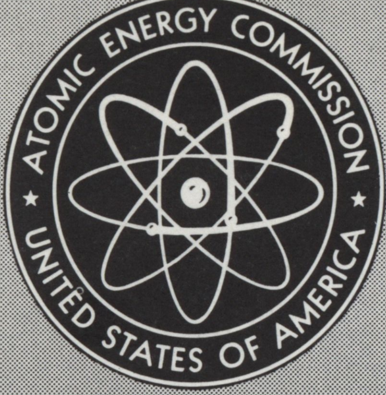

CEND-150(Pt. IV)

ADVANCED INDIRECT CYCLE WATER REACTOR STUDIES FOR MARITIME APPLICATIONS

Part IV. Steam Driven Coolant Pumps

October 23, 1961

Nuclear Division
Combustion Engineering, Inc.
Windsor, Connecticut

UNITED STATES ATOMIC ENERGY COMMISSION • DIVISION OF TECHNICAL INFORMATION

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CEND 150, Part IV
REACTOR TECHNOLOGY

ADVANCED INDIRECT CYCLE WATER REACTOR STUDIES FOR MARITIME APPLICATIONS

PART IV

STEAM DRIVEN COOLANT PUMPS

OCTOBER 23, 1961
CONTRACT AT(30-1)-2709
U.S. ATOMIC ENERGY COMMISSION

COMBUSTION ENGINEERING, INC.
NUCLEAR DIVISION
WINDSOR, CONNECTICUT

FOREWORD

This is the final report of a study directed toward the evolution, design, and demonstration of the principle design features of interim indirect cycle water cooled and moderated nuclear power plants which will be useful in early cooperative programs between the AEC and the U.S. Maritime industry. The basic design involved is generally similar to that proposed by Combustion Engineering, Inc., in Report NYO-2860 (CEND-62). This plant, which was capable of developing 30,000 shaft horsepower for tanker service, has been updated by the inclusion of recent technological developments such as self-pressurization and consolidation of auxiliary service equipment. Emphasis was placed on ideas which permit reduction of costs, simplification of control and mechanical systems, and minimum crew attention requirements during operation.

The studies included the development of the conceptual design of the reference plant for two different operating pressure ranges. A concept of a more advanced minimum attention plant which could logically evolve from the reference plant was developed. In addition, studies were made of several plant features which are significant to the present or future improvements.

The report consists of six parts which are titled as follows:

Part I - Cost Analysis and Future Development

Part II - Plant Conceptual Studies

Part III - Analog Simulation of Reactor Plant Transients

Part IV - Steam Driven Coolant Pumps

Part V - Spiked Core Concept

Part VI - Natural Circulation Capabilities

The work was conducted in compliance with U.S. Atomic Energy Commission Contract AT(30-1)-2709.

ABSTRACT

A comparison is made of the relative merits of steam turbines and electric motors as drivers for maritime nuclear reactor coolant pumps. The comparison is made from both a technical viewpoint and an economic viewpoint. The two are almost equal from an economics standpoint with the turbines having a slight advantage for the particular application of the reference plant. There is a capital cost advantage to the steam driven pumps; but, because of the low efficiency of small turbines, the fuel costs are higher. The designer might select turbine drivers for a specific application for the purpose of adding reliability and flexibility to the operation of the plant. This might be done where non-propulsion steam demand of the plant was appreciable such as process heat for refrigeration or special heating loads. The turbine drives also add a safety feature to coolant circulation startup by permitting, without adding special features, a gradual increase in flow rate rather than a sudden one.

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A. INTRODUCTION AND SUMMARY

In the study of a nuclear reactor powered tanker, as reported in NYO-2860, electric motors were used as reactor coolant main circulating pumps. The successful use of steam turbines in other pump applications suggested the possibility that steam turbines might have advantages over electric motors as pump drivers for nuclear powered ships. The possible decreases in capital costs and increases in operating reliability, combined with the increased operating flexibility possible with variable speed pump drivers, provide incentive to study the use of steam turbines. Therefore, this study was undertaken with the objective of evaluating the relative merits of steam turbines and electric motors as nuclear reactor coolant circulating pump drivers. Cycle arrangement, equipment layout, capital costs, operating costs, operating procedures, and plant reliability for ships with both types of drivers are evaluated. Comparisons are made using the self-pressurized nuclear reactor tanker, as reported in Part II, as a reference design.

The results of this study show that the use of steam turbines instead of electric motors as reactor coolant pump drivers will reduce the capital costs and increase the fuel costs of nuclear powered ships. The results of cost studies for this particular plant show that the capital costs saved by turbine drivers when amortized amount to $4,400 per year. The reduction of capital costs is primarily due to savings in electric generating equipment costs. The cost studies also show that the fuel cost is increased by $3,600 per year for an east coast to Persian Gulf trip with the reference plant. The increase in fuel costs is primarily due to the pump turbine inefficiency which makes the net plant thermal efficiency of a ship with turbine driven pumps less than that of a ship with motor driven pumps. Therefore, for this particular combination of circumstances, the steam turbine driven pumps show a net annual saving of $800.

Aside from the relatively small gain in costs, there are technical features that make turbine driven pumps attractive to the plant. They add to the reliability of the plant since they would not be affected in the event of a failure of the ship's electric power system. The ability to vary the speed of the turbines adds to the flexibility of plant operation and allows slow pump start-up to avoid cold water surges into the reactor.

B. TURBINE APPLICATION

Before a comparison of turbines and motors is possible, the selection of a suitable cycle arrangement and turbine type must be made. The sources of turbine inlet steam and the uses for exhaust steam which are available in the ship's propulsion plant limit the possible cycle arrangements and are discussed first. The selection of a suitable type of turbine is considered next. Finally, the effect that pump turbines have on plant cycle efficiency is evaluated.

1. Inlet and Exhaust Conditions

The superheater main steam header is the best source of steam for the pump turbines in the reference design. This source is selected because it provides the best steam conditions and requires the least amount of piping. Since the pump turbine efficiency is a function of inlet steam pressure and temperature, the use of this steam with the highest pressure and the highest superheat available gives the best pump turbine efficiency. Fewer containment vessel penetrations and less piping are required with this arrangement than with any other because both the superheater and the pump turbines are located within the reactor containment vessel.

Four possible uses for the pump turbine exhaust steam were considered. These uses are the main propulsion low pressure turbine, the turbine-generators, the deaerating feedwater heater, and the main condenser. Admission of the exhaust steam to the low pressure main propulsion turbine, with provision for bypassing exhaust steam to the condenser at low propulsion loads, is the arrangement selected for the reference design. This arrangement requires a minimum of controls and piping and permits the use of commercially standard equipment.

As an alternate choice, the steam from the pump turbine exhaust could be used to drive the turbine-generators. To do this, the pump turbine exhaust steam flow must equal or slightly exceed the turbine-generator inlet flow. These flows are balanced by the proper selection of the inter-turbine pressure, which is the pressure between the pump turbine exhaust and the turbine-generator inlet. As shown in Figure IV-1, Steam Flow vs. Inter-Turbine Pressure, the pump turbine flow increases with increasing exhaust pressure while the turbine generator flow decreases with increasing inlet pressure and the flows are balanced at only one pressure. Varying the pump output relative to turbine-generator output or the turbine efficiencies can change the pressure at which the flows balance. In the reference plant, a 200 psia inter-turbine pressure would be required to balance flows. In addition, a valve to maintain constant inter-turbine pressure by venting steam, possibly to the deaerating heater, would be required for conditions when the turbine-generator steam flow is less than pump turbine flow. This arrangement will also require more expensive equipment than the reference design. The pump turbines will have a high exhaust pressure and each will cost up to $6000 more than the reference design turbines which have low exhaust pressures. Most turbine vendors quote an additional cost if an exhaust pressure above 75 psig is required. If a pressure less than 200 psia is selected, thereby decreasing the cost of pump turbines, a special turbine-generator which is not a standard design will be required.

Use of the exahust steam in the deaerating feedwater heater is also possible. For the reference plant at normal propulsion power, the pump turbine exhaust flow and the deaerating heater requirements are approximately equal. At reduced loads, steam would have to be vented to the condenser. The pump turbine flow does not vary in direct proportion with propulsion load and would exceed the feedwater heating requirements as the feedwater flow decreased with decreasing load.

The last possibility, exhausting to the main condenser, would result in lower over-all plant efficiency because of the low efficiency of single stage condensing turbines.

2. Turbine Selection

The selection of the type of turbine driver is based on the relative cost, efficiency, and ease of installation of available machines. Only commercially available turbines were considered since a special turbine, developed specifically for this application, would be expensive. A single stage turbine is the most suitable because its cost and weight are less than a multiple stage machine.

A vertical unit is selected. This type unit requires the least complex mounting since it is compatible with the vertical reactor coolant pumps and can be supported by the reactor coolant piping. A horizontal unit would require either a horizontal pump or a complex gear train. The use of a horizontal pump would require development to design high pressure seals for a horizontal shaft. If the turbine and pump are not supported by the piping, they will act as anchors, limit pipe expansion, and increase pipe stresses.

The majority of pumps suitable for service as main coolant pumps and presently offered by manufacturers are designed for either 1200 or 1800 rpm operation. To match the available pumps, the turbine selected for the reference design has an 1800 rpm output shaft. Since an 1800 rpm turbine has a very low efficiency, as shown by the heat balance presented in the Appendix, a 3600 rpm geared unit is used for this study. The variation in turbine efficiency with speed is shown in Figure IV-2, Variation in Turbine Efficiency with Speed. Higher speed turbines with improved efficiencies are available and their use may be justified. However, the selection of a 3600 rpm geared turbine gives a conservative comparison with motors. A gain in efficiency and reduction in cost of both gear and pump may be made if 3600 rpm pumps become available.

As a result of these considerations, the turbine selected for comparison with a motor is a vertical, single stage 3600/1800 rpm geared unit with 600 psig, 600 F steam inlet conditions and exhaust to the low pressure propulsion turbine at 30 psig.

3. Cycle Efficiency

In the case of the reference plant, the substitution of steam turbines for motors as pump drivers will reduce the over-all plant efficiency. This is due to two effects. The first effect is caused by the fact that the efficiency of the pump turbine in converting the available energy into work is less than the combined turbine-generator and pump motor efficiency. By using a more expensive, higher speed pump turbine with higher superheat steam and more refined design, the pump turbine efficiency could be increased enough to equal or exceed the turbo-generator and motor efficiency.

The second effect occurs because the low pressure propulsion turbine engine efficiency is less than the high pressure propulsion turbine engine efficiency. Exhausting the pump turbine steam flow to the low pressure turbine increases the fraction of the total propulsion power produced by this low pressure section. The total power produced remains constant, but the power produced by the machine operating at a lower efficiency increases and the power produced by the machine operating at a higher efficiency decreases. The net effect is to decrease the over-all turbine efficiency.

C. COSTS

The use of pump turbines instead of motors will decrease capital costs and increase fuel costs. The causes of these changes in costs are discussed in this section.

1. Capital Costs

The total direct and indirect capital costs of the reference plant with turbine pump drivers is approximately $44,400 less than the plant with motor drivers, as shown in Table IV-1, Ship's Component Capital Cost Comparison. Even though the cost of the turbines and gears is greater than the cost of motors, the cost of the smaller turbine-generators required when turbine drivers are used results in a net saving of $35,000 in direct costs.

Eliminating the electric load of the pumps makes possible the use of smaller and, therefore, less expensive turbine-generators and stand-by diesel-generator. With motor drivers, two 750 KW rated turbine-generators are required to meet the electrical load requirements and a 750 KW diesel-generator is required as a stand-by. Reducing the required plant electric output by substituting steam turbine permits the use of two 600 KW turbine-generators and one 600 KW diesel-generator. Additional savings in indirect costs result in a total yearly saving of $4,400 based on 10 per cent per year capital cost amortization. The capital cost saving for other plants will be greater if the main coolant pumping power requirements are larger than for the reference plant. If pumps operating at greater than 1800 rpm become available, reduction of the size or elimination of the gear reducer can reduce capital costs further.

Additional capital cost savings are possible due to the less severe operating conditions required of pumps using turbine drivers. Forced circulation, water cooled nuclear reactor systems where subcooling is very small, such as the reference plant under low load conditions, have limited available net positive suction head (NPSH). For plants of this type, pump NPSH requirements must be met by proper provisions in the plant design. Available NPSH may be increased by increasing the elevation of the system's heat transfer equipment above the pumps to increase gravity head. Raising these components may require increasing the containment vessel height and, therefore, cost. Alternatively, pumps with low NPSH requirements and, therefore, large casings may be specified. The use of turbine pump drivers with inexpensive speed control allows the plant designer to specify pumps with higher NPSH requirements at design flow than if constant speed motor drivers are used. The low NPSH requirements at low loads can then be met by reducing pump speed to reduce coolant flow and the NPSH required. The motor driven pumps for the reference plant would have to operate with a minimum of 25 feet of NPSH at design flow. The turbine driven pumps would have to operate with a minimum of 40 feet of NPSH. The smaller casing, due to the less severe NPSH requirements, might result in a cost saving of as much as $17,000 for each pump.

2. Fuel Costs

The yearly fuel costs of the reference plant with turbine pumps is approximately $3,600 greater than the plant with motor driven pumps, as shown in Table IV-2, Ship's Fuel Cost Comparison. The higher reactor output and, therefore, the higher fuel cost of the plant using turbines are due to the lower efficiency of the turbine driver as compared to the combined efficiencies of the turbine-generator and motors. Using turbine rather than motor driven pumps on ships with smaller main coolant pumping power requirements would result in smaller differences in fuel costs.

TABLE IV-1

SHIP'S COMPONENTS CAPITAL COST COMPARISON

Turbine vs. Motor Driven Main Coolant Pumps

Component	Capital Cost Turbine Driver	Capital Cost Motor Driver
Two turbines; each with gear, generator exciter, coolers, voltage regulator, and spares	$262,880	$279,600
Two auxiliary condensers, each with turbine support structure, air ejector, and spares	67,950	74,400
Two turbine pump drivers; single stage, 190 HP, 3600 rpm with 2:1 reduction gears and spares	23,220	-
Two motors; squirrel cage, 1800 rpm, 200 HP, 440 V, 3 phase with reduced voltage starters and spares	-	18,550
One diesel-generator set	66,000	82,500
Total Direct Cost	$420,050	$455,050
Escalation (6% of direct cost)	25,200	27,300
Contingency (2% of direct cost)	8,400	9,100
G&A (10% of direct cost)	42,000	45,500
Total Direct & Indirect Cost	$495,650	$536,950
Cost of Construction Funds (7.5%)	37,200	40,300
Total Capital Cost	$532,850	$577,250
Differential Cost		$44,400
Amortized Cost at 10% Per Year		$4,400

TABLE IV-2

SHIP'S FUEL COST COMPARISON

Turbine vs. Motor Driven Main Coolant Pumps

27,300 SHP, Normal Ship's Services

Item	Power	
	Turbine	Motor
Turbine Generator Output	900 KW	1170 KW
Reactor Output*	72.0 MW	71.6 MW
Differential Reactor Output	0.4 MW	-
	34.4×10^6 Btu/day	-
Diff. Fuel Cost at 30¢/Million Btu	$10.32/day	-
	$3600/year	-

*Reactor power is based on heat balances presented in the Appendix

D. EFFECT ON SHIP OPERATION

Substitution of turbines for motors as pump drivers will produce a number of improvements in plant operating characteristics. These improvements result in more reliable pump operation, more stable electrical generation, safer coolant circulation startup, and more flexible pump operation. The use of turbines will not save weight or space since the difference in size and weight is not appreciable.

The use of pump turbines makes the ship operation more reliable by eliminating the turbine-generators from the system which supplies power to the pumps. This decrease in the number of components in the pump power supply system reduces the number of possible causes of failure and increases the reliability of the pumps. Pump stoppages due to short circuits, turbine-generator malfunction or other electrical system component failures are eliminated.

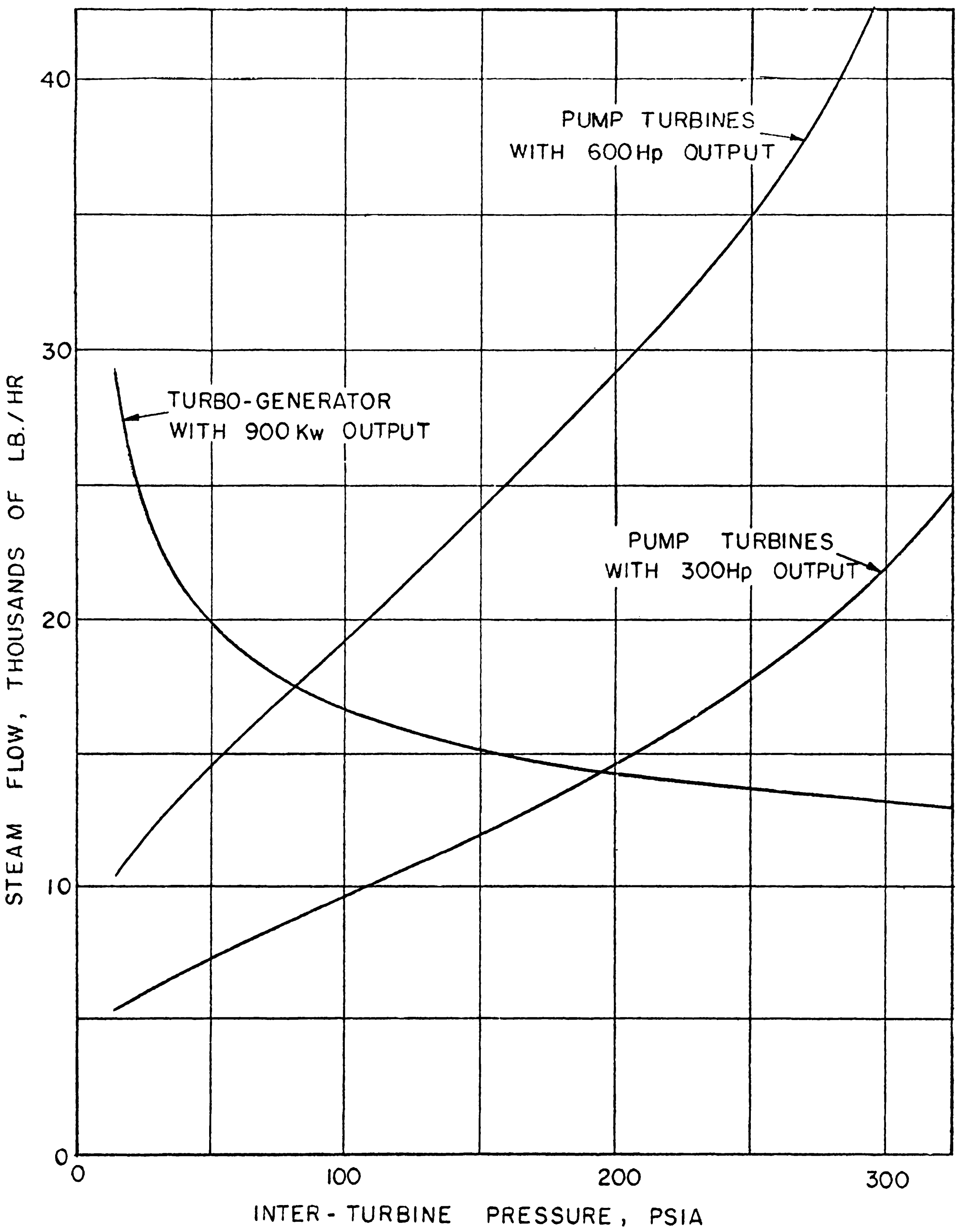
Pump motors, which use a large fraction of the turbine generator output, have a large effect on the electrical system. Sudden changes in power supplied to the motors due to startup, shutdown or malfunction would cause a large electrical disturbance in the ship's small distribution system. This disturbance might cause voltage and current transients large enough to affect the operation of other electrical equipment. Large variations in the supply voltage to the reactor instrumentation could initiate a reactor scram.

The use of turbines would make plant startup and operation safer. The variable speed control feature of turbines permits the pumps to be started slowly. This eliminates the sudden and large increase in power demand due to starting current surge of pump driver motors. Elimination of power demand transients makes startup of the reactor with natural circulation easier and safer. Controllable pump speed permits pump shutdown or startup without subjecting the reactor to the possibility of a cold water accident due to sudden large changes in coolant flow or coolant temperature. During periods of reduced plant output, one pump could be shut down and, thereby, improve the plant efficiency at low load.

E. CONCLUSIONS

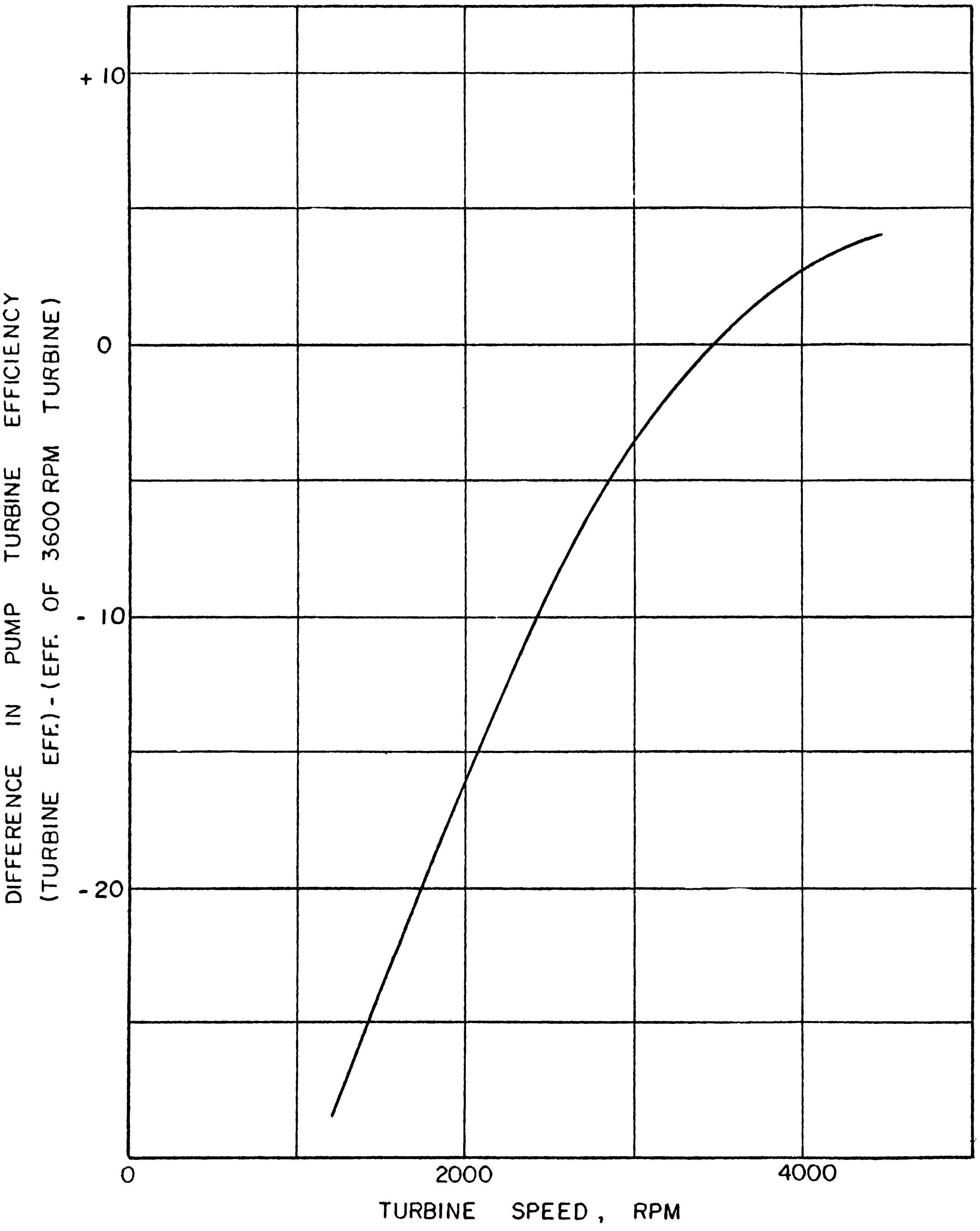
The savings in capital cost resulting from the use of turbine pump drivers are very nearly offset by the increase in fuel costs. Any changes in ships design which might affect equipment cost, fuel costs, or reactor coolant pumping power could easily reverse the situation and make the fuel cost increase due to the substitution of turbines greater than the possible capital cost savings.

The final decision on whether turbines are better pump drivers than motors will depend on the specific application. For the reference plant, the savings in capital costs and improvements in plant operation favor the use of turbine driven pumps.



STEAM FLOW VS INTER-TURBINE PRESSURE FOR 50% EFFICIENT PUMP TURBINES USING 600°FTT, 600 PSIG STEAM EXHAUSTING TO A 60% EFFICIENT TURBO-GENERATOR WITH A 1.75 IN. Hg ABS CONDENSER PRESSURE

FIG. IV-1

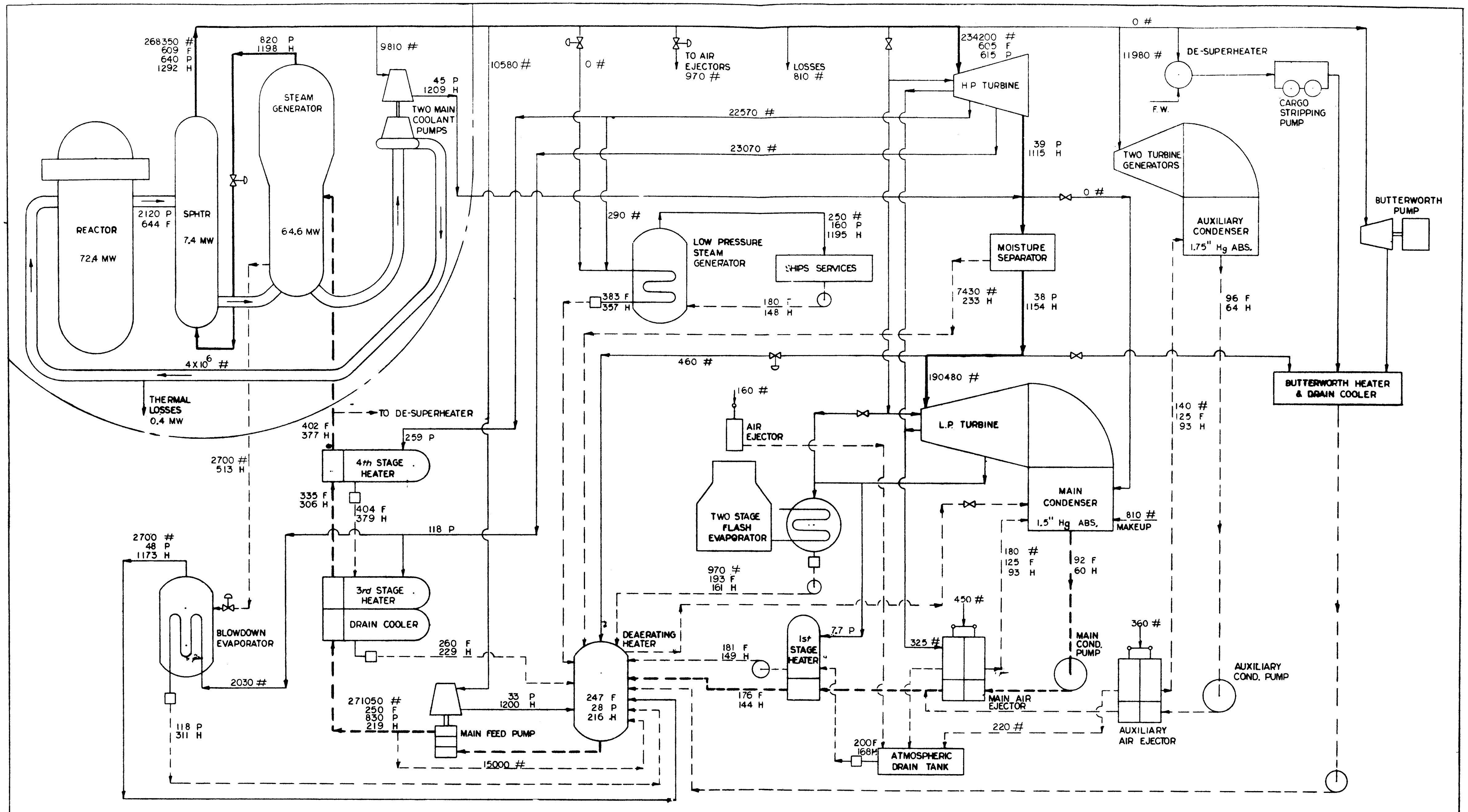


VARIATION IN TURBINE EFF. WITH SPEED
SINGLE STAGE; 600°F TT, 600 PSIG INLET, 30 PSIG EXHAUST

FIG. IV-2

PART IV

APPENDIX A



LEGEND

#	FLOW	LB/HR	──── STEAM LINE
P	PRESSURE	PSIA	– – – WATER LINE
F	TEMPERATURE	°F	═══ REACTOR COOLANT
h,H	ENTHALPY	BTU/LB	

SHIP OUTPUTS

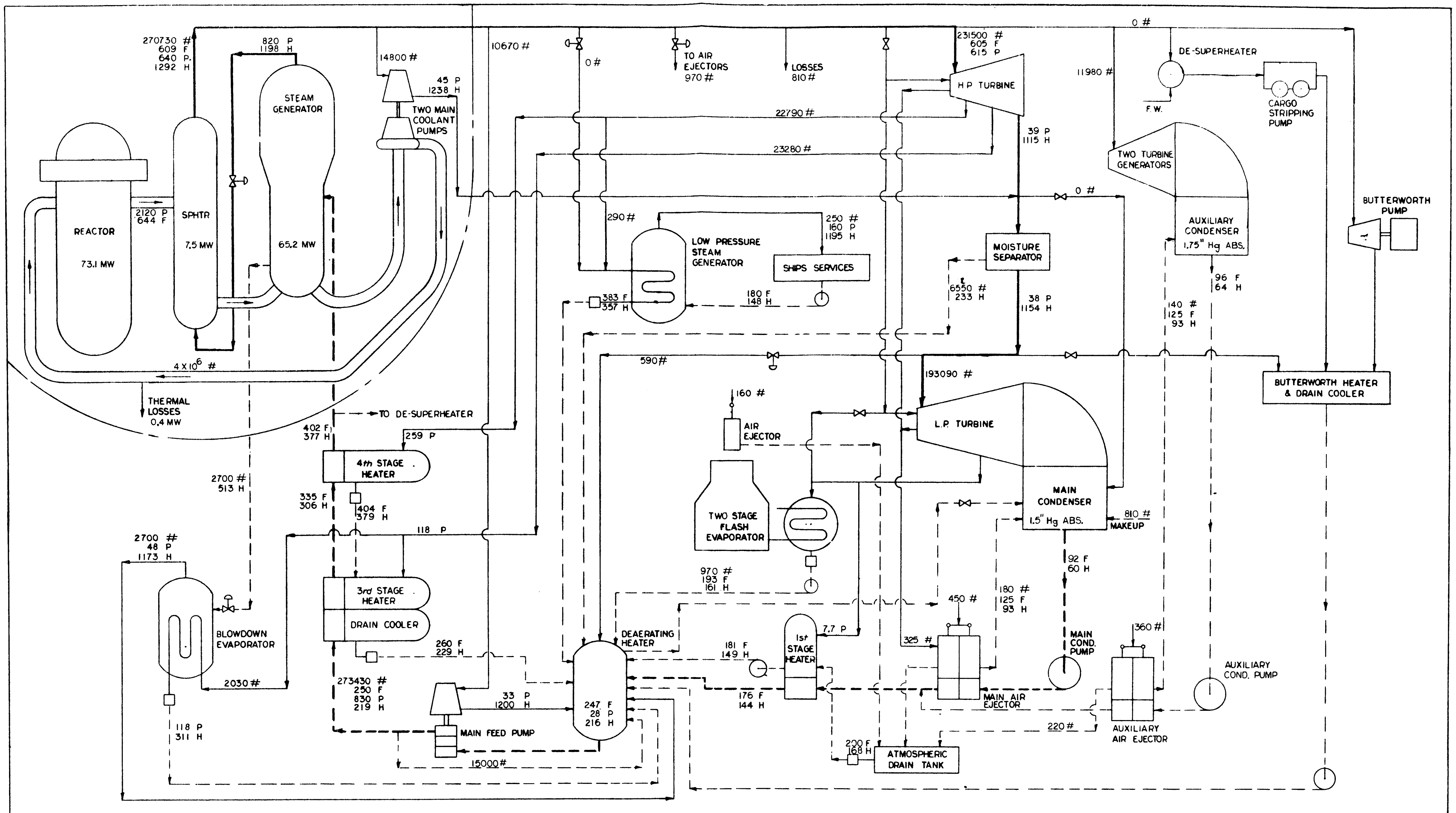
SHAFT-HORSEPOWER	27300	HP
TURBINE-GENERATOR LOAD	900	KW
EVAPORATOR LOAD	5000	GPD
LOW PRESSURE STEAM GENERATOR	250	LB/HR
BUTTERWORTH HEATER	0	BTU/HR

3600 RPM TURBINE – 1800 RPM PUMP

HEAT BALANCE DIAGRAM
TURBINE DRIVEN PUMPS

MARITIME REACTORS
DESIGN AND EVALUATION
United States Atomic Energy Commission
COMBUSTION ENGINEERING, INC.
JULY, 1961

Fig. A-1



LEGEND

#	*FLOW*	*LB/HR*	———	*STEAM LINE*
P	*PRESSURE*	*PSIA*	— — —	*WATER LINE*
F	*TEMPERATURE*	*°F*	═══	*REACTOR COOLANT*
h,H	*ENTHALPY*	*BTU/LB*		

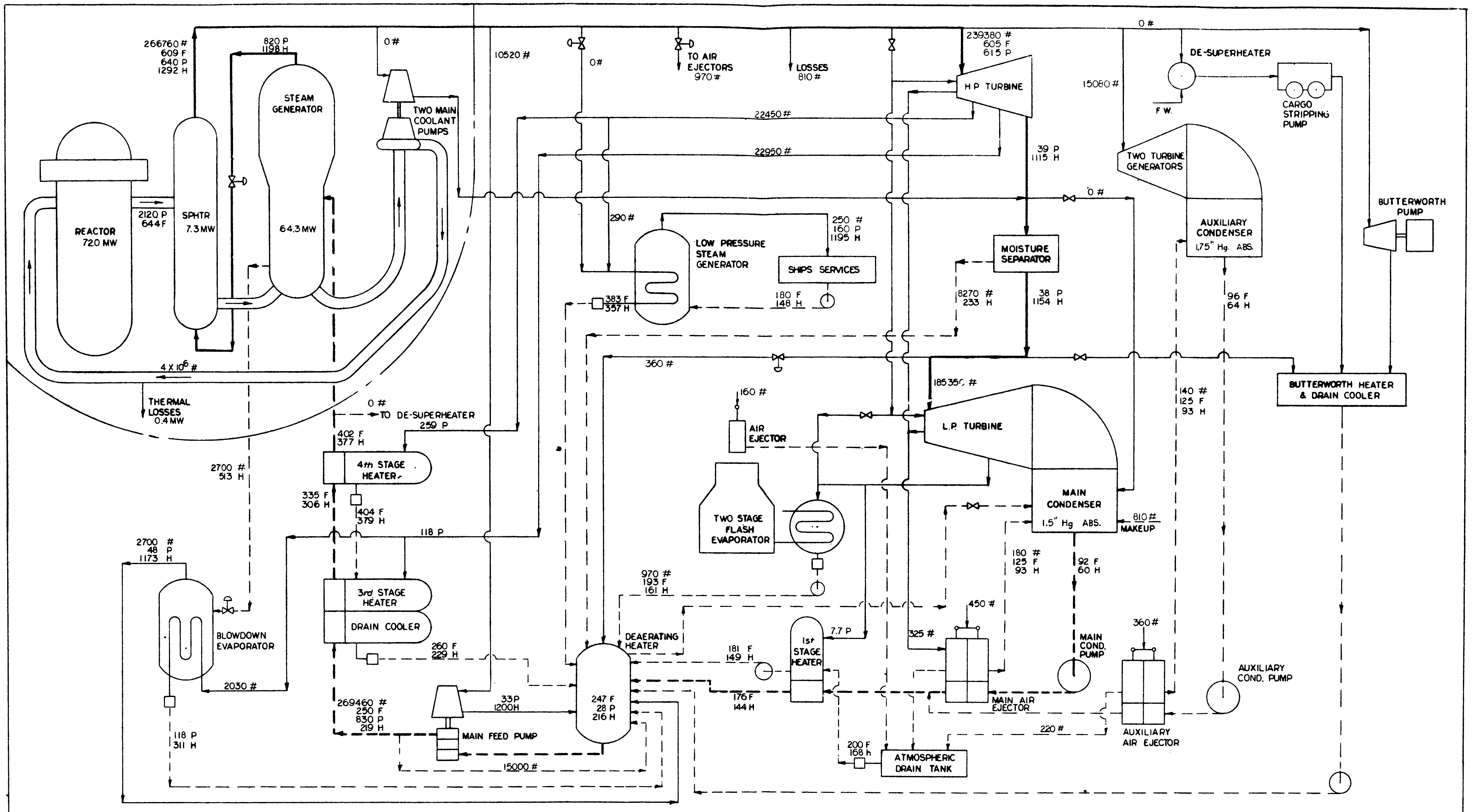
SHIP OUTPUTS

SHAFT HORSEPOWER	27300	HP
TURBINE-GENERATOR LOAD	900	KW
EVAPORATOR LOAD	5000	GPD
LOW PRESSURE STEAM GENERATOR	250	LB/HR
BUTTERWORTH HEATER	0	BTU/HR

1800 RPM TURBINE - 1800 RPM PUMP

HEAT BALANCE DIAGRAM
TURBINE DRIVEN PUMPS
MARITIME REACTORS
DESIGN AND EVALUATION
United States Atomic Energy Commission
COMBUSTION ENGINEERING, INC.
JULY, 1961

Fig. A-2



LEGEND

#	FLOW	LB/HR	———	STEAM LINE
P	PRESSURE	PSIA	— — —	WATER LINE
F	TEMPERATURE	°F	═══	REACTOR COOLANT
h,H	ENTHALPY	BTU/LB		

SHIP OUTPUTS

SHAFT HORSEPOWER	27300	HP
TURBINE-GENERATOR LOAD	1170	KW
EVAPORATOR LOAD	5000	GPD
LOW PRESSURE STEAM GENERATOR	250	LB/HR
BUTTERWORTH HEATER	0	BTU/HR

1800 RPM MOTOR–1800 RPM PUMP

HEAT BALANCE DIAGRAM
MOTOR DRIVEN PUMPS

MARITIME REACTORS
DESIGN AND EVALUATION
United States Atomic Energy Commission
COMBUSTION ENGINEERING, INC.
JULY, 1961

Fig. A-3