ORNL-2500
Part 4
Plant Design

THE ORNL GAS-COOLED REACTOR

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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By

The Staff

of the

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10. PROPOSED PLANT DESIGN

10.1 Description

10.1.1 Basic Design: The basic design of the power plant is predicated on conventional power-station practice insofar as possible. The plant is designed for base-load operation, with the provision of load-following ability. The reactor is designed to produce a gross thermal power output of 687 Mw. The turbine-generator plant will produce a gross electrical power of approximately 250,000 kw at a turbine heat rate of 9458 Btu/kwh. With a net efficiency of 32.8% the net electrical power output of the power plant is 225 Mw. The optimization studies described in various sections in this report were the bases for the selection of the nuclear power plant design. The parameters used in these studies, which are nearly identical to the final parameters, are summarized in Table 10.1. A summary of the principal features and equipment is given in Table 10.2.

10.1.2 Site Selection: The site data used as a basis for the proposed plant design are believed to be fairly representative of many locations throughout the United States and should be considered as hypothetical. There is an advantage, however, in having detailed information available about the site, and therefore, the site data used in this study describe an actual site considered by the Tennessee Valley Authority to be suitable for construction of a steam plant. The existence of this actual location aided materially in the cost estimating and building design phases of the work, because the actual subsurface structure of the area was already known, river temperature data were available, and construction costs in the area could be estimated from actual experience. A tabulation of typical construction labor costs is given in Table 10.3

At the site a layer of loose soil (clay, sand, silt, and gravel) covers an irregular layer of weathered limestone up to 7 ft thick which in turn covers a sound formation of thin-bedded, fissile, vari-colored shale. This sound shale is found at an elevation of approximately 680 ft on the river side of the powerhouse and at an elevation of 710 ft on the west side of the service bay.

TABLE 10.1

ORNL GAS-COOLED REACTOR-2 DESIGN DATA

Over-all	
Number of reactors	1
Reactor thermal output, Btu/hr	2.34×10^9
Reactor thermal output, Mw	687
Gross electrical output, Mw	252
Net electrical output, Mw	225
Net over-all efficiency, %	32.8
Fuel	
Fuel composition	UO_2
Fuel enrichment, %	2
Total weight of uranium, tons	150.8
Burn-up, Mwd/t	7350
UO_2 average density (95% theoretical), g/cm^3	10.4
UO_2 minimum density (94% theoretical), g/cm^3	10.28
Fuel temperature coefficient per °C	-4.7×10^{-5}
Fuel Element	
UO_2 slug OD, in.	0.75 ± 0.005
UO_2 slug ID, in.	0.32 ± 0.010
UO_2 slug length, in.	0.50 ± 0.003
UO_2 slug internal temperature (Maximum) °F	2200
UO_2 slug thermal stress (for ideal rigid body) psi	150,000
Weight of UO_2 slugs per capsule, kg	2.31
Number of UO_2 slugs per capsule	75
Capsule material	304 SS
Capsule OD, in.	0.80
Capsule wall thickness, in.	0.020
Capsule length, in.	38.5
Capsule internal surface, ft^2 per linear ft	0.199
ft^2 per capsule	0.6375
ft^2 per reactor	42,760

Table 10.1 (continued)

Fuel Element (continued)	
Capsule external surface, ft^2 per linear ft	0.2094
ft^2 per capsule	0.6717
ft^2 per reactor	45,050
Capsule internal surface heat flux:	
Maximum, Btu/hr-ft^2	96,000
Average, Btu/hr-ft^2	56,000
Capsule average surface temperature, °F (Approx.)	1000
Capsule maximum design surface temperature in hot zone, °F	1200
Capsule maximum allowable surface temperature (including hot spots) °F	1500
Absorption cross section at 2200 m/sec of capsules and and supports, cm^2/ft - U	19.0
Weight of 304 SS per capsule, kg	0.248
Number of capsules per element	7
Number of capsules per reactor	67,074
Number of elements per channel	6
Number of elements per reactor	9582
Nominal length of element, in.	40
Reactor Core	
Material	Graphite, Grade TSF
Nominal core height, ft	20
Nominal core diameter, ft	30
Height of graphite, ft	25
Distance across corners of graphite, ft	35
Machined weight of graphite, tons	1122
Core graphite density, g/cm^3	1.65
Core graphite absorption cross section, millibarns	4.0
Reflector graphite density, g/cm^3	1.65
Reflector graphite absorption cross section, millibarns	4.0
Graphite blocks, length, in.	40
width, in.	8
depth, in.	8

Table 10.1 (continued)

Reactor Core (continued)	
Total graphite volume, ft^3	21,784
Number of fuel channels	1597
Number of fuel charge tubes	69
Pitch of channels, in.	8
Type of pitch	square
Diameter of fuel channels, in.	345 at 3.45 400 at 3.25 852 at 3.05
Moderator temperature coefficient,	
at T_m = 400°C, per °C, Maximum	-14×10^{-5}
Minimum	-4×10^{-5}
Total excess reactivity, %	10
Thermal flux at 2200 m/sec, η/cm^2-sec	5×10^{12}
Control Rod	
Number of control rods	61
Control rod: OD, in.	2
ID, in.	1.25
material	silver
Control rod sheath	SS
Control rod length, ft	18
Suspension	SS cable
Drive: Slow in and out	AC motor, winch
Fast in	Pneumatic
In speed, fast, in./min	84.8
slow, in./min	8.48
Out speed, in./min	8.48
Reactivity invested in rods, % $\delta k/k$	14.5
Reactivity per rod, %	0.24 (Average)
Number of rods on temperature servo	4
Nominal in speed, average $\Delta k/k$/sec	10^{-4}
Fast in speed, average $\Delta k/k$/sec	10^{-3}

Table 10.1 (continued)

Control Rod (continued)	
Normal out speed, average $\Delta k/k$/sec	10^{-4}
Shielding	
Thermal neutron shield material	Borosilicate glass
Thermal neutron shield thickness, in.	0.5
Biological shield material	concrete
Biological shield thickness, ft	9
Biological shield density, lb/ft^3	145
Biological shield shape	octagon
Biological shield distance across flats, ft	76
Biological shield height, ft	67
Total weight on foundation, tons	23,400
Cooling, forced	Air
Pressure Vessel	
Shape	sphere
Diameter, OD, ft	50
Material	SA212-B
Thickness, in.	3.250
Working pressure, psig	300
Design stress, psi	15,000
Maximum temperature, °F	650
Volume, ft^3	63,333
Weight of graphite support structure, lb	144,000
Weight of vessel support structure, lb	38,000
Gross vessel weight (including vessel and graphite supports, thermal barriers, nozzles, and insulation), lb	1,541,000
Coolant	
Gas	helium
Working pressure, psia	300
Total flow (normal) lb/sec	972
Reactor inlet temperature, °F	460
Reactor outlet temperature, °F	1000
Number of inlet pipes	4

Table 10.1 (continued)

Coolant (continued)	
Number of outlet pipes	4
Diameter of pipe, ID, ft	5
Mean coolant velocity:	
Cool pipe, ft/sec	100
Hot pipe, ft/sec	161
Total volume occupied by helium, ft^3	107,000
Circuit pressure drop, psi	6.61
Specific heat capacity of helium, Btu/lb°F	1.24*
Coolant Blowers	
Type	axial
Number per reactor	4
Number per steam generator	1
Adiabatic efficiency, %	80
Compression power, Bhp	5700
Speed (constant), rpm	3580
Power for 4 blowers, Mw	18.3
Blower drive motor, Bhp	6000
Steam Generator	
General:	
Type of generator	once-through
Number per reactor	4
Shell height between heads, ft	40
Shell height including heads, ft	60
Shell ID, ft	20
Shell thickness, in.	2.75
Gas inlet ID, ft	5.0
Gas outlet ID, ft	5.0
Gas bypass ID, ft	2.5
Steam outlet drums:	
Length, ft	21.5
OD, in.	28
Wall thickness, in.	1.875

*Used in calculations.

Table 10.1 (continued)

Steam Generator (continued)	
Feed-water inlet drums:	
Length, ft	19.5
OD, in.	28
Wall thickness, in.	1
Gas inlet temperature, °F	1000
Gas outlet temperature, °F	450
Feed-water inlet temperature, °F	325
Feed-water pressure, psia	1020
Feed-water enthalpy, Btu/lb	297.1
Steam outlet temperature, °F	950
pressure, psia	950
Superheat, °F	411.6
Requirements Per Steam Generator	
Number of tubes per generator	82
Gas flow (normal), lb/sec	243
Steam flow (normal), lb/hr	505,000
Feed-water flow plus losses, lb/hr	510,000
Heat removed from gas, Mw	175
Volume with flowing gas, ft^3	10,600
stagnant gas, ft^3	3,800
Total weight of gas (operating), tons	0.68
Economizer section:	
Tube OD, in.	1.50
Tube wall thickness, in.	0.120
Fin OD, in.	2.50
Fin thickness, in.	0.040
Fins per ft	105.6
Tube element length (avg), ft	321
Total tubing length, ft	26,300
Outside area, ft^2	122,000
Inside area, ft^2	8,280

Table 10.1 (continued)

Requirements Per Steam Generator (continued)

Evaporator section:	
Tube OD, in.	1.75
Tube wall thickness, in.	0.135
Fin OD, in.	2.50
Fin thickness, in.	0.040
Fins per ft	105.6
Tube element length (avg), ft	358
Total tubing length, ft	29,400
Outside area, ft^2	112,700
Inside area, ft^2	11,580
Superheater section:	
Tube OD, in.	2.375
Tube wall thickness, in.	0.250
Tube element length (avg), ft	328
Total tubing length, ft	26,900
Outside area, ft^2	15,750
Inside area, ft^2	12,400
Total outside area, ft^2	250,500
Total inside area, ft^2	32,300
Total length of tubing, ft	82,600

TABLE* 10.2

SUMMARY OF PRINCIPAL FEATURES AND EQUIPMENT

GENERAL DATA

Access

Highway	0.5 mi constructed from main highway
Railroad	0.75 mi constructed from the existing access railroad
Water	On 9-ft navigable channel connected with Inland Waterway System

River Stages

Maximum elevation	718.0 ft
Minimum elevation	675.0 ft

Construction Quantities

Excavation (unclassified)	460,000 yd^3
Reinforced concrete	39,000 yd^3
Backfill	56,600 yd^3
Powerhouse superstructure volume	2,333,000 ft^3

POWERHOUSE, ADMINISTRATION WING, AND SERVICE BAY

Structural Data

Foundation:

Material	Shale rock
Allowable bearing pressure	Average ten tons per square foot over large areas. Maximum twenty tons per square foot under heavy loads

Type of construction:

Substructure	Reinforced concrete
Superstructure	Structural steel and tile

Principal dimensions:

Turbine-generator room	105 ft x 154 ft x 60 ft above grade
Control bay	66 ft x 66 ft x 60 ft above grade
Reactor bay	105 ft x 105 ft x 90 ft above grade

*Estimated by the Tennessee Valley Authority.

Table 10.2 (continued)

Architecture

Exterior walls	Structural steel frame, glazed facing tile with structural tile backup. Glass block at top of reactor house and north wall of turbine-generator room.
Interior walls	Glazed tile in turbine generator room, control room, toilet and locker rooms, service bay, and administration wing. Plaster in office and conference room. Movable metal partitions in offices. Concrete brick elsewhere.
Roof	Built-up roofing over rigid insulation on cellular steel decking. Extruded aluminum gravel stops and copings.
Ceilings	Accoustical tile on suspended metal lath and plaster in administration wing. Luminous ceiling in control room.
Floors	Tile in turbine-generator room, toilet and locker rooms, and entrance lobby. Rubber tile in control room and administration wing. Colored metallic hardened cement in service bay. Treated concrete elsewhere
Windows	Aluminum sash with heat absorbing glass. Insulated porcelain-enameled panels in administration wing windows.

Turbines (Two)

Type and speed	Tandem compound, triple-flow exhaust, condensing, 3600 rpm.
Maximum capability, each unit	125,000 kw
Throttle pressure	950 psia
Throttle temperature	950°F
Extraction points	3
Design back pressure	1-1/2-in. Hg.Abs.
Turbine heat rate (at guaranteed maximum capability and 1-1/2-in. Hg. exhaust pressure)	9458 Btu/kwh

Generators (Two)

Rating, each unit	125,000 kva, 112,500 kw, 0.9 pf, 3 p, 60 c, 18,000 v, 3600 rpm
Maximum capability, each unit	143,750 kva, 125,000 kw, 0.87 pf
Cooling	Hydrogen, 0.3 psig at rated capacity, 45 psig at maximum capability

Table 10.2 (continued)

Condensers (One per unit)

Type	Single pass, surface, divided water boxes
Surface area	60,000 ft^2
Steam condensed, each unit	801,400 lb/hr
Back pressure	1-1/2-in. Hg. Abs.
Cooling water temperature	66°F
Cooling water flow	88,500 cpm
Tube velocity	7 fps
Tubes	
Outside diameter	7/8 in.
Over-all length	30 ft
Material	Inhibited Admiralty

Feed-water Equipment

Closed Heaters (Two per unit)

Type	Horizontal
Shell design pressure	
Heater No. 1	120 psig
Heater No. 3	50 psig and 30-in. Hg. vacuum
Tube design pressure	
Heater No. 1	150 psig
Heater No. 3	1500 psig

Deaerating Heater (One per unit)

Type	Deaerating tray
Design pressure	25 psig

Evaporator (One per unit)

Type	Horizontal, single effect
Evaporative capacity, each unit	10,000 lb/hr
Shell design pressure	25 psig
Tube design pressure	120 psig
Tube design temperature	500°F

Boiler Feed-water Pumps (Two per unit)

Type	Horizontal, centrifugal
Rated capacity, each pump	950 gpm
Rated head	3160 ft
Motors	1250 hp, 3570 rpm

Condensate Pumps (Two per unit)

Rated capacity	2000 gpm
Rated head	250 ft
Motors	200 hp

Table 10.2 (continued)

Internal Water Treatment	
Hydrazine and morpholine pumps....	Three duplex-plunger type, one head for hydrazine and one for morpholine, 5 gph at 100-psi rated capacity, 1/3-hp motor. System complete with two 250-gal storage tanks, measuring tanks, and hand pumps and piping.
Demineralizers....................	Two scavenger-type located in a bypass in condensate flow between hotwell pumps and deaerator. Capacity of 5% of flow or 110 gpm and ability to produce effluent containing not over 0.05 ppm of dissolved solids. Systems include four 3-ft-dia mixed bed tanks, acid and caustic day tanks and pumps, acid and caustic storage tanks, bitter water tank, supply, wash, rinse, and waste pumps, conductivity recorders, instruments, and controls.
Miscellaneous Mechanical Equipment	
Compressed Air Facilities	
Instrument air....................	Two nonlubricated compressors Y-type, 2 stage, 640 cfm each at 100 psig discharge pressure, direct connected, motor driven, with aftercoolers, and one air receiver.
Station service air...............	Two lubricated compressors, horizontal, 2 stage, 660 cfm each at 100 psig discharge pressure, V-belt motor driven, with aftercoolers and two air receivers.
Oil Purification Facilities	
Lubricating oil...................	Two 55 gpm at 70-psi TDH dirty oil transfer pumps. One 50 gpm at 70-psi TDH clean oil transfer pump. One 600-gph stationary centrifuge type purifier. One 210-gph portable cellulose media purifier. One dirty and one clean oil storage tank of 5800-gal capacity each.

Table 10.2 (continued)

Oil Purification Facilities (continued)

Insulating oil	One 200 gpm at 50-psi TDH dirty oil transfer pump. One 200 gpm at 110-psi TDH clean oil transfer pump. One 1200-gph stationary centrifuge type purifier with filter paper and drying oven. Two dirty and one clean oil storage tank of 12,000-gal capacity each.

Vacuum Cleaning Equipment

Machine	One multi-stage centrifugal exhauster with primary and secondary collectors, complete with floor outlets, hose, and cleaning tools.

Elevators

Operators	Two in reactor bay, 1500-lb capacity at 300 fpm
Operator	One in control bay, 2000-lb capacity at 200 fpm
Freight	One in service bay, 10,000-lb capacity at 30 fpm

Miscellaneous Pumps

Raw water service	Three horizontal centrifugal, each 2000 gpm at 200-ft TDH with 150-hp motors.
Boiler feed-water system	Two heater drain pumps. Two condensate drain tank pumps. Two distilled water pumps. One gasoline-engine-driven emergency distilled water pump. Two gland seal water pumps.
Vacuum priming	Two pumps and one vacuum tank.
Building drainage	Two 2000 gpm at 50-ft TDH, vertical centrifugal deepwell turbine type.
Distilled well leakage	Two 50 gpm at 25-ft TDH, vertical centrifugal duplex type.

Piping Systems

Complete with pipe, valves, fittings, accessories, hangers, and insulation	Main steam extraction steam Boiler feed water Condensate Heater drains Heater vents Turbine vents Raw water cooling Raw water service Compressed air service

Table 10.2 (continued)

Piping Systems (continued)

Instrument air
Vacuum cleaning
Water fire protection
CO_2 fire protection
Hydrogen
CO_2 Purging
Lubricating oil
Insulating oil
Gland seal
Vacuum priming
Drinking water
Plumbing
Softened water
Chemical feed
Condenser circulating water
Building heating
Drainage
Instrument lines

Heating, Ventilating and Air Conditioning

Powerhouse

Basement exhaust fans........................10 at 30,000 = 300,000 cfm
Boiler room exhaust fans.....................14 at 18,000 = 252,000 cfm
Heater bay exhaust fans.......................3 at 30,000 = 90,000 cfm
Charging room exhaust fans....................5 at 18,000 = 90,000 cfm
Electrical board room exhaust fans............2 at 10,000 = 20,000 cfm
Oil rooms exhaust fan.........................1 at 10,000 = 10,000 cfm
250-v board room exhaust fan....................1 at 3,000 = 3,000 cfm
Battery charger rooms exhaust fans..............2 at 3,000 = 6,000 cfm
Miscellaneous rooms exhaust fans................3 at 5,000 = 15,000 cfm
Control room air conditioning..................2 packaged units = 35 hp
Battery room air conditioning..................2 packaged units = 20 hp
Miscellaneous air-conditioning systems.........8 packaged units = 45 hp
Unit heaters......................................14 at 100,000 Btu
Unit heaters.......................................14 at 80,000 Btu
Unit heaters.......................................30 at 60,000 Btu

Service Bay and Offices

Main air-conditioning system (Built-up system)....................50 hp
Miscellaneous air-conditioning system (Four packaged units).......40 hp
Roof exhaust fans.........................12 at 5,000 cfm = 60,000 cfm
Shop exhaust fans..........................3 at 4,000 cfm = 12,000 cfm
Toilet and locker rooms exhaust fan..........1 at 8,000 cfm = 8,000 cfm

Table 10.2 (continued)

Service Bay and Offices (continued)

Miscellaneous exhaust fans	3 at 3,000 cfm = 9,000 cfm
Miscellaneous supply fans	4 at 15,000 cfm = 60,000 cfm
Miscellaneous supply fans	3 at 10,000 cfm = 30,000 cfm
Basement supply fans	3 at 10,000 cfm = 30,000 cfm
Basement exhaust fans	3 at 10,000 cfm = 30,000 cfm
Offices air-conditioning supply fan	1 at 10,000 cfm = 10,000 cfm
Public spaces a-c, supply fan	1 at 8,000 cfm = 8,000 cfm
Conference room a-c, supply fan	1 at 4,000 cfm = 4,000 cfm
Building heating boiler	1 at 150 hp

Cranes

Turbine bay	One 100-ton
Reactor bay	One 20-ton
Machine shop	One 5-ton
Service bay railroad unloading dock	One 5-ton

Permanent Shop Equipment (In service bay)

Machine shop

Engine lathe	24 in. x 24 ft
Engine lathe	18 in. x 12 ft
Toolmaker lathe	10 in. x 34 in.
Milling machine	No. 3 size
Shaper	24 in.
Radial drill	4 ft
Floor drill	15 in.
Bench drill	10 in.
Hydraulic press	200-ton
Arbor press	3-ton
Horizontal metal saw	9 in. x 9 in.
Vertical metal saw	26 in.
Pedestal grinders	Two 12-in.
Bench grinder	One 10-in.
Surface plate	36 in. x 72 in.
Assembly and balancing ways	For 16-ft shaft
Tool cabinets	Fourteen 36-in.
Work benches	6

Blacksmith and welding shop

Metal rolls	1/2 in. x 4 ft
Metal brake	3/16 in. x 8 ft
Metal shear	1
Radial drill	3 ft
Forging hammer	100-lb pneumatic
Forge	1
Anvil	1

Table 10.2 (continued)

Blacksmith and welding shop (continued)	
Pedestal grinders	Two 12-in.
Horizontal metal saw	12 in.
Oil bath	1
Lime vat	1
Induction heater	1
Tool cabinets	Fourteen 36-in.
Work benches	6
Steamfitter shop	
Horizontal metal saw	9 in. x 9 in.
Floor drill	15 in.
Pedestal grinder	10 in.
Pipe threading and bolt machine	Portable
Tool cabinets	Eight 36-in.
Work benches	3
Electrical shop	
Floor drill	15 in.
Bench grinder	10 in.
Pedestal grinder	12 in.
Drying oven	1
Dipping vat	1
Test bench	1
Tool cabinets	Two 36-in.
Work benches	2
Carpenter shop	
Portable dust collector	1
Radial saw	1
Bandsaw	36 in.
Bench drill	15 in.
Jointer-planer	1
Paint shop	
Spray booth	10 ft x 10 ft
Wall storage cabinet	Steel
Work benches	3
Cranes and hoists	One 2-ton jib crane and hoist. Two 2-ton monorail hoists.

Table 10.2 (continued)

Mechanical Control Equipment

Principal features	Centralized control for two turbine-generator units and accessory steam plant equipment from the unit control room; including boiler feed-water controls, flowmetering equipment, temperature recorders, conductivity and pH recorders, thermometers, pressure, flow and level recorders, annunciators, electrical switches, ammeters, megawatt meters, indicating lights, etc.

Principal Electrical Equipment

Station service transformers	Two 17.1 - 4.16-4.16 kv
Primary	29,000/36,666 kva OA/FA
Secondary	19,000-10,000/25,666-13,333 kva OA/FA
Generator oil circuit breakers	Two 18 kv, 5000 amp, 1,500,000 kva
Generator bus	Welded aluminum construction, segregated phase, 5000 amp at 30°C rise over 40°C ambient, field fabricated.
Disconnect switches	Two 18 kv, 5000 amp, gang manually operated. Two 18 kv, 2000 amp, gang motor operated.
Auxiliary board transformers	Five 4160-480 v, 1250 kva, 3 p Two 4160-480 v, 1000 kva, 3 p Two 4160-480 v, 500 kva, 3 p
Lighting board transformers	Four 480-240/120 v, 200 kva, 1 p Two 480-240/120 v, 100 kva, 1 p One 480-240/120 v, 35 kva, 1 p
Powerhouse 4.16-kv auxiliary switchboard (breaker ratings)	1200 and 2000 amp, 250,000-kva interrupting capacity.
Reactor building 4.16-kv auxiliary switchboard (breaker ratings)	Incoming feeder, 3000 amp with supplementary fan for 3500 amp, 350,000-kva interrupting capacity. Feeder and tie breakers 1200 and 2000 amp, 350,000-kva interrupting capacity.
Powerhouse, reactor building, and miscellaneous 480-v auxiliary boards (breaker ratings)	Incoming feeder, 1600 amp, 60,000-amp interrupting capacity at 480 v. Feeder and tie breakers 600 and 800 amp, 35,000-amp interrupting rating at 480 v.

Table 10.2 (Continued)

Principal Electrical Equipment (continued)

Powerhouse, reactor building and miscellaneous 480-v control centers and lighting boards (breaker ratings)	Moulded case type, 100 and 225 amp, 15,000-amp interrupting capacity.
Batteries	Two main control batteries, 250 v, 960 amp-hr at 8-hr rate to 1.75 v per cell. One annunciator battery, 125 v, 240 amp-hr at 8-hr rate to 1.75 v per cell. One telephone battery, 48 v, 140 amp-hr at 8-hr rate to 1.75 v per cell.
Battery chargers	Three main control batteries, M-G set. Motor - 480 v, 3 p, 50 hp. Generator - 30 kw, 280 v d-c diverter pole type. One annunciator battery charger, rectifier type, 5 kw, 40 amp, 125 v, input 240 v, single p. One telephone battery charger, rectifier type, 12 amp, 48 v, input 120 v, single p.
Emergency M-G set	One 25 kw, 120 v a-c, 40 hp, 250 v d-c. One 25 kw, 120 v a-c, 40 hp, 250 v d-c with an inertia flywheel for continuous operation.

WATER SUPPLY

Circulating Water for Condensers and Raw Water System

Intake

Channel	Excavated, ~ 600 ft long from lake
Structure	Reinforced concrete
Trashracks	Two per unit
Traveling screens	Two per unit
Stop logs	2
Trash rake	1
Lifting beam	1
Circulating pumps	Two per unit, 54-in. discharge, vertical mixed flow, each 50,000 gpm at 30-ft head, 500-hp motors.
Screen wash pumps	Two vertical turbines, each 1000 gpm at 270-ft head, 100-hp motors.
Sump pumps	Two 40 gpm at 50-ft head each, 1-hp motors.
Vacuum priming pumps	Two 130 cfm at 20-in. Hg. each, 5-hp motors.

Table 10.2 (continued)

Intake (continued)

Gantry crane	One 15-ton
Water conduits	600 ft of 78-in.-dia reinforced concrete pressure pipe.

Discharge

Conduit	450 ft of 79-in.-dia reinforced concrete pressure pipe.
Structure	Reinforced concrete with stop log guides and one stop log.
Channel	Excavated ~ 770 ft long to lake.
Weir	25 tons sheet piling.

Water-Treatment Plant

Structure

Substructure	Reinforced concrete
Superstructure	Steel framing
Architecture	Glazed facing tile, aluminum sash windows with heat absorbing glass.

Equipment

Flocculator	One 30-min retention
Settling basins	Two 6-hr retention
Filters	Two 55 gpm each
Storage wells	
Filtered water	28,000 gal
Softened water	21,000 gal
Potable water	8,000 gal
Brine	12,000 gal
Pumps	
Filter raw water supply	Two pumps
Filter wash water	One pump
Potable supply	Two pumps
Potable service	Two pumps
Softener supply and wash	Three pumps
Softener service	Two pumps
Lubricating water	Two pumps
Brine	Two pumps
Duplex sump	Two pumps
Zeolite softening system	One system capacity equal to 1% of steam flow plus an allowance for regeneration or 55 gpm total. System to include two softener tanks, brine day tank, multi-port valves, meters, and controls for automatic operations.

Table 10.2 (continued)

OTHER BUILDINGS AND YARD FEATURES

Fuel Dock and Pond

Fuel dock	Reinforced concrete substructure, with steel frame superstructure and glazed tile walls. Decontamination room ~ 20 ft x 20 ft. Locker and toilet facilities and 10-ton monorail hoist.
Pond	Reinforced concrete, ~ 100 ft long, 25 ft wide, 12 ft deep with covered top. Five-ton overhead traveling crane.
Tunnel	Reinforced concrete, 3 ft wide by 5 ft high.
Helium Storage	Concrete paved and fenced area ~ 200 ft x 200 ft, 6 in. thick with wire mesh reinforcement.

Yard

Roadways and parking areas	13,000 yd^2 6-in. stabilized base and bituminous surface.
Sidewalks	900 yd^2 4-in. thick, concrete
Concrete curbs	45,000 lin. ft
Fence	Protective type around entire plant area
Piping systems Complete with pipe, valves, fittings, wrapping tape and accessories	Raw water fire protection and service including hydrants and one elevated steel water storage tank of 50,000-gal capacity, 100 ft high to walkway. Compressed air service, softened water from water treatment to powerhouse, building drain lines to storm sewers, storm drainage system.
Hydrogen system	Consists of 2 reinforced concrete trailer storage ports with fire-protection facilities, reducing valves, control valves, metering equipment, underground piping system to powerhouse and three 49,000 ft^3 (38 tube) hydrogen transport trailers (one spare).

Table 10.2 (continued)

CONSTRUCTION PLANT BUILDINGS

Buildings (Incomplete list, special buildings only)

Type	Prefabricated metal with concrete floors including interior partitions and building services (exclusive of equipment).
Heat exchanger fabrication shop	100 ft x 200 ft x 30 ft high (insulated)
Pipe fabricating shop	50 ft x 100 ft x 15 ft high (insulated)
Instrument shop	20 ft x 20 ft x 12 ft high (insulated)
Graphite inspection and storage	50 ft x 100 ft x 12 ft high
Fuel element inspection and storage	20 ft x 20 ft x 12 ft high
Radiograph inspection	20 ft x 60 ft x 15 ft high
Pipe and equipment cleaning area	100 ft x 200 ft x 30 ft high

TABLE 10.3

CONSTRUCTION LABOR RATES*

	(Rates $/hr)
Bricklayers	3.625
Boilermakers	3.45
Carpenters	2.95
Electricians	3.325
Structural Iron Workers	3.20
Lathers	3.075
Plasterers	3.15
Sheet-Metal Workers	3.15
Machinists	3.10
Operating Engineers (heavy equipment)	3.20
Painters	3.025
Roofers (composition)	2.45
Plumbers and Steamfitters	3.325
Teamsters (heavy trucks)	2.375

*Construction labor rates negotiated by the Tennessee Valley Authority and the Tennessee Valley Trades and Labor Council for 1958.

Representative river temperatures are: maximum 84°F, minimum, 41°F, and average, 62°F. The flow averages approximately 23,000 day-second-feet and the minimum flow can be regulated as required from a dam which is situated one mile upstream. The elevation of the river can be expected to fluctuate between a minimum level of 675 ft and a maximum probable flood (regulated) of 718 ft. The average fluctuation is much less than this. The general topography of the site is indicated by the contour lines on the general plan, (Fig. 10.1). Prevailing winds are from the southwest and representative ambient temperatures are: maximum, 103°F, minimum, 10°F, average, 60°F.

The site is sufficiently remote from heavily populated areas to be acceptable, and yet it is near enough to several industrial load centers to assure that unreasonable transmission costs would not be incurred. The nearest incorporated towns are approximately 23 mi distant, and the load centers are about 40 to 60 mi from the plant site.

10.1.3 Plant Layout: An architectural perspective of the power station is shown in Fig. 10.2. A cut-away view of the power station is shown as Fig. 10.3.

The proposed powerhouse location is shown on the general plan, Fig. 10.1. The reactor-powerhouse-service bay complex is located approximately 900 ft from the river and stands on a slope whose elevation near the river is 700-ft mean sea level and which rises away from the river to an elevation of 740 ft at the west side of the service bay. The ground floor of the building is located at an elevation of 720 ft. The reactor bay and the turbine-generator bay extend 35 ft below grade to an elevation of 685 ft in order to reach sound shale and thus provide for a high unit loading on the foundations. The main entrance to the administration area is on the south side of the service bay. Approximately 0.5 mi of access highway will be required and 0.8 mi of access railroad track will provide railroad facilities to the powerhouse, the service-bay loading dock, and the helium storage area, which will be serviced from helium tank cars. The intake for the condensing water runs approximately 600 ft to the pump house, which is located 200 ft west of the powerhouse. The outlet for the condensing water runs from the reactor bay approximately 1200 ft southwest and discharges over a weir 1000 ft downstream from the water intake. An area 350 x 600 ft located south of the plant is a possible construction plant area.

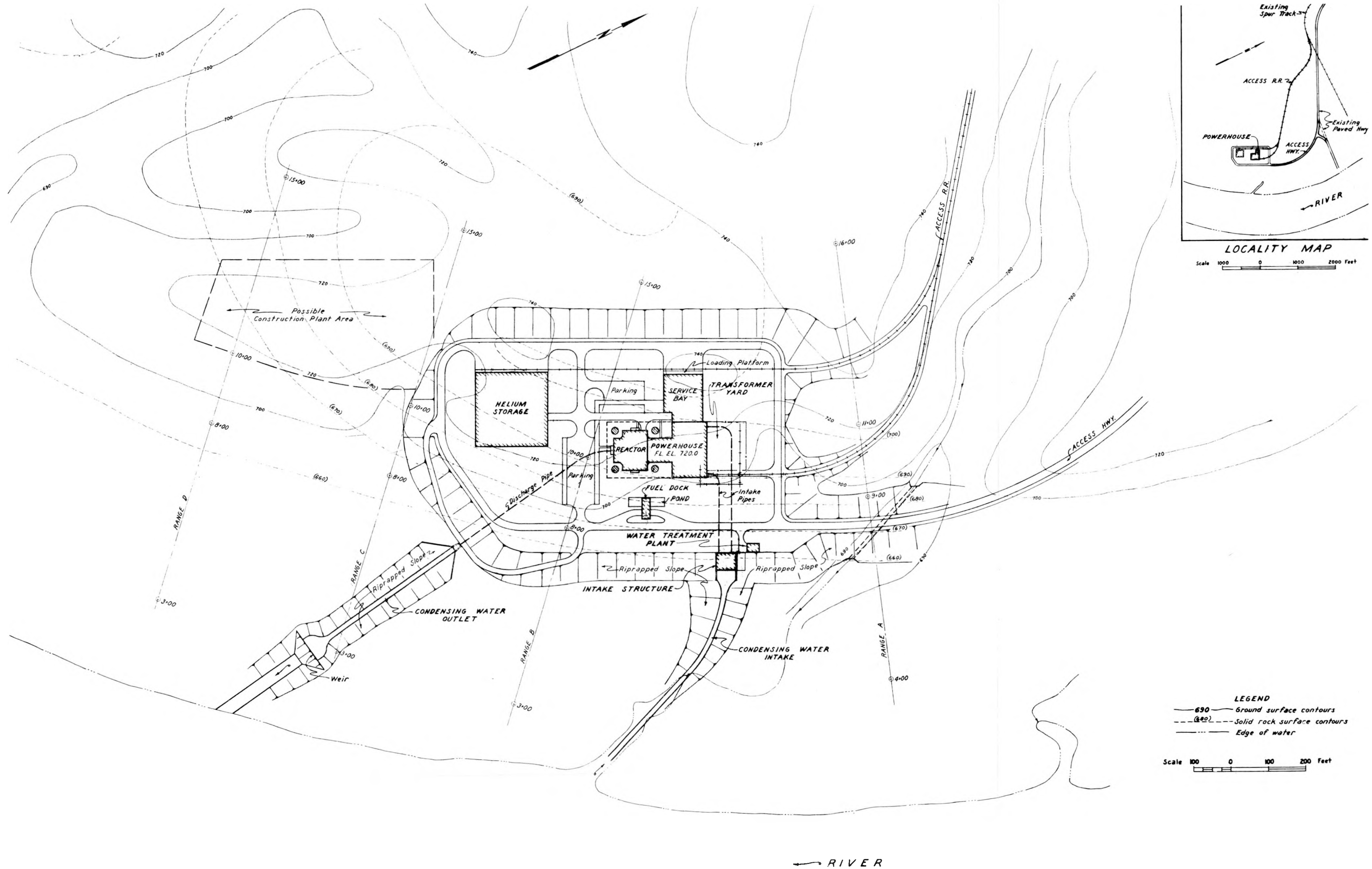


Fig. 10.1. Site Plan – ORNL Gas-Cooled Reactor Plant (GCR-2) (Design Div., Tennessee Valley Authority).

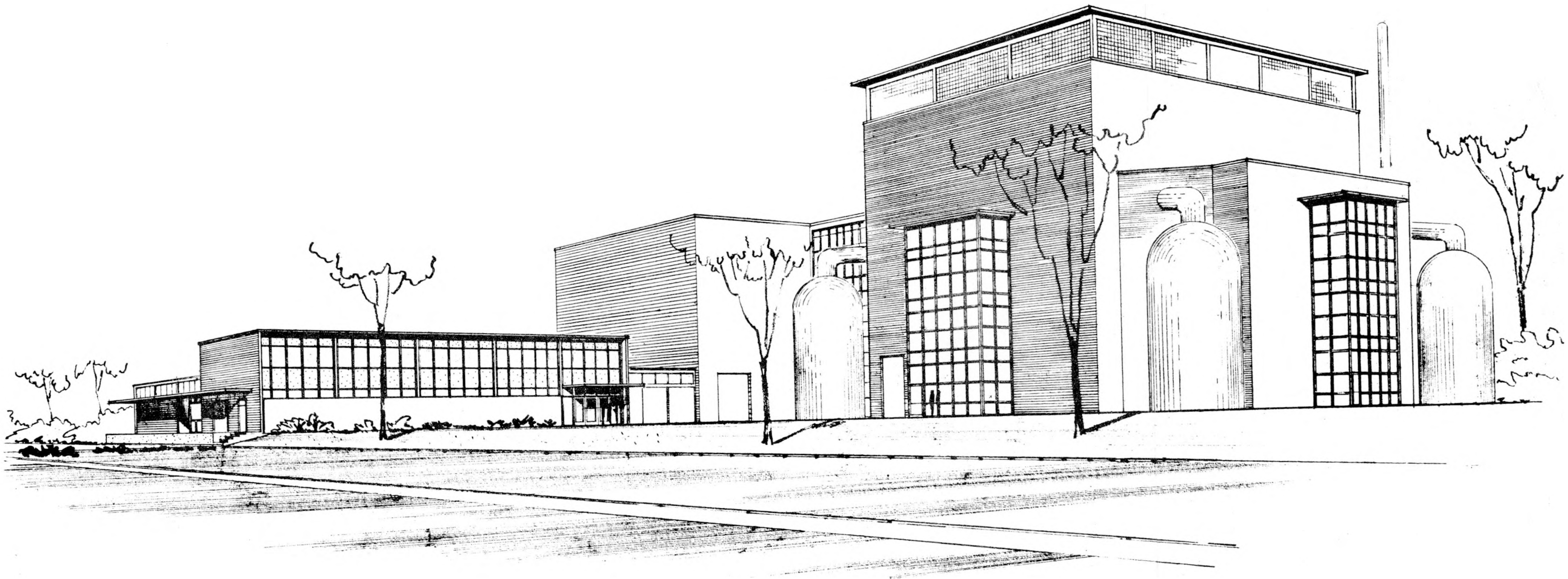


Fig. 10.2. Architectural Perspective – ORNL Gas-Cooled Reactor Plant (GCR-2) (Design Div., Tennessee Valley Authority).

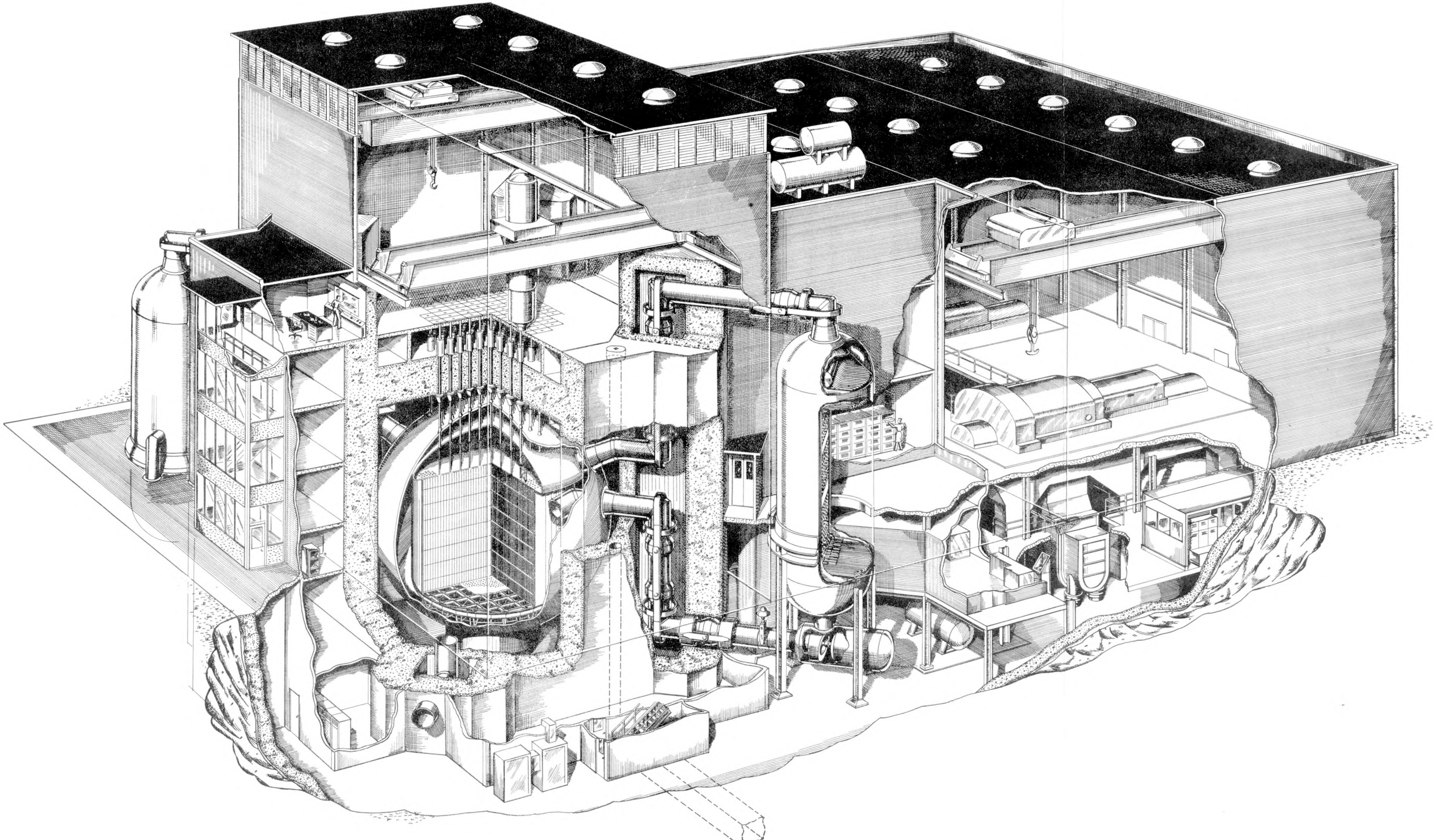


Fig. 10.3. Cutaway Perspective of ORNL Gas-Cooled Reactor Plant (GCR-2).

10.1.4 Reactor Bay: The nuclear reactor building houses the reactor, the blowers and motors and associated equipment. An outdoor steam generator is located at each corner of the building. The building is a seven-story masonry structure, 105 ft wide, 105 ft long, and 125 ft high from basement elevation, as shown in Figs. 10.4 and 10.5. The reactor shield is octagonal in plan and consists of 9 ft of 142 lb/ft^3 concrete with reinforcing steel, as shown in Fig. 10.6. Space between the pipe enclosures on the east, south, and west sides of the reactor shield is utilized for the various services associated with the reactor. The allocation of space within the building is given in Table 10.4. The reasons for the specific allocations and the functions to be performed at each location are discussed below.

The seventh floor houses only the fuel-loading equipment and areas requiring access to the top of the reactor. A 20-ton crane is provided to service the fuel-loading and discharge machine. It will also be a supplemental lifting device for handling shield plugs, control-rod drives, and other heavy equipment.

The floor is divided into three areas. The area on the east side is used exclusively for handling contaminated equipment. It is isolated from the remaining areas by a wall. Normally, access to this area is limited to entrance from the stairs in the hot change house below, however, an emergency outside stairway is also provided.

The area on the west side is limited to servicing uncontaminated equipment. Personnel will have direct communication from this area to other areas by an elevator as well as by an outside stairway.

A 10 x 10-ft hatchway is located on one side of this area through which the 20-ton overhead bridge crane can lift and lower uncontaminated equipment.

The remote operating panel for the fuel-loading machine is located on the south side of the floor. This room is closed in with lead-glass windows to protect the operators during remote operation.

The fuel-charging machine is positioned accurately over the reactor, by means of a bridge spanning the reactor from east to west, and a trolley, which traverses the bridge. A fuel-discharge chute is located in the east side of the concrete shield through which fuel elements can be lowered to a transfer dolly located in a tunnel below basement level.

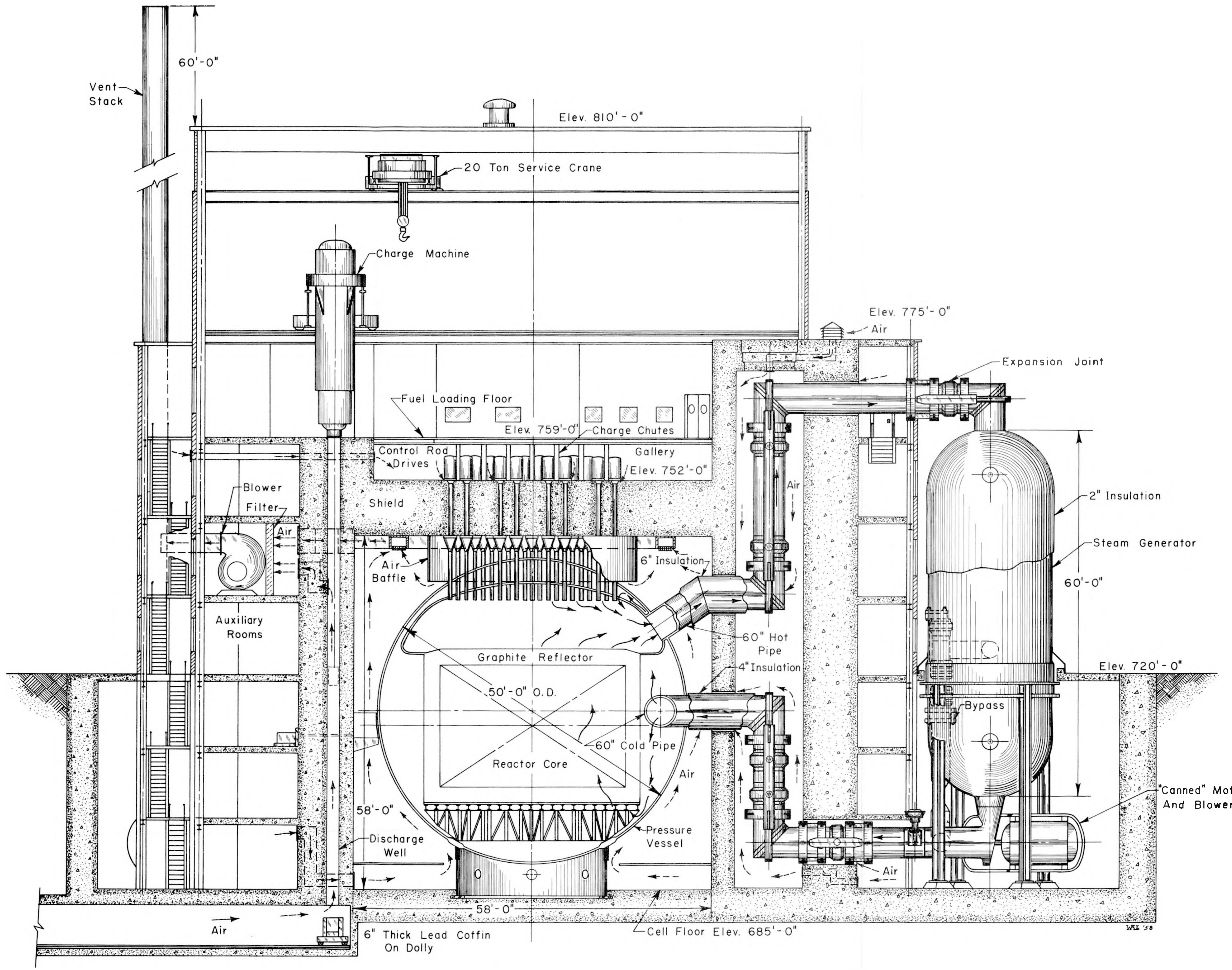


Fig. 10.4. Sectional View Through Reactor and Reactor Bay (ORNL – GCR-2).

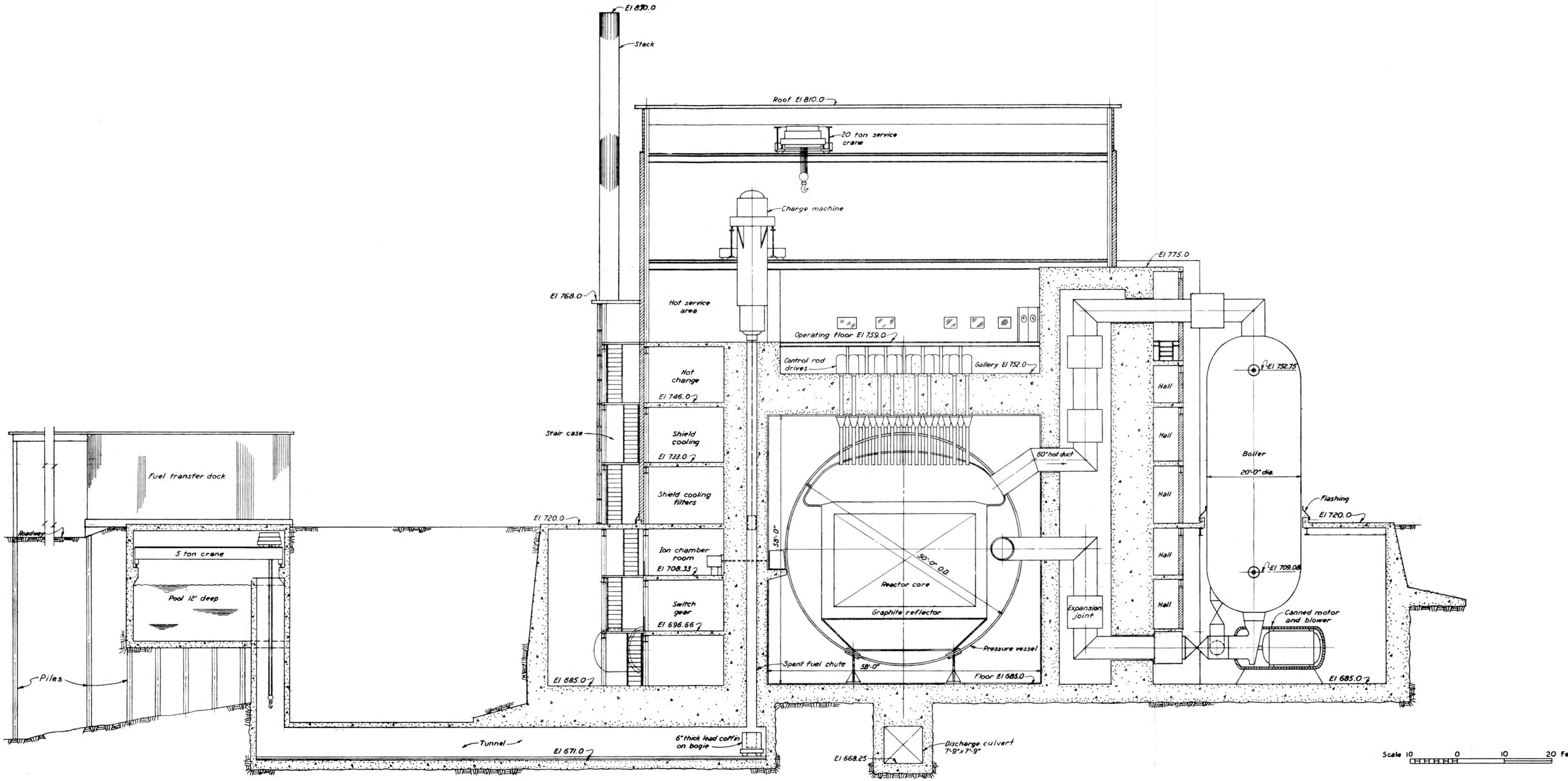


Fig. 10.5. Longitudinal Section BB Through Reactor Bay and Steam Generator (ORNL – GCR-2) (Design Div., Tennessee Valley Authority).

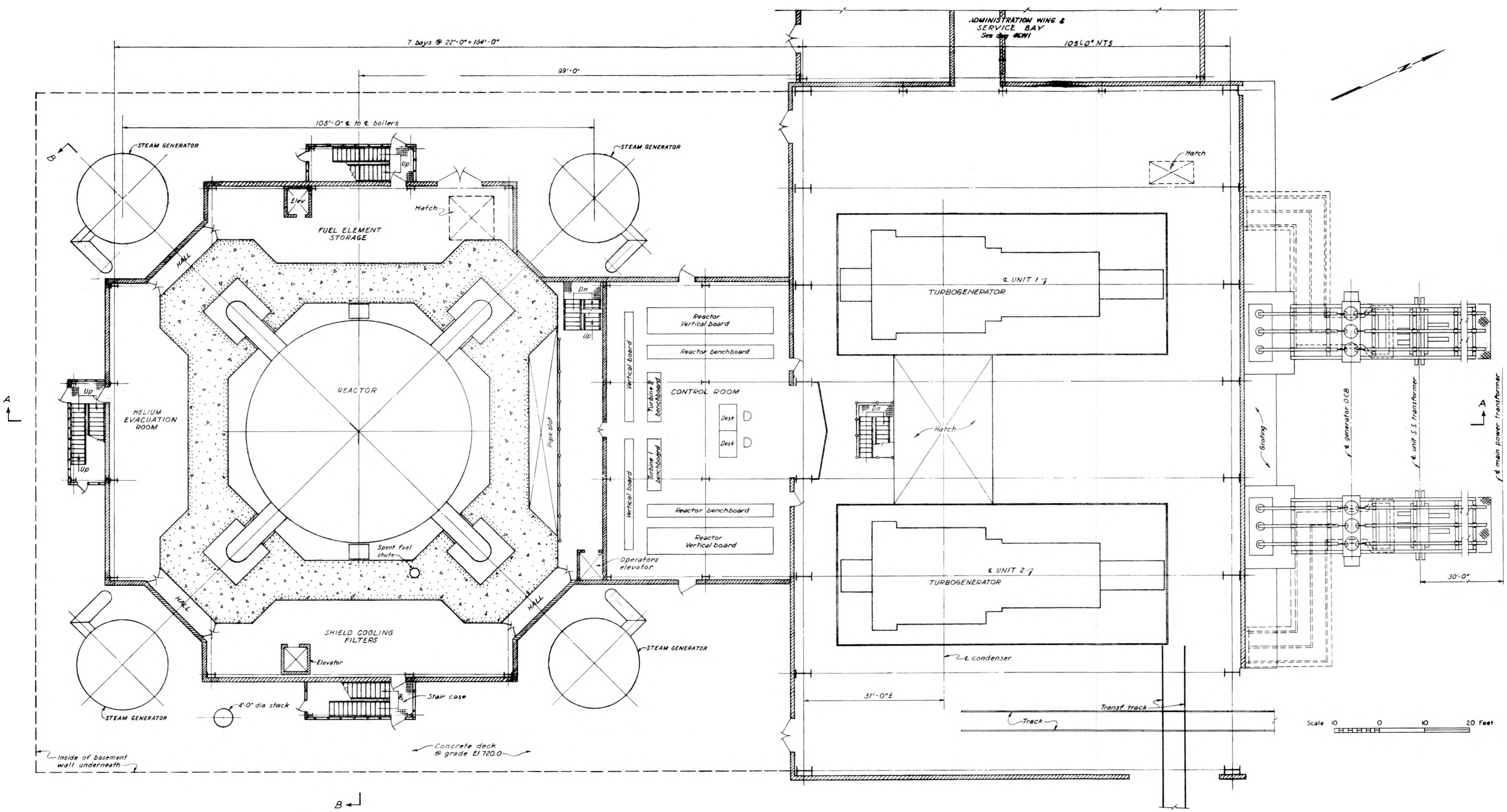


Fig. 10.6. Equipment Layout at Elevation 720.0 (ORNL – GCR-2) (Design Div., Tennessee Valley Authority).

TABLE 10.4

ALLOCATION OF ROOMS IN REACTOR BUILDING

FLOOR	SOUTH	EAST	WEST
7 Fuel Loading Floor	Fuel Load Control Room AC.	Service Elevator Hot Service Area FA - SE	Service Elevator Cold Service Area FA - SE
6	Cold Change House	Hot Change House FA	Evacuation
5	Gas Sampling FA - SE	Shield Cooling	Fuel Element Storage FA
4	Helium Evacuation FA - SE	Shield Cooling Filters	Fuel Element Storage
3	Helium Filters and Dryers FA - SE	Ion Chamber Room AC - FA	Ion Chamber Room AC - FA
2	Health Physics AC	Switchgear FA	Switchgear FA
1	Battery Charger and Distribution FA - SE	Service Elevator	Service Elevator

NOTE: FA - Filtered Air
AC - Air Conditioned
SE - Separate Exhaust

North - Adjacent to Turbine-generator Building.

The sixth floor provides a change house for radioactive service. The hot change area locker room contains 60 lockers. This area is on the east side of the building. A stairway permits direct access to the hot work area on the floor above.

The cold change area is on the south side of this floor. It contains 60 lockers, toilet facilities, and showers for 15 persons. This area has direct access to the hot change area on the east side.

The west side is devoted to vacuum pumping equipment which can be used for initial vacuum testing of the pressure vessel, steam generators, and adjoining piping.

The shield-cooling blowers are located on the east side of the fifth floor. Air is directed to this area from the filter room. The blowers exhaust air out of this room into a 4-ft-dia vent stack exterior to the building. The stack extends 60 ft above the roof.

On the south side is the gas sampling room. This room contains valves, pumping equipment, and counters for monitoring gas samples from the fuel channels. The sample lines are approximately 3/8-in.-dia stainless steel tubing, and one line ties into each fuel channel. The lines are carried to the sample room through the duct that carries evacuation lines to the room above. On the west side there is a storage room for new fuel elements.

The fourth floor houses, on the east side, the filter equipment for the shield-cooling system. On the south side are the helium compressors for charging the reactor and storage system. The compressors handle gas at pressures from 20 to 2000 psig. All gas pumped into the reactor system is fed through the filters and dryers in this room. On the west side there is a fuel storage room to hold new fuel elements.

The third floor contains on the south side, equipment for drying and filtering the helium that circulates through the reactor. The equipment is designed to filter particulate matter carried through the reactor and therefore to retain activity. Piping connects to the reactor circuits tapping in at points in the cold gas piping on the suction and discharge side of the main blowers.

On the east and west sides there are ion chamber rooms for monitoring the neutron flux in the reactor. The two rooms are connected directly into the wall of the reactor vessel by 1-in.-dia piping.

The second floor houses the electrical equipment required for reactor operation. The east and west rooms contain load centers and switchgear associated with the reactor electrical equipment. The south side contains Health Physics equipment.

The first floor, or basement, contains on the south side, a battery room. This floor, also, houses the primary blowers, their lubricating oil pumps and coolers, and the drive motors and switchgear for this equipment. Space around the building permits transportation of the canned motors and blowers by skidding to the area under the hatch in the center of the turbine-generator room and then lifting through the hatch by the turbine room crane. Cooling air for the reactor shield is brought in at this level. The air is filtered before being fed into the shield.

The elevators on the east and west sides are 8 x 8 ft. The shafts extend from the basement to the upper floors. The elevator shaft in the east end stops at the hot change house so that access to the top floor on this side is limited to the stairway from the hot change house in the hot service area. An operator's elevator is located in the bay between the reactor and the turbine-generator plant at the northeast corner.

In Table 10.4 the rooms and the type of ventilation or air conditioning required are tabulated. The ventilation is provided by individual exhausters in each room that are equipped with dampers to prevent backflow. Inlet air is supplied through fiberglas filters. Air conditioning of specific rooms is provided by packaged units as required. Room heat loads have not been completely determined, and therefore the total required capacity of the units is assumed to be 40 tons, for estimating purposes. Ventilation in the crane bay is provided by conventional ceiling-mounted exhausters in the roof of the crane bay.

10.1.5 Turbine-Generator Bay: The over-all height of the turbine-generator building is somewhat less than that of the structure required to house the reactor. The turbine-generator building has a basement elevation of 685 ft and a roof elevation of 780 ft (Fig. 10.7). The turbine-generator building covers an area 154 ft x 105 ft.

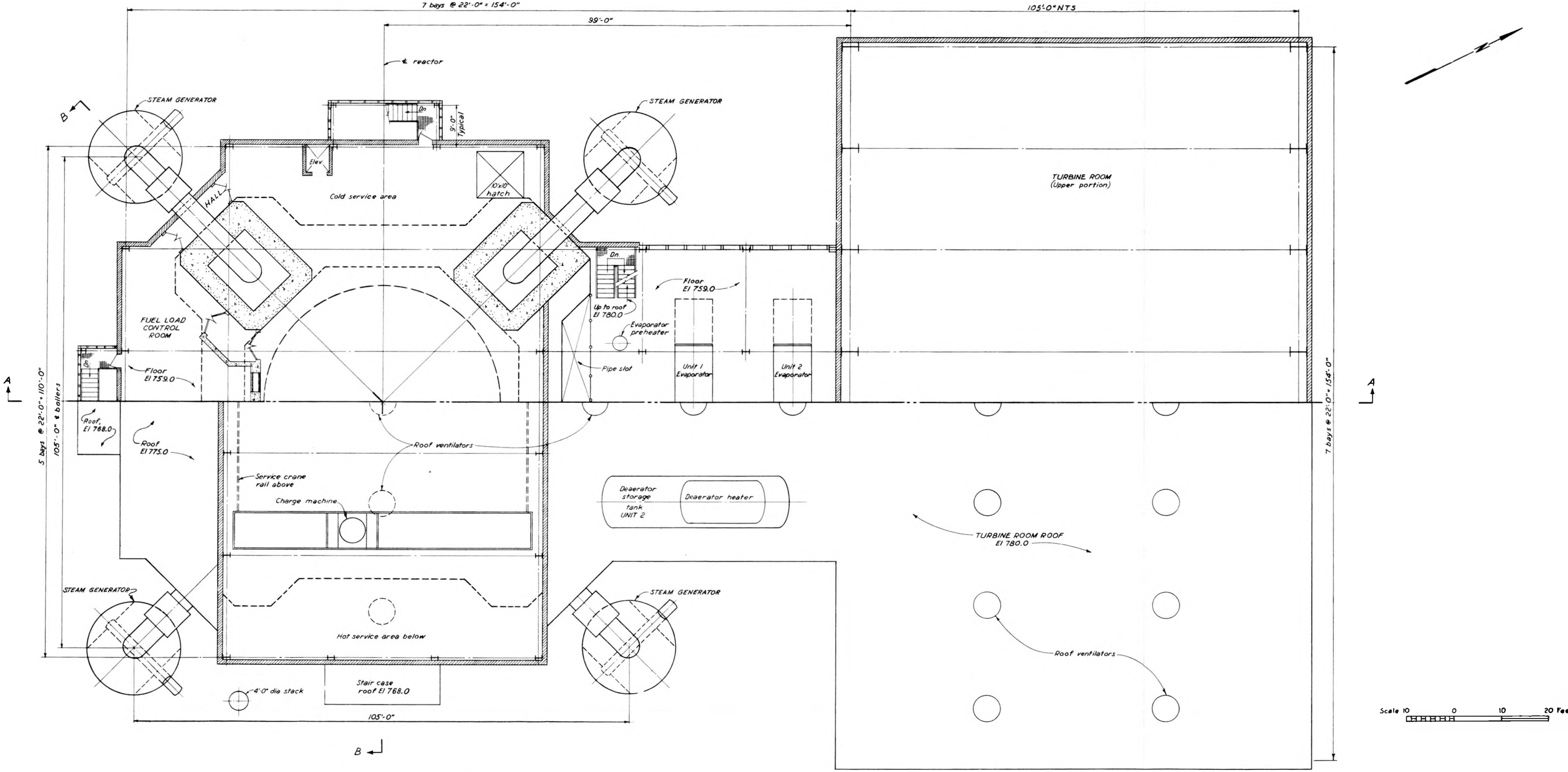


Fig. 10.7. Equipment Layout at Elevations 759.0 and 780.0 (ORNL – GCR-2) (Design Div., Tennessee Valley Authority).

The condenser inlet and outlet cooling-water ducts, the station sump, and two distilled water storage reservoirs, each of 40,000 gal capacity (one for each turbine-generator unit), are in the base slab below the basement floor. While the turbine-generator assembly is on the ground floor level (elevation 720 ft), its supporting structure extends upward from the basement floor, which is anchored to the rock below, as shown in Fig. 10.8.

The basement (elevation, 685 ft; Fig. 10.9) provides space for boiler feed pumps, condensate, or hot-well pumps, the station sump pumps, the station raw-water pumps, the distilled water pumps, and the demineralizer service pumps. The main condenser, the condensate demineralizer units, the generator hydrogen-seal oil detrainment unit, the instrument and station air compressors, and the feed-water chemical treatment equipment are also located on the basement floor. Further, the CO_2 cylinders used in purging the generator prior to charging with hydrogen are stored on the basement floor. The hydrogen supply for the generator casing is stored outdoors and is remotely monitored and controlled from the unit control room.

The second floor of the turbine-generator building at an elevation of 702 ft, Fig. 10.10 houses the oil tanks and associated pumps for each turbine unit, the turbine-generator plant, battery room and associated equipment, the lubricating oil storage room, the insulating oil and lubricating oil purification room, the chemical storage room, the heavy-rigging storage area, the 4160 and 480 v units and their common boards, the 480 v chemical feed and miscellaneous board and two lighting transformers. The low-pressure feed-water heater may be seen protruding from the condenser neck at this elevation, and the steam jet-air pumps are located almost directly under the high-pressure turbine section of each unit.

On the ground floor (elevation 720 ft, Fig. 10.8) are the two turbine-generator units, the 22 x 34-ft open hatch to the basement floor, and the generator leads to the outdoor oil circuit breaker and the unit station service transformers.

The turbine-generator units are visible from the unit control room through a large glass window. The railroad track runs into the turbine-generator room at the northeast corner of the building; the inside of the building will accomodate one freight car. A 100-ton bridge crane is provided over this

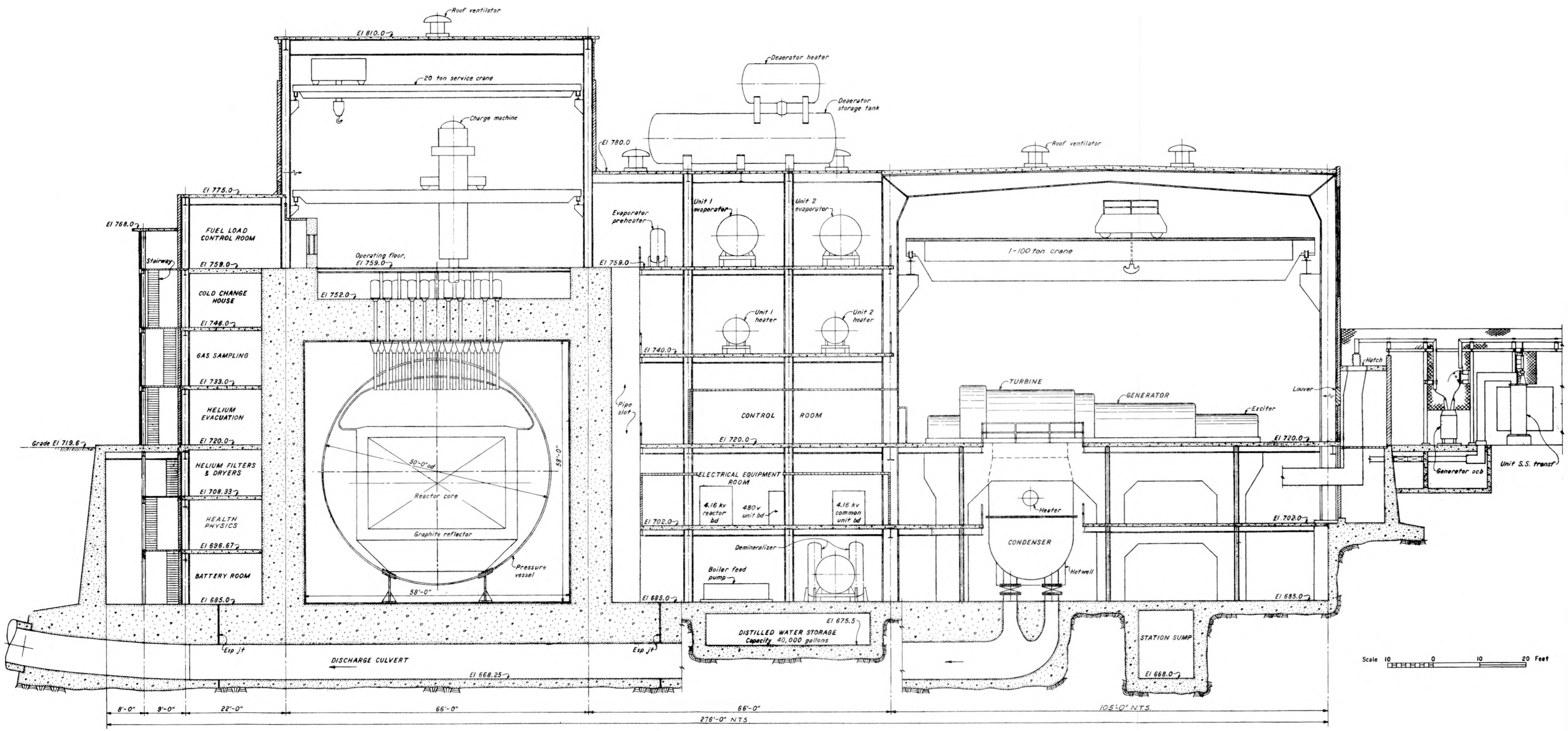


Fig. 10.8. Transverse Section AA Through Reactor Bay and Turbine-Generator Bay (ORNL – GCR-2) (Design Div., Tennessee Valley Authority).

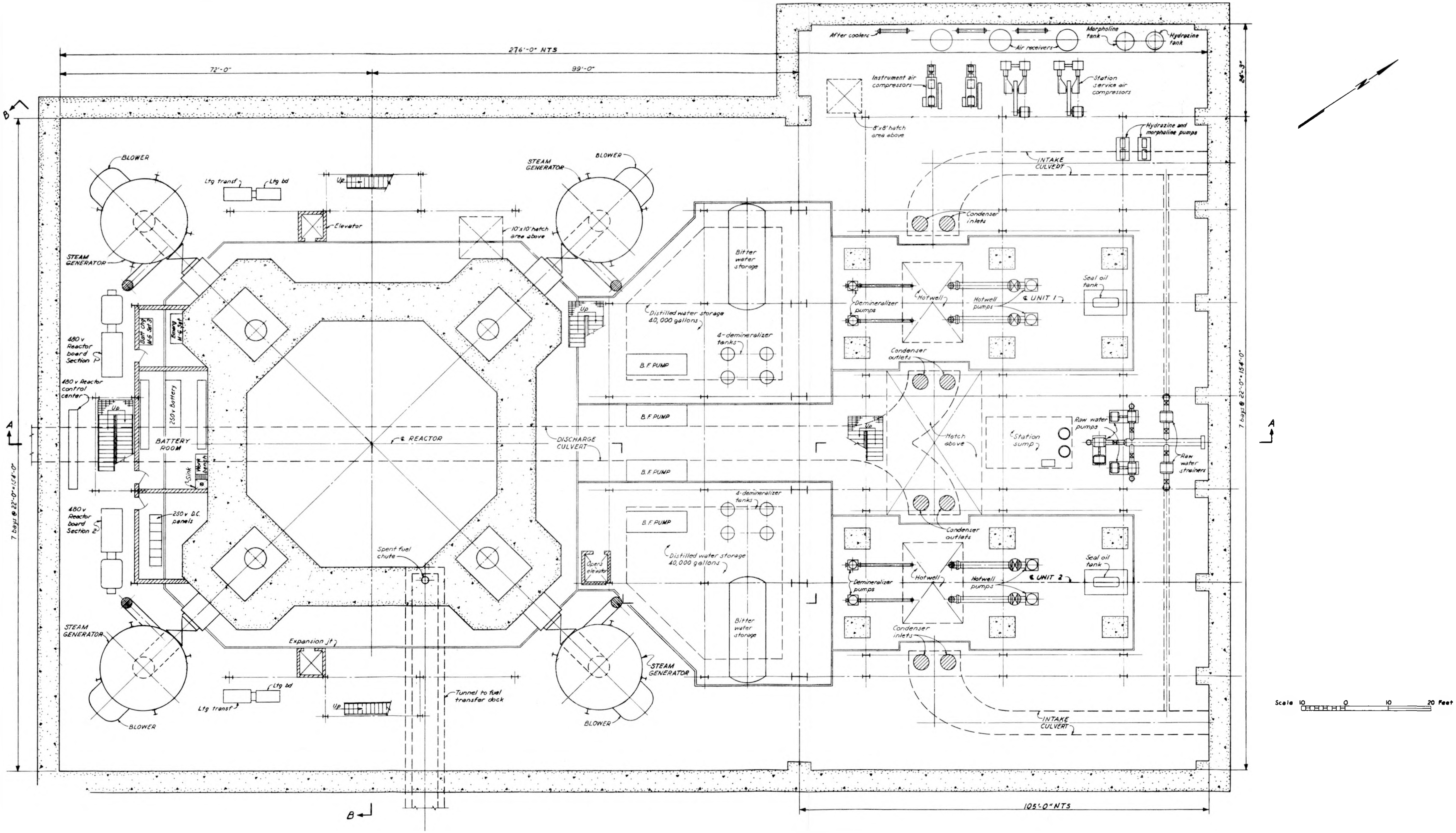


Fig. 10.9. Equipment Layout at Elevation 685.0 (ORNL – GCR-2) (Design Div., Tennessee Valley Authority).

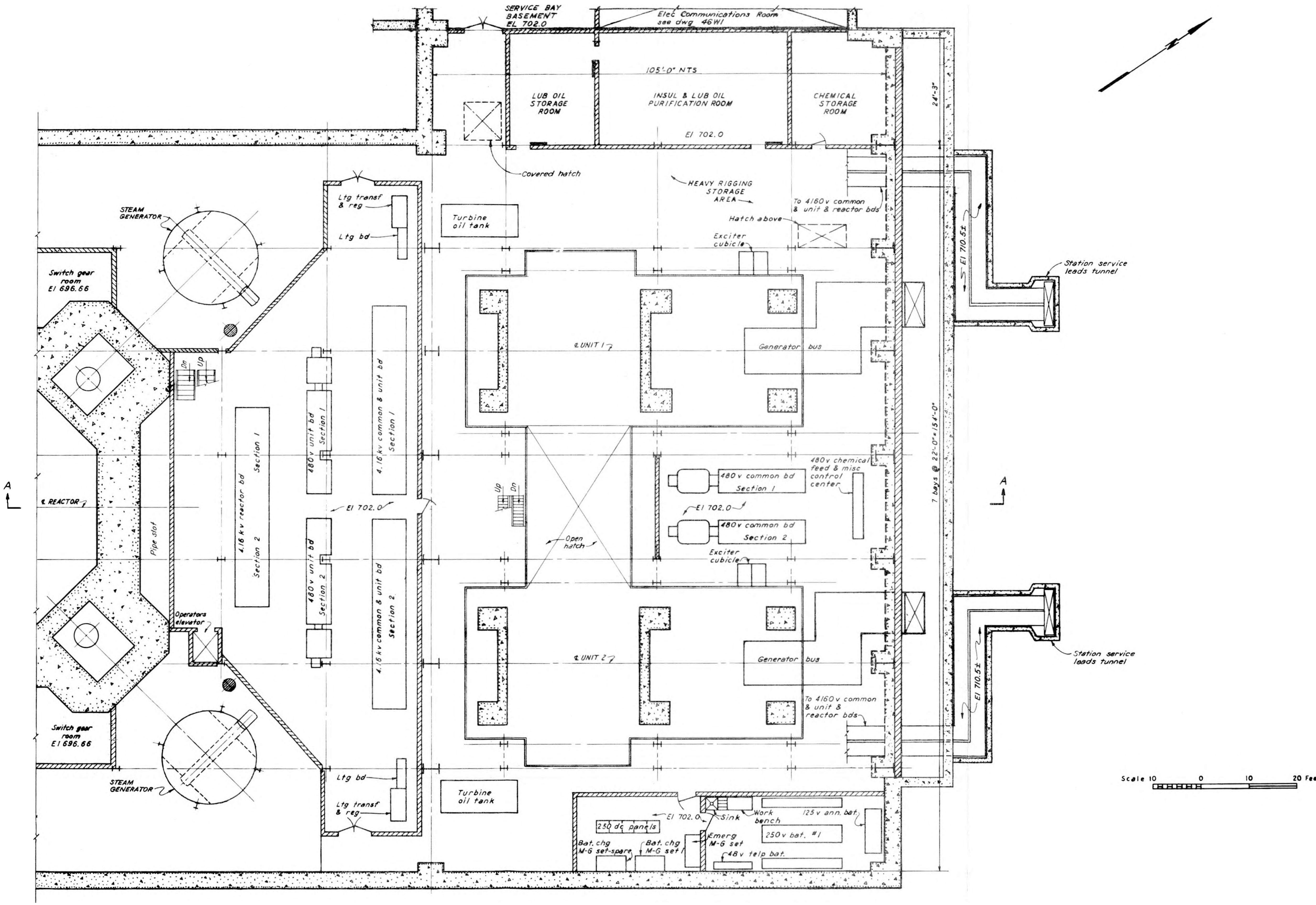


Fig. 10.10. Equipment Layout at Elevation 702.0 (ORNL – GCR-2) (Design Div., Tennessee Valley Authority).

floor. This crane is used for handling the turbine-generator parts during erection and maintenance and for moving heavy equipment to and from the basement floor through the hatch in the center.

The relatively narrow section of the building between the turbine room and the reactor housing above the unit control room has floor levels at elevations of 740 and 759 ft, Fig. 10.8. The high-pressure feed-water heaters (one for each unit) are located at the 740-ft level. The evaporator preheaters and the evaporators are at an elevation of 759 ft. The make-up vapor from the evaporators is added to the cycle in the deaerator unit, which also serves as a stage of feed-water heating. The deaerator heater is a direct contact heater, with a continuous vent to atmosphere through a small condenser for the removal of noncondensibles. The deaerator heaters and their associated deaerated water-storage tanks for each unit are located on the roof of the heater bay (elevation 780 ft). While not shown on Fig. 10.8, it is likely that head tanks for both raw water and potable water will also be located on the roof, as well as the housing for the operators' elevator.

10.1.6 <u>Unit Control Room</u>: As in modern fossil fuel-fired power plants, the unit control room is the control and monitoring center for the entire plant. The control room is shown in Figs. 10.6 and 10.8. It is located at an elevation of 720 ft, between the reactor bay and the turbine-generator bay and contains the reactor and turbine panel boards and benchboards, and the electrical boards.

10.1.7 <u>Administrative Wing and Service Bay</u>: This structure, shown in Fig. 10.11, is located on the west side of the turbine-generator bay. The ground floor of the building is at an elevation of 720 ft and covers an area of 110 x 110 ft. At this level are the maintenance shops, instrument shop and laboratory, stock storage, locker rooms, lunch room, and dispensary. A loading dock is located at the west end of the service bay. The lower level of the service bay is below grade at an elevation of 702 ft and forms a continuous floor with the floor of the turbine-generator bay that is at the same elevation. The second floor, at an elevation of 732 ft, contains the reception room, office space, conference room, lunch room, and lockers.

10.1.8 <u>Hot Fuel Storage Pond and Dock</u>: The hot fuel is to be stored in a pond 100 ft long x 25 ft wide x 12 ft deep. The pond is large enough to

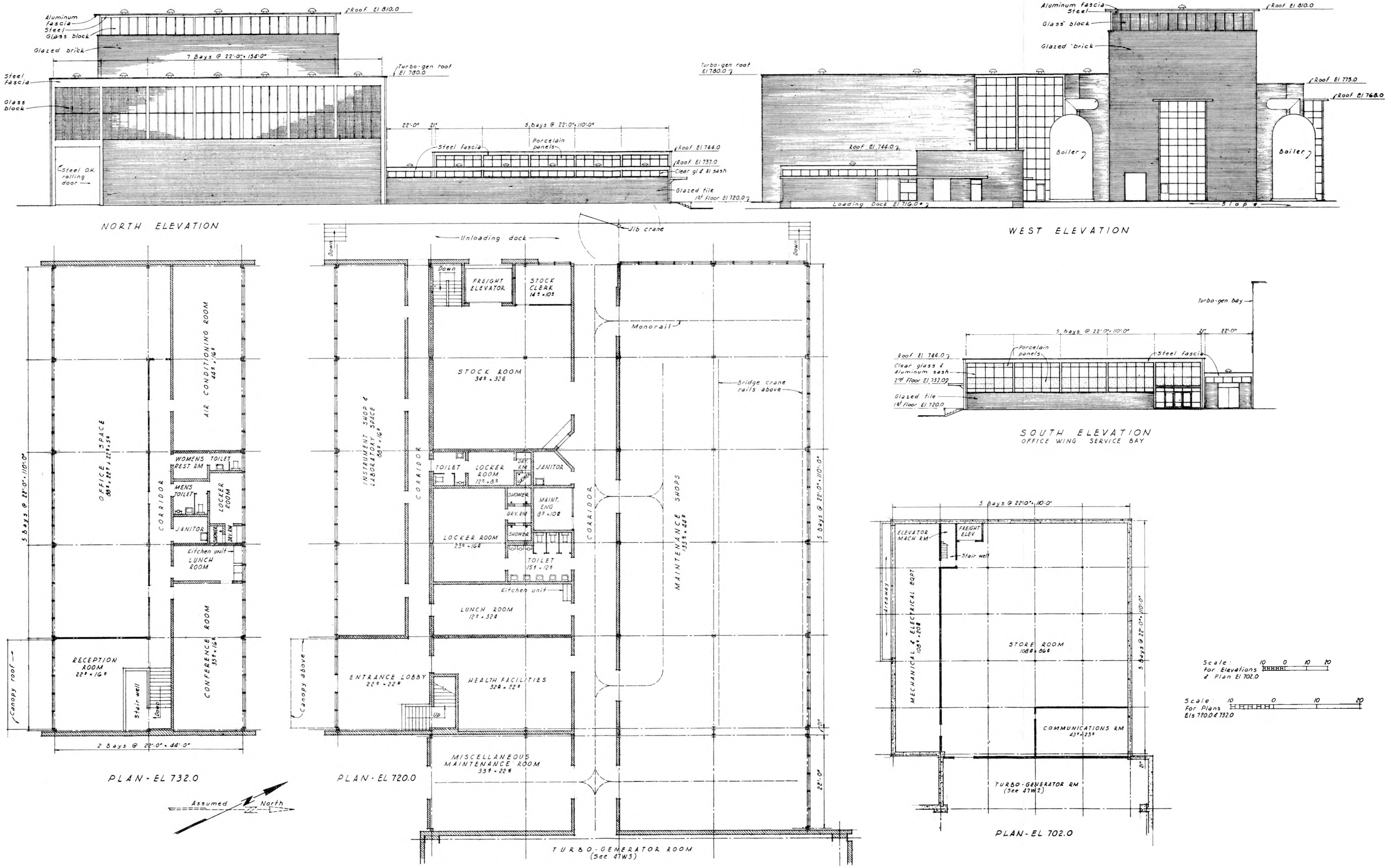


Fig. 10.11. Architectural Plans and Elevations (ORNL – GCR-2) (Design Div., Tennessee Valley Authority).

hold an entire reactor fuel charge. The activity level of the pond is maintained at acceptable levels.

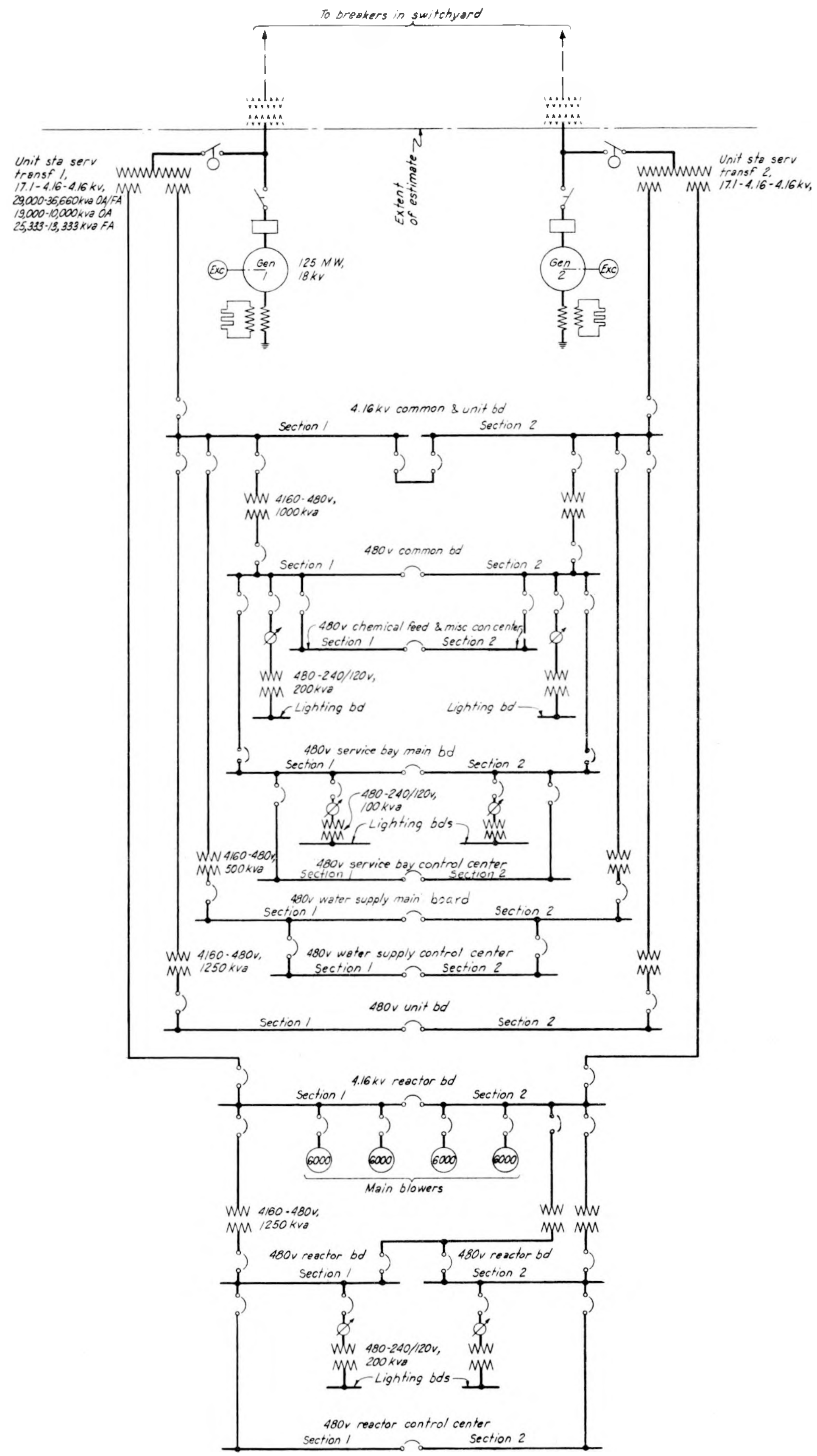
The pond is connected with the reactor fuel discharge shaft on the east side by a concrete tunnel. The tunnel is 3 ft wide and 5 ft deep. Tracks in the tunnel permit a dolly to carry the spent fuel in its container to the unloading station. The spent fuel in its shield is then lifted from the dolly by an overhead 5-ton jib crane and lowered either into the storage pond or into a decontamination room. After being lowered into the pond, the fuel element is removed from its shield by an underwater hoist and transported to a storage location. The empty container is then transported to the decontamination area, a 20 x 20-ft room , where the shield is decontaminated and returned to the reactor loading floor.

When spent fuel is to be shipped for reprocessing, the underwater hoist picks up the fuel element from its storage point and carries it to the unloading decontamination area. There the shield is decontaminated and lifted out of the area to a loading dock by a 10-ton monorail, where it is placed on a truck for shipment to the reprocessing plant. The dock is capable of supporting a 3,300 lb/ft^2 load of fuel and shield and has an area of 20 x 15 ft.

The entire area, including the pond and dock, is under roof. The pond is covered by light concrete slabs about 2 in. thick. The decontamination room is closed off with air tight partitions. A locker room and toilet facilities to accomodate 6 persons are also located in this building.

10.1.9 Electrical Equipment: The main and auxiliary electric power systems are shown on Figs. 10.6, 10.9, 10.10, and 10.12. The main leads from each of the 125 Mw, 18 kv generators are routed through the floor at an elevation of 702 ft to an oil circuit breaker located north of the turbine-generator structure. Space is allocated for the main transformer and the switchyard, but these items of equipment were not included in the study.

Two 18/4.16 kv station service transformers supply power for the station auxiliary loads. One transformer is supplied from each line connecting the generator circuit breaker to the main transformer. The station service transformers would normally be fed from the generated power; however, if a



TABULATION - AUXILIARY SWITCHBOARDS

POWERHOUSE

4.16KV COMMON & UNIT BOARD - SECTION 1, SECTION 2 SIMILAR

CIRCUIT NO.	DESCRIPTION	CIRCUIT RATING	CIRCUIT BKR RATING AMPS
1	Incoming feeder		2000
2	Feeder to 480v common bd, section 1	1000 kva	1200
3	" " water supply main bd, section 1	500 kva	1200
4	" " 480v unit bd section 1	1250 kva	1200
5	Boiler feedwater pump 1	1250 hp	1200
6	" " " 2	1250 hp	1200
7	Condenser circulating water pump 1	500 hp	1200
8	" " " " 2	500 hp	1200
9	Spare		1200
10	Tie breaker		1200
	Connected load	6250 kva	

480V COMMON BOARD - SECTION, SECTION 2 SIMILAR

CIRCUIT NO.	DESCRIPTION	CIRCUIT RATING	CIRCUIT BKR RATING AMPS
1	Incoming feeder		1600
2	Spare		600
3	Station drainage pump 1	40 hp	600
4	Main transf 1 pumps and fans	40 hp	600
5	Battery charging M-G set 1	50 hp	600
6	" " " " 2	50 hp	600
7	Air conditioning for control rm	25 hp	600
8	Feeder to 480v service bay main bd, section 1	275 kva	600
9	Powerhouse lighting transformer 1	200 kva	600
10	Feeder to chemical feed and misc. control center, sect. 1	65 kva	600
11-16	Miscellaneous circuits	60 hp	600
17	Tie breaker		800
	Connected load	805 kva	

480V UNIT BOARD - SECTION 1, SECTION 2 SIMILAR

CIRCUIT NO.	DESCRIPTION	CIRCUIT RATING	CIRCUIT BKR RATING AMPS
1	Incoming feeder		1600
2	Raw water service pump 1	150 hp	600
3	" " " " 2	150 hp	600
4	" " " " 3	150 hp	600
5	Spare		600
6	Future		600
7	Vacuum pump 1	5 hp	600
8	Scavenger demineralizer supply pump 1	5 hp	600
9	" " " " 2	5 hp	600
10	" " " " 3	5 hp	600
11	Demineralized water to deaerator pump 1	15 hp	600
12	" " " " " 2	15 hp	600
13	Hotwell pump 1	200 hp	600
14	" " 2	200 hp	600
15	Distilled water pump 1	50 hp	600
16	Turbine aux oil pump 1	100 hp	600
17-21	Misc small motor circuits	50 hp	600
22	Tie breaker		800
	Connected load	1100 kva	

480V CHEMICAL FEED & MISC CONTROL CENTER - SECTION 1, SECTION 2 SIMILAR

CIRCUIT NO.	DESCRIPTION	CIRCUIT RATING	CIRCUIT BKR RATING AMPS
1	Incoming feeder		
2	Demineralizer waste pump	25 hp	100
3	" acid & caustic pump 1	$\frac{1}{4}$ hp	100
4	" " " " 2	$\frac{1}{4}$ hp	100
5	Hydrazine and morpholine pump 1	$\frac{1}{3}$ hp	100
6	" " " 2	$\frac{1}{3}$ hp	100
7-11	Turbine rm vent fan circuits	15 hp	100
12	Station service transf cooling fans	5 hp	100
13-17	Miscellaneous circuits	20 hp	100
18	Tie breaker		225
	Connected load	65 kva	

REACTOR BUILDING

4.16KV REACTOR BOARD - SECTION 1, SECTION 2 SIMILAR

CIRCUIT NO.	DESCRIPTION	CIRCUIT RATING	CIRCUIT BKR RATING AMPS
1	Incoming feeder		3000
2	Feeder to 480v reactor board, section 1	1250 kva	1200
3	Main blower 1	6000 hp	1200
4	" " 2	6000 hp	1200
5	Spare		1200
6	Pot. transf and instrument compt		
7	Tie breaker		2000
	Connected load	13250 kva	

480V REACTOR BOARD - SECTION 1, SECTION 2 SIMILAR

CIRCUIT NO.	DESCRIPTION	CIRCUIT RATING	CIRCUIT BKR RATING AMPS
1	Incoming feeder		1600
2	Lighting transf 1, reactor bldg	200 kva	600
3	Shield cooling blower 1	100 hp	600
4	" " " 2	100 hp	600
5	General service air compressor 1	100 hp	600
6	Instrument air compressor 1	150 hp	600
7	" " dryer	100 kw	600
8	Helium dryer 1	100 kw	600
9	Battery charger M-G set 3	50 hp	600
10	Helium evacuation and storage compressor 1	200 hp	600
11	480v welding receptacle circuits	75 kva	600
12	Feeder to reactor control center, section 1	260 kva	600
13	Spare		600
14	Emerg transf bkr		800
	Connected load	1435 kva	

480V REACTOR CONTROL CENTER - SECTION 1, SECTION 2 SIMILAR

CIRCUIT NO.	DESCRIPTION	CIRCUIT RATING	CIRCUIT BKR RATING AMPS
1	Incoming feeder		
2	Helium system evacuation eqpt 1	10hp, 4kw	100
3	" " " " 2	10hp, 4kw	100
4	Fuel tube evacuation pump 1	2 hp	100
5	Helium conditioning compressor 1	30 hp	100
6	Lube oil pump 1	2 hp	100
7	" " " 2	2 hp	100
8	" " " 3	2 hp	100
9	" " " 4	2 hp	100
10	Elevator, freight and passenger	40 hp	100
11	Operating floor service crane	40 hp	100
12	Air conditioning unit 1, for ion chamber rm	10 hp	100
13	Ventilation fan 1, for normal room ventilation	$7\frac{1}{2}$ hp	100
14	" " 2, " " "	$7\frac{1}{2}$ hp	100
15	Fuel loading equipment	$7\frac{1}{2}$ hp	100
16	Feeder to pond and dock	50 hp	100
17	Air conditioning unit for loading control rm	10 hp	100
18	Operating floor ventilation fan	2 hp	100
19-22	Miscellaneous circuits	20 hp	100
23	Tie breaker		225
	Connected load	260 kva	

MISCELLANEOUS

480V SERVICE BAY MAIN BOARD - SECTION 1, SECTION 2 SIMILAR

CIRCUIT NO.	DESCRIPTION	CIRCUIT RATING	CIRCUIT BKR RATING AMPS
1	Incoming feeder		600
2	Lighting transf 1	100 kva	600
3	Air conditioning compressor	30 hp	600
4	Feeder to service bay control bd, section 1	145 kva	600
5	Tie breaker		600
	Connected load	275 kva	

480V SERVICE BAY CONTROL CENTER - SECTION 1, SECTION 2 SIMILAR

CIRCUIT NO.	DESCRIPTION	CIRCUIT RATING	CIRCUIT BKR RATING AMPS
1	Incoming feeder		
2	480v machine shop power cabinet	35 hp	100
3	480v maintenance shop service power cabinet	35 hp	100
7-17	Air conditioning and ventilating circuits	25 hp	100
18-22	Supply and exhaust fans	10 hp	100
23-24	Water heater circuits	20 kw	100
25-30	Miscellaneous circuits	20 kw	100
31	Tie breaker		225
	Connected load	145 kva	

480V WATER SUPPLY MAIN BD - SECTION 1, SECTION 2 SIMILAR

CIRCUIT NO.	DESCRIPTION	CIRCUIT RATING	CIRCUIT BKR RATING AMPS
1	Incoming feeder		600
2	Screen wash pump 1	125 hp	600
3	Feeder to 30 ton gantry crane	45 hp	600
4	Lighting transformer	35 kva	600
5	Feeder to water supply control center, section 1	125 kva	600
6	Tie breaker		600
	Connected load	330 kva	

480V WATER SUPPLY CONTROL CENTER - SECTION 1, SECTION 2 SIMILAR

CIRCUIT NO.	DESCRIPTION	CIRCUIT RATING	CIRCUIT BKR RATING AMPS
1	Incoming feeder		
2	Lubricating water pump 1	1 hp	100
3	Raw water supply pump 1	4 hp	100
4	Traveling screen 1	2 hp	100
5	" " 2	2 hp	100
6	Electric operated valves (2)	$1\frac{1}{2}$ hp	100
7	Vacuum pump 1	5 hp	100
8	Flocculator drive	2 hp	100
9	Chemical solution feeder (2)	$\frac{1}{2}$ hp	100
10	Brine pump 1	1 hp	100
11	Potable water supply pump 1	1 hp	100
12	" " service " 1	10 hp	100
13	Softener supply pump 1	5 hp	100
14	Soft water service pump 1	15 hp	100
15-22	Heater circuits	50 kw	100
23-26	Supply and exhaust fan circuits	5 hp	100
27-30	Miscellaneous circuits	20 hp	100
31	Tie breaker		225
	Connected load	125 kva	

Fig. 10.12. Single Line Wiring Diagram (ORNL – GCR-2) (Design Div., Tennessee Valley Authority).

generator is not operating, the transformer can be supplied directly from the switchyard by opening the generator circuit breaker.

Each station service transformer is provided with two 4.16 kv secondary windings. One secondary winding of each station service transformer feeds power to the 4.16 kv turbine-generator common and unit switchboard, and the other secondary winding of each transformer feeds power to the 4.16 kv reactor switchboard. Each switchboard is sectionalized at the center, with each section being fed from a station service transformer. Normal operation is with the sectionalizing breakers open and with each generator feeding its own auxiliaries. Interlocking is provided to prevent paralleling of the two supply sources.

Emergency power for a bus section is obtained by opening the normal power source and closing the sectionalizing breaker. Operating requirements permit a transformer and associated devices to be sized for starting only one 6000 hp main blower at a time.

The 4.16 kv switchboards feed the boiler feed-water pumps, condenser circulating water pumps, main blowers, and 480-v switchboards. The 480-v switchboards are also sectionalized and are fed from two power sources to provide emergency power when required.

The turbine-generator switchboards, battery room, battery-charging motor generator sets, dc panelboards, and the reactor 4.16 kv switchboards are located on the floor at an elevation of 702 ft as shown in Fig. 10.10. The reactor 480-v switchboards, battery room, battery-charging motor generator sets, dc panelboards, and dc-ac motor generator set are located on the basement floor, as shown in Fig. 10.9. The battery-powered dc-ac motor generator set provides additional emergency power for reactor instrumentation and control. A summary of the station auxiliary loads for full power operation of both generators is shown in Table 10.5.

TABLE 10.5

STATION AUXILIARY POWER AT FULL POWER OPERATION

Item	Number, Nameplate Rating, and Percent Load	Operating Shaft Horse-Power	Operating Kilovolt-Amperes
Boiler feed pumps	4 - 1250 hp at 95%	4,750	
Condenser circulating water pumps	4 - 500 hp at 95%	1,900	
Station drainage pumps	1 - spare, 1 - 40 hp at 75%	30	
Transformer pumps and fans	2 - 40 hp	80	
Battery chargers	1 - spare, 2 - 50 hp at 75%	75	
Air conditioning, control room	2 - 25 at 50%	25	
Powerhouse lighting transformers	2 - 200 kva		400
Miscellaneous circuits	2 - 60 hp	120	
Raw water service pumps	1 - spare, 2 - 150 hp at 100%	300	
Vacuum pumps	2 - 5 hp	10	
Scavenger demineralizer supply pumps	6 - 5 hp at 100%	30	
Demineralizer water to deareator pumps	4 - 15 hp at 100%	60	
Hotwell pumps	2 - spares, 2 - 200 hp at 100%	400	
Miscellaneous circuits	2 - 50 hp at 100%	100	
Demineralizer waste pumps	2 - 25 hp at 100%	50	
Turbine room ventilating fans	2 - 15 hp at 100%	30	
Station service transformer fans	2 - 5 hp at 100%	10	
Miscellaneous circuits	2 - 20 hp at 100%	40	
Lighting transformers, reactor building	2 - 200 kva at 100%		400
Shield cooling blowers	2 - 30 hp at 100%	60	
General service air compressors	2 - 100 hp at 50%	100	
Instrument air compressors	2 - 150 hp at 50%	150	
Instrument air dryers	2 - 100 kva at 50%		100
Helium dryers	2 - 100 kva at 100%		200
Welding receptacles	2 - 75 kva at 20%		30
Lube oil pumps	4 - spares, 4 - 2 hp at 100%	8	
Elevators	3 - 40 hp at 25%	30	
Cranes	2 - 40 hp at 25%	20	
Air conditioning, ion chamber room	2 - 10 hp at 50%	10	
Normal room ventilating fans	4 - 7-1/2 hp at 100%	30	
Feeders to pond and dock	2 - 50 hp at 25%	25	

Table 10.5 (continued)

Item	Number, Nameplate Rating, and Per Cent Load	Operating Shaft Horse-Power	Operating Kilovolt-Amperes
Air conditioning, loading control room	2 - 10 hp at 50%	10	
Operating floor ventilating fan	2 - 2 hp at 100%	4	
Miscellaneous circuits	2 - 20 hp at 100%	40	
Lighting transformers, service bay	2 - 100 kva at 100%		200
Air conditioning, service bay	2 - 30 hp at 50%	30	
Machine shop	2 - 35 hp at 25%	17	
Maintenance shop	2 - 35 hp at 25%	17	
Air conditioning and ventilating circuits, service bay	2 - 25 hp at 50%	25	
Supply and exhaust fans	2 - 10 hp at 100%	20	
Water heaters	2 - 20 kva at 100%		40
Miscellaneous circuits	2 - 20 kva at 100%		40
Screen wash pumps	2 - 100 hp at 100%	200	
Lighting transformer, water supply	2 - 35 kva at 100%		70
Water supply control center	150 hp and 100 kva at 50%	75	50
SUBTOTAL		8,881	1,530
Main blowers	4 - 6000 hp at 95%	22,800	

$$\text{TOTAL POWER} = \frac{(8{,}881 \text{ hp} \times 0.746 \text{ kw/hp})}{95\% \text{ eff}} + (1{,}530 \text{ kva} \times 1.0 \text{ pf}) + \frac{(22{,}800 \text{ hp} \times 0.746 \times \text{kw/hp})}{93\% \text{ eff}}$$

$$= 6{,}980 + 18{,}300 + 1{,}530$$

$$= 26{,}810 \text{ kw}$$

SECTION 11

COST ANALYSIS

11. COST ANALYSIS

Contents

11. COST ANALYSIS

11.1 Basis of Cost Analysis

The over-all cost of producing power was divided in conventional fashion into fixed and operating charges.

Fixed charges include:

1. Capital charges against the cost of the power plant, computed at 14% per year.
2. Capital charges against interest on construction funds (interest computed at 6% per year during construction; capital charges computed at 14% per year).
3. Capital charges against fuel fabrication costs for the first core, computed at 14% per year.
4. Interest charge on initial value of in-pile fuel inventory, computed at 4% per year.

Operating charges include:

1. Fuel burn-up cost, less plutonium credit.
2. Cost of recovering fissile material from spent fuel ($12.40/kg U).
3. Cost of fabricating replacement fuel elements ($30.90/kg U).
4. Interest charge on fuel inventory held up outside reactor.
5. All other operating and maintenance costs.

Among the important assumptions made in the cost analysis are the following:

1. Annual charges against the fixed investment in the plant (exclusive of fuel inventory) are 14% of the investment. This rate includes return to the investors, corporate income tax, amortization of principal, ad valorem taxes, and insurance.
2. Annual interest, or rental, charges for the fuel are 4% of the initial value of the fuel. This rate is firmly established by the Atomic Energy Commission.
3. Plant load factor is 0.80[1]. It is assumed throughout that this plant would be a base load plant.

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[1]Most of the calculations for the optimization of major parameters presented in other sections of this report were based on a plant factor of 0.85, which was understood to be the prescribed value for this study. A load factor of 0.80 was chosen by the AEC at the last minute. The final cost analysis contained in this section is based upon the latter figure.

4. A value of \$12/g is assigned to the plutonium content in spent fuel. This is an approximate value established by the Atomic Energy Commission as the worth of plutonium as a reactor fuel (without regard to its isotopic composition). It is possible that a lower figure would be more realistic if based exclusively on thermal reactors. For the present, the Atomic Energy Commission continues to offer \$30/g for plutonium, and reactor cost studies are frequently based on this value. The effect on power costs of varying this and other assumptions is discussed at the end of this chapter.
5. It must be assumed that progress payments will be necessary as construction proceeds. If these are assumed to be equally spaced over the construction period, an annual rate multiplied by one-half the construction period will give the total capital cost for the use of the construction funds; 14% of this capital cost must then be added to the annual fixed costs of the plant.
6. It has been assumed that construction costs rise 6% per year. For a three year construction period from 1959 to 1961, an average end escalation date of mid-1960 was chosen, in view of the uniformly spaced progress payments referred to in the previous paragraph. For comparison purposes cost estimates have also been made without provision for escalation.

11.2 Basic Cost Data

The bases for estimating the various charges that contribute to the power cost are explained in this section.

11 2.1 Fixed Costs: Pressure Vessel. The pressure vessel design is discussed in some detail in Sections 3 and 5. Because of its size and the thickness of the material from which the vessel will be fabricated, the cost of this vessel is subject to considerable uncertainty. It is a known fact that fabrication costs increase with thickness of the pressure vessel, and it is also clear that erection and testing problems become more difficult with increasing thickness. In Fig. 11.1 is shown a cost index for the fabrication costs of pressure vessels as a function of thickness. The index was determined from an extrapolation of the data for two pressure vessels

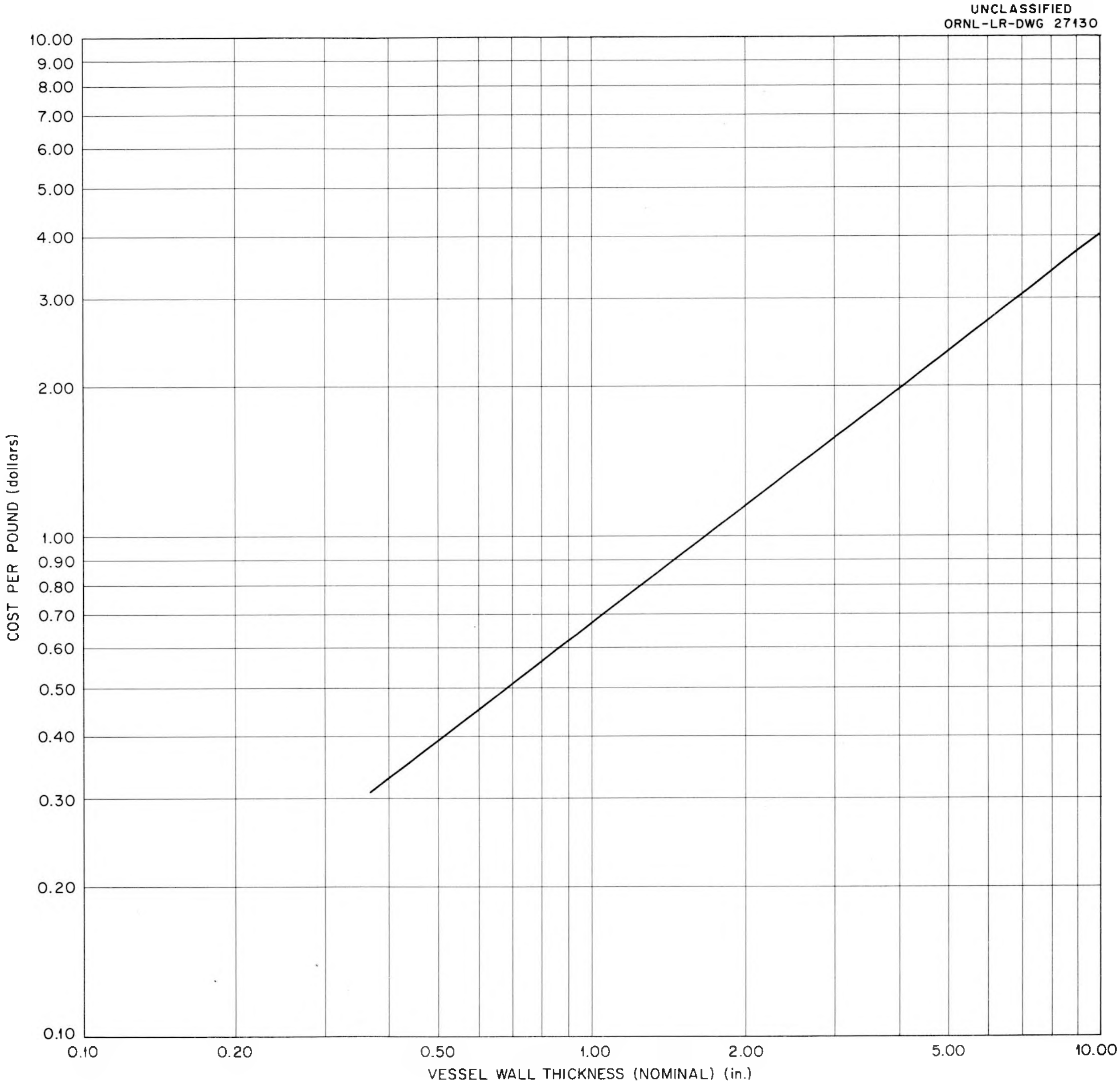

Fig. 11.1. Vessel Fabrication Cost vs Nominal Wall Thickness for Spherical Vessels.

fabricated at Oak Ridge National Laboratory, which were 30 ft in diameter by 1/2 in. thick and 24 ft in diameter by 2 in. thick, respectively. These data were supplemented by information from Lukens Steel Company and Chicago Bridge and Iron Company. These data point up the importance of holding thicknesses to a minimum from a cost standpoint.

The estimated cost of the pressure vessel including its important components is given in Table 11.1. This value is close to a later estimate for a vessel of this design obtained from Chicago Bridge and Iron Company, and the costs are believed to be reliable, subject to normal escalation factors.

TABLE 11.1

REACTOR PRESSURE VESSEL COST ESTIMATE

Item	Unit	Cost
Pressure Vessel Shell, Support and Nozzles (69 - 12 in., 8 - 60 in.)	1,308,000 lb	$ 1,960,000
Graphite Support Structure Including Peripheral Bands	149,000 lb	185,000
Thermal Barrier and Supports	50,000 lb	63,000
Insulation (7850 ft^2 - 4 in. thick)	26,000 lb	23,000
Graphite Support	8,000 lb	100,000
TOTALS	1,541,000 lb	$ 2,331,000

Graphite. The cost of graphite installed in a reactor has been obtained from several sources. An installed cost of $1.18/lb has been given by the Argonne National Laboratory.[2] An estimate obtained from the General Electric Company at Hanford was $1.20/lb. The installed cost of graphite in the Sodium Reactor Experiment, according to personnel at North American Aviation Company, was about $0.70/lb; this material was used essentially as received from the National Carbon Company, with little or no machining. A separate estimate has been prepared for the gas-cooled reactor on the basis

[2] Engineering Construction and Cost Report, ANL-5704 (March 1, 1957).

of cost data supplied by National Carbon Company. Cost of AGOT graphite was quoted as $0.47/lb and that of TSF graphite as $0.615/lb. The TSF grade, with the lower neutron cross section, was selected for this design. Machining costs were estimated by the Y-12 graphite fabrication shop. Over-all costs for the graphite installed in the gas-cooled reactor are summarized in Table 11.2.

TABLE 11.2

GCR-2 GRAPHITE MODERATOR INSTALLED COSTS FOR GRAPHITE PRISM 35-FT DIA AND 25 FT HIGH WITH 2,160,000 LB OF GRAPHITE (NET WEIGHT)

Raw Graphite* Cost (3,045,000 lb at $0.615/lb)	$ 1,860,000
Machining Cost	370,000
Packaging Cost	15,000
Machining Contingency at 30%	110,000
Fabrication Subtotal	$ 2,395,000
Shipping Cost	50,000
Installation Cost at 0.20/lb	430,000
Installation Cost Contingency at 30%	129,000
Installation Subtotal	$ 609,000
Total Installed Cost	$ 3,004,000

$$\text{Installed Cost/lb} = \frac{\$3,004,000}{2,160,000} = \$1.40$$

* Note: Graphite is furnished in 8 3/4-in. x 8 3/4-in. rough blocks and are finish machined to 8 in. x 8 in. Holes are bored in approximately 1600 blocks. Five per cent spoilage is allowed.

Gas Piping System. Cost data on fabrication of large piping for the pressure requirements were obtained through consultation with Midwest Piping Company and the Alco Products Division of the American Locomotive Company. Figure 11.2 gives the cost per pound for fabrication of piping as a function of temperature and pressure for various pipe diameters. An over-all estimate for the fabrication of this system obtained from both the Midwest Piping Company and Alco Products is shown in Table 11.3.

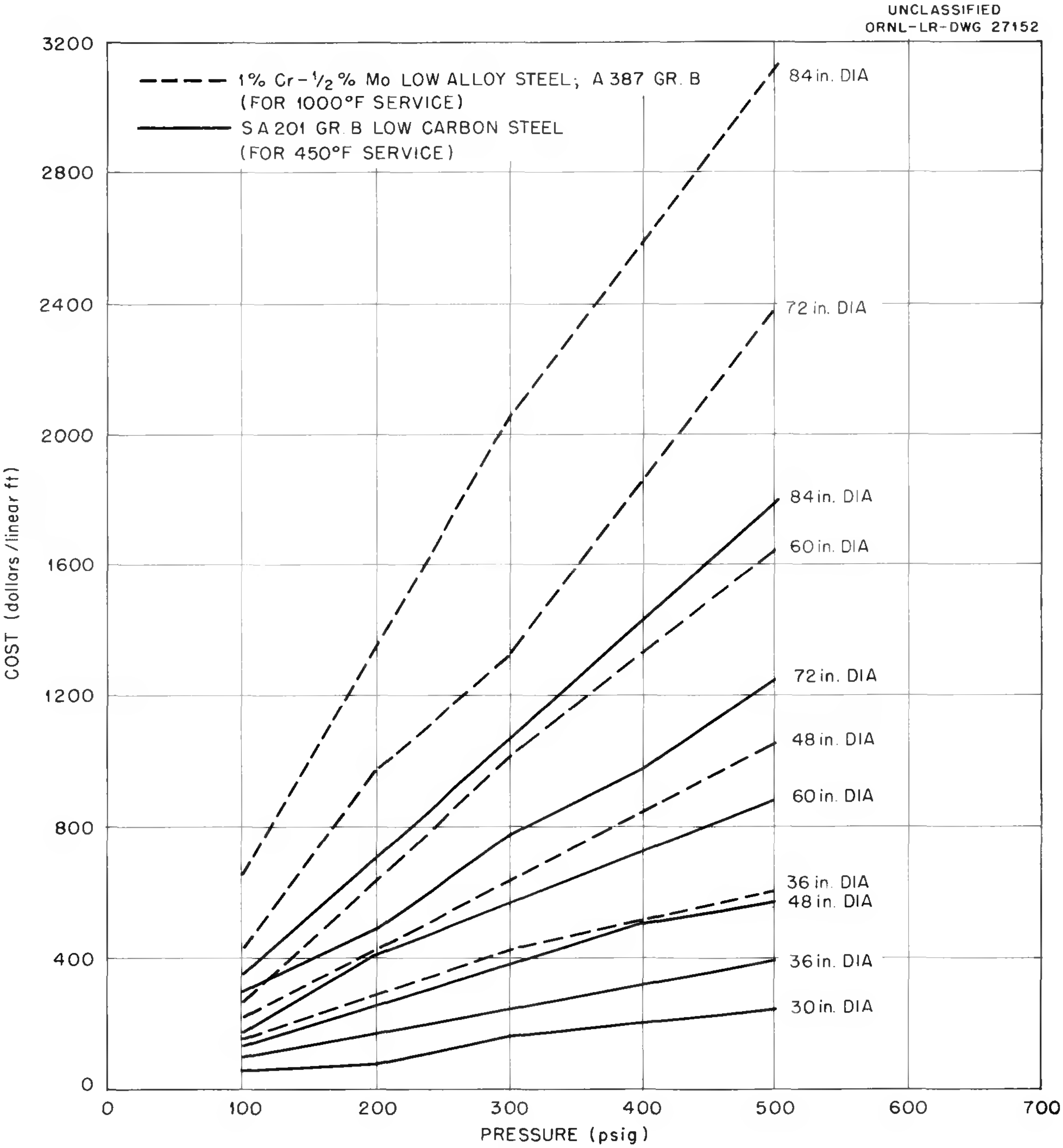

Fig. 11.2. Pipe Fabrication Costs.

TABLE 11.3

HELIUM PIPING SYSTEM INSTALLED COSTS

	Pipe	Valves	Joints	Supports	Insulation	Total
1000°F System	488,000	--	132,000	50,000	55,600	725,600
460°F System	268,000	86,000	100,000	37,000	19,000	510,000
TOTAL	756,000	86,000	232,000	87,000	74,600	1,235,600

Information on the fabrication of expansion joints for this system was obtained from Zallea Brothers Company who have furnished expansion joints of comparable size for other installations in this country and in Europe.

The valve cost information was obtained through consultation with the Black, Sivalls, and Bryson Company, and the Henry W. Pratt and Company. Only the Pratt Company indicated experience in producing a valve of the required tightness for this installation. The cost data used in this report are based on information received from the Pratt Company.

Steam Generators. The once-through boiler selected was suggested by the Babcock and Wilcox Company, but the design was further modified by the use of finned tubes. Ultimately, the design appeared to be closer to that of a shell and tube heat exchanger than of a conventional steam power plant boiler, and the cost estimating methods applied were those usually used in heat exchanger estimating. The surface area was estimated from the design requirements and the cost per square foot of surface was determined through consultation with Griscom-Russell Company, the Grinnell Company and the Wolverine Tube Company. Additional information was obtained from Combustion Engineering on the fabrication of special fittings which would be required for the installation. The vessel fabrication costs were estimated in the same manner as that used in developing the reactor-vessel fabrication cost. The cost estimate for the heat exchanger is given in Table 11.4 which shows the make-up of the cost elements included in this design.

TABLE 11.4

GCR-2 STEAM GENERATOR INSTALLED COSTS

Vessel Including Heads, Sleeves, Manholes, Gas Enclosure/Unit	$ 586,400
Tubing and Structural Supports/Unit	711,700
Steam and Gas Manifolds and Ducts/Unit	51,800
Insulation Internal and External/Unit	19,500
TOTAL per Unit	$ 1,369,400
TOTAL 4 Units	$ 5,477,600

Cost/kw = $24.3

Blowers and Drives. Blower costs were extrapolated from data available for the fabrication of blowers for pumping air under conditions comparable to those of this reactor design, and also from data obtained in the fabrication of blowers for the gaseous-diffusion plant at Oak Ridge, Paducah, and Portsmouth. The cost of the electrical drives,which costwise are comparable in importance to the blowers, was obtained from the Westinghouse Electric Company and the General Electric Company. Additional costs were also estimated for the fabrication of the containment vessel to hold the blower and motor which would be inside the gas system. These costs are summarized in Table 11.5.

TABLE 11.5

MAIN HELIUM CIRCULATING BLOWER DRIVE UNITS INSTALLED COSTS

Blowers	$ 1,100,000	($500,000 for development and $150,000 for each unit)
Motors	805,000	(including lubrication and coolant systems)
Pressure Containment Vessels	200,000	
TOTAL	$ 2,105,000	

Instrumentation and Controls. The cost of instrumentation which has been estimated from a detailed count of the equipment for the nuclear portion of the plant is believed to be realistic. The cost of control rods and control-rod drives has been estimated only approximately. The cost of the control-rod drives was estimated to be about $250,000.00 Control-rod costs have been estimated from the basic cost of the material plus an allowance for fabrication. Included in the instrumentation is a cost estimate for the gas-sampling system for monitoring fuel-element leaks. The principal cost consideration of this item is the tubing running from each fuel channel to the sampling device. Table 11.6 summarizes the costs of instrumentation and controls for the reactor system.

Steam System Components. The steam-electric portion of the gas-cooled reactor plant, from the steam-generator nozzles outward, is quite conventional. In the preliminary selection of system parameters, a cost of $130/kw was assumed for this portion of the plant including the turbine-generators, condensers, steam-piping, pumps, auxiliaries, etc. For the final reference design, the cost analysis of the steam system components was performed by the Design Engineering Department of the Tennessee Valley Authority. The estimates are based on cost data from recent Tennessee Valley Authority installations and also from suppliers of major equipment for power plants, including General Electric Company, Westinghouse Electric Company, and many others. A detailed summary of the cost estimate is given in Table 11.7.

Auxiliary Facilities. A number of special facilities are required for operation of the gas-cooled reactor plant, including fuel handling and storage facilities and helium gas storage and evacuation equipment.

Cost estimates for the fuel-storage pond and transfer equipment were based on conventional construction, with allowance for equipment to handle spent fuel elements.

Estimates for the helium storage system were based on discussions with United States Steel Company, regarding storage vessels working at 2000 psig, with Chicago Bridge and Iron Company, regarding larger storage vessels working at 75 psig, and with Ingersoll-Rand Company regarding helium compressors. Costs for vacuum-pumping equipment were based on

TABLE 11.6

INSTRUMENTATION, CONTROLS AND ELECTRICAL SYSTEM INSTALLED COSTS

Reactor System Instruments and Controls	
Instrument panel boards	$ 213,000
Instrument bench boards	70,000
Local instruments and sensors	90,000
Health Physics monitors	50,000
Communications	8,000
Fuel element leak detection system	1,000,000
Control rods (61 at $3500 each)	213,500
Control rod drives	250,000
Miscellaneous hardware	54,000
	1,948,500
Steam System Instruments and Controls	
Instrument panel boards	142,000
Instrument bench boards	98,000
Sensors	132,000
Miscellaneous hardware	50,000
	422,000
Electrical Instruments and Controls	
Instrument panel boards	114,000
Electrical bench boards	57,000
Sensors and local instruments	35,000
Miscellaneous hardware	28,000
	234,000
Electrical Equipment	
Switchgear	992,000
Switchboards	826,000
Protective equipment	57,000
Electrical structures	120,000
Conduit	653,000
Power and control wiring	558,000
Station service equipment	651,000
	$3,857,000
Cost Per kw(E) Net	
Reactor instruments and controls	$ 8.6/kw(E)
Steam system instruments and controls	1.9/kw(E)
Electrical system, including instruments and controls	18.6/kw(E)

TABLE 11.7

CAPITAL COSTS ORNL GCR-2 EXCLUDING FUEL ELEMENTS

(FPC - Account Numbers)

10.	Land and Land Rights	$ 450,000
11.	Structures and Improvements	7,695,000
13A.	Reactor System	19,414,700
13B.	Steam System	3,349,000
14.	Turbine-Generator Plant	12,030,000
15.	Accessory Electrical Equipment	4,091,000
16.	Miscellaneous Power Plant Equipment	875,000
	Direct Costs Subtotal	47,904,700
	7.5% Contingency Items 11, 13B, 14, 15, 16	2,103,000
	30% Contingency Item 13A	5,824,500
	Contingency Subtotal	7,927,500
18.	General Expense Excluding Design	7,615,000
	Design Costs	2,510,000
	TOTAL COST	65,957,200
	Escalation at 6%/yr from 1-1-58 to 7-1-60 on all items above except design	9,517,000
	TOTAL ESCALATED COST	$ 75,474,200

TABLE 11.7 CONTINUATION

10.	Land and Land Rights		$ 450,000
11.	Structures and Improvements		
	110.	Permanent Access Road	
	111.	Preparation of Site	700,000
	112.	General Yard Improvements	
	113.	Powerhouse	
		Care of Water	144,000
		Excavation and Backfill	467.000
		Foundation Preparation and Treatment	100,000
		Concrete (17,500 c.y. at $60.00)	1,056,000
		Joints, Stops, and Drains	35,000
		Total Substructure	1,802,000
		Superstructure 2,333,000 c.f. at 1.97	4,783,000
		Total Powerhouse	6,585,000
	118.	Shoreline Improvements	
		Intake and Discharge Canals including weir	410,000
		TOTAL Structures and Improvements	7,695,000

TABLE 11.7 CONTINUATION

13A.	Reactor Plant Facilities		
	13A1.	Reactor Shielding	
		Neutron Curtain	$ 32,000
		Biological Shield Walls - 10,570 yd^3 at $123/c.y.	1,294,000
		Biological Shield Top - 980 yd^3 at $150/c.y.	147,000
		Shield Cooling	54,000
			1,527,000
	13A2.	Pressure Vessel Including Supports and Insulation	2,331,000
	13A3.	Graphite	3,004,000
	13A4.	Fuel Handling	
		Loading Machinery	500,000
		Indexing Chutes	250,000
		Loading Racks	60,000
		TV Inspection Cameras	50,000
		Grappling Tools and Manipulators	100,000
		Fuel Storage Pond, Dock, and Decontamination Building Including Tunnel	171,000
		Fuel Transfer Dolly	100,000
			1,231,000
	13A6.	Helium Gas System	
		Helium Storage and Evacuation System	441,000
		Helium Clean up Systems	64,000
		Helium Piping Including Values, Expansion Joints, and Insulation	1,235,600
		Blowers and Motors Including Containers	2,105,000
			3,845,600

TABLE 11.7 CONTINUATION

13A7.	Instruments and Controls	
	Instrument Boards	$ 283,000
	Local Instruments	90,000
	Health Physics Monitors	50,000
	Control Rods and Drives	463,500
	Leak Detection System	1,000,000
	Communications and Miscellaneous	62,000
		1,948,500
13A8.	Steam Generators Including Insulation	5,477,600
13A9.	Miscellaneous Laboratory Equipment	50,000
	TOTAL	19,414,700
13B.	Steam Plant Equipment	
	Feed-water Equipment	643,000
	Water Supply and Treatment System	925,000
	Steam Plant Boards, Instruments and Controls	422,000
	Steam Plant Piping	1,359,000
	Total Steam Plant Equipment	3,349,000

TABLE 11.7 CONTINUATION

14.	Turbine-Generator Units		
	140.	Turbine-Generators-Foundations	$ 165,000
		-First Cost	8,367,000
		-Proration	586,000
		-Erection	380,000
		-Proration	27,000
		Total Turbine-Generators	9,525,000
	141.	Condenser Cooling Water System	
		Intake Structure	416,000
		Intake Equipment	544,000
		Supply Conduit	80,000
		Valves and Piping at Condenser	90,000
		Discharge Conduits	68,000
		Outlet Structure	65,000
		Total Condenser Cooling Water System	1,263,000
	142.	Condensers	930,000
	143.	Central Lubricating System	50,000
	144.	Instruments and Meters	35,000
	145.	Turbine Plant Piping	60,000
	146.	Auxiliary Equipment for Generators	142,000
	149.	Other Turbine Plant Piping	25,000
		Total Turbine-Generator Units	12,030,000
15.	Accessory Electrical Equipment		
	151.	Switchgear	992,000
	152.	Switchboards	1,050,000
	153.	Protective Equipment	57,000
	154.	Electrical Structures	120,000
	155.	Conduit	653,000
	156.	Power and Control Wiring	558,000
	159.	Station Service Equipment	651,000
		TOTAL	4,091,000
16.	Miscellaneous Power Plant Equipment		
	160.	Miscellaneous Foundations	---------
	162.	Station Maintenance Equipment	176.000
	165.	Cranes and Hoisting Equipment	332,000
	166.	Compressed Air and Vacuum Cleaning System	50,000
	169.	Other Miscellaneous Equipment	317,000
		TOTAL	875,000
		TOTAL STEAM PRODUCTION PLANT	47,904,700

TABLE 11.7 CONTINUATION

18.	General Expense (Indirect Costs)		
	182.	Employee Housing	$ 500,000
	185.	General Expense	
		1851. Field Expense	3,000,000
		1852. Administrative Expense	600,000
		1853. Personnel	225,000
		1854. Police and Guide Service	350,000
		1856. Health and Safety	350,000
		Subtotal	5,025,000
		1857. Steam System Construction Services	
		-1 Procurement	300,000
		-2 Construction Mobilization	100,000
		-3 Operating Costs	480,000
		Subtotal	880,000
		1858. Reactor System Construction Services	
		-1 Shops, Storage and Inspection Buildings	315,000
		-2 Ventilation, Filters, and Dehumidification	100,000
		-3 Cranes and Hoists	80,000
		-4 X-ray and Leak Detector Equipment	75,000
		-5 Cleanliness Control Equipment	140,000
		Subtotal	710,000
		1859. Design Costs Including Planning Surveys, Completion Reports at 5% of Direct Costs Except Land	2,510,000
		GENERAL EXPENSE TOTAL	9,625,000

experience with comparable equipment in the Gaseous-Diffusion Plant at Oak Ridge. Costs of all these components are summarized in Table 11.7.

Building and Structural Items. Structures for supporting and shielding the reactor components and the steam generator make up the important building items in the reactor installation. These were estimated by Tennessee Valley Authority personnel using construction costs equivalent to those for conventional steam plant installations. The cost of architectural items has also been based on costs of materials for steam plants with which the Tennessee Valley Authority has been associated. Similarly, space allocated for shops, administrative facilities, laboratories, and other items normally associated with the steam plant installation has been based on Tennessee Valley Authority costs,but where appropriate, these have been modified to allow for the fact that a nuclear reactor is to be installed in place of normal coal-burning boilers. Table 11.7 gives the cost of the various building items in the reactor installation, as well as the steam system installation and related facilities. Site costs are also included in this tabulation.

Construction Facilities. Cost estimates in the above summary allow for normal construction features associated with steam-power plant construction. However, a nuclear power plant of this type involves some additional requirements which are not normally accounted for in steam plant cost estimates. Because the steam generators and containment vessels require a substantial amount of on-site fabrication, and since the operations must be performed under rigid cleanliness requirements, additional facilities, involving substantial construction expenses must be included in the costs. In Table 11.7 are listed additional construction buildings with their associated costs which should be added to the total cost estimate for this reactor installation. These buildings include the steam-generator-fabrication building, the piping-fabrication building, the graphite-storage building, fuel-storage building, cleaning building, and other miscellaneous handling equipment. An attempt has been made to estimate the cost of equipment which would be installed in these facilities but without more complete and detailed information about the plant design a substantial degree of uncertainty must be anticipated with respect to these costs.

A significant cost item not readily allocated to specific installations is general expense including such indirect costs as employee housing, G and A, and personnel recruiting.

The general expense cost is included in Table 11.7. It is based on Tennessee Valley Authority experience in conventional steam plants and is a function of the construction time span rather than the over-all job magnitude. The time span considered in this cost study was three years.

Design and engineering costs are also included and are computed at 5% of direct costs before escalation and contingency. This basis was developed from information furnished by the Atomic Energy Commission Oak Ridge Construction Office and does not include research and development costs. It is somewhat higher than conventional steam plant design costs which Tennessee Valley Authority data indicate are in the range of 2–3% of direct costs.

Fuel Inventory Costs. Included in the fixed costs is a rental charge for the uranium (which is owned by the Atomic Energy Commission) based upon the initial value of the fuel. The rate currently established by the Atomic Energy Commission is 4% per annum. For the gas-cooled reactor, the uranium inventory is 136.8 tonnes. At a value of $220,000/tonne for fuel enriched to 2% U^{235} (Fig. 11.3), the uranium inventory is valued at $30,000,000. For a load factor of 0.80, therefore, the contribution to the power cost is

$$\frac{\$30 \times 10^6 \times 0.04/\text{yr}}{225 \text{ Mw (E)} \times 8760 \times 0.8 \text{ hr/yr}} = 0.76 \text{ mills/kwh.}$$

An annual capital charge must also be applied to the cost of fabrication of the first set of fuel elements. An annual rate of 14% has been applied in this case, as for other investment items. For the gas-cooled reactor, with a fuel fabrication cost of $30.90/kg of uranium (see below) this charge amounts to

$$\frac{\$30{,}900\text{, tonne} \times 136.8 \text{ tonnes} \times 0.14/\text{yr}}{1.578 \times 10^6 \text{ Mwh/yr}} = 0.38 \text{ mills/kwh.}$$

These two fixed-fuel charges add 1.14 mills/kwh to the power cost. A summary of fixed costs, exclusive of the fuel inventory, is given in Table 11.7, itemized according to FPC account numbers.

11.2.2 Operating Expenses: Fuel Element Fabrication. The fabrication cost of fuel elements has always posed serious cost uncertainties in solid-fuel reactors. In a majority of cases fuel-element fabrication has proved to be one of the more important factors in fuel element costs, and in some cases, the overwhelming factor. The fabrication costs of gas-cooled reactor-fuel elements have been explored with a number of manufacturers (see Appendix C). Results of this investigation are given in Table 11.8. The quoted cost includes an allowance for a 10% rejection rate. Since there is little experience on which to base the spoilage rate for UO_2 fuel elements of this design, the assumption was made in this study that the spoilage rate will be similar to that for other ceramic materials produced by similar processes.

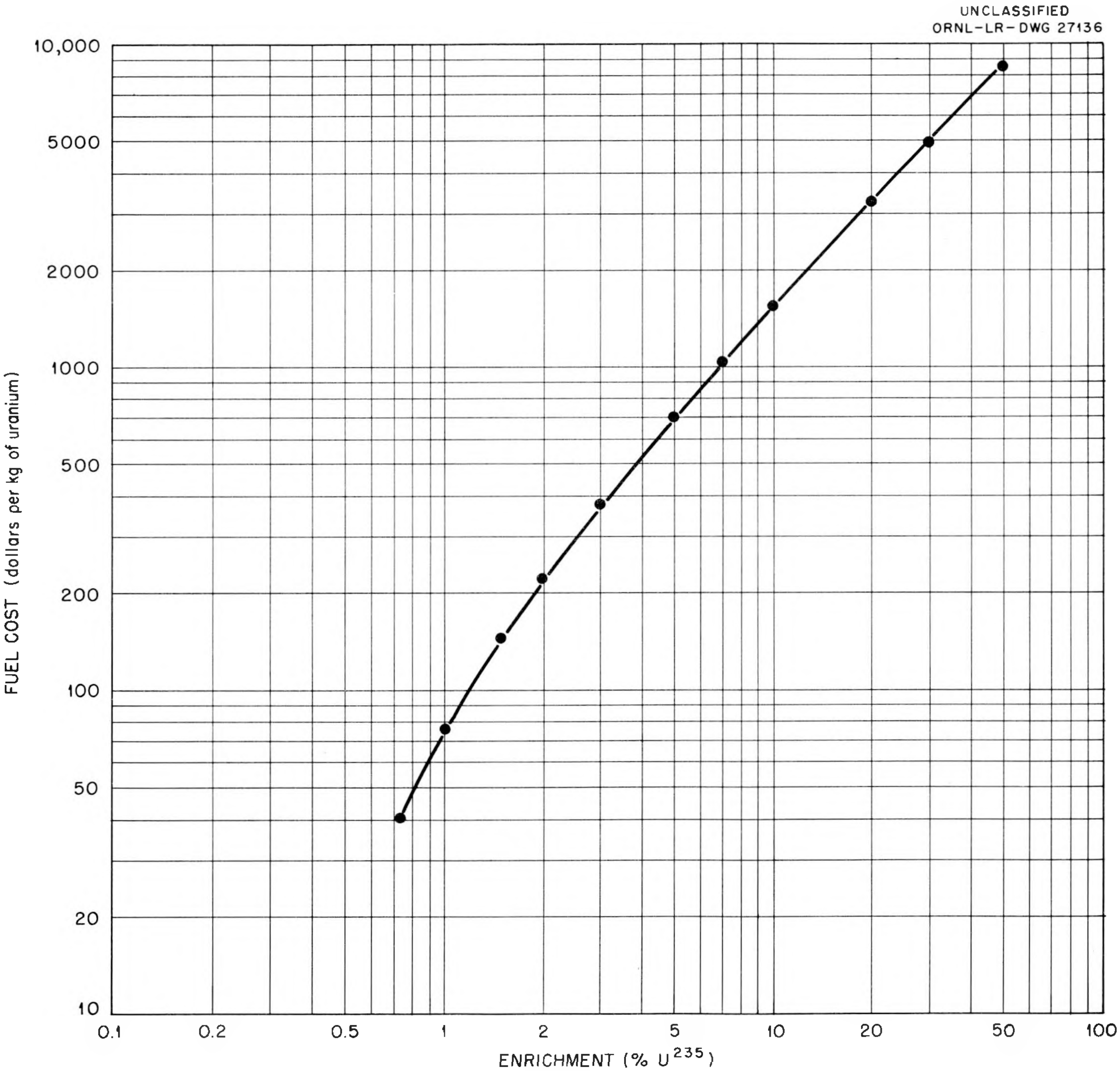

Fig. 11.3. Fuel Cost (as UF_6) vs Enrichment.

TABLE 11.8

GCR-2 FUEL ELEMENT FABRICATION COSTS*

Item	Cost/Kg Uranium
Conversion UF_6 to UO_2	$ 9.35
Preparation UO_2 Slugs from Powder	8.57
Manufacture and Assembly of Capsules	9.60
Spacers and Hangers	.46
Facilities and Tooling	.70
Methods Development	1.49
Miscellaneous Costs	.33
Transportation to Site	.08
Site Assembly of Cluster	.23
TOTAL	$ 30.91

Fabrication Cost for 150.8 tons U(136.8 tonne)	=	$4,230,000
Annual Charge at 14%/yr	=	591,000
Cost/kwh (First Core)	=	0.37 mills

* Included 10% Spoilage Factor

The fuel element fabrication cost contributes to the power cost in two ways:

1. Fabrication of the first core is considered part of the plant investment, and is capitalized at 14% per year. This contribution was discussed above.
2. Fabrication of replacement-fuel elements is regarded as an operating expense and is inversely proportional to the fuel exposure (Mwd/T). With a fabrication cost of $30.90/kg U and a net electrical efficiency of 32%, the contribution to the power cost is

$$\frac{30{,}900 \text{ \$/tonne}}{24 \times 0.32 \times \text{Mwd/T}} = \frac{4020}{X} \text{ mills/kwh.}$$

For the GCR-2, with X = 7400 Mwd/T, the cost is 0.54 mills/kwh.

Fuel Reprocessing. Fuel reprocessing has been investigated by the Chemical Technology Division of the Oak Ridge National Laboratory for a number of reactor types, including the gas-cooled reactor. Costs have been estimated on two bases:

A. A single purpose plant with a capacity of one tonne per day, which would handle fuel from a number of reactors of the same type. Reprocessing costs are $12,400/tonne of uranium, and the contribution to the power cost is inversely proportional to the fuel exposure in Mwd/T. For a net electrical efficiency of 32%, the charge is

$$\frac{12,400 \text{ \$/tonne}}{24 \times 0.32 \times X \text{ Mwd/T}} = \frac{1610}{X} \text{ mills/kwh.}$$

For GCR-2, with an average fuel exposure of 7400 Mwd/T, the contribution to the power cost would be 0.22 mills/kwh.

B. A multipurpose plant with a capacity of one tonne of uranium per day, which would require an 8-day clean-up operation after processing gas-cooled reactor fuel. Such a plant would have equipment suitable for high assay fuel. Since this equipment would not be required for low-enrichment fuel, the extra capital charges are not included in the reprocessing costs for gas-cooled reactor fuel. The charge for reprocessing gas-cooled reactor fuel on this basis is $12,400/tonne plus 8 x $12,400 per batch.

With an average fuel exposure of 7400 Mwd/T and a load factor of 0.80, the fueling rate for the gas-cooled reactor would average 27.6 tonnes/yr. This amount of fuel would be reprocessed in a single batch at a cost per kilowatt hour given by

$$0.22 \left(\frac{27.6 + 8}{27.6}\right) = 0.28 \text{ mills/kwh.}$$

For the purposes of this study the second method of operation (B) was assumed to apply.

In addition to the chemical reprocessing cost, rental charges on the out-of-pile inventory must be considered. The following holdup times out of pile have been assumed:

1.	Fabrication	2 months
2.	Stand-by storage	1
3.	Cooling of spent fuel	3
4.	Transfer to chemical plant and recovery	2
	Time out-of-pile	8 months

Since the average fuel-replacement rate is (27.6 tonnes yr/136.8 tonnes in-pile inventory) = 20% per yr, the out-of-pile inventory is (8/12) 20% = 13% of the in-pile inventory, and the rental charge per kilowat hour will be 13% of the in-pile inventory charge, or 0.10 mills/kwh.

Fuel Burn-up Cost. The burn-up cost is equal to the initial value of the fuel, less the value of the uranium and plutonium in the spent fuel. The composition of the fuel for a given exposure was obtained from the burn-up calculations described in Section 2. It turns out that the burn-up cost for a given initial enrichment of the fuel is not strongly dependent upon the fuel exposure, if the plutonium is valued at $12/g. For the gas-cooled reactor, the burn-up costs for both $12/g and $30/g plutonium are shown in Table 11.9.

TABLE 11.9

FUEL BURN-UP COSTS

(Annual Replacement Rate of 27.6 Tonnes/yr, Exposure of 7400 Mwd/T)

	Annual Cost	
	$12/g Pu	$30/g Pu
2% U^{235} Fuel, Initial Value at $220/kg	5,850,000	5,850,000
1.23% U^{235} Spent Fuel at $108.5/kg	2,900,000	2,900,000
Net U^{235} Burn-up	2,950,000	2,950,000
Plutonium Credit (5.1 g Pu/kg U)	1,640,000	4,090,000
Net Fuel Burn-up Cost	1,310,000	- 1,140,000
Net Cost, mills/kwh	0.83	- 0.73

Operating Costs Exclusive of Fuel. Though the design of this plant is not sufficiently detailed to spell out all the operating charges to be applied against it, an investigation has been made of the probable costs of operation. These include estimated manpower requirements, maintenance costs, helium usage, and miscellaneous material charges. The results, which, indicate an operating cost of 0.89 mills/kwh exclusive of fuel, are summarized in Table 11.10. The estimates are based on the collective opinions of Oak Ridge National Laboratory personnel with regard to the probable cost of reactor operation, and of Tennessee Valley Authority personnel with regard to steam-power plant operational problems.

TABLE 11.10

OPERATING COSTS EXCLUSIVE OF FUEL FOR GCR-2

	Annual Costs
Wages (100 men at $6,000/yr) Includes Supervision	$ 600,000
Water, Lubrication, Helium and Supplies	400,000
Maintenance	400,000
TOTAL	$ 1,400,000

Cost Summary. A summary of the cost of producing electric power with the gas-cooled reactor plant is given in Table 11.11. The over-all cost is given on the basis of the construction costs discussed in the previous section, and includes a case which an allowance is made for rising costs during the construction period.

11.3 Effect of Variations in Design Parameters and Assumptions

It is important to establish the sensitivity of the power cost, both to variations in design parameters within the control of the engineer, and to possible deviations of key variables from the values assumed for them in this cost analysis.

The effect of varying the reactor size was examined for two different thicknesses of the pressure vessel. Layouts were prepared for each core size to determine the pressure vessel and shield dimensions that would be

TABLE 11.11

TOTAL POWER COSTS FOR ORNL GCR-2 WITH A NET ELECTRICAL OUTPUT OF 225 Mw AT A PLANT FACTOR OF 0.80

Item	Capital Cost ($)	Annual Charge Rate	Annual Cost ($)[1]
I. Fixed Costs			
1. Reactor plant	$ 47,904,700		
2. Contingency (item 1)	7,927,500		
3. General expense	7,615,000		
4. Design cost	2,510,000		
SUBTOTAL	$ 65,957,200	14%	$ 9,234,000
5. Fuel element fabrication at $30.90/kg	$ 4,230,000	14%	592,000
6. Uranium fuel	30,000,000	4%	1,200,000
7. Construction charges[2] on items 1-4 at 6%/yr for 1.5 yr	5,936,100	14%	831,000
TOTAL Annual Fixed Costs			$ 11,857,000

$$\text{Fixed costs in mills/kwh} = \frac{\text{Annual fixed cost (in mills)}}{\text{Net electrical capacity (kw) x plant factor x hrs/yr}} =$$

$$\frac{11{,}857 \times 10^6}{225 \times 10^3 \times 0.8 \times 365 \times 24} = 7.52 \text{ mills/kwh}$$

II. Operating Costs	Annual Cost ($)	Cost (mills/kwh)
1. Cost exclusive of fuel	$ 1,400,000	0.89
2. Fuel burn-up less Pu credit at $12/g	1,310,000	0.83
3. Fuel element replacement fabrication at $30.90/kg U	822,000	0.52
4. Spent fuel recovery (multipurpose plant)	423,000	0.28
5. Fuel in process outside reactor at 13% of inventory	136,000	0.10
TOTAL Operating Cost	$ 4,091,000	2.62 mills/kwh
TOTAL Power Cost		10.14 mills/kwh

[1] Allowing for escalation costs during construction as discussed under Construction Facilities, the Total Annual Fixed charges become $13,321,200 which corresponds to a Total Power Cost of 11.12 mills/kwh.

[2] No construction charge is made against fuel-element fabrication because of the short time between fabrication and use.

required with adequate allowance for flow passages, clearances, etc. The gas pressure is inversely proportional to the pressure-vessel diameter for a given wall thickness. Core height was assumed to be proportional to core diameter, although this need not be the case. The power level is then related to the core dimensions and the pressure by the expression

$$P = P_o \left(\frac{p}{p_o}\right)^{0.8} \frac{V}{V_o} \left[1 - k\left(\frac{H}{H_o} - 1\right)\right] ,$$

where V and H are the core volume and height respectively, p is the gas pressure, the subscript o indicates the reference design, and the constant k is proportional to the gas pumping power in the reference design. Figure 11.4 shows the capital cost of those reactor components directly affected by a change in core diameter, for example, graphite, pressure vessel, and shield, both with and without the fuel inventory and first-core fabrication charges (which rise with increasing core size because the reduced gas pressure leads to reduced specific power). Also shown are total plant cost and over-all power cost. It will be noted that reactor costs, including fuel, are rather insensitive to core diameter. Over-all capital costs, however, and hence the power cost, do fall with increasing core diameter since a number of fixed costs are spread over a larger power output. A cost reduction of approximately 1 mill/kwh could be realized by going to a much larger core; however, the net electrical output from one reactor would then be 500 or 600 Mw.

A number of important but somewhat uncertain variables such as fuel-fabrication cost, plutonium credit, fuel exposure, and the cost of the reactor relative to other plant components, not only affect the final power cost, but may also influence the choice of system parameters, such as lattice pitch and fuel enrichment. In Figs. 11.5 through 11.8, a number of curves are given which show the over-all power cost as a function of lattice pitch and fuel enrichment for several values of the variables enumerated above. These curves illustrate the balance between capital costs, which decrease with decreasing lattice pitch, and fuel-cycle costs, which increase with decreasing lattice pitch (because of reduced reactivity and hence reduced

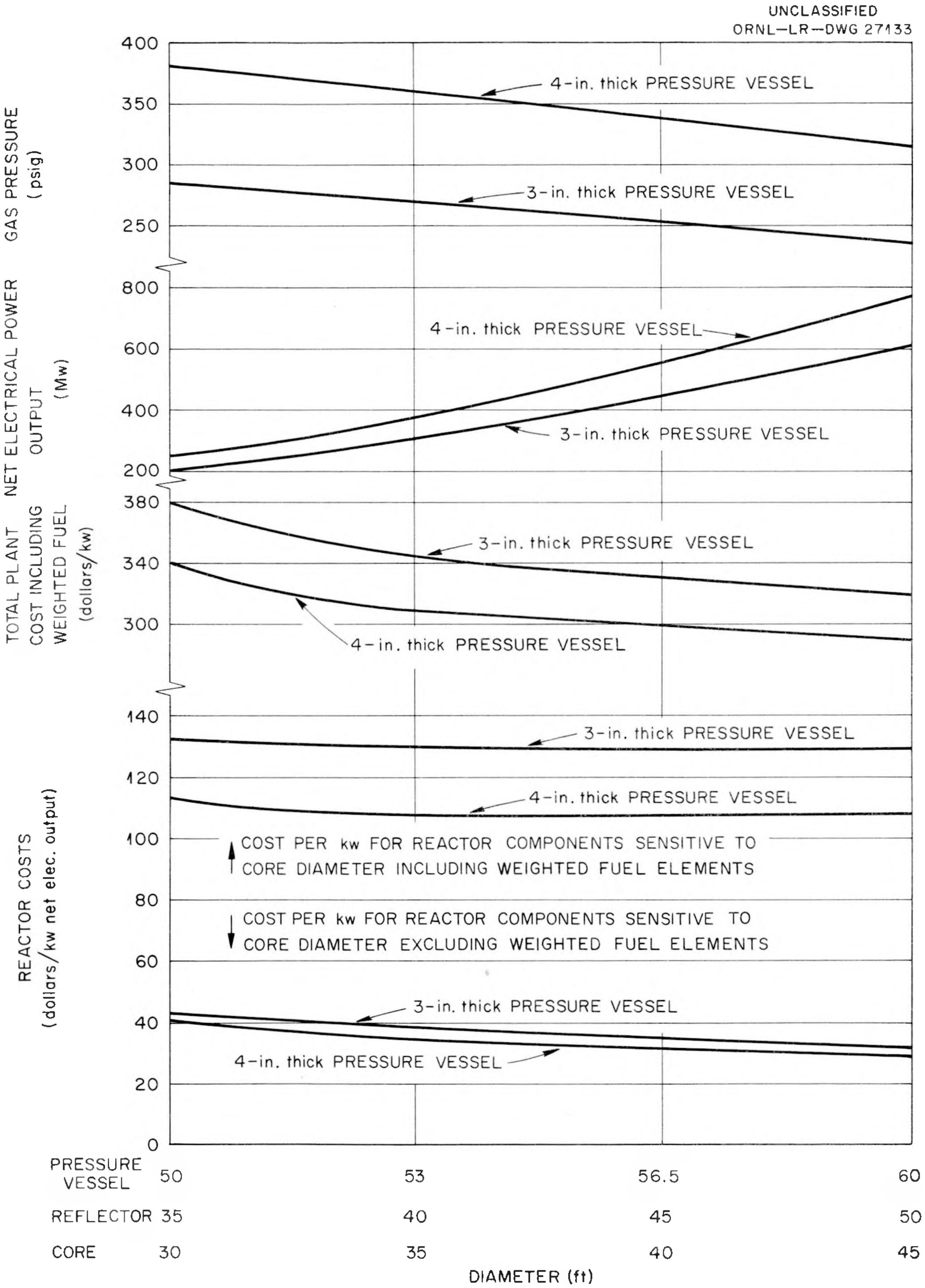

Fig. 11.4. Reactor Costs, Gas System Pressure, and Power as a Function of Reactor Size.

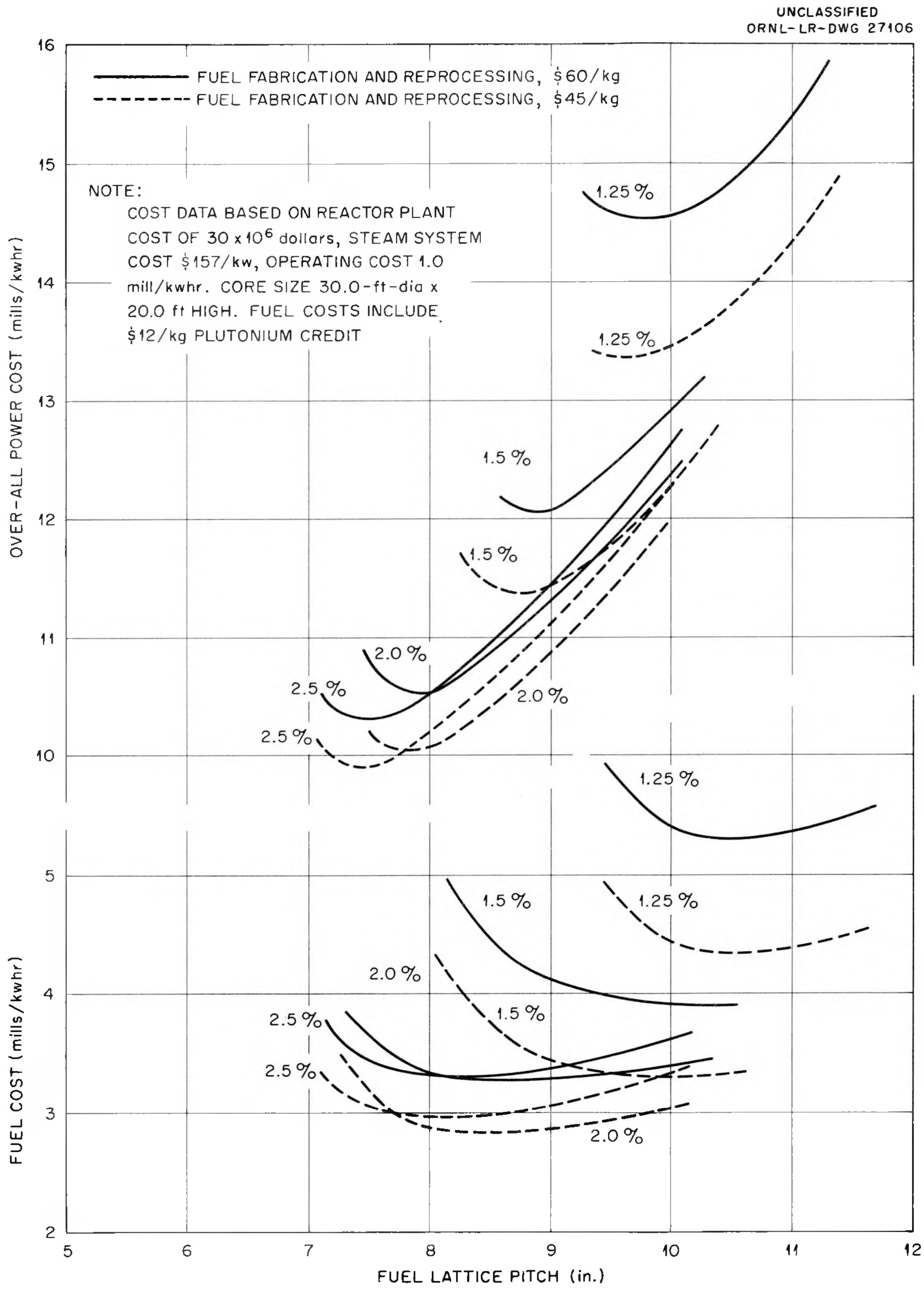

Fig. 11.5. Over-all Power Costs and Fuel Costs for Various U^{235} Enrichments.

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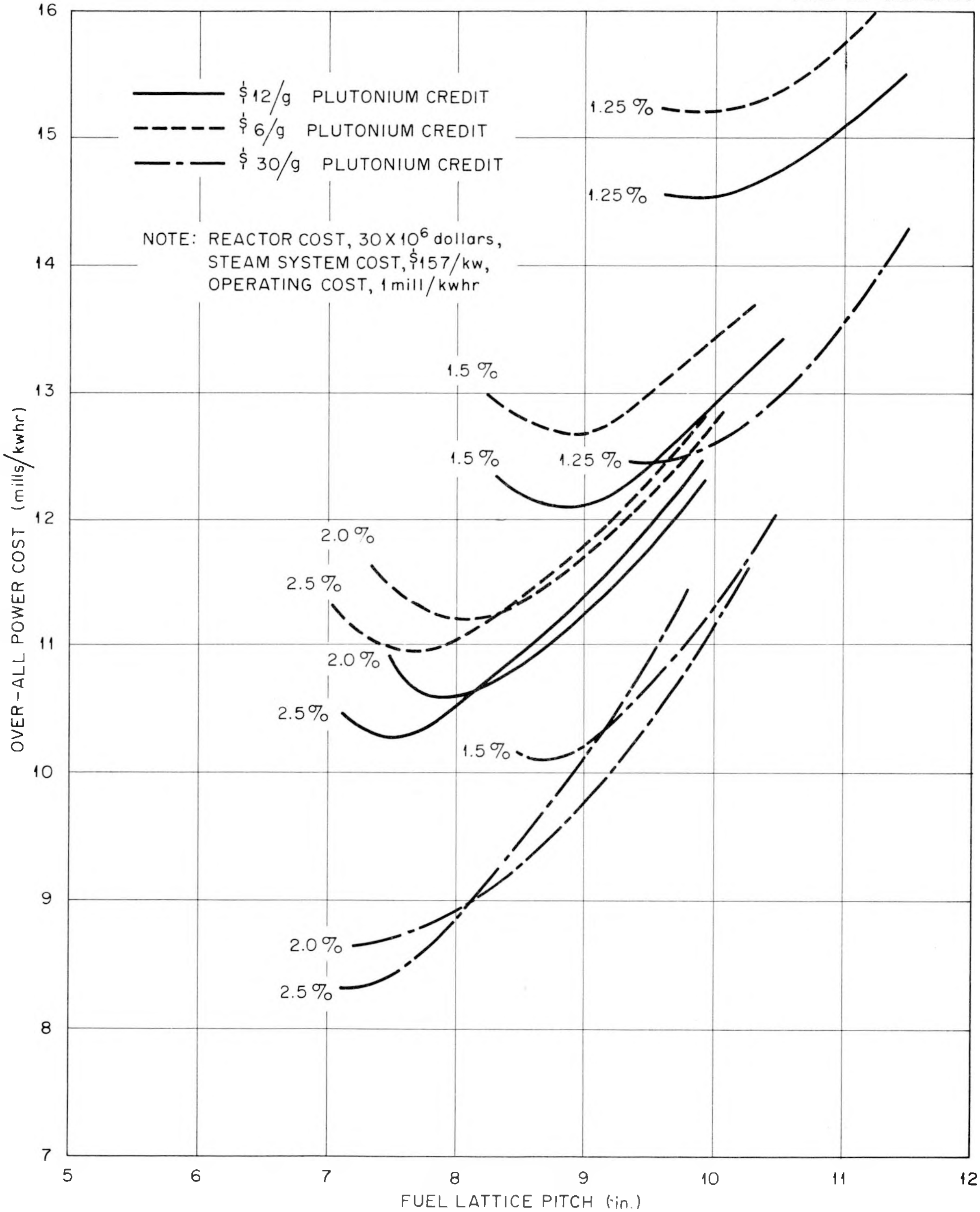

Fig. 11.6. Power Cost vs Fuel Lattice Pitch for Various U^{235} Enrichments Showing the Effect of Plutonium Credit Values.

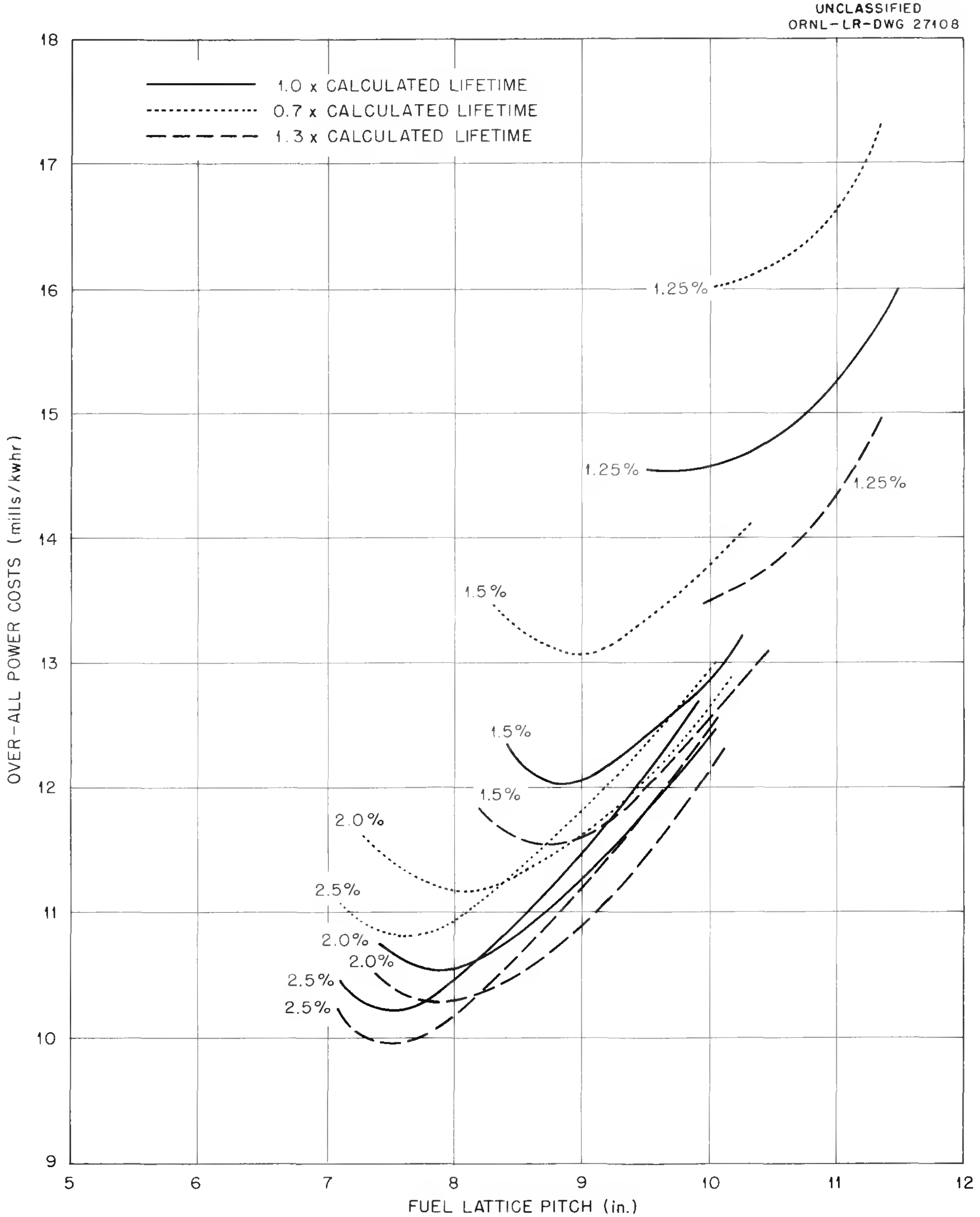

Fig. 11.7. Over-all Power Costs vs Fuel Lattice Pitch for Various Enrichments, Showing the Effect of Fuel Lifetime on Power Cost.

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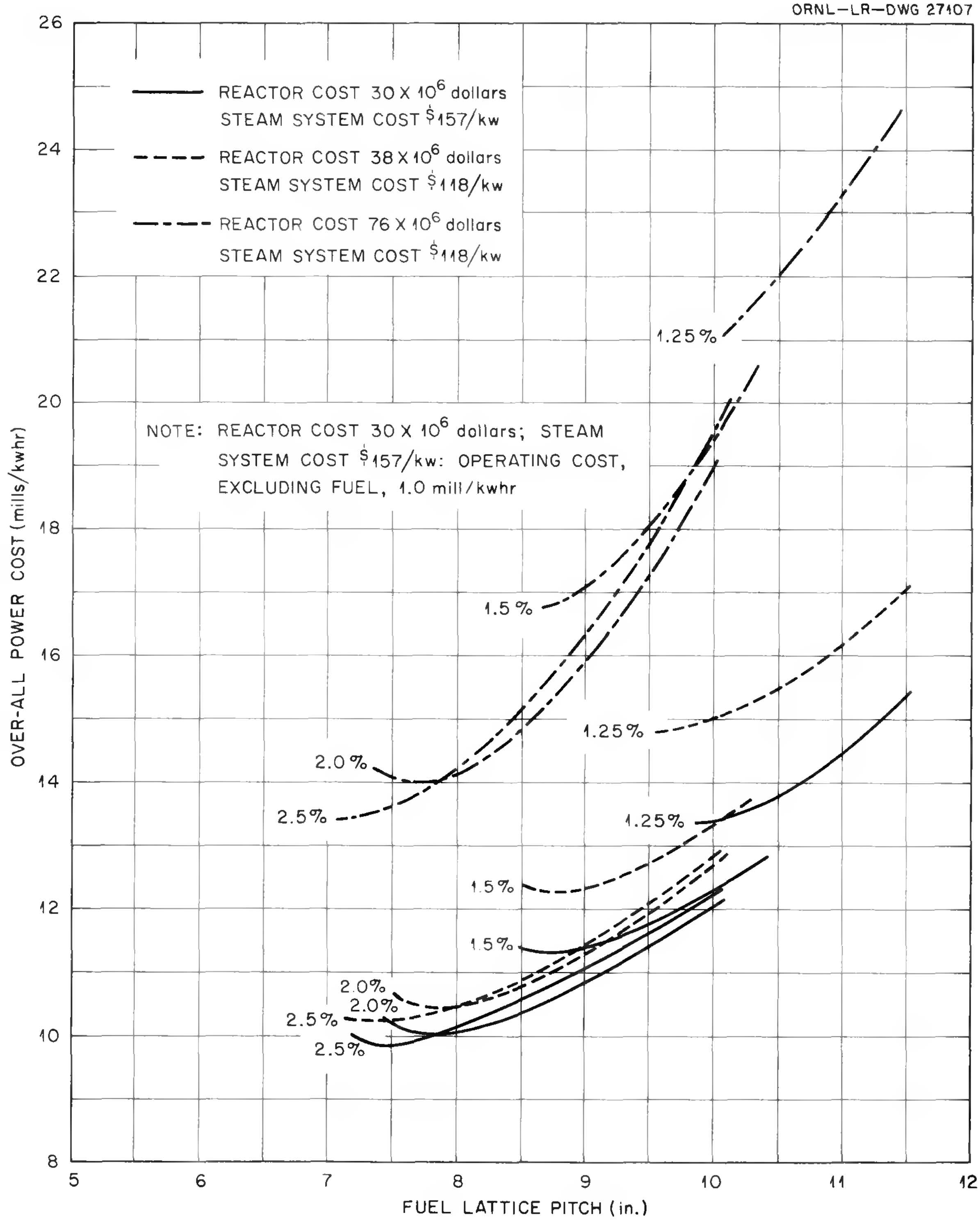

Fig. 11.8. Power Cost vs Lattice Pitch for Various Enrichments.

fuel exposure). In each of these figures, it can be seen that the power cost decreases quite markedly with increasing fuel enrichment, up to about 2%, and decreases very little for enrichment above 2%. In each case, the power cost with 2.5% enrichment is indeed somewhat less than with 2%, but the difference is quite small. Thus, the selection of core parameters is not significantly affected by changes in the values of these parameters. The most pronounced effect stems from the cost of those reactor components that are essentially independent of power output, for example, reactor, buildings, auxiliary facilities, instrumentation, etc. If these constitute a much larger fraction of the investment than presently appears to be the case, there would be an incentive to increase the fuel enrichment and reduce the lattice pitch (Fig. 11.8). (The cost data shown on these figures do not include contingency and escalation factors, and are intended only to show relative power cost.)

In preparing Fig. 11.7, the fuel exposures for all combinations of lattice pitch and fuel enrichment were increased or reduced by the same factor. Actually, the uncertainties in the burn-up calculations need not affect all of the cases equally. In particular, a slight increase in the initial multiplication factor for each case, which seems the most probable correction to the present results, would increase the exposure for lower fuel enrichment by a larger factor than for higher enrichment. This could shift the optimum choice towards lower enrichments. It is interesting to note the effect on fuel cost of reducing the enrichment (at 8 in lattice pitch) to a value which would permit a fuel exposure of 3000 Mwd/T. A comparison of this case with the GCR-2 is given in Table 11.12. (In this comparision, as in the curves of Fig. 11.7, the fuel cost includes the inventory charges and cost of fabricating the first core. In the cost summary of Table 11.11, these charges are included with the fixed costs of the plant.)

The effects of capital charge rates and contingency factors on power cost are shown in Fig. 11.9. Without a detailed design of the plant, it is impossible to establish the degree of accuracy of the cost data. Within the knowledge of the designers all items of expense which are involved in

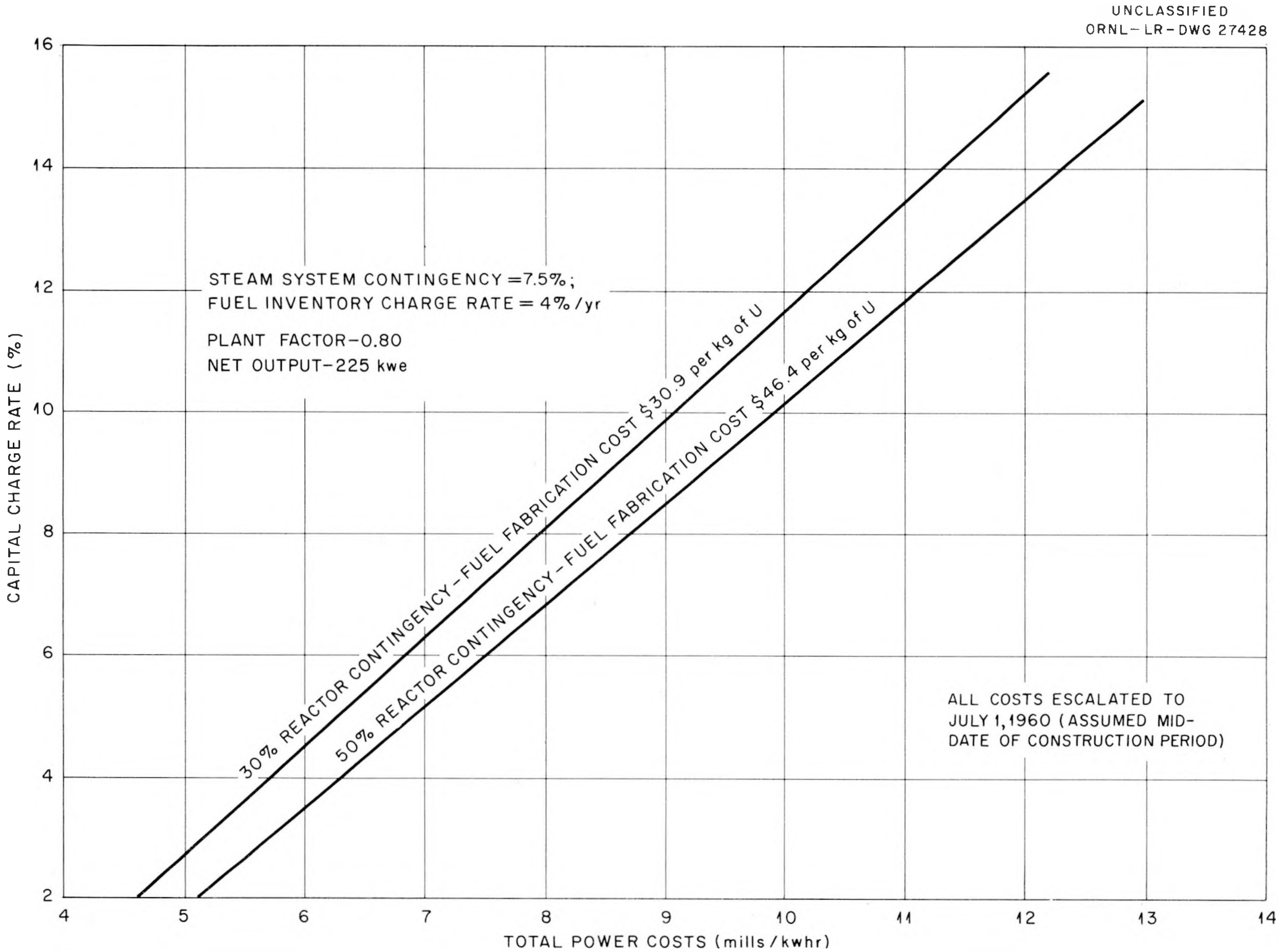

Fig. 11.9. Power Cost vs Capital Charge Rate for 30% and 50% Reactor Contingency Factors.

the cost and operation of the reactor installation have been included, but since such a reactor has never been built in the United States, it is probable that omissions have occurred which were not considered in the cost estimate. This consideration applies much more strongly with respect to the reactor design than with respect to the steam plant portion of the installation. For this reason, a contingency factor of 30% was applied to the estimated base cost of the reactor installation while a 7.5% factor was applied to the steam plant portion. On this basis, it is believed there is at least a 75% certainty that the plant can be built within the estimated cost.

TABLE 11.12

COMPARISON OF FUEL COSTS FOR REACTORS HAVING FUEL LIFETIME CONTROLLED BY U-235 ENRICHMENT

	Fuel Lifetime 3000 Mwd/Tonne V	Fuel Lifetime 7400 Mw/Tonne V
Enrichment Required	1.6%	2%
Specific Power*	5.1 Mw/Tonne	5.1 Mw/Tonne
Fuel Costs	mills/kwh	mills/kwh
Inventory Charge	0.56	0.77
Fuel Element Fabrication		
Capsule Charge	0.43	0.43
Fixed Charge - SUBTOTAL	0.99	1.20
Burn-up Charge (Net)**	0.80	0.83
Fuel Fabrication and Recovery	1.95	0.80
In Process Fuel Charge	0.15	0.10
Operating Charge SUBTOTAL	2.90	1.73
TOTAL	3.89	2.93

* 700 MwT Reactor with 8 in. Lattice Pitch
Net Electrical Output - 225 MwE
Plant Factor - 0.80

** Based on Plutonium Credit of $12/g.

APPENDIX A

HEAT TRANSFER PERFORMANCE

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HEAT TRANSFER PERFORMANCE

This section presents the study of the heat transfer performance of the over-all system on the basis of which the relevant system parameters have been selected. The helium temperature to the core is set at 450°F as discussed in Section 6 and the reference fuel rod configuration of Section 4 has been studied throughout. The channels in the graphite are 25 ft long; the fuel rod clusters are 20 ft long. It was further decided that only one type of fuel rod cluster would be used in the reactor; i.e., the spacing between the 3/4 in. rods, and, therefore, the outside diameter of the cluster are fixed. This in turn restricts the range in graphite-channel sizes which may be used. If the variation in graphite-channel sizes is large then the clearance between the outside rods and the graphite becomes so large that the flow tends to bypass the center part of the cluster, thereby reducing the heat transfer rate from the rods. The minimum graphite-channel size is fixed at 3.0 in. to facilitate the handling of the fuel rods and also examination of the channels by television cameras. Pressure shell studies fixed the helium pressure at 300 psia.

The parameters which are varied during this study were maximum fuel-capsule-surface temperature, mixed-mean-helium-exit temperature, reactor-power output, number of regions (graphite-channel sizes), orifices and flux distribution.

The parameter which has the most effect on the performance of the over-all system is the allowable fuel-capsule-surface temperature. Using a 304 stainless steel capsule, the maximum hot-spot temperature was set at 1500°F. The nominal, or design, maximum temperature must be less than 1500°F to allow for the inevitable hot spots which arise from flow irregularities, caused by the spacers which hold the rods in place or by the flow disruption between clusters. Calculations have been made for nominal maximum surface temperatures of 1200 and 1300°F, thus allowing 300°F and 200°F, respectively, for hot spots.

The mixed-mean-helium exit temperature depends upon the method of metering the flow through the reactor. The power generated in any channel is a function of the neutron flux in the channel which is in turn a function of the radial position of the channel in the core. To realize high-mixed-mean temperatures, it is necessary to restrict the flow through the channels in the areas of low-power density. This flow control may be accomplished by varying the channel size in the graphite, by orificing the channels, or by a combination of both methods.

The reactor-power level was set at 700 Mw (T) for the over-all study. Most of the data presented below is at this power. Power costs for power levels up to 1500 Mw (T) were calculated, and the effects of fuel element temperature and flux distribution on the cost of power generated were determined.

Calculation Procedure

Most of the calculations were made using a peak to average-heat-generation rate of 1.5 to 1 ($P_{max}/\overline{P} = 1.5$). For simplicity, the relation between power-reactor radius which follows a $J_o(\alpha r)$ function was replaced by a cosine $(\frac{\pi r}{2})$ function. This approximation greatly reduces the complexity of numerical calculations without affecting the optimization procedure, as shown in Fig. A.1.

The axial-power distribution was assumed to be a sine curve cut off at 72° (see Fig. A.2). This represents a $P_{max}/\overline{P} = 1.32$.

The temperature of the gas can then be related to the axial position by

$$T_x = T_{in} + K \left[0.9511 - \cos \frac{\pi x}{25} \right]$$

where K is a function of the power and gas flow for any particular channel. For 700 Mw

$$Q = 700 \times 10^6 \times 3.413 = 2.39 \times 10^9 \text{ Btu/hr}$$

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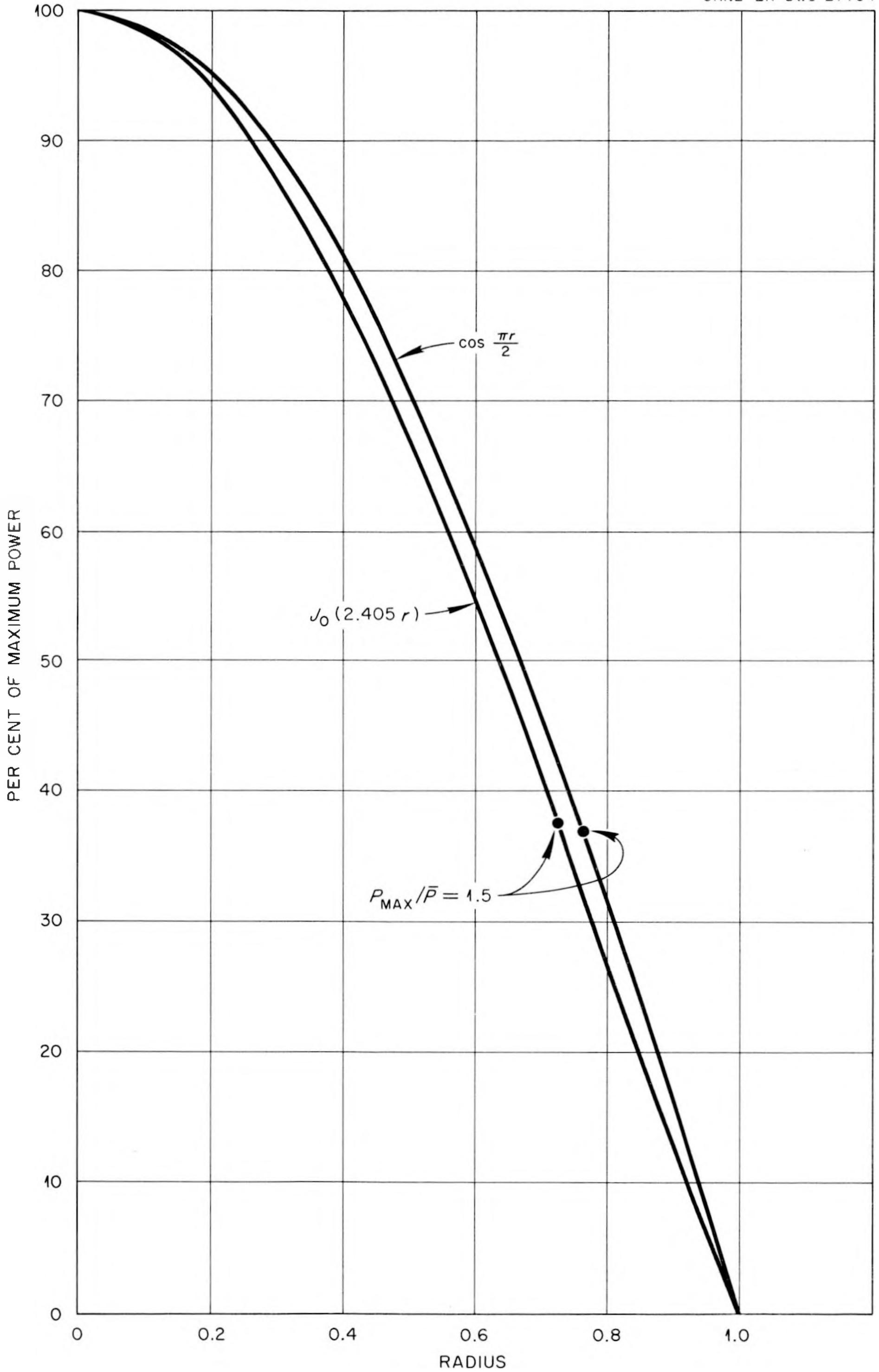

Fig. A.1. Reactor Radial Power Distribution.

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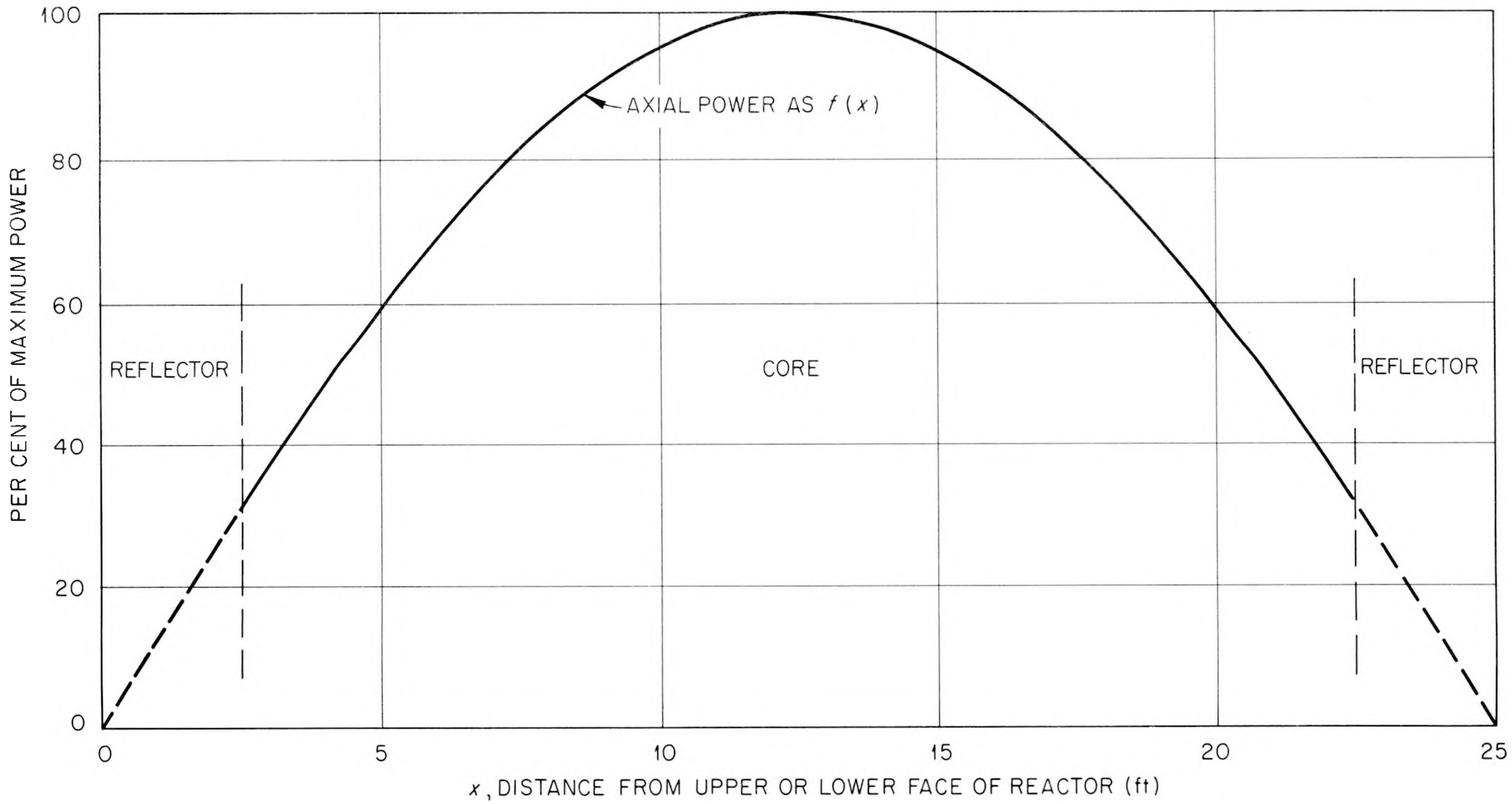

Fig. A.2. Reactor Axial Power Distribution.

Reactor face area $= \pi(15)^2 = 707\ ft^2$

$$Q_{avg} = 3.38 \times 10^6 \text{ Btu/hr ft}^2 \text{ of reactor face}$$

$$Q_{max} = 1.5\ Q_{avg} = 5.07 \times 10^6 \text{ Btu/hr ft}^2$$

For a square lattice with an 8-in. pitch

$$\text{Channels/ft}^2 = \frac{144}{64} = 2.25$$

Q_{max} per channel $= 2.25 \times 10^6$ Btu/hr for 1590 channels

The power at any radius in core is

$$P(r) = P_{max} \cos \frac{\pi(0.76\ r)}{30}$$

For any channel

$$Q(r) = 2.25 \times 10^6 \cos \frac{\pi(0.76\ r)}{30}$$

Therefore

$$K = \frac{2.25 \times 10^6 \cos \frac{\pi(0.76\ r)}{30}}{2 \times 0.9511\ w\ C_p}$$

where w is the coolant mass flow in the channel

For $T_{in} = 450°F$

$$T_{gas}\ (r,x) = 450 + \frac{2.25 \times 10^6 \cos \frac{0.76\pi r}{30} \left[0.9511 - \cos \frac{\pi x}{25}\right]}{1.902\ w\ C_p}$$

In most of the subsequent calculations the fuel-rod temperature for any specific case is fixed. Therefore, it is necessary to determine the maximum rod temperature as a function of r and x.

The temperature of the fuel rod is

$$T_{wall}(r,x) = T_g(r,x) + \Delta T_{w\ to\ g}(r,x)$$

The temperature difference between the wall and the gas

$$\Delta T_{w\ to\ g} = \frac{Q}{hA}$$

In these calculations the value of the heat transfer coefficient h, is assumed to be constant and is evaluated at the average conditions in a channel. This approximation is good to within 5% of the true integrated value and is probably well within the accuracy of the data used to determine h. The equation used for h is

$$\frac{hD_e}{k_f} = 0.021 \left(\frac{C_p\mu}{k}\right)_f^{0.4} \left(\frac{D_e V_b \rho_f}{\mu_f}\right)^{0.8} \left[1 + \left(\frac{L}{D_e}\right)^{-0.7}\right]$$

where h = heat transfer coefficient Btu/hr ft^2°F

D_e = equivalent diameter ft

k = thermal conductivity Btu/hr ft°F

C_p = specific heat Btu/lb°F

μ = viscosity lb/hr ft

V = velocity ft/hr

ρ = density lb/ft^3

L = channel length ft

Subscript f means properties are evaluated at the film temperature and subscript b is for evaluation at bulk temperature.

The heat generated in any channel is

$$Q(r) = 2.25 \times 10^6 \cos \frac{0.76\pi r}{30}$$

which is equal to

$$Q = 2K' \int_{2-1/2}^{12-1/2} \sin \frac{\pi x}{25}\, dx \text{ per ft of length}$$

$$= 2K' \frac{25}{\pi} \left[0.951\right] = 15.1\ K$$

Therefore

$$15.1\ K' = 2.25 \times 10^6 \cos \frac{0.76\pi r}{30}$$

$$K' = 2.25 \times 10^6 \cos \frac{0.76\pi r}{30}$$

$$Q(r,x) \text{ per ft} = 1.49 \times 10^5 \cos \frac{0.76\pi r}{30} \sin \frac{\pi x}{25}$$

For a fuel rod cluster of seven 3/4 in. rods

$$\frac{Q}{A}(r,x) = 1.082 \times 10^5 \cos(\frac{0.76\pi r}{30}) \sin(\frac{\pi x}{25})$$

and the rod temperature

$$T_{wall}(r,x) = 450 + \frac{2.25 \times 10^6 \cos\left(\frac{0.76\pi r}{30}\right)\left[0.9511 - \cos \frac{\pi x}{25}\right]}{1.902\ w\ C_p} + \frac{1.082 \times 10^5 \cos\left(\frac{0.76\pi r}{30}\right) \sin\left(\frac{\pi x}{25}\right)}{h} \qquad (A.1)$$

To be useful, the above equation must always be evaluated at its maximum. Setting

$$\frac{dT_{wall}}{dx} = 0$$

gives $\tan \frac{\pi x}{25} = -0.1134\ w/h$

This enables one to solve Eq (A.1) by iteration. In evaluating the friction head loss, the friction factor was assumed constant at 0.006 and the length was taken as 25 ft.

As an example consider the following specific case:

$$T_{wall}(max) = 1300°F$$

$$\Delta P_f = 4000 \text{ ft lb/lb}$$

$$T_{gas} \text{ (exit at } r = 0) = 1050$$

$$\text{Number of regions} = \text{infinite}$$

The number of regions refers to the number of different graphite-channel sizes, each region having the same channel size. The case in which the channel size varies continuously with radius is referred to as infinite regions. Figure 6.7 shows the results of the previously described calculation method. The mixed-mean-exit temperature may be found from the expression

$$T_{mixed\text{-}mean} = \frac{\int_0^{15} WTRdr}{\int_0^{15} WRdr} = 1134°F$$

Both the numerator and denominator of this expression may be readily obtained by graphical integration.

The mixed-mean temperature for a single region system is

$$T_{mixed\text{-}mean} = 450 + \Delta T_{gas} \ (r = 0) \ \times \frac{\overline{P}}{P_{max}}$$

or for the above example

$$T_{mixed\text{-}mean} = 450 + (1050 - 450) \ \times \frac{1}{1.5}$$

$$= 450 + 400 = 850°F$$

For a reactor in which the number of regions is different than one or infinite, the calculations become much more complex.

In optimizing the mixed-mean temperature for more than one region, it is necessary to determine the inside and outside radius of each region. It should be noted that the optimum temperature is not that in which the mean temperature leaving each region is the same. The region at the largest radius should always have the highest mean temperature. This can readily be seen by examining the results of the one region and infinite region calculations shown above. If the mean-exit temperatures of all regions are equal than the over-all-mean temperature cannot exceed the exit temperature of the channel at r = 0. For the case of the true optimum, the maximum temperature is given by the infinite region case. The true optimum for a two-region reactor will occur when

$$\frac{\overline{\Delta T}_I \, W_I + \overline{\Delta T}_{II} \, W_I}{W_T} = \text{maximum} \qquad \text{(A.2)}$$

where $\overline{\Delta T}_I$ is the mean temperature rise in region I and is

$$= \Delta T_{Max\ I} \frac{2\pi \int_0^{r_1} \cos \frac{0.76\pi r}{30} \, rdr}{2\pi \int_0^{r_1} rdr}$$

$\overline{\Delta T}_{II}$ is the mean temperature rise in region II and is

$$= \Delta T_{maxII} \frac{P(r = 0)}{P(r = x_1)} \frac{2\pi \int_{r_1}^{15} \cos \left(\frac{0.76\pi r}{30}\right) rdr}{2\pi \int_{r_1}^{15} rdr}$$

W_I is the total weight flow in region I and is

$$= \int_0^{x_1} 2\pi \, W \, rdr = 2\pi \, W_1 \int_0^{x_1} rdr$$

$W_1 = $ wt/channel in region I

W_{II} is the total weight flow in region II and is

$$= 2\pi \, W_2 \int_{x_1}^{15} rdr$$

$W_2 = $ weight/channel in region II

$W_T = W_I + W_{II}$

$$W_I \, \overline{\Delta T}_I = 2\pi W_1 \, \Delta T_{max\ I} \int_0^{r_1} \cos\left(\frac{0.76\pi r}{30}\right) rdr$$

$$W_{II} \, \overline{\Delta T}_{II} = 2\pi \, W_2 \, \Delta T_{max\ II} \frac{P(o)}{P(r_1)} \int_{r_1}^{15} \cos\left(\frac{0.76\pi r}{30}\right) rdr$$

$$W_T = 2\pi \left[W_1 \int_0^{r_1} rdr + W_2 \int_{r_1}^{15} rdr \right]$$

Equation (A.2) is then solved as a function of r_1. For the above example with ΔP_f of 4000 ft lb/lb, the mean-exit temperature is found to be 968°F. The optimum radius r_1 is 10 ft. For the three-region case, it would be necessary to locate the maximum point on a curved surface in 3-space. As this would be very time consuming, the optimum radii were assumed and the mean temperatures determined for more than two regions.

A second method to improve the mixed-mean temperature is to use orifices to control the flow through different regions of the reactor. This method is less expensive, simpler, and more flexible than varying the channel size. The only case considered below is for a different orifice size for each radius. Orifices can be placed at the bottom of the core and will not interfere with fuel loading or unloading which will be done from the top.

An example of the effectiveness of this method is shown by the following case:

T_{wall}(max) = 1300°F

ΔP_t = 4000 ft lb/lb

T_{gas}(exit at r = 0) = 1050°F

1 region - each radius orificed separately

It is assumed that the flow is throttled to some value so that the nominal maximum rod temperature at each radius reaches 1300°F. The results of this example are shown in Fig. A.3. Again the mixed-mean temperature is found by graphical integration and is 1070°F.

It was found that a one region separately orificed system gave approximately the same results as a six-region no-orifice system. By a combination of regions and orifices, it should not be difficult to attain mixed-mean temperatures equivalent to the one region separately orificed system at a reasonable cost.

Figures 6.9 and 6.10 show the effect of core-friction-head loss on the mixed-mean-exit temperature for several reactor-core configurations. A comparison of Figs. 6.9 and 6.10 shows the advantage of a 1300°F fuel-rod-surface temperature over that of 1200°F. Figure A.4 gives the minimum-graphite-channel size required for some of the configurations. The minimum-channel size will always be at the outer radius of the reactor in the low-heat flux region. The channel size for the separately orificed case is that corresponding to the one region case.

Figure A.5 is a plot of the system-head loss external to the core. Figure A.6 is a plot of the core-head loss exclusive of the friction loss. This loss consists of a contraction loss entering the core, expansion and contraction losses around the spiders holding the fuel rods in place and an expansion loss leaving the core. The entering loss was taken to be one-half of a velocity head based on the inlet velocity, the spider losses were taken as one velocity head based on the average velocity and the exit-expansion loss was taken as one velocity head based on the exit velocity. Figure A.7 gives a temperature-correction factor to be applied to Fig. A.6. The correction factor is necessary to compensate for the change in average and exit density as the exit temperature changes.

Figure A.8 is a plot of the thermal efficiency as a function of mixed-mean-exit temperature. Figure 6.6 shows the effect of mixed-mean temperature on the net electrical output and the required blower horsepower.

In determining the cost of power generated as a function of output, the cost figures were broken down into fixed costs, those costs which increase as the gross electrical output is increased. Thus, the total capital cost of

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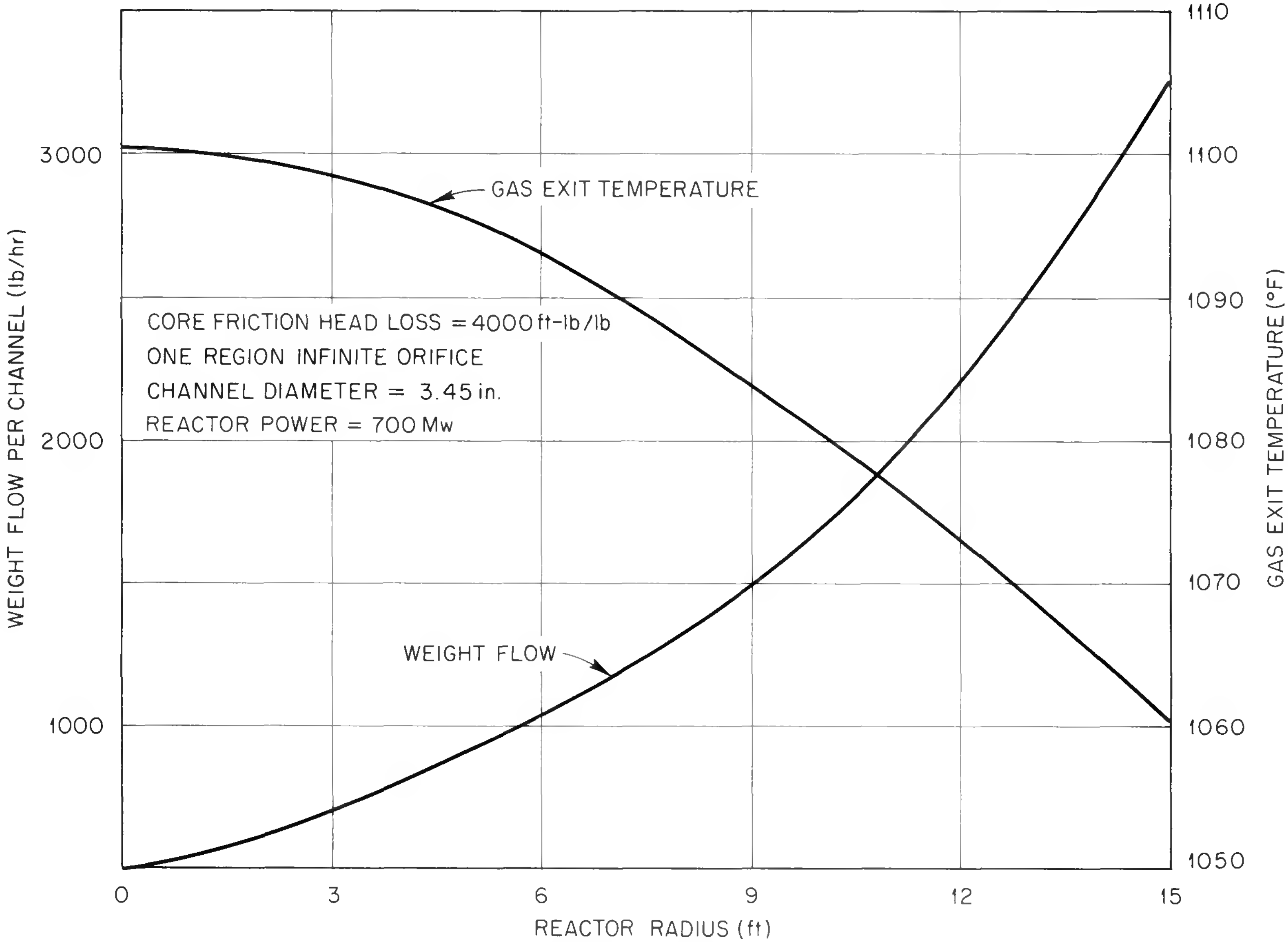

Fig. A.3. Effect of Radial Power Distribution on Exit Channel Temperature and Weight Flow per Channel for Core-Friction-Head Loss = 4000 ft lb/lb – One Region – Infinite Orifice, Graphite Channel Diameter = 345 in. and Reactor Power = 700 Mw (T).

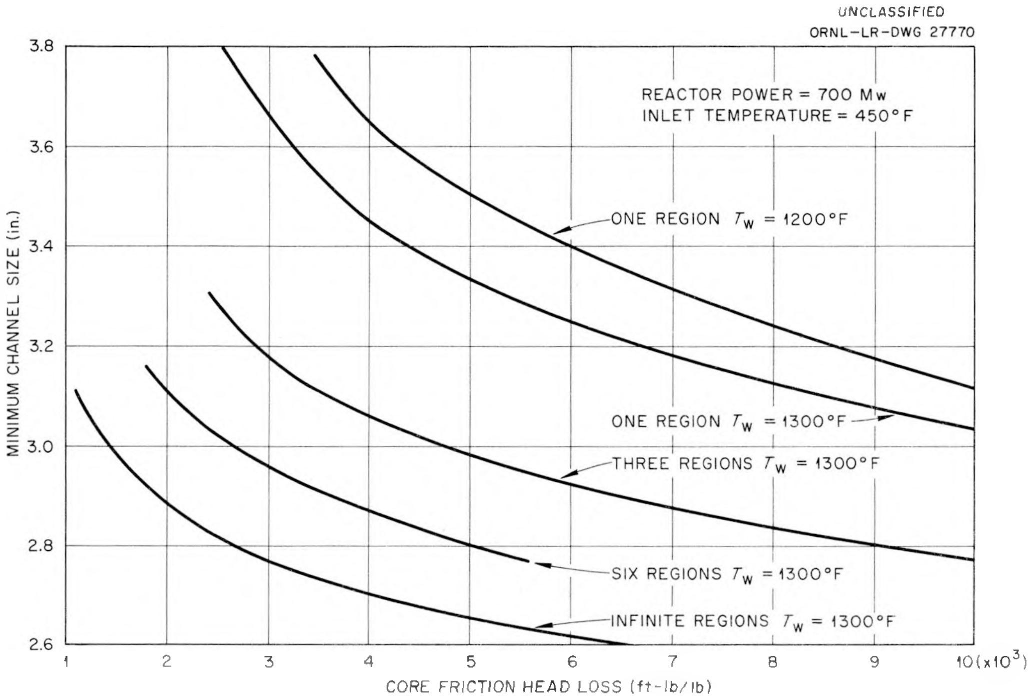

Fig. A.4. Minimum Channel Size vs Core-Friction-Head Loss for Reactor Power = 700 Mw (T) and Inlet Temperature = 450°F.

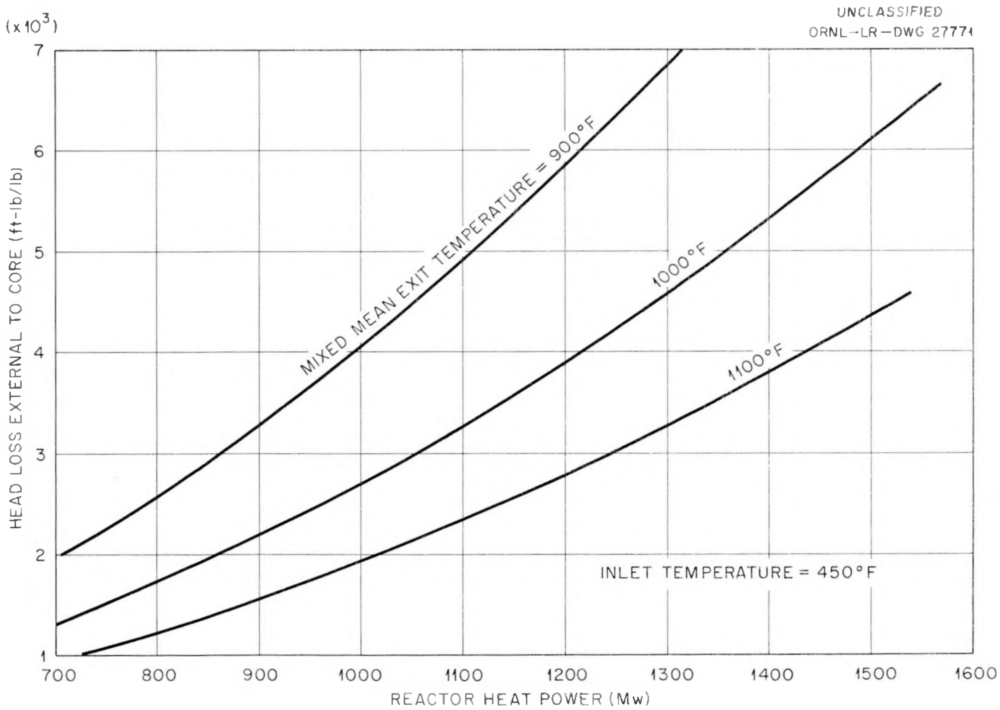

Fig. A.5. Head Loss External to Core vs Reactor Power.

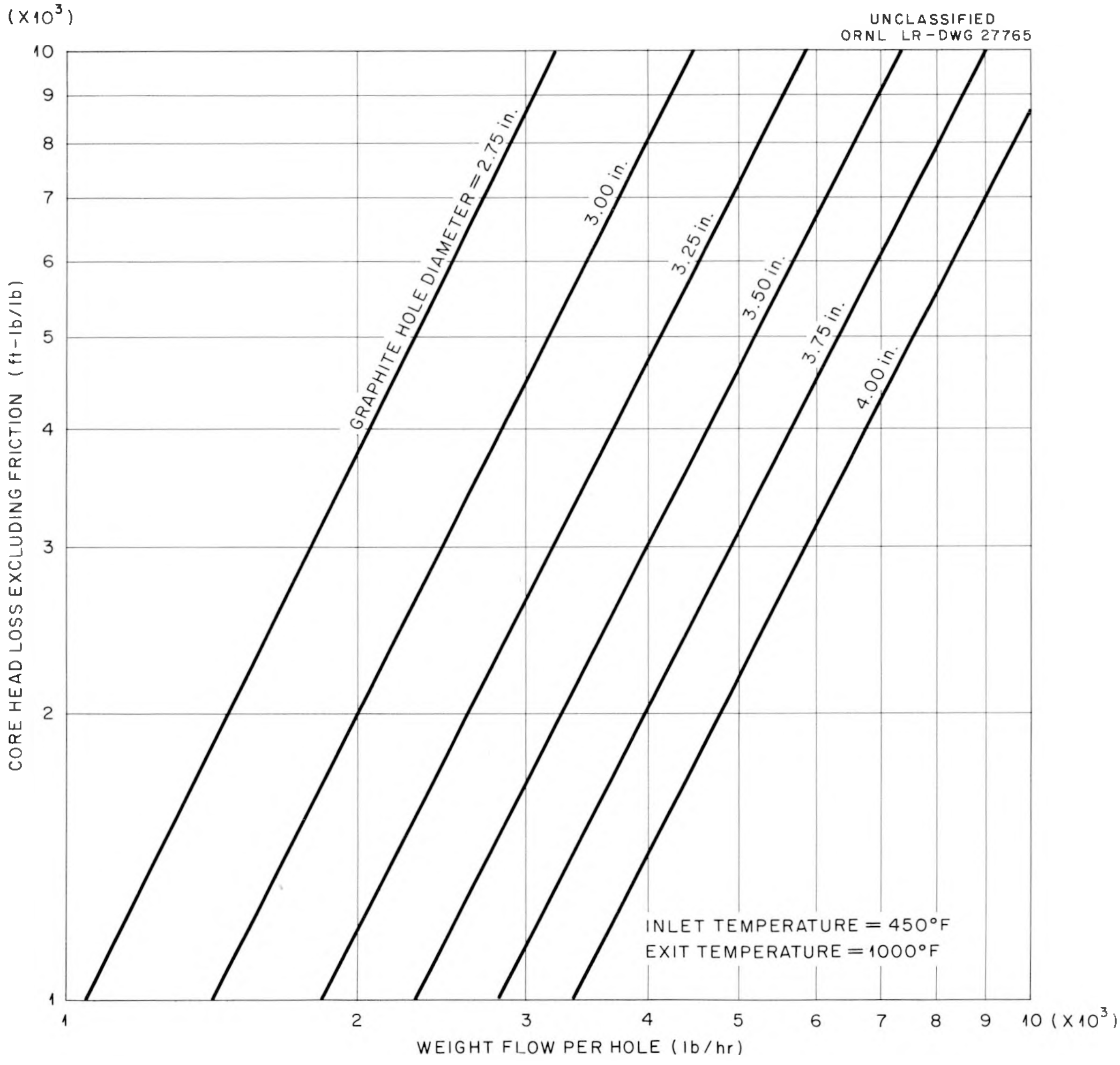

Fig. A.6. Core Head Loss Excluding Friction vs Weight Flow per Channel.

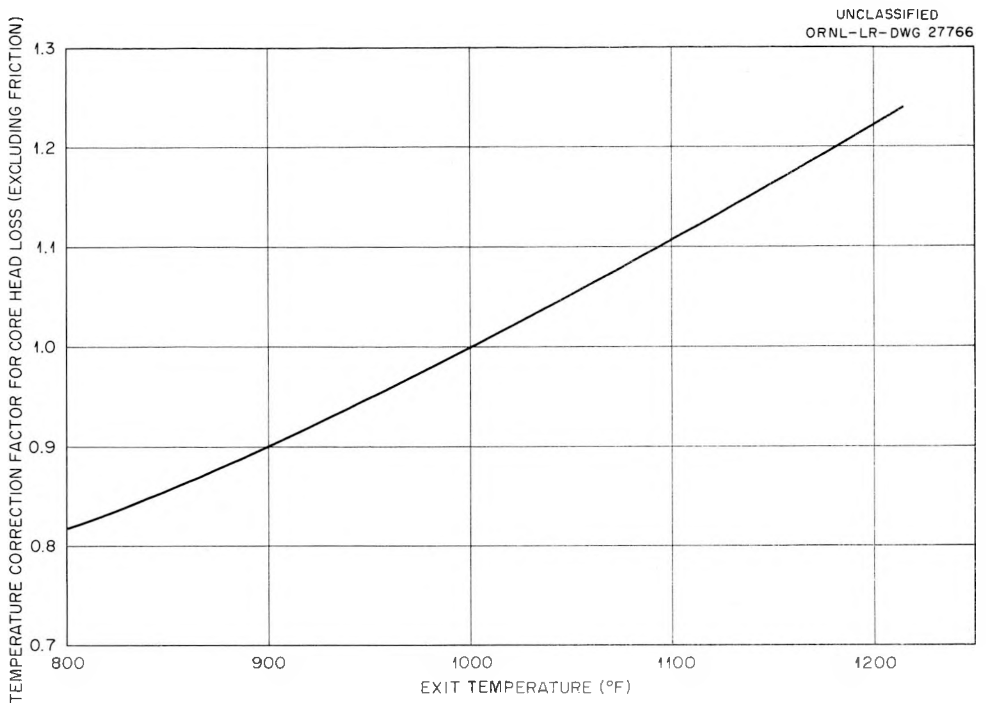

Fig. A.7. Temperature Correction for Core Head Loss Excluding Friction vs Exit Temperature.

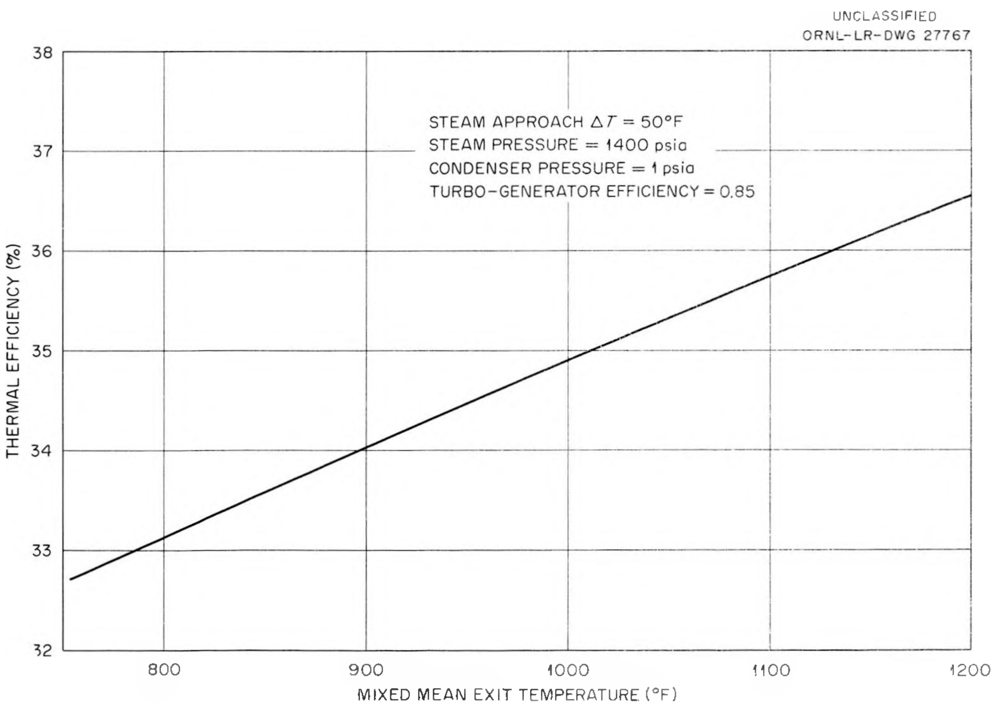

Fig. A.8. Thermal Efficiency vs Mixed-Mean-Exit Temperature.

\$63,800,000 was split up with \$33,000,000 variable cost and \$30,800,000 fixed cost. The fuel costs used for estimation purposes in this section are set at 2.1 mills/kwh variable and 1.3 mills/kwh fixed. The operating cost was assumed to be independent of total output. The cost equations are as shown below.

$$\text{Capital Cost} = \left\{ \left[\frac{33,000,000}{365 \times 24 \times 0.85} (0.14 + 0.06 \times 1.5 \times 0.14) \right] \frac{P_{Gross}}{231} + \left[\frac{30,800,000}{365 \times 24 \times 0.85} (0.14 + 0.06 \times 1.5 \times 0.14) \right] \right\} \frac{1}{P_{Net}}$$

$$\text{Fuel Cost} = \left(2.1 \times \frac{P_{Gross}}{231} + 1.3\right) \frac{210}{P_{Net}} \text{ mills/kwh}$$

$$\text{Operating} = 1 \times \frac{210}{P_{Net}} \text{ mills/kw-hr.}$$

In the above equations the base figures used are for 210 Mw net and 231 Mw gross electrical output.

In all of the following calculations, the mixed-mean-exit temperature is fixed at 1000°F and the flow metering is assumed to be done by the one region separate orifice method. The steam conditions are set at 950°F and 1400 psia inlet with expansion to 1 psia. The turbine-generator efficiency is assumed to be 85% and the blower efficiency 75%. In one case the peak to average-radial power was changed from 1.5 to 1.3. The flux profile was assumed to be as shown in Fig. A.9. The power required to drive the auxiliaries was assumed to be 6 Mw for a reactor-heat rate of 700 Mw and to increase in proportion to the heat rate.

The core-friction-head loss at the higher output rates is shown in Fig. A.10. Figure A.11 shows the net electrical output as a function of reactor-heat output and Fig. 6.5 gives the corresponding power cost.

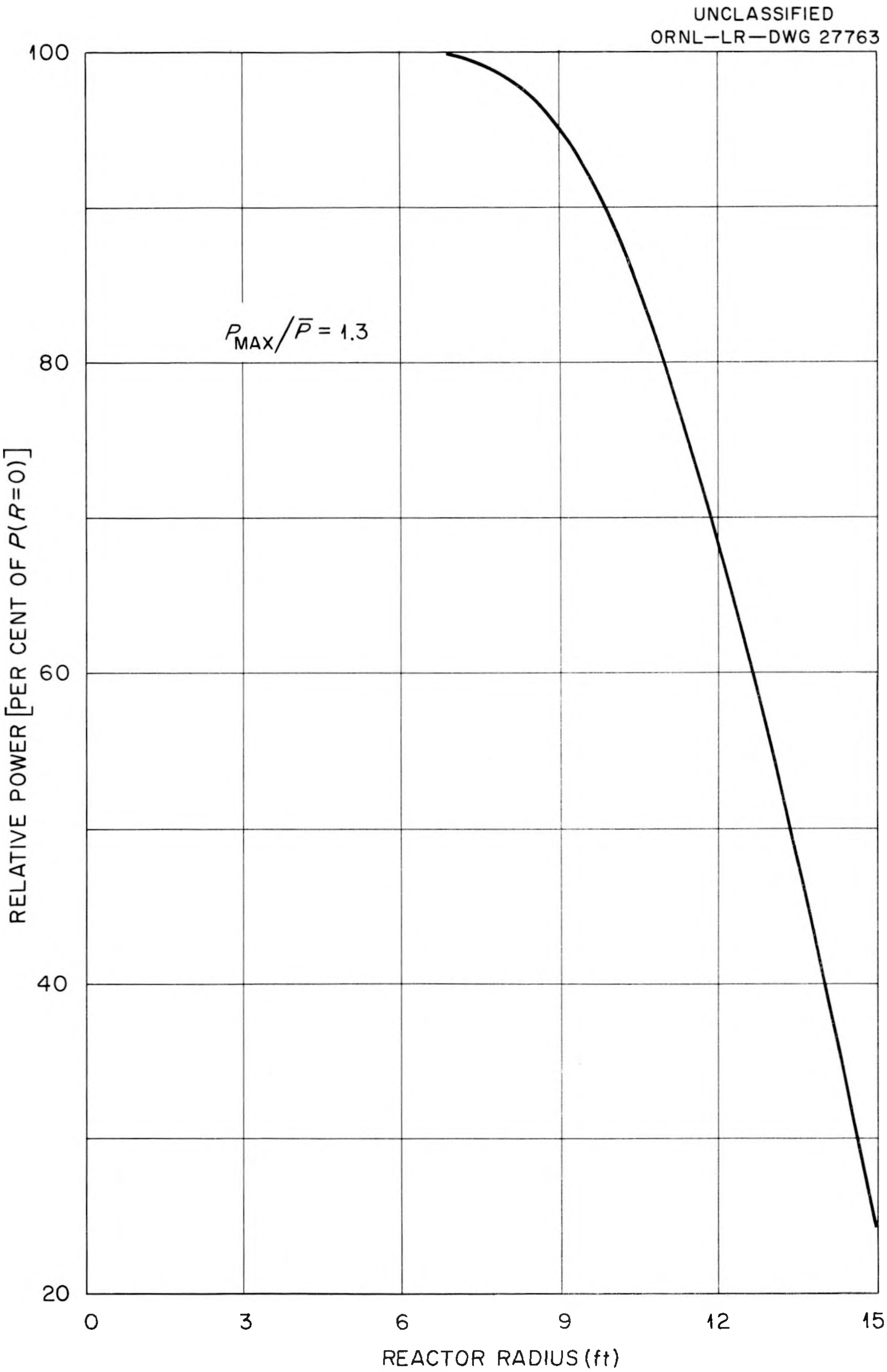

Fig. A.9. Reactor Radial Power Distribution for $P_{max}/\bar{P} = 1.3$.

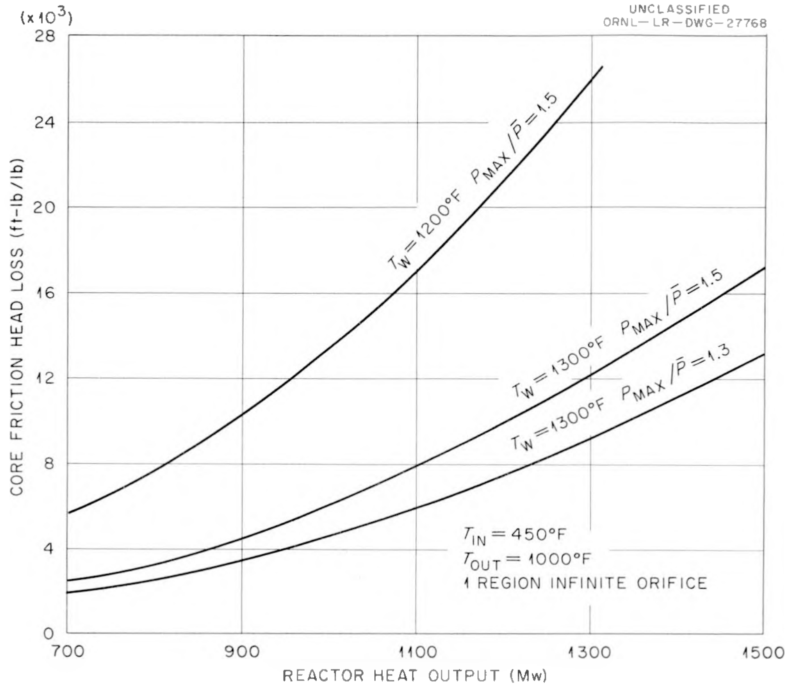

Fig. A.10. Core-Friction-Head Loss vs Reactor Heat Output.

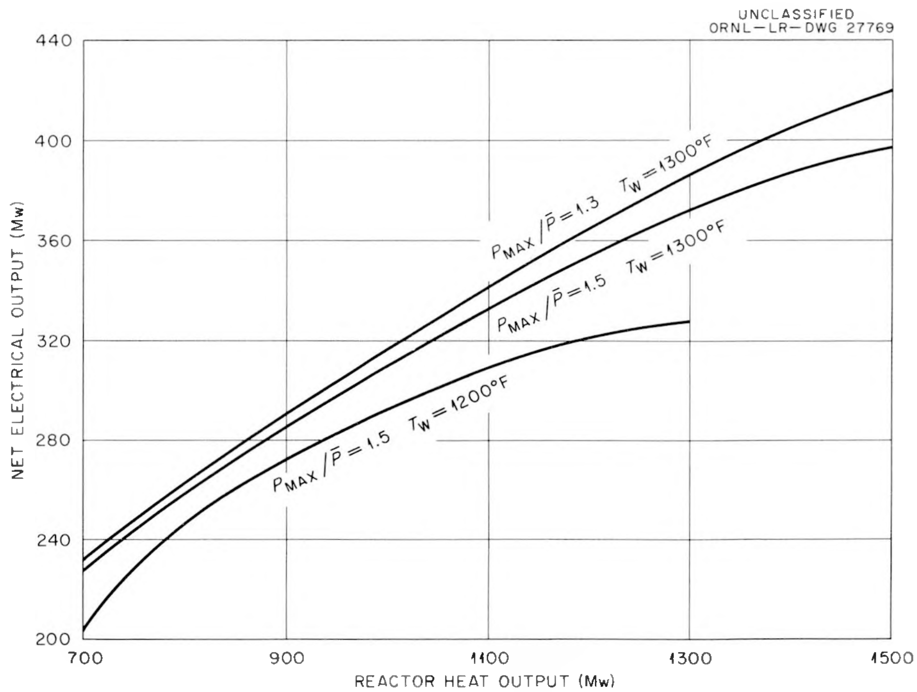

Fig. A.11. Net Electrical Output vs Reactor Heat Output.

APPENDIX B

REACTOR SUPPORT AND CHARGING MACHINE

APPENDIX B

REACTOR SUPPORT AND CHARGING MACHINE

The figures contained in this appendix summarize the results of detailed studies for the reactor platform and the fuel charging and discharging equipment. These drawings were developed only in sufficient detail to indicate the feasibility of design. A discussion of the design features is given in Section 5.

Figure B-1 is a plan view of the truss configuration which supports the "I" beam support grid. Figure B-2 shows a plan view of the "I" beam support grid for the floor plate. Figures B-3 through B-7 show side elevations of the five detailed truss configurations for the reactor platform. Figures B-8 and B-9 show a design for the fuel charging chute and Fig. B-10 shows the general features of the fuel charging and discharging machine.

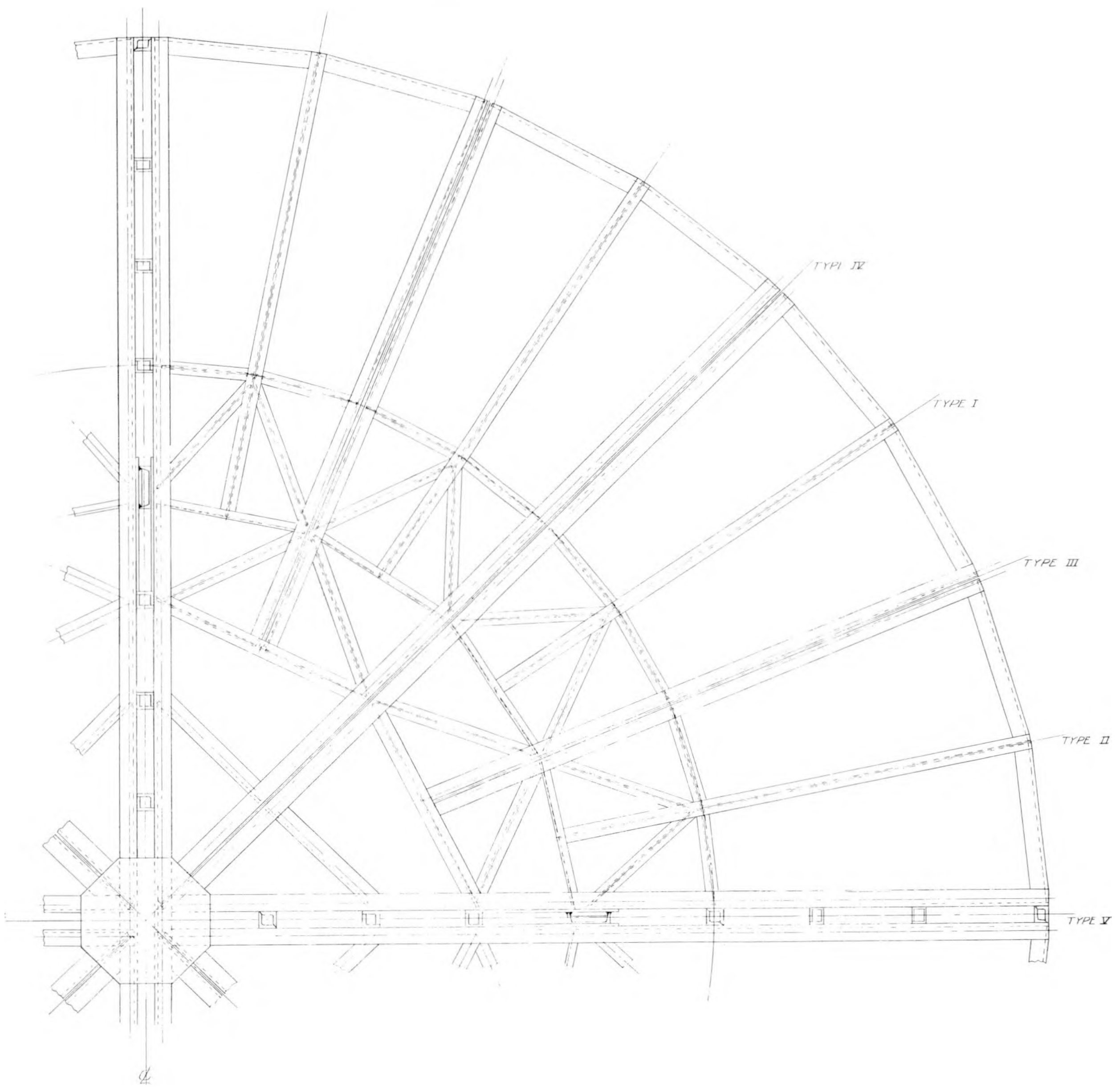

Fig. B.1. Quadrant Plan View of the Truss Configuration for the Reactor Support Platform.

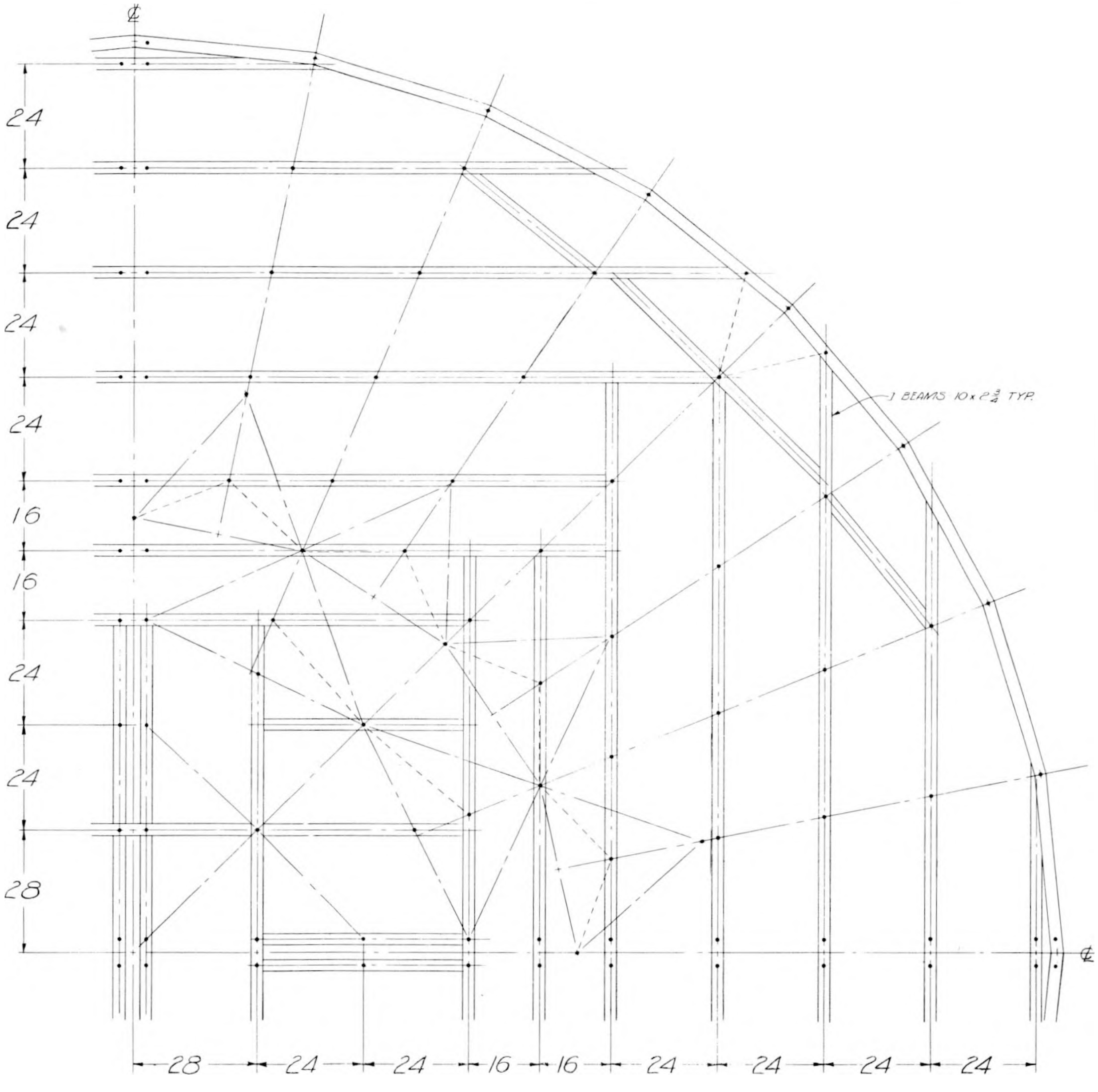

Fig. B.2. "I" Beam Support Grid for the Floor Plate.

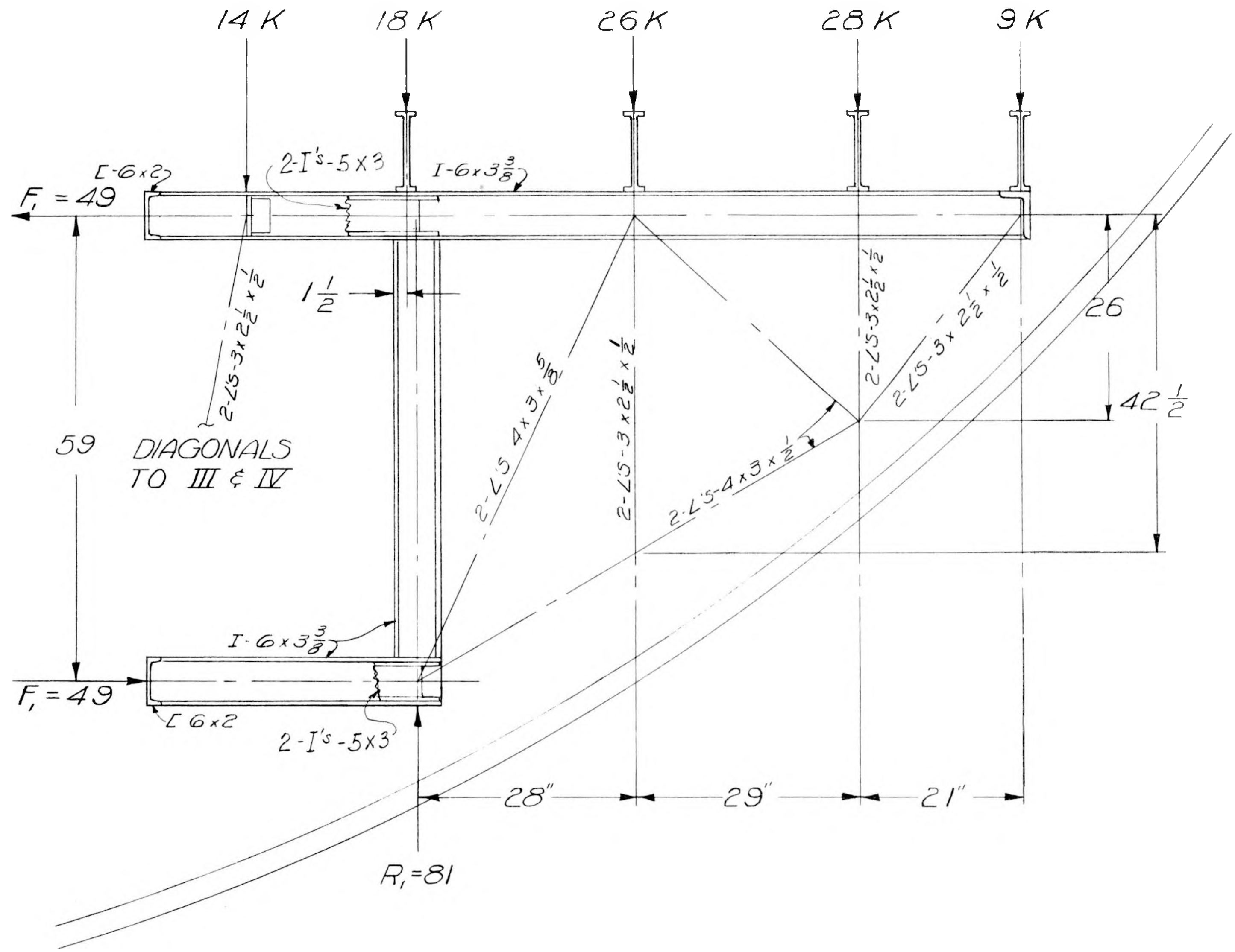

Fig. B.3. Truss Configuration, Type I.

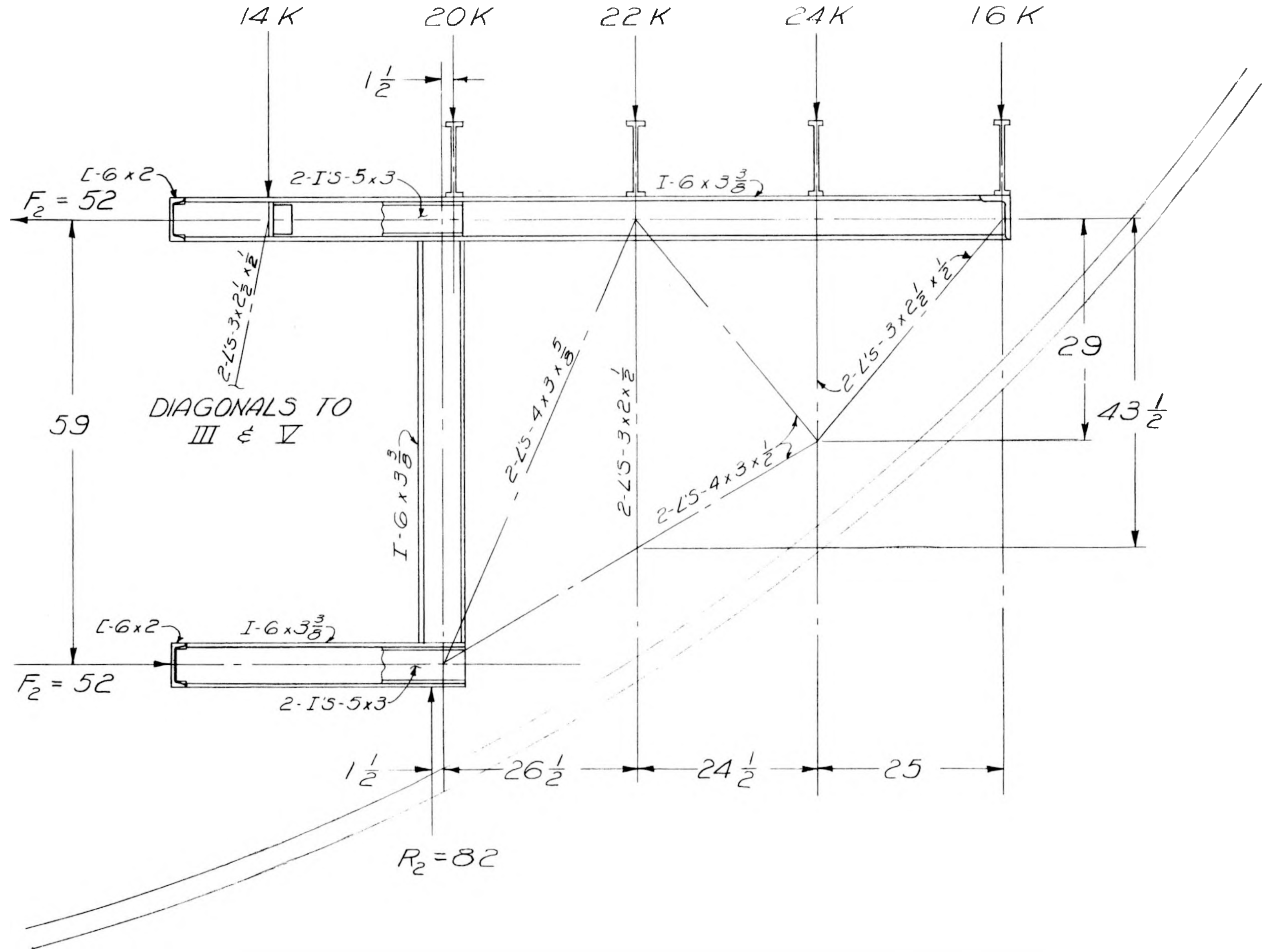

Fig. B.4. Truss Configuration, Type II.

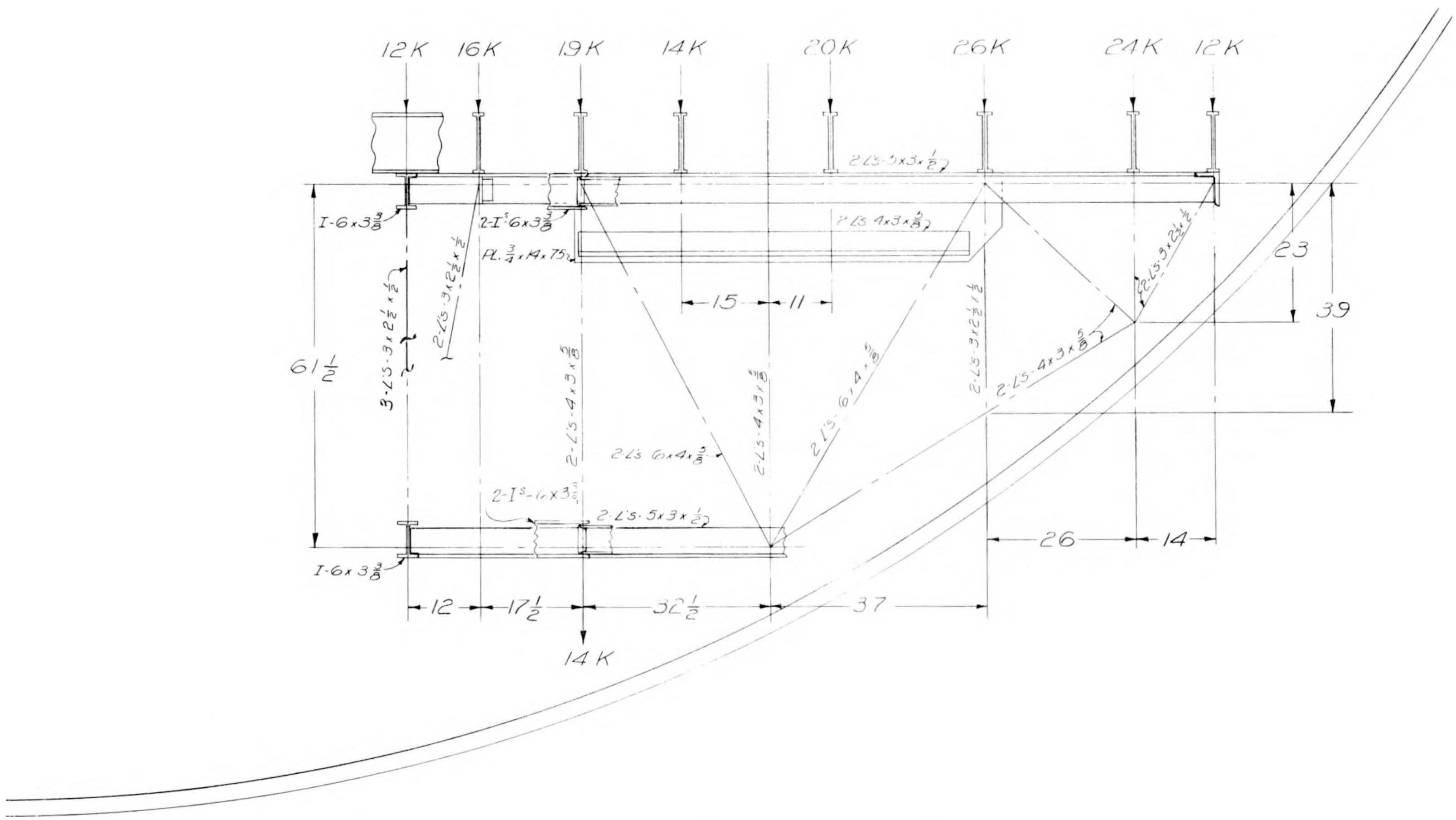

Fig. B.5. Truss Configuration, Type III.

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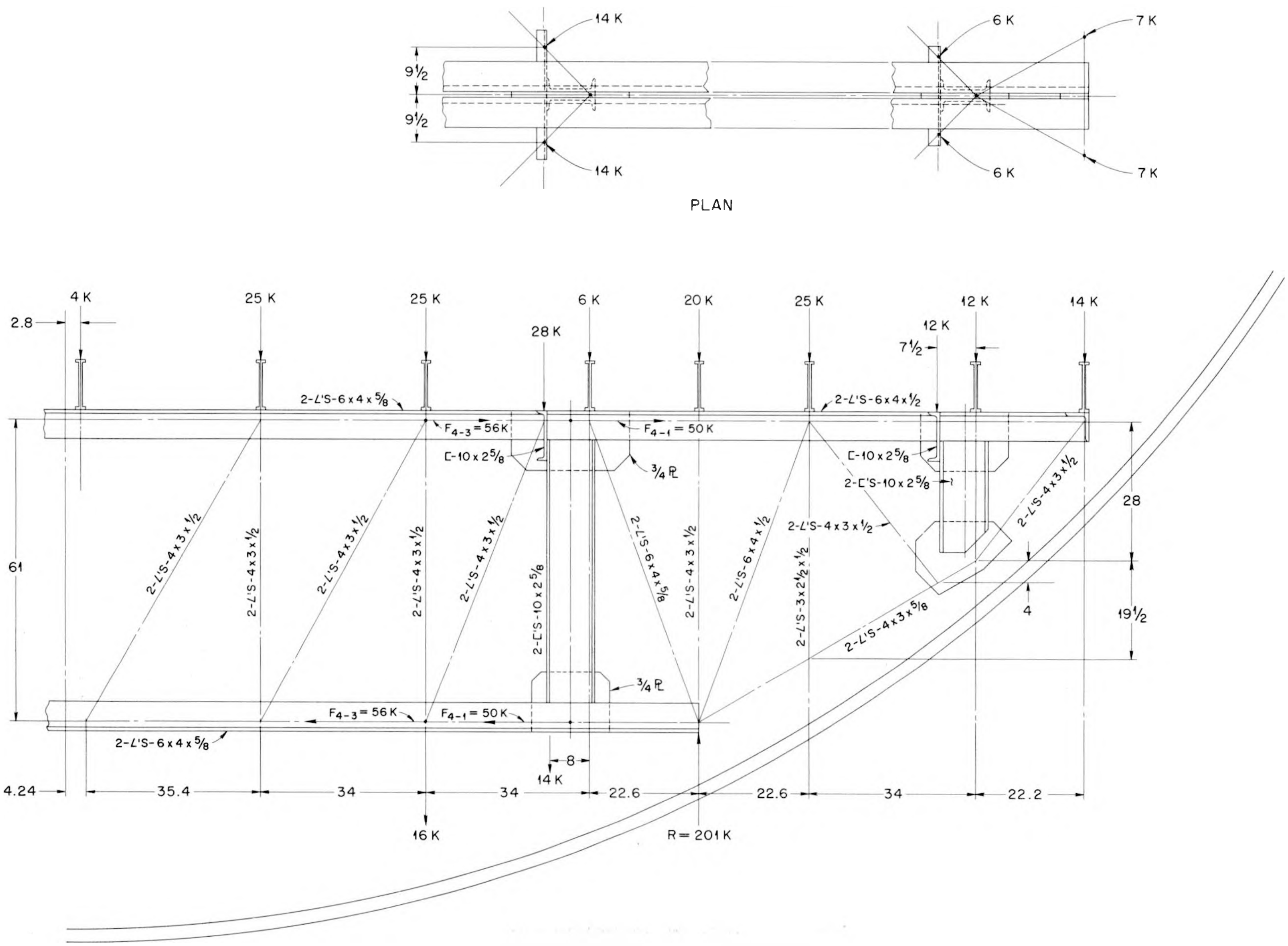


Fig. B.6. Truss Configuration, Type IV.

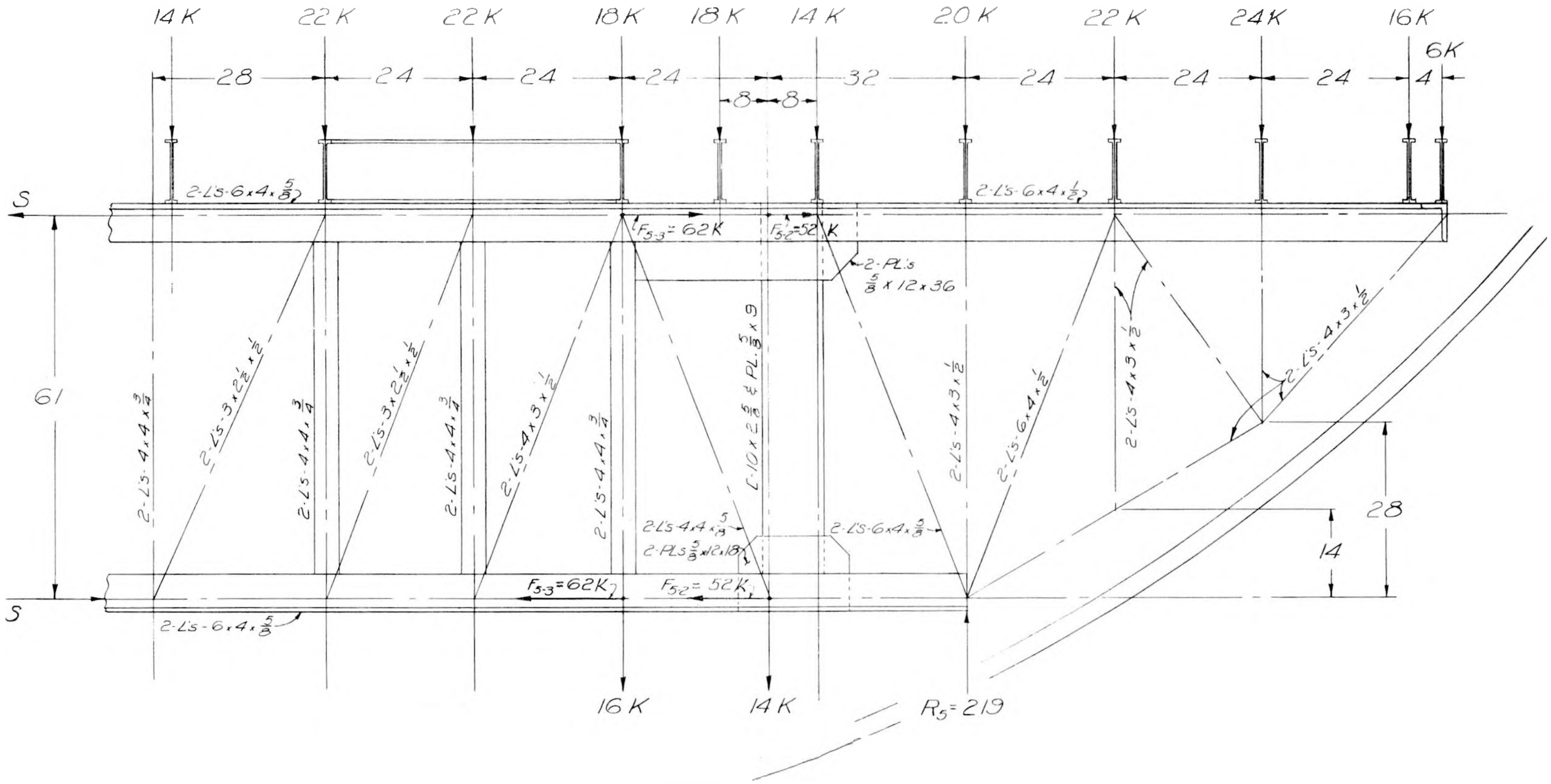


Fig. B.7. Truss Configuration, Type V.

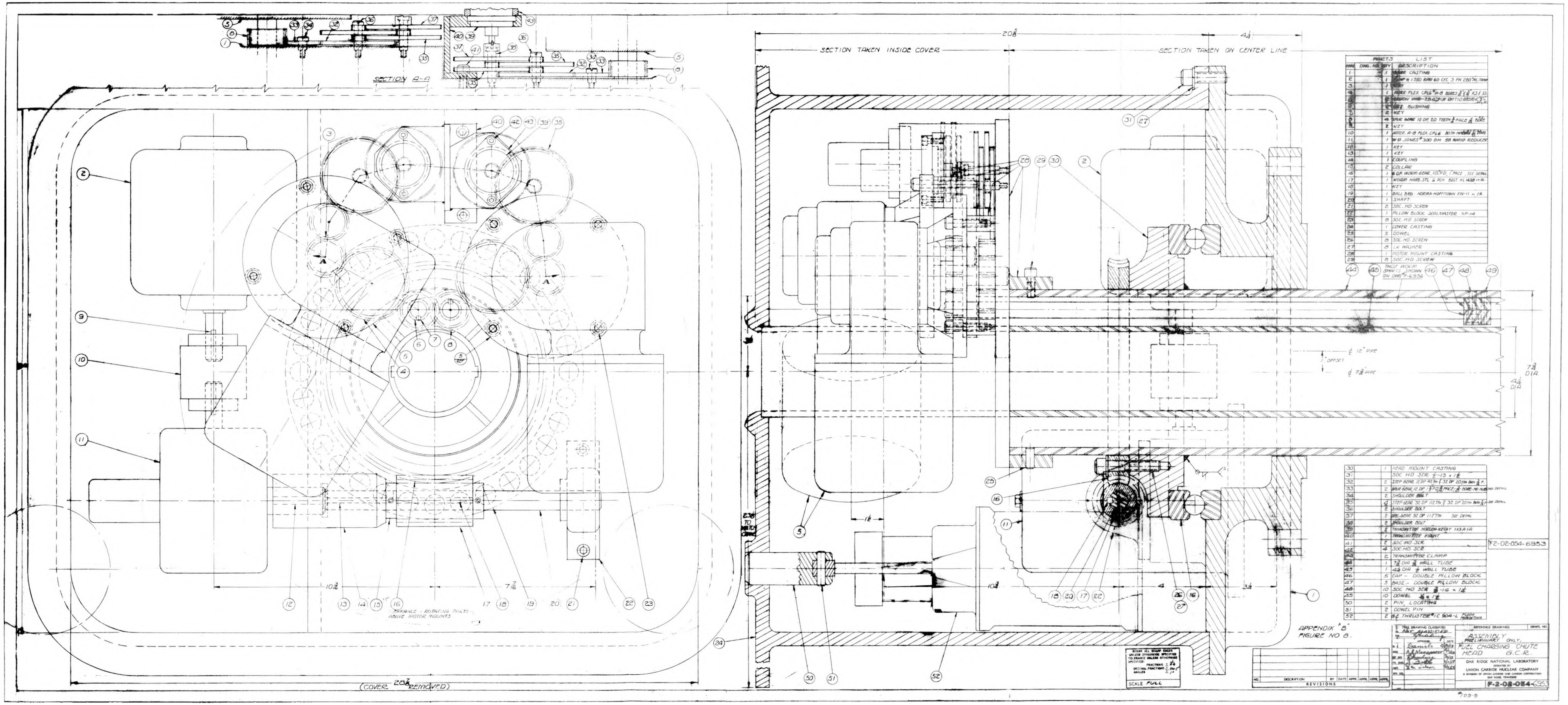


Fig. B.8. Fuel Charging Chute Head.

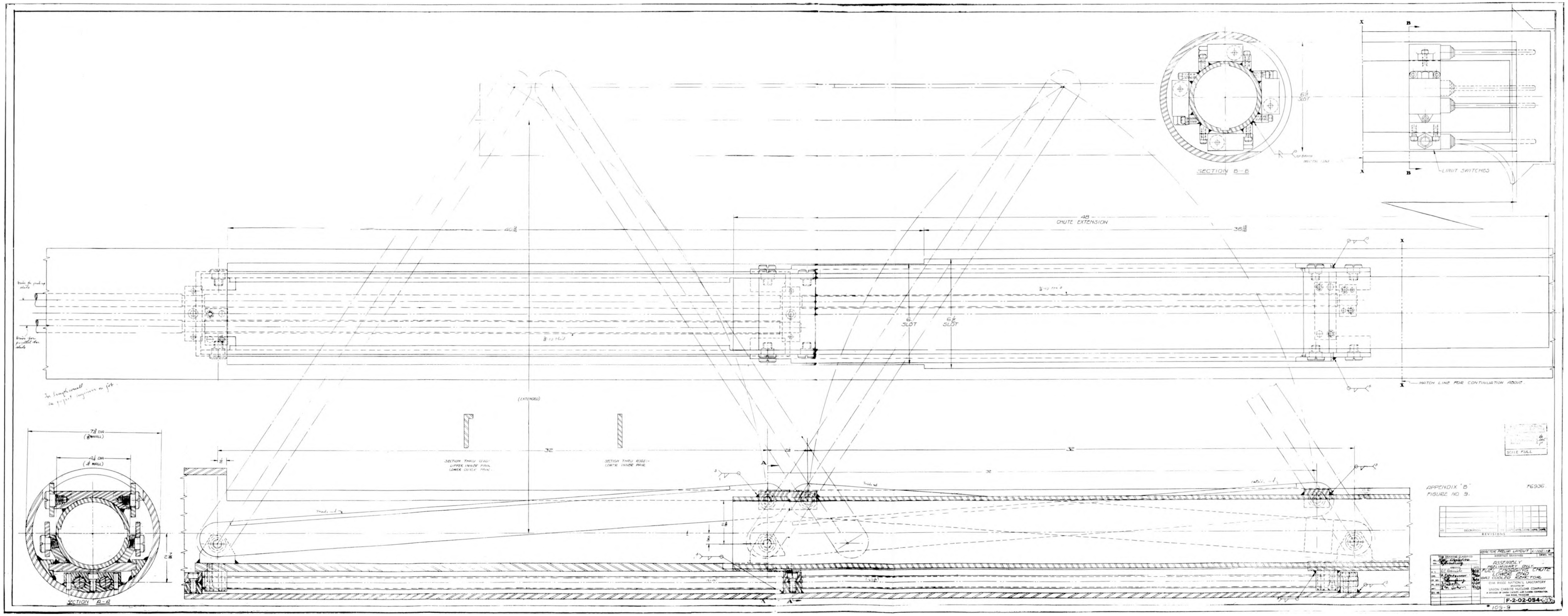


Fig. B.9. Fuel Charging Chute Bottom.

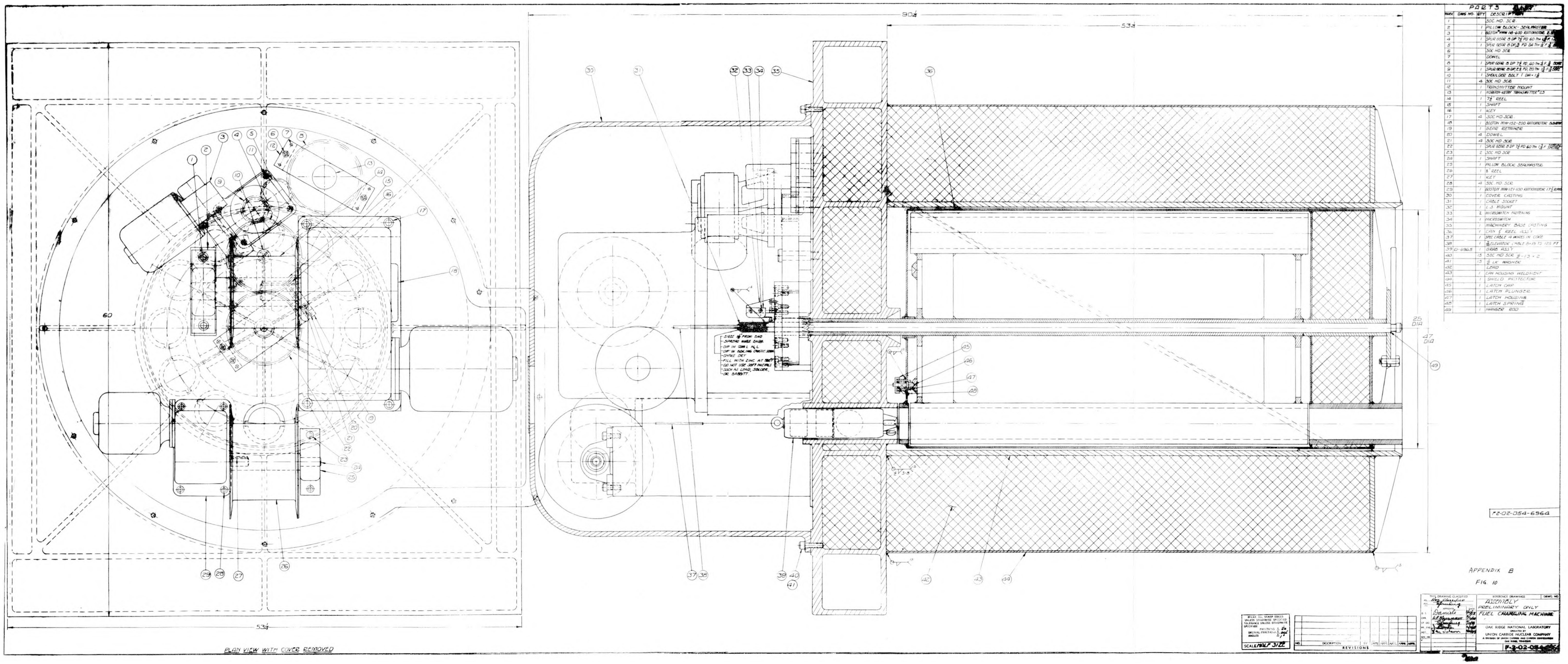


Fig. B.10. Fuel Charging Machine.

APPENDIX C

FUEL ELEMENT COST DATA

APPENDIX C

FUEL ELEMENT COST DATA

The Y-12 Plant of Union Carbide Nuclear Company was asked to prepare a cost estimate on the preparation of UO_2 from UF_6, the production of UO_2 slugs, and the canning of UO_2 slugs to make fuel element assemblies. They were also asked to prepare a cost estimate on the machining of graphite for the reactor moderator and reflector sections. Their report is given in its complete form in this section.

Industrial concerns were asked to submit bids on the fabrication of the fuel elements in order to arrive at a realistic cost estimate. The reactor parameters and the fuel element requirements, shown in Tables C.1 and C.2, were given to them as a basis for their cost estimates. Costs were later adjusted by ORNL on the basis of the new parameters shown in Table C.3.

In examining the bids received from industry, it was found that the average estimated cost of fabricating fuel elements is approximately $30.00 per kg/$UO_2$. All the bids from industry are given in Table C.4.A – P. It can be seen that the cost of fabricating the fuel elements varies from $15.19 – $78.93 kg/$UO_2$. Also some companies bid only on the hangers and bottom supports, whereas, others bid on the entire fabrication job.

ESTIMATED COSTS FOR FABRICATING COMPONENTS OF THE PROPOSED ORNL GAS-COOLED REACTOR

Jointly Prepared by the Following Y-12 Groups:
Chemical Division
Development Division
General Engineering Division
Mechanical Inspection Department
Mechanical Operations Division

SUMMARY

Costs have been estimated for the Y-12 fabrication of components of the proposed gas-cooled reactor. If a comparison or evaluation of these costs is to be made, two important factors must be recognized: (1) The estimates presented herein should be considered as preliminary, because of the early status of design information; (2) the costs do not necessarily represent "out of pocket" costs to the Y-12 Plant or the AEC, as a certain amount of fixed costs are included which would be absorbed in other accounts if the work were not done at Y-12.

A summary of the estimates is given in Table I, and a brief discussion of each of the items follows:

UO_2 Reactor Fuel

The Y-12 Plant has had considerable experience in the production of various types of UO_2 powder at different levels of U-235 enrichment. Recently the ORNL Ceramics Laboratory successfully fabricated Y-12 UO_2 powder into small dense bushings, using an original technique which is a substantial simplification of conventional fabrication methods. The UO_2 cost in Table I includes fabricating bushings by this method and loading the shapes into fuel tubes.

Fuel Rods

The estimated cost of welding fuel rods for the GCR is necessarily high for several reasons: (1) The quantity involved (approximately

8,000); (2) the specification that only butt welds can be used, and (3) the thin wall (0.020 in.) tubing used. Also a factor is the necessity for making the final weld in a helium atmosphere in a dry box.

Hardware

Each cluster of seven fuel rods in the GCR will be suspended from a 304 stainless steel hanger and isolated from each other at the bottom with a wire spacer. Hardware costs in Table I include the cost of fabricating end caps for the fuel rods, brazing pins to the end caps, and fabricating the hangers and spacers.

Graphite

Costs have been established for purchasing and machining graphite components of the reactor based upon a conceptual design of the core.

Inspection

Past Y-12 inspection experience with tubing and hardware for other reactors was used as a basis for estimating inspection costs.

TABLE I

SUMMARY OF Y-12 ESTIMATED COSTS FOR THE GCR

Item	Units	Unit* Cost ($/unit)	Total* Cost ($)
UO_2 Bushings	Kg UO_2	15.31**	2,004,000**
MGO	Pieces	0.05	6,000
Hardware	-	-	173,000
Welding of Fuel Rods	Fuel Rods	2.63	152,000
Inspection	-	-	695,000
Packaging of Fuel Rods		0.23	13,000
Packaging of Hardware	-	-	1,000
Sub-Total			3,044,000
Seamless Tubing	Feet	1.34△	295,000△
Weldrawn Tubing	Feet	0.95△	208,000△
Sub-Total			
With Seamless Tubing			3,339,000
With Weldrawn Tubing			3,252,000
Cost Contingency at 10%			
With Seamless Tubing			334,000
With Weldrawn Tubing			325,000
Total			
With Seamless Tubing	Fuel Clusters	445	3,673,000
With Weldrawn Tubing	Fuel Clusters	433	3,577,000
Cost of Graphite	Tons	1,230	2,179,000△△
Machining of Graphite	Tons	254	450,000
Packaging of Graphite	Tons	8	15,000
Sub-Total Graphite Cost			2,644,000
Cost Contingency at 10%		149	264,000
Total Graphite Cost	Tons	1,641	2,908,000

* Not including transportation, assembly of fuel clusters or installation in reactor. All units costs except graphite costs are based on net fabrication (= reactor requirements + 10%).

** Including the cost of losses in chemical processing and the cost of loading fuel tubes. See note to Table II for explanation on equipment costs.

△ Including initial tubing cost and trimming costs.

△△ Based on 1540 tons + 231 tons (15%) contingency.

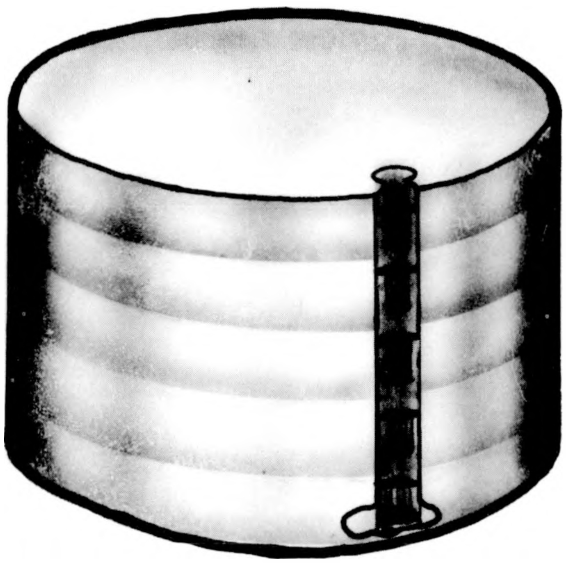
GENERAL DESCRIPTION OF THE REACTOR CORE

The proposed gas-cooled reactor (GCR) will have a graphite core cylindrical in shape, 35-feet in diameter by 24-feet high. These over-all dimensions include a 2-1/2-foot thick graphite reflector around the sides and at the bottom, and a 1-1/2-foot thick graphite shield at the top.

Fuel assemblies will be placed in 1,500 vertical holes 3-1/4 ± 1/4 inches in diameter, extending from the top to the bottom of the graphite. Control rods will be used in 100 holes 1-1/2 inches in diameter, also extending the entire length of the core.

An illustration of the core is given in Figure I. A typical fuel assembly will be positioned in the core as shown in Figure 2.

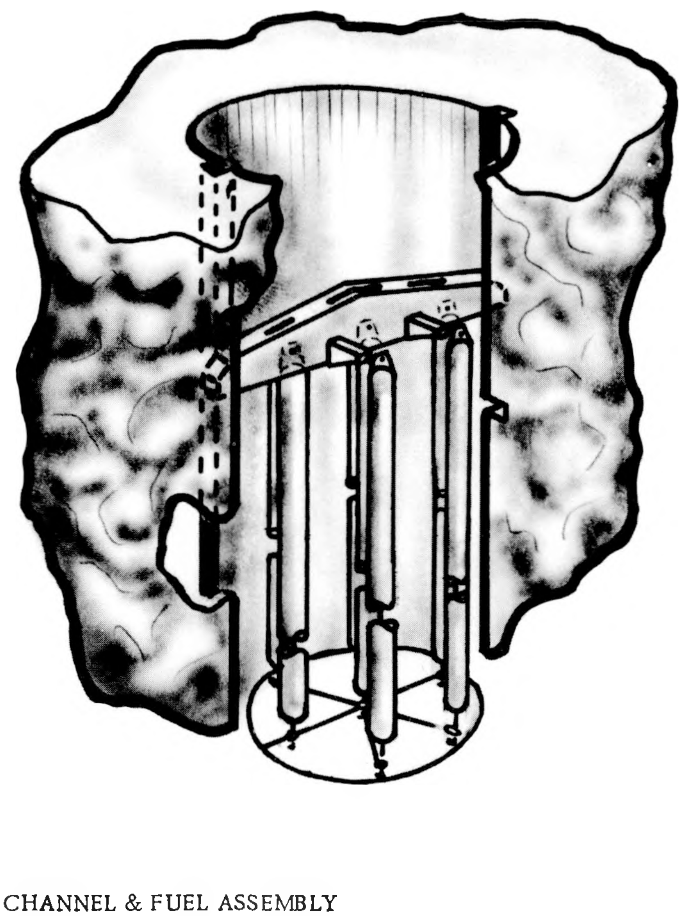
Five fuel assemblies (clusters) will be placed in each of the 1,500 fuel channels. A typical fuel assembly, illustrated in Figure 3, will consist of seven 304 SS fuel rods containing UO_2, a hanger and a bottom spacer, also fabricated from 304 SS. In addition to the UO_2, the fuel rods will contain a magnesium oxide shape in each end cap. Some details of a fuel rod and the UO_2 and MgO shapes are shown in Figure 4.



Reactor Core (Graphite) Showing Typical Channel with Fuel Assemblies.

There are 1500 channels in core. Each channel contains 5 fuel assemblies. Diameter of reactor core will probably be 35 ft., including a $2\frac{1}{2}$ ft. thick graphite reflector. Height will be about 24 ft. Channels will be spaced on an 8 in. pitch if 2% enriched UO_2 is used as fuel.

FIGURE 1. REACTOR CORE



Typical Channel and Fuel Assembly

A special device will load fuel assemblies in channel by lowering to the proper level and rotating approximately 10° in horizontal grooves. Vertical grooves in graphite shown (on right), serve as guides for the ends of the fuel rod hanger.

FIGURE 2. TYPICAL CHANNEL & FUEL ASSEMBLY

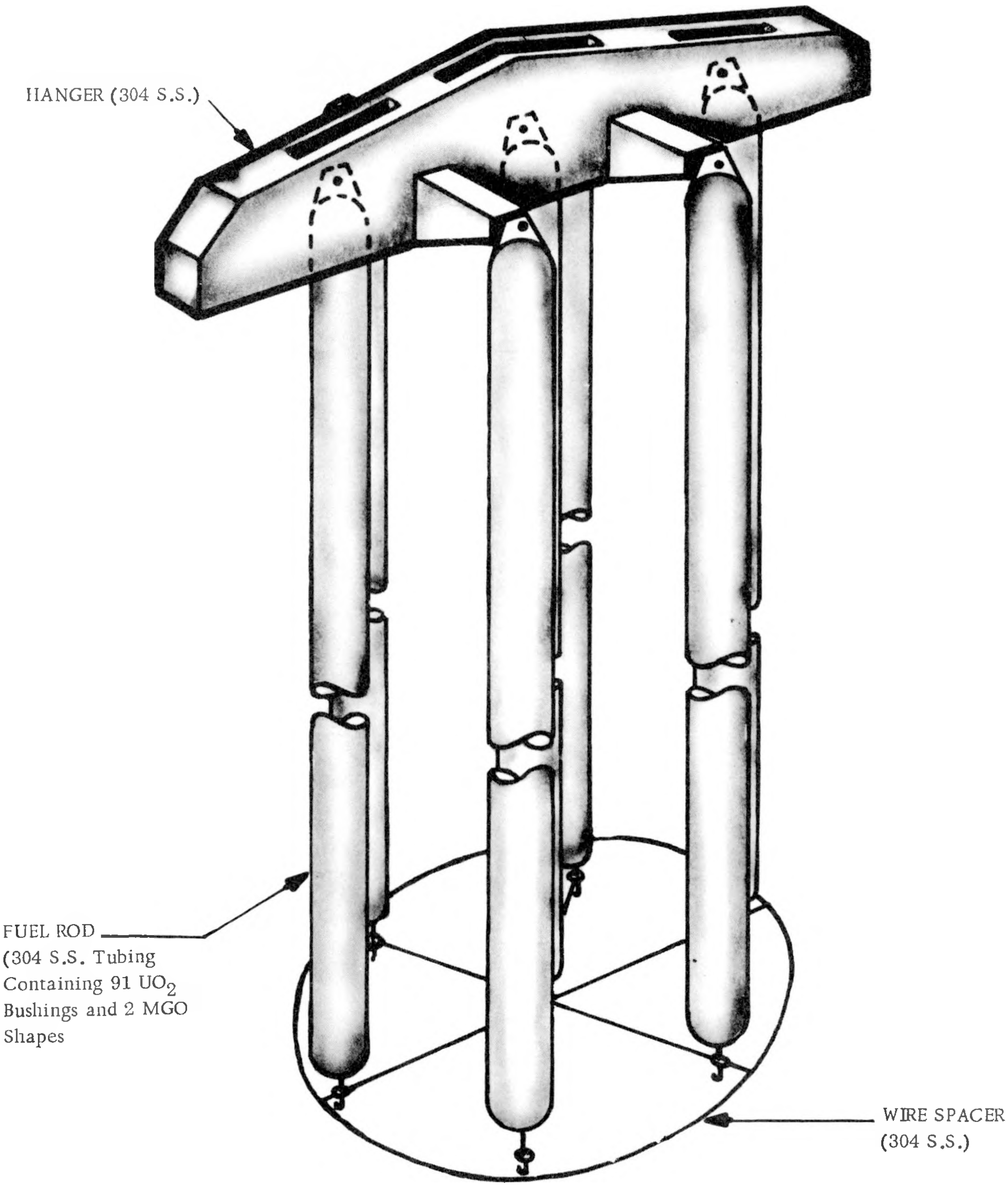
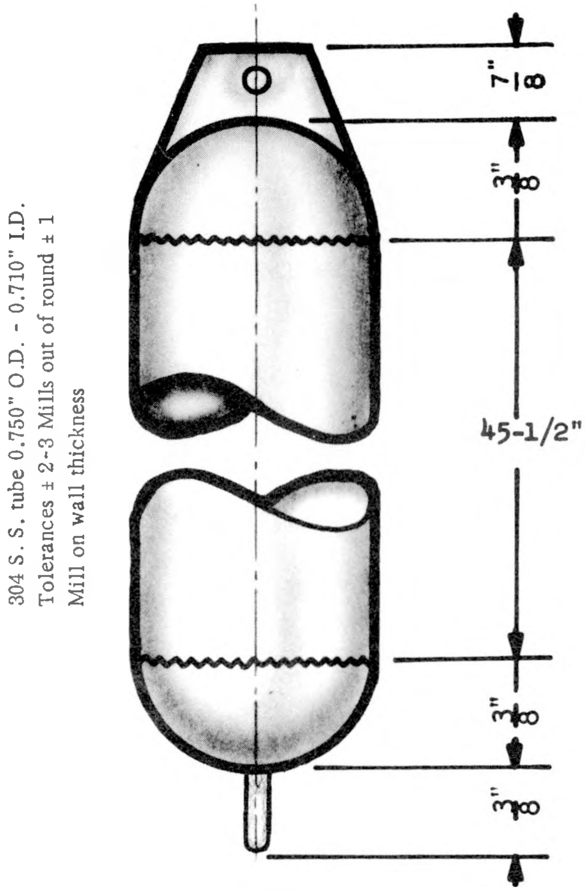
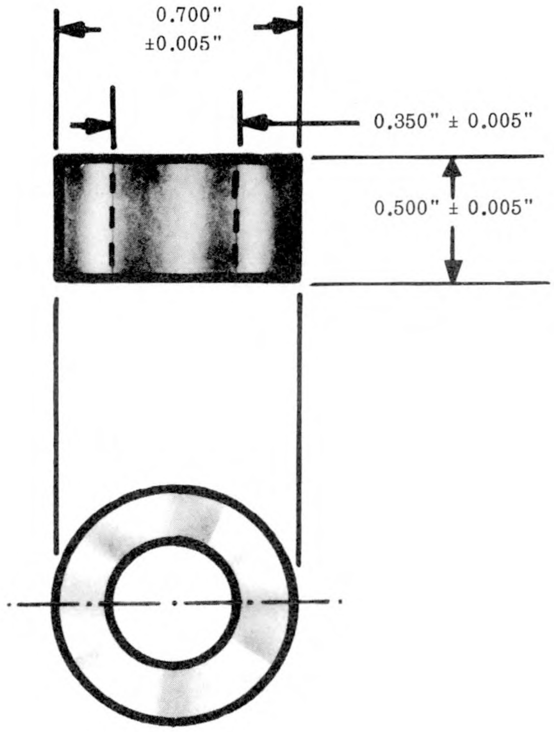


FIGURE 3. TYPICAL FUEL ASSEMBLY FOR PROPOSED ORNL GAS COOLED REACTOR



FUEL TUBE

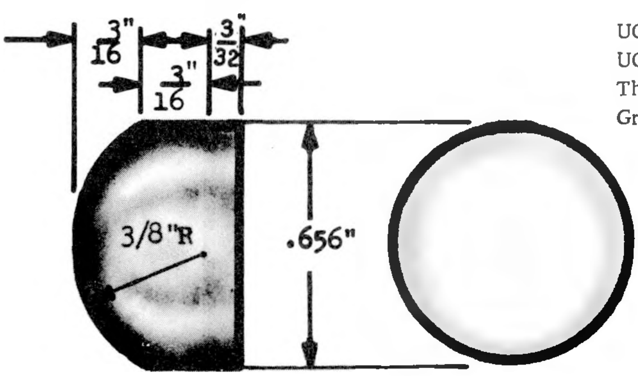
7 Tubes/1 Assembly



UO_2 FUEL ELEMENT

91 Required/Fuel Tube

UO_2 Enriched to 2% U-235 in U.
UO_2 Pressed and Sintered to 95% of Theoretical Density ± 1% (10.40 ± 0.11 Grams/CC)



MAGNESIUM OXIDE SHAPE

2 Required/Fuel Tube

FIGURE 4. TYPICAL FUEL ROD DETAILS

Y-12 PRODUCTION AND FABRICATION OF TWO PERCENT ENRICHED UO_2 REACTOR FUEL

Fuel Requirements for the GCR

Current ORNL plans for the GCR include the use of approximately 131 tons of UO_2 for fuel. The UO_2 will be enriched to about two percent U-235 in U, and will be in the form of bushings, 0.700" O.D. x 0.350" I.D. x 0.500" high, with a density 95% ± 1% that of the theoretical density of UO_2 (10.95 grams/cc). Close dimensional tolerances on the UO_2 bushings are required in order to achieve maximum utilization of the heat released in fission, and still retain enough clearance so that the UO_2 slugs can be loaded in the fuel tubes.

UO_2 Production and Fabrication Process

UF_6 is continuously dissolved in deionized water. Ammonium diuranate (ADU) is precipitated from the solution by the addition of aqueous ammonia. The precipitate is filtered and redissolved in nitric acid. An extremely fine ADU is then precipitated and filtered from solution. The ADU cake is dried, calcined to U_3O_8, and reduced to UO_2 in a hydrogen atmosphere at 850°C. The resulting UO_2 powder is prepressed, milled to -35 mesh, pressed, and sintered in nitrogen at approximately 1800°C. Figure 5 illustrates the flow pattern of the UF_6 to UO_2 process.

The fabrication process described above, starting from the UO_2 powder, was developed by the ORNL Ceramics Laboratory, and is simple and economical in comparison with some conventional UO_2 fabrication procedures. The sintered UO_2 bushings will meet dimensional and density specifications without being machined.

Proposed Building 9211 Facility for GCR Fuel Production

Part of the existing basic Y-12 UO_2 facility in Building 9211 is applicable to the production of fuel for the GCR. As indicated in Figure 5, existing installed equipment would be used for hex dissolution, and the initial ADU precipitation and filtration.

In order to minimize fluoride contamination of the final product it will be necessary to install equipment for redissolving the ADU cake in nitric acid and for precipitating and filtering ADU from the nitrate solution. ADU cake from the second precipitation would be dried in an endless belt conveyor housed in an electrically heated furnace. Dried cake would then be calcined and reduced in a closed vibrating tray reactor. The conveyor and vibrating tray reactor are available in the Oak Ridge area as surplus equipment.

Fabrication of the UO_2 powder would be accomplished by compacting in a briquetting press available in Y-12, pulverizing the compacts to -35 mesh, and pressing into green forms in a 25 ton 5-cavity automatic press. The green pressings would be inspected before being charged into either of two continuous sintering furnaces. After passing final inspection, finished oxide shapes would be transferred to a tube assembly station for canning.

UO_2 Production and Fabrication Costs

Table II lists estimated costs for producing UO_2 and fabricating dense bushings from the oxide. Also included as a separate item is the interest charge on fuel inventory in the reactor for a 2 or 3 year fuel life. It is noteworthy that the total cost of equipment and alterations for installation of a bushing fabrication facility includes a generous allowance for reserve capacity because of the somewhat unpredictable downtime for maintenance and repairs on this type of equipment.

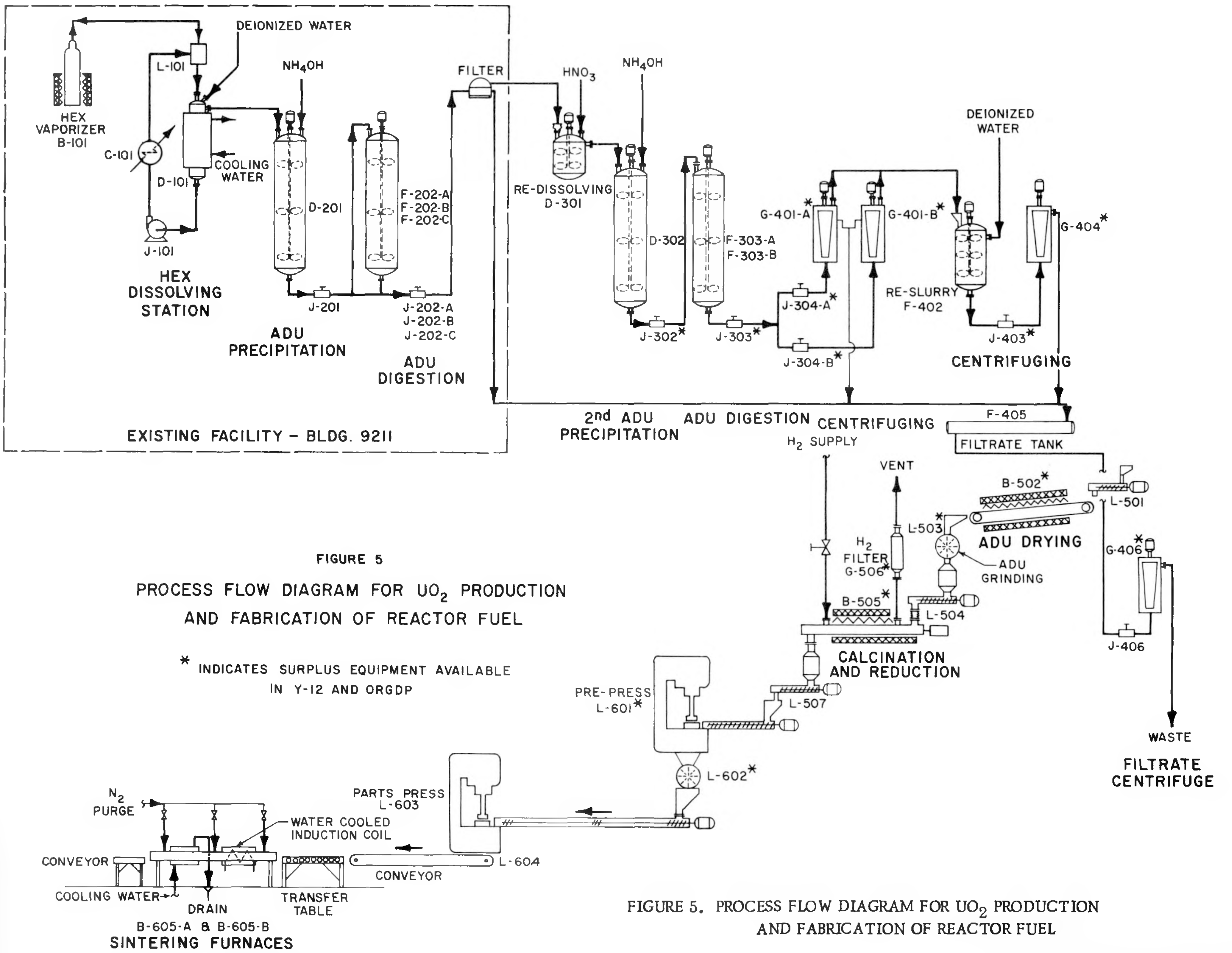


FIGURE 5. PROCESS FLOW DIAGRAM FOR UO_2 PRODUCTION AND FABRICATION OF REACTOR FUEL

TABLE II

FUEL COST FOR INITIAL LOADING OF THE GCR

Item	Unit Cost ($kg UO_2)	Total Cost ($)
UF_6 to UO_2 Powder	8.23△	1,077,000△
Fabrication of UO_2 Bushings	5.71△	748,000△
Total UO_2 Cost Less Uranium Losses in Processing*	13.94	1,825,000
Loading UO_2 in Tubes	0.34	44,000
Interest Charges** on Fuel Inventory in Reactor		
1. Fuel Life - 2 years	16.90	2,010,000
2. Fuel Life - 3 years	25.80	3,060,000
Grand Total Cost of Fuel*** For Initial Loading of the GCR		
1. Fuel Life - 2 years	32.21	4,014,000
2. Fuel Life - 3 years	41.11	5,064,000

* Uranium losses in processing are estimated as 0.5% of production. For 2% enriched material the cost of losses would be $135,000 or $1.03/kg UO_2 produced. Production basis = 131 tons UO_2 + 13 tons (10%) contingency. Operation would be 0.5 tons/day, 24 hrs./day, 7 days/week.

** Based on 4% of $220/kg U in inventory/year.

*** Including chemical processing losses, but not including the cost of loading the reactor.

△ Including costs for necessary alterations and additions.

ESTIMATED COSTS FOR FABRICATION OF HARDWARE AND WELDING OF FUEL RODS

Design Considerations

ORNL has supplied some general information and suggestions on design and fabrication of hardware for the GCR fuel clusters. It was pointed out that these ideas were preliminary in nature, and that modified or improved designs would be considered.

Limited time was available for thoroughly examining hardware configurations that would satisfy basic operating criteria of the GCR, and simultaneously result in minimum costs. Because of this, initial Y-12 efforts along these lines were directed toward establishing detailed designs upon which fabrication estimates could be made. It was possible, however, to consider three different bottom spacers and two hangers.

The three bottom spacer designs are illustrated in Figure 6. Figure 7 is the original ORNL hanger design and Figure 8 shows an alternate hanger configuration. Detailed dimensions and the welding sequence for the fuel rod are given in Figure 9.

Cost Considerations

Hardware and welding costs are itemized in Table III. Although the individual costs are subject to change because of their dependency on design and fabrication methods, the list is instructive in that it indicates which of the items contribute most of the costs. Accordingly, to minimize hardware cost, principal efforts should be on the most expensive pieces of hardware, with only secondary attention (if any) given to the cheapest items. For example, it is apparent that the cost of hardware material (excluding tubing) is relatively small. On the other hand, the fabrication of end caps, the brazing of pins and brackets to the end caps, the fabrication of hangers, and the welding and trimming of the tubing (either seamless or weldrawn) are comparatively expensive.

A summary of hardware and welding costs is given in Table IV. The total cost of hangers of $50,000 is approximately the same for either hanger design. Bottom spacer No. 3 was used in the cost summary since it does not differ appreciably in cost from the least expensive spacer (No. 2) and probably is stronger, structurally.

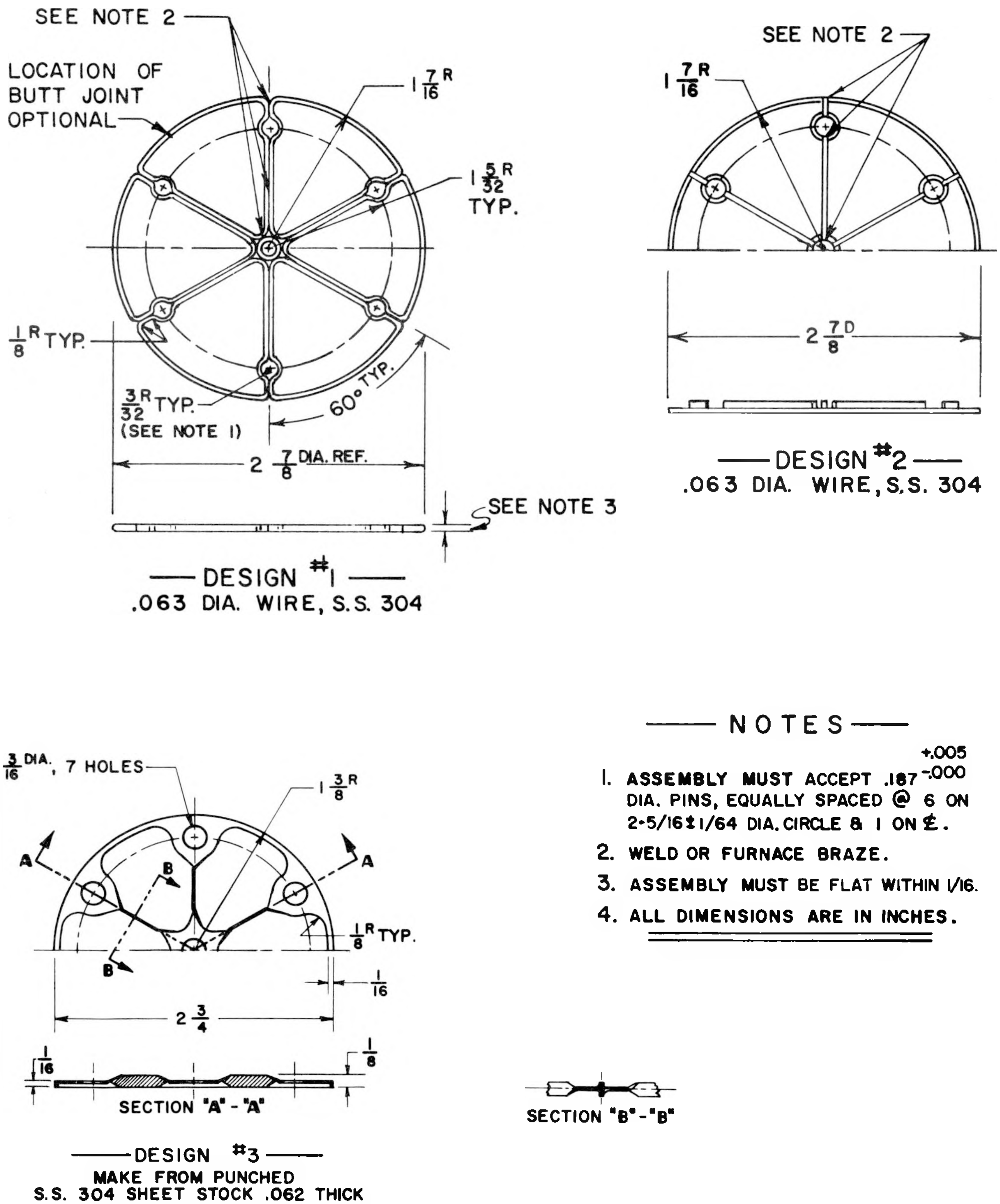


FIGURE 6. BOTTOM SPACER DESIGNS

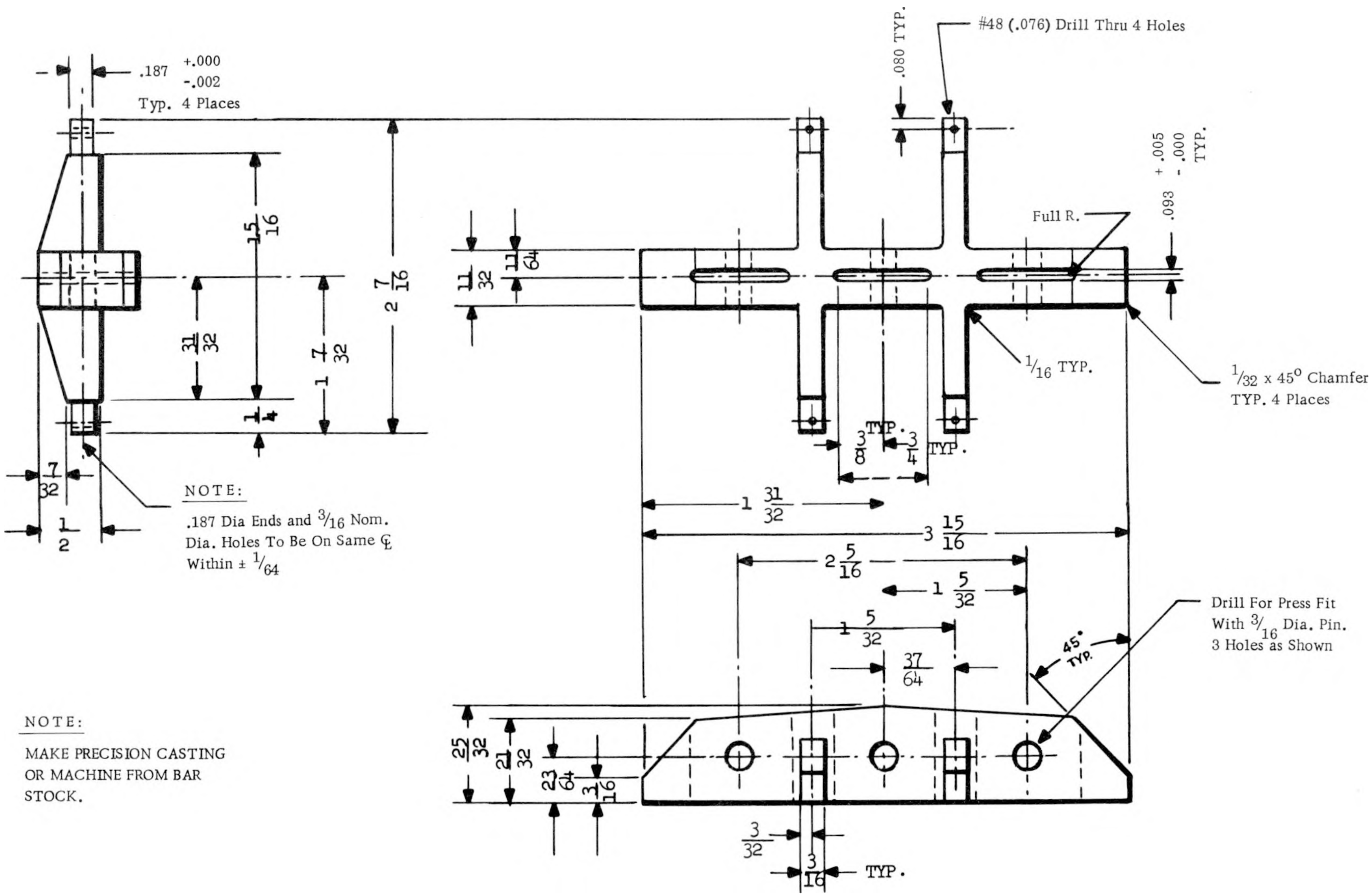
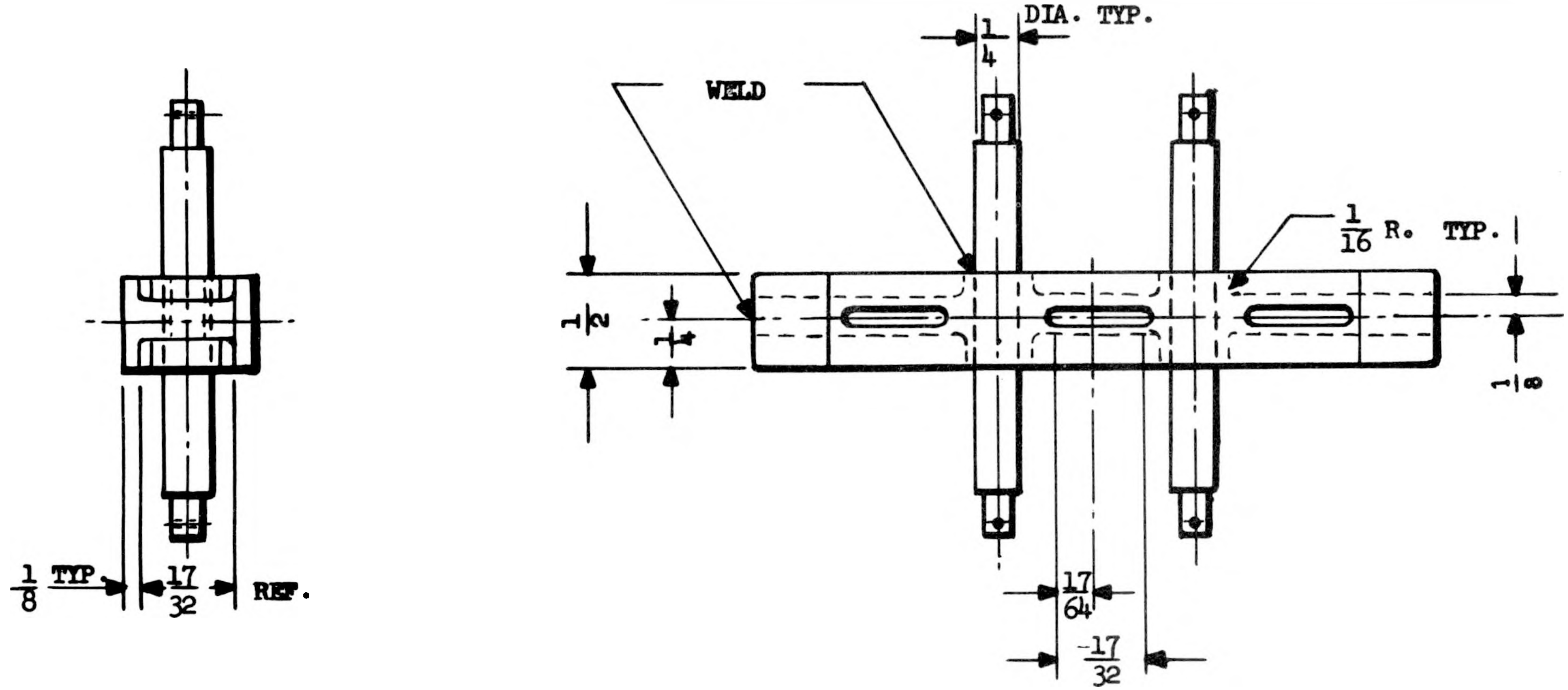


FIGURE 7. HANGER - ORIGINAL ORNL DESIGN



NOTE:

1. CAST TWO PIECES FROM S.S. 304 AND WELD TOGETHER
2. ALL DIMENSIONS SAME AS ORIGINAL DESIGN EXCEPT AS NOTED.

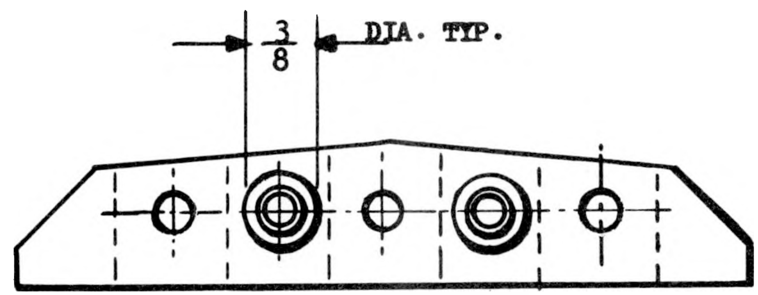
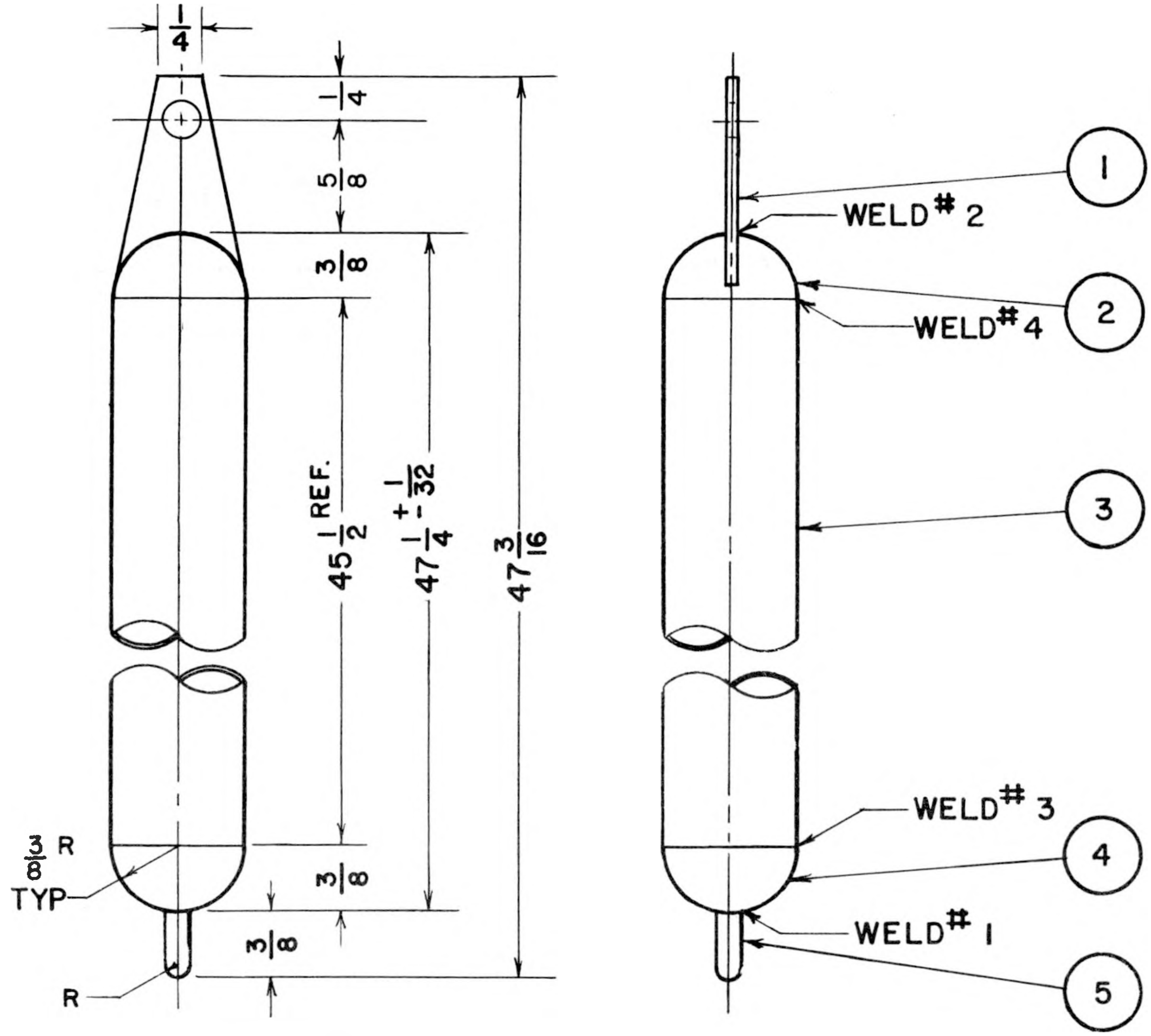


FIGURE 8. HANGER ALTERNATE DESIGN



ITEM	QT'Y	MATERIAL
1	1	.063 SHEET, S. S. ASTM-A167, TYPE 304
2	1	.020 SHEET, S. S. ASTM-A167, TYPE 304
3	1	3/4 X .020 TUBING. S. S. TYPE 304 ASTM-A 213 SEAMLESS ASTM-A 270 WELDRAWN
4	1	.020 SHEET, S. S. ASTM-A167, TYPE 304
5	1	1/8 DIA. BAR, S. S. ASTM-A276, TYPE 304L

FIGURE 9. FUEL ROD DESIGN

TABLE III

ITEMIZED HARDWARE AND WELDING COSTS*

Item	Gross** Parts Fabricated	Material Cost ($)	Brazing Labor And Material ($)	Fabrication Labor ($)	Tooling ($)	Grand Total ($)	Net** Parts Fabricated	Unit Cost $/Net Part
Either Hanger	8,497	8,500	-	31,400	10,000	49,900	8,250	6.05
Wire Spacer # 1	8,415	2,900	1,700	1,000	6,500	11,200	8,250	1.47
# 2	8,415	2,000	1,700	800	3,000	7,500	8,250	0.91
# 3	8,415	800	-	400	8,000	9,200	8,250	1.14
End Caps	149,740	3,000	30,000	59,800	14,000	106,800	115,500	0.93
Weldrawn Tubing	361,825 ft.	156,000	-	52,000***	-	208,000	219,000 ft.	0.95
Seamless Tubing	361,825 ft.	243,000	-	52,000***	-	295,000	219,000 ft.	1.34
Top Bracket	57,750	250	-	2,600	1,200	4,000	57,750	0.07
Bottom Pin	57,750	800	-	2,000	400	3,200	57,750	0.06
Welding Caps To Tube	-	-	-	99,000	53,000	152,000	57,750 Fuel Rods	2.63
Packaging of Fuel Rods						13,000		0.22
Packaging of Hardware						1,000		

* Transportation costs are not included

** Gross parts fabricated include parts rejected in inspection. Net parts fabricated are accepted parts only = reactor requirements + 10% Contingency. See inspection flow sheet, Figure 15.

*** Trimming and deburring tubes

TABLE IV

SUMMARY OF HARDWARE AND WELDING COSTS

Item	Unit Cost* ($/part)	Total Cost** ($)
Hangers	6.05	50,000
Wire Spacers (#3)	1.47	9,000
End Caps	0.93	107,000
Top Brackets	0.07	4,000
Bottom Pins	0.06	3,000
Sub-Total	----	173,000
Welding of Fuel Rod	2.63	152,000
Packaging of Hardware	----	1,000
Packaging of Fuel Rods	0.22	13,000
Sub-Total		339,000
Weldrawn Tubing	0.95△/ft.	208,000
Seamless Tubing	1.34△/ft.	295,000
Total with Weldrawn Tubing		547,000
Total with Seamless Tubing		634,000

* Based on net production (see Table III).

** Rounded off to the nearest $1,000.

△ Includes the cost of trimming and deburring tubes.

ESTIMATED COSTS FOR MACHINING GRAPHITE COMPONENTS OF THE GCR

Information on Graphite

ORNL has supplied the following information on graphite: 8-3/4" x 8-3/4" x 61" blocks of Grade TSF graphite (a gas purified stock, let down in helium), priced at $1,230*/ton F.O.B. Cleveland, Ohio, could be delivered at the rate of one carload (71,500 lb.) per week, starting in 18-23 weeks. Density of the graphite will be about 1.67 grams/cc.

Graphite Components of the GCR

Other than the fact that fuel rods and control rods will be located in that portion of the core inside the shield, there is no other distinction between the graphite in the center of the core and the graphite in the reflector; also, the outside surface of the center and the inside surface of the reflector are in contact with each other, so that the two regions of the core constitute, in effect, an integral unit.

The 1500 vertical holes for fuel assemblies and the 100 vertical holes for control rods will be cylindrical, except that the former will have keyways for guiding and supporting fuel rod hangers.

Basically, the 8-3/4" x 8-3/4" x 61" graphite blocks will be machined to blocks 8" x 8" x 60" and 8" x 8" x 48", except for the shapes on the periphery of the core and those requiring holes for the control rods. The core will consist of five layers of graphite, the top layer being 4' high and each of the next four layers being 5' high.

Although design data are incomplete on the exact pattern of holes for control rods and fuel elements, it is probable that the latter will be spaced on an 8 inch pitch for 2 percent enriched UO_2. From the known information on core

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* This price has been estimated for large quantity processing (1,500-6,000 tons) and the exact tonnage has little effect on the price per lb.

dimensions, graphite block sizes, and channel spacing, the hole and block pattern illustrated in Figure 10 was developed with the basic assumption that a square pitch would be used. The square pitch arrangement minimizes machining costs, since it requires that the 1500 fuel channels be machined through the centers of the 8" x 8" blocks. Although it seems necessary to place control rod holes at the junction of four adjacent blocks for this pattern, resulting in a somewhat more difficult machining job, only 100 control rod holes are required, and the total machining cost is not affected appreciably.

Figure 11 is an elevation of a typical quarter of the top layer of the reactor core. An elevation of the entire height of a typical quarter of the core is shown in Figure 12. Figure 13 is a section of a typical fuel channel, showing the vertical keyways for guiding fuel rod hangers; also illustrated are two horizontal grooves in the channel wall, which serve as supports for a fuel rod hanger (a fuel assembly is lowered down a channel to the proper level and rotated 10° into its final position in the horizontal grooves).

Figure 14 shows a cross section of each of the 14 different shapes per quarter constituting the periphery of the core. Machining requirements for these shapes are listed in Table V . Table VI contains a summary of graphite machining required for the entire core.

The cost of fabricating graphite for the reactor core configuration in Figures 10 - 14, is listed in Table VII. It is apparent that a radical departure in core design from that illustrated would significantly affect these costs. More complicated patterns might be justified of course because of: (1) nuclear characteristics, (2) heat transfer considerations - particularly in the shield, and (3) structural requirements.

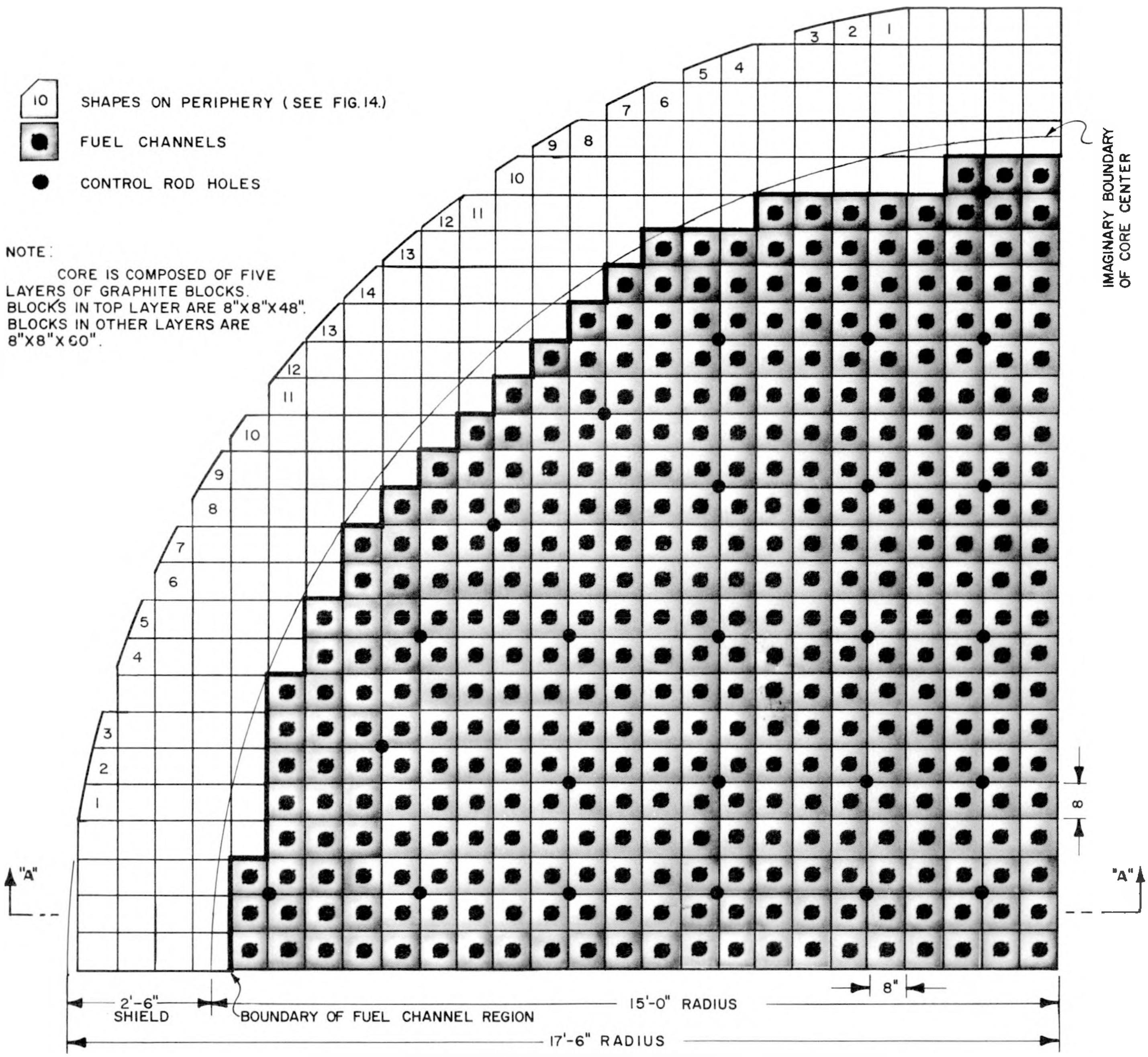

FIGURE 10. PLAN VIEW OF TYPICAL QUARTER OF REACTOR CORE

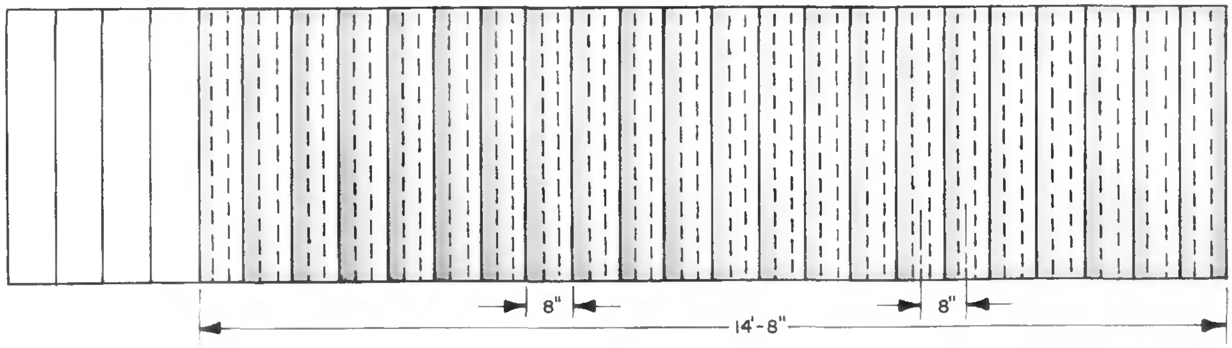

FIGURE 11. ELEVATION OF TOP LAYER IN ONE QUARTER OF REACTOR CORE

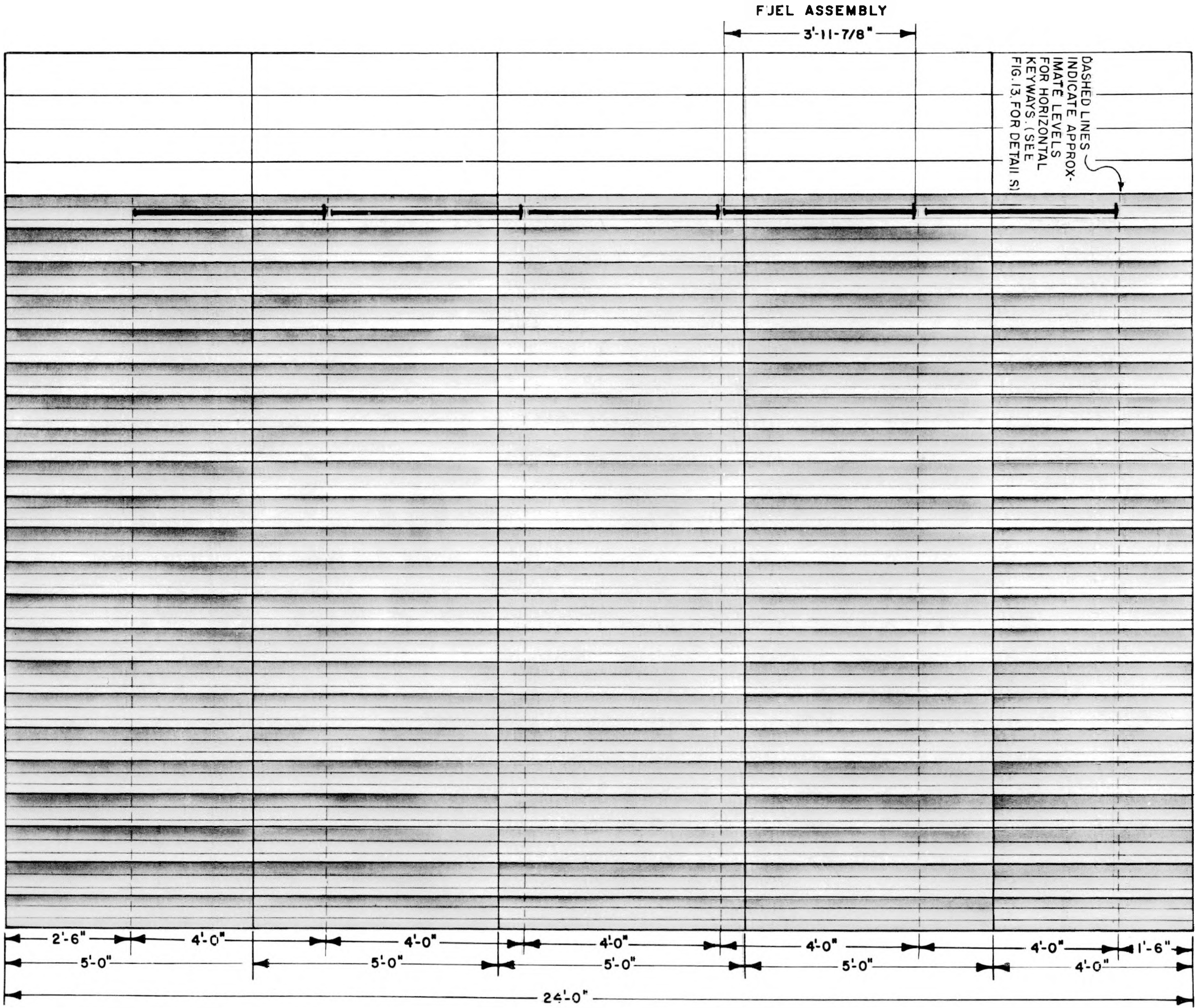

FIGURE 12. SECTION* A-A THROUGH REACTOR CORE (*See Plan View of Core, Figure 10, for Location of Section)

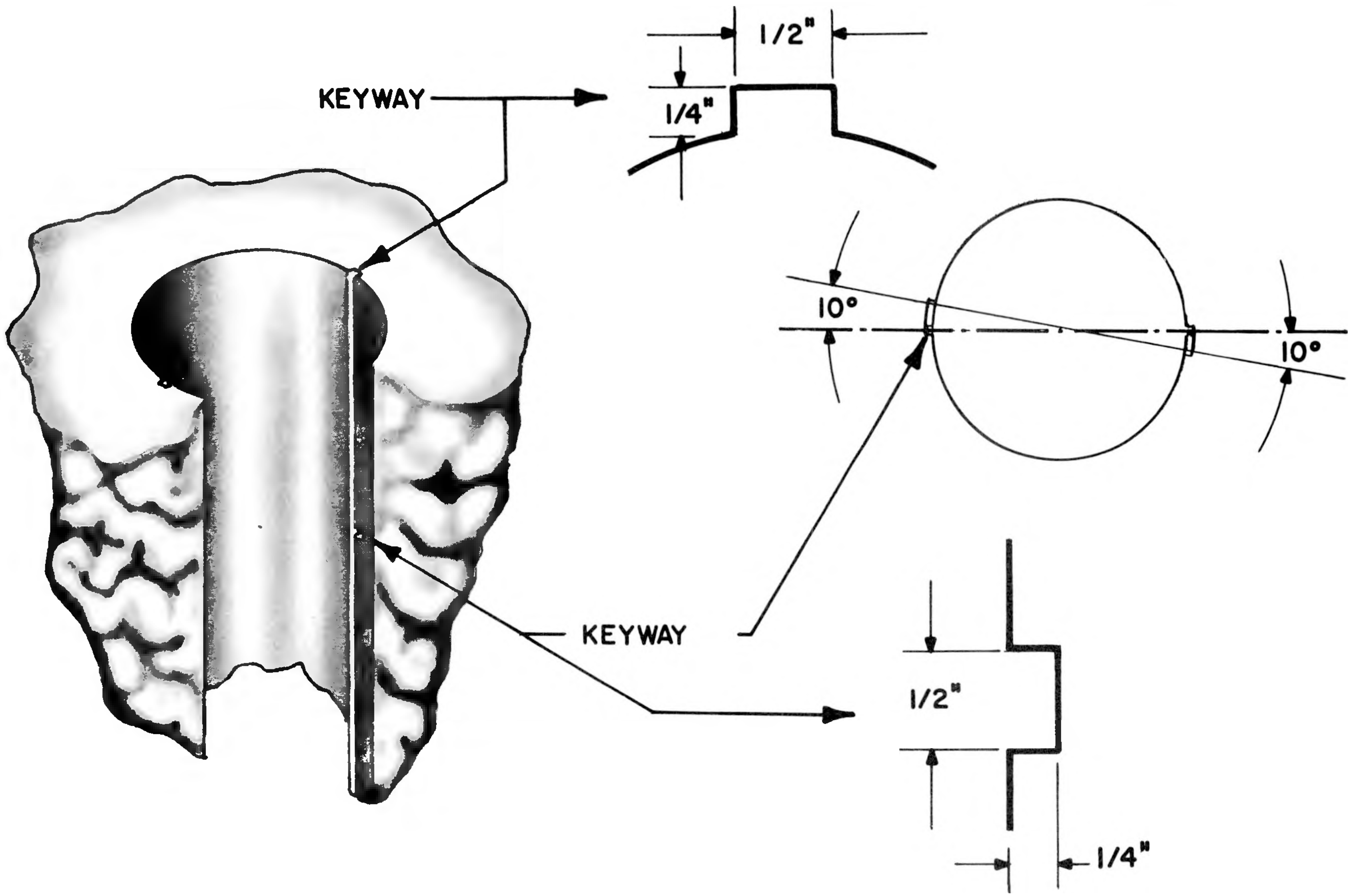

FIGURE 13. DETAILS OF VERTICAL & HORIZONTAL KEYWAYS IN FUEL CHANNELS

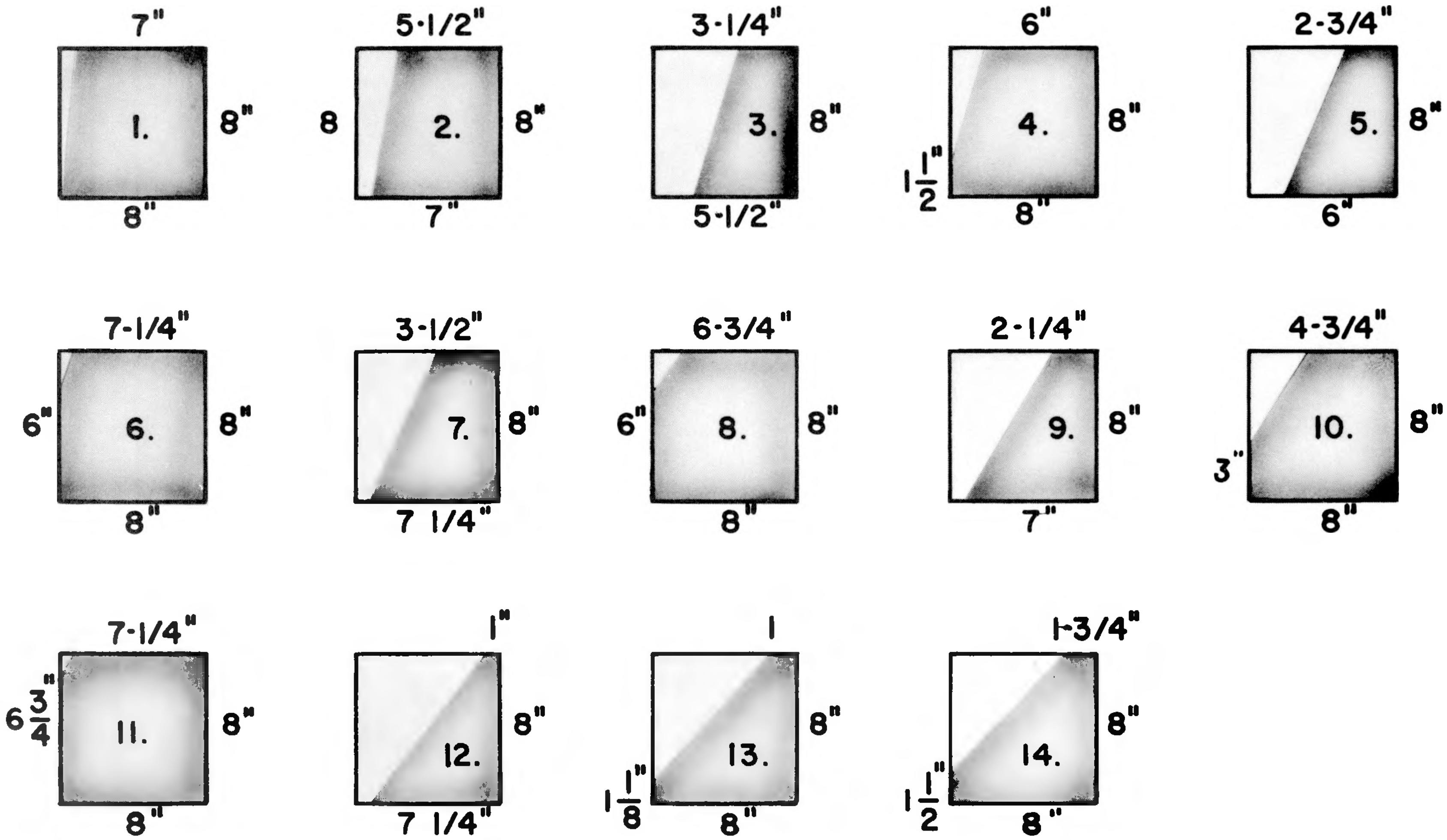

FIGURE 14. PLAN VIEW OF SHAPES ON PERIPHERY OF REACTOR CORE*

TABLE V

MACHINING OF GRAPHITE SHAPES FOR PERIPHERY OF REACTOR CORE

No. of Pieces	Finished Length of Each Piece (inches)	Shape* of Each Piece	No. of Pieces	Finished Length of Each Piece (inches)	Shape* of Each Piece
8	48	No. 1	32	60	No. 1
8	48	No. 2	32	60	No. 2
8	48	No. 3	32	60	No. 3
8	48	No. 4	32	60	No. 4
8	48	No. 5	32	60	No. 5
8	48	No. 6	32	60	No. 6
8	48	No. 7	32	60	No. 7
8	48	No. 8	32	60	No. 8
8	48	No. 9	32	60	No. 9
8	48	No. 10	32	60	No. 10
8	48	No. 11	32	60	No. 11
8	48	No. 12	32	60	No. 12
8	48	No. 13	32	60	No. 13
4	48	No. 14	16	60	No. 14
Total 108			432		

* Refer to Figure 14 for description of shapes.

TABLE VI

SUMMARY OF GRAPHITE MACHINING REQUIRED FOR ENTIRE REACTOR CORE

No. of Blocks to be Machined	Size and Shape of Finished Blocks
576	8" x 8" x 48"
2,304	8" x 8" x 60"
108	See Table
432	See Table
1,500*	8" x 8" x 48" machined for fuel assemblies
6,000**	8" x 8" x 60" machined for fuel assemblies
Total 10,920 blocks	

Total weight*** of 8-3/4" x 8-3/4" x 61" blocks = 1,540 tons

* Including 400 blocks which require machining for control rods and fuel assemblies.

** Including 1600 blocks which require machining for control rods and fuel assemblies.

*** No allowance is made for blocks that may be broken or rejected in machining, transportation, and assembly of core.

TABLE VII

COST OF GRAPHITE FABRICATION

Item	Cost ($) Labor	Material	Total
Cost of Graphite*	——	$2,179,000	$2,179,000
Tooling	98,000	56,000	154,000
Fabrication	296,000	——	296,000
Total Cost**	394,000	2,235,000	2,629,000

* 1540 tons + 231 tons (15% contingency and losses) at $1,230/ton F.O.B. Cleveland, Ohio

** Excluding transportation and packaging costs.

MECHANICAL INSPECTION COSTS

In the manufacture of fuel rods and fuel assembly hardware for a project such as the gas cooled reactor, inspection of these parts is a necessary and important part of the fabrication procedure. The consequences of assembling a reactor with materials containing an imperfect weld or flaw, particularly in the fuel rods, could be costly, and in some cases hazardous.

Several different inspection procedures and techniques are used in inspecting fuel hardware. A brief description of these follows:

Boroscope (B) - a device used to make an internal inspection of a pipe or tubing. Surface flaws are magnified through an extended periscope.

Dye Penetrant (DP) - Either a liquid dye or fluorescent material is applied to the outer surface of hardware, and the excess wiped off. Pores and/or fissures will retain the penetrant, and are detected by application of a white liquid for the liquid dye or black light for the fluorescent material.

X-Ray (XR) - an efficient method of detecting both surface and internal imperfections.

Helium Leak Test (He) - used to check an entire assembly (in this case fuel rod) for leaks. Fuel rods containing helium are leak tested in a vacuum chamber.

Two other inspection techniques not requiring further explanation are Visual (V) and Dimensional (D).

Proposed inspection procedures for each stage of the fabrication of fuel rods for the GCR is shown in Figure 15. The percentages on the flow diagram indicate the probable amount of material that will be rejected at each stage of the operation. These quantities are based on previous experience on other reactor projects, and were used to determine material and manpower requirements for inspection.

Estimated inspection labor costs for each piece of hardware are listed in Table VIII. Table IX contains a summary of inspection costs for hardware to be used in the GCR.

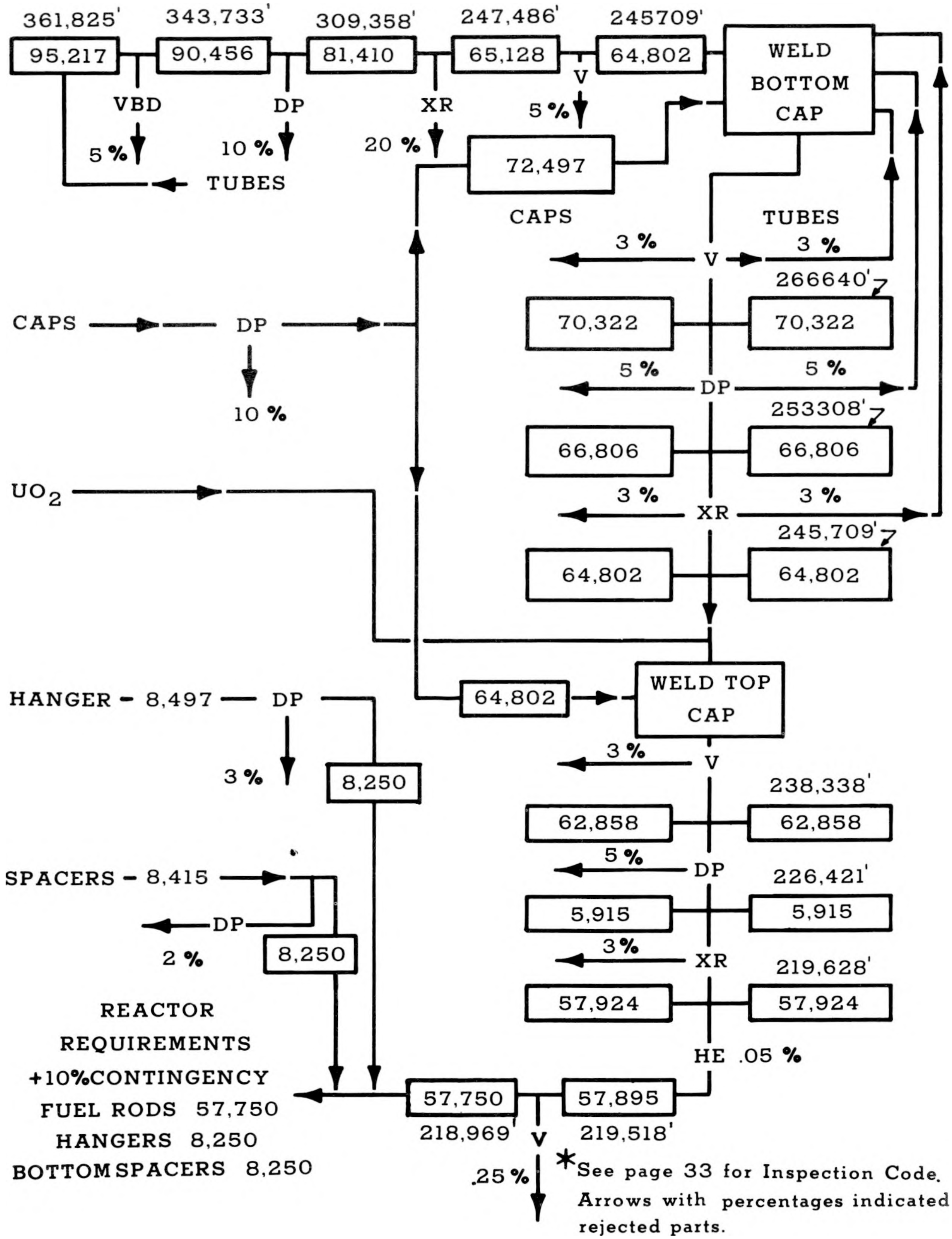

FIGURE 15. *INSPECTION FLOW SHEET

TABLE VIII

INSPECTION LABOR COSTS

Inspection Procedure	End Caps	Hangers	Bottom Spacers	Tubes	Bottom Cap Weld	Top Cap Weld	Welded Fuel Rod	Total
	Cost (in thousands of dollars)							
Visual	-	-	-	56**	41	37	16**	150
Boroscope	-	-	-	8*	-	-	-	8
Dye Penetrant	17	4	2	139	40	36	-	238
X-Ray	-	-	-	105	57	48	-	210
Helium Leak Test	-	-	-	-	-	-	21	21
TOTAL	17	4	2	308	138	121	37	627

* Spot visual check, boroscope and dimensional tolerance

** Final visual inspection

TABLE IX

SUMMARY OF INSPECTION COSTS

Item	Cost ($)
Material and Supplies	46,000
Alterations and Equipment	22,000
Inspection Labor	
End Caps	17,000
Hangers	4,000
Bottom Spacers	2,000
Tubing	308,000
Welds	259,000
Fuel Rods	37,000
GRAND TOTAL	695,000

TABLE C.1

INITIAL REACTOR PARAMETERS

Helium temperature, reactor out	950°F
Helium temperature, reactor in	450°F
Helium pressure	300 psia
Thermal heat load	700 Mw
Reactor core diameter (graphite moderated)	30 ft
Reactor core height	20 ft
Reflector thickness (graphite)	2.5 ft
Fuel element channel diameter	3.25 in.
Lattice pitch	8 in.
Fuel Element - 7 capsules/element (Current design is for a type 304 stainless steel or can to contain UO_2)	UO_2 rods
Spherical shell	50 ft dia, 3-in. thick
Fuel loading at top of reactor	
Control rods at top of reactor	
Number of control rods	100
Concrete thickness	9 ft
Clearance between shield and pressure vessel at equator	4 ft
No thermal shield between pressure vessel and concrete	
Number of heat exchangers	4

TABLE C.2

INITIAL GAS-COOLED REACTOR FUEL ELEMENT REQUIREMENTS

Description of Item	
Fuel channels in graphite	1500
Active length of channel	20 ft
Fuel Elements per channel	5
Fuel Capsules per element	7
Fuel Capsules per loading	52,500
Capsule Hangers per loading	7500
Bottom Spacers per loading	7500
Rod End Caps per loading	105,000
Tubing length per fuel capsule	45-1/2 in.
Total tubing per loading	199,000 ft
Number of UO_2 discs per fuel capsule	91
Number of UO_2 discs per loading	4.77×10^6
Weight of UO_2 disc	approx. 0.055 lb
Total weight UO_2 per loading	approx. 131 tons
Estimated burnup	5000 Mwd/ton
Estimated burnup	10,000 Mwd/ton
Fuel replacement rate (est.)	950 day/loading
Fuel replacement rate (est.)	1900 day/loading
UO_2 production rate for initial loading (est.)	0.19 ton/day

(1) Channel diameter is 3-1/4 in. nominal.
(2) Tubing is 3/4-in. dia., with 0.020-in. wall, type 304 stainless steel.
(3) Dimensions of UO_2 slugs; 0.700-in. OD x 0.350-in. ID x 0.500-in. length.
(4) Assuming approximately two years required for reactor construction. If loading is required in one year, the production rate will have to be 0.38 ton/day.
(5) Design stress for capsule hangers - 2500 psi.

TABLE C.3

CURRENT REACTOR PARAMETERS

Description of Item	
Helium temperature, reactor out	1000 °F
Helium temperature, reactor in	460 °F
Helium pressure	300 psia
Thermal heat load	687 Mw
Reactor core diameter (graphite moderated)	30 ft
Reactor core height	20 ft
Reflector thickness (graphite)	2.5 ft
Fuel cluster channel diameter	3.25 – 3.45 in.
Lattice pitch	8 in.
Fuel element - 7 capsules (Current design is for a type 304 stainless steel)	UO_2 slugs
Spherical shell	50 ft dia, 3-in. thick
Fuel loading at top of reactor	
Control rod at top of reactor	
Number of control rods	61
Concrete thickness	9 ft
Clearance between shield and pressure vessel at equator	4 ft
No thermal shield between pressure vessel and concrete	
Number of heat exchangers	4
Fuel channels in graphite	1,597
Active length of channel	20 ft
Fuel elements per channel	6
Fuel capsules per element	7
Fuel capsules per loading	67,100
Fuel hangers per loading	9582
Bottom spacers per loading	9582
Rod end caps per loading	134,200
Tubing length per capsule	37-1/2 in.[2]
Total tubing per loading	215,260
Number of UO_2 slugs per capsule[3]	75
Number of UO_2 slugs per loading	5.17×10^6
Weight of UO_2 slugs per capsule	~ 2.31 kg
Total weight UO_2 per loading	~ 171 tons
Estimated burnup	5000 Mwd/ton
Estimated burnup	10,000 Mwd/ton

Fuel replacement rate (est.)	950 day/loading
Fuel replacement rate (est.)	1900 day/loading
UO_2 production rate for initial loading (est.)	0.40 ton/day

---

(1) Design stress for capsule hangers - 2500 psi.
(2) Tubing is 0.800-in. dia, with 0.020-in. wall, type 304 stainless steel.
(3) Dimensions of UO_2 disc (bushing); 0.750-in. OD x 0.320-in. ID x 0.500-in. length.
(4) Assuming approximately two years required for reactor construction. If loading is required in one year, the production rate will have to be 0.80 ton/day.

TABLE C.4.A

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	$ 6.74*	$ 802,727.00
Hangers	0.34	39,996.00
Spacers	0.03	2,728.00
Fabrication of Capsule	8.88	1,057,639.00
Tooling Costs:		
a. UO_2 Slugs		
b. Hangers	0.08	10,000.00
c. Spacers	0.07	8,000.00
d. Fabrication of Capsules	0.77	90,600.00
Development Costs:		
a. UO_2 Slugs		
b. Fabrication of Capsules		
Facilities		
Other Related Costs:		
Packaging	0.11	12,728.00
Materials and Supplies	0.35	41,818.00
Cost Contingency	2.56	304,550.00
Total Fabrication Cost	$ 19.93	$ 2,370,786.00
Conversion of UF_6 to UO_2	8.23	979,091.00
Transportation to Site	0.01	1,000.00
Assembly at Site	0.20	22,500.00
TOTAL Estimate Cost	$ 28.37	$ 3,373,377.00
Cost/Capsule	$ 64.39	

* Cost includes 0.5% production loss.

TABLE C.4.B

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	Not Included	
Hangers		
Spacers		
Fabrication of Capsule*	$ 8.18	$ 975,000.00
Tooling Costs:		
a. UO_2 Slugs		
b. Hangers		
c. Spacers		
d. Fabrication of Capsules		
Development Costs:		
a. UO_2 Slugs		
b. Fabrication of Capsules		
Facilities		
Other Related Costs:		
Total Fabrication Cost	$ 8.18	$ 975,000.00
Conversion of UF_6 to UO_2		
Transportation to Site		
Assembly at Site		
TOTAL Estimate Cost		
Cost/Capsule		

* MgO not included.

TABLE C.4.C

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	Included in Capsule Fabrication	
Hangers	$ 0.36	$ 42,500.00
Spacers	0.36	42,500.00
Fabrication of Capsule	20.26	2,415,000.00
Tooling Costs, General	0.36	42,500.00
Development Costs:		
a. UO_2 Slugs		
b. Fabrication of Capsules		
Facilities		
Other Related Costs:		
Packaging	0.15	17,500.00
Total Fabrication Cost	$ 21.49	$2,560,000.00
Conversion of UF_6 to UO_2	8.23	979,091.00
Transportation to Site	0.25	30,000.00
Assembly at Site	0.20	22,500.00
TOTAL Estimate Cost	$ 30.17	$3,591,591.00
Cost/Capsule	68.49	

TABLE C.4.D

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	$ 10.42	$ 1,242,150.00
Hangers	0.08	9,750.00
Spacers	0.01	975.00
Fabrication of Capsule	5.97	711,900.00
Development Costs:		
a. UO_2 Slugs	0.47	56,320.93
b. Fabrication of Capsules	0.90	107,154.32
Facilities	5.38	641,925.20
Other Related Costs:		
Total Fabrication Cost	$ 23.23	$ 2,770,175.45
Conversion of UF_6 to UO_2	8.23	979,091.00
Transportation to Site	0.20	25,000.00
Assembly at Site	0.20	22,500.00
TOTAL Estimate Cost	$ 31.86	$ 3,796,766.45
Cost/Capsule	$ 72.32	

TABLE C.4.E*

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	Not Included	
Hangers	$ 0.71	$ 84,225.00
Spacers	0.03	4,125.00
Fabrication of Capsule**	8.11	967,050.00
Tooling Costs:		
a. UO_2 Slugs		
b. Hangers		
c. Spacers		
d. Fabrication of Capsules	0.75	89,475.00
Development Costs:		
a. UO_2 Slugs		
b. Fabrication of Capsules		
Facilities		
Other Related Costs:		
Packaging	0.28	33,600.00
Total Fabrication Cost	$ 9.88	$1,178,475.00
Conversion of UF_6 to UO_2		
Transportation to Site		
Assembly at Site		
TOTAL Estimate Cost		
Cost/Capsule		

* Assembly Only.
** MgO not included.

TABLE C.4.F

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	$ 7.04	$ 839,680.00
Hangers	0.63	75,120.00
Spacers	0.04	4,800.00
Fabrication of Capsule	15.52	1,849,960.00
Development Costs, General	0.84	100,000.00
Facilities		
Other Related Costs:		
Total Fabrication Cost	$ 24.07	$ 2,869,560.00
Conversion of UF_6 to UO_2	8.23	979,091.00
Transportation to Site	0.05	7,000.00
Assembly at Site		
TOTAL Estimate Cost	$ 32.35	$ 3,855,651.00
Cost/Capsule	$ 73.43	

TABLE C.4.G

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	$ 3.21	$ 382,200.00
Hangers	0.54	64,500.00
Spacers	0.03	3,000.00
Fabrication of Capsule	4.71	561,750.00
Tooling Costs:		
a. UO_2 Slugs	0.39	47,000.00
b. Hangers		
c. Spacers		
d. Fabrication of Capsules	0.20	25,000.00
Development Costs:		
a. UO_2 Slugs	0.59	70,000.00
b. Fabrication of Capsules	0.34	40,000.00
Facilities		
Other Related Costs:		
Health Physics	0.02	2,000.00
Accountability	0.09	11,000.00
Total Fabrication Cost	$ 10.12	$ 1,206,450.00
Conversion of UF_6 to UO_2	8.23	979,091.00
Transportation to Site	0.05	7,000.00
Assembly at Site (Included above)		
TOTAL Estimate Cost	$ 18.40	$ 2,192,541.00
Cost/Capsule	$ 41.76	

NOTE: Prices listed were submitted as separate estimates. If vendor received complete job, the price would be estimated at $2,129,716.00, resulting in a Cost/Capsule of $40.56.

TABLE C.4.H

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	$ 3.87	$ 461,500.00
Hangers	0.72	85,900.00
Spacers		
Fabrication of Capsule	9.51	1,133,500.00
Tooling Costs, General	1.97	235,000.00
Development Costs:		
a. UO_2 Slugs		
b. Fabrication of Capsules		
Facilities		
Other Related Costs:		
Assembly of Element	0.16	19,100.00
Total Fabrication Cost	$ 16.23	$ 1,935,000.00
Conversion of UF_6 to UO_2	8.23	979,091.00
Transportation to Site	0.05	6,000.00
Assembly at Site (Included above)		
TOTAL Estimate Cost	$ 24.51	$ 2,920,091.00
Cost/Capsule	$ 55.63	

Not Included:

a. Packaging
b. Special Garments and Clothing
c. Decontamination
d. Special Buildings to meet structural requirements
e. Special safety equipment
f. Special plant protection requirements
g. Adjustment of insurance rates
h. Shrinkage allowance for process materials
i. Travel Expenses
j. Local Government Restrictions
k. Development Engineering

TABLE C.4.I

FUEL ELEMENT COST ESTIMATE - GCR*

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	$ 22.21	$ 2,647,000.00
Hangers		
Spacers		
Fabrication of Capsule		
Tooling Costs, General	1.24	148,000.00
Development Costs:		
a. UO_2 Slugs		
b. Fabrication of Capsules		
Facilities		
Other Related Costs:		
Total Fabrication Cost	$ 23.45	$ 2,795,000.00
Conversion of UF_6 to UO_2	8.23	979,091.00
Transportation to Site	0.04	5,000.00
Assembly at Site (Included above)		
TOTAL Estimate Cost	$ 31.72	$ 3,779,091.00
Cost/Capsule	$ 72.00	

* Firm bid within 90 days.

TABLE C.4.J

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	$ 14.03	$ 1,672,125.00
Hangers	0.41	48,750.00
Spacers	0.05	6,000.00
Fabrication of Capsule	12.33	1,470,000.00
Tooling Costs, General	0.42	50,000.00
Development Costs, General	1.69	200,000.00
Facilities		
Other Related Costs:		
Total Fabrication Cost	$ 28.93	$ 3,446,875.00
Conversion of UF_6 to UO_2	8.23	979,091.00
Transportation to Site	0.07	8,000.00
Assembly at Site	0.20	22,500.00
TOTAL Estimate Cost	$ 37.43	$ 4,456,466.00
Cost/Capsule	$ 84.97	

TABLE C.4.K

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	$ 9.33	$ 1,112,000.00
Hangers	0.33	39,500.00
Spacers	0.04	5,300.00
Fabrication of Capsule	5.51	657,000.00
Tooling Costs:		
a. UO_2 Slugs		
b. Hangers	0.04	4,700.00
c. Spacers	0.04	4,700.00
d. Fabrication of Capsules	0.21	25,000.00
Development Costs:		
a. UO_2 Slugs		
b. Fabrication of Capsules		
Facilities		
Other Related Costs:		
Assembly of Unit	0.40	47,300.00
Total Fabrication Cost	$ 15.90	$ 1,895,500.00
Conversion of UF_6 to UO_2	8.23	979,091.00
Transportation to Site	0.05	7,000.00
Assembly at Site (Included above)		
TOTAL Estimate Cost	$ 24.18	$ 2,881,591.00
Cost/Capsule	$ 54.89	

TABLE C.4.L

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	$ 4.22	$ 504,000.00
Hangers	0.34	40,875.00
Spacers	0.23	27,750.00
Fabrication of Capsule	8.02	955,500.00
Tooling Costs, General	0.17	21,000.00
Development Costs:		
a. UO_2 Slugs		
b. Fabrication of Capsules		
Facilities		
Other Related Costs:		
Total Fabrication Cost	$ 12.99	$ 1,549,125.00
Conversion of UF_6 to UO_2	8.23	979,091.00
Transportation to Site	0.07	9,000.00
Assembly at Site	0.18	20,000.00
TOTAL Estimate Cost	$ 21.47	$ 1,557,216.00
Cost/Capsule	$ 48.74	

TABLE C.4.M*

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Hangers	\$ 0.18	\$ 15,300.00
Spacers	0.06	7,125.00
Tooling Costs:		
a. Hangers	0.02	2,950.00
b. Spacers	0.02	2,785.00
Total Fabrication Cost	\$ 0.28	\$ 28,160.00
Conversion of UF_6 to UO_2		
Transportation to Site		
Assembly at Site		
TOTAL Estimate Cost		
Cost/Capsule		

* Hangers and Spacers Only.

TABLE C.4.N*

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Hangers	$ 0.08	$ 9,750.00
Spacers	0.01	1,125.00
Fabrication of Capsule-one end only	2.49	298,200.00
Tooling Costs:		
a. UO_2 Slugs		
b. Hangers	0.03	2,970.00
c. Spacers	0.02	1,980.00
d. Fabrication of Capsules	0.05	6,470.00
Total Fabrication Cost	$ 2.68	$ 320,495.00
Conversion of UF_6 to UO_2		
Transportation to Site		
Assembly at Site		
TOTAL Estimate Cost		
Cost/Capsule		

* Partial Assembly Only.

TABLE C.4.0

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	$ 13.21	$ 1,574,000.00
Hangers		
Spacers	13.29	1,583,775.00
Fabrication of Capsule		
Tooling Costs, General	5.82	693,860.00
Development Costs:		
a. UO_2 Slugs		
b. Fabrication of Capsules		
Facilities	38.34	4,569,650.00
Other Related Costs:		
Total Fabrication Cost	$ 70.66	$ 8,421,285.00
Conversion of UF_6 to UO_2	8.23	979,091.00
Transportation to Site	0.04	5,000.00
Assembly at Site (Included above)		
TOTAL Estimate Cost	$ 78.93	$ 9,405,376.00
Cost/Capsule	$ 179.17	

TABLE C.4.P

FUEL ELEMENT COST ESTIMATE - GCR

Item	Cost/Kg UO_2	Total Cost
Fabrication of UO_2 Slugs	$ 2.24	$ 267,000.00
Hangers (not included)		
Spacers (not included)		
Fabrication of Capsule	3.25	388,000.00
Tooling Costs, General	0.35	42,000.00
Development Costs, General	0.16	20,000.00
Facilities	0.59	70,000.00
Other Related Costs:		
Packaging	0.32	38,000.00
Total Fabrication Cost	$ 6.91	$ 825,000.00
Conversion of UF_6 to UO_2	8.23	979,091.00
Transportation to Site	0.05	7,000.00
Assembly at Site (Included above)		
TOTAL Estimate Cost	$ 15.19	$ 1,811,091.00
Cost/Capsule	$ 34.48	

1. Contingencies for scrap, rejection, etc., are not included.
2. Hangers and spacers would be sub-contracted. No prices quoted.

APPENDIX D

DESIGN DATA FOR GAS-COOLED REACTOR

APPENDIX D

DESIGN DATA FOR GAS-COOLED REACTORS

Early in the study it proved useful to have a detailed comparison of the technical features of the various existing gas-cooled reactor designs. Although it was not possible to obtain all details on every reactor, those which were available have been used many times. Accordingly, the following tables summarize the material which was gathered incidental to the GCR-2 study. The non-GCR-2 data, which are for natural uranium plants, permit the reader to make a personal estimate of the technological development prospects of enriched gas-cooled reactors based on the available development experience for natural uranium, gas-cooled systems.

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

PRODUCTION CAPACITY

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Number of reactors	4	2	2	2	2	1	1	1
Heat rating per reactor (Mw)	182	530	530	980	550	687	327	314
Electrical rating per reactor (Mw)	42	150	150	250	170	252	64.8	82.7
Feed back per reactor (Mw)	7.5					27		
Net over-all thermal efficiency (%)	23	28.3	28.3	25.5	30.9	32.8	19.8	26.3
Reactor thermal output (Btu/hr $\times 10^{-6}$)	621.239					2340	1116.182	1071.808
Distribution to grid (Kv)	132					154		
FUEL								
Total weight per reactor (tonnes)	120			370		150.8 (tons)		
Number of channels	1696	2620	3288	4500	3000	1597	1824	1832
Fuel composition	Natural U	Natural U	Natural U	Natural U	Natural U	2% enriched UO_2	Natural U	Natural U
Diameter of channels (in.)	256 at 4.16 576 at 3.95 864 at 3.61					345 at 3.45 400 at 3.25 852 at 3.05		
Diameter of elements (in.)	1.15	1.15	1.15	1.125		0.80 (capsule dia)		
Length of elements (in.)	40.0	40.0	24.0	36		40.0		
No. of elements per channel	6	8	10	8		6		
Total No. of elements	10176	20960	32880	36000		9582		
Density of uranium (g/cm^3)	18.7	18.7	18.7	18.7		10.4	18.7	18.7
Average temperature of element ($^{\circ}F$)	797	788				Surface temp. 1000		
Burnup (Mwd/ton)						7350		
Temperature coefficient per $^{\circ}C$		-2.3×10^{-5}				-4.7×10^{-5}		

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

CANNING

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Material	Mg Alloy	Mg Alloy	Mg Alloy	Mg Alloy	Mg Alloy	SS 304	Mg Alloy	Mg Alloy
Length of can (ft)	3.3		2	3		3.21*	3.3	2.0
Wall thickness (in.)	0.072					0.020*	0.072	0.072
Can diameter (in.)	1.30					0.80*	1.31	1.31
Cooling fin tip diameter (in.)	2.125					None	2.125	2.125
Cooling fin root diameter (in.)	1.30						1.31	1.31
Cooling fin thickness (in.)	0.025						0.025	0.025
Can internal surface (ft^2/ft)	0.303					0.199* (1.393)	0.305	0.305
Can internal surface/can (ft^2)	1.009					0.6375* (4.4625)	1.017	0.611
Can internal surface/reactor (ft^2)	10,265					42,760	11,135	13,421
Can external surface (ft^2/ft)						0.2094* (1.4658)		
Can external surface/can (ft^2)						0.6717* (4.702)		
Can external surface/reactor (ft^2)						45,050		
Fuel can internal surface heat flux (Btu/hr-ft^2)						96,000 Max 56,000 Avg		
Fuel slug internal temperature ($^{\circ}F$)						2200 Max		
Can maximum temperature ($^{\circ}F$)	766.4					1200		
Slug thermal stress (psi)						150,000		
Absorption cross section of cans and supports (cm^2/ft-U)	0.51					19.0 at 2200 m/sec		

NOTE: 1 can equals 1 fuel element equals 7 capsules in parallel. Six fuel elements per channel. Items with asterisk pertain to 1 capsule.

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

MODERATOR

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Material	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite
Core size: Height (ft)	21	25.6	23	25	24	20		
Diameter (ft)	31	40	44.5	49	42	30		
Overall size (incl. ref)								
Height (ft)	27	31	28	30	30	25	26	
Across corners (ft)	36	45	50.5	50	48	35	41	
Weight of graphite (tons)	1146	1910	2150	2000	2000	1122		
Blocks – Length (in.)	25					40		
Cross section ($in.^2$)	64					64		
Average temperature (°F)	482							
Total volume (ft^3)						21,784		
Temperature coefficient per °C		-4.4×10^{-5}				Max. -14×10^{-5} Min. -4×10^{-5} (at tm = 400°C)		
Core graphite density (gm/cm^3)	1.73					1.65		
Reflector graphite density (gm/cm^3)	1.60					1.65		
Core graphite absorption cross section (measured in air in GLEEP) millibarns	4.0					4.0		
Reflector graphite absorption cross section (measured in air in GLEEP) millibarns	4.8					4.0		

LATTICE

Stations	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Type	Square	Square	Square	Square	Square	Square	Square	
Pitch (in.)	8.1	8.0	8.250	7.750	8.16	8.0	9.25	

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

REACTIVITY

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Total excess (%)	4	4.9	4.5			10		
Central channel increment (%)	0.015							
Increment per rod (%)	~0.2					0.24 (avg)		
Flux (n/cm^2-sec)		2.76×10^{13}	2.0×10^{13}			5×10^{12} at 2200 m/sec		

COOLANT

Stations	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Gas	CO_2	CO_2	CO_2	CO_2	CO_2	He	CO_2	CO_2
Working pressure (psig)	100	150		166		300-psia		
Flow (normal) (lb/sec)	1964		5640	1000	6194	972	3500	3350
Flow (maximum) (lb/sec)	2160							
Inlet temperature (°F)	284	356	400		320	460	300	400
Outlet temperature (°F)	636	734	745	707	662	1000	657	743
Number of inlet ducts	2	6	8	6	8	4		
Number of outlet ducts	2	6	8	6	8	4		
Diameter of ducts (ft)	4.5	5	5	6.5	5	5		
Mean coolant velocity								
Cool duct (ft/sec)	49					100		
Hot duct (ft/sec)	74					161		
Total volume occupied by helium (cu ft)						107,000		

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

PUMPING

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Type of blower	Centrifugal	Axial	Centrifugal	Axial	Axial	Axial		
Number per heat exchanger circuit	1			1		1		
Number per reactor	4	6	8	6	8	4		
Mass flow (normal) (lb/sec)	500			10000		972		
Mass flow (maximum) (lb/sec)	550							
Circuit pressure drop (psi)	5.53					6.61		
Maximum (psi)	6.69		7.5					
Isentropic efficiency (%)	78					80		
Compression power (Bhp)	1497		2190		3000	5700		
Speed control type	Ward Leonard	Variable frequency induction motor	DC motor mercury arc rectifier	Squirrel-cage motors fed by variable frequency alternators	Vulcan Sinclair fluid coupling	Constant speed		
Range	10:1		10:1		5:1			
Power required (4 circulators) (Mw)	5.44	61.5	12.6		17	18.3		
Speed – Low (rpm)		600						
High (rpm)		3300	1000	2900		3580		

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

PRESSURE VESSEL

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Shape	Cylinder	Sphere	Sphere	Sphere	Cylinder	Sphere	Sphere	Sphere
Height (ft)	70				80			
Inside diameter (ft)	37	66.75	70	67	50	50 (OD)	57	57
Material	Steel	Spec. steel	Coltuf-28	Mild steel	Mild steel	SA 212 B		
Thickness (in.)	2	3 & 4	2.875 & 3	3	3	3.250	4	4
Pressure (psi)			150	200	125	300 psia	335	335
Design stress (psi)	1200			1500		15,000		
At temperature (^{o}F)	752					650 Max	700	750
Volume (ft^3)						63,333		
Graphite support structure (lb)						144,000		
Vessel support structure (lb)						38,000		
Weight (lb)				3,808,000		1,541,000	1,720,000	1,720,000

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

CONTROL

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Number of channels	112	120	208		150	61		
Diameter of channels (in.)	3.25		3.5			3 in. square		
Diameter of rod OD (in.)						2		
Coarse, maximum No. of rods	60					61		
Fine, maximum No. of rods	4							
Normal operating rods	40							
Rod material	Boron St.	Boron St.	Boron			Silver		
Rod sheath	SS		SS			SS		
Length (ft)	22		21			18		
Suspension	SS cable					SS cable		
Drive	Motor & winch	Variable-speed induction motor				AC motor & winch (pneumatic, fast)		
Ratio of gear	20:1							
In speed – Slow (in./min)	5					8.48		
Fast (in./min)	50					84.8		
Out speed (in./min)	$\frac{1}{2}$					8.48		
Shutdown speed (ft/sec)	4							
Last $2\frac{1}{2}$ ft (in./sec)	6							
Reactivity invested in rods (%)		7				14.5		
No. of rods on temperature servo						4		
Normal in speed, Av. $(\Delta k/k)$/sec						10^{-4}		
Fast in speed, Av. $(\Delta k/k)$/sec						10^{-3}		
Normal out speed, Av. $(\Delta k/k)$/sec						10^{-4}		

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

SHIELDING

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Thermal	Steel plate				Mild steel	Borosilicate glass		
Thickness (in.)	6				$\frac{1}{2} + \frac{1}{2}$	0.5		
Biological	Concrete	Concrete				Concrete		
Thickness – Top (ft)	8	10		11	10	9 nominal		
Sides (ft)	7	9		7	8.5	9		
Density minimum (lb/ft^3)	150							
Density average (lb/ft^3)	160					145		
Shape	Octagon					Octagon		
Size across flats (ft)	60					76		
Height (ft)	90					67		
Total weight on foundation (tons)	33000					23,400		
Cooling	Air	Air			Air	Air		

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

HEAT EXCHANGERS

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Number per reactor	4	6	8	6	8	4	4	4
Main shell height over flanges (ft)	73.3					40		
Main shell height over-all (ft)	77.3	87		90	70	60		
Main shell ID (ft)	17.25	19		21.6	17.5	20.0		
Wall thickness (in.)	1.937			2.375	1.125	2.75		
Gas inlet diameter (ft)	6					5		
Gas outlet diameter (ft)	4.5					5		
Steam drums length (ft)	19.66					21.5 & 19.5		
Steam drums ID (ft)	4.0					2.17 & 2.02		
Wall thickness (in.)	0.687					1.875 & 1.00		
Headers OD (in.)	10.25							
Headers thickness (in.)	1.0							
Economizer tubes OD (in.)	1.5					1.500 (incl. fins)		
Economizer tubes wall (in.)	8 SWG					0.120		
Boiler tubes OD (in.)	2					1.750 (incl. fins)		
Boiler tubes wall (in.)	7 SWG					0.135		
Super heater tubes OD (in.)	2					2.375		
Super heater tubes wall (in.)	6 SWG					0.250		
Gas volume (live) (ft^3)	7370					10,600		
Gas volume (dead) (ft^3)	6600					3,800		
Gas volume (total) (ft^3)	13970		18000			14,400		
Total weight of gas (operating) (tons/unit)			5.2			0.68		

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

HEAT EXCHANGER HEATING SURFACES

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Area of tubes in live gas((outside)								
HP superheater (ft^2)	4450					15,750		
LP superheater (ft^2)	785							
HP evaporator (ft^2)	31500					112,700		
LP evaporator (ft^2)	31500							
HP HT economizer (ft^2)	15750					122,000		
LP HT economizer (ft^2)	15750							
Total (ft^2)	99,735					250,500		
Area of tubes in live gas (inside)								
HP superheater (ft^2)	3580					12,400		
LP superheater (ft^2)	632							
HP evaporator (ft^2)	5886					11,580		
LP evaporator (ft^2)	5886							
HP HT economizer (ft^2)	3304					8,280		
LP HT economizer (ft^2)	3304							
Total (ft^2)	22,592					32,300		

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

HEAT EXCHANGER LENGTHS

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Length of tubes per heat exchanger								
HP superheater (ft/element)	152.5					328 (avg)		
HP superheater (ft/bank)	9764.0					26,900		
HP evaporator (ft/element)	253.75					358 (avg)		
HP evaporator (ft/bank)	16143.0					29,400		
HP HT economizer (ft/element)	286.75					321 (avg)		
HP HT economizer (ft/bank)	12044.0					26,300		
LP superheater (ft/element)	59.25							
LP superheater (ft/bank)	1898.0							
LP HT economizer (ft/element)	292.5							
LP HT economizer (ft/bank)	12333.0							
Total 1.5 in. OD tubing/bank (ft)	24378.0							
Total 2 in. OD tubing/bank (ft)	43949.0							

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

HEAT EXCHANGER

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Gas and steam conditions for one heat exchanger at full load								
Gas flow rate (lb/sec)	491					243		
Gas temp. at HE inlet °C (F°)	336 (637)		396 (745)		(660)	(1000)		
Gas temp. at HE outlet °C (F°)	135 (275)		200 (392)		(318)	(450)		
HP St. flow rate (77% total) (lb/hr)	99000		143100		140000	505,000 (100%)		
HP St. exit temp. °C (F°)	313 (595)	373 (704)	(700)	(685)	(612)	(950)		
HP St. exit pressure (psig)	210	770	575	650	320	950 psia		
HP St. exit enthalpy (Btu/lb)	1,318.3		1351.1			1477.6		
Power of HP cir. pump (HP)	40							
LP St. flow rate (23%) (lb/hr)	29,650		69,500		65,000			
LP St. exit temp. °C (F°)	171 (350)	373 (704)	(670)	(670)	(612)			
LP St. exit pressure (psig)	62.7	210	145	180	77			
LP St. exit enthalpy (Btu/lb)	1,207.4		1360.5					
Power of LP cir. pump (HP)	12.5							
Feed water pres. at HE inlet (psia)	340					1020		
Feed water temp. at HE inlet °C (F°)	37.8 (100)		(160)			(325)		
Feed water enthalpy at HE inlet (Btu/lb)	68.9		127.85			297.1		
Feed water flow rate plus losses (lb/hr)	128650					510,000		
Heat taken up by water and steam (Mw)	46.15					175		

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

TURBO ALTERNATORS

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Number of sets per reactor	2	6	6	6	4	2	2	1
Maximum cont. rating (Mw)	23	52 ±5%	60	93.5	85	125 at 45 psig hydrogen		
Lagging power factor	0.8		0.8			0.87		
Speed (rpm)	3000	3000	3000		3000	3600		
Generator voltage (Kv)	11.5	11.8	11.8	13.8	11.8	18		
(phase)	3					3		
(c/s)	50					60		
HP St. pressure at turbine stop valve (psig)	200	745	555			950	340	725
HP St. temp. at TSV °C (°F)	310 (590)	371 (700)	(690)			(950)	(600)	(700)
HP St. per set (lb/hr)	198,000		382,000			1,009,000	577,000	647,000
LP St. pressure at TSV (psig)	53	195	135				60	150
LP St. per set (lb/hr)	59,300		186,000				448,000	342,000
Output (Mw)	21					126.0		
Flow rate condenser/set (lb/hr)	257,300					797,900		
Maximum cooling water temp. °C (°F)	29.4 (84.9)	8.5 (47.3)				(85)		
LP steam temp. at TSV °C (°F)		371 (700)	(660)				(330)	(670)
Final feed temp. at CMR °C (°F)			(296)			(325) at economizer		
Cooling				Hydrogen	Hydrogen	Hydrogen		

THERMAL HETEROGENEOUS POWER REACTORS – DATA SHEETS

COOLING TOWERS

Stations	British					ORNL	American Studies	
	Calder Hall	Bradwell	Scotland	Hinkley Point	Berkeley	GCR-2	Atomics Int. No. 1	Atomics Int. No. 2
Number per reactor	1					None		
Half basin capacity (gal)	687,500							
Cooling – High °C (°F)	30.5 (86.9)							
Cooling – Low °C (°F)	21.1 (70)							
Wet bulb temperature °C (°F)	8.3 (46.9)							
Dry bulb temperature °C (°F) (humidity 60%)	11.1 (52)							
Tower height above sill (ft)	290.0							
Tower diameter at ring beam (ft)	200.0							
Throat diameter (ft)	104.0							