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EVALUATION OF

MERCURY COOLED BREEDER REACTORS

(A Paper Presented at the 1960 Winter
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By

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EVALUATION OF
MERCURY COOLED BREEDER REACTORS

Donald W. Battles

In response to a proposal by Advanced Technology Labs, the AEC has sponsored under the New Reactor Concepts Program a technical and economic evaluation of a promising new power reactor concept - a mercury cooled fast breeder reactor.

The basic objectives of the program are twofold:

1. To establish the technical feasibility of a fast breeder reactor cooled with boiling mercury and
2. To evaluate the long range potential of such a reactor power plant for production of economic power.

The program has been conducted in two phases until recently under the direction of Mr. John Bradfute. Unfortunately, Mr. Bradfute is in Pakistan on an exhibition reactor startup and was unable to present this paper to you today.

The first phase of the program was completed in late 1959 and established a feasible reference power plant design, which is economically competitive with similar sodium cooled fast reactor plants. Results of this work were summarized in AEC Research and Development Report ATL-A-102.⁽¹⁾ The second phase which is now in progress includes an analysis of the nuclear and thermal stability of the reference design and an evaluation of the economics of advanced designs.

I would first like to review briefly some of the important details of the initial phase of the program, concentrating on the problems and interesting design aspects peculiar to the use of boiling mercury as a reactor coolant.

Evaluation of the technical feasibility and economic potential of the mercury cooled breeder reactor concept (which we refer to as the MCBR) required rather extensive core design parametric studies leading to the conceptual design of a complete power plant. For the considerable background information required, we drew heavily on experience gained in conventional power plants employing the so called mercury topping cycle and on fast breeder reactor technology developed for the EBR and Enrico Fermi programs.

(1) "An Evaluation of Mercury Cooled Breeder Reactors," Advanced Technology Laboratories, AEC Research and Development Report ATL-A-102, 31 October 1959.

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BACKGROUND INFORMATION

It was first necessary to determine the advantages and limitations of mercury as a coolant in a fast reactor and to obtain all heat transfer, fluid flow, physics and materials corrosion data available for mercury. I believe that it would be of interest to briefly review some of the properties of mercury and considerations pertinent to its use as a fast reactor coolant prior to discussing the basis for and results of the studies.

Consideration of mercury as the thermodynamic fluid in fast breeder reactors stems from the valuable attributes of this material listed below:

1. Hg is an element and is not subject to thermal or radiation decomposition.
2. It is a liquid at normal ambient temperatures.
3. Known deposits are large and annual world production in 1959 approached 20,000,000 #.
4. In common with other liquid metals, it possesses good heat transfer properties.
5. It is chemically inert to air and water.
6. At high saturation temperatures of say 950°F, its vapor pressure is only 120 psig.
7. Mercury vapor may be used directly as a working fluid in a turbine.

An important consideration is that many years of operating experience with boiling mercury as a heat transfer medium has been gained in conventional mercury binary cycle power plants, several of which are still in operation. This experience has proven-out components, such as pumps and mercury turbines and has established the following fundamental criteria for design of plants using Hg as a coolant:

1. Although extremely toxic, high temperature mercury can be handled and contained safely. This is attested by the excellent safety record of the conventional plants during many years of operation.
2. To insure wetting of heat transfer surfaces and to inhibit corrosion of ferrous materials, mercury must be inhibited with small amounts of magnesium and titanium. The titanium acts as an inhibitor forming a protective Ti-Fe film. The magnesium improves the inhibiting action of the titanium as well as acting as an oxygen getter and a wetting agent. If so inhibited, a five per cent chrome steel has contained mercury at temperatures to 1,000°F with essentially no metal loss for periods of many years.
3. To sustain the exceptionally high heat fluxes required in a nuclear reactor, or for that matter in a conventional mercury boiler, the heat

transfer surfaces must be continuously coated with a tenacious film of inhibited liquid mercury. This film can be maintained only if the coolant mercury is present as a liquid-vapor mixture having the character of a "fog". Extensive experience has shown that this fog must contain a minimum of 4 to 5 parts of liquid per part of vapor by weight.

Liquid Hg also possesses high absorption and inelastic-scattering cross sections to fast neutrons and low heat capacity relative to other liquid metals, such as sodium. A Hg cooled fast reactor can, therefore, be competitive only if the mercury is boiled in the core. The above experience with the mercury fog and inhibited mercury is thus directly applicable to the MCBR. In addition, sufficient fluid flow, heat transfer and physics data were available on mercury to permit design without extensive original experimental work. Data are presented in the literature which indicate that heat fluxes as high as 200,000 Btu/hr./sq. ft. had been measured experimentally. Nucleate boiling fluxes as high as 1,000,000 Btu/hr./sq. ft. are theoretically predicted. In the course of this program, a simple boiling mercury heat transfer experiment was conducted which indicated that values up to at least 600,000 Btu/hr./sq. ft. were indeed possible. With this background of Hg data and experience, we were then able to proceed with design of an optimum MCBR power reactor.

BASIS FOR CONCEPTUAL DESIGN

In accordance with the contract, the initial studies were limited to a plant employing an indirect mercury cycle (in other words, one with no direct cycle mercury turbine) and to a core employing a uranium-10% Mo fuel. Although it is recognized that Pu fuels would ultimately be used, this fuel was chosen since the technology developed for the first core of the Enrico Fermi would apply. An additional requirement was that more fissionable material be produced than was consumed.

The following ground rules were established for the design:

1. No attempt was made to extend the design beyond the technology developed in the existing conventional plants. Maximum coolant temperature was, therefore, limited by material considerations to 1,000°F and the quality of the fog in the core was limited to a maximum of 30% by weight.
2. Average burnup was limited to 10,000 MWD/MT.
3. Fuel centerline temperature was limited to 1112°F.
4. The plant was designed for a power output of 100 electrical megawatts. This power level was chosen primarily to permit direct comparison with capital and fuel cycle costs of the sodium cooled

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fast breeder reactor, the Enrico Fermi Atomic Power Plant. It was assumed that 90% of the reactor power was generated in the core and 10% in the blanket.

With these ground rules as a basis, we then proceeded with a series of core parametric studies leading to the conceptual design of a complete power plant. I shall not attempt to go into the physics, thermodynamic and hydrodynamic design of the core because of the limited time available. I would like to point out some of the significant results of the core parametric studies and to describe the conceptual reactor plant design.

The studies revealed that the upper limit of performance for the reactor core was imposed not by heat flux but by the pressure drop associated with boiling two phase mercury flow because of the large mercury volume change upon vaporization. In addition, a core consisting of a cluster of straight circular U-alloy fuel pins of optimum diameter and spacing with boiling mercury coolant flowing axially to them can sustain an average power density of about 100 kilowatts per liter without unreasonably high pressure drops. This relatively low power density requires a high critical mass of about 2300 kg of U-235. It was further found that breeding is readily achieved but that thick blankets of depleted uranium are required.

Based on the core parametric study, an optimum core and breeder blanket was selected and a complete reactor plant designed.

PLANT DESCRIPTION

I would now like to discuss some of the details of the conceptual design of the 100 MW(e) reactor and systems. This will provide some feeling for the magnitude of the plant on which capital cost estimates were based.

Figure 1 shows sections of the reactor vessel. The reactor contains a core of enriched U-10% Mo fuel surrounded by radial and axial breeder blankets of depleted uranium. Design of the core and blanket assemblies was based on existing technology developed for the EBR-II and Enrico Fermi reactors. As shown in Figure 2, the 256 fuel assemblies are composed of three sections: a fuel section containing 127-0.18" OD fuel elements and upper and lower axial blanket section containing 19 and 37 blanket elements respectively. The 462 radial blanket assemblies contain 61 depleted uranium elements. All of the blanket elements are 0.424 inch OD. The assemblies are housed in stainless steel shrouds. Data on the fuel and blanket element assemblies are presented in Table 1. Core and blanket data are summarized in Table 2. You will note that the core is 55.7 inches long and has equivalent circle diameter of 61.3 inches. The blanket is 50 centimeters thick in both radial and axial directions.

Reactor performance data are presented in Table 3. Of particular interest is the low average core power density of about 100 KW/liter which results in a critical

TABLE 1
DATA SUMMARY
CORE AND BLANKET ELEMENT ASSEMBLIES
100 MW(E) MCBR POWER PLANT

	<u>Core</u>	<u>Blanket</u>		
		<u>Upper</u> <u>Axial</u>	<u>Lower</u> <u>Axial</u>	<u>Radial</u>
Configuration	←————Hexagonal————→			
Structural materials	←————5 w/o Cr, 1/2 w/o Mo Steel————→			
Element pitch	←————Triangular————→			
Pitch/diameter ratio	1.68	1.81	1.31	1.03
Number of elements per assembly	127	19	37	61
Element-to-housing spacing	0.061	0.181	0.073	0.001
Outer dimension (across flats)(in.)	3.526	3.526	3.526	3.526
Over-all length (in.)	←————119.1————→			
Housing thickness (in.)	0.04	0.04	0.04	0.04

TABLE 2

DATA SUMMARY
CORE AND BLANKET

100 MW(E) MCBR POWER PLANT

	<u>Core</u>	<u>Blanket</u>		
		<u>Upper Axial</u>	<u>Lower Axial</u>	<u>Radial</u>
Equivalent circle diameter (in.)	61.3	61.3	61.3	100.9
Length (in.)	55.70	19.68	19.68	95.00
Number of element assemblies	258	258	258	462
Assembly spacing (in.)	0.03	0.03	0.03	0.03
Mass of uranium (kg)	8730	2520	5750	92,300
Composition (vol. %)				
Coolant	62.3	71.7	47.1	16.2
Fuel	22.2	15.2	33.4	67.2
Steel	13.10	13.5	16.0	11.7
Sodium	2.4	3.3	3.5	4.9
Structure-fuel alloy volume ratio	69.5	86.8	58.0	24.8

TABLE 3

REACTOR PERFORMANCE DATA

100 MW(E) MCBR POWER PLANT

Over-all reactor dimensions	10'OD X 20'8" length
Total fuel alloy loading (kg fuel alloy)	9700
Total blanket loading (kg depleted U)	100,570
Initial fuel enrichment (w/o)	26.5
Final fuel enrichment (w/o)	25.6
Core volume (liters)	2642
Core average heat flux (Btu/hr-ft ²)	119,000
Maximum heat flux (Btu/hr-ft ²)	446,000
Average power density (kw/liter)	96.5
Core average specific power (kw/kg U)	29.2
Discharged fuel average burnup (mwd/t)	10,000
Discharged blanket average burnup (mwd/t)	1,000
Heat transfer surface (ft ²)	
Core	7310
Upper axial blanket	645
Lower axial blanket	1511
Radial blanket	24,800
Pressure drop (psi)	
Core	50.0
Axial blanket	10.2
Radial blanket	14.0

mass of 2300 kg U²³⁵. The initial enrichment of the alloy fuel is 26.5 per cent and the core pressure drop is 50 psi.

Plant performance data are summarized in Table 4. The design was based on a net station efficiency of 33.4 per cent and a load factor of 0.8. The high mercury temperature of 920°F permits generation of 1,000,000 #/hr. of steam at rather modern steam conditions: 1,800 psig and 900°F. A mercury inventory of about 360,000 #, or 3.6 # Hg/KW(e), is required for the 100 MW(e) plant. This is about one half the quantity of mercury required for conventional mercury power plants.

I shall now briefly discuss some of the details of the reactor plant by referring to Figure 3. It is seen that a stream of saturated liquid mercury at 920°F is pumped through the reactor core and blanket where it boils. The mercury vapor generated enters the upper plenum in the form of a fog containing suspended droplets of liquid mercury. The two phases are separated at the reactor outlet and the saturated vapor passes to three condenser-boiler units where the vapor is condensed, generating 1800 psig steam. The saturated liquid flows downward through the thermal shield and is combined with the mercury condensate at the pump inlet. The combined liquid is then pumped back to the reactor inlet plenums. Major auxiliary systems include a Mg and Ti injection system, an oxide sludge removal system, a mercury recovery system, a shutdown cooling system and a safety system.

Forced circulation is employed in the primary system to insure constant outlet fog quality although natural circulation is certainly attractive because of the high density of liquid mercury. The condenser-boilers are once-through, vertical units with double wall tubes. The once-through units have apparently proven quite satisfactory during the Enrico Fermi development program. The annulus of the double wall tubes is filled with mercury.

The plant depicted in Figure 3 offers the following advantages over sodium cooled plants:

1. No intermediate heat transfer loop is required with the double wall condenser-boiler tubes.
2. The plant is basically of simple design and employs many components with which considerable experience has been gained in conventional plants.
3. The mercury systems are fabricated of low cost materials throughout.
4. The inertness of mercury permits opening the reactor for refueling; thereby eliminating many complex fuel handling mechanisms. Containment requirements are also reduced.

TABLE 4

PLANT PERFORMANCE DATA

100 MW(E) MCBR POWER PLANT

Net electric power (mw)	94.5
Net plant efficiency (%)	33.4
Reactor thermal power (mw)	283
Core	255
Blanket	28
Steam conditions:	
Pressure (psia)	1815
Temperature (°F)	900
Flow (lb/hr)	1,020,000
Mercury vapor conditions:	
Pressure (psia)	110
Temperature (°F)	920
Flow (lb/hr)	7,700,000
Plant load factor	0.80
Total mercury holdup (lb)	360,000

ECONOMICS

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The capital cost estimate presented in Table 5 is based on the conceptual plant design discussed above. The capital cost of \$32,815,000 estimated for the MCBR excludes all research and development costs and represents the cost of a plant designed with no allowance for expansion above 100 MW(e). This cost may be compared with the capital cost of \$54,600,000 reported for the Enrico Fermi plant, Core A, which has an initial power output of 100 MW(e). The Fermi figure, however, does include the cost of providing some flexibility for expansion to 156 MW(e). The low capital cost of the MCBR offers another distinct advantage over the sodium cooled plant.

An estimated fuel cycle cost breakdown for the MCBR is presented in Table 6. The MCBR fuel cost of 13.3 mils/kwh may be compared with 12 mils/kwh for the Enrico Fermi reactor. The MCBR fuel cost is high primarily because of the high inventory charges resulting from the low power density with the uranium alloy fuel and also because of the thick breeder blanket which is definitely not economic with Plutonium figured at \$12/gm. In spite of this high fuel cost, the estimated MCBR power cost of 21.4 mils/kwh, shown in Table 7, is competitive with the power cost for the initial Enrico Fermi plant.

It is recognized that both the MCBR and Enrico Fermi are severely penalized by use of the burnup-limited U-alloy fuel. The MCBR reference design has been further penalized by restriction to the indirect cycle and by restriction to breeding even though uneconomic. The full potential of MCBR can, therefore, be realized only through use of advanced Plutonium fuels and improved designs.

ADVANCED DESIGN STUDIES

It was apparent from the initial feasibility studies that investigation of the economics of advanced designs was essential to realistic evaluation of the potential of the MCBR concept. Improved designs must take advantage of the following:

1. Increased thermal efficiencies possible with a direct mercury turbine cycle.
2. Reduced fuel cycle costs through use of advanced Plutonium oxide and carbide fuels and a higher temperature operation.

Table 8 shows the results of a rough study made some time ago to evaluate the economics of advanced MCBR designs for comparison with advanced sodium cooled breeders. This study indicated that reasonably low power costs can be expected with the advanced designs and that the concept was sufficiently promising to warrant further development work.

The second phase of the program was, therefore, initiated. This work includes a brief kinetic analysis of the reference design as well as a more detailed evaluation of improved designs. The current program is not yet far enough along to make definite

TABLE 5

ESTIMATED CAPITAL COST SUMMARY

100 MW(E) MCBR POWER PLANT

Acct. No.	Item		
310	Land and land rights	\$ 186,000	
311	Reactor plant structures and improvements	\$ 4,772,000	
312	Reactor plant equipment	<u>12,463,000</u>	
	Subtotal - Reactor Portion of Plant	\$17,235,000	
314- 316	Turbine-Generator portion of plant excluding substation	<u>\$12,700,000</u>	
	Total - Power Plant With Land		\$30,121,000
	Interest During Construction		<u>2,694,000</u>
	TOTAL CAPITAL COST		<u>\$32,815,000</u>

TABLE 6

FUEL-COST SUMMARY

100 MW(E) MCBR POWER PLANT

	<u>Core</u>	<u>Blanket</u>		
		<u>Radial</u>	<u>Upper</u>	<u>Lower</u>
Fuel-cycle costs	\$10,097,000	\$9,002,000	\$363,000	\$592,000
Length of cycle (years)	1.17	12.3	1.17	1.17
Annual Fuel Costs	\$ 8,615,000	\$ 732,000	\$309,000	\$505,000

Total Annual Fuel Cost	\$10,161,000			
	<u>Pu at \$12/gm</u>	<u>Pu at \$30/gm</u>		
Annual plutonium credit	\$ 814,000	\$2,208,000		
Net Annual Fuel Cost	\$9,347,000	\$7,953,000		
Unit Fuel Cost	13.3 mils/kwh	11.3 mils/kwh		

TABLE 7

UNIT POWER COSTS

100 MW(E) MCBR POWER PLANT
(1959 basis)

Fixed charges at 14% of capital cost	6.6 mils/kwh
Fuel cost (Pu at \$12/gm)	13.3 mils/kwh
Operating and maintenace cost	<u>1.5 mils/kwh</u>
Total Unit Power Cost	21.4 mils/kwh

TABLE 8

ESTIMATED COSTS FOR PROJECTED PLUTONIUM-FUELED BREEDER REACTORS

	MCBR				Sodium-Cooled Breeders	
	I	II	III	IV	Detroit Edison	AEC
Cycle	Indirect	Direct	Direct	Direct	Indirect	Indirect
Power Level, mw	100	100	300	300	340	300
Net Station Efficiency, %	33.4	40	40	48	32	-
Max. Mercury or Sodium Temperature, °F	1000	1000	1000	1300	830	-
Fuel Reprocessing	On site	On site	On site	On site	On site	Off site
Fuel	Pu 239	Pu 239	Pu 239	Pu 239	Pu 239	Pu 239
Plant Cost, \$/kw	328	294	189	190	265	222
Power Cost, mills/kwh						
Capital Costs	6.6	5.9	3.8	3.4	5.5	4.4
Fuel-Cycle Costs	5.9	4.9	4.9	2.6	1.5	2.0
Operating and Maintenance	1.5	1.5	0.8	0.8	0.8	0.8
Reprocessing Plant	<u>0.5</u>	<u>0.5</u>	<u>0.5</u>	<u>0.5</u>	<u>0.5</u>	<u>--</u>
TOTAL	14.5	12.8	10.0	7.3	8.3	7.5

statements on the stability of the reference design or on the economics of advanced designs.

CONCLUSIONS

In conclusion, it can be said that the MCBR is a technically feasible fast breeder reactor concept with promising long-range economic potential. Additional analytical and experimental work leading ultimately to a reactor test would appear to be justified.

A-A

DESIGN NOTES:

SAFETY VALVE SETTING	125 PSIG
PRESSURE DROP ACROSS FUEL ELEMENTS	60 PSIG
HYDROSTATIC HEAD	25 PSIG
DESIGN PRESSURE	210 PSIG
DESIGN TEMPERATURE	1000°F
JOINT EFFICIENCY	100%
FULLY RADIOGRAPHED	YES
STRESS RELIEF	YES
EST.WT. OF VESSEL (INCLUDING COVER & NON-REMOVABLE INTERNALS)	157,000 LBS.

MATERIALS

ALL MATERIALS SHALL CONFORM TO ASME
SPECIFICATION NO. SA-357 UNLESS OTHERWISE
NOTED.

- CODE COMPLIANCES

DESIGNED AND FABRICATED IN ACCORDANCE WITH THE
1959 EDITION OF THE ASME BOILER & PRESSURE
VESSEL CODE-SECTION VIII FOR UNFIRED
PRESSURE VESSELS

- REFERENCE DRAWINGS -	
FUEL & AXIAL BLANKET ELEMENT ASSEMBLY	F-185
RADIAL BLANKET ELEMENT ASSEMBLY	D-184
PLANT ARRANGEMENT - MCBR	D-189

- NOTES -

1. FOR COMPLETE LIST OF REFERENCE DRAWINGS - SEE PLANT ARRANGEMENT Dwg. D-189.
2. CUT OUT THERMAL SHIELD AT NOZZLES AS REQ'D.
3. ALL DIMENSIONS SHOWN ARE FOR COLD CONDITION UNLESS NOTED OTHERWISE.

0 1 2 3 4
GRAPHIC SCALE - FEET

UNLESS OTHERWISE NOTED		REQD	PART NO	FIG	NAME OR DESCRIPTION	MATERIAL & MATL SPEC	THICKNESS
HEREAFTER ARE IN INCHES		NATURAL & OR HEAT TREAT		ASSEMBLY - REACTOR			
TOLERANCES:		NEXT ASMT		VESSEL, 100 EMM			
FRACTIONS 1/16				MERCURY COOL			
DECIMALS .001				BREEDER REACTOR			
ANGLES 30° & 45°				PROTECT SURF			
NONE ALL ROUNDS		APPROVALS		SCALE 1" = 1'-0"			
BREATHE BREAST PLOUSE 0175 48"		DRAWN DATE		C42			
MACHINE BLENDS OF R		JCC 1/1/59		AT 04-3109			
RBS		DATE		C42			
MACHINE FINISH		1/1/59		C42			
DO NOT SCALE DRAWING		1/1/59		C42

FIGURE 3