experiments, that the INOR pipe and tubing will not corrode rapidly in contact with radioactive fuel.

Some uncertainties which may affect the cost or holdup of the systems are the following:

- a) Development of maintenance equipment and procedures is needed in order to support a proposed plant layout and design. The feasibility of some types of operations has been demonstrated at the Remote Maintenance Facility, the HRE-2 and by the Pennsylvania Advanced Reactor Program. The maintenance will have to be done without introducing excessive oxygen contamination.

- b) Detailed design and stress analyses are needed to support holdup volume estimates.
- c) Detail component design requires further experimental investigation. The amount of work needed in this area is much larger than in the corresponding AHR area. For example, it is difficult to predict the heat transfer coefficients on the shell side of the fuel-to-intermediate coolant heat exchanger without additional model tests in an unbaﬄed spiral geometry with a high-viscosity (molten-salt) coolant. A sweep-gas system for the circulating-pump motor should be developed to prevent radiation damage by fission products. The dead fuel volume needed to disengage fission-gas bubbles from the fuel salt cannot be accurately predicted. Although the present pump seals and bearings are considered adequate for use in the pumps of a small experimental reactor, improved parts are needed to provide the service life presumed for a power breeder. No equipment problems which may be unsolvable are known.
- d) Insoluble materials are introduced into the fuel stream by some fission products, as a result of chromium leaching from INOR and from oxygen contamination. It is believed that the fouling of heat transfer surfaces by such materials will be unimportant, on the basis of loop tests.
- e) To prevent cavitation of the fuel circulating pump, a suction pressure of 100 psi is required.⁽²⁴⁾ This requirement might be relaxed as a result of experimental investigation, or the pump could be redesigned (with more holdup and cost) to reduce the net positive suction head.
- f) The thermal conductivity of INOR at the temperature of the intermediate heat exchanger may be about 35 per cent below that assumed in this study. The fuel holdup of the first generation plant might thereby be increased 8 per cent, and the heat exchanger area increased 10 per cent.
- g) In the first generation plant, the holdup of coolant salt might be reduced considerably by detail design and development of the steam generators.
- h) The INOR costs may be lower than estimated here.

4.4 Third Generation Plants

Substantial improvements in external specific power may be achieved in internally cooled designs, possibly using blanket salt or LiF-BeF₂ coolants.

It is believed that some holdup reductions are possible in first and second generation plants if further experimental information is gained as outlined in Section 4.3.

5. Design of LMFR Plants

The LMFR breeder station is assumed to contain 2 reactors, each of which supplies steam to a single 529 Mw turbogenerator. The net output of the station is 1000 Mw when both reactors are operating at design conditions.

5.1 First Generation LMFR Reactor Plant

The plant layout is essentially that proposed by B and W⁽⁶⁾ (Fig. 5). Bismuth containing 22 g $U_{233} + U_{235}$ per liter leaves the core at 1300°F and immediately passes up through the tantalum intermediate exchanger. The reactor surge volume, at 1000°F, is just above the heat exchanger exit. From this plenum liquid enters the propeller pump. A single pump is assumed, but the holdup volume would be independent of the number of pumps in parallel. The pump discharges directly into an annular plenum leading to the reactor.

The blanket circuit is essentially the same. The blanket fluid is a slurry of ThO_2 in bismuth, containing 1025 g Th/liter and $U-233 + Pa-233$ per liter.

The intermediate coolant is sodium.

Design pressure for this system is 400 psi which is the sum of the pump head developed, the net positive suction head to prevent cavitation and the elevation head.

The bismuth pumps are similar in design to large liquid metal pumps used elsewhere. It is not known to us whether pumps this big have actually been built. However, as indicated above, for purposes of the present study the number of Bi pumps is immaterial except from the standpoint of cost. Pumps are bayonet-mounted into the primary reactor shield for easy maintenance. Either pump or stator may be replaced, but the casing is permanently installed. Shielding of the pump-motor from radiation is installed.

The intermediate heat exchanger requires the conversion of tantalum from a material used in small quantities to one used in multi-ton assemblies. The design, outlined by B and W, is straightforward except a) to make the unit compact, the 1/2-in. tubes are swaged down to 3/8-in. in the tubesheet, b) because of the close tube spacing, high sodium pumping power is probably needed to remove the heat uniformly, c) in order to reduce the thickness and thereby the cost of the tubesheet, the sodium in the shell is kept at a higher pressure than that of the bismuth in the tubes.

The sodium leaves the reactor vessel and enters the pump and steam generator rooms as proposed by B and W. The steam is generated at the same conditions as used in the MSR plant, 1800 psi and 1050°F.

The only difficult equipment problem in this part of the system is the steam generator-superheater. Of all available designs which were reviewed, the most practical appeared to be one proposed by Alco⁽²⁾ for

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Fig. 5. Liquid Bismuth Breeder Reactor

generating 70 Mw of 2200 psi steam. The Alco design was modified to double its capacity, at an operating pressure of 1800 psi. This unit consists of bayonet tubes in the steam-generator section and straight through tubes in the superheater section. Sodium flows through the shell of both sections, leaving the steam generator at 725°F. The sodium is mixed with 1175°F fluid to gain an average temperature of 900°F at the entrance to the reactor vessel. This technique is used to minimize thermal stresses in the steam generator and in the intermediate heat exchanger.

5.2 Second Generation LMFR Plant

The second generation plant used somewhat more optimistic costs for tantalum, and used slightly more optimistic fuel heat exchanger design parameters. The heat exchanger tubes were reduced from 1/2-in. OD to 3/8-in.

5.3 Enumeration of LMFR Technical Problems and Design Uncertainties

Known problems affecting the feasibility of the LMFR heat removal system are:

- a) Problems similar to those cited for the MSR in Section 4.3, except that preliminary tests indicate that tantalum creep will not be important at 1300°F or below. (25)
- b) Satisfactory circulation of the blanket slurry in a system of appropriate complexity remains to be demonstrated.
- c) The possible interaction of slurry particles and fission gases may lead to difficulties with foaming.
- d) The feasibility of use of tantalum in large pieces requires demonstration.

The design uncertainties a, b, c, d and e listed under the MSR in Section 4.3 apply also to the LMFR.

5.4 Third Generation Plants

Substantial improvements in external specific power are possible with internally cooled designs, using Bi or Bi-ThO₂ coolants.

6. Results

The results of this evaluation are presented in the following tables:

- 6.1 Comparison of Fuel Heat Exchangers
- 6.2 Comparison of Blanket Heat Exchangers
- 6.3 Comparison of Steam Generators-Superheaters
- 6.4 Comparison of Reheaters
- 6.5 Cost of Heat Exchangers, \$10⁶
- 6.6 Pump Cost and Size Summary
- 6.7 Summary of Piping Assumed
- 6.8 Station Cost of Spare Equipment for Reactor Cooling System

- 6.9 Expected Life of Power Components
- 6.10 Turbo-Generator Plant Summary
- 6.11 AHR Breakdown of External Holdup Containing U, Basis 1 Reactor
- 6.12 MSR Breakdown of External Holdup Containing U, Basis 1 Reactor
- 6.13 LMFR Breakdown of External Holdup Containing U, Basis 1 Reactor
- 6.14 Station Summary of Holdup in Heat Removal System
- 6.15 Summary - Cost of Heat Removal and Turbogenerator Equipment

Table 6.1

Comparison of Fuel Heat Exchangers

	AHR		MSR		LMFR	
	1st Gen.	2nd Gen.	1st Gen.	2nd Gen.	1st Gen.	2nd Gen.
Thermal Load Per Unit, Mw	221	279	1051	1051	934	934
Number of Units per Station	14	10	2	2	2	2
Tube Side Fluid	UO ₂ SO ₄ -D ₂ O	UO ₂ SO ₄ -D ₂ O	Fuel Salt	Fuel Salt	LMF	LMF
Shell Side Fluid	Water	Water	LiF-BeF ₂	Na	Na	Na
Heat Exch. Layout	U	Straight	Spiral	Spiral	Straight	Straight
Tube Outside Dia., in.	0.5	0.375	0.375	0.375	0.5	0.375
Tube Wall Thickness, in.	0.049	0.049	0.035	0.028	0.028	0.018
Tube Material	347-CS	347-CS	INOR	INOR-316	Tantalum	Tantalum
Tube Velocity, ft/sec	15	15	20	20	10	10
Flow Rate, lb/hr	7.46 x 10 ⁶	10.52 x 10 ⁶	3.87 x 10 ⁷	3.87 x 10 ⁷	2.62 x 10 ⁸	2.62 x 10 ⁸
Fluid Temp., In, °F	554	554	1300	1300	1300	1300
Fluid Temp., Out, °F	473	473	1125	1125	1000	1000
Pressure Drop, psi	17.2	15.4	151	78	43	39.5
No. of Tubes in Unit	3120	9070	8787	8110	12,100	20,800
Length of Tubes, ft	32	17.34	22.11	11.13	9.4	6.5
Corrosion Allowance, mpy	0.3	0.3	0.3	0.3	0.3	0.1
Tube Bundle Dia., in.	40	52	71	69	87.5	92.5
Tube Sheet Thickness, in.	6.7	7.1	5.7	3.75, 5.0	1.7	1.7
Tube Sheet Material	347-CS	347-CS	INOR	INOR-316	Tantalum	Tantalum
Shell Material	CS	CS	INOR	INOR-316	Tantalum	Tantalum
Shell Flow Rate, lb/hr	9.10 x 10 ⁵	1.06 x 10 ⁶	3.01 x 10 ⁷	4.55 x 10 ⁷	3.99 x 10 ⁷	3.99 x 10 ⁷
Fluid Temp., In, °F	365	365	1000	900	900	900
Fluid Temp., Out, °F	446	448.5	1175	1175	1175	1175

Table 6.1 (Continued)

	AHR		MSR		LMFR	
	1st. Gen.	2nd Gen.	1st Gen.	2nd Gen.	1st Gen.	2nd Gen.
Pressure Drop, psi	nil	nil	100	100	100	100
Inside Film Coefficient	5830	6220	6200	8020	3820	4610
Tube Wall Coefficient	4120	4340	5600	7080	13,700	21,300
Scale Coefficient	2400	5000	10,000	10,000	10,000	10,000
Outside Film Coefficient	15,000	15,000	6800	48,900	19,700	17,850
Overall Coefficient, Btu/hr ft ² °F	1120	1520	1580	2620	1915	2250
Outside Tube Area, ft ²	13,050	15,400	18,200	8320	14,880	12,650

Table 6.2

Comparison of Blanket Heat Exchangers

	<u>AER</u>		<u>MSR</u>		<u>LMFR</u>
	<u>1st Gen.</u>	<u>2nd Gen.</u>	<u>1st Gen.</u>	<u>2nd Gen.</u>	
Thermal Load per Unit, Mw	105	139.5	104	104	254
Number of Units per Station	7	5	2	2	2
Tube Side Fluid	D ₂ O	D ₂ O	Blk. Salt	Blk. Salt	LM Slurry
Shell Side Fluid	Water	Water	LiF-BeF ₂	Na	Na
Heat Exchanger Layout	Straight	Straight	Spiral	Spiral	Straight
Tube Outside Diameter, in.	0.5	0.049	0.035	0.028	0.035
Tube Material	347-CS	347-CS	INOR	INOR-316	Ta
Tube Velocity, ft/sec	15	15	14.1	14.1	10
Flow Rate, lb/hr	1.61×10^7	1.04×10^7	5.98×10^6	5.98×10^6	2.63×10^6
Fluid Temp., In, °F	498	522	1300	1300	1300
Fluid Temp., Out, °F	482	482	1150	1150	1000
Pressure Drop, psi	3.1	8.0	127.5	109	66.5
No. of Tubes in Unit	6650	8130	1050	1050	3120
Length of Tubes, ft	5.75	9.75	23.5	19.7	12.55
Tube Bundle Diameter, in.	56	49	27	27	46
Tube Sheet Thickness, in.	10.8	9.5	1.90	1.90	1.90
Tube Sheet Material	347-CS	347-CS	INOR	INOR-316	Ta
Shell Material	CS	CS	INOR	INOR-316	Ta
Shell Flow Rate, lb/hr	3.92×10^5	5.35×10^5	4.16×10^6	4.48×10^6	1.07×10^7
Fluid Temp., In, °F	364	364	1050	900	900
Fluid Temp., Out, °F	446	448.5	1175	1175	1175
Pressure Drop, psi	nil	nil	100	100	100
Inside Film Coefficient	5750	6220	5550	5550	3820

Table 6.2 (Continued)

	<u>AHR</u>		<u>MSR</u>		<u>LMFR</u>
	<u>1st Gen.</u>	<u>2nd Gen.</u>	<u>1st Gen.</u>	<u>2nd Gen.</u>	
Tube Wall Coefficient	4120	4340	5660	5660	13,700
Scale Coefficient	nil	nil	10,000	10,000	10,000
Outside Film Coefficient	9500	10,000	6800	40,000	19,700
Overall Coefficient Btu/hr Ft ² °F	1680	1425	1508	1845	1915
Outside Tube Area, ft ²	4440	6510	2105	1925	4050

Table 6.3

Comparison of Steam Generators-Superheaters

	AHR	MSR		LMFR
	2nd Gen.	1st Gen.	2nd Gen.	
Thermal Load per Unit, Mw	30.4	253	253	167.5
Number of Units per Station	5	8	8	12
Tube Side Fluid	D ₂ O Steam	Water	Water	Water
Shell Side Fluid	H ₂ O Steam	LiF-BeF ₂	Na	Na
Heat Exchanger Layout	Straight	Kinyon	Kinyon	Alco
Steam Gen. Section				
Tube Outside Diameter, in.				2
Tube Wall Thickness, in.				0.150
Tube Material				316 ss
No. Tubes				965
Length of Tubes, ft.				10
Superheat Section				
Tube Outside Diameter, in.	0.5	1.308	1.308	0.5
Tube Wall Thickness, in.	0.035	0.138	0.138	0.079
Tube Material	Incoloy	INOR	Hastalloy C	Inconel-316
No. Tubes	823	888	888	737
Length of Tubes, ft.	18.16	26.7	26.7	24
Tube Flow, lb/hr (net)	2.90×10^5	8.02×10^5	8.02×10^5	5.31×10^5
Fluid Temp., In, °F	879	488	488	488
Fluid Temp., Out, °F	596	1050	1050	1050
Pressure Drop, psi	5	100	100	90
Shell Materials	CS	INOR	Hastalloy	Croloy-316 ss
Shell Flow, lb/hr	2.65×10^6	7.3×10^6	1.065×10^7	4.32×10^6
Fluid Temp., In, °F	448.5	1175	1175	1175

Table 6.3 (Continued)

	AHR	MSR		LMFR
	<u>2nd Gen.</u>	<u>1st Gen.</u>	<u>2nd Gen.</u>	
Fluid Temp., Out, °F	500	1000	900	725
Pressure Drop, psi	10	40	25	23
Inside Film Coefficient	510	927	927	805
Tube Wall Coefficient	3430	1100	1100	1460
Outside Film Coefficient	548	4130	10,000	4000
Overall Coefficient, Btu/hr ft ² °F	226	450	500	460
Outside Tube Area, ft ²	1957	7900	7900	4290

Table 6.4

Comparison of Reheaters

	MSR		LMFR
	1st Gen.	2nd Gen.	
Thermal Load per Unit, Mw	118	118	118
Number of Units per Station	4	4	4
Tube Side Fluid	Steam	Steam	Steam
Shell Side Fluid	LiF-BeF ₂	Na	Na
Heat Exchange Layout	Straight	Straight	Straight
Tube, Outside Diameter, in.	0.5	0.5	0.5
Tube, Wall Thickness, in.	0.049	0.049	0.049
Number of Tubes	2740	2740	2740
Tube Material	INOR	Hastalloy C	Hastalloy C
Length of Tubes, ft	11.2	11.2	11.2
Shell Material	INOR	316 ss	316 ss
Tube Fluid Temp., In, °F	670	670	670
Temperature, Out, °F	1050	1050	1050
Pressure in psia	402	402	402
Pressure Drop, psi	40	40	40
Shell Fluid Temp., In, °F	1175	1175	1175
Shell Fluid Temp., Out, °F	1000	900	900
Outside Tube Area, ft ²	7300	7300	7300

Table 6.5

Cost of Heat Exchangers, \$10⁶

	AHR		MSR		LMFR	
	<u>1st Gen.</u>	<u>2nd Gen.</u>	<u>1st Gen.</u>	<u>2nd Gen.</u>	<u>1st Gen.</u>	<u>2nd Gen.</u>
Fuel Heat Exchangers						
Number of Units	14	10	2	2	2	2
Cost of Tubing, \$/ft	1.208	1.067	3.70	3.50	25.8	10.7
Cost of Material, Unit	0.157	0.240	1.12	0.494	5.55	3.29
Cost of Labor, Unit	0.105	0.130	0.33	0.306	0.32	0.53
Cost of Units in Station	3.67	3.70	2.90	1.60	11.74	7.64
Blanket Heat Exchangers						
Number of Units	7	5	2	2	2	2
Cost of Tubing, \$/ft	1.208	1.067	3.70	3.50	25.8	19.8
Cost of Material, Unit	0.076	0.153	0.14	0.073	2.88	2.22
Cost of Labor, Unit	0.150	0.111	0.03	0.033	0.096	0.096
Cost of Units in Station	1.58	1.32	0.34	0.21	5.96	4.64
Steam Gen.-Superheater						
Number of Units		5	8	8	12	12
Cost of Tubing, \$/ft		1.50	22.3	17.8	--	--
Cost of Material, Unit		0.038	1.055	0.845	0.54	0.54
Cost of Labor, Unit		0.040	0.395	0.395	0.305	0.305
Cost of Units in Station		0.39	11.6	9.6	10.1	10.1
Reheater						
Number of Units			4	4	4	4
Cost of Materials, Unit			0.476	0.33	0.33	0.33
Cost of Labor, Unit			0.074	0.07	0.07	0.07
Cost of Units in Station			2.2	1.6	1.6	1.6
Cost of All Units in Station	5.25	5.41	17.04	13.01	29.4	24.0

Table 6.6

Pump Cost and Size Summary

	<u>AER</u>		<u>MSR</u>		<u>LMFR</u>
	<u>1st Gen.</u>	<u>2nd Gen.</u>	<u>1st Gen.</u>	<u>2nd Gen.</u>	
Fuel Pump					
Number/Reactor	2	1	1	1	1
Motor Type	Canned	Canned	Shielded	Shielded	Shielded
Pump Speed, rpm	1150	875	1175	1175	350
Flow, gpm	19,550	44,300	40,800	40,800	52,800
Head, ft	100	100	138	110	30
Motor, h.p.	525	1175	3250	2600	4500
Motor Price (\$ Thou.)			98	75	135
Pump Price (\$ Thou.)	170	340	356	320	560
Internal Shielding (\$ Thou.)			155	155	155
Blanket Pump					
Number/Reactor	1	1	1	1	1
Motor Type	Canned	Canned	Shielded	Shielded	Shielded
Pump Speed, rpm	1150	1150	1750	1750	720
Flow, gpm	19,050	23,200	3550	3550	13,500
Head, ft	100	100	159	159	30
Motor, h.p.	518	630	550	550	1250
Motor Price (\$ Thou.)			17	17	37.5
Pump Price (\$ Thou.)	150	180	180	180	290
Internal Shielding (\$ Thou.)			75	75	100
Coolant Pumps					
Number/Reactor			6*	5	5
Flow, gpm			12,700	24,000	24,000

*Note that the 6 pumps are in series - parallel.

Table 6.6 (Continued)

	AHR		MSR		LMFR
	<u>1st Gen.</u>	<u>2nd Gen.</u>	<u>1st Gen.</u>	<u>2nd Gen.</u>	
Head, ft			100	300	300
Motor, h.p.			750	1750	1750
Motor Price (\$ Thou.)			22.5	52.5	52.5
Pump Price (\$ Thou.)			320	300	300
Cost, All Installed Pumps	$\$3.43 \times 10^6$	$\$2.60 \times 10^6$	$\$5.87 \times 10^6$	$\$5.17 \times 10^6$	$\$6.08 \times 10^6$

Table 6.7

Summary of Piping Assumed

	<u>AHR</u>		<u>MSR</u>	<u>IMFR</u>
	<u>1st Gen.</u>	<u>2nd Gen.</u>		
Fuel Piping Material		Cast 347	INOR	Croloy
Pipe Size	18 in., Sch. 140	24 in., 32 in. Sch. 140		
Velocity, ft/sec	25	25	40	25
Sodium Piping, Material			316	316
Sodium Piping, Size			18 in., Sch. 30	18 in., Sch. 30
Coolant Salt Pipe Material			INOR	
Pipe Size			12 in., Sch. 30	
Na, Salt Velocity, ft/sec			40	40
Per Reactor				
Approx. Length of 32 in. Pipe, ft		35		
Approx. Length of 24 in. Pipe, ft		90		
Approx. Length of 18 in. Pipe, ft	180		1300*	1300
Approx. Length of 12 in. Pipe, ft			780*	
Cost of Piping, Station				
1st Generation Plant	$\$1.29 \times 10^6$		$\$0.48 \times 10^6$	$\$0.89 \times 10^6$
2nd Generation Plant	$\$0.85 \times 10^6$		$\$0.89 \times 10^6$	$\$0.89 \times 10^6$

*18 in. pipe is used with Na coolant (2nd Gen.).
 12 in. pipe is used with salt coolant (1st Gen.).

Table 6.8

Station Cost of Spare Equipment for Reactor Cooling System

	<u>AHR</u>		<u>MSR</u>		<u>LMFR</u>	
	<u>1st Gen.</u>	<u>2nd Gen.</u>	<u>1st Gen.</u>	<u>2nd Gen.</u>	<u>1st Gen.</u>	<u>2nd Gen.</u>
Spares on Hand, No.						
Fuel Circ. Pump	2	2	0.5	0.5	0.5	0.5
Blkt. Circ. Pump	2	2	0.5	0.5	0.5	0.5
Intermediate Pumps			2	2	2	2
Fuel Heat Exchanger	1	1	0.5	0.5	0.5	0.5
Blanket Heat Exchanger	1	1	0.5	0.5	0.5	0.5
Cost of Spare Equipment						
Megabucks	1.13	1.67	1.82	1.46	5.64	4.28

Table 6.9

Expected Life of Power Components

	<u>Life, years</u>		<u>Type of Failures</u>	<u>Type of Repair</u>
	<u>1st Gen.</u>	<u>2nd Gen.</u>		
<u>AHR</u>				
Fuel and Blanket Circulating Pumps- Rotating Assembly	5	8	Bearing	Hot Shop Replacement
Stator	5	8	Leak, Rad. Damage	Replacement
Casing	30+	30+	Wear-ring Damage	In Place
Steam Generators	30+	30+	Multiple Tube Damage	Replacement
	5	8	Tube Leak	In Place
<u>MSR</u>				
Fuel and Blanket Circulating Pumps- Rotating Assembly	5	10	Bearing, Seal	Replacement
Stator	5	8	Rad. Damage	Replacement
Casing	30+	30+	Wear-ring Damage	Replacement
Fuel and Elkt. Heat Exchanger	5	10	Fatigue, Tube	Replacement
Intermediate Pumps	8	8	Bearing, Seal	Hot Shop
Steam Generators-Superheaters	30	30	Fatigue, Creep	Replacement
	3	5	Tube Leak	In Place
<u>LMFR</u>				
Fuel and Blanket Circulating Pumps- Rotating Assembly	5	10	Bearing, Seal	Replacement
Stator	5	8	Rad. Damage	Replacement
Casing	30+	30+	None	
Fuel and Blanket Heat Exchanger	5	30	Fatigue, Tube	Replacement
Intermediate Pumps	8	8	Bearing, Seal	Hot Shop
Steam Generators-Superheaters	30	30	Fatigue, Creep	Replacement
	3	5	Tube Leak	In Place

Table 6.10

Turbo-Generator Plant Summary

	<u>AHR</u>		<u>MSR</u>	<u>LMFR</u>
	<u>1st Gen.</u>	<u>2nd Gen.</u>		
Number of Turbogenerators	3	3	2	2
Gross Output, MWE	1037	1037	1052	1057
Net Output, MWE	1000	1000	1000	1000
Net Plant Efficiency, %	26.7	27.5	42.3	42.1
Steam Throttle Pressure, psia	400	416	1800	1800
Steam Throttle Temperature, °F	Sat.	500	1050	1050
Stages of Reheat		0	1	1
Stages of Regenerative Feedwater Heating		3	8	8
Stages of Moisture Separation		1	0	0
Condenser Pressure, in Hg abs		1.5	1.5	1.5
Cooling Water Temperature, °F		63	63	63
Capital Cost of Equipment, Megabucks				
Turbogenerators		34.45	33.58	33.74
Condensers		6.50	3.33	3.34
Deaerators		1.05	0.48	0.49
Feedwater Heaters		0.60	1.59	1.60
Boiler Feed Pumps		0.52	1.56	1.56
Condensate Pumps		0.05	0.97	0.97
Boiler Recirculating Pumps		----	0.50	----
Total Cost of Listed Equipment		43.2	42.0	41.7

Table 6.11

AHR Breakdown of External Holdup Containing U, Basis 1 Reactor

	<u>1st Gen.</u>	<u>2nd Gen.</u>
Assumed Concentration, U-233 and 235, kg/ft ³	0.0424	0.0424
Heat Exchangers, ft ³	132	164
Pump	47.0	46.2
Main Circuit Piping	175	158
I-Xe Removal System	11.1	----
Underflow Pot of Clones, etc.	3.5	5.7
Feed and Letdown Line	0.3	1.0
Dump Tanks	<u>0</u>	<u>3.5</u>
Total, ft ³	368.9	378.4

External Holdup Containing No Uranium

Blanket Cooling System D ₂ O	175	199
Station External Fuel Holdup, ft ³ /MwE Net	2.58	1.89
Fuel System External Holdup, ft ³ /MwT Core	0.833	0.643

Table 6.12MSR Breakdown of External Holdup Containing U, Basis 1 Reactor

	<u>1st Gen.</u>	<u>2nd Gen.</u>
Assumed Concentration of U-233 and 235 in Fuel, Kg/ft ³	0.279	0.279
Holdup of Fuel, ft ³		
Pipe, Core to Pump	50.6	25.3
Pump	18.0	16.0
Heat Exchanger Tubes	98.5	49.3
Heat Exchanger Heads	30	30
Surge Volume	<u>20</u>	<u>20</u>
Total	217.1	140.6
Assumed Concentration of U + Pa-233 in Blanket, Kg/ft ³	0.0328	0.0328
Holdup of Blanket Salt, ft ³		
Pipe, Pump, Heat Exchanger	35	35
Surge Volume	<u>50</u>	<u>50</u>
Total	85	85
Station External Fuel Holdup, ft ³ /MwE Net	0.434	0.281
Fuel System External Holdup, ft ³ /MwT Core	0.206	0.1337

Table 6.13LMFR Breakdown of External Holdup Containing U, Basis 1 Reactor

	<u>1st Gen.</u>	<u>2nd Gen.</u>
Assumed Concentration of U-233 and 235 in Fuel, Kg/ft ³	0.625	0.625
Holdup of Fuel, ft ³		
Heat Exchanger Inlet Plenum	20	10
Tubes	123	85
Annulus Between Heat Exchanger and Vessel	20	10
Surge Volume	74	74
Pump and Piping	89	75
Pump Discharge Plenum	<u>25</u>	<u>25</u>
Total	351	279
Assumed Concentration of U + Pa-233 in Blanket, Kg/ft ³	0.178	0.178
Holdup of Blanket Slurry, Total, ft ³	100	100
Station External Fuel Holdup, ft ³ /MwE Net	0.702	0.558
Fuel System External Holdup, ft ³ /MwT Core	0.375	0.299

Table 6.14

Station Summary of Holdup in Heat Removal System

	AHR		MSR		LMFR		
	1st Gen.	2nd Gen.	1st Gen.	2nd Gen.	1st Gen.	2nd Gen.	
Fuel Volume, ft ³ at Temperature	2582	1892	434	281	702	558	
Blanket Material Volume, ft ³	1225	995	170	170	200	200	
Reserve D ₂ O, ft ³ at 25°C	300	300					
Total D ₂ O, ft ³ at 25°C	3345	2610					
Total Carrier Salt, ft ³			5100	451			
Total Bismuth, ft ³					902	758	
Total Sodium, ft ³				20,000	20,000	20,000	
Fissionable U in Fuel, Kg	110	80	121	78	440	349	
Total Pa + U in Blanket Fuel, Kg	None	None	5.6	5.6	36	36	34
Total Th in Blanket Fuel, Kg	None	None	7450	7450	5800	5800	
Megabucks							
Value, D ₂ O Inventory	6.44	5.02					
Value, LiF-BeF ₂ Inventory			8.65	0.77			
Value, Bi Inventory					1.22	1.02	
Value, Na Inventory				0.20	0.20	0.20	
Value, U Inventory	1.65	1.20	1.90	1.26	7.13	5.77	
Value, Th Inventory			0.16	0.16	0.13	0.13	
Total External Inventory	8.09	6.22	10.71	2.39	8.68	7.12	

Table 6.15

Summary - Cost of Heat Removal and Turbogenerator Equipment - Megabucks

	AHR		MSR		LMFR	
	<u>1st Gen.</u>	<u>2nd Gen.</u>	<u>1st Gen.</u>	<u>2nd Gen.</u>	<u>1st Gen.</u>	<u>2nd Gen.</u>
Heat Exchangers	5.25	5.41	17.04	13.01	29.4	24.0
Fuel and Intermediate Pumps	3.43	2.60	5.87	5.17	5.17	6.08
Piping	1.29	0.85	0.48	0.89	0.89	0.89
Turbogenerator Plant	<u>43.2</u>	<u>43.2</u>	<u>42.0</u>	<u>42.0</u>	<u>41.7</u>	<u>41.7</u>
Total of Above Capital Equipment	51.67	50.56	65.39	61.07	77.16	72.67
Inventory of Special Material	8.09	6.22	10.71	2.39	8.68	7.12
Spare Equipment	<u>1.13</u>	<u>1.67</u>	<u>1.82</u>	<u>1.46</u>	<u>5.64</u>	<u>4.28</u>
Total	62.39	59.95	77.92	64.92	91.48	84.07*

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*This compares with about $\$77 \times 10^6$ estimated by B and W for this part of the plant in BAW-1171.

7. Discussion and Conclusions

- 7.1 The results indicate that the external U holdup in the heat removal systems of the AHR and MSR are considerably below that of the LMFR. The chief advantage of the AHR in this respect is its low U concentration; the advantage of the MSR is its relative compactness.
- 7.2 The cost of heat removal and turbogenerator equipment (not including installation) is lowest for the AHR, next for the MSR and highest for the LMFR. However, the overall spread is less than \$25 per Kwe. The slight cost advantage of the AHR may be nullified by its requiring a greater volume of radioactive fuel and a greater number of reactors, thereby increasing shielding, building and containment costs.
- 7.3 The reason for the cost advantage of the AHR in heat removal equipment lies in the use of stainless steel and carbon steel components based largely on existing technology, compared to more expensive materials used in MSR and LMFR requiring the use of a technology requiring considerable development.
- 7.4 The heat removal system of the AHR requires comparatively a minimum of development because of benefits accruing from the PWR and HRE-2 programs. Some benefits, particularly in steam generator development, will be gained by MSR and LMFR programs from SGR and fast breeder activities; however, it appears that reactor experiments are needed to resolve other questions.
- 7.5 Both MSR and LMFR can achieve better thermal efficiency by raising steam pressure. Whether this would be economically advantageous cannot be determined without detailed knowledge of fuel and capital costs.
- 7.6 Comparing sodium and $\text{Li}^{7}\text{F}-\text{BeF}_2$ as coolants in MSR plants, there appears to be a significant advantage in initial outlay using sodium. On the other hand is an expected savings in operating cost using salt. It is believed that careful and compact design of the salt intermediate system may considerably reduce the required salt inventory charges.

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Appendix IIHeat Exchanger DesignsA. Heat Exchangers for AHR Plants

As discussed in the body of the memorandum, the first generation plant was based on a U-tube design with 1/2-in. tubes and the second generation plant on a straight-tube design with 3/8-in. tubes.

Thermal Design

The AHR heat exchangers were designed in accordance with procedures developed by A. L. Gaines(15,26) for the TER study. Inside film coefficients are calculated by the Dittus-Boelter equation(27).

Boiling-film coefficients are calculated from the relation $h = \alpha \Delta T^\beta$, α and β being temperature-dependent constants.

The equation

$$\Delta T_{\text{LM}} \left[\frac{1}{\beta+1} \phi_1 - \frac{1}{\beta+1} \phi_2 - \alpha \frac{1}{\beta+1} \left[\frac{D_o}{D_i h_i} + \frac{D_o}{D_i h_s} + \frac{D_o}{D_w h_w} \right] \phi_1^{\frac{\beta}{\beta+1}} \right] = 1$$

is used to determine terminal heat fluxes ϕ_1 and ϕ_2 and

$$a = wc \left[\frac{D_o}{D_i h_i} + \frac{D_o}{D_i h_s} + \frac{D_o}{D_w h_w} \right] \ln \frac{\phi_1}{\phi_2} + \frac{wc}{\beta} \left[\frac{1}{\phi_2^{\frac{\beta}{\beta+1}}} - \frac{1}{\phi_1^{\frac{\beta}{\beta+1}}} \right]$$

is used to calculate the required surface.

Fouling factors used in the first generation design were based on HRE-2 experience. For the second generation plants it was assumed that in-phase descaling procedures would be developed and that fouling factors could be reduced accordingly.

Mechanical Design

It was assumed that the tubes could be laid out on a triangular pitch of 1.25 tube diameter. Thus the first generation plant with 1/2-in. tubes uses 5/8-in. pitch and the second generation plant with 3/8-in. tubes uses 1/2-in. pitch. Similar assumptions were made for the LMFR and MSR plants. It is recognized that increased tube pitch may be necessary to meet the requirements for high performance tube-to-tubesheet attachments. (The HRE-2 exchanger has 3/8-in. tubes on 5/8-in. triangular pitch.) If this proves necessary, the diameter of the shell must increase and thicker shells, heads and tubesheets will be required. Holdup will be increased due to the larger head diameter and to the slight increase in tube length required with thicker tubesheets.

The first generation exchanger is visualized as a U-tube design; the second as a straight-tube design with some sort of offset bends to take care of thermal expansion. For both plants, the heat exchanger shells are carbon steel, the tubes are carbon steel-stainless steel composite, tubesheets and heads are stainless clad carbon steel.

In the second generation AHR plant, 4.18 per cent of the energy produced is recovered by recombining the radiolytic gases produced in the core circuit at a relatively high temperature and using the steam so produced to superheat the steam going to the generators.

The superheater must necessarily be designed for low pressure drop on both the shell and tube sides. The design selected is a conventional shell and tube exchanger, using 1/2 in. x 0.035 in. wall tubes. Superheated steam from the recombiner enters the tube side at 879°F and a mixture of saturated steam and condensate leaves at 596°F. The uncondensed steam is recirculated through the recombiner and acts as a diluent for the D₂ and O₂ being recombined. A jet pump, using the D₂-O₂-D₂O vapor mixture being let down to the recombiner as motive fluid, provides the power for recirculating the D₂O vapor. Saturated steam at 448.5°F and 415 psia enters the shell and steam leaves at 407.8 psia and 500°F.

B. Molten Salt Reactor Heat Exchangers

For both the first and second-generation plants, the core heat exchangers are considered to be annular, mounted directly above the reactor core. The circulating pump suction line is placed at the center of the annulus and the pump discharge flows down through the heat exchanger tubes back to the reactor. For the first generation plant, the coolant is LiF-BeF₂; for the second generation plant, it is sodium. Tubes are 3/8-in. for both plants.

For both plants, a modification of an arrangement proposed by B. W. Kinyon in which the tubes are formed into 45° spirals, wound right hand, and left hand in alternate rows, is used. The modification consists of providing straight end sections to permit radial flow distribution. Shell inlet and outlet connections are presumed to be made through the outer shell wall near the ends of the tube bundle.

Emphasis has been placed on minimizing the holdup, particularly in the first generation exchanger. An optimization has been made with respect to core inlet temperature, leaving the core outlet temperature and the coolant temperatures fixed. This shows that the optimum fuel exit temperature is very close to 1125°F. Investigation of tube side velocity and tube diameter indicates that the holdup decreases as the former increases and the latter decreases; it was arbitrarily decided to limit velocity to 20 ft/sec and diameter to 3/8-in.

Thermal Design, Intermediate Heat Exchanger

a. Fuel (inside) film coefficients - For Reynolds numbers below 12,000, empirical data obtained by Amos et al.⁽⁴⁾ are used. Above 12,000 the Dittus-Boelter equation applies.

b. Shell-side film coefficients - For the first generation plant, it is assumed that the Dittus-Boelter equation will apply, with the constant increased from 0.023 to 0.046. This is based on the presumption that the alternating spiral tube layout will provide enhanced turbulence. Experimental verification of the assumption is required.

It was also assumed that the spiral-tube sections only would be effective in heat transfer and that all radial flow would occur in the straight-tube end sections. The first of these assumptions obviously cannot be correct, but a calculation which tapes the end section heat transfer into account would require far more time than is available for the present study. It would require row-by-row treatment of the radial flow end sections and of the axial flow in the channels between the bent tubes. The second assumption appears not to be greatly in error - a row-by-row calculation based on this assumption indicates axial velocities in adjacent channels differ by 0.1 ft/sec at most and pressure differences will therefore be fairly small.

For the sodium-cooled case, shell coefficients are based on the equation (28)

$$Nu = 0.19 (De')^{0.6} \frac{D_o G_e^{0.6}}{\mu} \frac{C}{k}^{1/3}$$

Fouling Factors, Intermediate Heat Exchanger

A fouling factor of 0.0001 has been assumed for both the first- and second-generation plant heat exchangers. Although it has been argued that no oxide film or other deposit which would interfere with heat transfer will be present in the molten fluoride system, development of a thin (approx. 0.0002 in.) film on a hot INOR-8 surface exposed to fuel salt number 130 in a forced-convection system has been reported. (29) Until experimental proof to the contrary is obtained, it seems prudent to assume that any such deposit is likely to represent an increased heat transfer resistance. Also, fission or corrosion products produced in a reactor may foul the heat transfer surface.

Mechanical Design, Intermediate Heat Exchanger

The basic exchanger design used for the MSR practically dictates the arrangement of the tubes in concentric circles. For the salt-cooled exchanger, the 3/8-in. tubes are placed on 1/2-in. radial pitch, since this appears to be the minimum which normally would be employed. A circumferential pitch of 5/8-in. is used, largely dictated by the necessity of providing some clearance between the bent tubes. This gives 0.093 in. clearance in the bent section.

The straight-tube end sections were assumed to be 12-in. long. This is not necessarily optimum but does appear to give reasonably good radial flow distribution.

Shell and tube wall thicknesses were calculated from the formulas given in the ASME Boiler Construction Code, Section VIII, Unfired Pressure Vessels. A design temperature of 1260°F was used, and it was assumed that the internal annulus would be thermally shielded from the core outlet fluid. Tube sheet thicknesses were calculated in accordance with the

TEMA formula for Class R heat exchangers with U-tubes. It was again assumed that tube-to-tubesheet joint design requirements would not influence the tube spacing and that no reduction in allowable stresses would be required to allow for the effects of hydraulic noise or thermal shocks. For this type reactor, an increase in tube spacing to satisfy joint design requirements would produce a far more severe penalty than for the AHR, since it would lead to lower shell-side film coefficients and therefore increased tube length.

The shell-side fluid flow calculations also indicated that the annuli between the inner and outer tube rows and the shells must be kept quite narrow by baffling or by designing the shell so that its inside diameter opposite the bent tube section is less than at the ends. This applies particularly to the annulus between the outer tube row and the outer shell, since if this annulus is not restricted, 15-20 per cent of the flow will go through it and essentially bypass the exchanger.

Design, Steam Generators for MSR

The steam generators were designed as proposed by B. Kinyon. The tube size was selected to be 1.032 in. inside diameter. Based on several steam flows per tube investigated by Kinyon, 900 lb of steam per hour per tube was selected to give a reasonable combination of tube side pressure drop (100 psi) and length (at constant enthalpy change).

Each tube contains a) an annulus through which steam is flowing, receiving heat from the secondary coolant and giving heat up to b) a second annulus through which water is pumped at high pressure so that it boils. The water and steam leaving this annulus, at 50 per cent quality, pass through c) a small steam separator. The water is discharged through d) a central tube to a water chest. The water is pumped by a boiler recirculating pump from the water chest to annulus b).

The bayonet tubes are collected in several headers, a) the superheated steam header, b) the water inlet header and c) the water chest or water outlet header.

Steam coefficients were computed from the usual Dittus-Boelter equation. The outside film coefficients were from baffles shells.

Design, Reheater for MSR

The reheaters were entirely conventional shell-and-tube exchangers selected such that the steam pressure drop was 40 psi, from 400 psia in to 360 psia out. This was the same drop used in the TVA John Sevier plant reheaters.

C. LMFR Heat Exchanger Designs

LMFR Intermediate Heat Exchanger Design

The design closely follows the proposal in BAW-1171. Straight 1/2-in. OD tubes, swaged down to 3/8-in. OD where they pass through the tubesheets, are used. Tubesheets are made the same thickness as the cylindrical shell.

This mechanical design is based on the premise that the intermediate coolant pressure will be maintained higher than the fuel pressure and that the tubes can therefore be assumed to act as staybolts to support the tubesheets. This is common practice in fire-tube steam boilers and is permitted under the ASME Boiler Construction Code, Section I, Power Boilers. We have accepted the above premise with some reservations, since the tube side pressure will be substantially greater than atmospheric and it seems unreasonable to rule out an accident which could result in depressuring the shell. Accepting the assumption decreases the tubesheet thickness compared to that required by TEMA Class "R" standards by a factor of the order of 5.

Static axial pressure and thermal stresses in the tubes and shell have been investigated and do not exceed allowable values. As in the case of the MSR, the presence of significant hydraulic noise and thermal transients must be recognized. Such factors might well cause a reduction in allowable stresses where a component is designed for long-term life.

Although tantalum apparently is not corroded measurably by bismuth-uranium solutions, significant corrosion by liquid sodium has been reported. (30) Corrosion rates were reported as 0.1 mpy in oxygen-free sodium and 3 mpy in sodium containing approximately 40 ppm O_2 at 1200°F. Based on this information, a 3-mil corrosion allowance was provided in establishing the tube wall thickness.

Thermal Design

a. Tube side - Tube side film coefficients were calculated from:

$$Nu = 0.625 (Re Pr)^{0.4}$$

b. Shell side - Shell side coefficients were calculated from:

$$Nu = 0.19 (De')^{0.6} \left(\frac{D_o G_s}{\mu} \right)^{0.6} \left(\frac{c_p \mu}{k} \right)^{1/3}$$

Appendix IIICost Estimates for Heat Exchangers

All heat exchangers were priced by estimating the cost of the parts, the cost of assembly and inspection. Materials costs were based on present-day quotations for large orders, engineering cost indices, trade journal price information, etc.

In addition to the basic tubing costs cited in the earlier tables, the following material costs were used:

<u>Material</u>	<u>Forging</u> <u>\$/lb</u>	<u>Plate</u> <u>\$/lb</u>	<u>Tubes</u> <u>\$/lb</u>
Carbon Steel	0.63	0.40	
Carbon Steel Clad with 347	1.00		
347 Stainless Steel, HRP Grade	3.38	1.46	
316 Stainless Steel, HRP Grade	3.97	1.52	
Inconel	4.90	1.88	
INOR-8	13.00	4.17	
Tantalum	100.00	35.00	80.00
Tantalum, Second Generation Plant	77.00	27.00	61.00

In most heat exchangers, tubing material was over 50 per cent of the total materials cost.

One method of judging the reasonableness of the method of estimating is to compare it with a known cost. The FWR heat exchangers contain, in general, the materials and workmanship representative of what is needed in the AHR plants. They were quoted as follows:

	<u>Area</u>	<u>Price</u>	<u>\$/sq.ft.</u>	<u>Cost Index Adjusted</u> <u>1959 \$/sq.ft.</u>
Babcock-Wilcox Units	8900 ft ²	\$ 236,000	26.50	33.90
Foster-Wheeler Units	9900 ft ²	255,000	25.75	33.00
AHR Gen. 1 Plant	214,000 ft ²	5,250,000		24.50
AHR Gen. 2 Plant	187,000 ft ²	5,410,000		28.90

Note that the AHR Gen. 2 heat exchanger surface is more expensive because of the smaller tubes chosen.

Design, Steam Generators for LMFR

The AEC sponsored design studies of sodium steam generators for "advanced" reactors. Of the studies published (1,2,3,8,13), Alco Products, Inc. proposed units which appeared to the authors of this paper to have the highest probability of success in a LMFR. There were small revisions in the design to accommodate to the particular pressure, temperature and size chosen for this paper.

Design, Reheaters for LMFR

The design was similar to that for the MSR.

Appendix IVCirculating Pumps

The selection of the pump designs was based on obtaining a minimum holdup while maintaining high efficiency and keeping the velocities within reasonable limits. No design features were used which are not presently fully developed or in the process of being developed. For example, it was possible to use a higher specific speed pump and therefore lower holdup volume in the MSR pumps than in the AHR because a molten salt lubricated bearing is currently under development which can reduce the large impeller overhang which is inherent in high specific speed pumps. The MSR pump also is designed without a volute because of the package layout.

The AHR pump cost estimates were based on the cost per horsepower of several large canned rotor pumps (Westinghouse S4G; LSR and PWR) having a cost of approximately \$225 per horsepower. A factor of 1.3 was applied to this number to cover special materials and differences in speed giving a cost of \$290 per horsepower.

The MSR and LMFR pump costs were based on the costs of similar pumps and on estimates which were obtained from Byron Jackson and Pratt and Whitney. These costs were adjusted for differences in size and materials. The motor costs were estimated at \$30 per horsepower to cover Class "H" insulation, special cooling system, and special lubrication system. The costs of the MSR fuel and blanket pumps do not include the casing since this is contained in the reactor structure.

A tabulation of pump information appears in Table IV-1.

Table IV-1

Pump Designs for Thermal Breeder Study

	<u>Capacity</u>	<u>Head</u>	<u>Specific Gravity</u>	<u>Hydraulic Efficiency</u>	<u>Horsepower</u>	<u>Kw Input</u>	<u>Speed rpm</u>	<u>Specific Speed</u>	<u>Impeller Diameter in.</u>	<u>Diffuser Diameter in.</u>	<u>Holdup Vol. ft³</u>	<u>Pump Price</u>	<u>Motor</u>	<u>Shield.</u>
<u>AHR</u>														
Fuel	44,300	100	0.89	85	1175	1055	875	5800	26.2	42.5	46.2	340,000	-----	-----
Blanket	23,200	100	0.89	85	615	560	1150	5520	20.4	36.0	23.5	178,000	-----	-----
<u>MGR</u>														
Fuel	40,800	110	1.95	85	2600/2500	2150	1175	6980	21.4	40	16.0	320,000	75,000	135,000
Blanket	3550	159	3.28	85	554/550	459	1750	2320	14.5	22.5	2.5	180,000	16,500	75,000
Intermediate	24,000	300	0.82	88	1695/1750	3300	1750	3750	21.9			300,000	52,500	
<u>LMFR</u>														
Fuel	52,800	30	9.66	85	4570/4500	3800	350	6240	31.0	40	5.85	560,000	135,000	155,000
Blanket	14,300	30	9.70	85	1240/1250	1030	720	6730	15.1	19.5	0.54	290,000	37,500	100,000
Intermediate	24,000	300	0.82	88	1695/1750	1405	1750	3750	21.9			300,000	52,500	

Appendix VTurbogenerator Selection and PriceA. 500 Mw Turbogenerator for 1801-2400 psi; 1050°F Initial, 1050° Reheat; MSR and IMFR

The GE catalog lists the following 500 Mw units:

<u>Type</u>	<u>Blade Length</u>	<u>Price</u>	<u>Cost/Kw</u>
3600/1800 C.C. - Double Flow	43 in.	\$16,084,000	\$32.17
3600/1800 C.C. - Double Flow	50 in.	16,600,600	33.20
3600/3600 C.C. - Four Flow	29 in.	15,811,000	31.62
3600/3600 C.C. - Six Flow	26 in.	15,955,300	31.92
3600/3600 C.C. - Six Flow	29 in.	16,471,900	32.94

The efficiency and frequency of maintenance varies with the design. For the present study, the 3600 rpm cross-compound six-flow turbine with 26-in. blade length was chosen as a reasonable compromise. The total cost of the plant unit was taken to be the gross electrical output multiplied by the price per Kw.

B. 333 Mw Turbogenerator for 401-600 psi Saturated or Slightly Superheated Steam, AHR

The following GE units are listed:

<u>Type</u>	<u>Blade Length</u>	<u>Price</u>	<u>Cost/Kw</u>
1800 T.C. Double Flow	43 in.	\$9,967,700	\$33.22
1800 Double Flow	43 in.	9,881,900	32.97

The tandem-compound double-flow turbine was chosen.

C. Reconciliation of Relative Cost of Turbogenerators for MSR and AHR Plants

Turbogenerators are apparently designed by the suppliers using trade-confidential methods. As a result it is not possible to explain quantitatively why one turbogenerator costs more than another. However, one can study the catalogs and deduce the effect of variations in speed, pressure, size, etc. on the price per Kw.

The following approximations appear to be valid in the turbine size range 300 to 500 Mw:

An 1800 rpm machine is 20 per cent more expensive than a 3600 rpm machine (because of heavier rotating parts).

A 400-600 psi machine is 10 per cent cheaper than a 1800-2400 psi machine (the savings in pressure shell thickness more than overcomes the advantage of compact high pressure rotating machinery).

A tandem-compound machine is 15 per cent cheaper than a cross-compound machine (one shaft is cheaper than two).

A 300 Mw machine is 10 per cent more expensive per Kw than a 500 Mw machine of the same family. (This assumes that as the machine gets larger one will permit the blades to get longer, keeping the efficiency and the maintenance frequency about the same.)

Appendix VICost of Turbine-Condensers

The condenser costs of the 800-MwE TVA John Sevier plant, adjusted for change in Engineering Price Index, were used to compute condenser costs in the present study. It was assumed that cost was proportional to the amount of heat dumped. The costs cited in the present study are believed to be conservative, since the cost should be proportional to less than the first power of size.

Appendix VII

Holdup of Solution in AHR Auxiliaries

We were asked to estimate the uranium holdup in AHR equipment for removing I-Xe, solids, letdown and feed system and dump tanks.

Three estimates were made depending on the I-Xe removal system selected:

1. High Pressure Soup-Gas Contactor. In this system, a 200 gpm stream of soup is withdrawn at the core outlet, passed through a multi-clone solids remover, and after 20-sec delay a vapor contactor to strip iodine. I₂ is dissolved in 10 gpm of condensate letdown to low pressure for I₂ removal. Since no fuel is letdown, there is no need to store U in dump tanks. Holdup breakdown is as follows: Charged to I₂ removal, 11.1 ft³; Underflow pot, 3.5 ft³; Letdown heat exchanger, 0.3 ft³; Dump tanks, feed line, etc., 0; Total 14.9 ft³ for a single reactor.

2. Main Circuit Gas Separator. In this system, vapor is withdrawn from the core outlet pipe in a gas-separator and letdown. Recombination is partly internal and partly external. Xenon and I₂ are both stripped. O₂ and fuel solution must be recycled. An HRT-type clone system is used for solids removal. Holdup is as follows: Clone piping and pump, 2.2 ft³; Underflow pot, 3.5 ft³; Letdown heat exchanger and feed line, 1.0 ft³; Dump tanks, 3.5 ft³; Total 10.2 ft³.

3. Liquid Letdown System. If a substantial fraction of I₂ is circulating, then I₂ can be removed in a 100 gpm liquid letdown stream. This would require continuous 100 gpm fuel recycle. An HRT-type clone system is used for solids removal. Holdup is as follows: Clone piping + letdown heat exchanger + feed line, 10.0 ft³; Dump tanks, 3.5 ft³; Underflow pot, 3.5 ft³; Total 17 ft³.

The equipment cost of recycle pumps was estimated:

10 gpm feed pump, fuel or condensate	\$25,000
20 cfm O ₂ compressor, 100 psia to 2000 psia	\$25,000

Appendix VIIIReferences

1. Alco Products, Inc., "Steam Generator Preliminary Design - Intermediate Heat Exchanger Preliminary Design," APAE No. 41, Vol. I, Feb. 28, 1959.
2. Alco Products, Inc., "Steam Generator Preliminary Design - Steam Generator Preliminary Design," APAE No. 41, Vol. II, Feb. 28, 1959.
3. Alco Products, Inc., "Steam Generator Preliminary Design - Intermediate Heat Exchanger and Steam Generator Concept Study," APAE No. 41, Vol. III, Feb. 28, 1959.
4. J. C. Amos et al, "Preliminary Report of Fused Salt Mixture No. 130 - Heat Transfer Coefficient Test," ORNL-CF-58-4-23.
5. ASME Boiler and Pressure Vessel Code, Unfired Pressure Vessels, Sec. VIII, 1959 Edition.
6. The Babcock and Wilcox Company, "The Liquid Metal Thorium Breeder Reactor," BAW-1171 C-81, January, 1960.
7. M. Blander, W. R. Grimes, N. V. Smith and G. M. Watson, "Solubility of Noble Gases in Molten Fluorides. II. In the LiF-NaF-KF Eutectic Mixture," Reprinted from the Journal of Physical Chemistry, 63, 1164 (1959).
8. Combustion Engineering, Inc., "Sodium Component Study," Report Number CENC-1038, February, 1959.
9. O. E. Dwyer and Allen M. Eshaya, "On the Removal of Volatile Fission Products from Uranium-Bismuth Reactor Fuels," Nuclear Science and Engineering: 6, 350-360 (1959).
10. Foster Wheeler Corporation, "Final Report - Heat Exchanger Equipment for 50,000 Kw Nuclear Plant Phase I (a,b,c) Preliminary Design Evaluation," 8-51-8526, Dec. 15, 1956.
11. Foster Wheeler Corporation, "Final Report - Investigation of the Feasibility of Design of the Largest Capacity Steam Generating Heat Exchanger," 8-51-8529, Nov. 15, 1956.
12. W. R. Grimes, N. V. Smith and G. M. Watson, "Solubility of Noble Gases in Molten Fluorides. I. In Mixtures of NaF-ZrF₄ (53-47 mole %) and NaF-ZrF₄-UF₄ (50-46-4 mole %)," Reprinted from the Journal of Physical Chemistry, 62, 862 (1958).
13. The Griscom-Russell Company, Final Report to Atomic Energy Commission, Customer's Order No. AT (11-1)-664, Griscom-Russell Order No. 18030, Feb. 25, 1959.
14. Kern, Process Heat Transfer, McGraw Hill (1950).

15. R. B. Korsmeyer et al, TBR Design Study, (unpublished).
16. J. A. Lane, H. G. MacPherson and Frank Maslan, Eds., Fluid Fuel Reactors, Addison-Wesley Publishing Co., Inc., First Printing, Sept. 1958.
17. H. G. MacPherson, "Molten-Salt Breeder Reactors," ORNL-CF-59-12-64, Dec. 22, 1959.
18. John Sevier, Technical Monograph No. 55, TVA Plant.
19. I. Spiewak and F. N. Peebles, "Tentative Evaluation of Thorium Breeder Reactors with Pebble Blankets," HRP-60-1, Jan. 4, 1960.
20. O. P. Steele, III, "Fused Salt Pump Feasibility Study," Westinghouse Electric Corporation, AED-47.
21. A. J. Stepanoff, Centrifugal and Axial Flow Pumps, John Wiley and Sons, Inc., 2nd Ed., 1957.
22. Westinghouse Electric Corporation, PAR Project, "Layout and Maintenance," Part I, Vol. IV, WCAP-1104, March, 1959.
23. Westinghouse Electric Corporation, PAR Project, "Layout and Maintenance," Part 2, Vol. IV, WCAP-1105, March, 1959.
24. J. C. Moyers and L. F. Parsly, "MSR and LMFR Design Pressure," HRP-60-45, April 19, 1960.
25. Glenn Murphy and Robert E. Uhrig, "Observations on Creep of Tantalum," Ames Laboratory, IS-26, August, 1959.
26. A. L. Gaines; "TBR Memo No. 7," ORNL-CF-54-11-122, Nov. 12, 1954.
27. W. H. McAdams, Heat Transmission, 2nd Ed., McGraw Hill Book Co., New York (1942), p 168.
28. R. A. Tidball, "Performance of Small Liquid Metal Heat Exchangers," Preprints of Papers for AIChE Heat Transfer Symposium, Dec. 5, 1952, p 99.
29. Metallurgy Division Annual Progress Report for Period Ending Sept. 1, 1959, ORNL-2839.
30. Battelle Memorial Institute, "Corrosion and Creep Behavior of Tantalum in Flowing Sodium," BMI-1284, Aug. 21, 1958.

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