MASTER

1000 MWe

L M F B R

Liquid Metal Fast Breeder Reactor

FOLLOW-ON STUDY

WESTINGHOUSE ELECTRIC
TASK I REPORT

Topical Report
Moisture Separation or Steam
Reheat vs. Sodium Reheat
Plant Cycle Technical and
Economic Evaluation

Prepared for ARGONNE NATIONAL LABORATORY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

This report has been reproduced directly from the best available copy.

Printed in USA. Price \$3.00. Available from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U. S. Department of Commerce, Springfield, Virginia 22151.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

WARD-2000-20

REACTOR TECHNOLOGY (TID-4500)

WARD-20

1000 MWe FAST BREEDER REACTOR FOLLOW-ON STUDY

MOISTURE SEPARATION OR STEAM REHEAT

VS

SODIUM REHEAT PLANT CYCLE

TECHNICAL AND ECONOMIC EVALUATION

by

I. M. Keyfitz
Thermal Systems

APPROVED:

W. E. Gunson
W. E. Gunson - Manager
Thermal Systems

APPROVED:

C. A. Anderson, Jr.
C. A. Anderson, Jr.
Project Manager

Prepared for Argonne National Laboratory

Under Contract No. 31-109-38-200

April, 1968

Reissued January, 1969

Westinghouse Electric Corporation
Advanced Reactors Division
P. O. Box 158
Madison, Pennsylvania 15663

This document is
PUBLICLY RELEASABLE

B. Steele
Authorizing Official

Date: *5-4-67*

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Prices and costs given herein are for estimating purposes only. They should not be considered as Westinghouse prices and quotations.

WESTINGHOUSE
ELECTRIC
CORPORATION
PITTSBURGH, PA.
15222-4199

TABLE OF CONTENTS

Section	Title	Page
ACKNOWLEDGEMENT		vii
ABSTRACT		viii
1	INTRODUCTION	1
	1.1 Purpose	1
	1.2 Background	1
	1.3 Scope	2
2	CONCLUSIONS AND RECOMMENDATIONS	4
3	QUALITATIVE SCREENING	5
4	TURBINE PLANT CYCLE AND EQUIPMENT	8
	4.1 Turbine Plant Cycle	8
	4.2 Condenser	23
	4.3 Feedwater Heaters	34
5	STEAM GENERATORS AND REHEATERS	41
6	PLANT CAPITAL PRICE	44
7	EVALUATION OF CYCLES	51
	7.1 Technical Factors	51
	7.2 Economic Factors	51
	7.2.1 Capital Price	51
	7.2.2 Fuel Cost	53
	7.2.3 Combined Differential Power Cost Due to Capital and Fuel	54
	7.2.4 Value of 1 Btu/kWh	57
REFERENCES		58

LIST OF ILLUSTRATIONS

Figure	Title	Page
1	Variation of Heat Rate with Temperature and Pressure	6
2	Moisture Separation Cycle, Turbine Plant, Detailed Heat Balance	10
3	Moisture Separation Turbine	12
4	Dimensions, Moisture Separation Turbine	13
5	Layout Moisture Separators	14
6	Heat Balance Schematic, Sodium Reheat	15
7	Sodium Reheat Turbine, Shaft A	17
8	Dimensions, Sodium Reheat Turbine, Shaft A	18
9	Sodium Reheat Turbine, Shaft B	19
10	Dimensions, Sodium Reheat Turbine, Shaft B	20
11	Mollier Diagram, Moisture Separation and Sodium Reheat	21
12	Comparison of Turbine Plant Net Heat Rates for Various Throttle Steam Conditions	22
13	Base Plant Condenser	27
14	Reheat Plant Condenser	28
15	Air Ejector	30
16	Priming Ejector	31
17	Circulating Water Pump (CT-20207)	32
18	Circulating Water Pump (CT-20208)	33
19	Condensate Pump	35
20	Base Plant Hemispherical Head High Pressure Feedwater Heater (1,2,3,4)	37
21	Base Plant Hemispherical Head High Pressure Feedwater Heater (5,6,7)	38
22	Reheat Plant Hemispherical Head High Pressure Feed-water Heater (1,2,3,4)	39

LIST OF ILLUSTRATIONS (Cont)

Figure	Title	Page
23	Reheat Plant Hemispherical Head High Pressure Feedwater Heater (5,6,7)	40
24	Differential Power Cost Envelope for Sodium Reheat-Moisture Separation	55
25	Differential Power Cost Envelope for Sodium Reheat-Moisture Separation as a Function of Δ Heat Rate	56

LIST OF TABLES

Table	Title	Page
1	Major Work Areas for Steam Cycle Selection	3
2	Possible Steam Cycles	5
3	Turbine Plant Functional Specifications	8
4	Comparison of Moisture Separation and Reheat Cycles	24
5	Condenser Parameters	26
6	Circulating Water Pump Parameters	29
7	Condensate Pump Parameters	34
8	Sodium-Heated Steam Generator and Reheater Parameters	42
9	Capital Items Affected by Moisture Separation or Sodium Reheat Cycles	46
10	Differential Power Costs Due to Capital Reheat Minus Moisture Separation, Δf_p	53
11	Differential Power Cost Due to Fuel	54
12	Differential Power Cost for Reheat-Moisture Separation Plant	57

ACKNOWLEDGEMENT

This evaluation utilized the efforts of several groups and many individuals. The principal contributors are:

United Engineers and Constructors, Inc., U-E	J. H. Crowley
	C. L. Newman
	H. L. R. Newbold
Westinghouse Large Turbine Divisions, <u>WLTD</u>	H. A. Langston
	S. W. W. Mitchell
	J. Bushey
Westinghouse Heat Transfer Division, <u>WHTD</u>	A. R. Giardina
	M. Gross
	G. F. Pierson
Westinghouse Advanced Reactors Division, <u>WARD</u>	J. Wasko

ABSTRACT

An evaluation of a moisture separation or steam reheat cycle versus a sodium reheat cycle for a nominal 1000-MWe Sodium-Cooled, Fast Breeder Reactor verifies that, from both a technical and economic viewpoint, moisture separation or steam reheat is superior to sodium reheat. The economic advantage is estimated at from 0.014 to 0.06 mills/kWh power cost, depending upon the assumed total capital price in the range of 120 to 160 \$/kW and the assumed fuel cost in the range of 7 to 16 cents per million Btu. Expenses incurred by the customer are not included in the total capital price.

SECTION 1

INTRODUCTION

1.1 Purpose

This report evaluates and selects the most suitable type of steam cycle for the 1000-MWe Fast Breeder Reactor Follow-on Study as part of Task I.

1.2 Background

The trend in power plant design has been to ever-higher, steam temperature and pressure conditions. The ultimate was encompassed by Philadelphia Electric Company's Eddystone Unit No. 1 having throttle steam at 5000 psig and 1200°F with double reheat to 1050°F. Undoubtedly this is an engineering achievement of the first magnitude and plants of this type might be justified in very high fuel cost areas. However, in a fast breeder reactor, where fuel costs may be of the order of 7 to 16 cents/million Btu, such extreme steam conditions are not warranted. When additional capital costs, reduced reliability, and safety are balanced against fuel cost savings the results will probably favor a more conservative approach.

Westinghouse assisted Argonne National Laboratory in an earlier feasibility study^[1] of a conceptual design for a nuclear steam supply system using a 10,000-MWt, sodium-cooled breeder reactor. A comparison of a sodium reheat plant with 2400 psig/900°F/900°F steam and a moisture separation or steam reheat cycle at 2400 psig/900°F steam was made. The results indicated an apparent economic gain of less than 0.01 mill/kWh for sodium reheat. In view of additional plant complexity and reduced reliability, sodium reheat was rejected. In the current study, more detailed design information is being assembled to assist in arriving at a more substantial conclusion.

1.3 Scope

Two main cases were considered in detail:

- a. A moisture separation or steam reheat cycle with two sodium-heated steam generators and 2400 psig/900°F throttle steam
- b. A sodium reheat cycle with two sodium-heated steam generators and two sodium reheaters with 2400 psig/900°F/900°F steam

Each involves the work area shown in Table 1. It will also be shown how extrapolation of the results for these two cases may be applied to a more generalized result. Moreover, results are reviewed to ensure that assumptions are not made which will unintentionally bias either concept.

TABLE 1

MAJOR WORK AREAS FOR STEAM CYCLE SELECTION

Plant	Item	Group Performing Work
Reactor	1. Reactor and heat transfer equipment structure design and cost	U-E
	2. Steam generator specification, design, and cost	<u>W</u> ARD & <u>W</u> HTD
	3. Reheater specification, design and cost	<u>W</u> ARD & <u>W</u> HTD
	4. Secondary sodium piping design and cost	<u>W</u> ARD & U-E
Turbine	5. Plant specification and heat balance	<u>W</u> ARD & <u>W</u> LTD
	6. Turbine generator selection and cost	<u>W</u> LTD
	7. Condenser design and cost	<u>W</u> HTD
	8. Feedwater heater design and cost	<u>W</u> HTD
	9. Estimate of turbine plant structure and systems based on U-E study for ANL	U-E

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

The moisture separation or steam reheat cycle is superior both technically and economically to the sodium reheat cycle. Only 2400 psig/900°F and 2400 psig/900°F/900°F were studied in detail; however, the conclusion is valid over a range of throttle steam pressures and temperatures due to the continuous nature of the heat rate versus pressure curve.

Sodium reheat is more complex, less reliable, and has a higher initial plant capital cost than the moisture separation or steam reheat cycle. The savings due to the lower heat rate of sodium reheat was not sufficient to balance the higher capital cost. The power cost increase of sodium reheat over moisture separation was found to vary from 0.06 mill/kWh down to 0.014 mill/kWh depending upon the fuel cost and other assumptions.

In view of the above, it is recommended that the Reference Design in Task II utilize the moisture separation cycle. Also, only moisture separation or steam reheat cycles are recommended as the basis for Task III plant optimization.

SECTION 3

QUALITATIVE SCREENING

There are four potential cycles, all independent of steam pressure and temperature conditions. Table 2 lists these possibilities. The first three involve only differences in the turbine plant and have no especially significant effect on the secondary sodium heat-removal system of the reactor plant. The last cycle requires branching of the sodium pipe to the steam generator to supply parallel flow to the reheater.

TABLE 2

POSSIBLE STEAM CYCLES

1. Straight Expansion
2. Moisture Separation
3. Steam Reheat
4. Sodium Reheat

Straight steam expansion is impractical because the low pressure cylinder steam would have excessive moisture, thereby causing unacceptable blade erosion. Moisture separation between the high-pressure and low-pressure cylinders is possible for several, but not all combinations of steam temperatures and pressures. Steam reheat will be practical for most steam conditions. The difference between cycles 2 and 3 is less important than that between either cycle 2 or 3 and the sodium reheat cycle.

If plant gross heat rate is plotted as the ordinate and throttle pressure as the abscissa, for a given steam temperature, the resulting curve has a decreasing heat rate with increasing pressure. Figure 1 shows curves plotted^[2] for 900°F/900°F and 1000°F/1000°F.

Figure 1 Variation of Heat Rate with Temperature and Pressure

The curves are nearly parallel and it is reasoned that a family of similar curves could be drawn for many steam conditions. Therefore, in this study, differences in heat rate between moisture separation or steam reheat and sodium reheat have been assumed to be independent of pressure. Hence, the results obtained by comparing throttle steam at 2400 psig/900°F with moisture separation or steam reheat and steam at 2400 psig/900°F/900°F should be reasonably constant, regardless of the base pressure or temperature used. Moreover, with the selected sodium reactor outlet temperature of 1000°F, the average range to be examined in Task III, 900°F steam is reasonable. This temperature provides a good heat rate and yet allows sufficient heat exchanger ΔT for the steam generator surface area. The selected throttle pressure of 2400 psig meets modern advanced steam conditions, leading to use of standard turbine plant equipment.

SECTION 4

TURBINE PLANT CYCLE AND EQUIPMENT

4.1 Turbine Plant Cycle

The turbine plant functional specifications for steam reheat or moisture separation, and for sodium reheat are presented in Table 3. A constant heat input of 2600 MWt was selected to provide a nominal net power output of 1000 MWe. Condenser back-pressure of 1.5 inches of mercury absolute and 0 percent make-up were assumed to conform to the rating requirements of TID-7025.^[3]

TABLE 3

TURBINE PLANT FUNCTIONAL SPECIFICATIONS

	Steam Reheat or Moisture Separation	Sodium Reheat Cycle
Throttle Steam Pressure (psig)	2400	2400
Throttle Steam Temperature (°F)	900	900
Reheat Steam Temperature (°F)	To be determined	900
Feedwater Temperature (°F)	500	500
Heat Input (MWt)	2600	2600
Condenser Back Pressure (in Hg A)	1.5	1.5
Make-Up (%)	0	0
No. Separate Turbine-Driven BFP	2	2
Condenser Suitable for 40% Full-load Steam Dump at Full Pressure for 4 min.	Yes	Yes

A preliminary evaluation of numerous different combinations of low-pressure end size, configuration, moisture separation, and steam reheat at several bleed points was made, comparing rough incremental heat rates and equipment price differences. For the throttle steam conditions used, moisture separation was selected over steam reheat.

Based upon the above work, a heat balance was prepared for the moisture separation cycle utilizing an 1800 rpm tandan compound unit with quadruple flow, 44-inch, low-pressure blades. The detailed heat balance is presented in Figure 2. This shows a turbine cycle heat rate of 8264 Btu/kWh with a generator output of 1073.8 MWe and separate turbine-driven feedwater pump power of 32.13 MW or gross power output of 1106 MWe. Seven stages of regenerative feedwater heating were selected and the feedwater returns at 500°F to the steam generator.

The separate, turbine-driven, twin 50-percent capacity, high-pressure feedwater pumps require 32.13 MW. A description of the turbine-generator unit follows:

One 1,073,843 kW indoor-type, turbine-generator unit for use with a sodium-cooled, fast breeder nuclear reactor consisting of:

One Tandem compound, four-flow, three-casing, impulse-reaction, indoor-type, condensing 1,800-rpm turbine, utilizing 44-inch last row blades guaranteed to deliver 1,073,843 kW net (measured at the generator terminals) when operating with rated steam conditions of 2,415 psia, 900 degrees FTT (Final Throttle Temperature) at the turbine stop valves, one stage of external moisture separation between the HP (High-Pressure) and LP (Low-Pressure) elements, 1.5-inch-Hg abs exhaust, all seven stages of feedwater heating in service, zero percent makeup, and while extracting steam for condensing-type boiler feed pump turbine(s). This corresponds to the NSSS (Nuclear Steam Supply System) output of 2,600 MWt;

To provide for manufacturing tolerances, the main turbine will be designed with five percent flow margin above the flow required to meet the guaranteed output. Thus, the turbine-generator unit has a maximum calculated (not guaranteed) net output (measured at the generator terminals) of 1,117,028 kW, when operating with the governing valves wide open at steam conditions of 2,415 psia, 900-degree FTT at the turbine

10

Figure 2. Moisture Separation Cycle, Turbine Plant, Detailed Heat Balance

stop valves, external moisture separator in service, 1.5-inch-Hg abs exhaust, all seven stages of feedwater heating in service, zero percent makeup, and while extracting steam for condensing type boiler feed pump turbines.

One 1,241,100 kVa, 0.90 p-f, 0.58 SCR, at maximum hydrogen pressure, 3-phase, 60 cycle, 22,000-volt, 1,800-rpm, hydrogen inner-cooled generator.

One 600-volt dc, 1,800-rpm, self-ventilated, air-cooled, shaft-driven brushless exciter complete with static-type voltage regulator and associated excitation switchgear.

The quoted price includes moisture separators, standard features and accessories, f.o.b. point of shipment with freight prepaid to rail siding nearest the installation site, and installation services of a qualified engineer. The size and weight of major components of the turbine-generator unit and external moisture separator are presented in Figures 3, 4, and 5.

To make a valid comparison, the sodium reheat plant incorporated the same low-pressure ends that were used for the moisture separation turbine. The detailed heat balance for this sodium reheat cycle is shown in Figure 6. As before, there are seven stages of regenerative feedwater heating resulting in a net turbine plant heat rate of 8063 Btu/kWh. The heat rate gain is approximately 200 Btu/kWh. The turbine-generator unit description follows:

One 1,100,777 kW indoor-type turbine-generator unit consisting of:

One cross-compound, four-flow, four-casing, impulse-reaction, indoor-type condensing, 3600/1800-rpm turbine, utilizing 44-inch, last-row blades guaranteed to deliver 1,100,777 kW net (measured at the generator terminals) when operating with rated steam conditions of 2415 psia, 900-degree FTT at the turbine stop valves, reheating to 900 degrees FTT, 1.5-inch-Hg abs exhaust, all seven stages of feedwater heating in service, zero percent makeup, and while extracting steam for condensing-type boiler feed pump turbines. This corresponds to the NSSS output of 2600 MWt;

Figure 3. Moisture Separation Turbine

WESTINGHOUSE TURBINE-GENERATOR UNIT PROPOSAL OUTLINE

TURBINE	GENERATOR
KW <u>1,073,843</u>	KVA <u>1,241,100</u>
TYPE <u>TC4P-44</u>	POWER FACTOR <u>0.90</u>
LAST ROW BLADE LENGTH <u>44"</u>	KW _____
STEAM CONDITIONS:	S.C.R. <u>.58</u>
INITIAL PRESSURE PSIG <u>2400</u>	GAS PRESSURE PSIG _____
INITIAL TEMPERATURE FTY <u>900</u>	RPM <u>1800</u>
REHEAT TEMPERATURE FTY <u>--</u>	☐ COLLECTOR HOUSING ☐ GEARED EXCITER ☒ ROTATING RECTIFIER EXCITER
EXHAUST PRESSURE IN. HG. A <u>1.5</u>	

OUTLINE DIMENSIONS			
A <u>6' 5"</u>	M <u>8' 6"</u>	X <u>19' 1"</u>	SHAFT-DRIVEN BOILER FEED PUMP: ☐ GENERATOR END ☐ TURBINE END ERECTION HEAVIEST PIECE DURING Gen. Stator <u>710,000</u> LBS AFTER Gen. Rotor <u>365,000</u> LBS MINIMUM CRANE HOOK HEIGHT <u>36' 6"</u> LP EXHAUST CONNECTION ☐ FLANGED ☒ WELDED
B <u>8' 2 1/2"</u>	N <u>22' 0"</u>	Y <u>25' 6"</u>	
C <u>12' 1"</u>	O <u>7' 4"</u>	Z <u>4' 6"</u>	
D <u>23' 4"</u>	P <u>3' 6"</u>	A ₁ <u>15' 7 1/2"</u>	
E <u>167' 8-3/4"</u>	Q <u>10' 6"</u>	B ₁ <u>6' 6"</u>	
F <u>19' 9 1/2"</u>	R <u>27' 0"</u>	C ₁ <u>4' 6"</u>	
G <u>16' 3 1/2"</u>	S <u>30' 0"</u>	D ₁ <u>19' 8"</u>	
H <u>23' 0 1/2"</u>	T <u>32' 0"</u>	E ₁ <u>8' 7 1/2"</u>	
I <u>12' 1-3/4"</u>	U <u>16' 0"</u>	F ₁ <u>11' 3"</u>	
J <u>10' 5 1/2"</u>	V <u>22' 9"</u>	G ₁ <u>18' 8"</u>	
K <u>16' 10 1/2"</u>	W <u>6' 9"</u>		

DISTANCE REQUIRED TO REMOVE GENERATOR ROTOR		
SKEWED OUT		STRAIGHT OUT
A <u>31' 3"</u>	B <u>58' 4"</u>	C <u>63' 4"</u>

FOUNDATION LOADING DIAGRAM		
LOAD VALUE A <u>88,000</u> LBS	LOAD VALUE M <u>38,000</u> LBS	DIMENSION K <u>5' 2 1/2"</u>
LOAD VALUE B <u>780,500</u> LBS	LOAD VALUE N <u>273,900</u> LBS	DIMENSION L <u>9' 0"</u>
LOAD VALUE C <u>780,500</u> LBS	LOAD VALUE O <u>360,800</u> LBS	DIMENSION M <u>5' 2 1/2"</u>
LOAD VALUE D <u>42,700</u> LBS	DIMENSION B <u>38' 9 1/2"</u>	DIMENSION N <u>9' 0"</u>
LOAD VALUE E <u>42,700</u> LBS	DIMENSION C <u>9' 2"</u>	DIMENSION P <u>13' 6"</u>
LOAD VALUE F <u>232,200</u> LBS	DIMENSION D <u>12' 10 1/2"</u>	DIMENSION Q <u>28' 3"</u>
LOAD VALUE G <u>232,200</u> LBS	DIMENSION E <u>9' 2"</u>	DIMENSION R <u>22' 6"</u>
LOAD VALUE H <u>95,300</u> LBS	DIMENSION F <u>14' 3 1/2"</u>	
LOAD VALUE J <u>17,900</u> LBS	DIMENSION G <u>9' 2"</u>	
LOAD VALUE K <u>198,400</u> LBS	DIMENSION H <u>9' 0"</u>	
LOAD VALUE L <u>198,400</u> LBS	DIMENSION J <u>9' 0"</u>	

NOTE:
ALL DIMENSIONED LOAD VALUES ARE SAME FOR EACH SIDE OF CENTERLINE OF UNIT.

All dimensions are approximate.

PURCHASER ARD 1000 MW LMFBR Study Contract

Figure 4 Dimensions, Moisture Separation Turbine

MOISTURE SEPARATOR TANKS MAY BE
LOCATED EITHER ABOVE OR BELOW FLOOR.

OPERATING WEIGHT OF EACH MOISTURE SEPARATOR TANK 70,000 LBS

Figure 5. Layout Moisture Separators

Figure 6. Heat Balance Schematic, Sodium Reheat

To provide for manufacturing tolerances, the main turbine will be designed with five percent flow margin above the flow required to meet the guaranteed output. Thus, the turbine-generator unit has a maximum calculated (not guaranteed) net output (measured at the generator terminals) of 1,143,665 kW, when operating with the governing valves wide open at steam conditions of 2415 psia, 900-degree FTT at the turbine stop valves, reheating to 900 degrees FTT, 1.5-inch-Hg absolute exhaust, all seven stages of feedwater heating in service, zero percent makeup, and while extracting steam for condensing-type boiler feed pump turbines.

One 664,300 kVa, 0.90 p-f, 0.58 SCR, at maximum hydrogen pressure, 3-phase, 60-cycle, 20,000 volt, 3600-rpm, hydrogen inner-cooled generator.

One 606,500 kVa, 0.90 p-f, 0.58 SCR, at maximum hydrogen pressure, 3-phase, 60-cycle, 20,000 volt, 1800-rpm, hydrogen inner-cooler generator.

One 500-volt dc, 3600-rpm, self-ventilated, air-cooled, shaft-driven brushless exciter.

One 500-volt dc, 1800-rpm, self-ventilated, air-cooled, shaft-driven brushless exciter.

One static-type voltage regulator and associated excitation switch-gear.

The quoted price includes standard features and accessories, f.o.b. point of shipment with freight prepaid to rail siding nearest the installation site, and installation services of a qualified engineer. Figures 7 through 10 show the size and weight of major components of the turbine-generator unit.

Figure 11 shows a comparison of the steam cycle expansion lines for the moisture separation cycle and sodium reheat cycle.

Figure 12 gives a comparison of the relative turbine performance for different nominal 1000 MWe plant studies. It is seen that for a sodium reheat cycle with 2400 psig and 900 or 950°F steam, Atomics International (AI), U-E, and WARD

GENERATOR END VIEW

TURBINE END VIEW

DISTANCE REQUIRED TO REMOVE GENERATOR ROTOR

FOUNDATION LOADING DIAGRAM

Figure 7 Sodium Reheat Turbine, Shaft A

TR1036

WESTINGHOUSE TURBINE-GENERATOR UNIT PROPOSAL OUTLINE

SHAFT A

TURBINE		GENERATOR	
KW	1,100,777	KVA	664,300
TYPE	CC4F-44	POWER FACTOR	.90
LAST ROW BLADE LENGTH	44 INCH	KW	
STEAM CONDITIONS:		S.C.R.	.58
INITIAL PRESSURE, PSIG	2400	GAS PRESSURE, PSIG	
INITIAL TEMPERATURE, FTT	900	RPM	3600
REHEAT TEMPERATURE, FTT	900	☐ COLLECTOR HOUSING ☐ GEARED EXCITER ☒ ROTATING RECTIFIER EXCITER	
EXHAUST PRESSURE, IN. HG. A	1.5		

OUTLINE DIMENSIONS			
A 14'6"	L 5'0"	V 21'7-1/2"	SHAFT-DRIVEN BOILER FEED PUMP: ☐ GENERATOR END ☐ TURBINE END ERECTION HEAVIEST PIECE: DURING Gen. Stator 685,100 LBS AFTER Gen. Rotor 120,200 LBS MINIMUM CRANE HOOK HEIGHT: 36'6" LP EXHAUST CONNECTION: ☐ FLANGED ☐ WELDED
B 7'3"	M 18'6"	W 5'0"	
C 10'5"	N 7'9"	X 16'7-1/2"	
D 25'4"	O 2'6"	Y 6'5"	
E 108'3"	P 23'0"	Z 17'4"	
F 18'2"	Q 30'9"	A 8'10"	
G 14'10-1/2"	R 15'4-1/2"	B 13'8"	
H 19'6-1/2"	S 34'6"	C 12'4"	
J 6'5"	T 5'8"	D 8'7"	
K 18'0"	U 17'1"	E 9'0"	

DISTANCE REQUIRED TO REMOVE GENERATOR ROTOR		
SKEWED OUT		STRAIGHT OUT
A 22'5"	B 48'0"	C 55'0"

FOUNDATION LOADING DIAGRAM			
LOAD VALUE A 55,500 LBS	LOAD VALUE F 451,800 LBS	DIMENSION H 11'0"	
LOAD VALUE B)	LOAD VALUE G 248,200 LBS	DIMENSION J 21'2"	
LOAD VALUE C) 476,500 LBS	DIMENSION B)	DIMENSION K 20'5"	
LOAD VALUE D)	DIMENSION C) 34'1-1/2"	NOTE: ALL DIMENSIONED LOAD VALUES ARE SAME FOR EACH SIDE OF CENTERLINE OF UNIT.	
LOAD VALUE E 216,700 LBS	DIMENSION D)		

All Dimensions Are Approximate

PURCHASER ARD 1000 MW LMFBR Study Contract

Figure 8 Dimensions, Sodium Reheat Turbine, Shaft A

Figure 9 Sodium Reheat Turbine, Shaft b

WESTINGHOUSE TURBINE-GENERATOR UNIT PROPOSAL OUTLINE

SHAFT B

TR1040

TURBINE		GENERATOR	
WGT	1,100,777	KVA	606,500
TYPE	CC4P-44	POWER FACTOR	.90
FAST ROW BLADE LENGTH	44 INCH	KW	
RIFAM CONDITIONS:		S.C.R.	.58
INITIAL PRESSURE, PSIG	2400	GAS PRESSURE, PSIG	
INITIAL TEMPERATURE, FTT	900	RPM	1800
REHEAT TEMPERATURE, FTT	900		
EXHAUST PRESSURE, IN.HG.A.	1.5	☐ COLLECTOR HOUSING ☐ GEARED EXCITER ☒ ROTATING RECTIFIER EXCITER	

OUTLINE DIMENSIONS			
A 13'9"	L 8'5-1/4"	V 21'7-1/2"	SHAFT-DRIVEN BOILER FEED PUMP: ☐ GENERATOR END ☐ TURBINE END ERECTION HEAVIEST PIECE: DURING Gen. Stator 640,000 LBS AFTER Gen. Rotor 235,000 LBS MINIMUM CRANE HOOK HEIGHT: 36'6" LP EXHAUST CONNECTION: ☐ FLANGED ☒ WELDED
B 6'10-1/2"	M 9'7-1/2"	W 4'6"	
C 9'10"	N 3'6"	X 15'7-1/2"	
D 21'8"	O 10'6"	Y 6'6"	
E 133'8-3/4"	P 32'0"	Z 6'6"	
F 20'2"	Q 16'0"	A 30'0"	
G 14'0"	R 3'6"	B 27'0"	
H 19'7"	S 23'0"	C 14'1-1/2"	
J 11'8-3/4"	T 5'2"		
K 10'5-1/4"	U 16'4-1/2"		

DISTANCE REQUIRED TO REMOVE GENERATOR ROTOR		
SKEWED OUT		STRAIGHT OUT
A 26'8"	B 50'4"	C 54'8"

FOUNDATION LOADING DIAGRAM		
LOAD VALUE A 57,900 LBS	LOAD VALUE M 38,000 LBS	DIMENSION K 5'2-1/2"
LOAD VALUE B) LBS	LOAD VALUE N 198,400 LBS	DIMENSION L 9'0"
LOAD VALUE C) 502,500 LBS	LOAD VALUE O 40,100 LBS	DIMENSION M 5'2-1/2"
LOAD VALUE D) LBS	LOAD VALUE P 95,000 LBS	DIMENSION N 9'0"
LOAD VALUE E 42,700 LBS	DIMENSION B)	DIMENSION O 5'2-1/2"
LOAD VALUE F 232,200 LBS	DIMENSION C) 33'3"	DIMENSION P 9'0"
LOAD VALUE G 85,400 LBS	DIMENSION D)	DIMENSION Q 10'4"
LOAD VALUE H 232,200 LBS	DIMENSION E 12'10-1/2"	DIMENSION R 28'3"
LOAD VALUE J 42,700 LBS	DIMENSION F 9'2"	
LOAD VALUE K 17,900 LBS	DIMENSION G 28'7"	
LOAD VALUE L 95,300 LBS	DIMENSION H 9'2"	
	DIMENSION J 9'0"	

NOTE:
ALL DIMENSIONED LOAD VALUES ARE SAME FOR EACH SIDE OF CENTERLINE OF UNIT.

All Dimensions Are Approximate
PURCHASER ARD 1000 MW LMFBR Study Contract

Figure 10 Dimensions, Sodium Reheat Turbine, Shaft b

Figure 11 Mollier Diagram, Moisture Separation and Sodium Reheat

Figure 12. Comparison of Turbine Plant Net Heat Rates for Various Throttle Steam Conditions

all arrived at heat rates which are within 100 to 150 Btu/kWh. The Westinghouse heat rate is the lowest, and is based on the most detailed of the three studies. For the moisture separation, or steam reheat cases, AI and U-E agree rather closely on heat rate, whereas the Westinghouse value is about 400 Btu/kWh lower. The Westinghouse moisture separation cycle uses the improvements developed for the Westinghouse prototype study. Preliminary considerations indicated that steam reheat does not give sufficient gain in heat rate to compensate for the additional reheater capital cost.

Table 4 compares the two plant cycles. The net plant heat rate is 8490 for moisture separation and 8281 Btu/kWh for the reheat plant.

4.2 Condenser Design

The condenser designs for the two steam cycles are based upon the heat balances shown in Figures 2 and 6. The following assumptions were used to size the equipment:

- a. Condenser cooling is supplied by river water at 57°F (to agree with AEC-selected Middletown Site).
- b. Elevation of the site with respect to minimum river level is such that an all-friction, circulating water system may be used.
- c. Circulating water friction external to the condenser is 15 feet of water.
- d. There will be a limit of 15°F placed on the circulating water temperature rise.
- e. The maximum width of the condenser shell will be four feet greater than the width of the turbine exhaust.
- f. A basement floor-to-turbine floor height of 40 feet is available with a 10-foot-deep turbine beam, with allowance for a five-foot diameter LP heater stage in the neck.
- g. The tubes are made of Type 304 stainless steel.
- h. The tubesheets are made of carbon steel.

TABLE 4
COMPARISON OF MOISTURE SEPARATION AND REHEAT CYCLES

	Moisture Separation	Sodium Reheat
High-Pressure		
Number of double flow cylinders	1	1
Inlet pressure (psig)	2400	2400
Inlet temperature (°F)	900	900
Inlet enthalpy (Btu/lb)	1391.6	1391.6
Flow (10^6 lb/hr)	9.813	8.33
Discharge pressure (psia)	122	704
Discharge temperature (°F)	342.5	512
Discharge enthalpy (Btu/lb)	1145.6	1209.2
Discharge moisture (%)	5.1	SH
Intermediate Pressure		
Number of double flow cylinders	Integral with HP	1
Inlet pressure (psia)	--	633
Inlet temperature (°F)	--	900
Inlet enthalpy (Btu/lb)	--	1461.3
Flow (10^6 lb/hr)	--	7.382
Discharge pressure (psia)	--	163
Discharge temperature (°F)	--	577
Discharge enthalpy (Btu/lb)	--	1313

TABLE 4 (Cont)

COMPARISON OF MOISTURE SEPARATION AND REHEAT CYCLES

	Moisture Separation	Sodium Reheat
Low-Pressure		
Number of double flow cylinders	2	2
Inlet pressure (psia)	114	159
Inlet temperature (°F)	337	577
Inlet enthalpy (Btu/lb)	1189.8	1313
Flow (10^6 lb/hr)	7.367	6.251
Discharge pressure (in Hg A)	1.5	1.5
Feedwater temperature (°F)	500	500
Power Conversion		
Heat input (MWt)	2600	2600
Gross power output (MWe)	1106.0	1128.1
Turbine plant auxiliary power (MWe)	33.8	29.4
Reactor plant auxiliary power (MWt)	27.0	27.0
Net plant output (MWe)	1045.2	1071.7
Net plant heat rate (Btu/kWh)	8490	8281
Net plant efficiency (%)	40.20	41.22

- i. The waterboxes and shell are made of A-285 Grade C steel.
- j. The expansion joint is made of rubber belting.
- k. A five-minute condensate storage will be provided in the hotwell.
- l. Tubes are one-inch-diameter 22 BWG.
- m. A cleanliness factor of 90 percent is used.
- n. The condenser pressure is fixed at 1.5-inch-Hg abs by the customer.

In both the base plant moisture separation cycle and the reheat plant alternate, two condensers are required, mounted perpendicular to the turbine shaft. The basic design information is presented in Table 5 and outlines are given in Figures 13 and 14. The associated condenser equipment is described in the following pages. Prices for the condensers and associated condenser equipment were estimated.

TABLE 5
CONDENSER PARAMETERS

	Base Plant	Reheat Plant
Number of condensers	2	2
Surface area of each (ft ²)	217,000	213,500
Circulating water required (gpm)	346,500	341,000
Velocity in tubes (ft/sec)	7.25	7.25
Tubes diam/gage (in/BWG)	1/22	1/22
Tube material	304 SS	304 SS
Cleanliness factor (%)	90	90
Number of passes	1	1
Inlet water temperature (°F)	57	57
Circulating water rise (°F)	14.85	14.85

Figure 13. Base Plant Condenser

Figure 14. Reheat Plant Condenser

Air Ejectors

One G-200 air ejector will be supplied with each condenser. This ejector is similar to the G-150 ejector except that the shell barrel will be 26 inches in diameter, the water nozzles will be 16 inches and the surface area 380 square feet (Figure 15).

Priming Ejector

One P-1200 priming ejector will be supplied for each condenser (Figure 16).

Circulating Water Pumps

The circulating pumps have been sized for quantity of water specified on the heat balance with no allowance for additional flow. The head was determined by the condenser friction plus 16 feet of external friction. The basic design information is presented in Table 6 and outlines are given in Figures 17 and 18.

TABLE 6
CIRCULATING WATER PUMP PARAMETERS

	Base Plant	Reheat Plant
Type of Pump	90BN	90BN
No. of Pumps/Condenser	2	2
Capacity of Each (gpm)	173,250	170,500
Total Dynamic Head (ft of H ₂ O)	26.7	26.7
Brake Horsepower (hp)	1345	1323
Speed (rpm)	294	294

Condenser Pumps

There are two, one-half capacity condensate pumps per condenser with no allowance for conditions which would require additional capacity such as overpressure. If additional capacity is specified, it is possible that a larger pump

Figure 16. Priming Ejector

TYPE 90 BN
(CT-20208)

Ratings

170,500 gpm 26.7 ft. tdh
1,323 bhp 294 rpm

Dimensions are preliminary, and are not to be used for construction purposes.

Discharge diameter 90 inches

Elevation 0

High water elevation

Normal water elevation

Low water elevation 6' - 6"

Down Thrust 34,000 # Continuous

Estimated Weights

Pump (Less Motor) 70000#

Elevation 20' - 1"

Figure 18. Circulating Water Pump (CT-20208)

may be required. The basic design information is presented in Table 7. An outline is given in Figure 19.

TABLE 7
CONDENSATE PUMP PARAMETERS

	Base Plant	Reheat Plant
Type of Pump	123 RW	123RW
No. of Pumps/Condenser	2	2
Capacity of Each (gpm)	3700	3415
Total Dynamic Head (ft of H ₂ O)	289	289
Brake Horsepower (hp)	345	345
Speed (rpm)	880	880

4.3 Feedwater Heaters

The feedwater heaters were sized for the conditions specified in the heat balances (Figures 2 and 6). Because of the large unit capacity required, a twin-stream system was employed. The following ground rules were applied to the design:

- a. Orientation - all horizontal
- b. Length Limits - 45 feet
- c. Tubeside Pressure Drop Limit - 12 to 14 psi per heater
- d. Shell-Side Design Pressure - Steam pressure plus 15 percent
- e. Tubeside Design Pressure - 3500 psi
- f. Tube Material - carbon steel - Type 304 stainless steel for FWH in condenser neck
- g. Design Temperature for Tubeside and Shell Side - per Feedwater Heaters Manufacturers Association

Figure 19. Condensate Pump

The outline dimensions, nozzle sizes and locations, and weights are presented in Figures 20 and 21 for the base plant and in Figures 22 and 23 for the reheat plant.

DIMENSIONS

Unit	Area	A	B	C	D	E	F	G	H	J ^a
Htr #1	26365	40.3'	45'-0"	74"	18"	(4) 34"	14"	43"	73"	39'-5"
Htr #2	12700	40.3'	44'-10"	64"	18"	(1) 36"	12"	38"	63"	39'-8"
Htr #3	13630	40.5'	45'-0"	64"	18"	(1) 30"	10"	38"	63"	40'-0"
Htr #4	11405	39.4'	43'-7"	58"	18"	(1) 22"	8"	35"	57"	39'-1"

^a Distance required for removal of _____

Unit	Horizontal	Bracket support	Shell rollers	Vertical	Head up	Head down
Htr #1	X	* X				
Htr #2	X		X			
Htr #3	X		X			
Htr #4	X		X			

Figure 20. Base Plant Hemispherical Head High Pressure Feedwater Heater (1,2,3,4)

DIMENSIONS

Unit	Area	A	B	C	D	E	F	G	H	J
Htr #5	10360	35.8'	39'-11"	55"	18"	(1) 14"	6"	33"	53 3/4	35'-8"
Htr #6	24275	38.7'	45'-0"	81"	22"	(1) 14"	14"	43"	73"	38'-1"
Htr #7	25580	38.5'	44'-11"	81"	22"	(1) 14"	12"	44"	75 1/4	37'-11"

• Distance required for removal of _____

Unit	Horizontal	Bracket support	Shell rollers	Vertical	Head up	Head down
Htr. #5	X		X			
Htr. #6	X		X			
Htr. #7	X		X			

Figure 21. Base Plant Hemispherical Head High Pressure Feedwater Heater (5,6,7)

DIMENSIONS

Unit	Area	A	B	C	D	E	F	G	H	J ^a
LP #1	23820	40.3'	45'-0"	71"	16"	(4)34"	12"	41"	70"	39'-7"
LP #2	11290	40.5'	44'-10"	61"	16"	(1)34"	10"	36"	60"	39'-11"
LP #3	12400	40.1'	44'-6"	62"	16"	(1)28"	10"	37"	61"	39'-7"
LP #4	12415	40.1'	44'-5"	60"	16"	(1)22"	8"	36"	59"	39'-9"

^a Distance required for removal of _____

WEIGHTS

Unit	Horizontal	Bracket support	Shell rollers	Empty Vertical	Operating Head up	Flooded Head down
LP #1	X	* X		77,800	99,900	144,200
LP #2	X		X	57,200	73,500	105,900
LP #3	X		X	60,100	76,800	110,100
LP #4	X		X	58,000	72,000	104,900

Figure 22. Reheat Plant Hemispherical Head High Pressure Feedwater Heater (1, 2, 3, 4)

DIMENSIONS

Unit	Area	A	B	C	D	E	F	G	H	J"
LP #5	10385	40.0'	43'-1"	56"	16"	12"	12"	34"	55"	38'-4"
HP #6	15625	31.5	37'-2"	71 1/2"	20"	12"	12"	40"	66 1/4"	30'-11"
HP #7	21370	38.8'	44'-8"	73"	20"	1"	10"	41"	69"	38'-4"

• Distance required for removal of _____

WEIGHTS

Unit	Horizontal	Bracket support	Shell rollers	Empty Vertical	Operating Hood up	Flooded Hood down
LP #5	X		X	49,400	62,600	89,000
HP #6	X		X	119,240	134,540	165,240
HP #7	X		X	181,610	200,810	239,110

Figure 23. Reheat Plant Hemispherical Head High Pressure Feedwater Heater (5,6,7)

SECTION 5

STEAM GENERATORS AND REHEATERS

The Westinghouse sodium-heated steam generator concept has been described elsewhere.^[4] Briefly, the units employed here comprise six separate serpentine tube bank modules resting in a vertical cylindrical shell with hemispherical heads. Six hemispherical inlet feedwater headers are arranged on the bottom head periphery and the six steam discharge headers are near the top of the unit shell.

The reheater is of the same general construction as the steam generator, but uses different tube sizes and materials. Table 8 presents a tabulation of the principal parameters.

The reheat concept is a modification of the base scheme which does not affect the primary system or the reactor containment building.

The secondary loops are modified by extending the steam generator bay an additional 30 feet to accommodate the separate reheaters and the somewhat smaller steam generators.

The reheater and steam generator in each sodium loop are piped in parallel with a flow control valve in the reheater flow path to adjust the flow ratio and thus control reheat temperature. The total sodium flow rate in the secondary loop is 92 million pounds-per-hour as in the base scheme and therefore the sodium pumps and intermediate heat exchangers (IHX's) are unchanged.

The addition of the reheater does increase the sodium inventory slightly and the estimates reflect this increase in both initial sodium charge and storage requirement. All other sodium auxiliary systems are unaffected.

TABLE 8

SODIUM-HEATED STEAM GENERATOR AND REHEATER PARAMETERS

<u>General</u>	<u>Base Plant</u> <u>Steam Generator</u>	<u>Reheat Plant</u> <u>Steam Generator</u>	<u>Reheater</u>
Number of Units	2	2	2
Unit Type	Once-through, Counter-Flow, shell and tube type		
Unit Rating (MWt)	1300	1100	200
Dry Weight (lb)	600,000	540,000	420,000
Overall Length (ft)	65.0	64.5	53.0
Distance between Shell Nozzles (ft)	44.3	44.1	32.3
Overall Diameter (ft)	15.0	14.58	15.0
<u>Shell Side</u>			
Fluid	Sodium	Sodium	Sodium
Flow Rate (10^6 lb/hr)	46.0	38.2	7.8
Inlet Temperature (°F)	965	965	965
Outlet Temperature (°F)	650	650	650
Design Temperature (°F)	1000	1000	1000
Inlet Pressure (psia)	32.3	32.3	39.3
Design Pressure (psi)	200	200	200
Flow Pressure Drop (psi)	15.0	11.0	11.0
Shell Hold-up (ft ³)	7800	5500	5700
Shell Inlet Nozzle Diameter (2)(in)	30	26	14
Shell Outlet Nozzle Diameter (2)(in)	30	26	14
Material	304 SS	304 SS	304 SS

TABLE 8 (Cont)

SODIUM-HEATED STEAM GENERATOR AND REHEATER PARAMETERS

<u>Tube Side</u>	<u>Base Plant</u> <u>Steam Generator</u>	<u>Reheat Plant</u> <u>Steam Generator</u>	<u>Reheater</u>
Fluid	Water/Steam		Steam
Flow Rate (10^6 lb/hr)	4.91	3.27	3.69
Inlet Temperature (°F)	500	500	596
Outlet Temperature (°F)	903	903	900
Design Temperature (°F)	1000	1000	1000
Inlet Pressure (psia)	2660	2660	685
Design Pressure (psi)	3000	3000	800
Flow Pressure Drop (psi)	225	225	30
<u>General</u>			
Number of Tubes	3600	3240	2100
Effective Tube Outside Surface (ft ²)	58,500	53,000	39,000
Tube Outside Diameter (in)	0.50	0.50	1.00
Tube Wall Thickness (in-min)	0.065	0.065	0.042
Square Pitch (in)	1.00	1.00	1.375
Effective Tube Length (ft)	124	125	71
Tube Side Hold-up (ft ³)	480	450	1015
Tube Inlet Nozzle Diameter (6)(in)	8	6	16
Tube Outlet Nozzle Diameter (6)(in)	12	10	16
Material	Incoloy 800	Incoloy 800	304 SS

SECTION 6

PLANT CAPITAL PRICE

The preliminary design and plant capital cost is based upon the Middletown site. The AEC Guide to Nuclear Power Cost Evaluation^[3] is used where practical. U-E performed the plant construction design and costs. WHTD performed the design and estimated the price of the steam generators, reheaters, condensers and feedwater heaters. WLTD performed the heat balance and supplied book prices for the turbine-generator units.

Estimated turbine plant costs are based principally upon data developed by U-E for the 1966 study^[5] performed for Argonne National Laboratory adjusted to the October 1, 1967 price level. Also, data has been adjusted for the specific machines and cycle arrangements presented on the Westinghouse heat balance diagrams and machine outline drawings. A cross-compound, four-flow with 44-inch, low pressure, last-row blading (CC4F-44) reheat machine with steam conditions of 2415 psia 900/900°F was compared to a tandem-compound, four-flow with 44-inch, low-pressure, last-row blading (TC4F-44) non-reheat machine with steam conditions of 2415 psia 900°F. Both cycles contemplate steam driven boiler feed pumps. Accordingly, U-E have re-estimated the turbine plant buildings to reflect the permissible shortening of the turbine hall associated with the elimination of the shaft driven pumps.

Subsequent to 1966, U-E's position concerning condensate polishing for installation using fresh water for condenser cooling has been revised. They are now recommending the use of POWDEX systems only, rather than precoated filters plus deep bed demineralizers. Cost of service facilities and condensate polishing systems have been adjusted to reflect this change in the basic design concept. The costs are specific for the condensate flows presented on the Westinghouse heat balances.

Cost of main feed pumps reflects actual bid prices received by U-E for identical discharge pressure requirements that have been adjusted to meet Westinghouse boiler feed pump flow requirements.

Condenser erection labor and circulation water piping systems screen well structure and associated equipment were estimated for the condensers.

Turbine plant piping estimate was reviewed not only from the viewpoint of the heat balances requirement but also was updated to reflect U-E's latest estimate of piping associated with moisture separators and low-pressure turbine intercept valve requirements. In the latter category, U-E now include safety valve vent piping and a major drains system associated with the moisture separators.

The erection labor cost estimate for the closed heater reflects the elimination of a deaerator from the cycle and the inclusion of seven heaters.

Costs for accessory electrical equipment have been adjusted to reflect specific motor loads anticipated for the primary and secondary system sodium pumps. For this equipment, U-E have used handbook prices to develop estimated cost.

All erection labor has been estimated by U-E at present day rates for a Western Massachusetts site.

The above estimates give direct cost of major buildings, equipment and systems affected by going from moisture separation plants to reheat. To allow for contingency, administration, engineering, etc. an adder of 45 percent was used for the reactor plant and 35 percent for the turbine plant. These costs and prices are presented in Table 9.

TABLE 9
CAPITAL ITEMS AFFECTED BY MOISTURE SEPARATION
OR SODIUM REHEAT CYCLES*
SUMMARY

Acct. No.	Description	Moisture Separation	Sodium Reheat
219	Reactor Containment Structure	7,315	7,570
221	Reactor Equipment	659	665
222	Heat Transfer Systems	18,834	24,745
225	Radioactive Waste Treatment	<u>9</u>	<u>12</u>
	Total Direct Reactor Plant Cost	26,817	32,992
	Indirect Reactor Plant Cost	<u>12,068</u>	<u>14,846</u>
	Estimated Reactor Plant Price (Items Affected)	38,885	47,838
212A	Turbine Building	3,379	3,181
227	Feedwater Supply and Treatment	4,236	3,685
231	Turbine Generator Plant	32,502	31,034
241	Generator Main & Neutral Circuit	298	357
251	Turbine Room Crane	<u>268</u>	<u>240</u>
	Total Direct Turbine Plant Cost	40,710	38,497
	Indirect Turbine Plant Cost	<u>14,248</u>	<u>13,474</u>
	Estimated Turbine Plant Price (Items Affected)	54,958	51,971
	Total Plant Price (Items Affected)	93,843	99,809
	Differential	Base	5,966

*Cost and prices in thousands of dollars.

TABLE 9 (Cont)

CAPITAL ITEMS AFFECTED BY MOISTURE SEPARATION OR SODIUM REHEAT CYCLES

Acct. No.	Description	Moisture Separation	Sodium Reheat
219	Reactor Containment Structure		
	Excavation	208	236
	Substructure Concrete	1216	1280
	Substructure Reinf. Steel	1555	1612
	Substructure Insulating Concrete	86	96
	Superstructure Concrete	600	600
	Superstructure Reinf. Steel	767	767
	Superstructure Struc. Steel	135	157
	Siding and Roofing	194	228
	Liner Plate	<u>2554</u>	<u>2594</u>
	219 Total	7315	7570
221	Reactor Equipment		
	Reactor Shielding		
	Shield Cooling System	134	140
	Reactor Plant Cranes		
	Reactor Bldg. Crane	245	245
	Pump Bay Crane	90	90
	Maintenance Cell Inside	60	60
	Outside	<u>130</u>	<u>130</u>
	221 Total	659	665

TABLE 9 (Cont)

CAPITAL ITEMS AFFECTED BY MOISTURE SEPARATION OR SODIUM REHEAT CYCLES

Acct. No.	Description	Moisture Separation	Sodium Reheat
222	Heat Transfer Systems		
	Reactor Coolant System		
	Primary Pumps	2950	2950
	Heat Wrap	24	24
	Insulation	10	10
	Pipe	307	307
	Insulation	67	67
	Heat Wrap	28	28
	Intermediate Cooling System		
	Secondary Pumps	1815	1815
	Heat Wrap	19	19
	Insulation	8	8
	Piping and Valves		
	Pipe	264	320
	Valves	249	353
	Insulation	65	89
	Heat Wrap	27	37
	Intermediate Heat Exchanger		
	IHX	3875	3875
	Heat Wrap	13	13
	Insulation	31	31
	Steam Generators		
	Steam Generators	8401	7739
	Heat Wrap	22	21
	Insulation	52	50
	Reheaters		
	Reheaters	---	6025
	Heat Wrap	---	18
	Insulation	---	42

TABLE 9 (Cont)

CAPITAL ITEMS, AFFECTED BY MOISTURE SEPARATION OR SODIUM REHEAT CYCLES

Acct. No	Description	Moisture Separation	Sodium Reheat
222 (Cont)	Heat Transfer Systems		
	Primary and Intermediate Coolant		
	Coolant Receiving and Storage	Base	100
	Primary Coolant	342	342
	Secondary Coolant	<u>265</u>	<u>462</u>
	222 Total	18,834	24,745
225	Radioactive Waste Treatment		
	Primary Drain and Vent System	9	9
	Intermediate Drain and Vent System	<u>Base</u>	<u>3</u>
	225 Total	9	12
212A	Turbine Building		
	Substructure	551	514
	Superstructure	2115	1972
	Service Facilities	<u>713</u>	<u>695</u>
	212A Total	3379	3181
227	Feedwater Supply and Treatment		
	Condensate Polishing System	535	497
	Feedwater Heaters		
	Closed Heaters	1829	1589
	Insulation	78	75
	Feedwater Pumps and Drives		
	Pumps	639	550
	Drives	<u>1182</u>	<u>974</u>
	227 Total	4263	3685

TABLE 9 (Cont)

CAPITAL ITEMS AFFECTED BY MOISTURE SEPARATION OR SODIUM REHEAT CYCLES

Acct. No.	Description	Moisture Separation	Sodium Reheat
231	Turbine Generator Plant		
	Generator Foundation		
	Concrete Fnd., Mat & Piles	220	242
	Support above Fnd. Mat.	507	578
	Turbine Generators		
	Turbogenerators	25,014	23,904
	Lube-Oil Equipment	80	87
	Condensers	2391	2359
	Turbine Plant Piping		
	Main Reheat & Extra Steam	1378	1523
	Condensate & Feedwater	1762	1490
	Cooling Water, etc.	782	578
	Service Water, etc.	<u>368</u>	<u>273</u>
	231 Total	32,502	31,034
241	Generator Main & Neutral Cir.		
	Isolated Phase Bus	298	357
251	Turbine Room Crane	268	240

SECTION 7

EVALUATION OF CYCLES

7.1 TECHNICAL FACTORS

There is a combination of technical and economic factors to consider in evaluating the reheat and moisture separation cycle. A reheat plant is basically more complex; therefore, the only valid reason for going to additional complications is for a resulting lower power cost. The reheat plant has a higher efficiency than the moisture separation plant; therefore, a smaller reactor plant is required to generate the same amount of power with reheat.

Some complicating features in the reheat plant were not economically evaluated in the study. These are:

- a. Reduced plant reliability due to reheaters and flow control valves
- b. More elaborate plant start-up system and procedure
- c. More complicated plant control system
- d. Additional reheater development work
- e. Additional maintenance due to reheaters and flow control valves

Apart from the above points, operation of both the reheat plant and moisture separation plant are the same.

7.2 ECONOMIC FACTORS

7.2.1 Capital Price

The scope of the study in Task I was such that the capital price of the complete plant was not priced. Only those items were priced which vary with the concept. The designs were based on the same reactor plant output of 2600-MWt; therefore the two cycles had a different net electrical output. This amounted to 1045-MWe for the moisture separation plant and 1072-MWe for the reheat plant.

To determine the power cost difference due to capital costs of the two plants (reheat minus moisture separation), the following expression was derived:

$$\Delta f_p = \left(\frac{0.13}{7} \right) \left\{ m \left[\left(\frac{H_r}{H_r + \Delta H} \right)^\eta - 1 \right] + \left(\frac{H_r}{8874} \right)^\eta R \right\} \quad (1)$$

where:

Δf_p = the differential power cost due to capital costs (reheat minus moisture separation) (mill/kWh)

m = the unit capital price of the moisture separation plant (\$/kW) exclusive of customer costs

H_r = the net plant heat rate of the reheat plant (Btu/kWh)

$H_r + \Delta H$ = the net plant heat rate of the moisture separation plant (Btu/kWh)

R = the additional cost of the Reheat plant over the Moisture Separation plant (\$10⁶)

η = size-price relationship exponent

In the above equation, a plant annual operating factor of 80 percent (7,000 hours per year) was assumed, together with an annual capital charge of 13 percent. Since m and n were not known, nor are they likely to be known very soon, a wide range of values was assumed -

120 - 160 \$/kW for m and 0.60 to 0.80 for n

The differential power cost due to capital are shown in Table 10 with the corresponding values of m and n .

The actual differential heat rate between the two plants is not great. This makes the moisture separation cycle a worthwhile possibility, since unit plant capital cost (\$/kW) is directly proportional to heat rate. An investigation of the heat rate effect on the differential power cost was also made. Table 10 shows the differential power cost due to capital if the net heat rate was 8874 Btu/kWh ($\Delta H = 593$). It must be emphasized that the turbine cycle heat rates are quite accurate. As a matter of fact, it would be possible to order the turbine-generator and heat transfer equipment from Westinghouse now, with performance as stated in the report.

TABLE 10
DIFFERENTIAL POWER COSTS DUE TO CAPITAL REHEAT
MINUS MOISTURE SEPARATION, Δf_p

Capital Price m (\$/kW)	Size-Price Exponent η	Δf_p mill/kWh ($\Delta H = 209$)	Δf_p (mill/kWh) (if $\Delta H = 593$)
120	0.60	0.075	+0.0175
	0.70	0.068	+0.0020
	0.80	0.062	-0.0135
140	0.60	0.069	+0.0020
	0.70	0.062	-0.0156
	0.80	0.055	-0.00336
160	0.60	0.064	-0.0132
	0.70	0.055	-0.0332
	0.80	0.047	-0.0535

$$H_r = 8281 \text{ Btu/kWh}; R = 6.1 (\$10^6)$$

7.2.2 Fuel Cost

Fuel cycle costs have not been established for this plant; moreover, there is a possibility for fuel cycle cost improvement. Thus it was decided to examine the effect of power costs due to fuel over a range of 7 to 16 cents per million Btu. This corresponds to a fuel cost range of about 0.6 to 1.4 mill/kWh which is approximately the range of expected fuel costs.

Let Δf_m be the differential power cost due to fuel (mill/kWh)

f_ϕ be the fuel cost ($\phi/10^6$ Btu)

ΔH be the differential plant net heat rate (Btu/kWh)

Then,

$$\Delta f_m = f_\phi \times 10^{-5} \Delta H$$

Table 11 gives the differential power cost due to fuel with a differential heat rate of 209 Btu/kWh, as actually computed for the two detailed heat balances of this study. The differential power cost if the heat rate difference were 593 Btu/kWh (an arbitrary difference) is also shown in Table 11.

TABLE 11
DIFFERENTIAL POWER COST DUE TO FUEL*

f_ϕ (¢/10 ⁶ Btu)	Δf_m (mill/kWh) $\Delta H = 209$ Btu/kWh	Δf_m (mill/kWh) $\Delta H = 593$ Btu/kWh
7	-0.015	-0.041
10	-0.021	-0.059
13	-0.027	-0.077
16	-0.033	-0.095

*Cost values shown are for reheat minus moisture separation

7.2.3 Combined Differential Power Cost Due to Capital and Fuel

In Table 12, the differential power cost due to capital and fuel is combined for a range of moisture separation plant capital price m , size exponents n , and fuel costs f_ϕ . The envelope of differential power costs plotted in Figure 24 shows the extreme values for the variables as discussed herein.

Figure 25 plots the envelope of differential power costs with varying differential heat rate.

Figure 24. Differential Power Cost Envelope for Sodium Reheat - Moisture Separation

* η = SIZE-PRICE RELATIONSHIP EXPONENT

Figure 25. Differential Power Cost Envelope for Sodium Reheat-Moisture Separation as a Function of Δ Heat Rate

TABLE 12

DIFFERENTIAL POWER COST FOR REHEAT-MOISTURE SEPARATION PLANT

m (\$/kW)	η	f_c	Δf_p	Δf_m	Δ Power Cost (mill/kWh)
120	0.60	7	0.075	-0.015	0.060
		10	0.075	-0.021	0.054
		13	0.075	-0.027	0.048
		16	0.075	-0.033	0.042
120	0.70	7	0.068	-0.015	0.053
		10	0.068	-0.021	0.047
		13	0.068	-0.027	0.041
		16	0.068	-0.033	0.035
160	0.70	7	0.055	-0.015	0.040
		10	0.055	-0.021	0.034
		13	0.055	-0.027	0.028
		16	0.055	-0.033	0.022
160	0.80	7	0.047	-0.015	0.032
		10	0.047	-0.021	0.026
		13	0.047	-0.027	0.020
		16	0.047	-0.033	0.014

$$H_r = 8281 \text{ Btu/kWh}; \Delta H = 209 \text{ Btu/kWh}; R = 6.1 (\$10^6)$$

7.2.4 Value of 1 Btu/kWh

In comparing plant economics it is sometimes useful to know the value of a 1 Btu/kWh heat rate change in terms of equivalent capital. If the capital cost range varies from \$120 to \$160/kWh and the fuel cost range varies from 7 to 16 cents per million Btu, then 1 Btu/kWh heat rate change is worth from \$12,000 to \$24,000 capital for a 1000 MWe net plant.

REFERENCES

1. K. A. Hub, I. M. Keyfitz, et al., Feasibility Study of Nuclear Steam Supply Using 10,000 Mwt Sodium-Cooled Breeder Reactor, ANL 7183, September 1966.
2. H. B. Holz, et al., 1000 MWe FBR Parametric Study of Secondary Sodium-Steam System, NAA-SR-12060.
3. Guide to Nuclear Power Cost Evaluation, TID-7025, March 15, 1962.
4. I. M. Keyfitz, Steam Generator Concept Selection, WARD-22, to be published.
5. Engineering Study for Large Steam-Electric Generating Units and Sodium-Heated Steam Generating Islands, United Engineers and Constructors, May 1966.