ANL-6178
Reactors - Power
(TID-4500, 15th Ed.)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

COST STUDY OF A 100-Mw(e) DIRECT-CYCLE BOILING WATER REACTOR PLANT

by

C. F. Bullinger and J. M. Harrer

Reactor Engineering Division

July, 1960

Operated by The University of Chicago
under
Contract W-31-109-eng-38

DISCLAIMER

TABLE OF CONTENTS

Page

I. INTRODUCTION 5

II. SUMMARY 9

- A. Plant Arrangement 9
- B. Power Conversion Cycle 17
- C. Design Characteristics 20
- D. Costs 24

III. COMPONENT DESCRIPTION 27

- A. Reactor Plant 27
  - 1. Containment Vessel 27
  - 2. Core 27
  - 3. Pressure Vessel 30
  - 4. Shielding 34
  - 5. Auxiliary Systems 36
    - a. Startup Heating 36
    - b. High-pressure Coolant Bypass Purification . . . 36
    - c. Shutdown Cooling 36
    - d. Shield Cooling 38
    - e. Chemical Poison Injection 38
    - f. Fuel Handling 38
    - g. Spent-fuel Storage Well Cooling 39
- B. Power Plant 39
  - 1. Turbine 39
  - 2. Condensing Equipment 40
  - 3. Condensate Filters 40
  - 4. Feed-water Heaters 41
  - 5. Reactor Feed-water Pumps 41
  - 6. Main Power Electrical Equipment 41
    - a. Generator 41
    - b. Generator Step-up Transformer 41
    - c. Switchyard 43

TABLE OF CONTENTS

Page

C. Plant Auxiliaries 43

1. Instrumentation and Control 43
2. Radioactive Waste Disposal System 45
3. Electrical Auxiliaries 45
4. Plant Utility Systems 46

IV. COST ESTIMATES 47

A. Plant 47
B. Fuel Cycle 60
C. Total Power Cost 63

APPENDIX A: Evaluation of Turbine Cycles 65

APPENDIX B: Full-flow Condensate Demineralization vs Full-flow Condensate Filtration Systems 75

APPENDIX C: High-pressure vs Low-pressure Reactor Water Bypass Purification System 77

APPENDIX D: Outdoor vs Indoor Emergency Water Storage Tank 80

APPENDIX E: Emergency Shutdown Cooler 82

APPENDIX F: Comparative Building Costs of Reactor Plant Arrangements 84

ACKNOWLEDGMENT 98

COST STUDY OF A 100-Mw(e) DIRECT-CYCLE BOILING WATER REACTOR PLANT

by

C. F. Bullinger and J. M. Harrer

I. INTRODUCTION

The study described in this report comprises a technical and economic evaluation of a type of nuclear reactor that holds promise of attaining competitive central station power costs: the direct-cycle, light water boiling reactor designed for natural circulation and internal steam-water separation.

The degree of development, and the advantage of simplicity of operation inherent in this type of reactor power plant has been demonstrated during three years of successful operation of the Experimental Boiling Water Reactor (EBWR) at power levels ranging from 20 Mw(t) (design), up to 60 Mw(t); conversion for operation at 100 Mw(t) is in progress.

The major effort of the study was to show how current boiling water reactor technology, combined with minor extrapolations from operating experience, could be applied toward reducing the costs associated with the design and construction of a boiling water reactor plant having a gross electrical output of 100 Mw.

The capital costs associated with the design and construction of such a plant are sensitive to many design parameters. Representative of these are the steam conditions at the turbine throttle valve, final feedwater temperature, method of coolant circulation, method of steam separation, and design and arrangement of reactor plant equipment and auxiliaries. The reactor plant concept which forms the subject of this report was evolved from exploratory studies made on a series of preliminary reactor plant designs. These designs were prepared to investigate the variation of plant investment cost as influenced by alternate design philosophies and alternate arrangements of plant equipment.

The following generalized design criteria were established for use in the development of the plant concept:

(1) The gross turbine-generator rating is to be 100,000 kw(e) when supplied with 1000 psig dry and saturated steam.

(2) The plant is to be designed for location on a river with an adequate water flow for the unit considered. Grade level is to be 5 ft above high water, with a maximum variation in river level of 15 ft.

(3) The plant is to be located on a site where soil conditions will sustain a unit pressure of 4,500 psf for foundation design, and the terrain is such that a minimum amount of dewatering is necessary for preparing foundations.

(4) The reactor is to be housed in a steel containment vessel.

(5) Turbine building, service buildings, and crib house are to be constructed of insulated protected metal siding.

(6) Rail and service facilities are assumed to be located at the edge of the plant site.

(7) Plant service water is to be strained, and the makeup feed water is to be demineralized.

(8) The cost estimate is to include the generator step-up transformer, but is not to include the switchyard.

(9) Alternate costs are to be estimated for a completely carbon steel system, and a system utilizing stainless steel or other alloys where cycle temperatures exceed 250°F.

The designs evaluated were, in general, differentiated by methods of spent-fuel handling and storage, control rod location, and method of effecting reactor coolant recirculation. More specifically, the studies considered internal versus external spent-fuel storage; wet versus dry-type fuel handling; bottom versus top-installed control rod drives; and location of the reactor vessel within the biological shielding in the containment building.

Comparisons were made between natural-circulation and forced-circulation system components and their effect on the overall dimensions of the containment vessel, plant structural requirements, and capital investment. In the majority of the systems studied, the diameter and overall height of the containment vessel were established to result in a maximum steel plate thickness of $1\frac{1}{2}$ in. to obviate the economic penalty of stress-relieving field welds of the vessel walls. However, in the case of the forced-circulation reactor design (with its attendant recirculation system risers and downcomers, steam drum, recirculation pumps, and piping), the minimum diameter of the containment vessel was set by physical space requirements. Comparisons between natural-circulation and forced-circulation systems showed that a forced-circulation plant with external steam separation would cost at least $1,500,000 (~$15 per kilowatt) more than a comparably sized natural-circulation reactor plant. Moreover, the pumping system for the forced-circulation plant would incur additional operating costs.

Consequently, cycle analyses were focused on plant designs utilizing a reactor with natural circulation and internal steam-water separation. The system parameters varied were the throttle steam pressure, the number and types of feed-water heaters in the regenerative cycle, and the disposition of the heater drains in the cycle. The results of these analyses indicated that a cycle with 1000-psig throttle steam pressure, 400°F final feed-water temperature, and pumped heater drains from the low-pressure heater, would be the most desirable arrangement compatible with a reactor designed for natural circulation and internal steam-water separation.

The foregoing preliminary studies supported the conclusion that the plant design leading to the lowest overall building cost ($1,150,000) would feature (1) a reactor with natural circulation and internal steam-water separation; (2) top-installed control rod drives; and (3) a dry-type, fuel-handling machine to transfer spent fuel elements to a storage pool located within the containment vessel.

The second most economical arrangement would be of similar design but would incorporate a wet-type fuel-handling system, with a cost differential of $52,500. This arrangement was cheaper only because of the cost of the fuel-handling coffin ($150,000) which must be added for the dry-type concept. The building cost for the wet-type system is $97,500 more than the arrangement of lowest cost.

The third most economical arrangement would feature a dry-type refueling system and differ from the two previous designs in that the control rods would be installed at the bottom of the reactor vessel. The cost differential would be about $95,500.

In weighing the advantages and the disadvantages peculiar to each plant concept, it was decided that the difficulties associated with the removal of the top-installed control rod drives for refueling operations were sufficient to warrant the additional expenditure incurred by the bottom-installed control rod design.

Accordingly, a more detailed plant design for cost estimates proceeded in accordance with the following criteria:

(1) The reactor is to be designed for natural circulation and internal steam-water separation, with bottom-installed control rod drives.

(2) The electrical power output is to be approximately 100 Mw.

(3) The reactor complex and cleanup loop are to be located in the containment vessel. Other equipment is to be located outside of the containment vessel.

(4) The plant is to be designed for unlimited access to areas requiring daily inspection and service.

(5) Spent fuel elements are to be transferred with a dry-type refueling machine to a spent-fuel storage well located inside the containment vessel. The design will provide for the transfer of fuel in and out of the containment vessel during reactor operation.

(6) The reactor site and plant costs are to conform with the requisites of "AEC Optimized Plant Studies," March, 1960, except that no allowance is to be made for cost escalation during construction.

II. SUMMARY

The reference 100-Mw(e) reactor power plant design evolved from this study should have the best chance (of any similar plants projected to date) of approaching the 8 to -9 mill/kw hr total power-cost level. Admittedly, the postulations used in arriving at these costs are subject to modification when warrantees become necessary. Guarantees of performance coupled with low cost are highly dependent upon the confidence and capability of the reactor designer's staff, ability of the Project Manager to retain the original simplicity of the conceptual design, and the completion of the plant in much less time than required for the present generation of reactors.

A. Plant Arrangement

The arrangement of the plant and on-site facilities is shown in Fig. 1. The reactor and its auxiliaries are housed in a separate vaportight, cylindrical steel containment vessel located centrally on the plant site. The turbine, condenser, and all of their related auxiliaries are installed in the turbine building proper, which is of conventional design and construction. Two extensions of the turbine building house, respectively, the control room section, and office space, machine shop and personnel facilities. Access is provided from the control room to both the containment vessel and the turbine building.

The arrangement of the equipment in the containment vessel and the turbine building is shown in Figs. 2 to 7. These arrangements reflect the results of studies of various reactor plant designs described in Appendix F.

The main transformer and switchyard are located immediately adjacent to the turbine building to shorten the main bus duct runs and to provide for an economical switchyard arrangement.

The circulating water system consists of the crib house, intake and discharge piping, seal well, and an outfall structure. The crib house is located at the water's edge.

Facilities for radioactive waste processing are located adjacent to the reactor building. A permanent waste disposal facility is provided at a location removed from the main buildings and the property lines. This facility consists of two concrete, stainless steel-lined, leakproof tanks for permanent storage of liquid and solid wastes.

The sewage disposal system is located to take advantage of the natural site drainage. Other service structures include a deep well pump and a gate house.

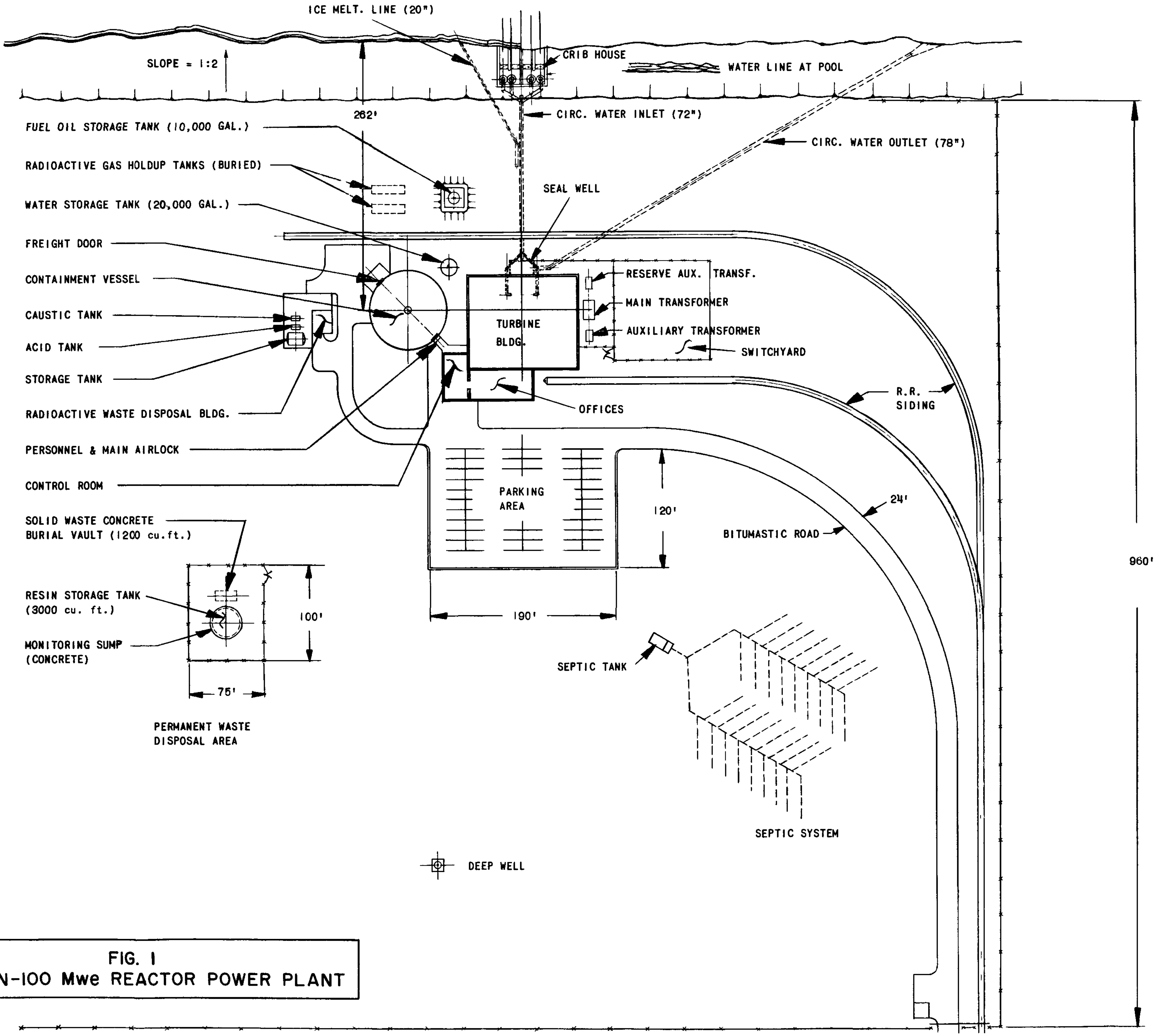
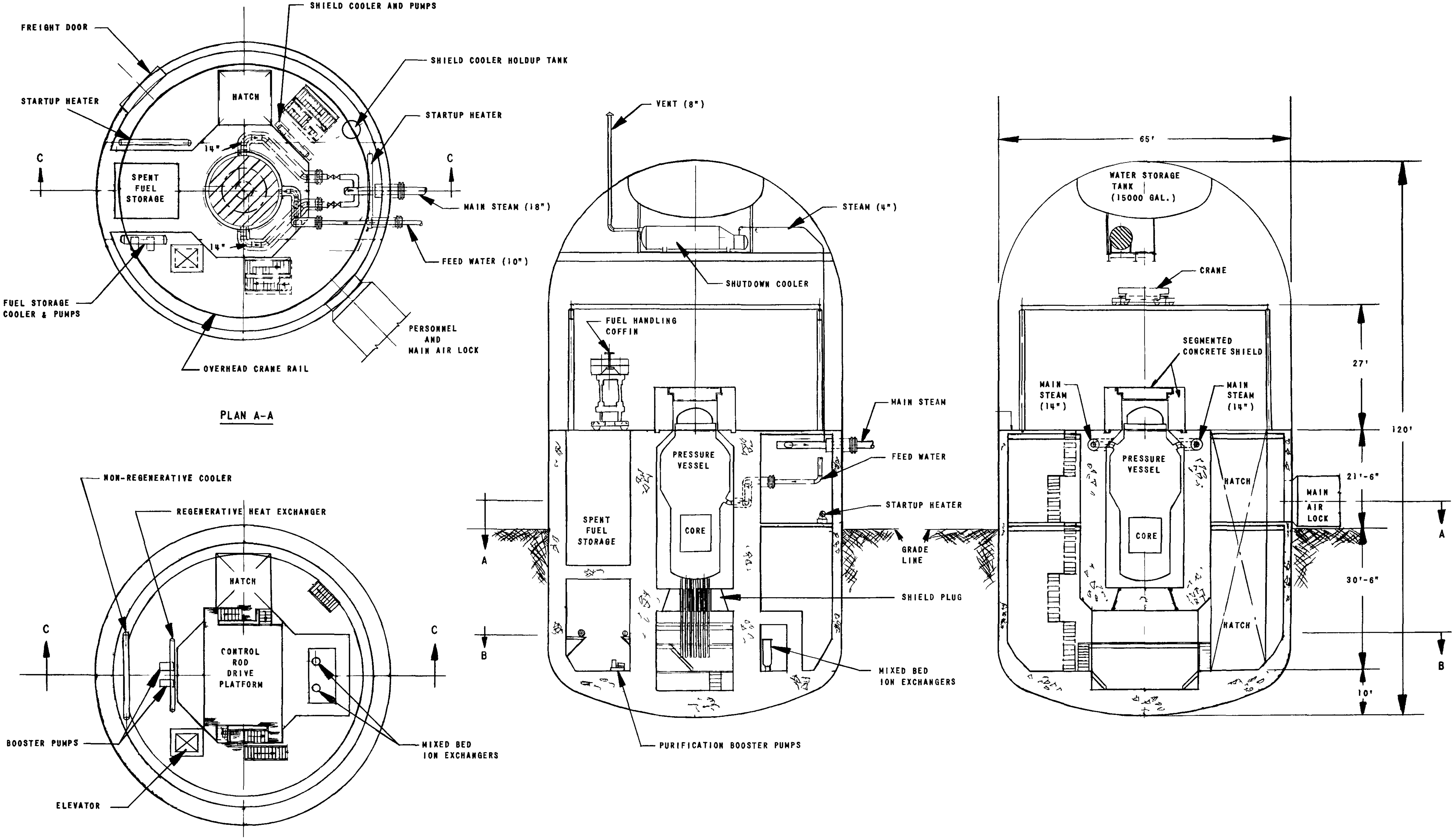


FIG. I
SITE PLAN-100 Mwe REACTOR POWER PLANT



PLAN A-A

PLAN B-B

SECTION C-C

SECTION D-D

FIG. 2
SECTIONAL VIEWS OF CONTAINMENT VESSEL

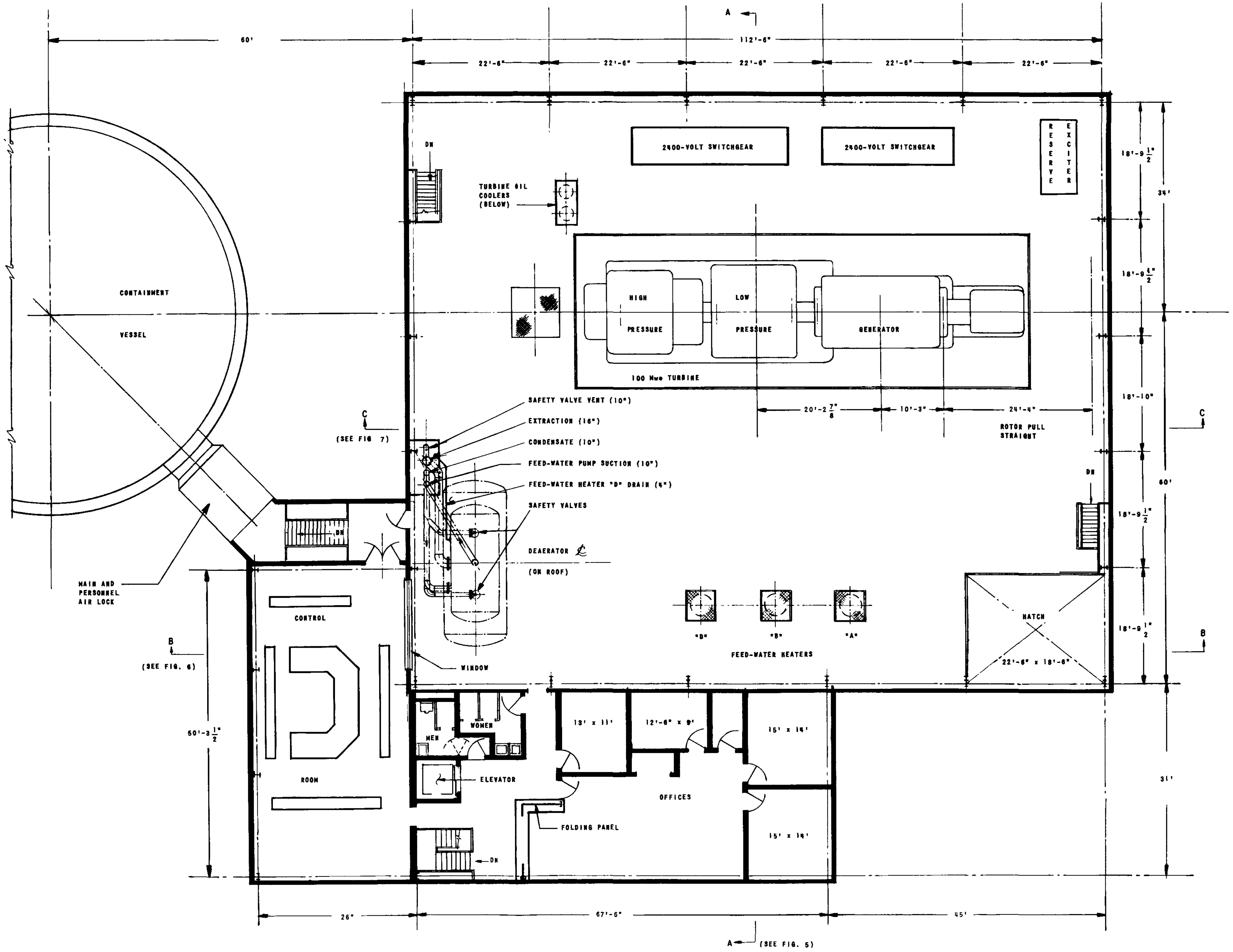


FIG. 3
PLAN OF MAIN FLOOR-TURBINE BUILDING

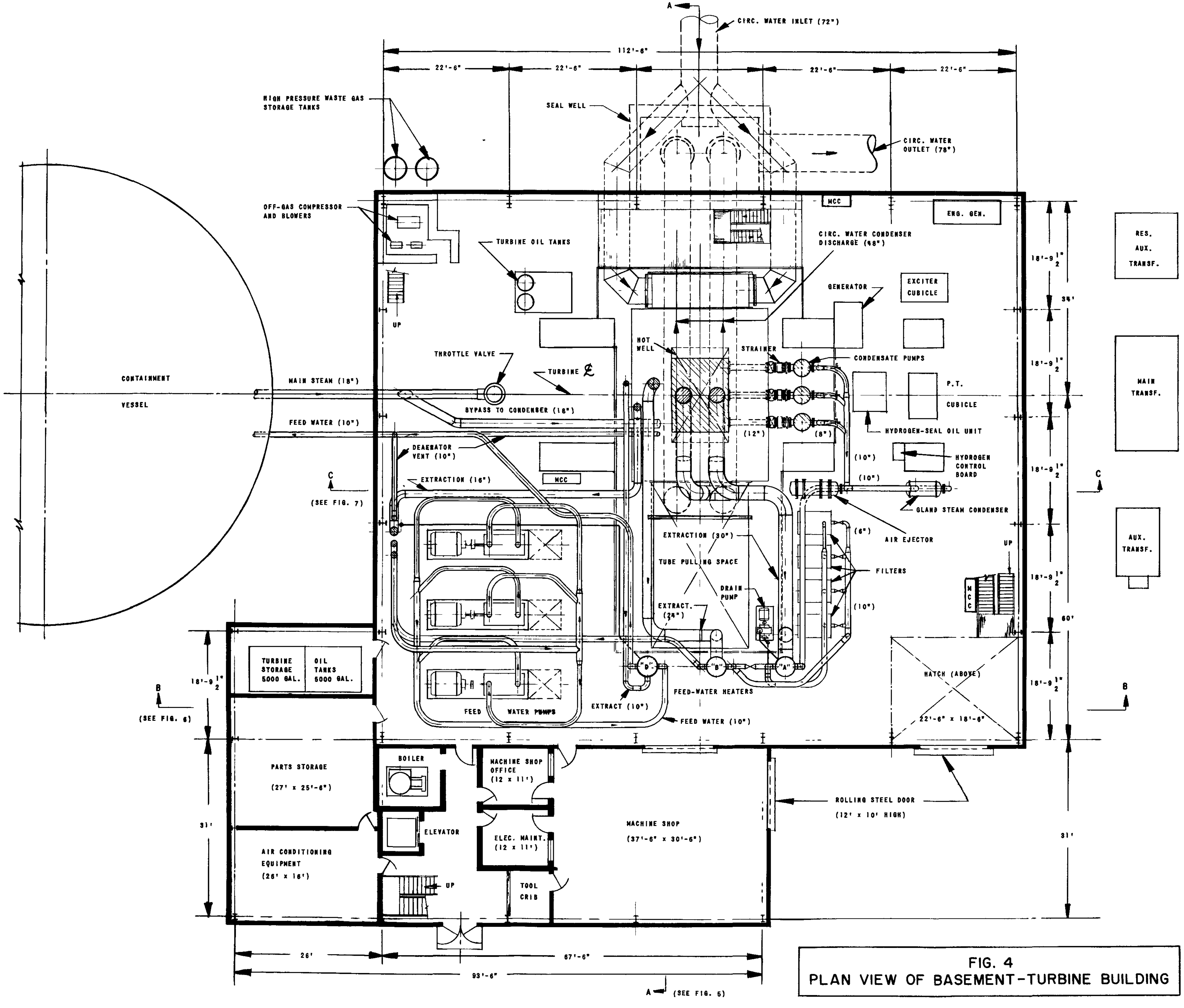


FIG. 4
PLAN VIEW OF BASEMENT-TURBINE BUILDING

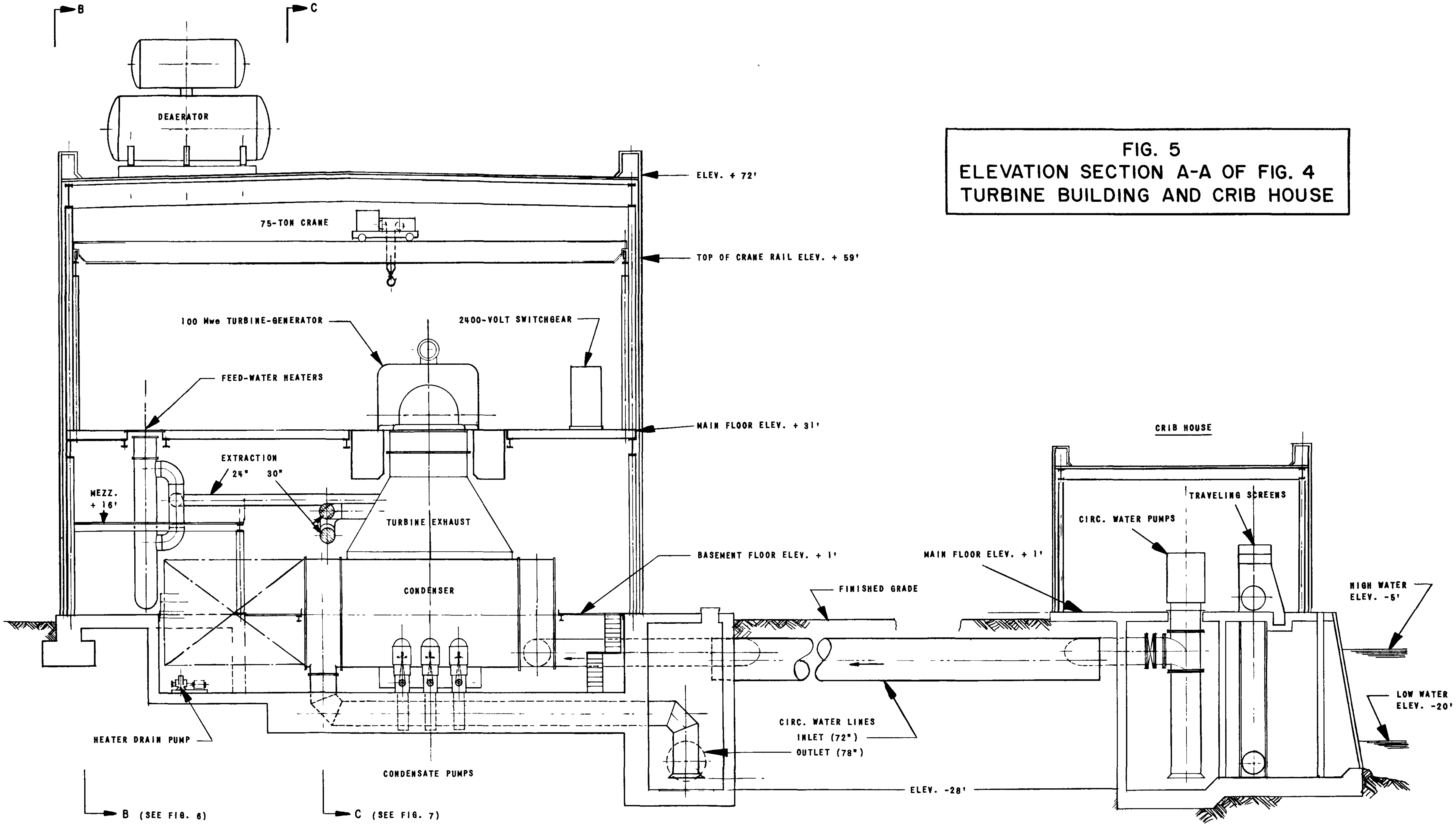


FIG. 5
ELEVATION SECTION A-A OF FIG. 4
TURBINE BUILDING AND CRIB HOUSE

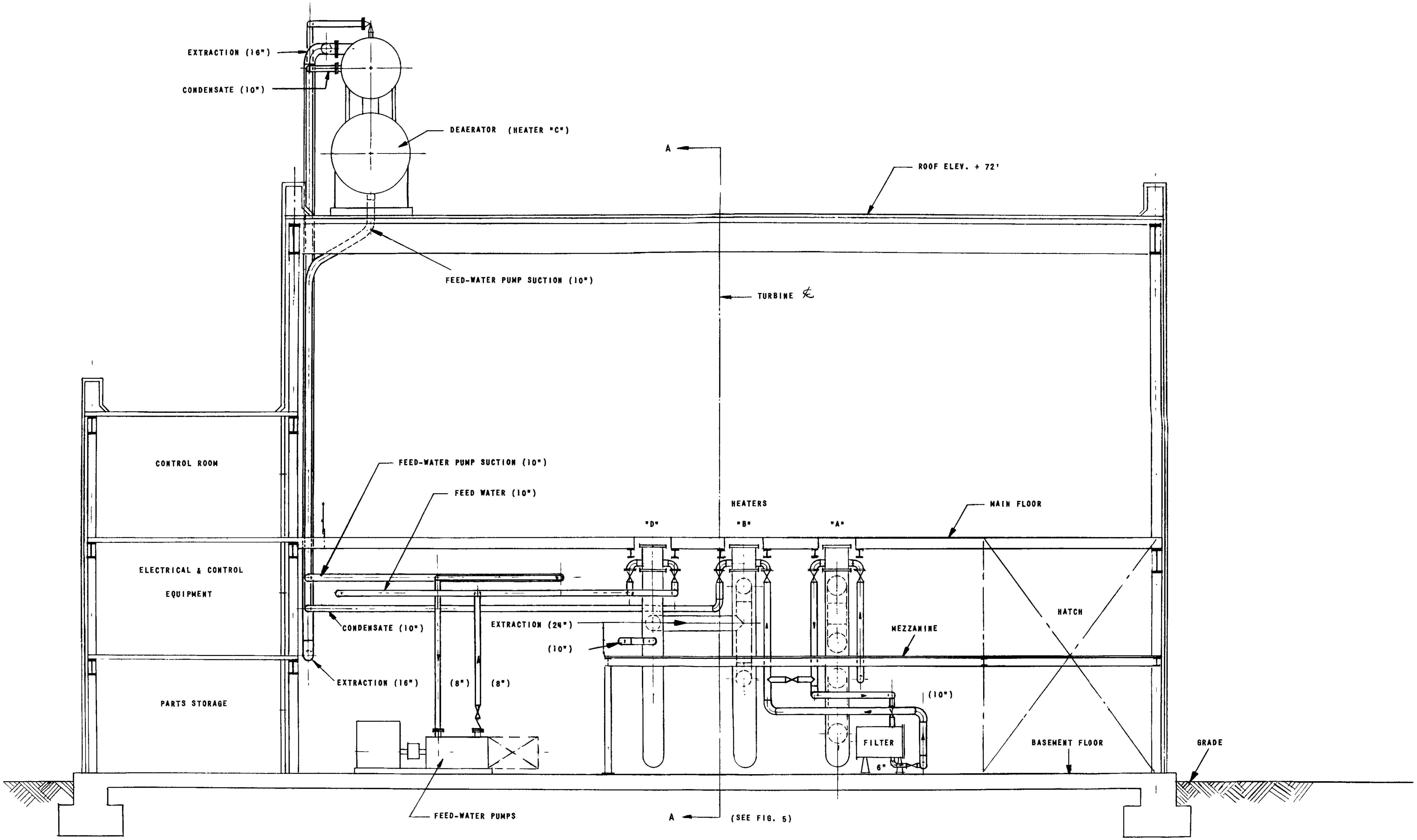


FIG. 6
ELEVATION SECTION B-B OF FIG. 4-TURBINE BUILDING

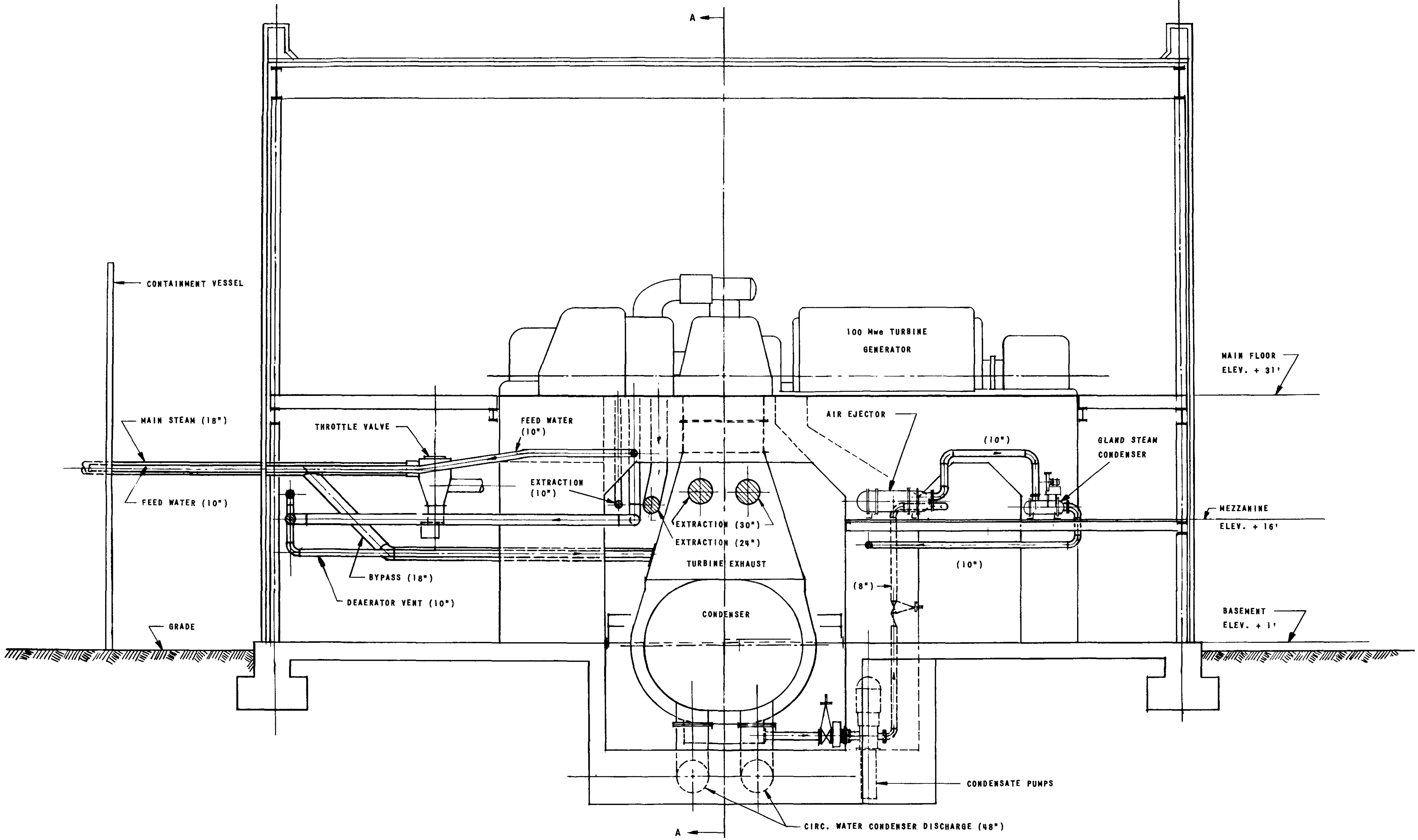


FIG. 7
ELEVATION SECTION C-C FIGS. 3 AND 4-TURBINE BUILDING

Yard facilities, including the oil storage tanks, miscellaneous tanks and related equipment, are located as shown on Fig. 1.

Parking facilities are provided for personnel concerned with the operation of the plant. Both the turbine building and the reactor building are served by the plant railroad system.

B. Power Conversion Cycle

The power conversion cycle and the plant auxiliary systems are shown in the flow diagram, (Fig. 8). The major equipment in the cycle consists of a boiling water reactor utilizing natural circulation and internal steam-water separation to generate and supply steam directly to the high-pressure element of a turbine-generator unit.

The reactor is fueled with Zircaloy-2-clad UO_2 fuel assemblies, and cooled and moderated with boiling water. The coolant enters the reactor through a feed-water distribution ring located below the top of the core shroud structure, and flows down through the downcomer areas, where it subcools the recirculated reactor coolant. The large downcomer area provides space for neutron attenuation to protect the steel pressure-vessel wall. The flow then continues upward through the core, where boiling occurs, to the steam-water interface. The steam is removed from the water-vapor mixture by appropriate internal vessel design.

The dry and saturated steam flows directly from the reactor vessel to the turbine-generator in the turbine building. The turbine is a 100-Mw(e), 3600-rpm, tandem compound double flow, multiple extraction unit designed for operation with 1000-psig dry and saturated steam. After passing through the high-pressure turbine, the excess moisture in the steam is removed by moisture-removal devices located in the crossover piping. The steam is then returned to the low-pressure turbine for further expansion. Moisture is also removed from the expanding steam at appropriate extraction stages to reduce corrosion and erosion of the turbine.

The steam from the turbine discharges to the main condenser. The main condenser is a two-pass, single tube sheet unit constructed of standard materials. The condensate is then returned to the reactor through four stages of extraction steam heating to complete the cycle.

As shown in the performance diagram (Fig. 9), the foregoing steam cycle is expected to lead to a turbine heat rate of 10,346 Btu/kw hr, when supplied with 1000-psig steam, exhausting at a condenser pressure of 1.5 in. Hg abs, and utilizing a regenerative feed-water heating cycle to effect an inlet feed-water temperature of 400°F. Assuming a reactor thermal efficiency of 100%, and an auxiliary power requirement of about 5100 kw,

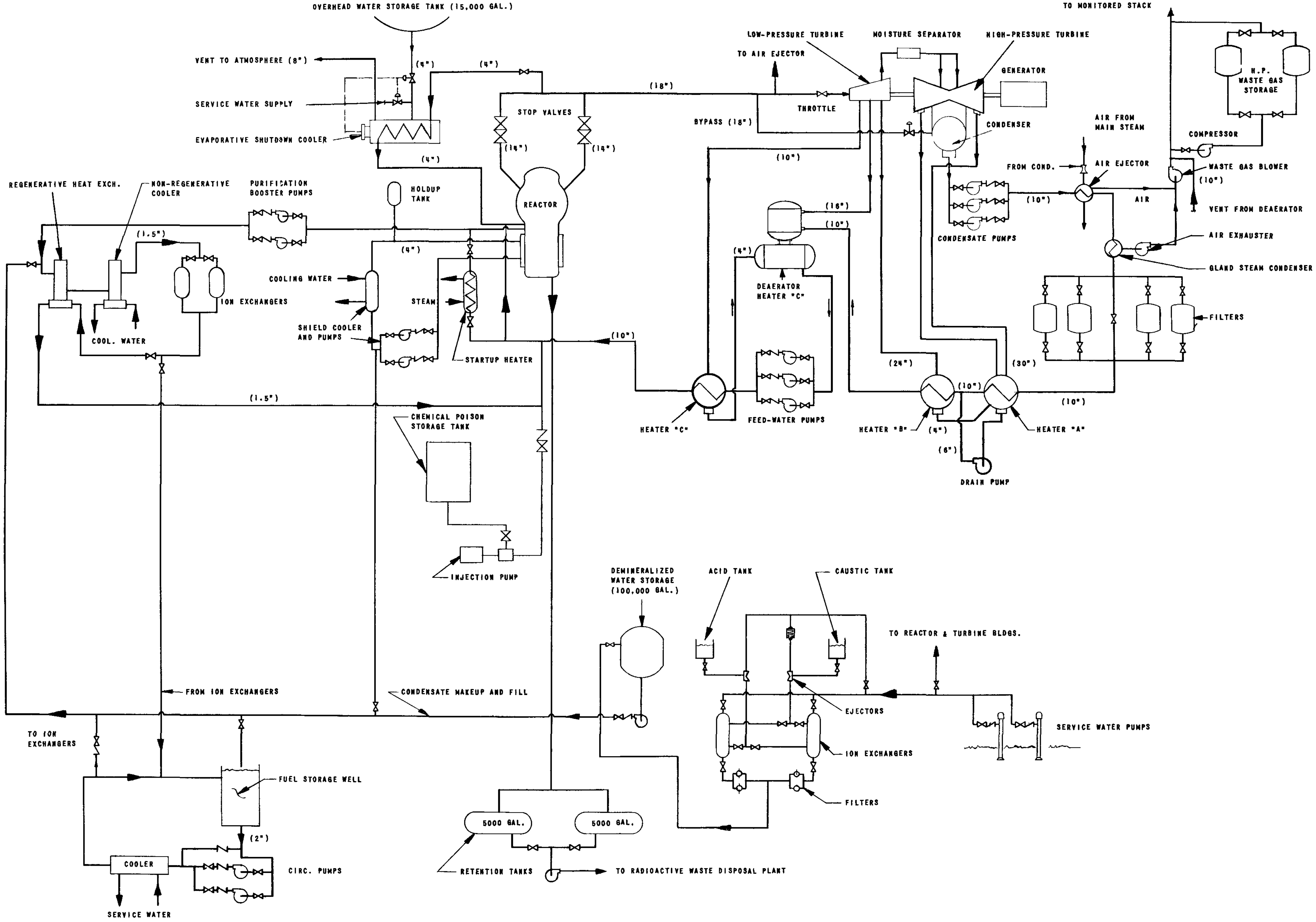
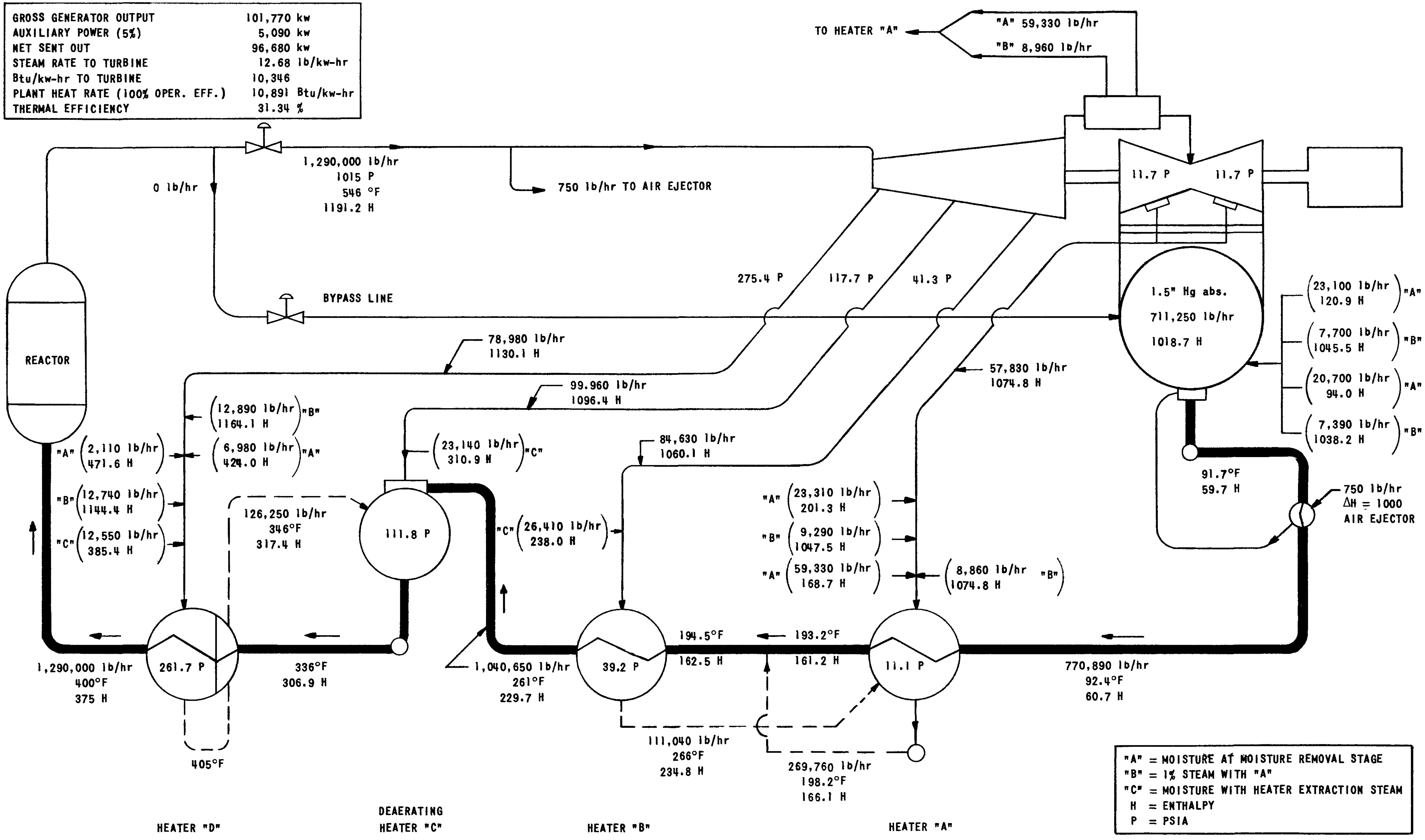


FIG. 8
FLOW DIAGRAM—REFERENCE 100 MWe REACTOR POWER PLANT DESIGN



GROSS GENERATOR OUTPUT	101,770 kw
AUXILIARY POWER (5%)	5,090 kw
NET SENT OUT	96,680 kw
STEAM RATE TO TURBINE	12.68 lb/kw-hr
Btu/kw-hr TO TURBINE	10,346
PLANT HEAT RATE (100% OPER. EFF.)	10,891 Btu/kw-hr
THERMAL EFFICIENCY	31.34 %

"A" = MOISTURE AT MOISTURE REMOVAL STAGE
"B" = 1% STEAM WITH "A"
"C" = MOISTURE WITH HEATER EXTRACTION STEAM
H = ENTHALPY
P = PSIA

FIG. 9
PERFORMANCE CHARACTERISTICS - REFERENCE DESIGN 100 Mwe REACTOR PLANT

the net plant heat rate is 10,891 Btu/kw hr. Based on this plant heat rate and a 100% operating efficiency, the plant thermal efficiency is 31.3%.

C. Design Characteristics

Table I lists the pertinent features and operating characteristics of the reference 100-Mw(e) reactor plant design.

Table I

DESIGN SUMMARY OF 100-Mw(e) BOILING WATER REACTOR POWER PLANT

CYCLE PERFORMANCE	
Total thermal power, Mw(t)	309
Gross generator output, Mw(e)	101.77
Auxiliary power, Mw(e)	5.09
Net plant output, Mw(e)	96.68
Net plant heat rate, Btu/kw hr	10,891
Net plant efficiency, %	31.34
CYCLE CONDITIONS	
Turbine throttle pressure, psig	1,000
Turbine throttle temperature, °F	546.4
Turbine throttle steam condition	Dry and saturated
Throttle steam flow, lb/hr	1,290,000
Condenser pressure, in. Hg abs	1.50
Reactor steam pressure, psig	1,050
Reactor steam temperature, °F	552.3
REACTOR	
Fuel material (pellets)	UO_2
Pellet diameter (nominal), in.	0.392
Gap thickness (nominal; cold), in.	0.0015
Fuel rod OD, in.	0.450
Clad	Zircaloy-2
Clad thickness, in.	0.025
Active fuel length per section, in.	33
Axial gap between sections, in.	1.75
Number of sections	3
Total fuel section length, in.	$104\frac{1}{16}$
Triangular lattice pitch, in.	0.621
Active diameter (equivalent), in.	75
Fuel assembly geometry	Hexagonal
Lattice pitch (hexagonal), in.	6.55
Rods per assembly	91
Assemblies per core (including control rods)	151

Table I (Cont'd.)

REACTOR (Cont'd.)

Number of control rods	19
Average power density, kw/liter of core	40
Average fuel enrichment, at-%	
Initial	2.25
Discharge	1.0
Plutonium content at discharge, at-%	0.65
Average burnup at discharge, Mwd/tonne U	15,000
Total maximum/average flux	4 (est.)
Total core loading, kg U	24,133
Water/total core material	1.4:1

PRESSURE VESSEL

Overall height, ft	44
Major inside diameter and wall thickness	14 ft-6 in. x 6.25 in.
Minor inside diameter and wall thickness	12 ft x 5.25 in.
Material	
Shell plate	SA-212-B
Flanges	SA-105-II
Nozzles	SA-106-B
Operating pressure, psia	1,065
Design Pressure, psia	1,250
Operating temperature, °F	552
Design temperature, °F	650
Vessel liner	
Thickness (minimum), in.	0.109
Material	SST Type 304

TURBINE PLANT

Turbine	
Rating, kw	100,000
Type	TCDF
Speed, rpm	3600
Exhaust pressure, in. Hg abs	1.50
Number of extraction stages	4
Sealing	Steam and air
Exhaust blade length, in.	23
Generator	
Capacity, kva	128,000
Voltage, kv	13.8
Cooling	Hydrogen
Pressure, psig	30

Table I (Cont'd.)

TURBINE PLANT (Cont'd.)	
Main exciter	
Type	Directly connected
Voltage, v	250
Rating, kw	300
Reserve exciter	
Type	Self-excited
Drive	Motor
Condenser	
Type	Horizontal-divided water box
Surface, ft^2	100,000
Number of passes	2
Capacity, lb/hr	711,250
Condensate pumps	
Number	3
Type	Vertical
Capacity, gpm	1,300
Total head, ft	340
Circulating water pumps	
Number	4
Type	Vertical
Capacity, gpm	22,600
Total head, ft	25
Air ejectors	
Number	2
Type	Twin two-stage
Capacity, cfm	12.5
Feed-water heaters	
Closed heat exchangers	
Number	3
Type	Vertical
Open heaters	
Number	1
Type	Horizontal, deaerating
Capacity, lb/hr	1,290,000
Feed-water pumps	
Number	3
Type	Horizontal, centrifugal
Capacity, gpm	1,400
Total head, psi	1,170

A rigorous study of physics and mechanical design problems was not performed since experience has shown there is a wide variation between conceptual design and the design selected for fabrication. The core is designed for zone-type fuel management. More uniform flux and power distribution may be obtained by this method, which contributes an advantage to overall fuel cycle performance and resulting economics. The values for fuel enrichment and plutonium content are estimates based on a uniformly enriched core. Zoned cores, with variations in enrichment in both axial and radial directions, must be considered in the detailed design stage.

Heat transfer parameters are also omitted. The assumed moderator/material ratio of 1.4: 1 is considered well within feasible limits for the current state of the art of hydraulics and mechanical design.

The excess reactivity requirement for cores with a long fuel lifetime precludes the use of mechanically actuated solid neutron absorbers as the sole means of effecting reactor control. The trend of reactor control development is away from mechanical, and toward chemical, methods of control. In keeping with this design philosophy, the number of control rods indicated will accommodate only hot shutdown requirements and variable load control. Cold shutdown will be effected by a chemical poison-injection system. The poison will be removed slowly from the bulk coolant by a cleanup loop when the plant is started on a power production cycle.

Results of the study indicate that the plant size is limited by pressure vessel fabrication. The pressure vessel specified approaches the maximum size that can be fabricated at this time. Moreover, the diameter of the vessel will limit the location of the plant to navigable bodies of water, or will require field assembly. The cost of the vessel represents about 10% of the total direct plant construction cost. Therefore, the total cost is not very sensitive to this component. The cost differential between a clad and unclad vessel is inexpensive insurance for vessel integrity. Therefore, an internal stainless steel clad has been specified regardless of the material selected for the exterior system. Other specifications include a laminated boron-stainless steel plate and water thermal shield designed to protect the vessel wall against over-embrittlement from neutron irradiation sustained during 20 years of operation.

The thermal and biological shielding extending radially outward from the vessel wall consists of stainless steel wool insulation, an air gap, a water-cooled tank liner, and the bulk biological shield of ordinary concrete (7 ft thick). The water-cooled tank liner is designed to maintain the temperature of the concrete below 180°F. The bulk shielding will reduce the radiation dose level to about 15 mr/hr at the outer face at a point corresponding to the horizontal center line of the core. This region is devoid of systems or components that would give rise to radiation hazards to personnel as a consequence of sustained maintenance or servicing periods. The level of activity will permit limited accessibility.

Standard materials have been used, wherever practicable, in the construction and fabrication of reactor and turbine plant auxiliary systems. These include reactor water purification, shield cooling, shutdown cooling, service water, circulating water, radioactive waste disposal, and other minor auxiliaries.

D. Costs

The estimated capital costs for the reference reactor power plant design are summarized in Table II. The indicated capital investment of $19,802,000 is based on utilizing a carbon steel primary system. The cost does not include the reactor core, spare parts, personnel training program, nor does it provide for escalation during design and construction.

Table II

COST SUMMARY FOR REFERENCE 100-Mw(e)
REACTOR POWER PLANT DESIGN

Land	$ 15,000.	
Structures	3,177,000.	
Equipment, piping, etc.	10,885,000.	
Electrical	1,437,000.	
Miscellaneous equipment	90,000.	
Startup supervision	50,000.	
	$ 15,654,000.	
Contingency (10%)	1,565,500.	
	$ 17,219,500.	
Top charges (15%)	2,582,500.	
TOTAL COST - CARBON STEEL PLANT		$19,802,000.
Cost differential for stainless steel plant		885,000.
TOTAL COST - STAINLESS STEEL PLANT		$20,687,000.

Table II shows a price differential of $885,000 is incurred by substituting stainless steel or other high-alloy components in the primary system where fluid temperatures are in excess of 250°F. The equipment affected includes the reactor vessel internals, high-pressure feed-water heaters, deaerating feed-water heater, reactor feed-water pumps, reactor water purification components, and related piping.

The resultant unit costs are \$198/kw for the carbon steel design, and \$207/kw for the stainless steel design. The ultimate achievement of a low-cost plant will depend upon the success of the project manager in keeping the design simple. A complex design will easily raise the cost to the \$300-\$350/kw level.

The fuel cycle costs were evolved from analyses made of a series of postulated cores incorporating feasible parameters (see Section IV). Experience has shown that, within the limits of accuracy of first assumptions and estimates, this approach is sufficiently accurate for practical purposes. The representative core fuel cycle costs summarized in Table III will result in a total net power cost of 3.01 mills/kwhr.

Table III

COST SUMMARY - REPRESENTATIVE CORE FUEL CYCLE

(Based on Core "E," Table V)

Gross power, Mw(e)	101.8	
Net power, Mw(e)	96.7	
Reactor power, Mw(t)	310	
Annual generation at 80% Load Factor, kwhr	7×10^8	
Specific power, kwt/kg U	12.8	
Core loading, kg U	24,133	
Fuel material	UO_2	
Clad material	Zircaloy-2	
Enrichment, % U^{235}		
Initial	2.25	
Final	1.0	
Avg. burnup, Mwd/tonne	15,000	
Plutonium production, gm Pu/kg U	6.5	
Fabrication cost, \$/kg	140.00	
Burnup cost, \$/kg	183.00	
Fabrication cost, mill/kwhr		1.21
Burnup cost, mill/kwhr		1.62
Shipment, reprocessing, conversion, mill/kwhr		0.83
TOTAL GROSS POWER COST, mill/kwhr		3.66
Pu credit, mill/kwhr		.65
TOTAL NET POWER COST, mill/kwhr		3.01

The achievement of an 80% load factor for a normally operated power plant allows 14 days of down time per year. Based on operating experience to date, it is doubtful that a refueling cycle could be accomplished in much less than 7 days of around-the-clock effort. Thus, more than one shutdown per year may have a significant impact upon the total power cost.

Assuming a favorable set of conditions, the total power cost may be postulated as follows:

Capital charges	4.00 mills/kw hr
Fuel cycle costs	3.01
Operation and maintenance	0.80
Insurance	0.34
Total	8.15 mills/kw hr

If allowances are made for variations likely to occur in a detailed design study, a final power cost approaching 8.4 to 9.0 mills/kw hr may be realized.

III. COMPONENT DESCRIPTION

A. Reactor Plant

1. Containment Vessel

The reactor plant and auxiliaries are contained in a cylindrical steel vessel (65 ft diameter x 120 ft high). The vessel is designed in accordance with Section VIII, ASME Boiler and Pressure Vessel Code for Unfired Pressure Vessels, and applicable code cases. The steel specified is A-201, Grade B, conforming to Specification A-300 for heat treatment and Charpy test. The vessel is designed to contain an internal pressure of 55 psig which would result from the maximum credible incident. It is also designed to sustain a combination of external loads.

Principal access to the containment vessel is through the personnel air lock which interconnects the containment vessel grade floor and the turbine building grade floor. The air lock will permit the removal of spent fuel (in shielded casks) from the containment vessel without compromising the integrity of the vessel during reactor operation. This is accomplished by double air lock doors that are mechanically interlocked and electrically operated such that only one door can be opened at a time.

The other opening in the containment vessel is a large, bolted freight door at grade floor level. The door will permit removal of large equipment during plant shutdown. During normal operation, the door must be kept closed to maintain vessel integrity.

The containment vessel also features a water-spray system which, in the event of a primary system rupture, will operate to lower the consequent internal pressure and temperature, and to wash radioactive materials to below ground level. The spray system is serviced by a 15,000-gallon water-storage tank located at the apex of the vessel dome. This method of providing an independent source of emergency cooling water was adjudged the most economical and desirable for reasons discussed in Appendix D.

2. Core

The proposed reference core comprises 132 fixed hexagonal fuel assemblies, and 19 movable, combination fuel-control rod assemblies arranged on a 6.550-inch triangular lattice (see Fig. 10).

The fixed fuel assembly features three fuel sections. Each section (Fig. 11) contains 91 fuel rods arranged on a 0.621-inch triangular lattice. Each fuel rod comprises 66 UO_2 pellets clad in Zircaloy-2, a gas-expansion gap, and Zircaloy-2 end fittings. The end fittings are welded to Zircaloy-2 grid support plates.

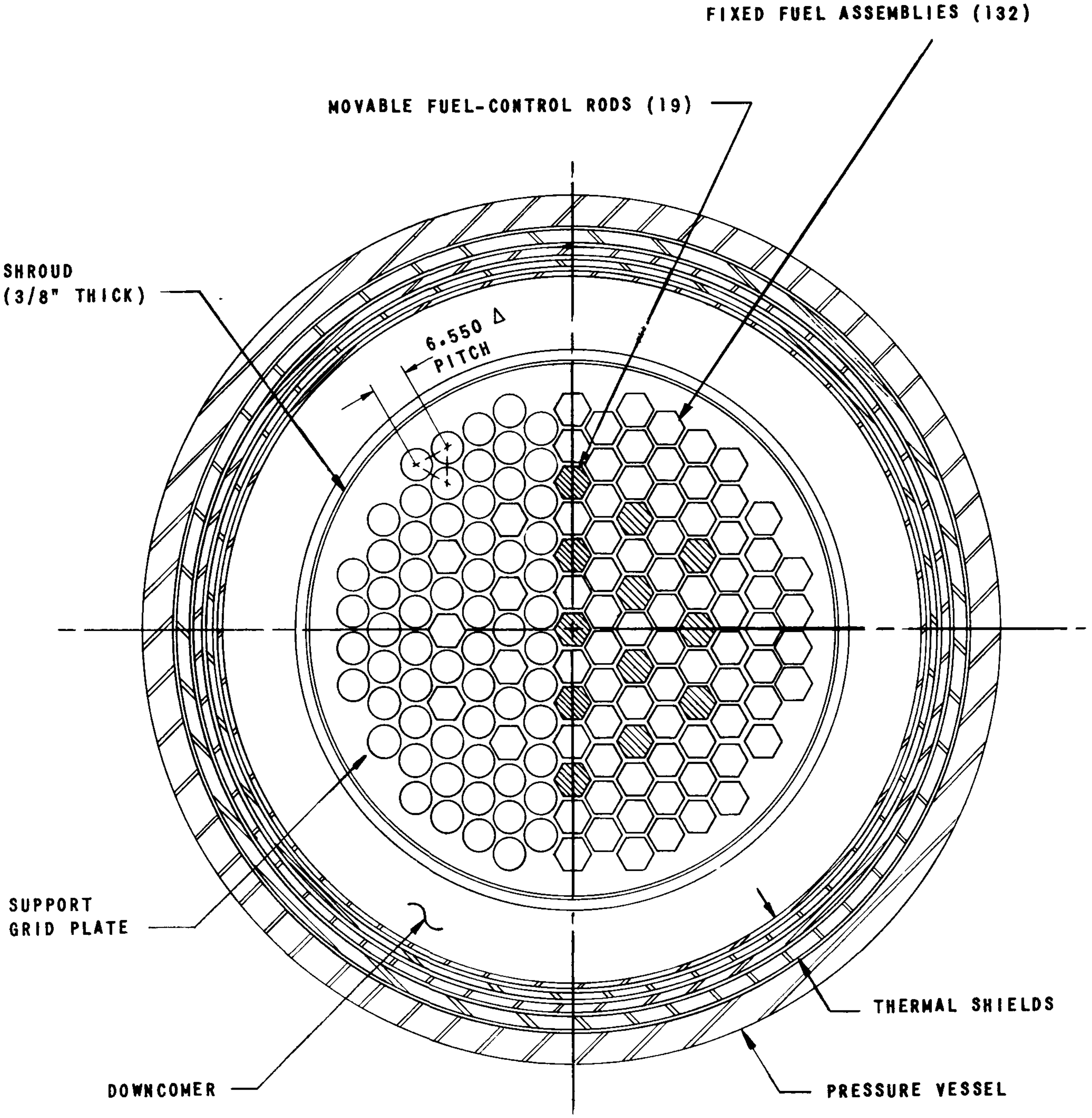


FIG. 10

CROSS SECTION OF REFERENCE DESIGN CORE AND PRESSURE VESSEL

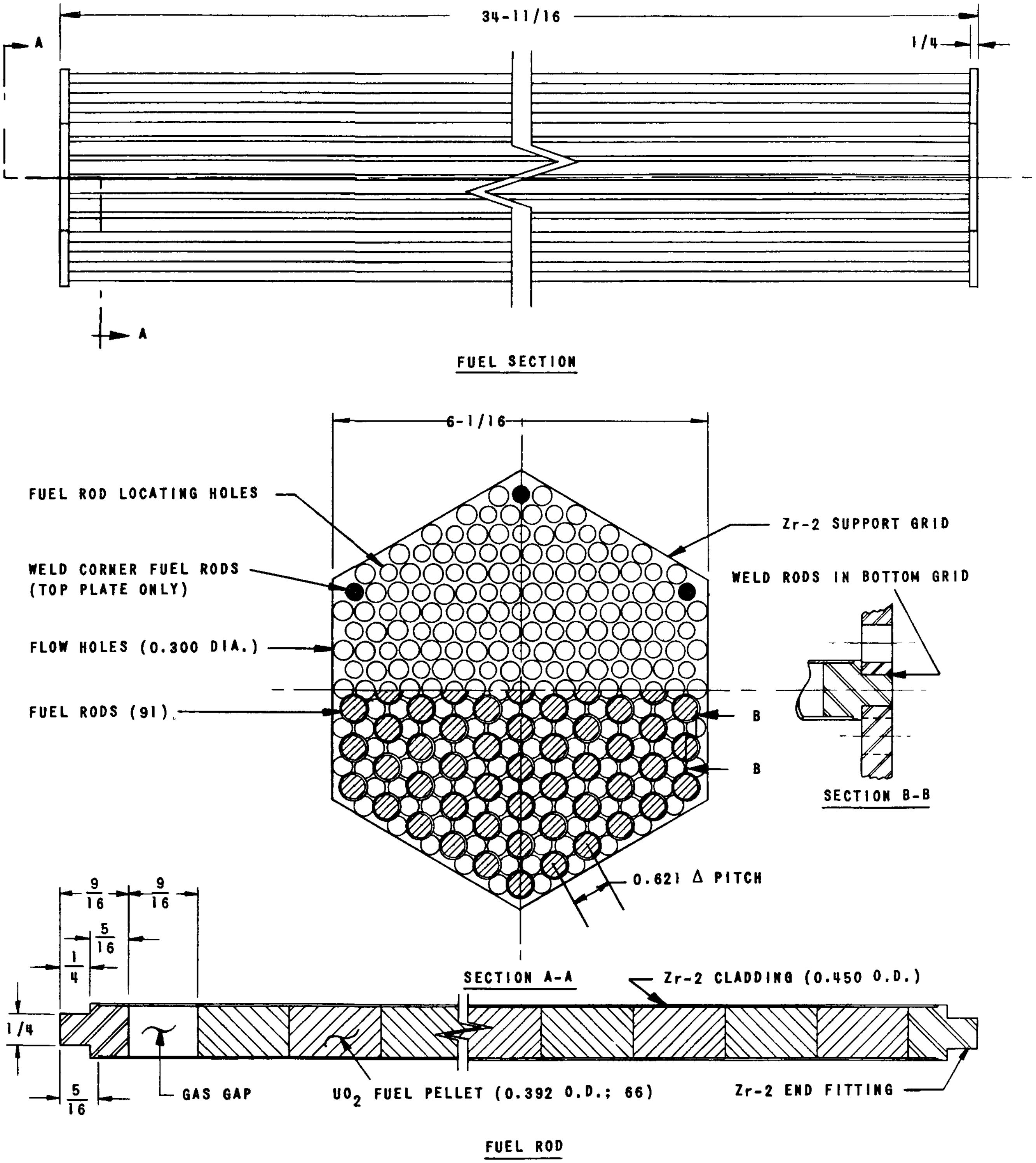


FIG. 11

TYPICAL FUEL ROD AND FUEL SECTION

The three fuel sections are connected by Zircaloy-2 tie strips and installed within a hexagonal "basket" or cartridge-type holder (Fig. 12) which forms the outer fuel-assembly structure. The holder is fabricated from Zircaloy-2 strut stampings rivoted to a stainless steel bottom alignment fitting, and welded to an upper Zircaloy-2 handling box. This method of assembly will permit individual fuel sections to be relocated consistent with any desired fuel-cycle program. Moreover, to effect some economy in fabrication and fuel-cycle costs, the spent fuel sections can be removed from their holders (in the fuel storage well) and the holders reloaded with fresh fuel sections for return to the core.

The movable, combination fuel-control rod assemblies (Fig. 13) comprise an upper stainless steel handling box, a fuel section, a boron-stainless steel absorber section, and a lower connector-latch block fitting. These assemblies are driven by hydraulic actuators located beneath the reactor pressure vessel. The rods are pulled down out of the core during startup and subsequent operation, and pushed up into the core to effect shutdown. This control concept assists in improving fuel-cycle characteristics. However, scramming such a heavy unit against gravity does present a formidable problem to the mechanism designer. Nonetheless, a similar unit has been developed and installed on a commercial reactor. The net cost advantage of this control concept, due to fuel-cycle gains, has been questioned in competent quarters. In the event that rigorous investigations show that a conventional fuel-on-the-bottom, absorber-on-the-top pushup control rod is equally satisfactory, a considerable cost saving will be realized.

3. Pressure Vessel

Figure 14 shows the core and shroud structure installed in the pressure vessel. The pressure vessel is supported near the top (at the enlarged diameter) by lugs which bear on steel plates embedded in the bulk concrete shielding. This method of support was selected to prevent introduction of thermal expansion stresses in the side walls which would be associated with a bottom-supported vessel.

The diameter of the vessel above the core is enlarged to provide sufficient area for a steam-water mixture separation velocity of about 1 ft/sec. Removable demisters are located between the steam outlet nozzles and the steam-water separation region.

The top closure opening will permit fueling operations without the use of an offset or telescoping tool.

The diameter of the vessel around the core is based on providing (1) a cross-sectional area corresponding to a coolant recirculation rate of 21 x 10^6 lb/hr at a velocity of ~3.1 ft/sec; and (2) space for

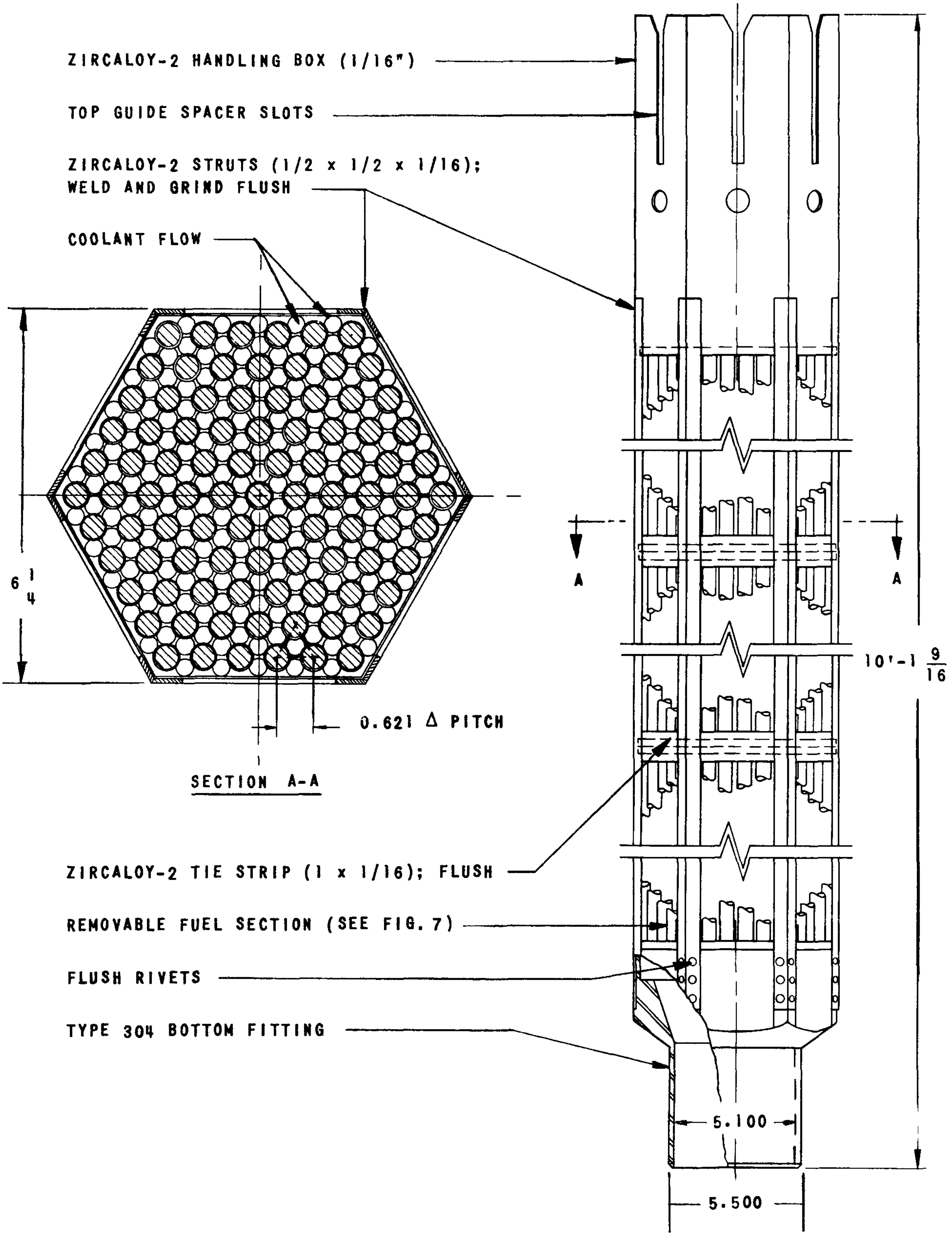
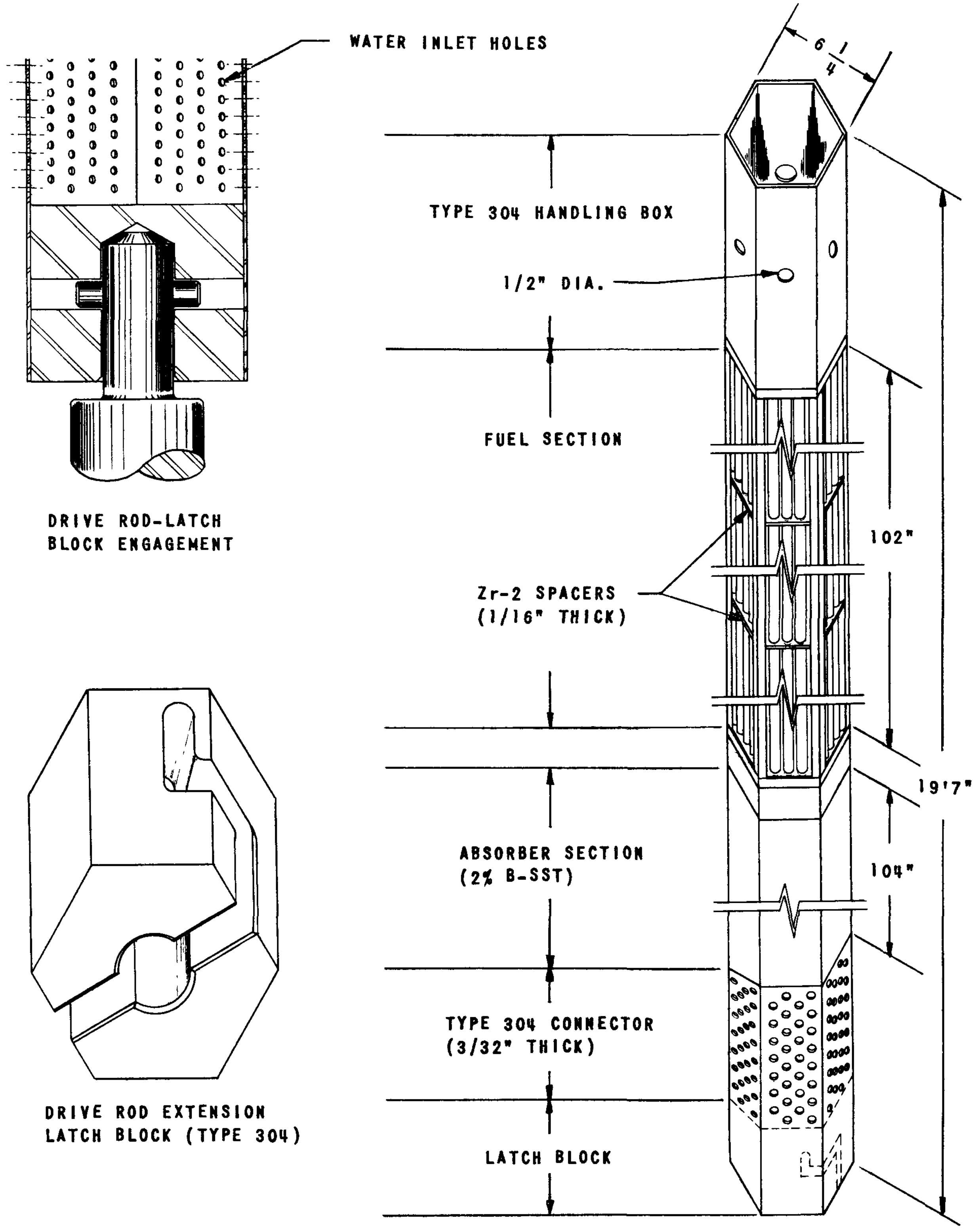


FIG. 12
FUEL SECTION HOLDER AND ASSEMBLY



DRIVE ROD-LATCH BLOCK ENGAGEMENT

DRIVE ROD EXTENSION LATCH BLOCK (TYPE 304)

FIG. 13
MOVABLE CONTROL ROD-FUEL FOLLOWER ASSEMBLY

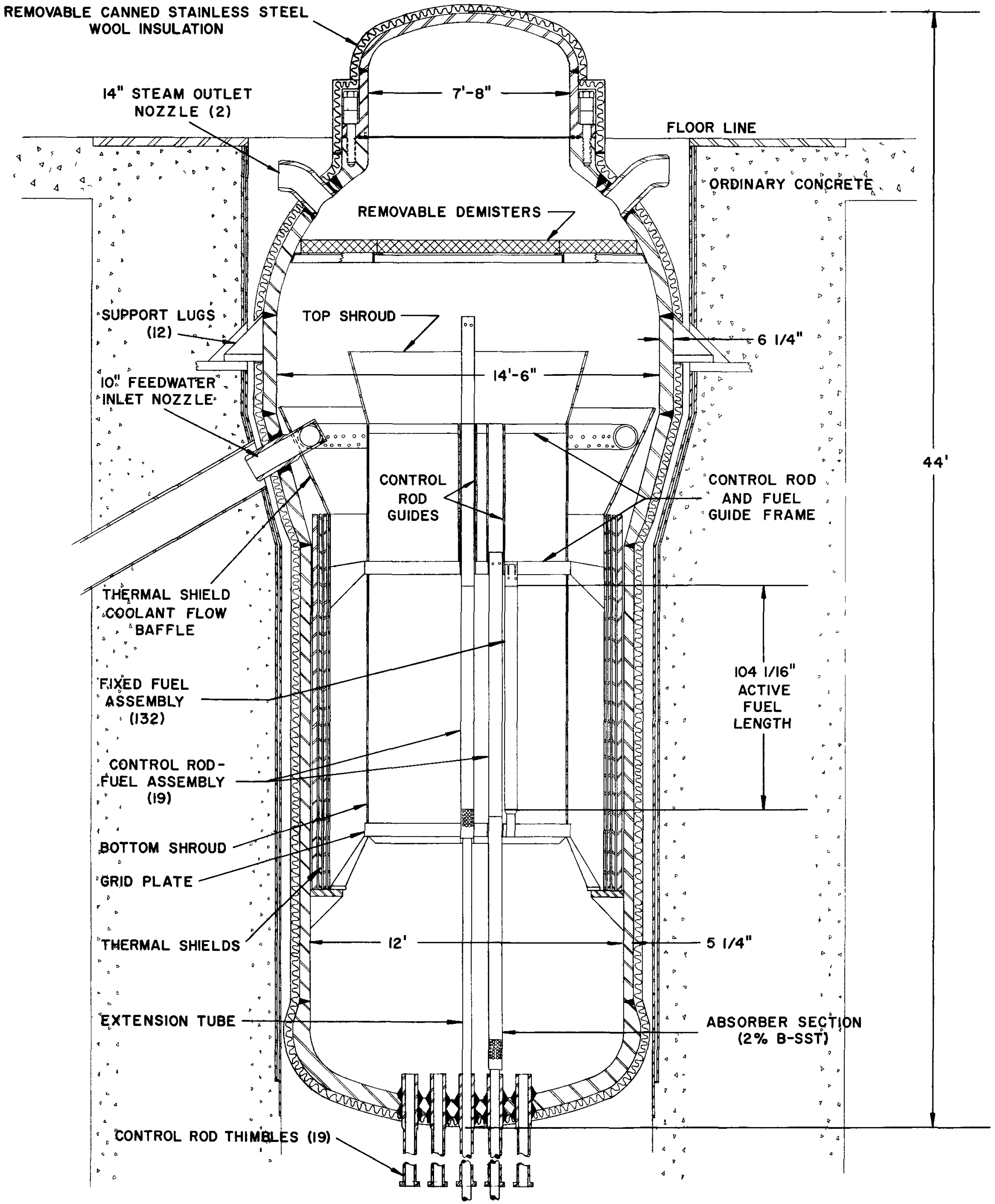


FIG. 14
REACTOR PRESSURE VESSEL

sufficient thermal and neutron shielding steel to afford a vessel life expectancy of 20 years at an 80% load factor. The allowance of 17 in. for the downcomer width also provides space for increasing the core diameter if warranted by detailed design studies.

The laminated boron-stainless steel plate and water thermal shield is designed to protect the vessel wall against over-embrittlement from neutron irradiation for 20 years of operation. The top of the thermal shield is capped with a chimney that extends up to the water line. This arrangement is provided to ensure upward flow of cooling water between the laminations, and to prevent heating of the downcomer flow.

In addition to the foregoing protective measures, a stainless steel clad has been specified for the inside vessel wall regardless of the choice of material for the exterior systems and auxiliaries. The cost differential between a clad and unclad vessel is inexpensive insurance for integrity of this vital component.

The bottom head of the vessel is machined to accommodate 19 control rod thimbles. After being accurately aligned, the thimbles are encased in a concrete shield plug.

The vessel materials of construction and support are of standard specifications. The methods of fabrication are well understood.

4. Shielding

The shielding design and arrangement will permit controlled access in the containment vessel during normal plant operation. Personnel may inspect equipment, perform limited preventative maintenance, and load and remove fuel shipping casks from the building.

The reactor foundation (see Fig. 2) is a large, reinforced concrete structure, with major dimensions established by radiation-shielding requirements. There are two major cavities: the reactor cavity, and the room beneath the pressure vessel which houses the control rod drive mechanisms. Openings and sleeves are provided for all piping, instrumentation, and controls that extend through the concrete support structure.

Extending radially outward from the pressure vessel wall, the thermal and biological shielding comprises stainless steel wool insulation, an air gap, a water-cooled steel tank liner, and ordinary concrete (see Fig. 15). The steel tank is designed to maintain the temperature of the concrete below 180°F. The concrete will reduce the activity level to about 15 mr/hr at the outer face and at a point corresponding to the horizontal center line of the core. This area of the plant can be designated for limited accessibility.

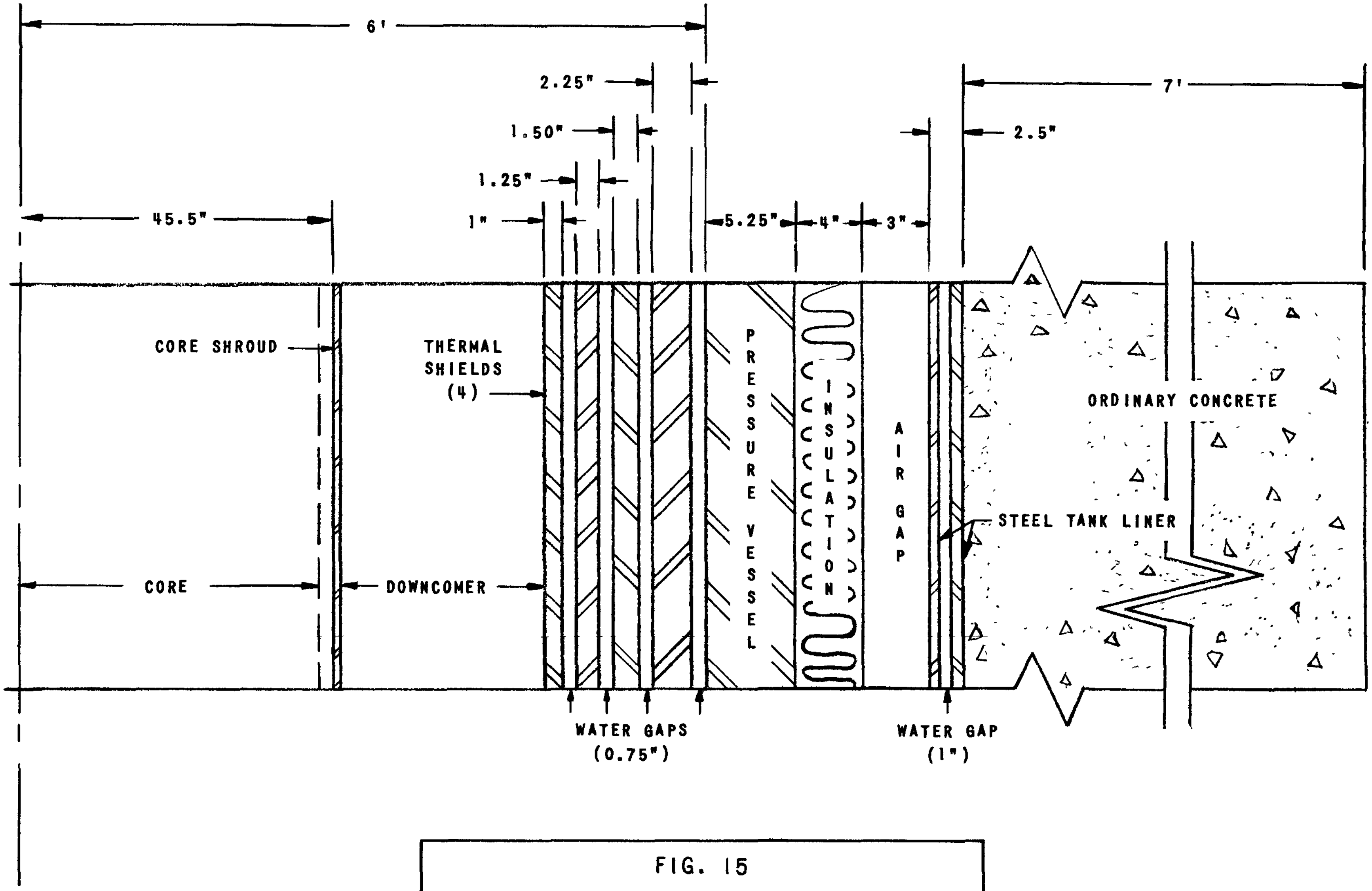


FIG. 15
RADIAL THERMAL AND BIOLOGICAL SHIELDING

The concrete shielding above the vessel is augmented by movable, concrete blocks that enclose the upper closure dome of the vessel which protrudes above the main floor. The weight of each block is within the capacity of the overhead crane.

5. Auxiliary Systems

a. Startup Heating

The startup heating system is a safety measure incorporated to (1) augment the worth of the control rod system through its temperature coefficient effect; and (2) prevent undue stresses in the primary system components and piping. Steam from the plant heating boiler is supplied to the shell side of a shell-and-tube heat exchanger. The reactor coolant in the tube side is circulated by natural convection.

b. High-pressure Coolant Bypass Purification

The reactor coolant is maintained at a purity of ~1-ppm total dissolved solids by the bypass purification system which operates at essentially the reactor operating pressure (1000 psig).

As indicated in Fig. 16, water at 546°F from the reactor flows through a regenerative heat exchanger where the temperature is reduced to 320°F. The water temperature is reduced further to 110°F by passage through a secondary heat exchanger which is cooled by the service water system. The flow continues through one of the two mixed-bed ion-exchange loops (about 30,000 lb/hr during normal operation). The effluent at 110°F is pumped back through the regenerative heat exchanger, to the reactor at 336°F to complete the cycle.

The ion-exchange vessels are carbon steel and are designed for a pressure of 1250 psig. A resin makeup slurry tank, and combination resin sluice and waste resin transfer pumps are provided to facilitate resin handling.

Circulation of the primary coolant through the purification system is effected by two mechanical shaft-sealed pumps. Leakage from the pump seals is directed to the retention tanks.

The relative merits of a low-pressure versus a high-pressure purification system are discussed in Appendix C. The latter is adjudged the more economical system for the conditions considered.

c. Shutdown Cooling

Normal and emergency shutdown cooling systems are provided to remove the decay heat. The normal shutdown cooling system

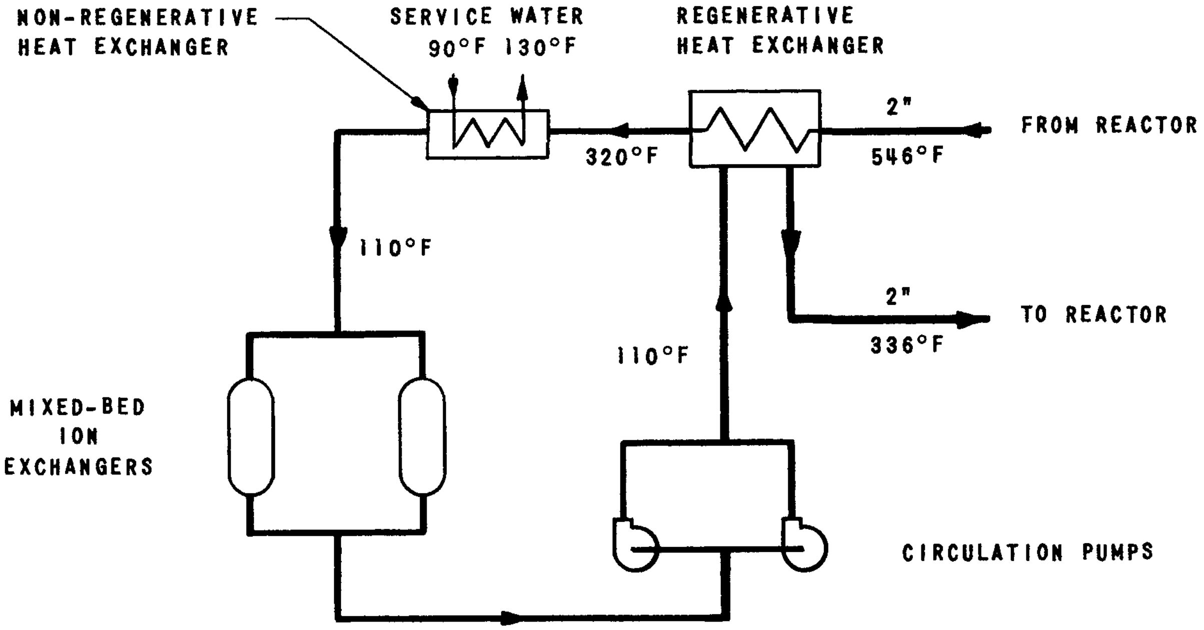


FIG. 16
HIGH-PRESSURE COOLANT BYPASS PURIFICATION SYSTEM

utilizes the main condenser to remove heat during the depressurizing stages. Both the startup heater and the nonregenerative heat exchanger in the purification system are interconnected and may be used to remove decay heat at appropriate power levels, with circulation of reactor water being effected by the pumps in the purification system.

The emergency shutdown cooling system consists of a natural-circulation evaporator. The steam coils are connected to the reactor system. The shell side is interconnected with the service water system and the overhead water-storage tank. The shell side is designed for an external pressure of 55 psig, and discharges through a vent stack to the atmosphere.

The foregoing method of effecting emergency shutdown cooling was selected in favor of other alternate designs for reasons discussed in Appendix E.

d. Shield Cooling

The shield cooling system comprises the service water-cooled steel tank liner on the inner face of the concrete shield, a shell-and-tube heat exchanger, and an expansion tank. The heat exchangers are designed for an inlet temperature of 120°F and an outlet temperature of 100°F. Circulation is effected by two 200-gpm pumps.

e. Chemical Poison Injection

A remotely operated system is provided to inject a poison solution (e.g., boric acid) into the reactor vessel in the event of an emergency promoted by a control rod failure. The system consists of a stainless steel storage tank and a positive displacement-type pump with a capacity of 25 gpm.

The injection system also may be utilized in connection with reactivity control during a cold shutdown.

f. Fuel Handling

Irradiated fuel assemblies will be transferred from the reactor to the spent-fuel storage well in a dry-type, lead-shielded coffin and transfer carriage which operates on the main floor. This system is favored because potential savings in building height and safety in handling ruptured assemblies offset the cost of a fuel transfer coffin.

Briefly, the unloading sequence will be as follows. After removal of the top shielding blocks and vessel closure, the rotating plug above the core will be indexed over the fuel assembly to be removed. The coffin and carriage will be positioned over the unloading port, and the assembly will be withdrawn into the coffin. The assembly will be transported and lowered into the receiving rack in the storage well. The well is designed to accommodate 1¼ spent cores. All latchings and delatching operations will be performed by direct vision.

A fresh fuel assembly will be loaded into the core with the aid of long-handled tools and the auxiliary hook of the overhead crane. The axial arrangement of fuel sections required for any fuel-management program will be performed underwater, also with long-handled tools.

After a suitable decay period, the spent fuel will be removed from the receiving rack (again with long-handled tools and the overhead crane), into a shipping cask for transfer out of the containment vessel via the air lock doors.

g. Spent-fuel Storage Well Cooling

The spent-fuel storage well-cooling system consists of two conventional 100-gpm circulating pumps, and a shell-and-tube heat exchanger designed for an inlet water temperature of 120°F and an outlet temperature of 100°F. The system is arranged for intermittent circulation of the water through one of the mixed-bed ion exchangers in the primary water-purification loops.

B. Power Plant

The power plant utilizes dry and saturated steam directly from the reactor pressure vessel to produce a gross electrical power output of approximately 100 Mw with a throttle steam flow of 1,290,000 lb/hr and a condenser pressure of 1.5 in. Hg abs. Condensate from the condenser is returned to the reactor through four stages of feed-water heating with fuel-flow condensate filtration to remove suspended particulate matter.

The turbine-generator, condenser, feed-water heaters, pumps, and related auxiliaries are housed in the turbine building adjacent to the containment vessel. The grade floors of both structures are connected by a personnel air lock in the containment vessel at a point which also provides convenient access to the control room and office extensions of the turbine building.

The main operating floor of the turbine building is 31 ft above grade level. Adequate "laydown" space is allocated for turbine dismantling and maintenance. Removable panels are installed in the floor to facilitate access of the overhead crane to all major equipment at lower elevations. A mezzanine is provided for access to the closed feed-water heaters, and for support of the air ejectors and other miscellaneous turbine auxiliaries. The grade floor and basement contains the condenser, reactor feed-water pumps, compressors, and supporting auxiliaries. The requisite biological shielding is provided around the condenser hot well and the air ejectors. Space has been allocated for additional shielding (if necessary) around certain components and equipment. Rolling steel doors provide access to the yard area.

1. Turbine

The turbine is a tandem compound, double flow unit with 23-in. exhaust blading designed for operation at 3600 rpm. Throttle steam conditions are 1000 psig, dry and saturated. To prevent excessive corrosion and erosion, moisture removal is effected at extraction points and by moisture-removal devices located in the crossover piping between the high- and the low-pressure sections of the turbine.

Extraction steam from four stages: one high-pressure closed heater stage, one deaerator heater stage, and two low-pressure, closed heater stages, are used to raise the final feed-water temperature to 400°F.

2. Condensing Equipment

The main condenser is a two-pass rectangular unit with 100,000 sq ft of condensing surface. The tubes are 1 in. OD with an active length of 30 ft. The condenser hotwell is capable of storing a 5-min supply of condensate.

In the event of a turbine trip-out, the main steam flow may be bypassed to the condenser for a limited period. To accommodate this additional steam flow, the condenser has been provided with steam distribution exhaust throat piping.

A twin-element steam jet air ejector is furnished to remove noncondensible gases from the condenser. These gases enter the condenser with the heater vent gases and turbine exhaust steam as dissociated H_2, O_2, and air. The air ejector discharge gas is vented to the atmosphere. A mechanical vacuum pump is also supplied for hogging purposes during startup.

Four mixed flow circulating water pumps supply cooling water to the condenser. The pumps are of standard design with cast iron drop pipe and inner casing, bronze impellers, forged carbon steel shafts, and rubber shaft guide bearings.

Three half-size vertical condensate pumps provide the head necessary to pump the condensate from the condenser hot well through the air ejectors, condensate filters, two low-pressure feed-water heaters, to the deaerating feed-water heater. Standard condensate pump design is suitable for this service. The shaft packing gland is sealed with condensate pump discharge water to prevent air inleakage.

3. Condensate Filters

Full-flow condensate filtering equipment is used to remove particulate matter which enters the system via the main steam system, turbine and condenser. Consideration was given to the use of a full-flow condensate demineralizer system, as discussed in Appendix B; however, with the cycle utilized, the use of a full-flow condensate demineralizing system would have a minimum effect on the size of the reactor bypass purification system. The majority of the corrosion products entering the system would occur on the outlet side of the demineralizing system due to its operating temperature limitations.

4. Feed-water Heaters

Feed-water heaters are incorporated in the steam cycle to improve the heat cycle efficiency by preheating the reactor feed-water temperature to 400°F. Four stages of turbine extraction steam heating are provided.

The merits of alternate arrangements for feed-water heating are discussed in Appendix A.

5. Reactor Feed-water Pumps

Three half-size standard boiler feed-water pumps are furnished for use as reactor feed-water pumps. These pumps are of the variable speed, multistage, horizontal, centrifugal type, motor driven through a hydraulic coupling.

To protect the feed-water pump from overheating when operating with the discharge valve shut, the design includes equipment for recirculating pump discharge water to the deaerating feed-water heater. This equipment consists of an open-shut regulating valve used in conjunction with a pressure breakdown orifice and accessory pump flow control equipment to initiate valve operation.

6. Main Power Electrical Equipment

The main electrical system is shown schematically in Fig. 17. A tie-in with an existing 138-kv system on the site is assumed. The main power transformer provides for voltage step-up from the generator voltage to 138 kv.

a. Generator

The generator is a direct-connected, hydrogen-cooled unit rated at 13,800 volts, and is 3-phase, 60-cycle, 128,000-kva, 0.85 pf, 0.64 short circuit ratio, with 30 psig hydrogen pressure. The excitation system consists of a direct-connected main exciter, and a motor-driven reserve exciter with a dc amplifier-type voltage regulator. Field breakers and voltage regulator equipment are located in the excitation switchgear. The generator neutral is grounded through a distribution transformer with a resistor across the low-voltage winding, all mounted within a metal enclosure.

b. Generator Step-Up Transformer

The generator step-up transformer is a Type FOA, 115,000-kva, 13.2-kv delta-138-kv wye, solidly grounded, 3-phase, 60-cycle design. It is directly connected to the generator through bus duct.

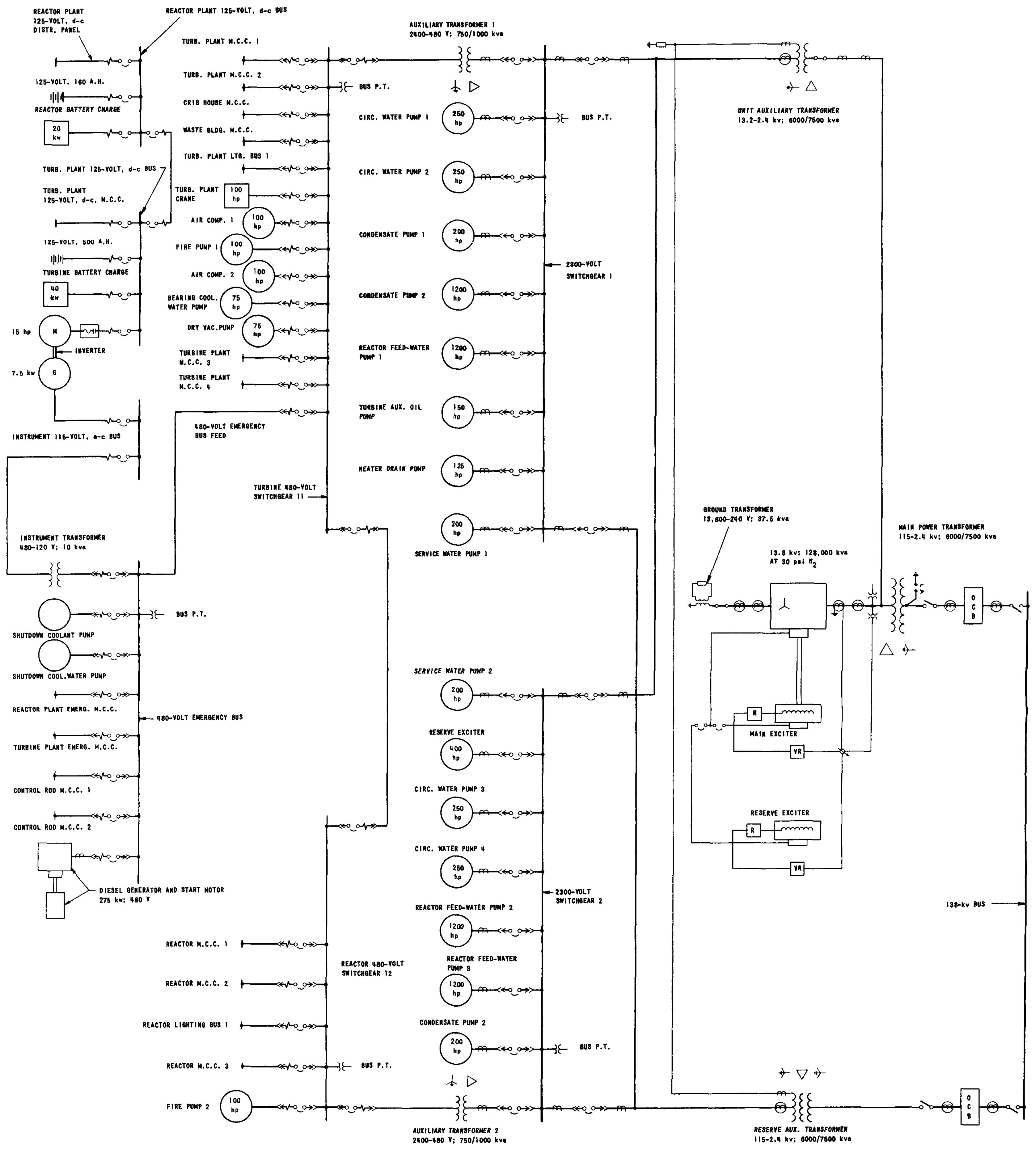


FIG. 17
ELECTRICAL SYSTEM-REFERENCE DESIGN 100 Mwe REACTOR POWER PLANT

c. Switchyard

Although the plant is assumed to be located on a new site, no provisions for a switchyard have been incorporated in the design. In estimating the costs, only the equipment up to the high side of the main power transformer and the reserve auxiliary transformers was considered.

C. Plant Auxiliaries

Certain components and systems are related to the operation of the plant as a whole, rather than being directly associated with the reactor or turbine plants. Such systems include instrumentation and control, radiation monitoring, radioactive waste disposal systems, and the electrical facilities for operation of the plant equipment.

1. Instrumentation and Control

The instrumentation and control systems comprise reactor instrumentation and control, plant instrumentation and control, and radiation monitoring. The purpose of these systems is to provide overall, integrated control and record of plant performance during all phases of operation consistent with safety and system integrity.

The nuclear instrumentation include startup channels, log and period channels, flux-level safety channels and linear level control channels. These instruments are for recording and indicating reactor neutron flux and period during startup and load-carrying conditions. The reactor will be shut down automatically if safety limits are exceeded.

The plant instrumentation transmits signals for control of the reactor and the steam bypass system, and complements the reactor instruments described previously. In addition to automatic control, these instruments furnish signals to the reactor safety system.

The plant is designed to operate either as a load following or as a base load plant, although it is assumed the plant will be operated primarily as a base load plant.

Primary control of the reactor plant output is achieved by the reactor control system (see Fig. 18) which adjusts the reactor control rods to maintain constant steam pressure at the turbine throttle valve. This control is limited by a neutron flux-level limiter which will not permit changes which exceed the capability of the reactor.

Several other control systems are necessary to achieve safe, overall plant control. Feed-water control comprises a three-element system that measures steam flow, feed-water flow, and reactor water level.

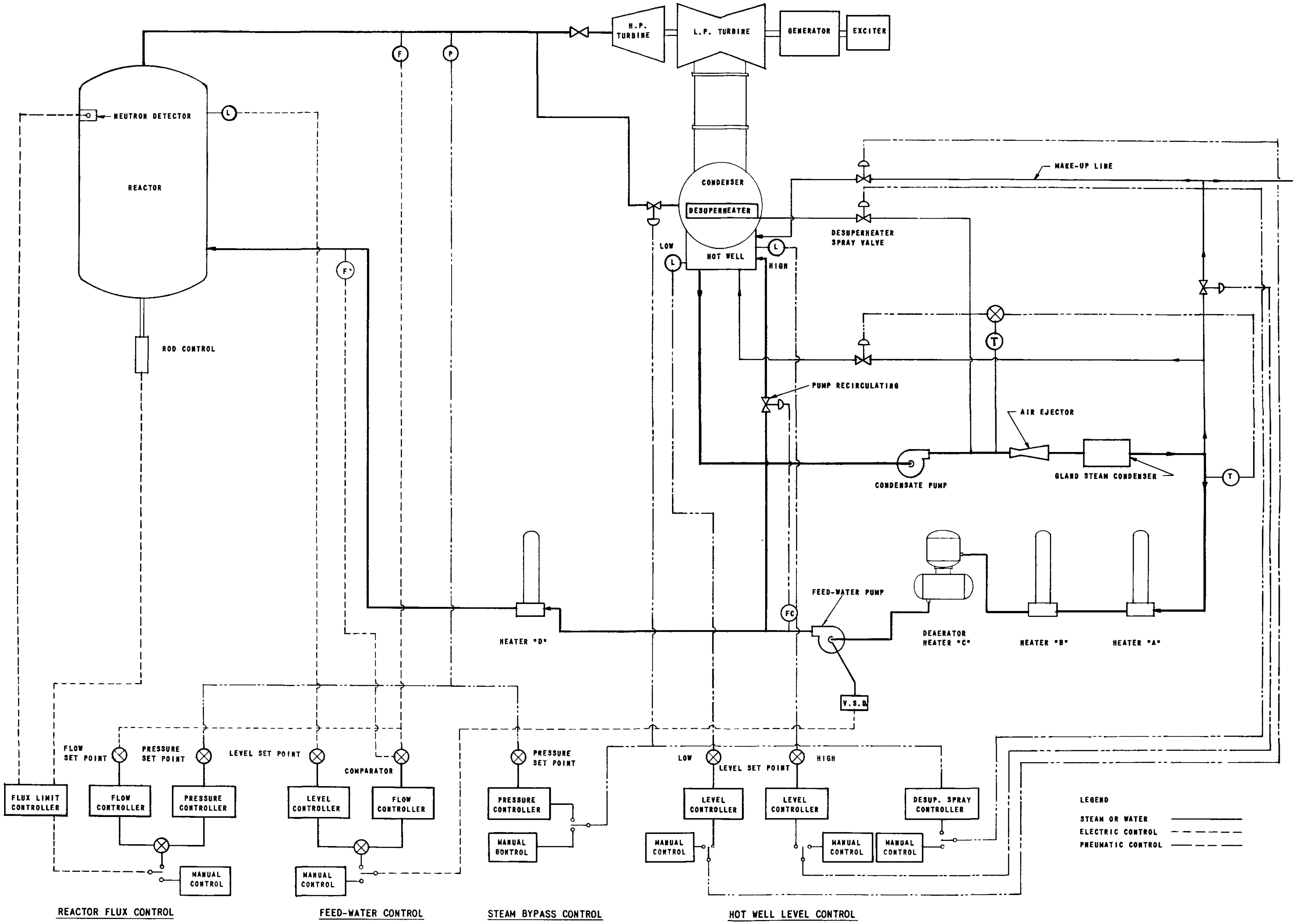


FIG. 18
CONTROL DIAGRAM-REFERENCE 100 Mwe REACTOR POWER PLANT

The steam bypass system cycles steam to the condenser for startup, shutdown, and for emergency heat dissipation. Radiation detectors monitor all areas of the containment vessel and certain areas of the turbine building which may be exposed to radiation. Instrumentation and alarms for recording and announcing high-radiation levels are installed in the control room.

2. Radioactive Waste Disposal System

Facilities are provided on the site for permanent disposal of a nominal amount of radioactive solid, liquid, or gaseous wastes generated in the plant.

The waste-treatment building is an underground, concrete structure, with a second story located at grade level. In the upper floor are located the control board and nonradioactive equipment.

3. Electrical Auxiliaries

During normal operation, all power for auxiliaries is supplied at 2300 volts from a 6000/7500-kva unit auxiliary transformer which is connected to the generator output.

For startup, or in the event of failure of the normal auxiliary power source, power is supplied from a reserve auxiliary transformer.

The major loads, including most of the larger motors, are supplied directly at 2300 volts from two groups of switchgear located in the turbine area. Two step-down transformers rated at 750-1000 kva, 2400-480 volts, supplied from the 2300-volt switchgear, furnish power for the smaller 480-volt auxiliaries through groups of switchgear. Two switch groups with direct-connected transformers are provided: one in the turbine building, and one in the containment vessel.

Small loads, which are not supplied directly from the 2300- or the 480-volt switchgear, are serviced by 440-volt motor-control centers at convenient locations in the turbine building and containment vessel.

In the event of failure of the normal and the reserve ac power sources, a diesel-generator unit, rated at 275 kw, 280 volts, will start automatically and supply emergency power for the site. Certain essential, dc-powered shutdown auxiliaries will be serviced from the station battery until the diesel unit comes on the line. An inverter set energized by the battery will supply 120 volts ac for the control and safety system. A 480-120-volt transformer provides a reserve source.

4. Plant Utility Systems

Plant utility systems are provided for maintenance and protection of plant equipment, disposal of nonradioactive plant wastes, and for the health and safety of operating personnel. These include, among others, the compressed air systems, service water system, heating and ventilating system, and plumbing and drainage system.

IV. COST ESTIMATES

A. Plant

The estimated costs for the reference design 100-Mw(e) reactor power plant are itemized in Table IV. The prices listed are effective as of January 13, 1960, and are based on a 40-hour work week. The indicated total capital investment of $19,802,000 is exclusive of the reactor core, spent fuel shipping casks, right-of-way for railroad tracks, spare parts, personnel training program, and cost escalation during design and construction.

Table IV

ITEMIZED COST ESTIMATE - REFERENCE DESIGN
100-Mw(e) REACTOR POWER PLANT

SITE AND GROUND IMPROVEMENTS

Power Plant Site	$15,000	
Ground Improvements		
Off Site		
Dredging	5,000	
Railroad Tracks		
Fill and grading; culverts and ditches	20,000	
Track work including ballast	60,000	
On Site		
Clearing site	5,000	
Fill and grading	25,000	
River bank protection	8,000	
Yard and miscellaneous drainage	20,000	
Sewage system	20,000	
Fence (not including switchyard)	15,000	
Roads	15,000	
Railroad tracks	30,000	
Parking lot	15,000	
Sidewalks	3,000	
Landscaping	3,000	
Test borings	10,000	
Deep well (200 ft), including pump, 25-hp motor, and appurtenances	10,000	
Miscellaneous other items	11,000	
TOTAL SITE AND GROUND IMPROVEMENTS:		$290,000.

Table IV (Cont'd.)

STRUCTURES

Containment Vessel		
Substructure		
Excavation	$ 32,000	
Backfill - compacted	18,000	
Disposal	4,000	
Dewatering - well pointing	42,000	
Concrete work outside vessel	31,000	
Miscellaneous	7,000	
Containment vessel steel, water tank, air lock doors, etc.	665,000	
Coating vessel below grade	3,200	
Insulation of vessel above grade	51,500	
Flexcell liner on interior of vessel	5,500	
Concrete: inside vessel; around reactor; shield walls; floors	200,000	
Structural steel	22,500	
Stainless steel liner plate in sump pit	3,500	
Liquid tile liner	2,200	
Bottom shield plug	10,000	
Top shield plugs	20,000	
Miscellaneous steel and iron	17,000	
Miscellaneous steel anchored in concrete	8,000	
Plumbing	7,000	
Elevator enclosure	4,500	
Painting	11,500	
Materials testing	2,000	
Miscellaneous other items	36,600	
Total, Containment Vessel:		$1,204,000

Table IV (Cont'd.)

STRUCTURES (Cont'd.)

Turbine Building		
Substructure		
Excavation and backfill	$ 27,000	
Concrete foundations and walls to grade floor; sheeting	210,000	
Materials testing	2,000	
Miscellaneous other items	15,000	
Superstructure		
Insulated metal siding exterior walls, interior partitions, floor, roof, windows, doors, hardware, etc.	350,000	
Louvers and roof ventilator	5,000	
Plumbing	37,000	
Miscellaneous steel and iron	35,000	
Elevator enclosure	Included	
Painting	25,000	
Miscellaneous other items	15,000	
Structural steel; girt steel	230,000	
Turbine and other equipment foundations		
Turbine foundation	65,000	
Other equipment foundations	25,000	
Total, Turbine Building:		$1,041,000
Waste Treatment Building		
Building	105,000	
Underground waste storage structures		
Solid waste burial pit	7,000	
Permanent resin storage tank (including stainless clad liner)	27,000	
Equipment foundations	5,000	
Foundations for two radioactive-gas holdup tanks	1,500	
Miscellaneous other items	4,500	
Total, Waste Treatment Building:		$ 150,000

Table IV (Cont'd.)

STRUCTURES (Cont'd.)

Circulating Water System		
Crib house		
Substructure; superstructure; structural steel	$ 275,000	
Painting	2,500	
Seal Well	35,000	
Discharge pipe - seal well to outfall	45,000	
Discharge outfall	18,000	
Miscellaneous other items	6,500	
Total, Circulating Water System:		$ 382,000
Miscellaneous Other Buildings		
Gate house	10,000	
Warehouses	65,000	
Field construction office and other construction buildings, including parking area	40,000	
Foundations - outside equipment and tanks	5,000	
Foundation and berm for 10,000-gallon oil tank	1,000	
Miscellaneous other items	4,000	
Total, Miscellaneous Other Buildings:		$ 125,000
TOTAL STRUCTURES		$ 2,902,000

EQUIPMENT, PIPING, ETC.

Containment Vessel		
Reactor and associated equipment		
Reactor vessel shell and cover	$1,625,000	
Reactor vessel internals, grid plate, core structure, thermal shield, and fuel-handling plug	460,000*	
Control rods and drives	175,000*	
		$2,260,000
Shielding equipment and work exterior to reactor		
Stainless steel wool insulation (4 in. thick)	20,000	
Water shield tank (four separate tank sections)	18,000	
		$ 38,000

---

* Estimated by Argonne National Laboratory

Table IV (Cont'd.)

EQUIPMENT, PIPING, ETC. (Cont'd.)

Shield cooling system		
One shield cooler	$ 5,000	
Two shield cooling circulating pumps (215-gpm capacity each; 20-ft suction head; 120-ft discharge head); and two 7.5-hp motors)	3,200	
One shield cooling hold-up tank (500 gal)	950	
		$ 9,150
Reactor purification system		
Two mixed bed ion exchangers (60-gpm capacity; no lead shielding required)	20,700	
Two strainers	1,500	
Two purification booster pumps (60-gpm capacity; 2,350-ft suction head and 2,540-ft discharge head, complete with 1-hp motor)	15,000	
One coolant purification system cooler	4,000	
One coolant purification system regenerative heat exchanger	5,200	
One resin makeup tank (300 gal)	500	
One waste resin transfer pump (50-gpm capacity; 10-ft suction head; and 150-ft discharge head), complete with 0.75-hp motor	1,400	
		$ 48,300
Shutdown cooling system		
One shutdown cooler	35,000	
One overhead water storage tank (15,000 gal)	*	
		$35,000
Fuel storage pool system		
One pool circulating water pump (200-gpm capacity; 10-ft suction head; and 130-ft discharge head, complete with 7.5-hp motor)	2,300	
One storage pool heat exchanger	5,000	
Fuel pool storage racks	9,000	
		$16,300

---

* Included in Containment Vessel Structure Cost

Table IV (Cont'd.)

EQUIPMENT, PIPING, ETC. (Cont'd.)

Containment Vessel (Cont'd.)		
Chemical poison injection system		
Chemical solution tank (300-gal capacity)	$ 1,500	
One 25-gpm high-pressure pump with motor drive	13,500	
		$15,000
Primary drain system		
Two retention tanks (5000 gal each)	3,500	
One retention tank drain and transfer pump with motor drive	700	
One filter	400	
		$ 4,600
Makeup water storage and fill equipment		
Two mono-bed ion exchangers	25,000	
Two twin filters	4,000	
One demineralized water storage tank (100,000 gal)	25,000	
One fill pump (100-gpm capacity; 125-ft net head) with motor drive	1,300	
Acid tank	600	
Caustic tank	600	
Acid ejector	300	
Caustic ejector	300	
Acid tank agitator	300	
Caustic tank agitator	300	
One electric heater	600	
		$ 58,300
Startup heater		$ 3,000
Fuel-handling machine and tools		$ 180,000*
Auxiliary equipment		
Heating, ventilating, and air conditioning	35,000	
One overhead crane main hook (50-ton capacity); and auxiliary hook (5-ton capacity)	55,000	
One duplex sump pump (100-gpm capacity; 150-ft discharge head) including motor	1,500	
One reactor cavity exhaust fan (20-cfm, 20 in. H_2O developed head), including motor	500	
Two sample coolers	1,000	
Elevator	20,000	
		$113,000

---

* Estimated by Argonne National Laboratory

Table IV (Cont'd.)

EQUIPMENT, PIPING, ETC. (Cont'd.)

Containment Vessel (Cont'd.)		
Equipment insulation		$ 7,500
Painting		2,500
Miscellaneous other equipment not listed above		79,350
Total, Containment Vessel		$ 2,870,000
Turbine Building		
One 100-Mw turbine-generator unit. (Turbine-throttle operating conditions: 1,000 psig saturated. TCDF with two 23-in. last stage buckets. Generator - 128,000 kva at 30-lb H_2 pressure - 0.85 PF. Complete with appurtenances	$ 4,195,000	
Turbine oiling equipment		
One two-compartment, clean and dirty oil tank (5,000 gal each)	4,500	
Oil purifier	3,700	
Two oil transfer pumps, including motors	1,000	
Oil filter	150	
Reserve Exciter	91,000	
Condenser and appurtenances		
One 102,000-sq ft surface condenser, 2-pass, divided water box, extended neck, backwash valves, etc. Steam jet air equipment Condenser tubes (Admiralty)	690,000	
Three vertical pit-type condensate pumps (1,050-gpm each; 550-ft discharge head) Three 200-hp condensate pump motors	50,000	
One dry vacuum pump, including motor	13,500	
Four full-flow precoat-type filters	94,000	
Feed-water heaters		
DC heater "C"	55,000	
Low-pressure heaters "A" and "B"	37,000	
One high-pressure heater "D"	40,000	

Table IV (Cont'd.)

EQUIPMENT, PIPING, ETC. (Cont'd.)

Turbine Building (Cont'd.)	
Feed-water pumps	
Three 1,400-gpm capacity pumps, 65-ft suction head, and 2,760-ft discharge head Three 1,250-hp motors and hydraulic couplings	$ 294,000
One bearing cooling water pump, 1,500-gpm capacity, 5-ft suction head, and 155-ft discharge head One 75-hp bearing cooling pump motor	3,400
One duplex bilge pump set, including motors	1,500
Tanks	
One domestic water tank (1,000-gal capacity)	1,300
Two high-pressure radioactive-gas holdup tanks (12,000-gal capacity; 300-lb design)	25,000
One domestic hot water tank (1,000-gal capacity)	1,300
One fuel oil storage tank (10,000-gal capacity)	2,600
Makeup water storage tank (20,000-gal capacity)	5,500
Air compressors	
Two station air compressors (500 cfm; 100-psig discharge pressure), including 100-hp motors	31,000
Two air receivers	2,500
One control air dryer (100 cfm)	3,800
Turbine room bridge crane (main hoist: 75-ton capacity; auxiliary hoist: 15-ton capacity)	62,500
Radioactive-gas compressor, including motor drive	2,500
Diesel generator unit	50,000
Turbine room elevator	20,000

Table IV (Cont'd.)

EQUIPMENT, PIPING, ETC. (Cont'd.)

Turbine Building (Cont'd.)		
Heating, ventilating, air conditioning, and two 20-ton water chillers	$30,000	
Heating boiler (150 b.h.p.)	7,500	
Two waste gas blowers, including motors	500	
Two waste gas coolers	1,700	
One heater drain pump (600 gpm at 600-ft net head; 125-hp motor)	5,000	
One seal gas blower, including motor	600	
One seal gas cooler	950	
One bearing water cooler	10,500	
Painting	5,000	
Miscellaneous other items not listed above	39,500	
Total, Turbine Building Equipment		$ 5,883,000
Piping and Insulation		
Piping		
Containment vessel and turbine building (including outdoors)	1,350,000	
Circulating water	90,000	
Piping insulation	150,000	
Total, Piping and Insulation		$ 1,590,000
Instruments, control, and gauge boards		
Nuclear instrumentation (in-core instruments not included)	75,000	
Other instruments and controls	55,000	
Gauge boards	70,000	
Electrical	30,000	
Total, Instruments, Control, and Gauge Boards		$ 230,000

Table IV (Cont'd.)

EQUIPMENT, PIPING, ETC. (Cont'd.)

Crib House Equipment		
Four travelling screens	$50,000	
Four vertical mixed-flow circulating water pumps (22,600-gpm capacity each; 25-ft discharge head)	145,000	
Four 250-hp motors for circulating water pumps		
Two vertical mixed-flow service water pumps (2,000-gpm capacity; 150-ft discharge head)	18,500	
Two 100-hp motors for service water pumps		
One diesel engine-driven service water pump (2,000-gpm capacity; 150-ft discharge head)	8,000	
Chlorination equipment	10,000	
Chlorine handling	2,000	
Two self-cleaning service water strainers	9,000	
Two bearing water filters	500	
Screen wash piping	1,500	
Painting	2,000	
Miscellaneous other items not listed above	3,500	
Total, Crib House Equipment		$250,000
Waste Disposal Equipment (In Waste Disposal Building)		
One radioactive-waste surge tank (10,000-gal capacity)	3,100	
One surge tank for dilute radioactive wastes (10,000 gal)	3,100	
Two waste surge tank transfer pumps (50-gpm capacity each, 100-ft discharge head), complete with motors	2,200	
Two septum-type filters (capacity: 10 gpm each)	2,500	
Two mixed-bed ion exchangers (capacity: 10 gpm each)	24,500	
One storage tank (10,000-gal capacity) for slightly radioactive deionized water	3,100	

Table IV (Cont'd.)

EQUIPMENT, PIPING, ETC. (Cont'd.)

Waste Disposal Equipment (In Waste Disposal Building) (Cont'd.)		
Two deionized water-transfer pumps (100-gpm capacity each, 175-ft discharge head), including motors	$ 2,300	
One waste evaporator	1,500	
One resin wash and separation tank (600 gal)	950	
One cation resin regeneration tank (300 gal)	600	
One anion resin regeneration tank (300 gal)	600	
One concentrated acid storage tank (1,000 gal)	1,700	
One 25% caustic storage tank (1,000 gal)	1,700	
Two transfer pumps for acid and caustic tanks (10-gpm capacity each, 100-ft discharge head), including motors	4,000	
One duplex sump pump, including motors	1,500	
One waste evaporator blow-down cooler	500	
One electric water heater (5-kw capacity)	150	
Two resin-storage decanting pumps (50-gpm capacity each, 50-ft discharge head), including motors	2,400	
One waste gas vent fan and filter, including motor (includes heating and ventilation)	1,500	
Insulation of equipment	1,500	
Painting	1,500	
Miscellaneous items not listed above	1,100	
Total, Waste Disposal Equipment		$62,000
TOTAL, EQUIPMENT, PIPING, ETC.		$10,885,000

Table IV (Cont'd.)

ELECTRICAL

Reactor Plant		
Structures and improvements		
Containment vessel	$ 3,000	
Miscellaneous yard	2,500	
Lighting	15,000	$ 20,500
Auxiliary electrical equipment		
Motor control centers	25,000	
Power and control cables	48,000	
Conduits, cable pans, etc.	14,000	
Cable penetration	9,000	
Auxiliary controls	8,000	
Grounding	6,000	
Miscellaneous	9,000	$119,000
Nuclear instrumentation		
Amplifiers	7,000	
Ionization and detector chambers	19,500	
Radiation monitors	59,500	$ 86,000
Communications		$ 8,000
Temporary power and light		$ 15,000
Total, Reactor Plant		$ 248,000
Turbine-Generator Plant		
Structures and improvements		
Turbine and office building	17,000	
Miscellaneous separate buildings	2,000	
Miscellaneous yard	16,000	
Lighting	32,000	$67,000
Primary electrical equipment		
Main power transformer	370,000	
Generator connections	70,000	
Power, control, and instrument cables	9,000	
Conduits	7,000	
Neutral equipment	7,000	
Grounding	8,000	
Miscellaneous	5,000	$ 476,000

Table IV (Cont'd.)

ELECTRICAL (Cont'd.)

Turbine-Generator Plant (Cont'd.)		
Auxiliary electrical equipment		
Auxiliary power transformers	$122,000	
2300-volt switchgear	150,000	
480-volt switchgear	70,000	
Motor control centers	22,000	
Auxiliary controls	13,000	
Power and control cables	116,000	
Conduits, cable pans, etc.	64,000	
Battery, etc.	7,000	
Grounding	10,000	
Miscellaneous	12,000	
		$586,000
Communications		$12,000
Temporary power and light		$22,000
Total, Turbine-Generator Plant		$1,163,000
Crib House		
Motor-control center	6,000	
Control equipment	3,000	
Cable and conduit	5,000	
Miscellaneous	1,500	
Total, Crib House		$15,500
Waste Disposal System		
Motor-control center	4,500	
Control equipment	2,000	
Cable and conduit	2,500	
Miscellaneous	1,000	
Total, Waste Disposal System		$10,000
TOTAL, ELECTRICAL		$1,437,000

Table IV (Cont'd.)

MISCELLANEOUS EQUIPMENT

First Aid Equipment	$ 2,500	
Office Furniture and Equipment	4,500	
Locker Room Equipment, and Other Miscellaneous Items	3,000	
Machine Shop, Machine Tools, and Miscellaneous Store Room Fixtures	75,000	
Fire-Fighting Equipment	5,000	
TOTAL MISCELLANEOUS		$ 90,000

RECAPITULATION

SITE AND GROUND IMPROVEMENTS	290,000
STRUCTURES	2,902,000
EQUIPMENT, PIPING, ETC.	10,885,000
ELECTRICAL	1,437,000
MISCELLANEOUS EQUIPMENT	90,000
STARTUP SUPERVISION	50,000
Subtotal (Including Contractor Overhead and Profit)	$15,654,000
Contingency (10%)	1,565,500
	$17,219,500
Top Charges (15%)	2,582,500
GRAND TOTAL	$19,802,000

NOTE: An additional cost of $885,000 is incurred by using stainless steel components in the main steam and boiler feed cycles where temperatures exceed 250°F.

B. Fuel Cycle

As stated previously, a rigorous study was not made of a specific core loading. Experience has shown that the final fuel cost is relatively insensitive to most parameters except core lifetime and fabrication costs. Consequently, a series of fuel-cycle costs were derived by changing the various core parameters.

The results are listed in Table V. All cores have a 310-Mw thermal capacity and are assumed (on an 80% load factor) to generate 7×10^8 kw(e) (net) per year. Cores A, B, and C are included to show that high power density per se does not afford any significant advantage in a "short" fuel cycle time of 10,000 Mwd/tonne. There is a significant savings for long burnup cores, however, as illustrated by cores H and I.

The charges and methods used to prepare the costs were as prescribed in "Nuclear Fuel Cycle Costs" (September, 1959), prepared by the Evaluation and Planning Branch, Division of Reactor Development, USAEC. The fuel-cycle costs in Table V were based upon the following criteria:

1. Cost of fresh UF_6 per AEC Schedule of Charges.
2. Fuel-use charge based on 4% per annum at following values of fuel:
    a. Full value for initial enrichment from time of delivery of UF_6 until delivery to fresh fuel storage. (This portion of use charge is assumed to be included in fabrication cost lump sum).
    b. Full value of initial enrichment during fresh fuel storage time on site.
    c. Average value of fuel during in-core residence as it progresses from initial enrichment to the depleted state.
    d. Final value of depleted fuel during time from removal from core to return to AEC as UF_6.

This method of charge has not been officially approved by the AEC. Since it is understood that periodic payments will be made out of operating capital for this cost, however, there is a probability that this method or one similar will be acceptable.

3. A plant load factor of 0.8 has been assumed, which results in the sale of approximately 7×10^8 electrical kilowatts per year. The load factor (LF) has been set at 0.8 rather than at 0.6 or 0.7 which is customary for conventional fossil-fired plants. Nuclear fuel cost must be lower than fossil fuel, or the nuclear plant can never be competitive because of inherently higher capital charges. If the fuel cost is lower for nuclear plants, there will be incentive to operate them as base load plants. Verification of this assumption must await extended plant operating experience.

Table V

INFLUENCE OF CORE PARAMETERS ON FUEL CYCLE COSTS

Parameter	"A"	"B"	"C"	"D"	"E"	"F"	"G"	"H"	"I"
Core Loading, kg U	31,853	24,183	18,869	24,133	24,133	24,133	18,869	24,133	18,869
Power Density, kw/liter of core	30	40	50	40	40	40	50	40	50
Average Burnup, Mwd/tonne	10,000	10,000	10,000	10,000	15,000	15,000	15,000	20,000	20,000
Initial Enrichment, % U^{235}	2.0	2.0	2.0	2.0	2.25	3.0	2.25	2.65	2.65
Final Enrichment, % U^{235}	1.15	1.15	1.15	1.15	1.0	1.75	1.0	1.0	1.0
Plutonium Production, gm Pu/kg U	5.5	5.5	5.5	5.5	6.5	7.5	6.5	6.5	6.5
Fabrication Cost, $/kg U	140	140	140	110	140	140	140	140	80
Burnup Cost, $/ kg U	124	124	124	124	183	193	183	244	244
Fabrication Cost, mill/kw-hr	1.83	1.83	1.83	1.43	1.21	1.21	1.21	0.92	0.52
Burnup Cost, mill/kw-hr	1.64	1.64	1.64	1.64	1.62	1.71	1.62	1.61	1.61
Shipment Reprocess, Conversion and Capital Charges, mill/kw-hr	1.08	1.02	0.97	1.03	0.83	0.90	0.71	0.79	0.61
Total Gross Power Cost, mill/kw-hr	4.55	4.49	4.44	4.10	3.66	3.82	3.54	3.32	2.74
Plutonium Credit, mill/kw-hr	0.83	0.83	0.83	0.83	0.65	0.82	0.65	0.50	0.50
Total Net Power Cost, mill/kw-hr	3.72	3.66	3.61	3.27	3.01	3.00	2.89	2.82	2.24

4. Cost of fabrication of fuel includes:
    a. conversion of UF_6 to UO_2;
    b. structural material required for cladding and supporting fuel material in assembly;
    c. labor of assembly;
    d. inspection, testing, and quality control;
    e. material losses, cost of scrap recovery, and rework;
    f. use charge for fissionable material during fabrication; and
    g. packaging for shipment.
5. Plutonium value of $12.00 per gram.
6. All reprocessing and conversion charges are per AEC published rates.
7. Capital costs for money used for fabricating fuel are based on interest rate of 6%. This rate is charged against the full cost of fabrication for the period required for fabrication and storage, and against the average value of the cost of fabrication during the in-core period. The value of fabrication capital is assumed to be zero when the fuel is removed from the core.

C. Total Power Cost

The total power cost includes capital costs, fuel-cycle costs, operation and maintenance costs, and insurance costs. With the capital costs estimated at ~ $20,000,000, and a fixed charge interest rate of 14%, the capital charge portion of total is about 4 mills/kw-hr.

The fuel-cycle cost is subject to many factors which produce a spread ranging from 3.7 to 2.2 mills/kw-hr. The 3.7 value is believed to be achievable in the near future. The 2.2 value may be achieved in the late 1960's or early 1970's after sufficient development and operating experience. Consequently, a value of 3.01 mills/kw-hr is used as an average value over the life of the reactor. It is also representative of a cycle (Core "E") which might be realized in the mid-1960's.

The operation and maintenance cost of 0.8 mill/kw-hr has been used by the AEC in its Plant Cost Normalization Studies of 1959. This cost is also subject to disagreement; in many estimates this charge is placed at a much higher level. It has been used here because the basic simplicity of the design should assist in holding costs down.

The insurance cost of 0.34 mill/kw-hr was also used in the AEC Normalization Studies.

A summation of the above costs is as follows:

Item	Mills/kw-hr
Capital Charge	4.00
Fuel Cycle	3.01
Operation and Maintenance	0.80
Insurance	0.34
Estimated Total Power Cost:	8.15 mills/kw-hr .

The successful design and construction of a plant capable of producing power at the estimated cost is subject to several critical factors:

1. experience of the designers;
2. confidence;
3. ability of the Project Manager to retain the original simplicity of the conceptual design; and
4. completion of plant in much less time than required for the present generation of reactors.

The reference power plant design presented in this study, if coupled with the above factors, should have the best chance of any similar plants projected to date, in approaching the 8- to 9-mill plant.

APPENDIX A

EVALUATION OF TURBINE CYCLES

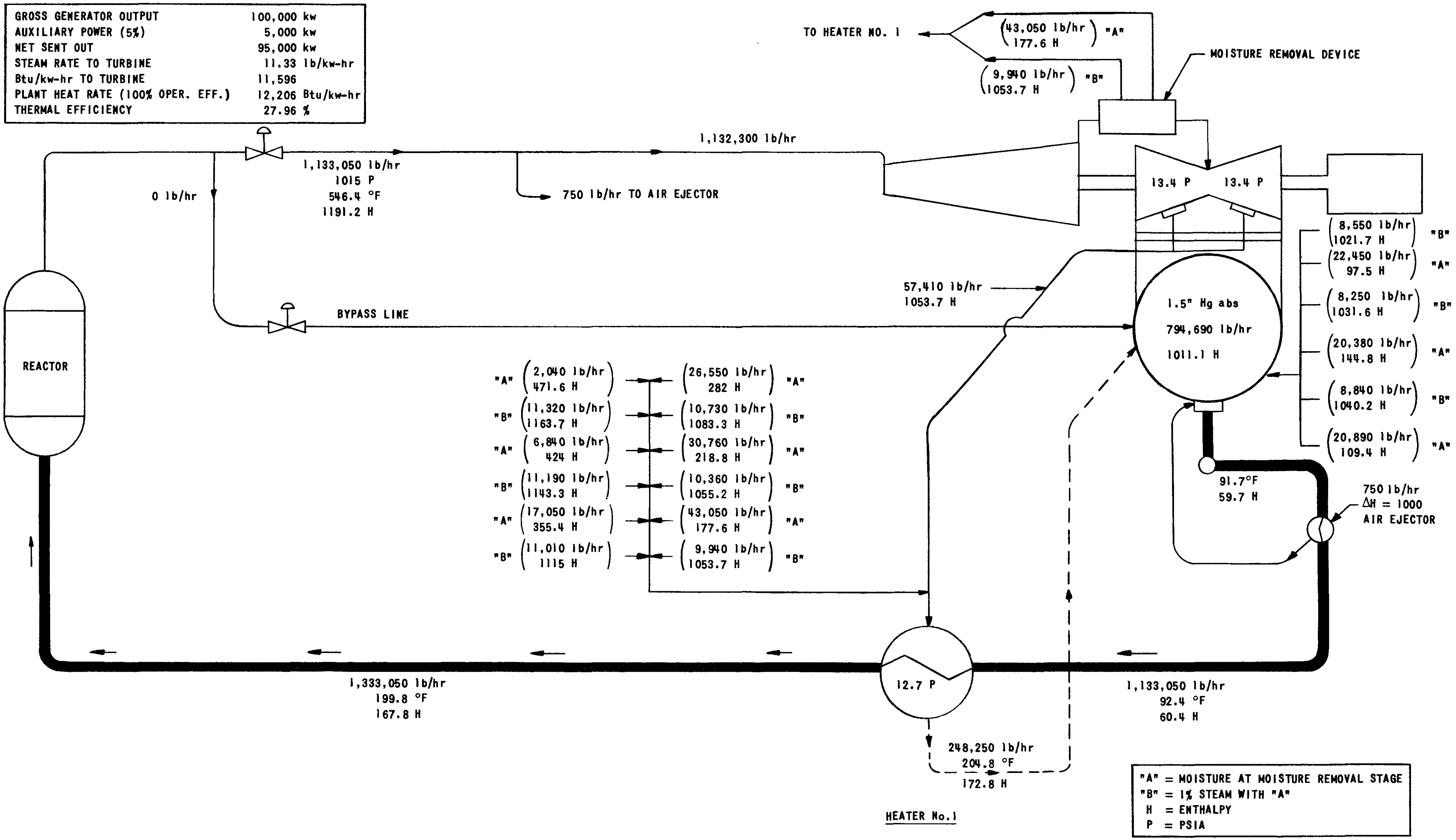
Preliminary analyses were made to evaluate the influence of steam conditions at the turbine throttle valve and final feed-water temperature on overall station efficiency. Heat balances were prepared for cycles using saturated steam at 1000 psig and at 850 psig, with regenerative feed-water heating cycles featuring one to four feed-water heaters. A TCDF, 3600-rpm turbine with 23-inch L.P. blading was considered for both throttle steam conditions. Moisture removed from the turbine at various extraction stages and crossover point was introduced into the appropriate heater cycle. All heater cycles were of the flashed drain type: drains from successive heaters are cascaded to the next lower pressure heater, and the combined drains are flashed to the main condenser.

The results are shown in Figs. 19 to 26. For the 1000-psig throttle steam condition, the thermal efficiencies were 27.96%, 29.47%, 30.04%, and 30.70%, for one to four feed-water heaters, respectively (see Figs. 19 to 22). With throttle steam at 850 psig, the comparable efficiencies were 26.69%, 28.31%, 29.07%, and 29.48% (see Figs. 23 to 26).

The foregoing analyses indicated that a cycle using 1000-psig saturated steam at the throttle valve, and four feed-water heaters to obtain a final feed-water temperature of 400°F, would be the most desirable system compatible with a reactor designed for natural circulation and internal steam separation.

An additional heat balance was prepared to determine the efficiency of a cycle using 1000-psig steam at the throttle valve and a deaerating feed-water heater, with the low-pressure heater drains being pumped ahead into the condensate system rather than being flashed to the main condenser. The deaerator feed-water heater replaced the third highest pressure feed-water heater in the cycle. The drains from the highest pressure heater were directed to the deaerator heater, while drains from the two lower pressure heaters were combined and returned to the system by a heater drain pump.

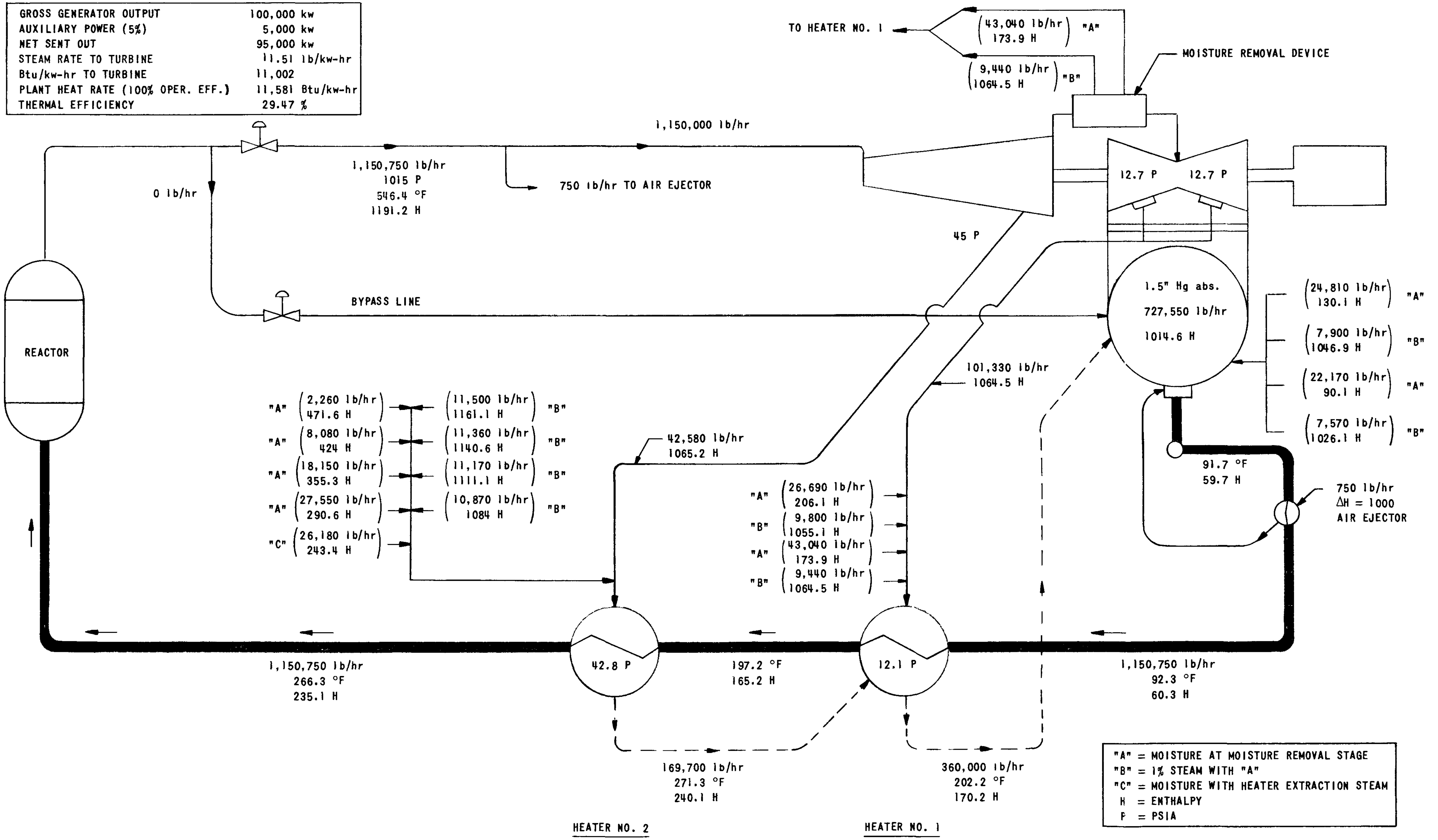
The result was an increase in thermal efficiency (31.34%) by comparison with an efficiency of 30.70% for the 1000-psig, 4-closed heater cycle. The increase is due partly to the higher efficiency of the deaerator feed-water heater compared with the closed heater it replaced in the cycle, and partly to the heat saving effected by pumping the drains which are otherwise rejected to the condenser circulating water in the flashed cycle.



GROSS GENERATOR OUTPUT	100,000 kw
AUXILIARY POWER (5%)	5,000 kw
NET SENT OUT	95,000 kw
STEAM RATE TO TURBINE	11.33 lb/kw-hr
Btu/kw-hr TO TURBINE	11,596
PLANT HEAT RATE (100% OPER. EFF.)	12,206 Btu/kw-hr
THERMAL EFFICIENCY	27.96 %

"A" = MOISTURE AT MOISTURE REMOVAL STAGE
"B" = 1% STEAM WITH "A"
H = ENTHALPY
P = PSIA

FIG. 19
PERFORMANCE CHARACTERISTICS - 1 FEED-WATER HEATER CYCLE; 1000-PSIG SATURATED STEAM



GROSS GENERATOR OUTPUT	100,000 kw
AUXILIARY POWER (5%)	5,000 kw
NET SENT OUT	95,000 kw
STEAM RATE TO TURBINE	11.51 lb/kw-hr
Btu/kw-hr TO TURBINE	11,002
PLANT HEAT RATE (100% OPER. EFF.)	11,581 Btu/kw-hr
THERMAL EFFICIENCY	29.47 %

"A" = MOISTURE AT MOISTURE REMOVAL STAGE
"B" = 1% STEAM WITH "A"
"C" = MOISTURE WITH HEATER EXTRACTION STEAM
H = ENTHALPY
P = PSIA

FIG. 20

PERFORMANCE CHARACTERISTICS - 2 FEED-WATER HEATER CYCLE; 1000-PSIG SATURATED STEAM

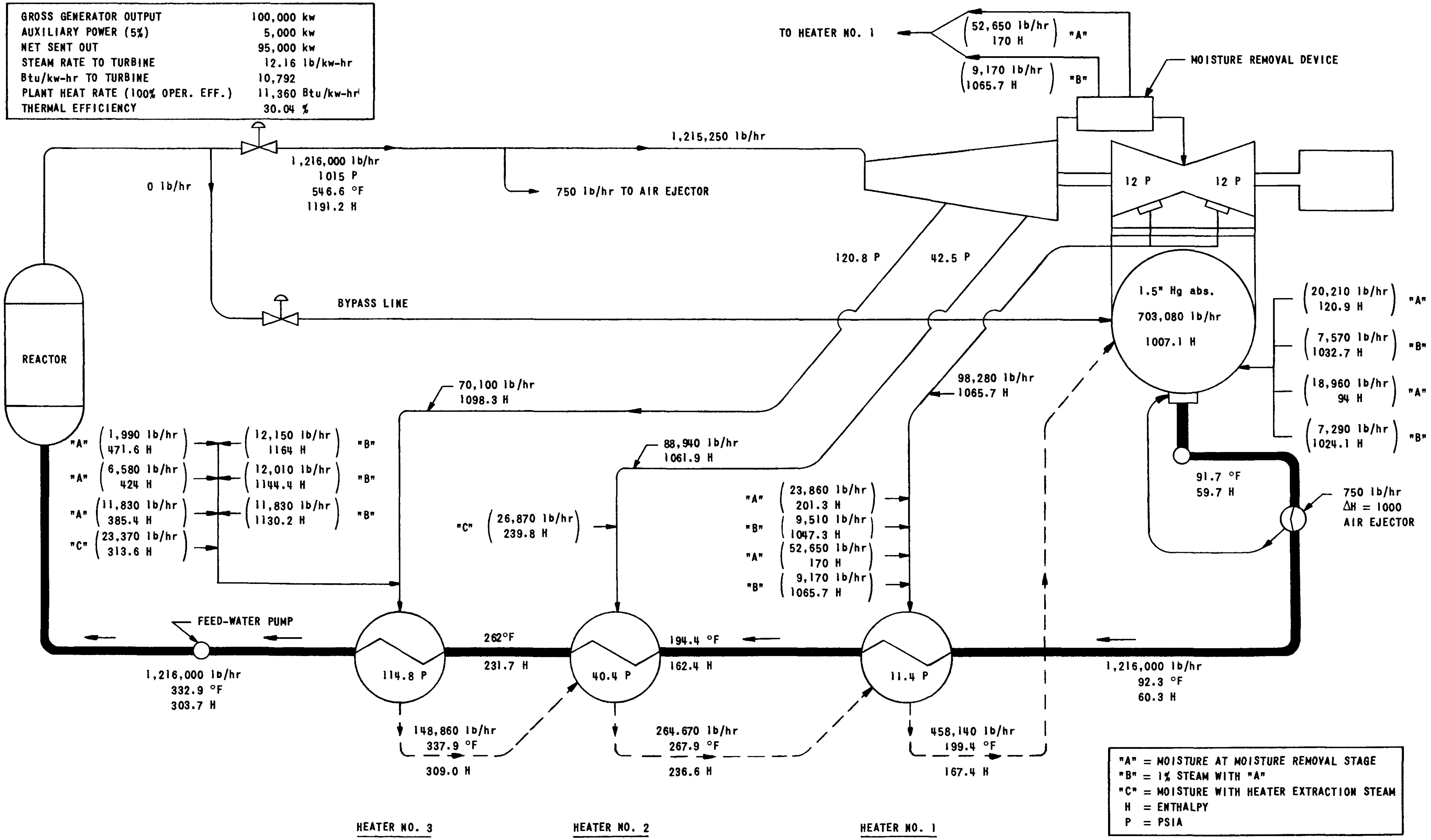
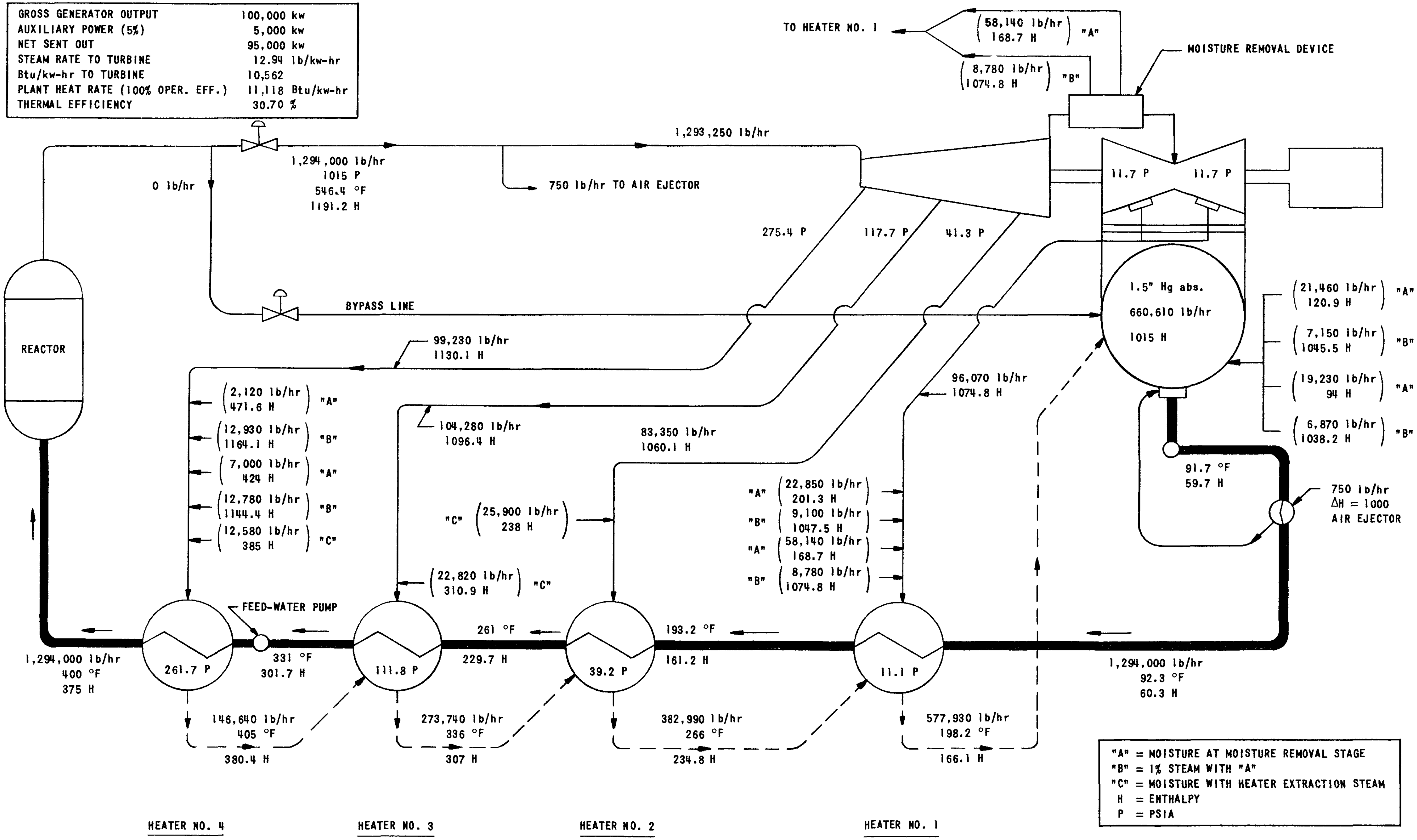


FIG. 21

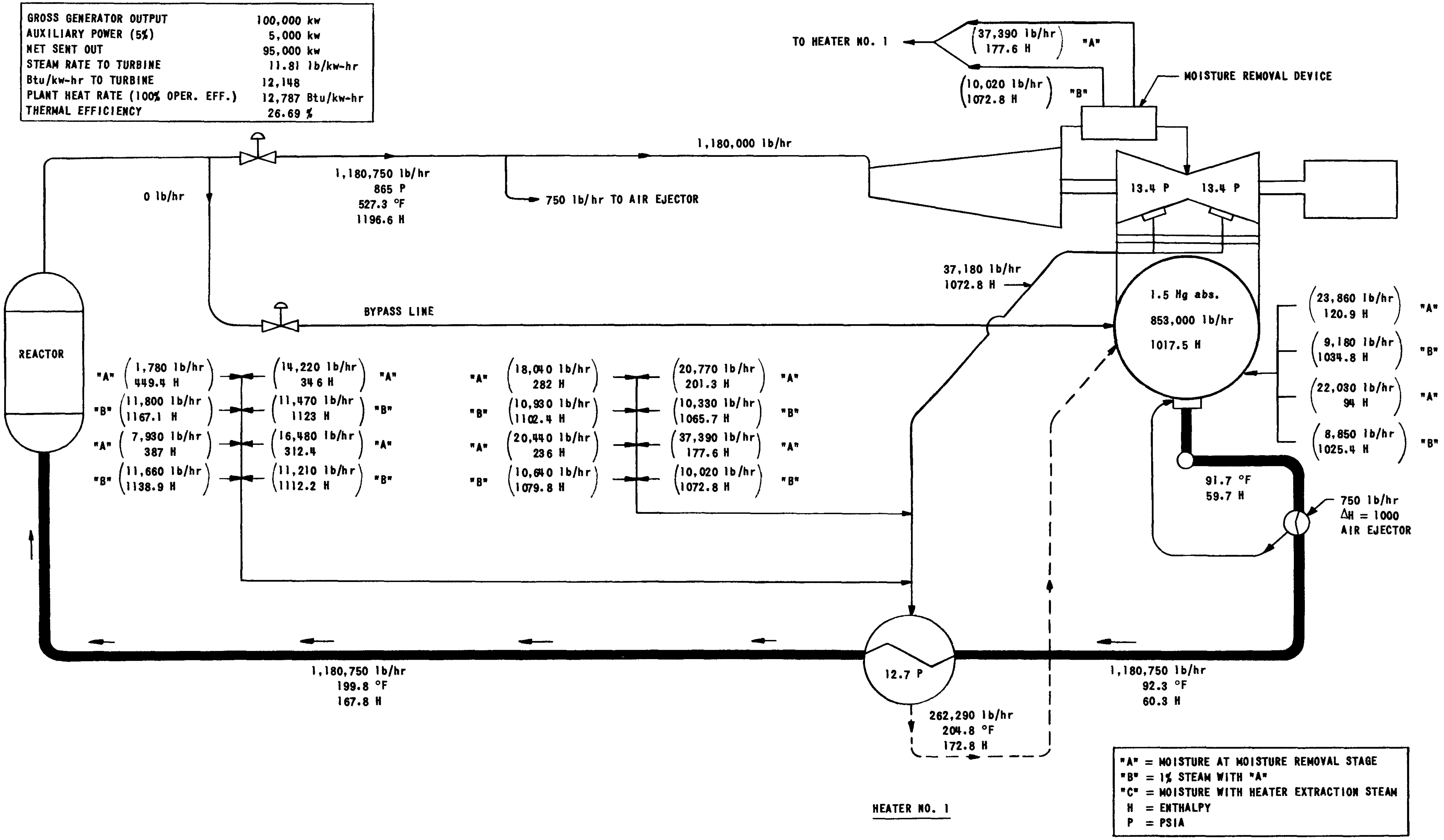
PERFORMANCE CHARACTERISTICS - 3 FEED-WATER HEATER CYCLE; 1,000-PSIG SATURATED STEAM



GROSS GENERATOR OUTPUT	100,000 kw
AUXILIARY POWER (5%)	5,000 kw
NET SENT OUT	95,000 kw
STEAM RATE TO TURBINE	12.94 lb/kw-hr
Btu/kw-hr TO TURBINE	10,562
PLANT HEAT RATE (100% OPER. EFF.)	11,118 Btu/kw-hr
THERMAL EFFICIENCY	30.70 %

"A" = MOISTURE AT MOISTURE REMOVAL STAGE
"B" = 1% STEAM WITH "A"
"C" = MOISTURE WITH HEATER EXTRACTION STEAM
H = ENTHALPY
P = PSIA

FIG. 22
PERFORMANCE CHARACTERISTICS - 4 FEED-WATER HEATER CYCLE; 1000-PSIG SATURATED STEAM

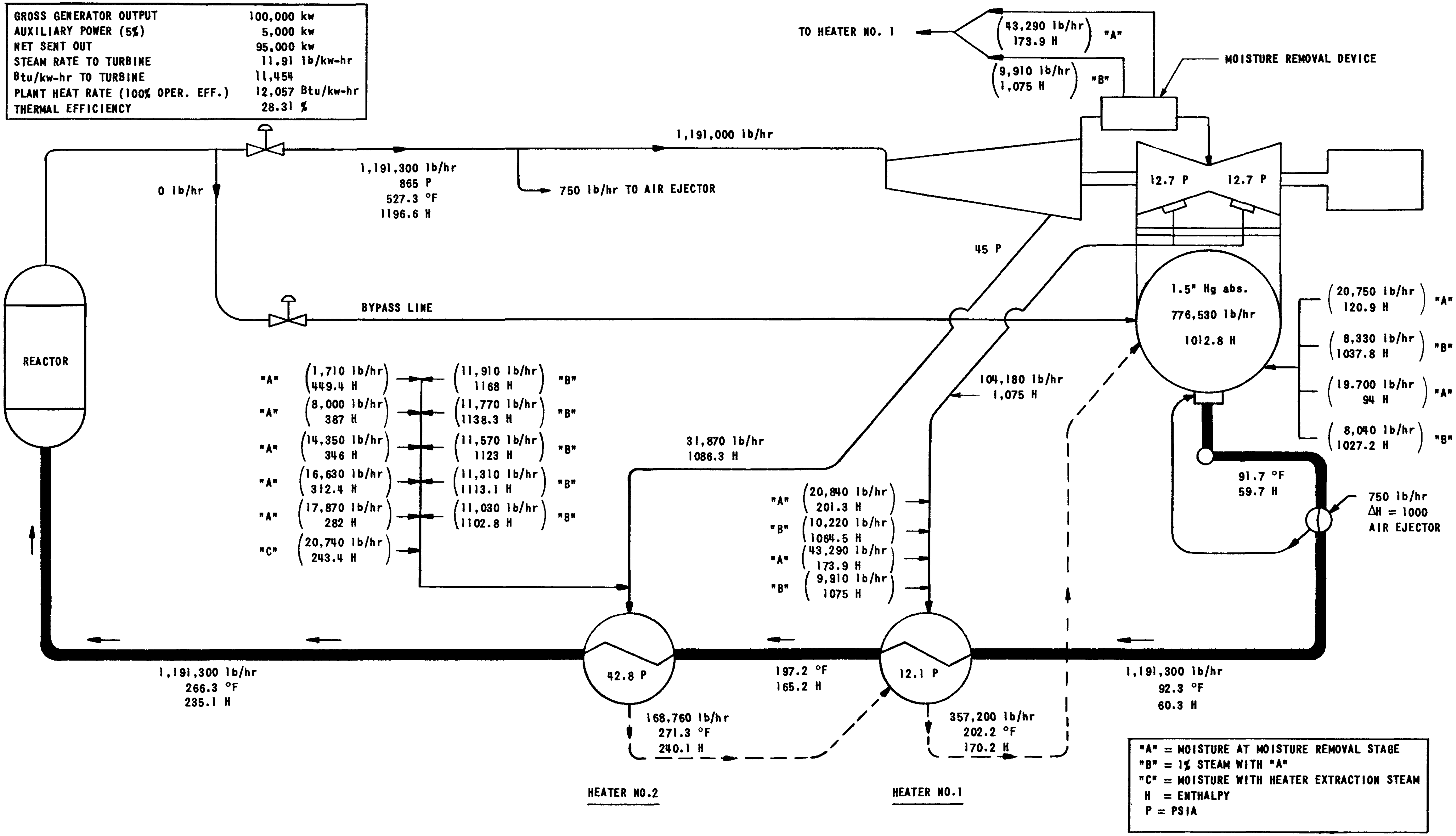


GROSS GENERATOR OUTPUT	100,000 kw
AUXILIARY POWER (5%)	5,000 kw
NET SENT OUT	95,000 kw
STEAM RATE TO TURBINE	11.81 lb/kw-hr
Btu/kw-hr TO TURBINE	12,148
PLANT HEAT RATE (100% OPER. EFF.)	12,787 Btu/kw-hr
THERMAL EFFICIENCY	26.69 %

"A" = MOISTURE AT MOISTURE REMOVAL STAGE
"B" = 1% STEAM WITH "A"
"C" = MOISTURE WITH HEATER EXTRACTION STEAM
H = ENTHALPY
P = PSIA

FIG. 23

PERFORMANCE CHARACTERISTICS - 1 FEED-WATER HEATER CYCLE; 850-PSIG SATURATED STEAM



GROSS GENERATOR OUTPUT	100,000 kw
AUXILIARY POWER (5%)	5,000 kw
NET SENT OUT	95,000 kw
STEAM RATE TO TURBINE	11.91 lb/kw-hr
Btu/kw-hr TO TURBINE	11,454
PLANT HEAT RATE (100% OPER. EFF.)	12,057 Btu/kw-hr
THERMAL EFFICIENCY	28.31 %

"A" = MOISTURE AT MOISTURE REMOVAL STAGE
"B" = 1% STEAM WITH "A"
"C" = MOISTURE WITH HEATER EXTRACTION STEAM
H = ENTHALPY
P = PSIA

FIG. 24

PERFORMANCE CHARACTERISTICS - 2 FEED-WATER HEATER CYCLE; 850-PSIG SATURATED STEAM

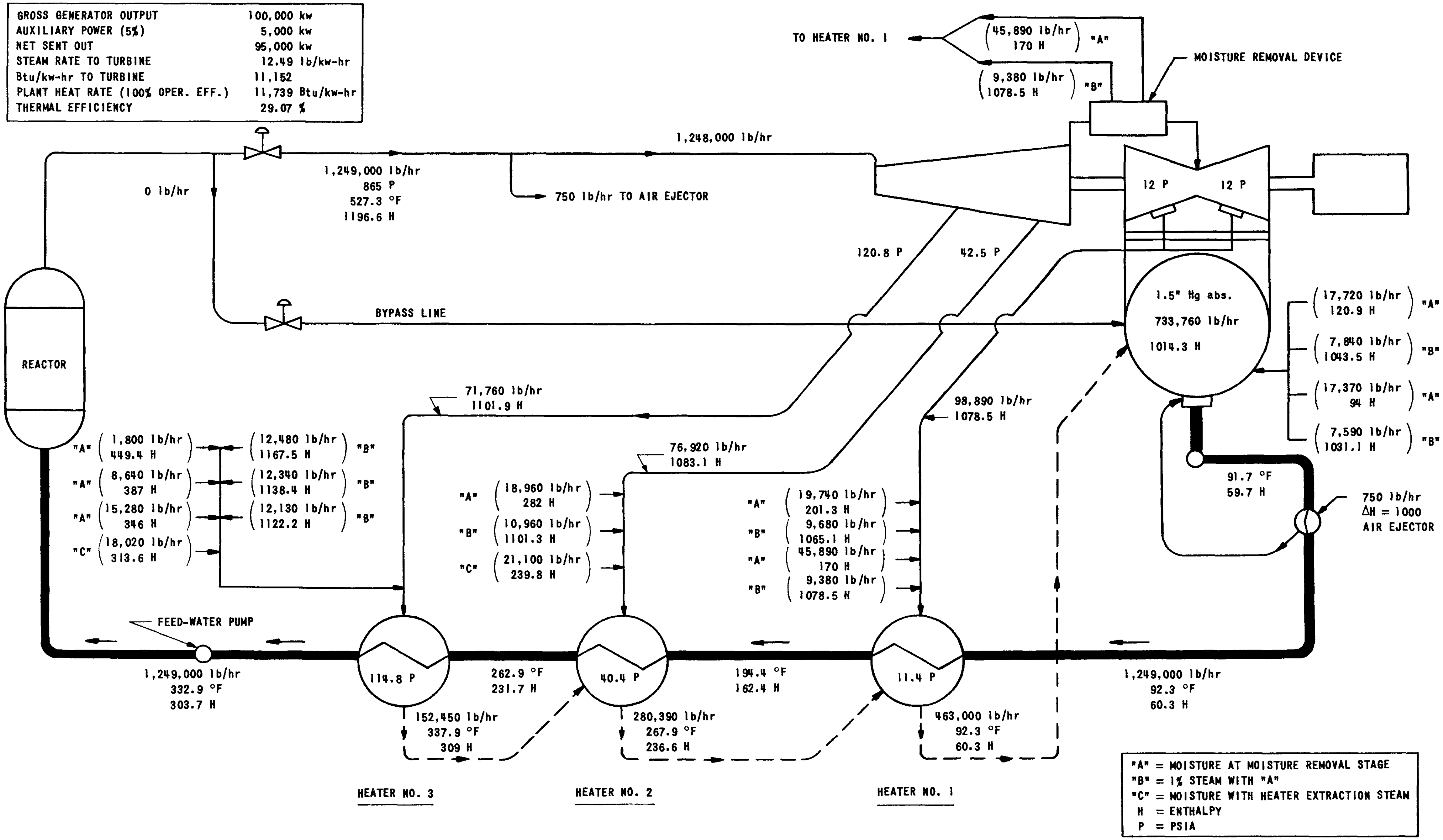


FIG. 25
PERFORMANCE CHARACTERISTICS - 3 FEED-WATER HEATER CYCLE; 850-PSIG SATURATED STEAM

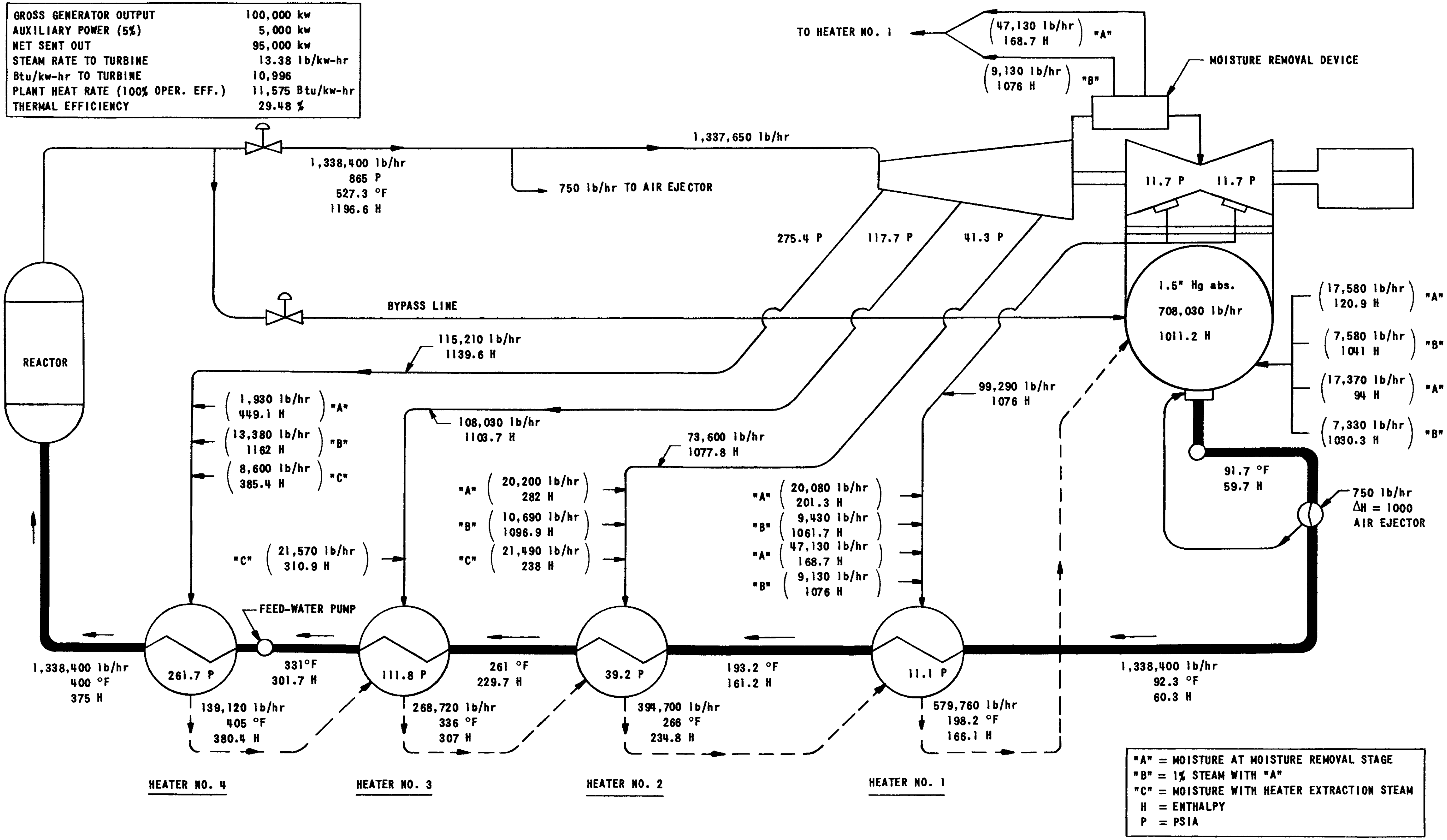


FIG. 26

PERFORMANCE CHARACTERISTICS - 4 FEED-WATER HEATER CYCLE; 850-PSIG SATURATED STEAM

A comparison of the economics pertinent to both cycles was also made. With a fuel cost of 4 mills/kw-hr assumed for the flashed cycle, the results showed that for a capital cost increase of about $16,000, an annual savings of about $60,000 would accrue to the cycle using a deaerating feed-water heater and a heater drain pump.

Accordingly, the cycle selected for more rigorous analysis featured (1) a TCDF, 3600-rpm turbine with 23-inch exhaust blading designed for operation with 1000 psig saturated steam at the turbine throttle valve; and (2) four extraction stages for regenerative feed-water heating, using a deaerating feed-water heater and a heater drain pump (see Fig. 9).

Venting of the deaerating heater into the condenser air ejector off-gas system should present no problem. In order to provide sufficient NPSH on the feed-water pumps, the deaerating feed-water heater, with its storage tank, is located on the roof of the turbine building (see Fig. 6). Normal practice is to provide a single heater drain pump and, in the event of pump failure, to flash the drains to the condenser and suffer the loss in heat rate while the pump is inoperative. Therefore, a similar arrangement is incorporated in this design.

APPENDIX B

FULL-FLOW CONDENSATE DEMINERALIZATION VS FULL-FLOW CONDENSATE FILTRATION SYSTEMS

Full-flow condensate demineralization has been utilized in boiling water reactor plants designed for operation with closed feed-water heaters. In these designs, the heater drains have been arranged for cascading to heaters at successively lower pressures and, finally, to the main surface condenser.

The location of the full-flow condensate demineralizer in the cycle is limited by the allowable operating temperature of the resins employed to remove dissolved solids from the condensate. With the recommended operating temperatures of 110 to 120°F (140°F, maximum), the unit is, in general, limited to placement at the discharge of the condensate pumps.

With the cycle arranged to receive all heater drains at the main surface condenser, the impurities in the fluid picked up in the main steam piping, turbine, condenser feed-water heater shells, and heater drain piping can be removed in a full-flow condensate demineralizer. The products of corrosion picked up in the condensate-return piping and tube side of the feed-water heaters are, however, unavoidably returned to the reactor with the feed water. When, as in the current study, the heater drains are pumped into the condensate-return system, the corrosion products from the extraction steam piping, feed-water heater shells, and heater drain piping are also returned to the reactor with the feed water. Thus, the value of a full-flow condensate demineralizer unit for the cycle under consideration rests, in large part, on the estimated quantity of corrosion products coming from a relatively few components of the complete cycle, and the effect of returning the additional dissolved solids and saturated matter to the reactor for removal in the bypass purification system.

For the design under consideration, two materials of construction have been analysed for equipment and components operating at temperatures in excess of 250°F. Thus, the annual accumulation of corrosion product will vary, depending on whether stainless steel or carbon steel systems are being considered. The materials of construction of the turbine and the condenser are assumed not to change in either case. Feed-water heaters normally would use Admiralty tubes for the two low-pressure units in either the carbon steel or the stainless steel system. The deaerating feed-water heater conventionally contains stainless internals and, in addition, would have a stainless steel-clad shell for the stainless steel system. The high-pressure closed feed-water heater would use cupronickel or Monel tubes in the carbon steel and the stainless steel systems, respectively. With an estimated corrosion rate of 50 mg/(dm^2)(mo) for carbon steel systems, and of 3 mg/(dm^2)(mo) for stainless steel systems operating at temperatures below 500°F, the total annual weight of corrosion products are calculated to be 467 and 205 lb, respectively.

A review of the calculations based on the above assumptions indicated that only a small portion of the total system corrosion products is contributed by the turbine and the condenser. The major contribution occurs in the condensate-return system and in the reactor. Since a sidestream purification system must be furnished in either event, with adequate facilities for disposal of radioactive resins (in addition to permanent spent-resin storage), it appears of little consequence whether the system is designed to handle 80 to 100% of the total annual corrosion products. Consequently, there does not appear to be valid support for a full-flow condensate demineralizer in the reference design. Moreover, such a facility would require additional provisions for regeneration, acid and caustic storage facilities, mixing tanks, controls, etc.

The merits of a leaf-type filter in the condensate system were also evaluated. The purpose of these filters would be to remove suspended solids which are believed to represent a significant portion of corrosion products entrained by the effluent from the condenser hot well. The advantages of leaf-type filtration are a lower capital investment and a lower operating cost when compared with similar charges associated with a full-flow condensate demineralizer system arranged for regeneration.

Accordingly, a full-flow condensate filtration system was incorporated in the plant design for removal of particulate matter originating in the main steam piping, turbine, and condenser.

APPENDIX C

HIGH-PRESSURE VS LOW-PRESSURE REACTOR WATER BYPASS PURIFICATION SYSTEMS

Two alternate systems for reactor water bypass purification were evaluated: (1) a high-pressure system, and (2) a continuous reactor blowdown and low-pressure cleanup system.

In the high-pressure system, a small percentage of the coolant flows from the reactor through heat exchangers, mixed-bed ion exchangers, booster pumps, and back to the reactor. The entire system (Fig.16) operates at essentially the reactor operating pressure (1000 psig).

In the continuous blowdown and low-pressure system (Fig. 27), the pressure of the water from the reactor is reduced to a nominal 25-30 psig, passed through heat exchangers, mixed-bed ion exchangers, and returned to the reactor by high-pressure injection pumps.

Both systems feature a standby mixed-bed ion exchanger and appropriate piping to facilitate use of the standby unit for cleanup of the spent-fuel storage well coolant, and the shield coolant.

In the high-pressure system, the design pressure of 1250 psig reflects additional costs for all system components, whereas the low-pressure system with blowdown permits an equipment design pressure of 50 psig. In particular, the relative costs of the booster pumps, with the same developed head and capacity in either system, vary in excess of 4:1 between system pressures of 1250 psig and 50 psig.

In the continuous blowdown system, a flash tank is required to allow a portion of the high-pressure, high-temperature water to flash to steam when reduced to the 25-30 psig system operating pressure. Since it may not be desirable to vent the flash steam outside the containment vessel, a water-cooled condenser is used and the resulting drains are combined with the drains from the flash tank for passage through the demineralizers.
In the low-pressure system, a flash tank, steam condenser, and drains-collecting tank are required in addition to the equipment common to both systems. Since both flashed and unflashed portions of the flow are recombined in this cycle, the pressure in the steam condenser and flash tank must be essentially equal; therefore, a booster pump is required to overcome the system friction losses.

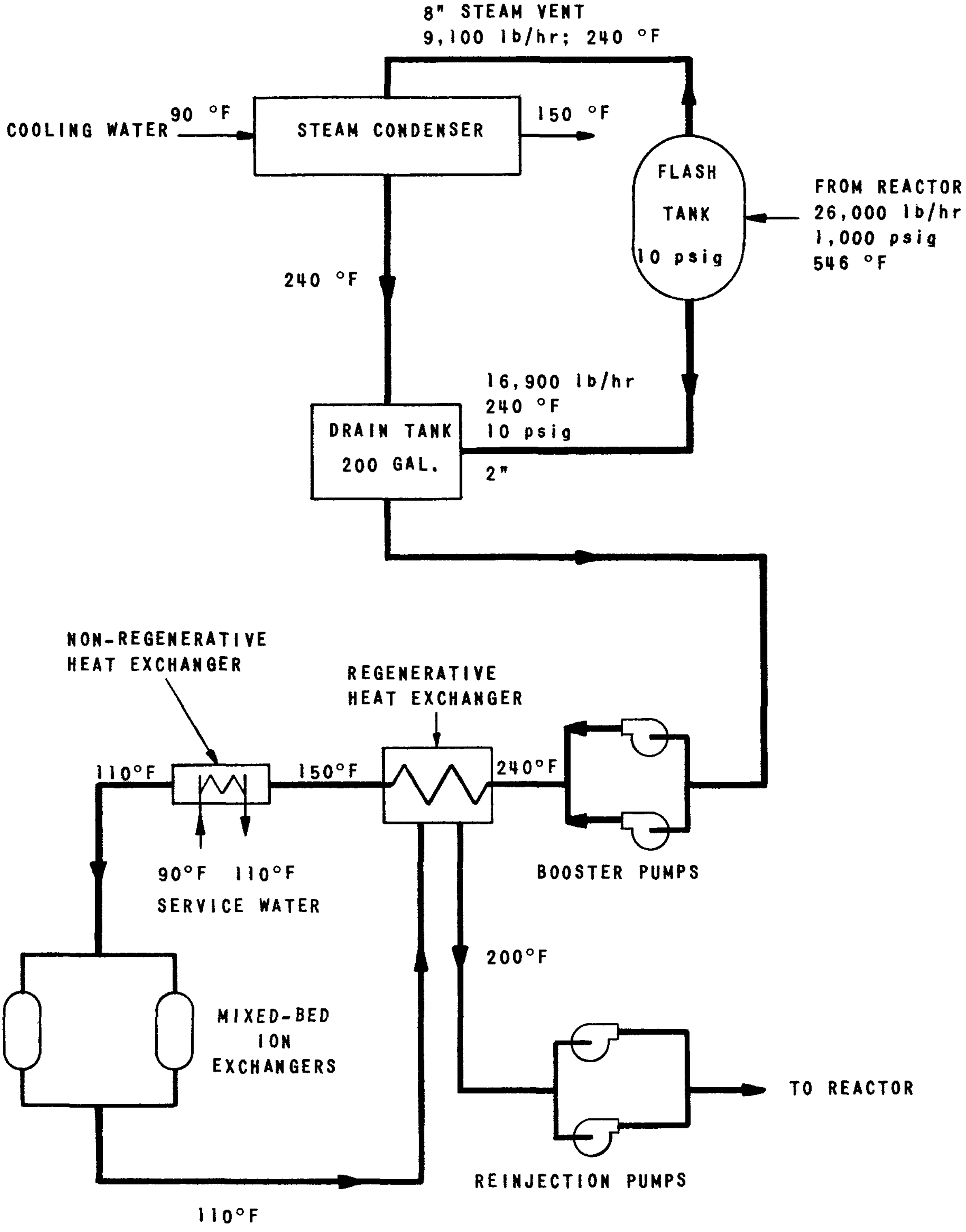


FIG. 27
CONTINUOUS BLOWDOWN AND LOW-PRESSURE BYPASS PURIFICATION SYSTEM

The low-pressure system with blowdown requires a positive displacement pump to reinject the demineralized water into the 1000-psig reactor system. The cost of these units is high and more than offsets the savings realized by using low-pressure components in the remainder of the system.

The high-pressure system was selected over the low-pressure blowdown system because of (1) the higher initial cost of the blowdown system, and (2) the greater simplicity in piping, less space requirements, and fewer pumps with attendant maintenance problems.

APPENDIX D

OUTDOOR VS INDOOR EMERGENCY WATER STORAGE TANK

The selection of a 15,000 or 30,000-gallon tank of emergency water supply for the reactor plant involved an economics evaluation of an outdoor storage tank versus a storage tank located in the dome of a conventional, steel containment vessel.

With an upper spray ring header located 50 ft above grade and a 10-psig pressure drop through the spray nozzle system, the supporting structure must have sufficient height to ensure gravity flow from the tank to suppress the pressure buildup within the containment vessel. Representative supporting structure heights for various containment pressures are listed below.

Internal Pressure, psig	Supporting Structure Height, ft
11.6	100
33.3	150
55	200

Estimates of erection costs were prepared for the two storage tank capacities and the three representative supporting structure heights. The costs listed in the following tabulation do not include concrete foundations. (The concrete masses estimated for the foundations are based on average soil conditions.)

Storage Capacity, gal	Height above Grade, ft	Erected Cost, $	Concrete Foundations, yd^3
15,000	100	16,680	23 (mass)
	150	22,650	28 (reinforced)
	200	26,080	37 (reinforced)
30,000	100	19,250	22.6 (mass)
	150	23,480	34 (mass)
	200	29,610	38 (reinforced)

As evidenced by the tabulation, a relatively small cost differential exists between the two storage tank capacities; most of the cost is associated with the supporting structures.

Tanks that are built into the dome of the containment vessel are estimated to cost about $6,000 for a 15,000-gallon capacity, and $8,000 for a 30,000-gallon capacity. The price differential can be attributed to the fact that, with proper venting of the tank, the height necessary to promote proper flow conditions is generally inherent in the containment vessel structure. Other advantages which favor the selection of the indoor storage tank include the absence of interconnecting piping, shell penetrations, and (depending upon the geographic location) anti-freeze precautions associated with the outdoor storage tank.

Accordingly, the plant design was prepared on the basis of an internal emergency water storage tank mounted in the dome of the containment vessel.

APPENDIX E

EMERGENCY SHUTDOWN COOLER

Three concepts of a 20-Mw(t) emergency shutdown cooler were investigated. The first concept featured a condenser-evaporator with service water supplied from the overhead storage tank through a level controller to the shell side of the unit. Water evaporated from the shell side is vented outside the containment vessel. The second design consisted of a bundle of condensing coils immersed in the overhead storage tank. The third concept featured a condenser cooled by natural convection flow of water from the overhead storage tank. This arrangement is similar to the emergency cooling coils located in the steam dryer of the Experimental Boiling Water Reactor (EBWR).

Successful operation of the condenser-evaporator depends on free convection heat transfer from the steam coil to the shell side water supply. Evaluation of the overall transient heat transfer coefficient is difficult since published heat transfer data do not adequately cover the range of conditions under which such a unit would operate. The extreme temperature differentials which exist immediately after a reactor scram may cause vapor blanketing of the tube wall surface, making the heat transfer coefficient unpredictable. Manufacturers of heat transfer equipment disagree both on a realistic heat transfer coefficient to use for evaluating surface requirements, and a true LMTD to use in the design of such a unit.

However, a unit has been sized using an overall heat transfer coefficient of 250 Btu/(hr)(ft^2)(F), with boiling on the shell side at about 15 psig (saturation temperature = 250°F). Bids received on a similar unit for a reactor plant under construction evidenced disagreement among the potential vendors as to whether this low boiling temperature could be realized (again due to a general lack of experience with units designed for these conditions). Thus vendors who believed that a higher shell side temperature would exist designed for a higher pressure rating of the shell. The end result was a considerable variation in prices quoted.

The shell of the cooler unit for the reference plant design must sustain an external loading comparable to the internal design pressure of the containment vessel; therefore the higher boiling pressure on the shell side does not markedly influence the design. Emergency shutdown coolers have been sized on this basis for several reactor installations either built or currently under construction.

Accordingly, an estimate of about \$35,000 was prepared for a condenser-evaporator unit that would satisfy the design requirements. The advantages peculiar to this type of cooler are: (1) the heat capacity of the cold water normally in the shell side; (2) the ease with which natural circulation can be established between the reactor and the condenser; and (3) the ease with which additional cold water can be added to the unit following extended operation.

With regard to the use of a condenser coil immersed in the overhead storage tank, again a realistic evaluation of the LMTD and the transient heat transfer coefficient is difficult because of the temperature extremes. Based on an overall heat transfer coefficient of 250 $\mathrm{Btu}/(\mathrm{hr})(\mathrm{ft}^2)(^\circ\mathrm{F})$, a unit was sized with a 6-inch, multiple-pass pipe coil designed for installation in the overhead storage tank. With a 15,000-gallon heat sink, it was estimated that boiling of the water would occur after about 45 min.

An estimate of \$16,400 for a Monel coil was obtained. In general, the advantages of the condenser-evaporator listed above also apply to the condenser coil unit. The disadvantages are the possibility of the coil being partially uncovered in the event storage water is required to supply the spray ring headers, or if sufficient water is boiled off to lower the storage water level. A unit of this type would be vented to the inside of the containment vessel; therefore the vapor evolved would saturate the building atmosphere. Thus, shortly after the onset of boiling of the storage water, condensation of the steam would also begin on the lower-temperature surface of the containment vessel.

A review of the third cooler concept, which is similar to the EBWR emergency cooler, revealed that the design is not feasible in view of the 20 Mw(t) heat dissipation requirement. Test data from the EBWR emergency shutdown cooler show that the unit does not operate strictly as a water-cooled condenser; rather, there is intermittent steam formation in the secondary side which causes wide fluctuations in the available thermal driving head and, consequently, wide variations in the coolant flow rate. In a large unit designed for 20 Mw(t), it is believed that similar operation would result in harmful vibrations or water hammer. Therefore no attempt was made to size a cooler of this type.

While the foregoing analyses indicate the immersed coil concept would afford a lower capital investment, the disadvantages and complications associated with the operation of such a unit were sufficient to warrant selection of the condenser-evaporator design.

APPENDIX F

COMPARATIVE BUILDING COSTS OF REACTOR PLANT ARRANGEMENTS

In order to evaluate their effect on capital investment, a series of plant structures, based upon alternate arrangements of equipment and alternate design philosophies, were prepared.

The general design considerations reviewed previously are applicable to these alternate designs. A natural-circulation, internal steam separation reactor is the reference reactor design. The alternate designs are differentiated by methods of spent-fuel handling and storage, control rod location, location of the reactor vessel within the biological shielding in the containment vessel, and methods of effecting recirculation of the reactor coolant. A forced-circulation, external steam separation reactor design is included for purposes of comparison.

These design alternates each, in turn, affect the overall dimensions of the containment vessel structural requirements and, consequently, the capital investment. In most cases, the diameter and overall height of the containment vessel has been established to result in a maximum steel plate thickness of $1\frac{1}{2}$ in. and, thus, to obviate the economic penalty of stress relieving field welds. In the case of the forced-circulation reactor design, with its attendant recirculation system risers and downcomers, steam drum, recirculation pump and piping, the minimum diameter of the containment vessel was set by physical space requirements.

Spent-fuel Handling

Methods of spent-fuel handling included wet- versus dry-type fuel handling and external versus internal spent-fuel storage facilities.

Plant arrangements based on external spent fuel storage are shown in Figs. 28 and 29. The spent fuel is removed from the reactor into a manually operated dry-type fuel-handling machine and carriage, and transported to a fuel chute opening in the main floor. The fuel is lowered into the water-filled chute which penetrates the containment vessel several feet below grade and interconnects with the bottom of the storage well in the adjacent fuel-handling building. Upon entry in the storage well, the submerged fuel may be repositioned (with manually operated tools) from the receiving rack to the storage racks for decay prior to shipment off site for reprocessing.

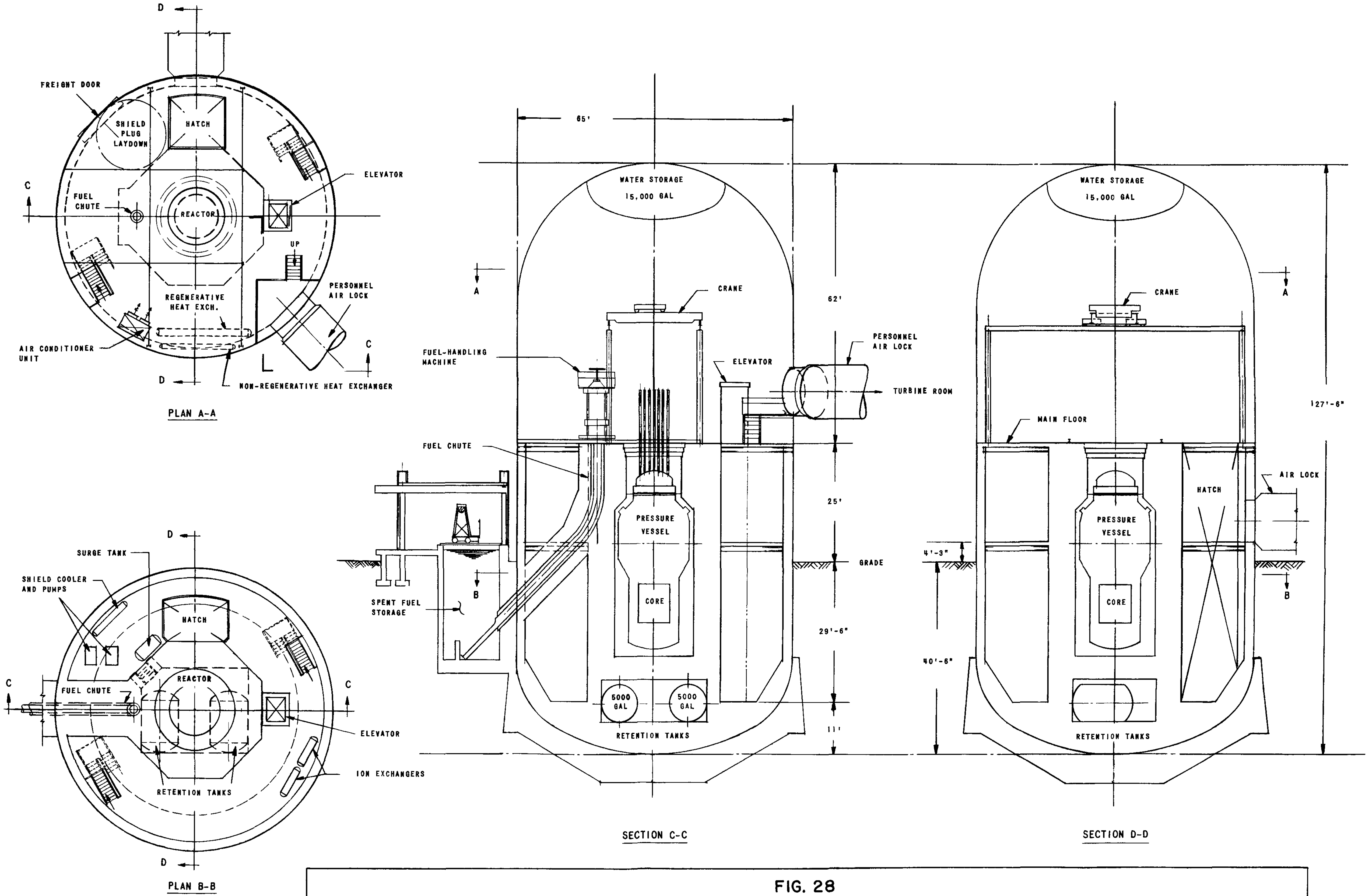


FIG. 28
PLANT ARRANGEMENT-NATURAL CIRCULATION; EXTERNAL FUEL STORAGE; CONTROL ROD DRIVES AT TOP

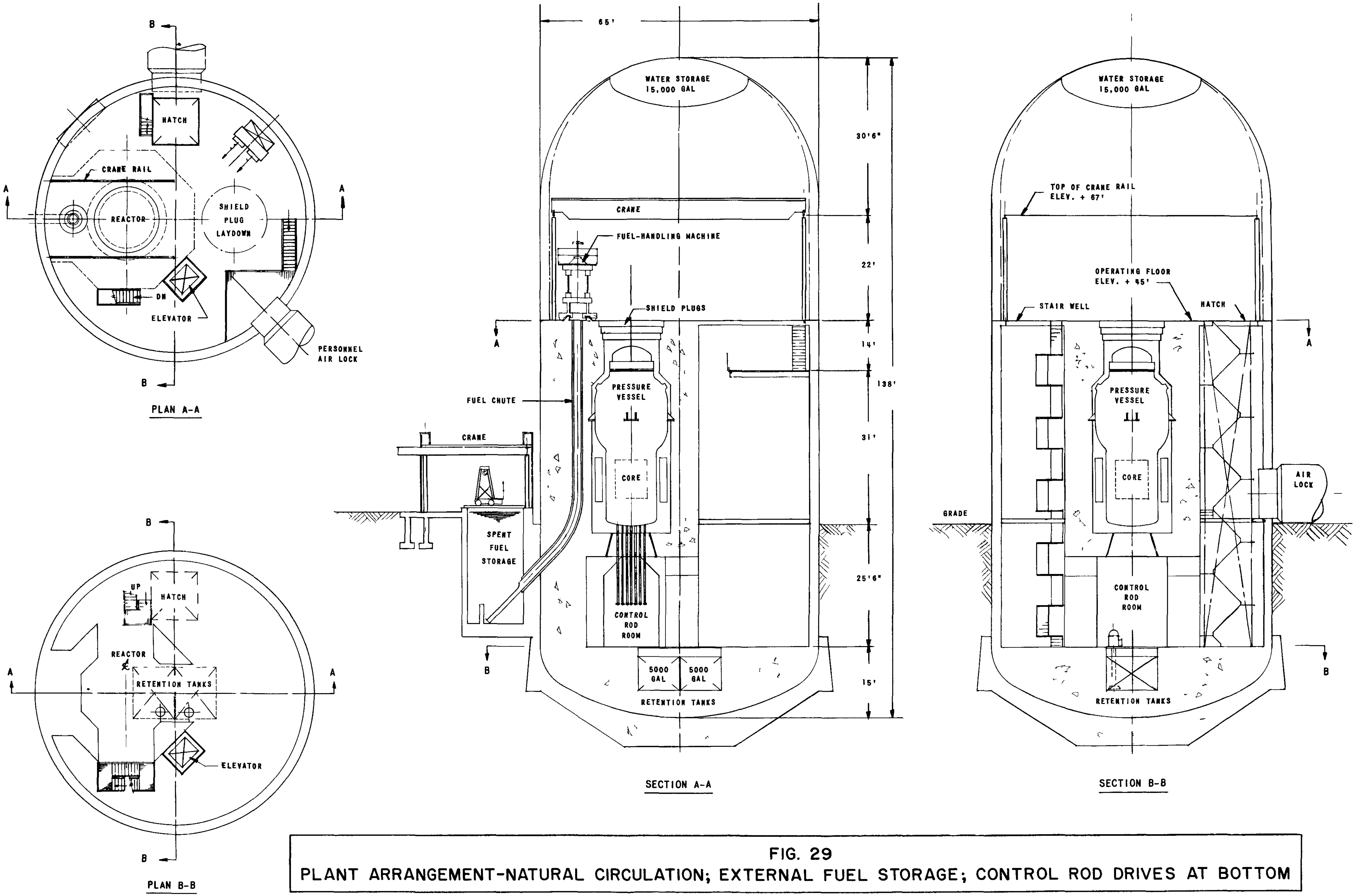


FIG. 29
PLANT ARRANGEMENT-NATURAL CIRCULATION; EXTERNAL FUEL STORAGE; CONTROL ROD DRIVES AT BOTTOM

This method of handling fuel poses certain structural problems. The chute is an integral part of the containment vessel and the fuel-handling building. Each building is founded separately; therefore uneven settling between the two structures could place the chute in shear. The use of a curved chute affords a more simplified and economical method of handling fuel when compared to a vertical chute interconnecting with a horizontal chute leading through the containment vessel into the external storage well. However, the possibility does exist that a fuel element may become lodged in the curved portion of the chute. Finally, the integrity of the containment vessel must be maintained. An appropriate valving system would be required in the chute with interlocks to ensure closure of the valves during reactor operation.

The internal spent-fuel-handling and storage arrangements are shown in Figs. 30 to 35. Spent fuel is removed by either a wet- or dry-type fuel-handling machine, transported, and lowered into a storage well adjacent to the reactor vessel shielding. The fuel-handling machine is also used to reposition the spent fuel in the receiving rack in the well. Subsequent transfer of the fuel to the storage rack is performed with manually operated tools.

The internal spent-fuel-handling system takes advantage of the containment vessel foundation and, particularly in the case of a natural-circulation reactor, uses containment vessel volume which is otherwise not required for equipment location. In addition, location of the storage well adjacent to the reactor vessel cavity permits a reduction in shielding thickness between the two structures.

With regard to removal and transfer of spent fuel after a suitable decay period, the concept of an external storage permits unrestricted access irrespective of reactor operations. With the storage well located inside the containment vessel, access is more restricted, in particular during reactor operation. Spent fuel (in shipping casks) must be removed through the equipment air lock in order not to compromise the integrity of the containment vessel.

The relative merits of dry- and wet-type fuel-handling procedures were also investigated. Generally, with a dry fuel-handling design the reactor water level is raised to its maximum elevation before removal of the vessel cover. A lead-shielded coffin is then positioned over the opening and fuel is withdrawn from the core and transported to the fuel chute (external storage) or to the internal storage well (see Figs. 28, 29, 34, and 35).

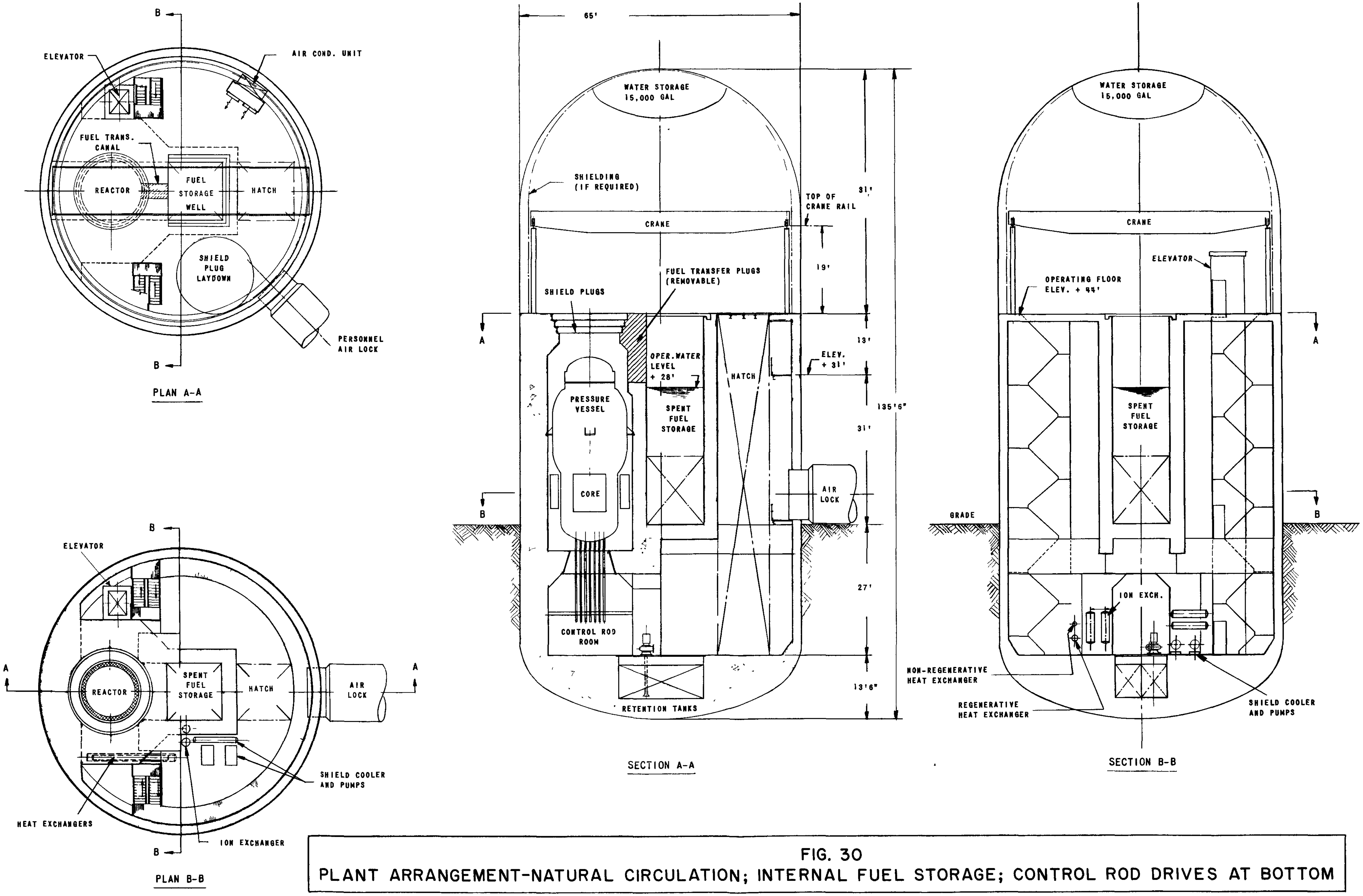
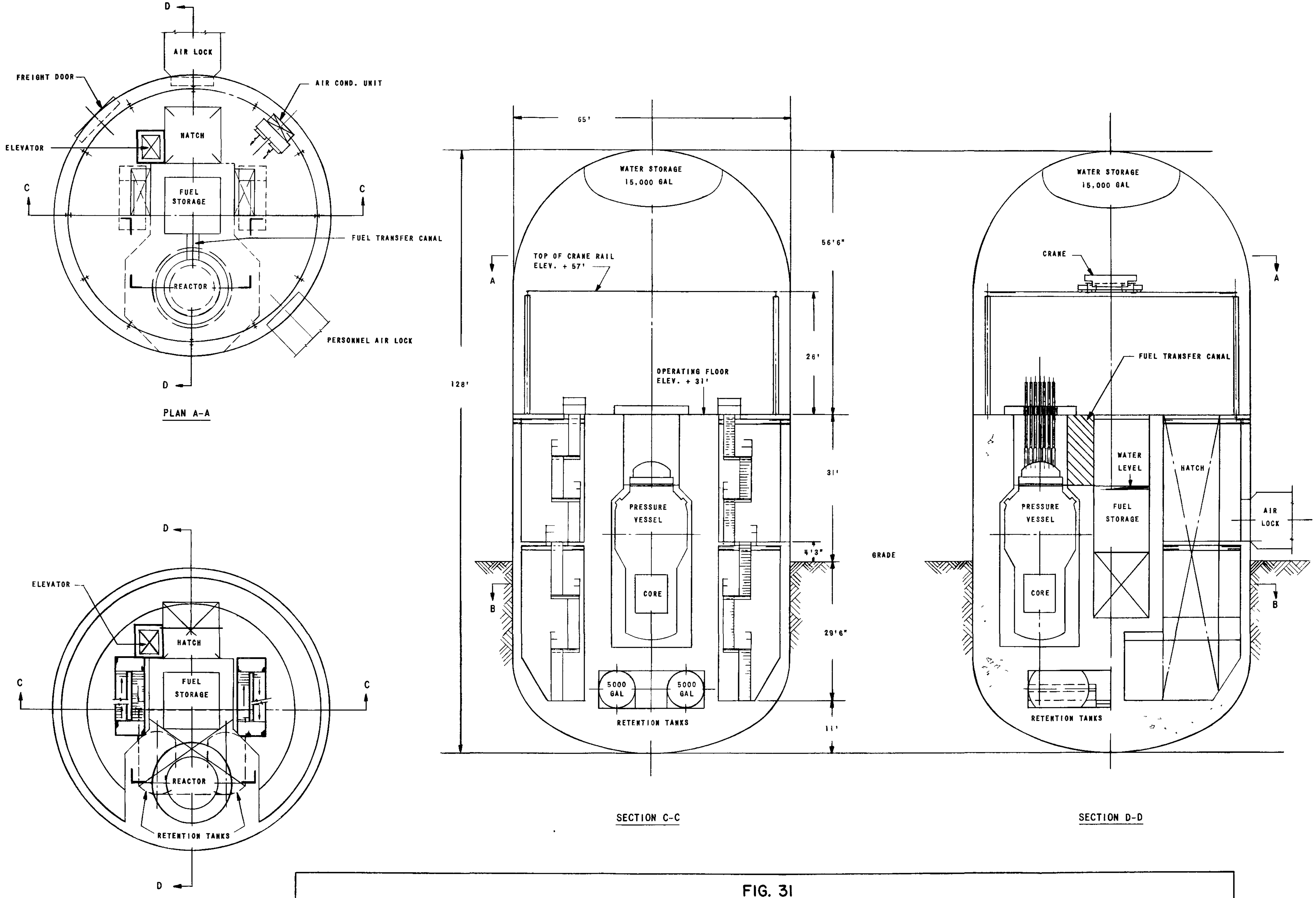


FIG. 30

PLANT ARRANGEMENT-NATURAL CIRCULATION; INTERNAL FUEL STORAGE; CONTROL ROD DRIVES AT BOTTOM



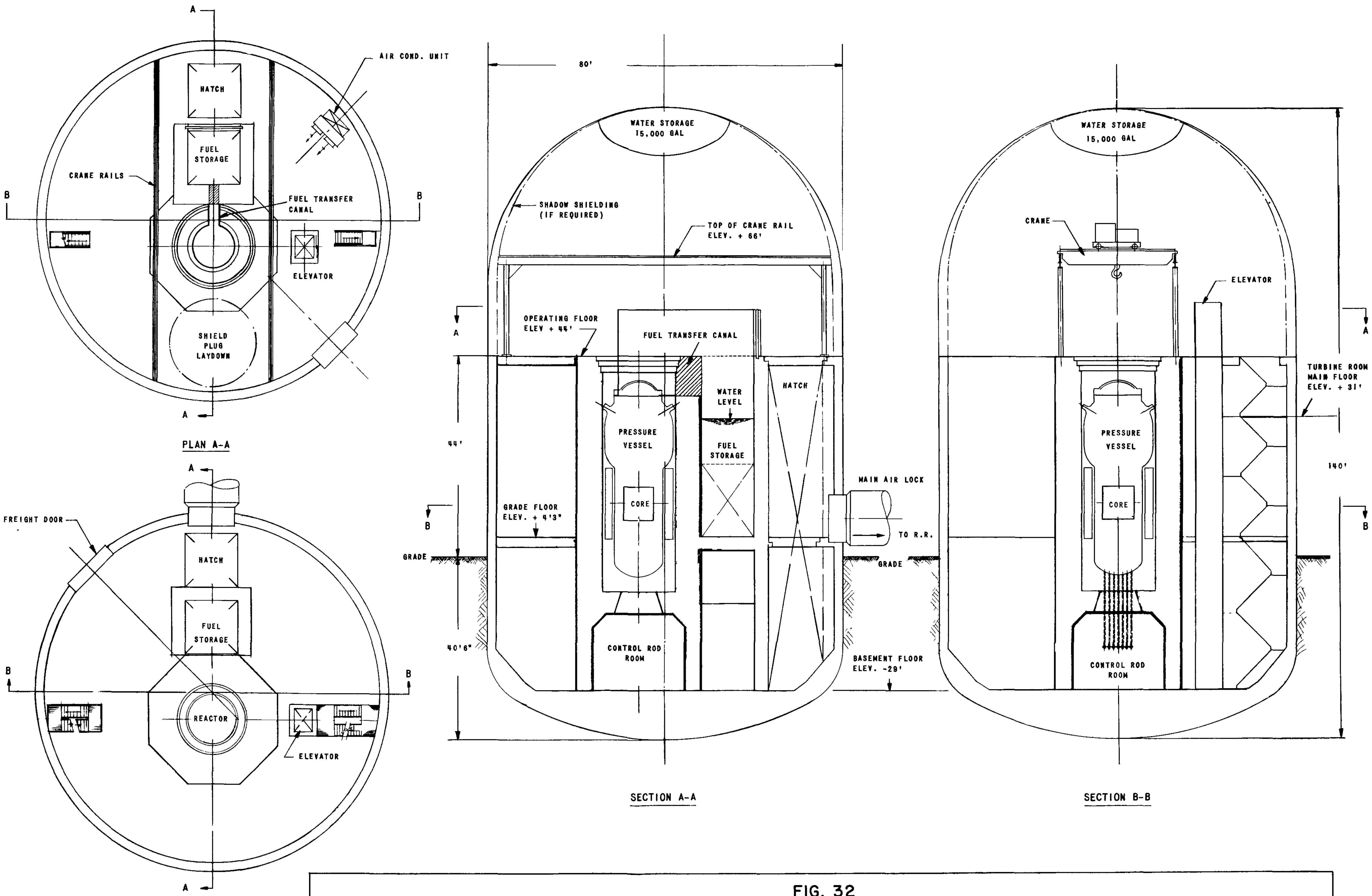
PLAN A-A

PLAN B-B

SECTION C-C

SECTION D-D

FIG. 31
PLANT ARRANGEMENT-NATURAL CIRCULATION; INTERNAL FUEL STORAGE; CONTROL ROD DRIVES AT TOP



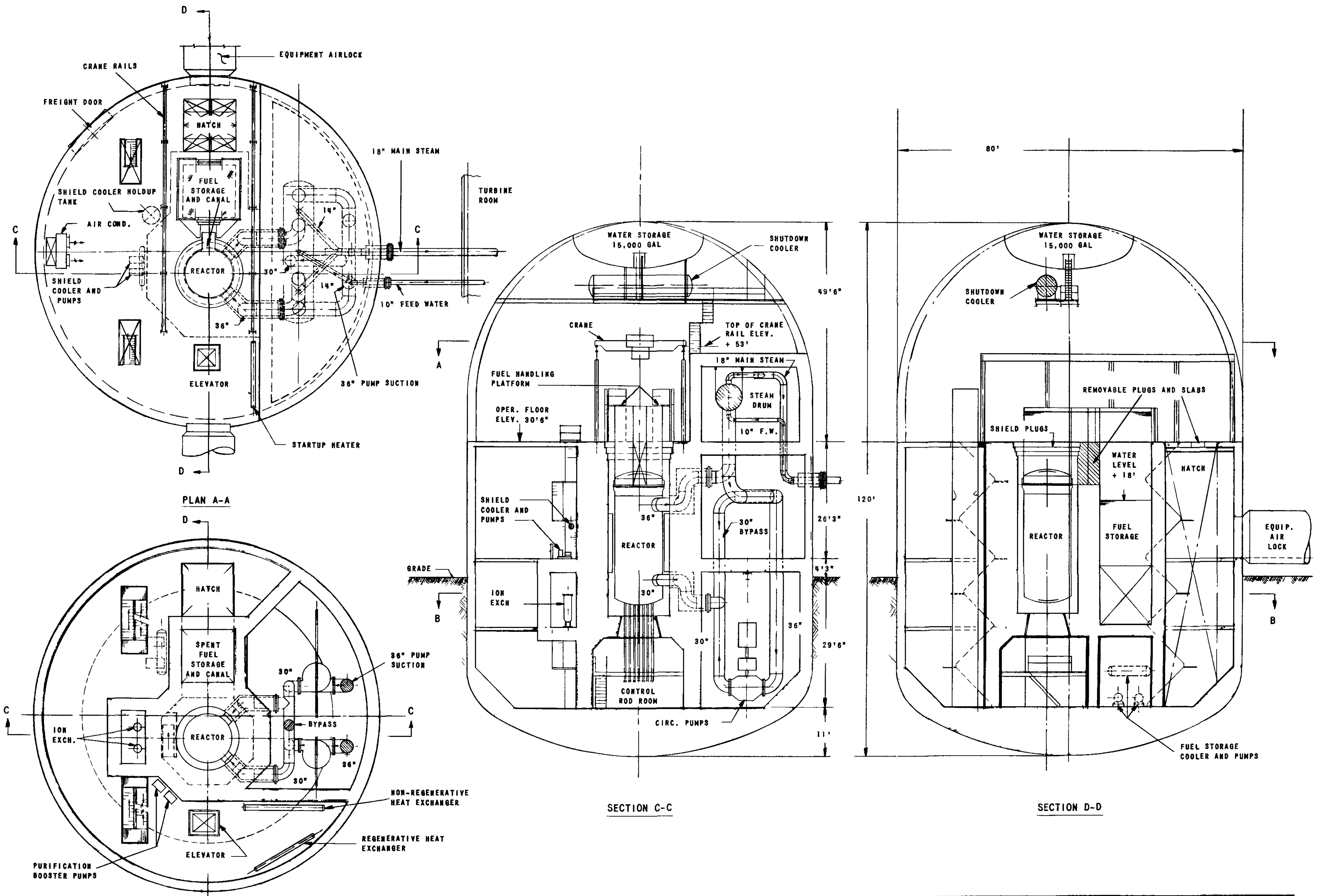
PLAN A-A

PLAN B-B

SECTION A-A

SECTION B-B

FIG. 32
PLANT ARRANGEMENT-NATURAL CIRCULATION; INTERNAL FUEL STORAGE; CONTROL ROD DRIVES AT BOTTOM



PLAN A-A

PLAN B-B

SECTION C-C

SECTION D-D

FIG. 33

PLANT ARRANGEMENT-FORCED CIRCULATION; INTERNAL FUEL STORAGE; CONTROL ROD DRIVES AT BOTTOM

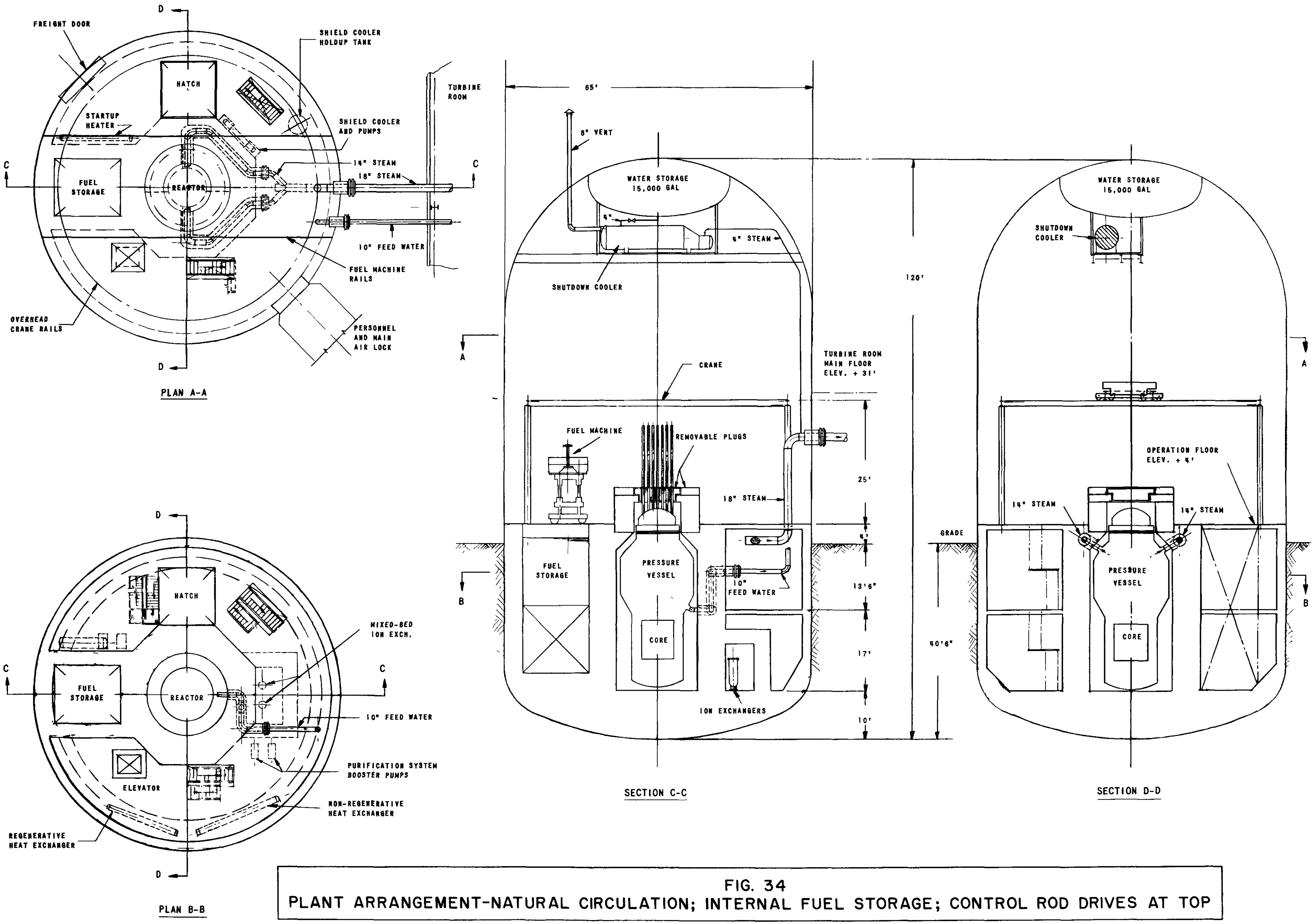
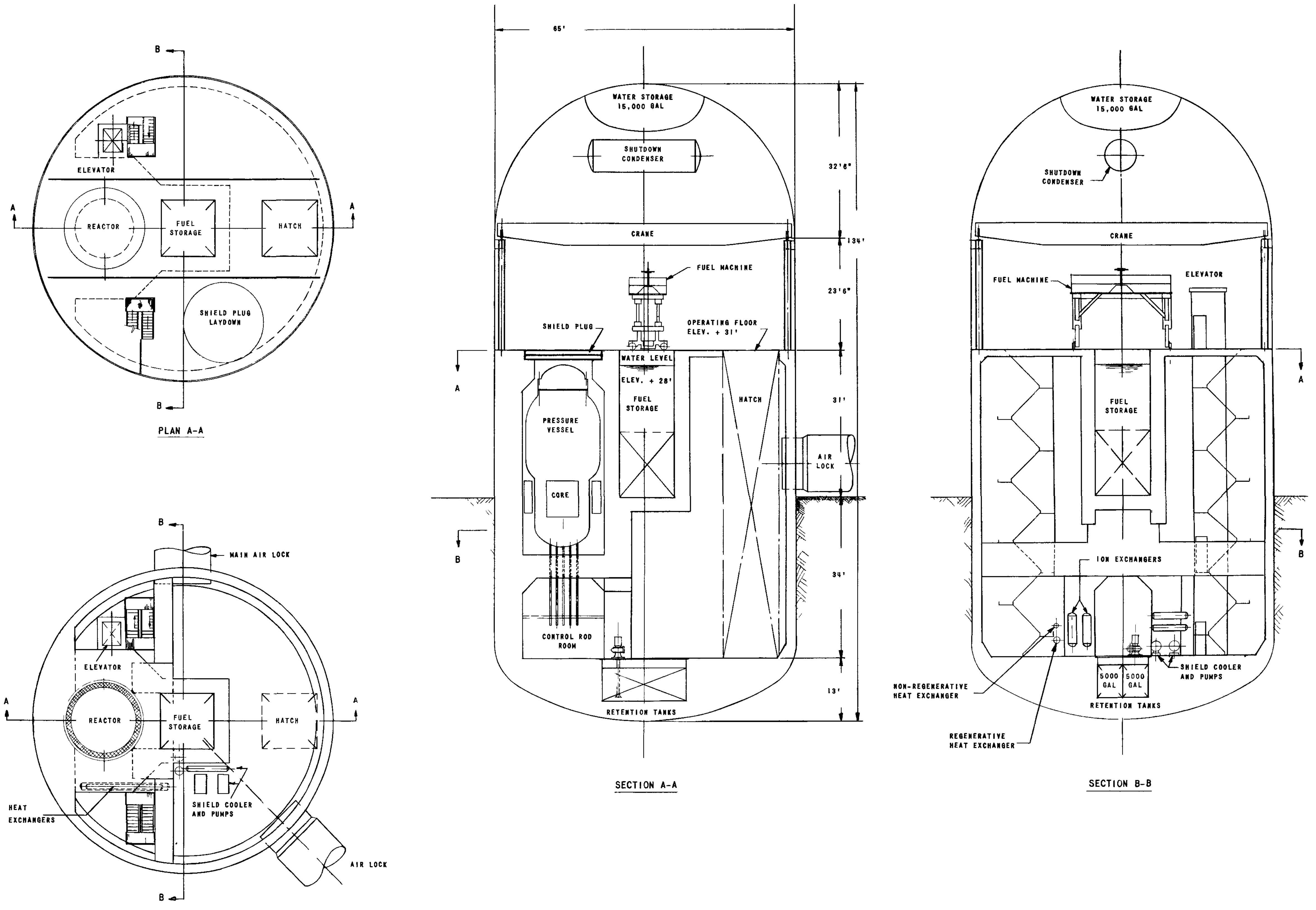


FIG. 34
PLANT ARRANGEMENT-NATURAL CIRCULATION; INTERNAL FUEL STORAGE; CONTROL ROD DRIVES AT TOP



PLAN A-A

PLAN B-B

SECTION A-A

SECTION B-B

FIG. 35
PLANT ARRANGEMENT-NATURAL CIRCULATION; INTERNAL FUEL STORAGE; CONTROL ROD DRIVES AT BOTTOM

In the wet-type fuel-handling system (Figs. 30 to 33), the reactor cavity is flooded after removal of the vessel cover. The water level in the storage well is also raised to a height which will afford maximum protection to operating personnel during the course of removing and transferring the spent fuel from the core to the storage well. The transfer is accomplished with a simple device generally suspended from an auxiliary hook of an overhead crane. However, the wet-type system does require either that the operating floor be located at an elevation consistent with the depth of the water required for biological shielding above the vessel, or that a water-filled tank be located above the operating floor level for the same reason. In either case, the concrete biological shielding exceeds that required for the dry-type system. If the reactor cavity is not filled with water, some other means must be provided to seal and support the head of water above the reactor.

The dry-type fuel-handling system allows the operating floor level to be about 16 ft lower than required for a wet-type system. The result is a decrease in both concrete mass and height of the containment vessel, particularly in those cases in which the free volume requirements have not been reduced to the critical point. The reactor vessel cover does extend above the main floor level; however, segmented shielding blocks will provide adequate shielding, and the blocks can be removed during refueling operations.

Bottom- Versus Top-Installed Control Rod Drives

Bottom-installed control rod drives require clearance below the bottom biological shielding equal to the control rod extension plus the rod travel, plus space for removal and maintenance of the rods. With a sufficiently thick bottom shield, the control rod room may be arranged as an open area encompassed by the reactor support columns. The necessary biological shielding can be integrated with the structural concrete requirements by appropriate placement of auxiliary within the containment vessel (see Figs. 30, 32, 33, 35).

Therefore, the major influence of bottom-installed control rod drives on the overall investment cost is the reactor and main operating floor elevations relative to the base of the containment vessel. The top installation, of course, allows placement of the reactor vessel at a lower elevation. In particular, with a natural-circulation reactor (and absence of recirculation piping) the vessel is the lowest piece of major equipment in the containment vessel. With reference to plant arrangements depicting the reactor located on the building centerline, the concept of a top-installed control rod drive permits the elevation of the main operating floor to be about 18 ft lower than for the case of the bottom-installed drives (see Figs. 31 and 34).

With the reactor vessel located against the containment vessel wall, the top-installed control rod drives allow a reduction in height of the containment vessel from 136 ft to 128 ft.

Other factors which influence the location of the rod drives are the thickness of the steel plate of the containment shell and the time required for refueling operations. With the reactor vessel located on the center line of the containment vessel, and with bottom-installed rod drives and dry-type fuel handling, the height of the containment vessel is reduced to 120 ft. From the standpoint of free volume available for expansion of pressurized water, the required steel plate thickness is $1\frac{7}{16}$ in. A design utilizing a top-installed rod allows the elevation of the main floor to be lowered 16 ft; however, the containment volume requirements do not permit any significant reduction in the overall height of the containment vessel. An overall height of 120 ft enables the use of $1\frac{3}{8}$-in. steel plate for this design.

Refueling operations are accomplished more rapidly with the bottom-installed rod drives since, unlike installations at the top, the drive mechanisms need not be removed to provide access for the refueling machine.

The top-installed control rod drives feature a composite steel-and-water shield that is an integral part of the rod assembly. This method of shielding is designed to reduce problems of misalignment incurred by the use of concrete liners around each rod drive. The integral shielding is augmented by segmented removable concrete plugs. Prior to refueling operations, the concrete plugs are removed, and the vessel cover and integral steel shielding are lifted (with the overhead crane) as a single assembly.

Natural Versus Forced Circulation of Reactor Coolant

Although the main objective of the overall study was directed toward a natural-circulation reactor with internal steam separation, a forced-circulation reactor with external steam separation was included for purposes of comparison.

The results showed that the additional costs for the external steam separation drum and recirculation equipment would be, in part, offset by a significant reduction in cost for fabrication of the reactor vessel. The vessel would be shorter in height and would not contain the enlarged section incorporated in the natural-circulation design.

With a recirculation ratio of 16.4:1 and a steam flow of 1,290,000 lb/hr, a steam-separation drum 84 in. diameter by 32 ft long would be required to furnish the desired quality of steam for use in the turbine. Recirculation of the coolant would be effected by two 25,000-gpm pumps. The requisite riser and downcomer piping and interconnecting piping between the reactor and steam drum are shown in Fig. 33.

The forced-circulation system would reflect an increase in the diameter of the containment vessel over that required for the natural-circulation system. The most desirable arrangements for the latter system can be housed in a 65-ft diameter containment vessel. As shown in Fig. 33, the forced-circulation system would require a vessel 80 ft in diameter and 120 ft in overall height.

Conclusions

The capital costs estimated for the various arrangements depicted in Figs. 28 to 35 are summarized in Table VI. From these estimates it is concluded that the design leading to the lowest overall cost would feature: (1) a natural-circulation reactor with internal steam separation; (2) top-installed control rod drives; (3) a dry-type fuel-handling machine; and (4) an internal spent-fuel storage well. This system is shown in Fig. 34.

The second most economical arrangement is shown in Fig. 31. The design is similar to that shown in Fig. 34, except for the wet-type fuel-handling system. The cost differential is $52,000.

The third most economical design features a dry-type fuel-handling machine, but differs from both previous designs in that the control rod drives are installed at the bottom of the reactor vessel (see Fig. 2). The resultant cost differential is $95,000 when compared to the system shown in Fig. 34.

In weighing the advantages and disadvantages of the three systems, it was concluded that the difficulties associated with the removal of the top-installed drives for refueling operations were sufficient to warrant the additional expenditure incurred with the bottom-installed control rod drives. Accordingly, the design arrangement shown in Fig. 2 was selected for detailed cost estimates.

Table VI

COMPARATIVE BUILDING COSTS OF REACTOR PLANT DESIGN CONCEPTS AND ARRANGEMENTS

(Prices as of January 29, 1960, and based on 40-hour work week)

Mode of Circulation	Natural	Natural	Natural	Natural	Natural	Forced	Natural	Natural	Natural
Location of Spent Fuel Storage	External	External	Internal	Internal	Internal	Internal	Internal	Internal	Internal
Location of Control Rod Drives	Top	Bottom	Bottom	Top	Bottom	Bottom	Top	Bottom	Bottom
Reference Figure No.	28	29	30	31	32	33	34	35	2
REACTOR PLANT STRUCTURES									
Excavation, Backfill and Disposal	20,000	20,000	20,000	20,000	25,000	25,000	20,000	20,000	20,000
Dewatering	Base	Base	Base	Base	Base	Base	Base	Base	Base
Containment Vessel (Incl. Testing)									
Steel Shell	640,000	675,000	680,000	640,000	585,000	655,000	540,000	655,000	560,000
Air-lock Doors	Base	Base	Base	Base	Base	Base	Base	Base	Base
Water Tank at Top of Shell	Base	Base	Base	Base	Base	Base	Base	Base	Base
Flexcell Liner on Interior of Shell	5,000	6,500	6,500	5,000	8,500	7,500	4,000	5,000	5,500
Coating of Shell below Grade	1,800	1,800	1,800	1,800	2,500	2,500	1,800	1,800	1,800
Insulation of Shell above Grade	53,500	62,500	61,000	54,000	75,000	59,500	51,500	59,500	51,500
Concrete									
Outside Shell	31,000	31,000	31,000	31,000	45,000	45,000	31,000	31,000	31,000
Inside Shell	185,000	250,000	260,000	215,000	280,000	280,000	135,000	250,000	180,000
Steel									
Structural	10,000	13,500	13,500	13,500	12,000	11,000	22,500	13,000	22,500
Gallery	8,500	13,500	13,500	8,500	13,500	12,500	15,000	10,000	17,000
Miscellaneous Steel Anchored in Concrete	3,000	3,000	3,000	3,000	4,000	4,000	3,500	3,000	4,000
Shielding for Reactor									
Upper Neutron-shield Plug	65,000	40,000	55,000	85,000	85,000	85,000	75,000	27,000	65,000
Shielding around Reactor	Base	Base	Base	Base	Base	Base	Base	Base	Base
Bottom Shield Plug	13,000	30,000	30,000	17,000	37,000	37,000	-	30,000	30,000
Liners									
Fuel-storage Well Coating	-	-	2,800	2,800	2,500	2,500	2,200	2,000	2,200
SST and SST-clad Fuel Drop Tubes	20,000	20,000	-	-	-	-	-	-	-
Plumbing	3,000	3,500	3,500	3,000	3,500	3,500	4,000	4,000	3,500
Elevator and Enclosure	22,000	25,000	25,000	22,000	25,000	25,000	15,000	23,000	22,000
Painting	10,000	11,500	11,500	10,000	13,000	12,000	11,500	10,500	11,500
Lighting	6,500	6,500	6,500	6,500	10,000	10,000	6,500	6,500	4,000
Air Conditioning	35,000	40,000	40,000	35,000	50,000	40,000	37,000	40,000	37,000
Miscellaneous	28,200	31,200	31,400	29,400	32,000	33,000	24,500	29,700	27,000
	$1,160,500	$1,284,500	$1,296,000	$1,202,500	$1,308,500	$1,350,000	$1,000,000	$1,221,000	$1,095,500
FUEL-HANDLING BUILDING									
Substructure, Superstructure, Supporting Steel	45,000	45,000	-	-	-	-	-	-	-
Lighting	2,000	2,000	-	-	-	-	-	-	-
Miscellaneous	3,000	3,000	-	-	-	-	-	-	-
Fuel-handling Machine	150,000	150,000	-	-	-	-	150,000	150,000	150,000
	$ 200,000	$ 200,000	-	-	-	-	$ 150,000	$ 150,000	$ 150,000
TOTAL ESTIMATED COST	$1,360,500	$1,484,500	$1,296,000	$1,202,500	$1,308,500	$1,350,000*	$1,150,000	$1,371,000	$1,245,500
DIFFERENCE - (Figure 34 as base)	+ 210,500	+ 334,500	+146,000	+ 52,500	+158,500	+200,000	Base	+221,000	+ 95,500

* Additional costs to be considered are	
Steam Drum	350,000
Two (2) Recirculation Pumps (25,000 gpm)	330,000
Recirculation Piping Only	750,000
TOTAL	$1,430,000

ACKNOWLEDGMENTS

The plant designs, arrangements, and cost data were prepared by Sargent and Lundy Engineers (Chicago, Illinois). The fuel cycle costs were estimated by V. M. Kolba; and the pressure vessel was designed by E. L. Martinec, both members of the Reactor Engineering Division, Argonne National Laboratory.