IDO-28584(Vol. I)

ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

STUDY OF MOBILE GAS-COOLED NUCLEAR POWER PLANTS

Volume I: Plant Description

September 1962

Aerojet-General Nucleonics
Subsidiary of Areojet-General Corporation
San Ramon, California

UNITED STATES ATOMIC ENERGY COMMISSION • DIVISION OF TECHNICAL INFORMATION

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IDO-28584 (Vol. I)
REACTOR TECHNOLOGY

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ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

STUDY OF MOBILE, GAS-COOLED NUCLEAR POWER PLANTS

VOLUME I: PLANT DESCRIPTIONS

Published
September 1962

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Contract AT(10-1)-880

AEROJET-GENERAL NUCLEONICS
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San Ramon, California

ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

STUDY OF MOBILE GAS-COOLED NUCLEAR POWER PLANTS

CONTENTS

ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

STUDY OF MOBILE, GAS-COOLED NUCLEAR POWER PLANTS*

ABSTRACT

The study considered a wide variety of possible designs for a mobile gas-cooled nuclear power plant to produce 500 kw(e) for military applications. It included consideration, optimization, and selection of coolants (air, nitrogen, helium, argon, or others); thermodynamic cycles (direct open-cycle, direct closed-cycle, and dual cycles, both regenerative and non-regenerative); reactor moderators (beryllium oxide, metal hydrides, water, or no moderator); shielding (during operation and transport following operation); high temperature materials (for reactor core, reflector, controls, shielding, structure, heat exchangers, and turbomachinery), and investigation of many other variables. Conceptual designs were completed for several systems.

The High Density Moderated Reactor System, designated HDMR, evolved as the optimum gas-cooled nuclear power plant for military applications, and is described in detail. This concept utilizes a closed regenerative Brayton cycle with air as the working fluid. Hastelloy-X pins are used in the 16-inch diameter core; some contain UO_2 fuel and some contain yttrium hydride moderator. The hydrogen moderation provides maximum safety within acceptable shield weights. Other systems studied are described in somewhat less detail.

The HDMR offers significant advantages over existing military power plants, both nuclear and fossil fueled, in terms of logistic support requirements, mobility, reliability and simplicity.

The study was performed under Contract AT(10-1)-880 with the U. S. Atomic Energy Commission and the U. S. Army.

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ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

STUDY OF MOBILE GAS-COOLED NUCLEAR POWER PLANTS*

I. INTRODUCTION

The study of mobile gas-cooled nuclear power plants, referred to in this report as the MLX study, was undertaken in accordance with agreements reached between Aerojet-General Nucleonics and the USAEC in March of 1962 (Appendix I). These agreements, with subsequent amendment, directed the performance of a detailed parametric study of possible gas-cooled reactor power plants which would satisfy the ML-1 Military Characteristics (Appendix 2) and, at the same time, represent significant improvements over the ML-1 design in military usefulness. Optimum conceptual designs were to be prepared for the several most attractive concepts and the optimum system selected. Finally, a recommendation was to be developed which outlined the next logical step in the program for development of a "second generation" plant for the Army Gas-Cooled Reactor Systems Program.

Volume I of this report presents the conceptual design of the optimum MLX plant and, in less detail, the conceptual designs of the other systems which were examined for comparison. Plant characteristics are presented in detail, and the operational characteristics of the optimum MLX system are fully outlined. Approximate costs and development schedules are included for all plants.

Volume II of this report includes the analyses of all systems studied and shows the methods by which these analyses were performed. The conclusions reached, and reasons therefore, are outlined as an integral part of the method.

Volume III of this report presents as appendixes the detailed information supporting Volume II. A bibliography and glossary of symbols and terms is included.

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II. STUDY OBJECTIVES

The mission for the MLX nuclear power plant is to furnish 500 kw of electrical power for a wide range of military applications. At present, generation of such power for extended periods requires considerable logistic support. A nuclear power plant can eliminate these logistic problems and can provide high quality electrical power for extended periods of time with a minimum of support. In order to be a useful item, however, a nuclear power plant must satisfy military requirements of mobility, safety, reliability, and maintainability.

A description of the ML-1 power plant is given in IDO-28550, "The ML-1 Design Report". The objective of the MLX study was to define the optimum gas-cooled nuclear power plant; one more useful to the military than the ML-1, specifically in the areas of:

1) Reliability
2) Safety
3) Mobility
4) Logistic support requirements
5) Maintainability
6) Cost

The Military Characteristics of the ML-1 (mobile, low power) nuclear power plant are included in Appendix 2.

The general characteristics listed above served as a basis for the development of design philosophy. The definition of each characteristic was expanded and examples of applications were developed as presented below:

1) Reliability: Military reliability is the capability of a system to successfully perform its mission without failure. For the MLX, this is the capability of the power plant to produce electrical power for extended periods of time without shutdown. To minimize possible causes of failure, the design should have as a goal maximum simplicity with a minimum number of parts, a minimum number of subsystems, and a minimum number of different materials. Each part should perform with a high

margin of safety. Fuel elements, for example, are more reliable if designed to operate considerably below the maximum capability of the materials. Maximum reliability can be achieved by designing all components to operate well below design values.

2) Safety: Reliability is a major contributor to safety, since a plant which operates without failure or incident for the intended lifetime is also a safe plant. In a nuclear power plant, where failures can result in serious consequences, the term implies, in addition, the reduction to essentially zero probability of conditions which could result in a nuclear accident. This goal can best be achieved by designing several nuclear safety characteristics into the reactor. Some of these safety characteristics are:

a) Temperature coefficients: The reactor should be designed so that the change in reactivity with increasing temperature is negative from room temperature to well above operating temperature for both prompt and delayed effects to prevent, or limit, the extent of a nuclear excursion. This temperature coefficient should be inherent in the design of the reactor and relatively independent of exact geometries which might be materially changed during a nuclear excursion.

b) Flooding control: The reactor should be designed to be safe in case of accidental water flooding during transport. While control of flooding accidents might be achieved by the reactor control mechanisms used in normal operation, the most desirable safety objective is a reactor core design in which the reactivity of the system is reduced by the addition of water.

c) Heat capacity: Within other limitations, the reactor should be designed with a large heat capacity to limit the consequences of a loss of coolant.

3) Mobility: Mobility of a field plant for military purposes includes the capability for transport by a minimum number of standard military cargo carriers as well as the capability for fast emplacement and startup, and for early access for maintenance or relocation after operation.

Maximum mobility is achieved by minimizing the number of packages, by minimizing the size and weight of the individual packages, by eliminating the requirement for extensive emplacement and startup procedures, by minimizing the restrictions on access for maintenance or relocation, and by maximizing the ability of the plant to withstand loading and transport shocks.

4) Logistics: Logistic support requirements include the expendable materials and supplies which must be furnished or replenished for operation of the power plant. Among such supplies are water, expedient shielding, special coolant materials, lubricating oil, and various chemicals. Minimum logistic support requirement is achieved by eliminating whenever possible each concept which depends on the availability of any material or supply which is expended in operation.

5) Maintainability: Maintainability is the capability to perform the routine servicing and replacement of damaged components as required for safe operation of the plant with minimum plant outage time. Maximum maintainability is achieved by designing components for fast servicing, eliminating servicing requirements where possible, designing for easy access to components which are prone to malfunction,and by standardizing components where possible.

6) Cost: The cost of military field plants, while less important than for commercial plants, must be consistent with the advantages the plant offers for a specialized application. Cost is minimized by use of developed materials and components, by simplified and easily fabricated designs, by minimized transport and operating manpower and supplies requirements, and by maximum component lifetime.

III. STUDY CONCLUSIONS

The study concluded that the HDMR system is the optimum gas-cooled, 500 kw(e), nuclear power plant for military applications. The plant is significantly more useful than the ML-1. The plant is simple to start up, operate and relocate. It is relatively efficient, extremely mobile and inherently safe.

The HDMR evolved as the best of several MLX concepts considered for the following basic reasons:

1) It is simpler and more mobile than the WMR system.

2) It uses established material technology and does not require the significant material development program associated with the MHX system.

3) It is more mobile than the BeO system.

4) It is safer than the Fast system.

A summary tabulation of design characteristics is shown in Table III-1.

TABLE III-1: SUMMARY OF DESIGN CHARACTERISTICS

GENERAL	HDMR	FAST	BeO	MHX	WMR
Electrical Output, net, kw*	500	500	500	500	500
Reactor Power Total, thermal, Mw	3.34	3.21	3.76	2.96	4.07
Reactor Power, to gas, thermal, Mw	3.2	3.05	3.6	2.8	3.5
Cycle Efficiency, %(at 100°F ambient)	20.3	18.1	18.1	23.2	18.6
Plant Thermal Efficiency, % (at 100°F ambient)	15.6	13.9	13.9	17.9	14.3
Coolant Flow, lb/hour	87,000	79,500	106,500	73,000	101,000
Shield to Satisfy MIL Characteristics	Integral	Integral	Integral & removable	Integral	Integral & expedient
Overall Plant Dimensions (major skids), in.	277.5x109x93	281x109x93	273x109x93	282x109x93	279x109x93
Number of Auxiliary Skids	3	3	4	2	3
Total Plant (including auxiliaries) weight, lb	67,700	68,660	85,500	61,450	69,050
REACTOR					
Power Density, Mw/ft^2	1.7	2.9	1.0	2.1	1.1
Heat Transfer Surface, ft^2	121	149	200	101.5	108
Fuel Clad Nominal Average Surface Temperature, max., °F	1440	1540	1500	1580	1565
Fuel Clad Hot Spot Surface Temperature, max., °F	1730	1690	1690	1728	1765
Core Dimensions, L/D, in.	16 x 16	14 x 14	20 x 20	14 x 16	19 x 19
Neutron Lifetime, seconds	0.6×10^{-6}	0.1×10^{-6}	2×10^{-6}	50×10^{-6}	50×10^{-6}
Prompt Temperature Coefficient, $\Delta k/k$-°C	-5×10^{-6}	-5×10^{-6}	-5×10^{-6}	-10×10^{-6}	-1×10^{-6}

* At 100°F ambient, 0.8 p.f.

	HDMR	FAST	BeO	MHX	WMR
Flooding Reactivity, % Δk/k	-0.2	+5.0	-3.0	-3.0	+4.0
Reflector Thickness in./materials	1-1/2-BeO 1-1/2-Ni	2-BeO 2-Ni	Ax 4-Ni (Inlet) 2-Ni (Outlet) Rad 2-BeO 2-Ni	Ax 2-YH (Inlet) Rad 1-YH	2-Pb
Core Geometry	Close packed pins	Close packed pins	Close packed pins	Pin clusters in coolant passages	Insulated pin clusters in pressure tubes
Number of Elements/Pins	11/1157 fuel 578 moderator	11/1345	7/571	37/661	55/1045
Fuel, vol., %	42.4	57.7	6.6	3.5	12.0
Moderator, vol., %	21.2	0	69.9	54.0	55.5
Void, vol., %	15.6	13.0	9.3	30.5	21.2
Fuel Loading, kg U-235	108	100	55	12	40
Moderator	$YH_{1.7}$ (in pins)	None	BeO	$YH_{1.7}$	Water
FUEL ELEMENT					
Dimensions, (fueled length), in.	0.35 x 16	0.35 x 14	0.76 x 14	0.44 x 16	0.27 x 19
Fuel	UO_2	UN	UO_2	UO_2	UO_2
Fuel Enrichment, Wt. %, U-235	48	42	93	93	40
Reflector	Ni/BeO	Ni/BeO	Ni/BeO	$YH_{1.7}$	Pb
Diluent	None	None	Gd_2O_3	None	None
Number Pins/Element	Varies	Varies	Varies	19(31)12(6)	19
Cladding Thickness, (min.) in.	0.020	0.030	0.030	0.010	0.020
Cladding	Hastelloy-X	Hastelloy-X	Hastelloy-X	Fe-Cr-Al	Hastelloy-X

	HDMR	FAST	BeO	MHX	WMR
CONTROL ELEMENTS					
Type	Drum	Drum	Drum	Rod	Blade
Location	Reflector	Reflector	Reflector	Core	Moderator
Number	16	12	12	6	6
Total Worth - %Δk/k	5.8	7.0	7.0	10.0	6.0
Scram Time, seconds	0.32	0.43	0.36	0.60	0.35
POWER CYCLE					
Reactor Outlet Temperature, ^{o}F	1400	1450	1300	1470	1330
Nominal System Pressure, psia	500	500	500	500	500
Working Fluid	Air	Air	Air	Air	Air
AUXILIARY SYSTEMS					
Number	4	3	4	3	4
Function	Lube oil, Shield cooling, Emer. Cooling, Transport Cooling	Lube oil, Shield cooling, Emer. Cooling	Lube oil, Shield Cooling, Emer. Cooling, Transport Cooling	Lube oil, Shield Cooling, Emer. Cooling	Lube oil, Moderator, Liquid Shield, Emer. Cooling

IV. SYSTEM DESIGNATIONS

It became apparent early in the analysis that, within the ground rules established for the MLX study, the only major component for which significant design latitude existed was the reactor. Having established the optimum cycle and coolant, the power conversion equipment design was essentially the same for all plants. Minor differences developed during the design of the immediate reactor auxiliaries (control devices, emergency cooling devices, etc.); these were considered to be part of the reactor design. The differences in auxiliaries design depended largely on the design of the reactor, the number of reactor associated components placed on the power conversion skid and, thus, the requirement for equipment not included on the two major packages.

As a consequence, the various power plants studied are identified by a "shorthand" reactor concept designation, usually associated with the moderator. The plants described in this section of the report (which includes all attractive candidates) are identified as follows:

1) HDMR System (High Density Moderated Reactor): A plant designed to operate with a very compact reactor of the heterogeneous solid moderated concept. The yttrium hydride moderator volume fraction and the fuel composition are optimized to provide desirable safety characteristics. The neutron spectrum is intermediate.

2) Fast System: A plant designed to operate with an extremely compact, unmoderated reactor. The neutron spectrum is fast.

3) Beryllium Oxide (BeO) System: A plant designed to operate with a reactor of the homogeneous solid moderated concept. The moderator is beryllium and the neutron spectrum is intermediate.

4) Metal Hydride (MHX) System: A plant designed to operate with a reactor of the homogeneous solid moderated concept. The moderator is a metal hydride and the neutron spectrum is essentially all thermal.

5) Water Moderated (WMR) System: A plant designed to operate with a reactor of the heterogeneous moderated concept. The neutron spectrum is essentially all thermal.

In the presentation which follows, a general description of each plant is followed by a detailed description of the significant systems, components, etc. The format of this portion of the report is designed for maximum usability; design data is presented on each left hand page with the appropriate drawing or tabulation on the facing page.

V. HDMR PLANT DESCRIPTION

A. GENERAL

The MLX power plant designed around the high density moderated reactor, designated HDMR, has been selected as the optimum mobile nuclear gas-cooled power plant for military applications. The plant is a completely self-contained unit, capable of producing electrical power at forward or remote military installations for periods in excess of one year.

The power plant consists of two major packages each weighing approximately 15 tons and each capable of being transported on standard military equipment:

1) Reactor Package: This package contains the nuclear reactor with the associated shielding, controls and auxiliaries; and is capable of supplying heated air to the turbomachinery at temperatures and flow rates sufficient to generate 500 kw electrical net output.

2) Power Conversion Package: This package includes the gas turbine and compressor operating with air, the precooler, the recuperator, the generator, and other equipment.

Three additional pieces of equipment are required for operation of the power plant:

1) Control Cab: The power plant controls are located in a 2-½ ton control cab which may be located up to 500 feet from the reactor during operation. A military operator will always be on duty in the cab during plant operation.

2) Auxiliary Equipment Skid: The storage reel for the electrical cables (which connect the power plant with the control cab) is mounted on this skid. The reel and skid weigh 3300 pounds. Space is available on the skid for operating supplies and equipment.

3) Auxiliary Power Unit: An auxiliary power unit, weighing approximately 1200 pounds, is provided to furnish electrical power during plant startup and shutdown.

The total weight of the power plant is 67,700 pounds. If the two main packages are transported separately, it is necessary to join the skids mechanically and connect the two gas ducts prior to operation. The plant layout is shown in Figure V-1.

The electrical power is developed by a 60-cycle generator driven by the turbine-compressor set through a reduction gear. Power for plant auxiliaries is furnished by a separate generator. The power cycle is a regenerative closed Brayton cycle using air as the working fluid as shown in Figure V-2. The radial flow compressor, with a compression ratio of 3.0, compresses the cooled air to 511 psia. The air is heated in the recuperator prior to entering the reactor at 934°F. The reactor outlet air at 1400°F is expanded through the gas turbine where the power is extracted. The air is then cooled, first in the recuperator, and finally in the precooler where the waste heat in the system is rejected to the atmospheric air heat sink. The cooled gas is returned to the compressor to complete the cycle. At an ambient air temperature of 100°F, the cycle efficiency is approximately 20.3% and the net plant thermal efficiency is 15.6%.

A very compact reactor core is required to satisfy the operational and shutdown shielding requirements as well as the maximum weight restriction of 15 tons for the reactor package. The compact reactor in the optimum system design requires a relatively high fuel loading in order to achieve criticality. It also incorporates some hydrogen moderator to insure reactor safety during inadvertent water flooding. The reactor core is composed of a bundle of 1735 closely packed Hastelloy-X clad fuel and moderator elements. Each element is, in essence, a pin, 0.347 inches in diameter. Uranium dioxide fuel, with an average uranium enrichment of approximately 48%, is loaded into 1157 of the pins; the remaining 578 contain yttrium hydride. The combination of partial enrichment and hydrogen moderation insures a negative Doppler coefficient.

The pins are supported from the top of the core and are contained within a surrounding shroud. Outside the shroud, the reactor core is surrounded radially by a 3-inch thick beryllium and nickel reflector which incorporates 16 rotating drums for reactor control. Coolant air enters through a duct at the bottom of the reactor and passes upward around the reflector to provide cooling for reflector and pressure vessel. The pressure vessel is placed between the reflector and solid shield. The air then passes down through the reactor core where it is heated to 1400°F, and is ducted directly to the turbine.

The reactor pressure vessel is surrounded by a shield of tungsten and lithium hydride to attenuate radiation and limit the dose levels in the control cab to acceptable values.

The lubrication system for the rotating machinery is designed to preclude the possibility of oil leaking into the main coolant loop. Since the coolant is air and since the radioactivity of air, either from argon or from fission product leakage, is low, substantial leaks to atmosphere can be tolerated in the main loop. This condition permits the inclusion of an unpressurized lubrication system and the direct discharge to atmosphere of any coolant which leaks into the oil. The plant does not incorporate any liquid systems except the lubrication system. Thus no problems will be encountered from freezing or liquid leakage, and no requirement exists for processing or charging liquids before operation. This permits rapid startup and shutdown of the plant.

It is anticipated that reactor startup can be accomplished within 6 hours after arrival at a site and that the power plant can be ready for relocation 18 hours after shutdown following extended operation. By operating the power plant on its mobile carrier, the startup and shutdown times can be reduced further to meet military requirements for missions involving extreme mobility.

B. DETAILED DESCRIPTION

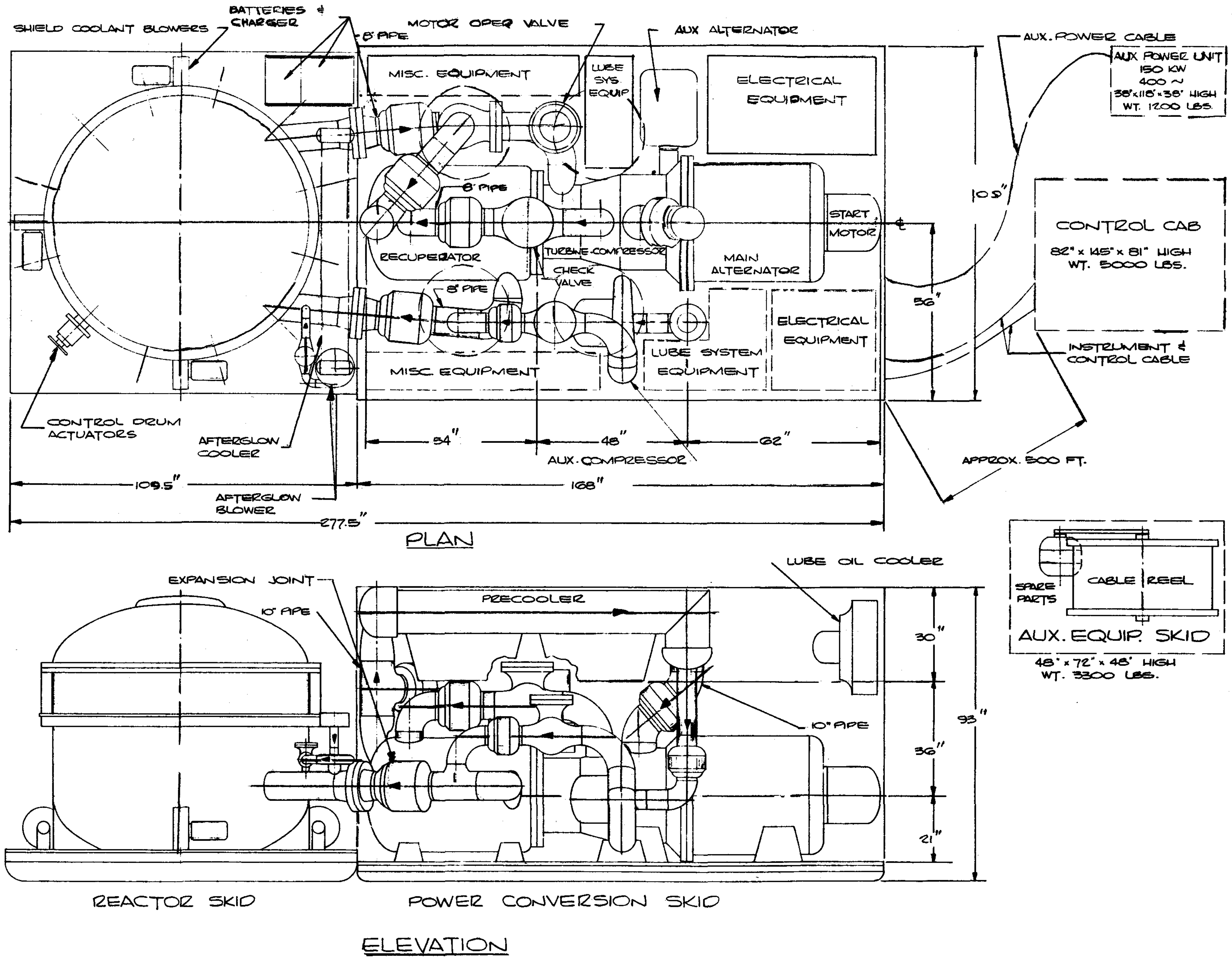
Beginning on page 22 are detailed descriptions of the major systems, components and characteristics of the HDMR power plant in the format described in section IV. A tabulation and index is provided on the next page for the convenience of the reader.

TABLE V-1: TABULATION AND INDEX: HDMR PLANT

HDMR PLANT LAYOUT

The HDMR power plant consists of two major skids, a control cab, and two small auxiliary skids. The power plant is self-sufficient in the field for operating periods of one year. The two major skids can be separated for air transport or coupled for land transport. The total truck convoy required consists of one tractor and trailer (M-172 or M-172-A-1) and three standard 2-½ ton trucks (M-35).

Sufficient radiation shielding is incorporated integrally on the reactor skid to permit operation from the control cab 500 feet away and to permit the plant to be transported 18 hours after shutdown following extended operation.



WEIGHT SUMMARY

REACTOR SKID		
SHIELD	19200	
PRESS VESSEL & CORE	5300	
CONTROL DRIVES & ACTUATORS	800	
STRUCTURE	3700	
SHIELD COOLING BLOWERS	250	
AFTERGLOW COOLING SYS.	500	
		29,750
POWER CONVERSION SKID		
TURBINE COMPRESSOR	3000	
RECUPERATOR	3500	
PRECOOLER	4900	
ALTERNATOR	6200	
START MOTOR	400	
LUBE SYSTEM	800	
AUX. COMPRESSOR	500	
STRUCTURE & ACC.	2500	
ELECTRICAL EQUIP.	3150	
PIPINGS & MISC.	3300	
AUX. ALTERNATOR	200	
		28,450
AUXILIARY EQUIP. SKID		3,300
CONTROL CAB		5,000
AUXILIARY POWER UNIT		1,200
TOTAL		67,700

FIGURE V-1

HDMR PLANT LAYOUT

HDMR FLOW DIAGRAM

The HDMR power plant utilizes air as the working fluid in a closed Brayton cycle with regeneration. The cycle state points and characteristics are listed below:

	Temperature (^{o}F)	Pressure (psia)
Compressor inlet	145	171
Compressor outlet	421	511
Reactor inlet	934	500
Reactor outlet	1400	463
Turbine outlet	1057	178
Precooler inlet	552	175

Core Δ P/P - 5%

Flow rate - 8.7 x 10^4 lb/hr

Reactor power (to gas) - 3.2 Mw(t)

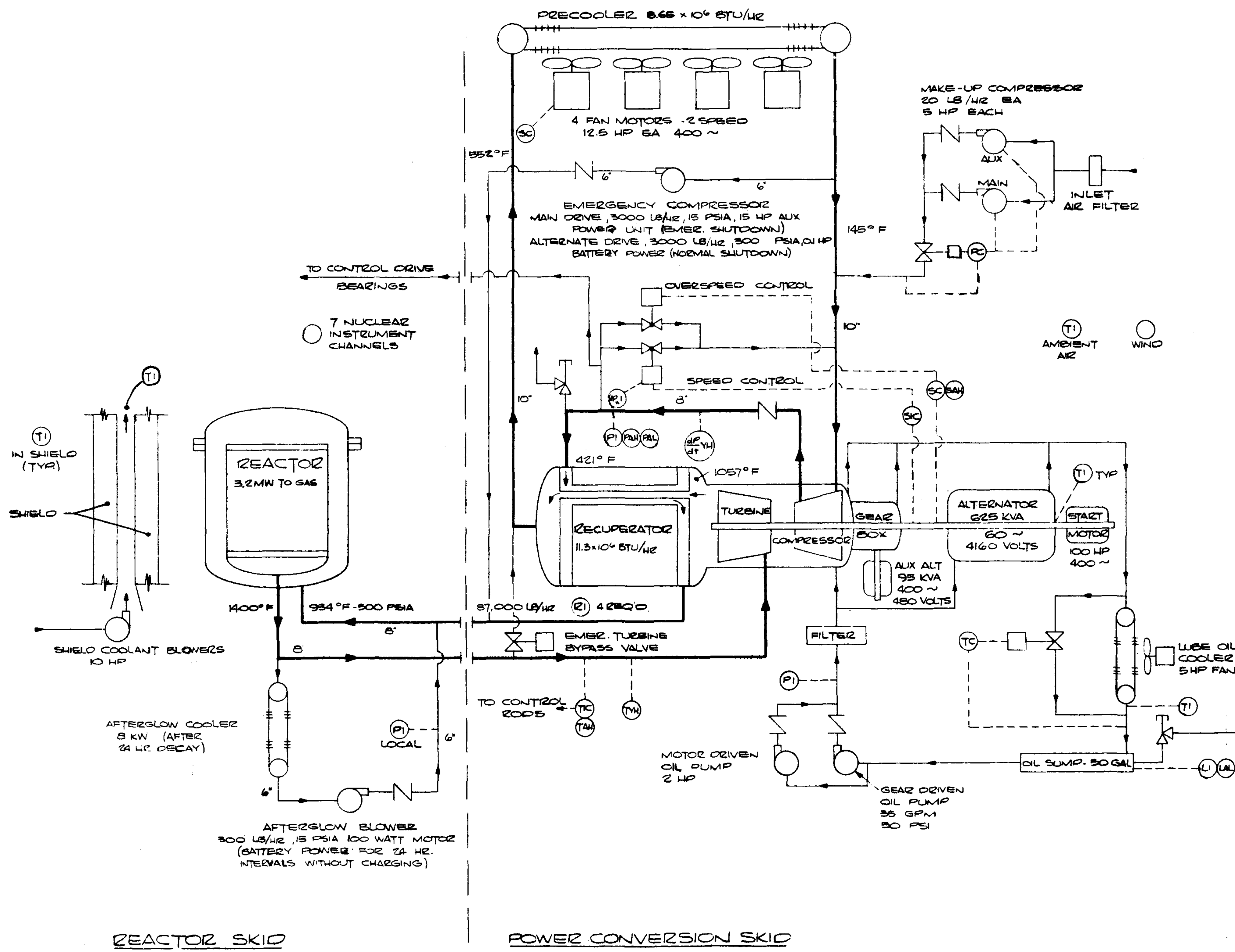
Recuperator heat load - 11.3 x 10^6 Btu/hr

Precooler heat load - 8.65 x 10^6 Btu/hr

Power, kw(e) - 575 gross; 500 net

Reactor blower and power required - Emergency blower, 11 kw

Precooler fans and power required - Four 2-speed fans, 12 hp each, total 38 kw



INSTRUMENT SYMBOLS

LETTER	1ST LETTER	2ND LETTER	3RD LETTER
A		ALARM	
C		CONTROL	CONTROL
I		INDICATING	
L	LEVEL		LOW
P	PRESSURE		
P_n		POSITION	
R	RADIATION	RECORDING	
S	SPEED		
T	TEMPERATURE		
V	VALVE		
Y		SCRAM	SCRAM
H			HIGH
$\frac{dP}{dt}$	RATE OF PRESS CHANGE NEG.		
d	SUBSCRIPT REFERRING TO DIFFERENTIAL		
e	" " " ERROR		

FIGURE V-2

HDMR FLOW DIAGRAM

HDMR PINS

The basic element of the HDMR core is a 0.347-inch diameter pin which has an active length of 16 inches. The cladding is modified Hastelloy-X 0.020 inches thick. Yttrium hydride is loaded into 578 moderator pins; partially enriched UO_2 is loaded into 1157 heat producing pins. Tungsten is loaded in the bottom of all pins for a radiation shield.

The fuel is UO_2 ceramic in the form of pellets. The average fuel enrichment is 48% but is varied both radially (3 regions) and axially (3 regions) to control temperature and power distribution and approach an optimum isothermal core.

A spiral spacer is provided on the outside diameter of the pin. This spacer contacts adjacent pins and maintains the correct core geometry for proper coolant flow, and eliminates pin movement. The radial height of the spacer is 0.010 in. The pin is supported from the upper end.

Heat transfer parameters for the fuel pin are listed in Table V-3.

HDMR PINS

FIGURE V-3

HDMR PIN CLUSTER

The fuel pins in the HDMR reactor are supported in clusters. The major support members are rectangular cross-section beams to which the pins are fastened. Vertical support is provided only at the top where the pins are welded to the beams. The integral pin spacers maintain the correct flow area.

The beams from which the pins are supported are formed in units, with several beams to a unit. These units are supported at the ends.

At the lower end of the core, the pin diameter is increased to provide full pin-to-pin contact. The core shroud contacts the outermost pins at operating temperature and provides lateral core constraint.

HDMR PIN CLUSTER

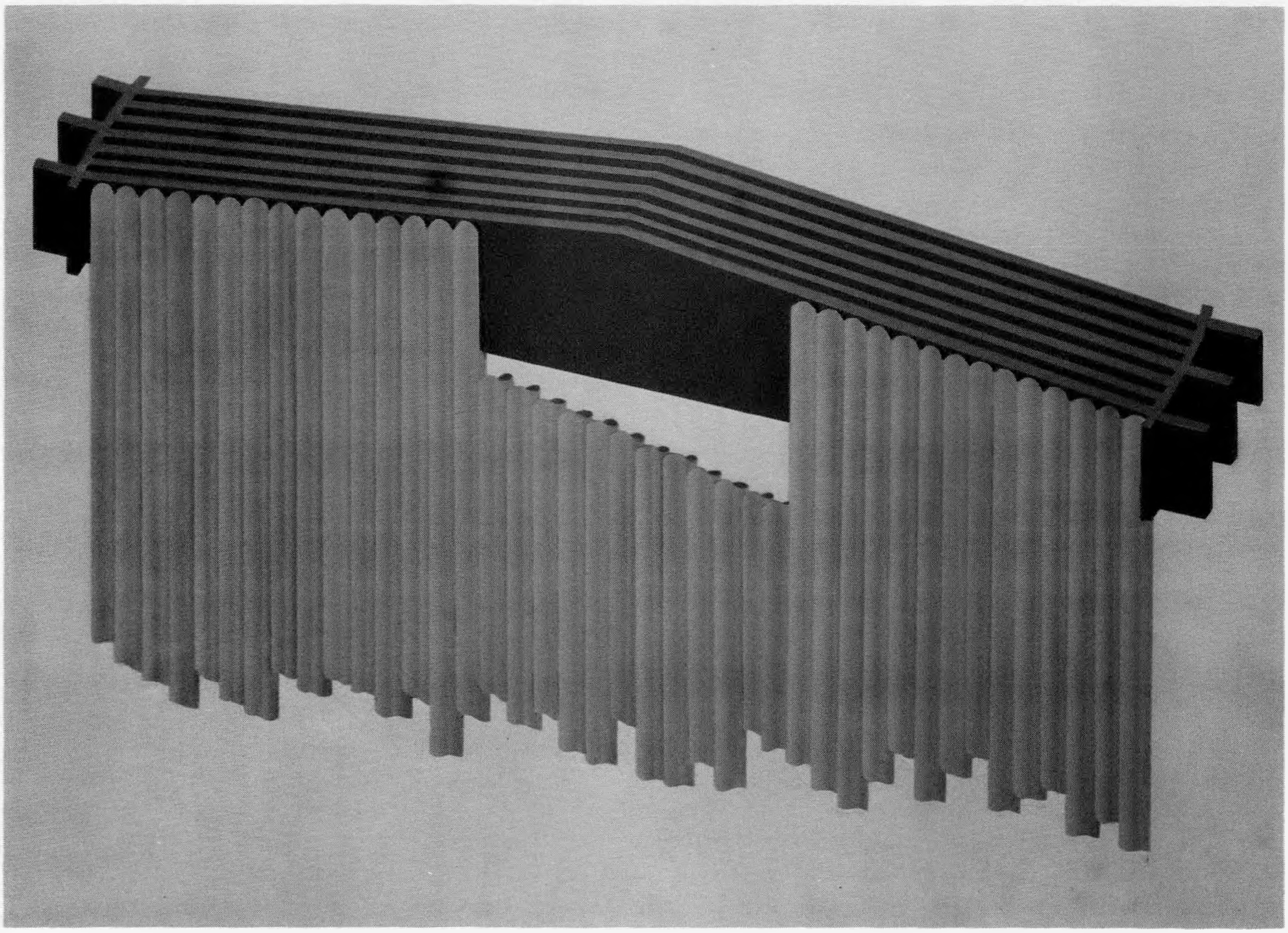


FIGURE V-4

HDMR REACTOR CORE

The HDMR active core is a right cylinder 16 inches in diameter and 16 inches high. The core is composed of 1735 pins; 1157 containing fuel and 578 containing moderator. Immediately surrounding the core is a thin metal shroud which separates the incoming and outgoing gas flows. This shroud also provides lateral constraint for the fuel pins.

A 3-inch thick radial reflector encloses the core and shroud. The reflector is composed of 1½ inches of beryllia (inside) and 1½ inches of nickel. Sixteen control drums are located in the reflector. The reflector is supported by bolted tie rods and, in turn supports the fuel clusters which make up the core.

The control drum is a composite structure including beryllium oxide and nickle in the reflecting (non-absorbing) portion and yttrium hydride and boron carbide in the absorbing portion. In Figure V-5 the drum is shown rotated with the absorbing portion toward the reader. The materials are, from front to back, B_4C (inserted into the exposed face of the next material), YHx, Ni and BeO.

The basic core parameters are listed in Table V-2.

The significant temperature coefficients of reactivity for the core are summarized below:

1) Doppler Effects: The use of hydrogen and uranium-238 results in a negative Doppler coefficient of approximately -4.0×10^{-6} $\Delta k/k \cdot {}^{o}F$. This is a prompt effect.

2) Fuel Expansion: The expansion of the ceramic fuel causes density changes in the core and results in axial elongation of the core. The reactivity coefficient associated with this effect is approximately -1.8×10^{-6} $\Delta k/k {}^{o}F$ and is considered to be a prompt effect although there actually is a few milliseconds delay.

3) Metal Expansion: At operating conditions, the Hastelloy-X pins are in contact with each other and with the shroud. The entire core expands with variations in gas temperature and this is a delayed effect. The metal temperature coefficient is approximately $+3.2 \times 10^{-6}$ $\Delta k/k {}^{o}F$.

HDMR REACTOR CORE

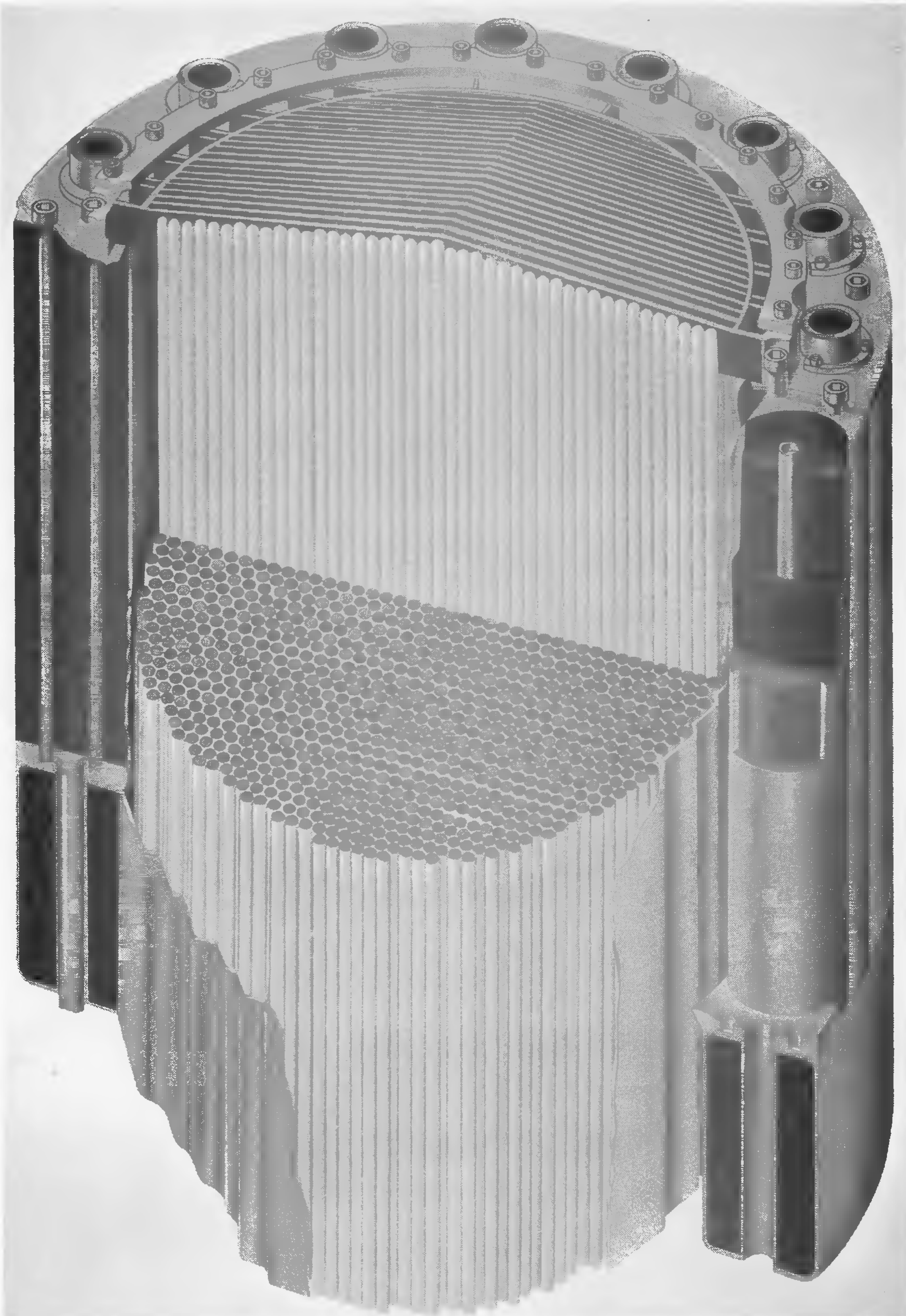


FIGURE V-5

HDMR PRESSURE VESSEL

The HDMR reactor is contained within a pressure vessel fabricated from AISI Type 347 stainless steel. The inlet and exit ducts are located at the bottom of the assembly where radiation streaming causes the least problem. This configuration minimizes the shield weight. Tungsten is included in the bottom of the fuel pins to attenuate radiation in the duct areas. A tungsten shield is located above the reactor.

Gas flow enters from the bottom and is directed around the reflector to provide cooling for the reflector, control drums, and pressure vessel. The entire pressure vessel operates near the inlet gas temperature (934 ^{o}F). In the upper plenum the gas turns and flows downward through the reactor core and exits through an internally insulated duct to the turbine.

HDMR PRESSURE VESSEL

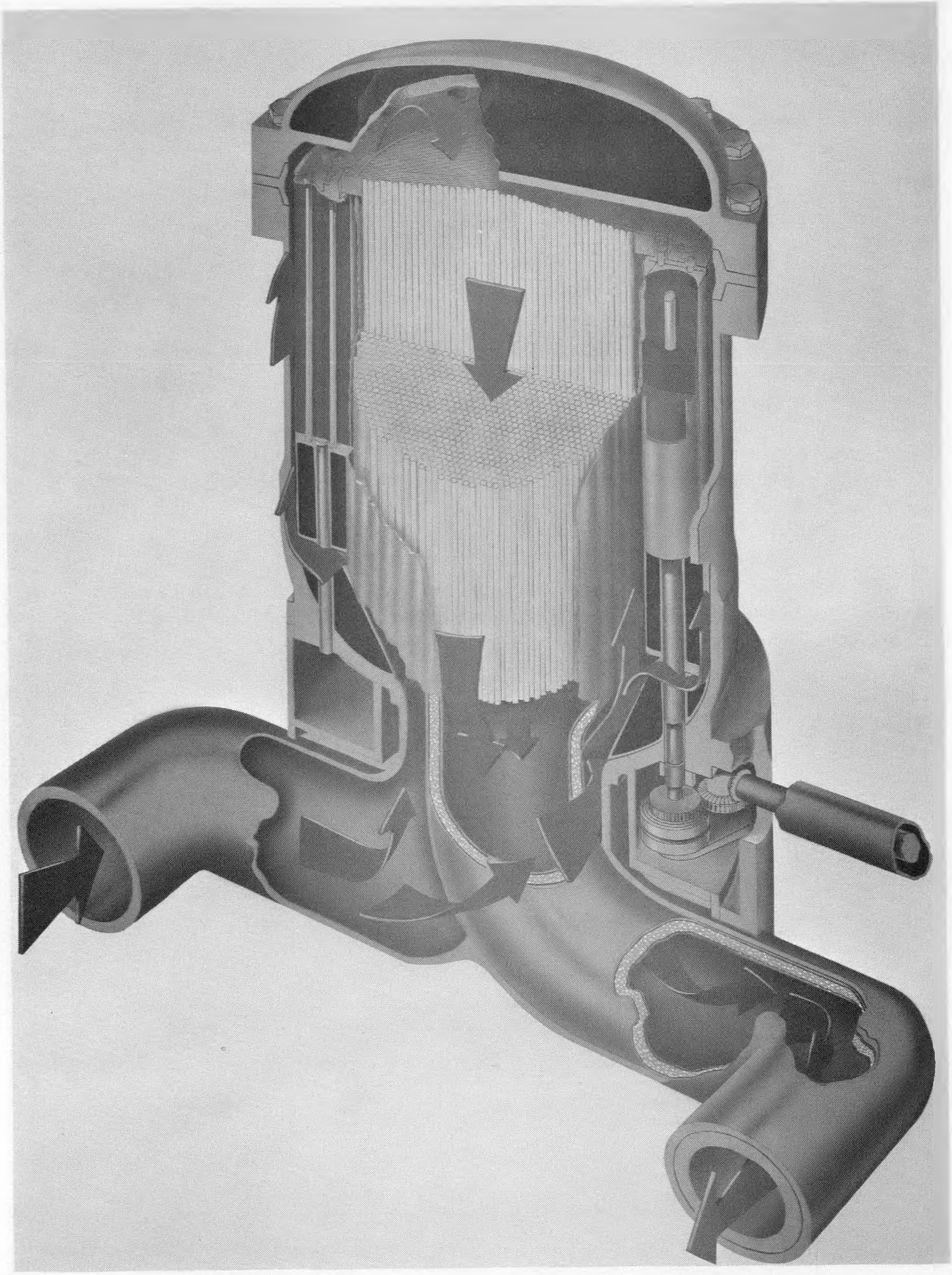


FIGURE V-6

HDMR REACTOR PACKAGE

Tungsten, the primary gamma ray shielding, surrounds the core, radially, adjacent to the pressure vessel and is included in the fuel pins below the active core region. Lead is used outside of the tungsten shield in regions where tungsten activation would present a shutdown radiation problem.

Shielding of fission-born neutrons during operations and photoneutrons from the beryllia reflector after shutdown is provided by lithium hydride. The tungsten, lead and lithium hydride are cooled during operation by air delivered by three shield cooling blowers located at the bottom of the package. A fourth blower is provided as a spare. The air flows upward through the shield and is exhausted through vents at the top of the package.

Eight electrically-energized actuators drive the sixteen control drums through the right-angle drives. The mechanisms are located external to the shielding, as shown, for easy access.

The overall package dimensions are:

Length	109.5	inches
Width	109	inches
Height	90	inches

The package weighs 29,750 pounds.

HDMR REACTOR PACKAGE

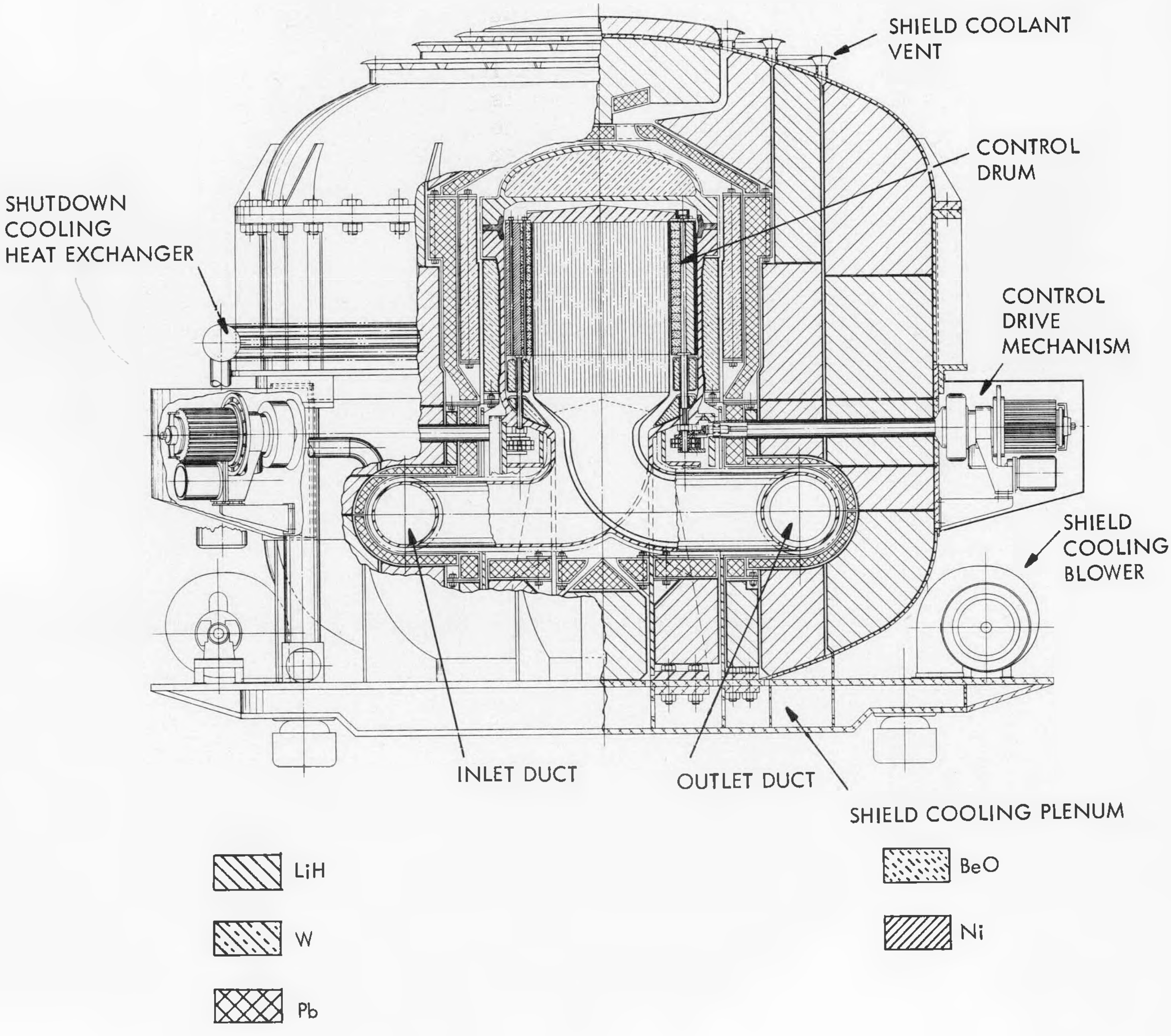


FIGURE V-7

HDMR FISSION SPECTRUM

As shown in Figure V-8, most fissions result from neutrons at fission energies or in the U-235 resonance region and virtually none at thermal energies. The mean fission energy is 10 kev.

Under flooded conditions, the fission spectrum is softened considerably. This results in a decrease in U-238 fissions at high energies and in an increase in neutron parasitic absorption in U-238 and structural materials at low energies. These negative reactivity effects more than offset the positive reactivity effect resulting from increased moderation and decreased core leakage. Thus the HDMR is inherently safe against accidental or deliberate water flooding.

HDMR NEUTRON FLUX

The neutron flux is normalized to a reactor power of 100 watts for comparison with other systems. At 3.2 Mw, the average neutron flux in the core is 1.4×10^4 n/cm^2-sec. The mean energy of the neutrons is 200 kev.

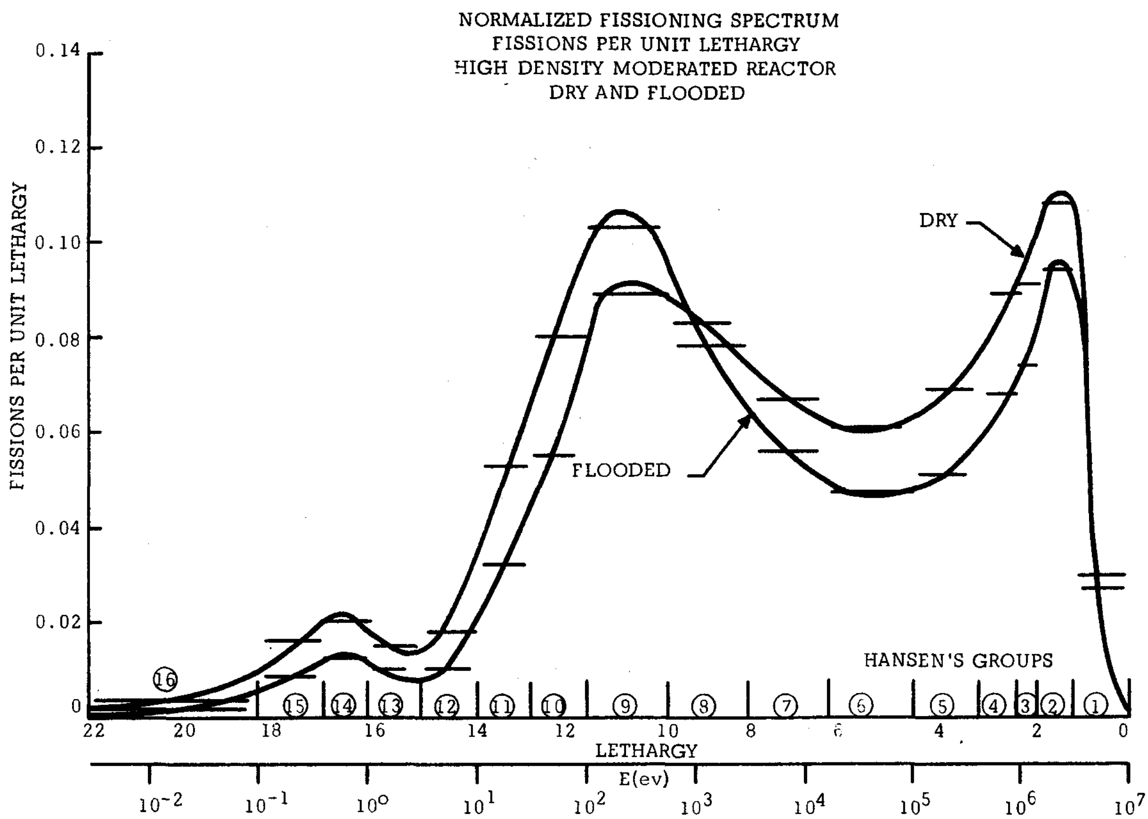


FIGURE V-8

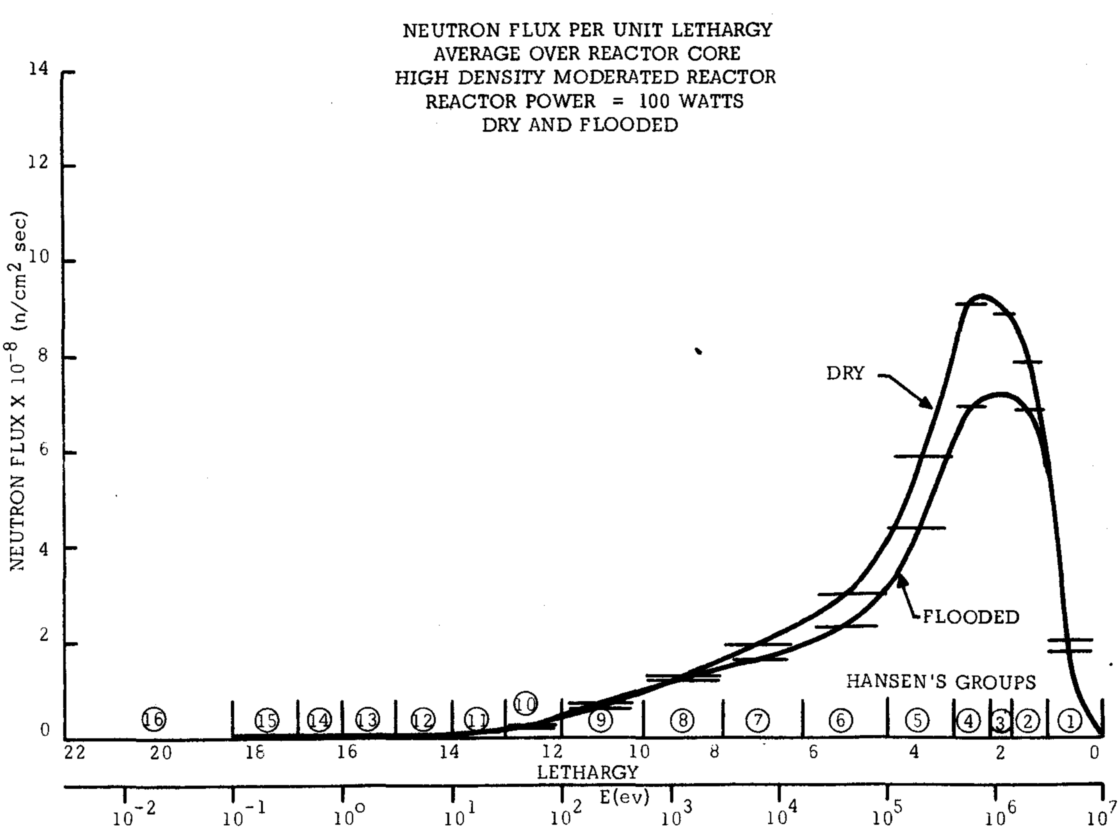


FIGURE V-9

HDMR CONTROL DRUM ACTUATOR

A single rotary actuator is used to control and position a pair of reflector drums. The drums are mechanically coupled to the actuator by a gear train consisting of spur gears mounted on the drum vertical drive shafts, a combination bevel and spur idler gear and a bevel gear driven by the actuator through an extension shaft. Operation of the actuator rotates the two drums in opposite directions. Two coiled springs are attached to the vertical drive shaft of each control drum to store energy for scram action.

The hermetically sealed, electromagnetically coupled rotary actuator is mounted horizontally to the integral reactor pressure vessel-gear housing. The actuator proper consists of a fixed thin wall pressure vessel (an extension of the main reactor pressure vessel) in which a solid steel rotor, supported by two radial bearings, is coupled directly to the gear train driving the control drum. A portion of the drive shaft is shaped to accommodate a crank arm and piston which act as a dash pot during scram. All of the internal parts are exposed to the reactor coolant which is also the working fluid for the dash pot. The solid steel rotor is electrically coupled to the external rotating assembly by radial magnetic flux lines produced by the electromagnet and transmitted through the thin wall portion of the pressure housing. Rotary motion is translated to the drive shaft by the rotation of the external electromagnet assembly which is driven by an electric gear motor through a spur type pinion and ring gear combination. The electric gear motor utilizes a harmonic drive type gear reducer which is self-locking to hold the entire system in position without power to the drive motor. Scram release is accomplished by de-energizing the electromagnet, allowing the internal rotor, gear train and drum to rotate in the fail safe direction under the power of the coiled scram springs. Scram time for the actuator is 320 milliseconds.

Position indication is accomplished by a cam-driven electrical indicator which provides a signal to a rod position indicator on the control console.

Maintenance can be accomplished on all parts except the control drum by withdrawal of the mechanism and all gears. Withdrawal is accomplished by disconnecting the mechanism at a Graylock clamp immediately exterior to the outer shield tank wall and removing the mechanism and drive shaft. Remote access is then possible to the gear drives on the reactor vessel, where removal of the gearbox cover and withdrawal of all gearing can be achieved by taking out gearbox flange bolts.

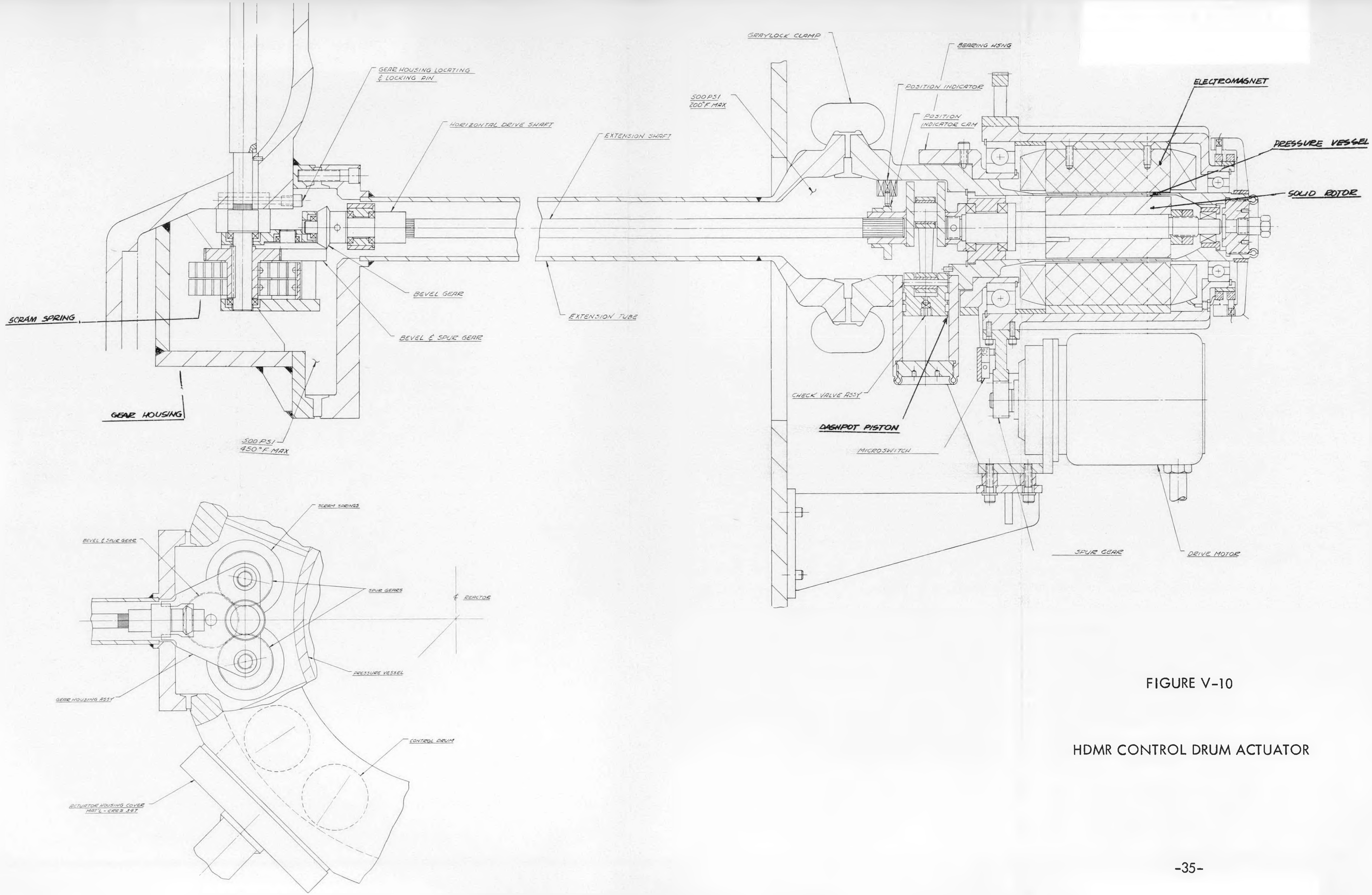


FIGURE V-10

HDMR CONTROL DRUM ACTUATOR

HDMR NUCLEAR INSTRUMENTATION SYSTEM

The HDMR nuclear instrumentation system consists of seven overlapping (in range) channels. Two channels provided in the start-up range employ fission or proportional counters as detectors and the pre-amplified output is indicated as cps (counts per second) at the control console. The output of this chassis is indicated on the control console and provided to the scram logic system.

The two channels of intermediate neutron flux measurement provided employ compensated ionization chambers as detectors. Detector output is amplified and converted for logarithmic display in the control console. Period analysis is also provided with indication in the control console and input to the scram logic system.

Three channels operate in the power range, utilizing uncompensated ionization chambers to provide, through appropriate amplifiers, a linear indication of power level on the control console. Input to the scram logic system is provided to scram the reactor at a preset indicated power level.

The scram logic system accepts inputs from the nuclear instrumentation system as described above, as well as from other selected process variables. The system functions to interupt the activation current on the rotating electromagnet in the control drum actuator (see previous page) and indicates both the normal and scram conditions of the electromagnet activation current and voltage on the console.

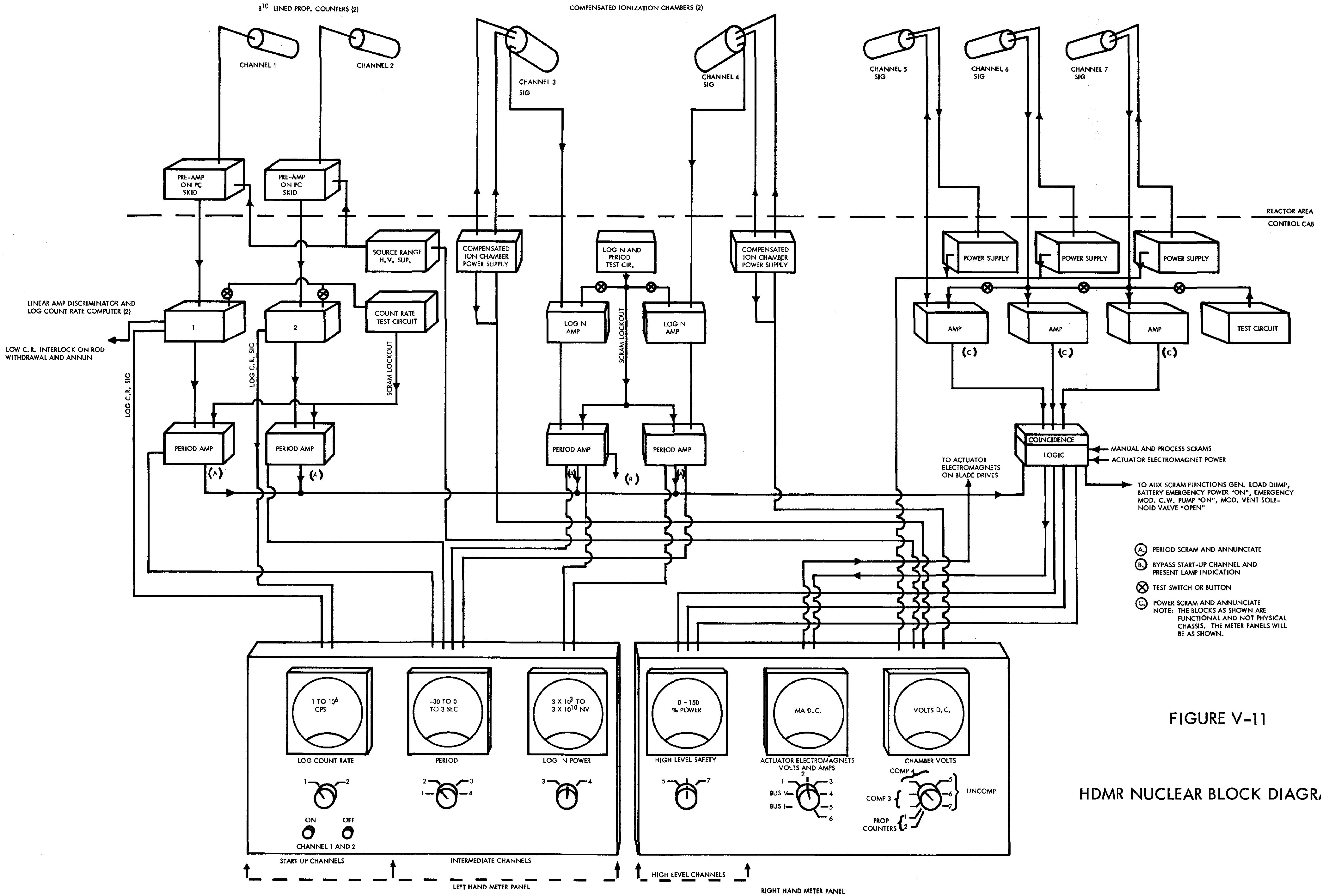


FIGURE V-11

HDMR NUCLEAR BLOCK DIAGRAM

HDMR ELECTRICAL SYSTEM

The HDMR electrical system is composed of two major sub-systems:

1) 60-cycle system: The main generator, driven by the turbine-compressor set through a gear reducer, develops 625 kva of electrical power at 2400/4160 volts at 60 cycles. This output is available, through appropriate protection networks, for direct connection to the load. The plant is capable of net 60-cycle electrical outputs up to 500 kw to connected loads with a 0.8 lagging power factor.

2) 400-cycle system: All plant auxiliary equipment is designed for 400-cycle operation. A 95-kva 400-cycle 277/480 volt generator is provided, driven by the turbine-compressor set to provide this power. Loads on this system are shown in Figure V-12. Note that a 400-cycle auxiliary power unit is provided to supply power during start-up, shutdown and emergencies.

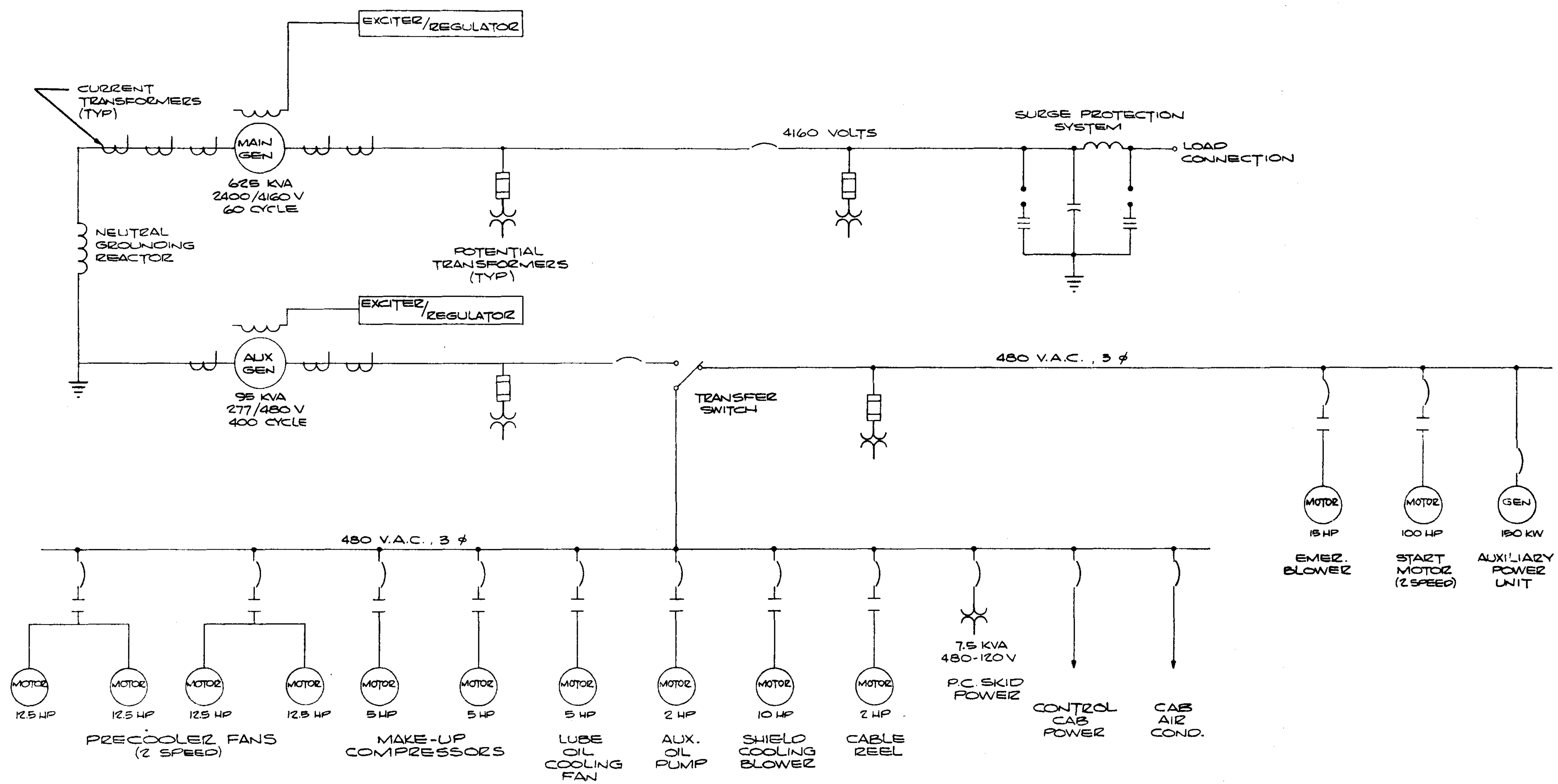


FIGURE V-12

SINGLE LINE DIAGRAM
60 CYCLE POWER PLANT

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POWER CONVERSION PERFORMANCE CHARACTERISTICS

The performance characteristics for the major items of power conversion equipment are presented below. No attemp has been made to include detail design characteristics such as material, quality control, military transport, etc. The characteristics do include, however, the primary performance specifications upon which related equipment depends. Design calculations, substantiated by ML-1 experience, have shown that equipment can be built to satisfy these performance characteristics with existing technology.

A. Turbine-Compressor Assembly (including gear reduction and lubrication system)

1. Performance requirements

   a. Working fluid - air

   b. Flow rate - 87,000 lb/hr

   c. Turbine inlet conditions - 1400°F @ 463 psia

   d. Compressor

      (1) Inlet - 145°F; 171 psia

      (2) Outlet - 421°F; 511 psi

   e. Power output (from gear box) - 500 kw @ 3600 rpm and 80 kw @ 4000 rpm.

2. Special requirements

   a. Seal leakage - total air leakage through seals to ambient shall not exceed 10 lb/hr.

   b. Lubricating oil leakage - there shall be no detectable oil leakage into the process gas.

   c. Lubricating oil cooling - Lubrication system shall include one direct-driven lubrication pump and one auxiliary electric motor-driven lubrication pump. Cooling is by ambient air at 100°F. Heat exchanger to be supplied by others.

   d. Size - The turbine-compressor set, complete with gear box, shall occupy space not larger than a horizontal cylinder 30 in. dia by 48 in. long and shall not weigh more than 3000 lb.

   e. Connections

      (1) Turbine to recuperator - the discharge from the turbine shall be flange-connected to the recuperator.

(2) Inlet to turbine - butt-welded to 8 inch AISI 300 series stainless steel pipe - with 1/2 in. internal insulation of type to be specified later.

(3) Inlet to compressor - butt-welded to 10 inch AISI 300 series stainless steel pipe.

(4) Outlet from compressor - butt-welded to 8 inch AISI 300 series stainless steel pipe.

B. <u>60 Cycle Alternator Assembly</u>

1. Performance requirements

   a. Output power - 625 kva @ 0.8 power factor

   b. Voltage - 2400/4160

   c. Frequency - 60 cycle

   d. Speed - 3600 rpm

2. Special requirements

   a. Design - unit shall be splash proof and cooled by ambient air at 100°F.

   b. Mounting - direct-coupled to turbine-compressor gear box with support from skid floor

   c. Size - maximum dimensions are 38 in. dia by 44 in. long. Maximum weight is 6200 lb.

C. <u>400 Cycle Alternator Assembly</u>

1. Performance requirements

   a. Output power - 95 kva @ 0.8 power factor

   b. Voltage - 277/480

   c. Frequency - 400 cycle

   d. Speed - 4000 rpm

2. Special requirements

   a. Design - unit shall be totally enclosed and cooled by ambient air at 100°F.

   b. Mounting - direct-coupled to turbine-compressor gear box with support from skid floor.

   c. Size - maximum dimensions are 24 in. dia by 44 in. long. Maximum weight is 2000 lb.

D. Precooler Assembly

1. Description - the precooler assembly includes a forced convection, gas-to-ambient air heat exchanger, complete with ambient air side coolant fans.

2. Performance requirements

		Tube side	Shell side
a.	Heat transfer	air	ambient air
b.	Flow (lb/hr)	87,000	*
c.	Inlet temperature (^{o}F)	552	100
d.	Outlet temperature (^{o}F)	145	*
e.	Inlet pressure (psia)	174	14.7
f.	Maximum pressure drop (psi)	3.06	*
g.	Design pressure (psia)	300	

*Note: Ambient side flow rate and pressure drop shall be designed so that total fan horse power does not exceed 50.

3. Special requirements

a. Size - maximum overall dimensions including fans and housings shall not exceed 105 in. by 140 in. by 30 in. deep. Maximum weight shall not exceed 5700 lb.

b. Connections - inlet and outlet shall be butt-welded to 10 in. AISI 300 series stainless stell pipe.

c. Supports - the assembly shall be mounted horizontally on flexible supports.

d. Fan motors - 480 volt, 3-phase, 400 cycle

e. Leakage - external leakage shall be less than 0.5 lb/hr

E. Recuperator

1. Description - this specification covers the requirements for a gas-to-gas heat exchanger.

2. Performance requirements

		Hot side	Cold side
a.	Heat transfer air		
b.	Flow (lb/hr)	87,000	87,000
c.	Inlet temperature (^{o}F)	1,051	421

d.	Outlet temperature (^{o}F)	552	934
e.	Inlet pressure (psia)	178	511
f.	Max. pressure drop (psi)	1.78	5.11

3. Special requirements

   a. Size - maximum overall dimensions shall be 36 in. dia by 54 in. long. Maximum weight shall be 4000 lb.

   b. Connections

      (1) Hot side inlet - flange connected to turbine outlet

      (2) Hot side outlet - butt-welded to 10 in. AISI 300 series stainless steel pipe.

      (3) Cold side - butt-welded to 8 in. AISI 300 series stainless steel pipe.

   c. Leakage - external leakage shall be less than 0.5 lb/hr

F. <u>Emergency Blower Assembly</u>

1. Description - assembly includes a compressor unit with a 400 cycle, ac motor drive for the loss of coolant accident, and an alternate dc motor drive with a throw-out clutch for a normal shutdown.

2. Performance requirements

   a. 400 cycle drive

      (1) Working fluid - air

      (2) Flow rate - 3000 lb/hr

      (3) Inlet conditons - 12.7 psia @ 200^{o}F

      (4) Outlet pressure - 14.7 psia

      (5) Motor characteristics - 480 volts, 3-phase, 400 cycle

   b. DC drive

      (1) Working fluid - air

      (2) Compressor speed - 400 rpm

      (3) Flow rate - 3000 lb/hr

      (4) Inlet conditons - 300 psia @ 200^{o}F

      (5) Motor characteristics - 72 volt, DC

3. Special requirements

   a. Size - the entire assembly shall fit within a cylindrical envelope with a diamter of 32 in. and length of 36 in. Total weight shall not exceed 500 lb.

b. Design pressure - the compressor and motor housing shall be designed for a pressure of 500 psia at 500°F.

c. Connections - inlet and outlet connectors shall be butt-welded.

d. Leakage - external leakage shall be less than 0.25 lb/hr.

e. Maintenance - rotating components shall be removable without disturbing piping.

G. Starting Motor

1. Performance requirements

a. Capacity - 100 hp

b. Voltage - 480, 3 phase

c. Frequency - 400 cycle

d. Speed - 1000 and 2000 rpm

2. Special Requirements

a. Design - unit shall be totally enclosed and cooled with ambient air at 100°F.

b. Mounting - direct coupled to 60 cycle alternator and mounted on end of alternator frame.

c. Size - maximum dimensions are 18 in. dia by 18 in. long. Maximum weight is 400 lb.

TABLE V-2 HDMR REACTOR CORE PERFORMANCE CHARACTERISTICS

1.	Thermal power (Mw)	3.34
2.	Bare core diameter (in.)	16
3.	Bare core height (in.)	16
4.	Coolant	Air
5.	Coolant flow rate (lb/hr)	87,000
6.	Core loading (kg. U-235)	108
7.	Inlet gas temperature (^{o}F)	934
8.	Outlet gas temperature (^{o}F)	1,400
9.	System pressure (psi)	500
10.	Core pressure drop (psi)	25
11.	Core void fraction (%)	15.6
12.	Cycle	Brayton closed regenerative
13.	Maximum cladding hot spot temperature (^{o}F)	1,730
14.	Average ΔT coolant-to-cladding (^{o}F)	210
15.	Aveage coolant velocity through element (ft/sec)	126
16.	Heat transfer surface area (ft^2)	121
17.	Average heat flux (btu/hr-ft^2)	0.905×10^5
18.	Core flow area (in.^{2})	31.4
19.	Volume fraction fuel (%)	42.4
20.	Core structural fraction (vol%)	20.8
21.	Core moderator fraction (vol%)	21.2

TABLE V-3 HDMR SHIELDING PERFORMANCE SPECIFICATIONS

Shutdown Dose Rate at 25 Feet
in Cab Direction
Following 10,000 hr Operation

Source	ML-1 24 hr decay (mr/hr)	HDMR 24 hr decay (mr/hr)	HDMR 12 hr decay (mr/hr)
Fission product gammas	5.0	5.0	6.5
Photoneutrons	1.0 (22.0 flooded)	0.0	0.0
Control rod shaft activation	3.5	1.5	2.7
Plenum and/or baffle can	5.1 1.7	2.0	3.6
Gas duct activation	6.0	3.0	5.4
Tungsten activation	0.8	8.0	12.3
Aluminum canning	4.1	8.2 (no annulus)	14.3
Inner stainless steel can	2.1	3.5	6.2
Moderator duct	1.0	---	---
Control blade slots	1.0	---	---
TOTAL	31.3	31.2	51.0

HDMR VARIABLE LOADING

The HDMR core design contemplates the use of variable uranium loading to optimize the temperature and power distribution in the core. The core is divided into nine regions, three radial and three axial. This requires three different types of fuel pins; each type of pin is divided axially into three regions each with different loading. The diagram below shows the fuel enrichments in percent.

Core Centerline

R → Gas Flow ↓

L ↓

0.850	0.932	0.850
0.510	0.590	0.510
0.355	0.435	0.355

This loading pattern results in the achievement of near-ideal power and temperature distribtuion within the core.

HDMR TEMPERATURE AND POWER DISTRIBUTION

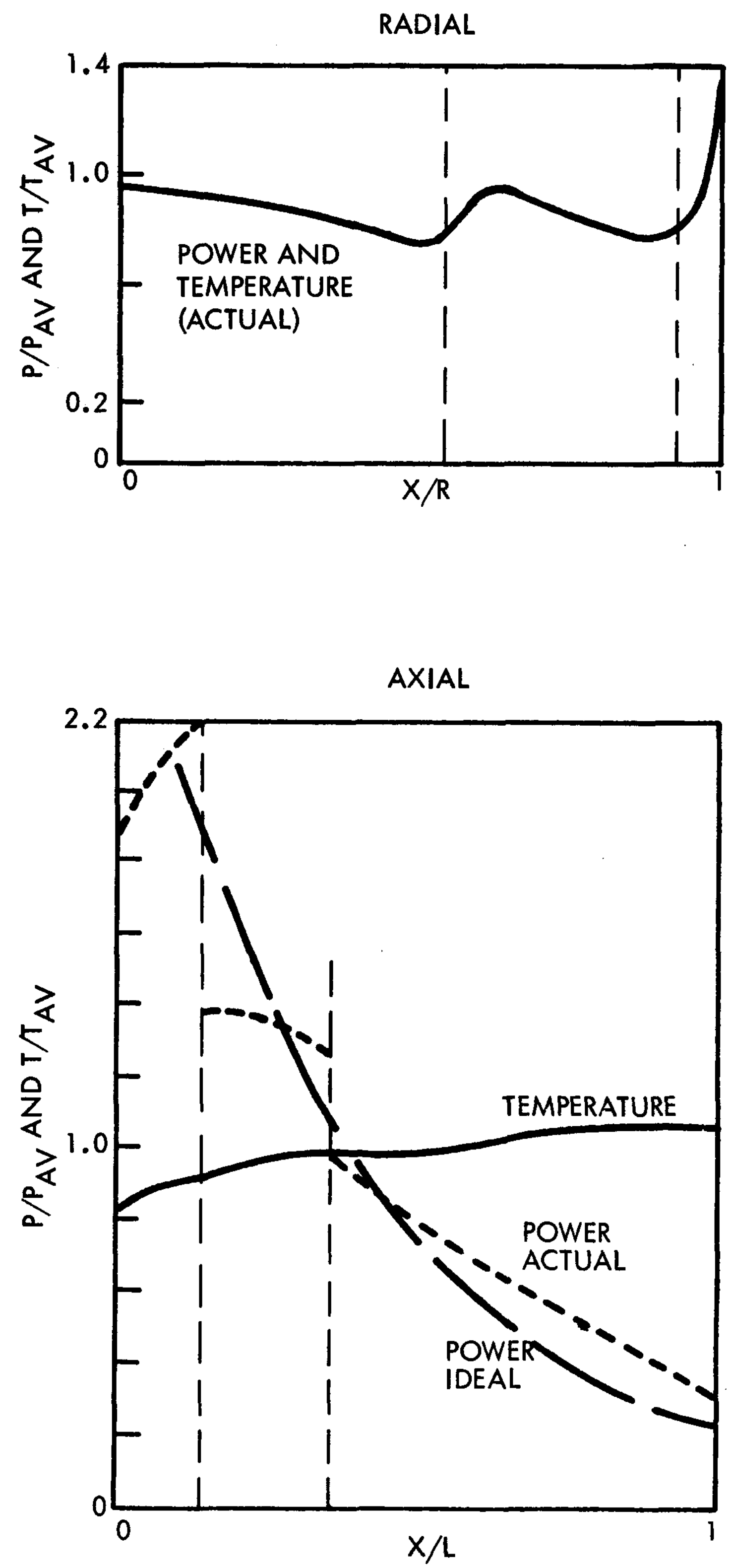

FIGURE V-13

TABLE V-4

This table presents the primary criteria which were applied in the selection of the design concept in the several listed design areas.

HDMR SELECTION CRITERIA

Design Area	Selection	Primary Criteria
Moderator material	$YH_{1.7}$	High temperature capability; maximum moderation.
Coolant	Air	Logistic advantages. Maintenance of oxidation barrier for hydride.
Cycle	Closed regenerative	Minimum reactor size and shield weight.
Compressor ratio	3	Maximum cycle efficiency, minimum reactor and heat exchanger size.
Recuperator effectiveness	0.80	Minimum system weight.
Precooler effectiveness	0.90	Minimum system weight.
Turbine-compressor aerodynamics	Axial turbine, centrifugal compressor	Maximum cycle efficiency; blade height requirements.
Shield requirements	Fully operational shield	Maximum mobility
Reactor active core size	16 x 16 in.	Minimum reactor temperatures consistent with shielding criteria
Duct location	Bottom inlet and exit	Minimum shield weight. Easy reflector cooling.
Reflector material	1.5 in. BeO + 1.5 in. Ni	Maximum reactivity and control. Acceptable shield properties. Best core power distribution.
Reflector location	Inside pressure vessel	Maximum reactivity and control. Easy reflector cooling.
Pressure vessel material	AISI Type 347 stainless steel	Developed technology.
Operating control	Rotating drums in reflector	Best available environment for moving parts; acceptable for reactivity control.

Design Area	Selection	Primary Criteria
Flooding control	U-238 plus hydrogen in core	Inherent control.
Core fuel geometry	Bundle of fuel pins and moderator pins	Negative temperature coefficient; maximum reliability; fission product containment.
Fuel materials	UO_2 in Hastelloy-X	High temperature characteristics; well known technology.
Fuel dimensions	0.347 in. pin diameter	Maximum diameter for acceptable cladding temperatures.
Turbine inlet temperature	1400^oF	Minimum reactor power and flow rate for acceptable clad temperature.
System pressure	500 psi	Minimum reactor temperatures within turbine blade height limitations.
Reactor Δ p/p	5%	Minimum reactor power and flow rate for acceptable clad temperature.
Shield material	W, LiH, Pb	Minimum reactor weight.
Shield cooling	Open cycle air	Mechanical simplicity.
Fuel distribution	Variable enrichment, radial and axial	Minimum clad temperatures.

HDMR BRIDGING CURVE

The bridging curve demonstrates the wide variety of system parameters possible within the general HDMR diameter and core limitations. The operating point selected (turbine inlet temperature = 1400°F; flow rate = 87,000 lb/hr) represents a near minimum for both reactor power and flow rate, and results in minimum reactor weight within material temperature limits. However, considerable flexibility is available to vary the operating point with only very minor effects on flow rate and reactor power should problems be encountered in the development of 1400°F turbomachinery. Note that the bridging curve does not reflect the surface temperature reduction obtained with variable fuel loading.

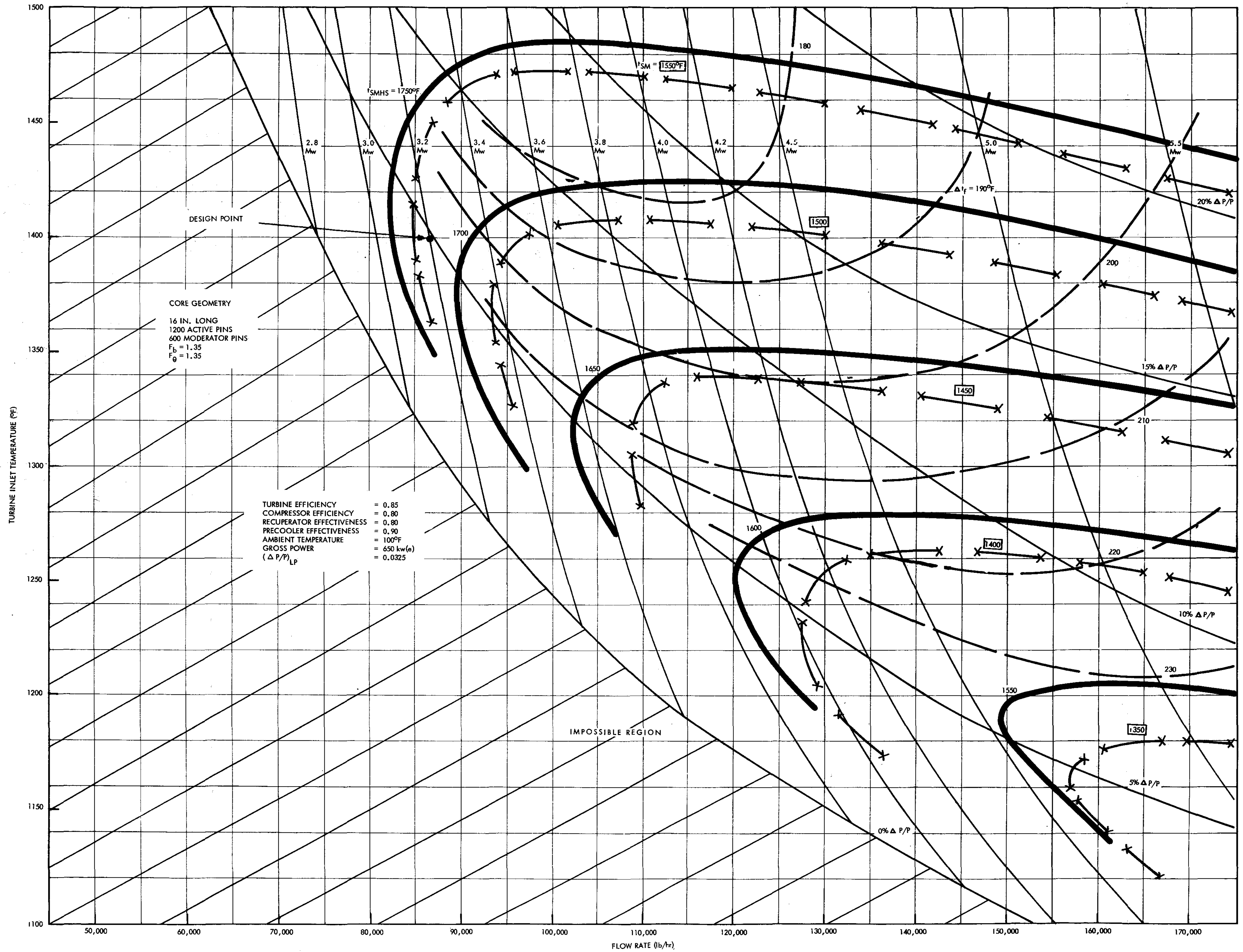

FIGURE V-14

HDMR SYSTEM BRIDGING CURVE

HDMR PROGRAM SCHEDULE

The schedule shown for the HDMR program is conservatively established to provide input from one phase of the program to support the others. For instance, GCRE-II operation is scheduled to occur six months prior to final MLX design approval. This insures that operating experience is factored into MLX prototype plant design. Fuel development continues past the beginning of MLX operation in order to provide test data which lead the irradiation of the prototype MLX fuel element by six months.

The fuel element development project includes all design and development activity, the in-pile test irradiation program and the analytical review of the performance of the fuel in the various experiments as well as during reactor operation.

The critical experiment project includes the design, fabrication and conduct of the experiment.

The GCRE-II project includes the design, fabrication, and installation of the test reactor (solid bar) as well as test operation (dotted bar) in Figure V-15.

The MLX (or HDMR) project includes the design and fabrication of a prototype power plant (solid bar) as well as the test operation of the plant.

HDMR PROGRAM SCHEDULE

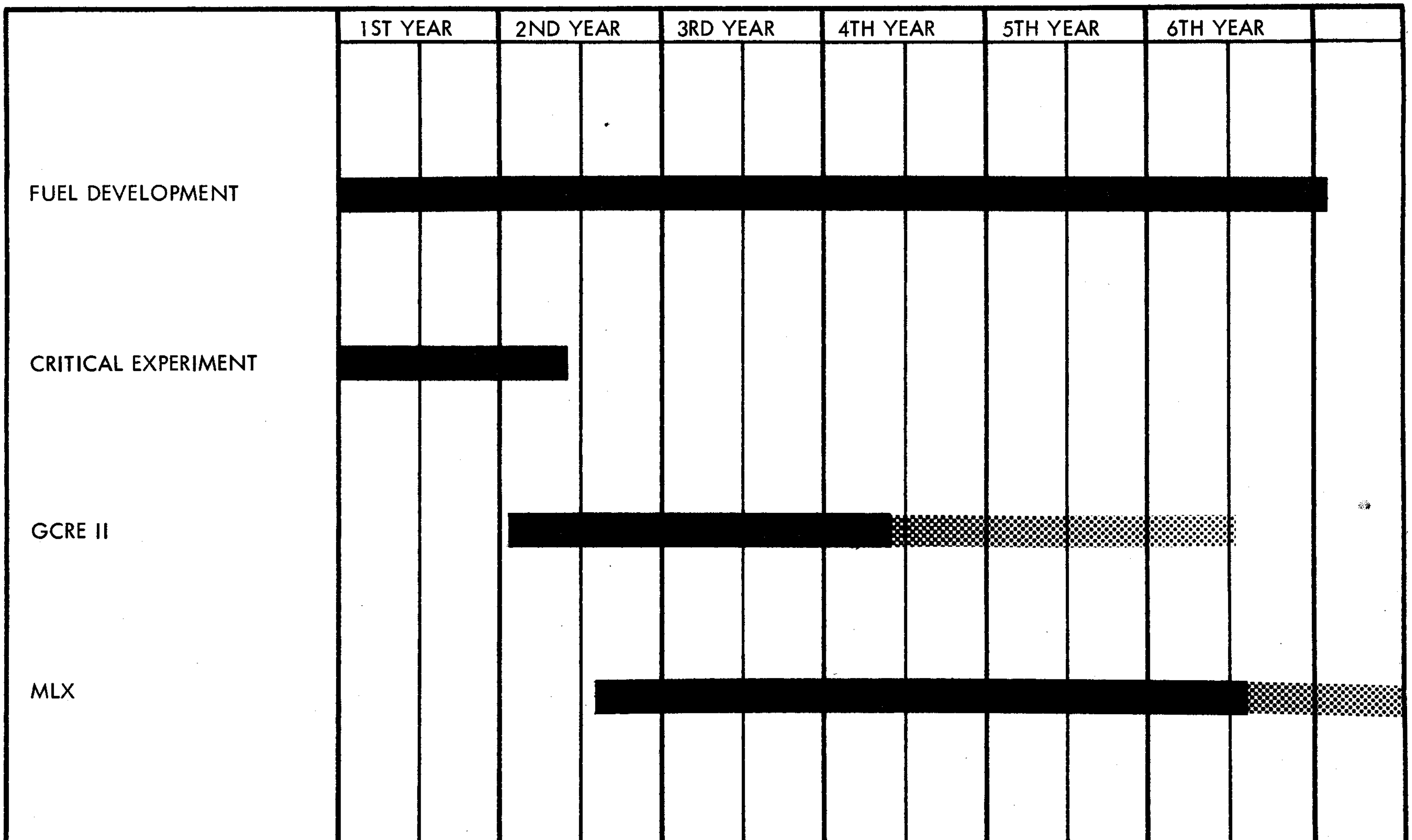

FIGURE V-15

HDMR PROGRAM COSTS

The estimate of HDMR program costs is based upon the following programmatic assumptions:

1) A methodical component development program for power conversion equipment will be undertaken including a "breadboard" test and the integration of the results of such a test into the design of the prototype units.

2) A conservative fuel development program will be undertaken, permitting the completion of desirable tests at each stage in the development before the next stage is initiated.

3) The GCRE-II test reactor will be as nearly a carbon copy of the expected MLX as possible to assure maximum validity of test results.

4) GCRE-II testing will be conducted in a "dry" facility.

5) The instruments and controls design will be a fully integrated and improved, though not radically different, version of the ML-1 design.

The estimate makes provision for only one year of GCRE-II operations and does not include any HDMR power plant test operation.

The last estimates presented were carefully prepared under a set of assumptions which would yield good data for comparison between plant concepts. However, it is pointed out that the estimates do not reflect accurate appraisals of the actual cost of the program and must, therefore, be considered "rough order of magnitude" estimates.

HDMR PROGRAM COSTS

(Thousands of Dollars)

DEVELOPMENT		
Fuel		$ 4378
Reactor		665
Power Conversion		6220
Controls		700
Critical		358
	Total Development	12,321
GCRE-II		
Facility		2500
Reactor		1680
Fuel		457
Operations		1000
	Total GCRE-II	5637
MLX		
Reactor		2270
Fuel		457
Power Conversion		1425
Controls		500
Auxiliaries		70
	Total MLX	4722
	Program Total	$22,700

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VI. FAST PLANT DESCRIPTION

A. GENERAL

The MLX power plant designed around the fast reactor has many of the same characteristics as the HDMR. The shielding required for full power operation is an integral part of the reactor skid. The reactor package, power conversion package, control cab, and auxiliary equipment are the same as for the HDMR. The only basic difference between the two plants is in the reactor core design. The plant layout is shown in Figure VI-1.

The fast system is unmoderated. As a consequence, moderator material temperature limitations do not pose a problem and no volume must be allocated to non-heat generating surfaces. The result is that the fast system can develop relatively high outlet temperatures. The design outlet temperature of the optimum fast reactor is 1450°F. At this temperature, the Hastelloy-X fuel cladding hot spot is 1750°F. Other system state points and the system flow diagram are shown in Figure VI-2.

The core of the fast reactor is composed of a bundle of fuel-containing pins which form a right circular cylinder 14 inches in diameter and 14 inches in height. The fuel is ceramic uranium nitride, approximately 42% enriched. The pins are supported in the same manner as in the HDMR.

The radial reflector is four inches thick, consisting of 2 inches of beryllia and 2 inches of nickel. Twelve rotating control drums in the reflector provide reactivity control.

The basic reason for the failure of the fast reactor to qualify as the optimum MLX system is that insufficient control exists to overcome the reactivity increase associated with water flooding. This is true even though low enrichment fuel is used in combination with the most effective control concept.

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B. DETAILED DESCRIPTION

Beginning on page 66 are descriptions of the major systems, components and characteristics of the fast power plant in the format described in Section IV. The following tabulation and index is provided for the convenience of the reader.

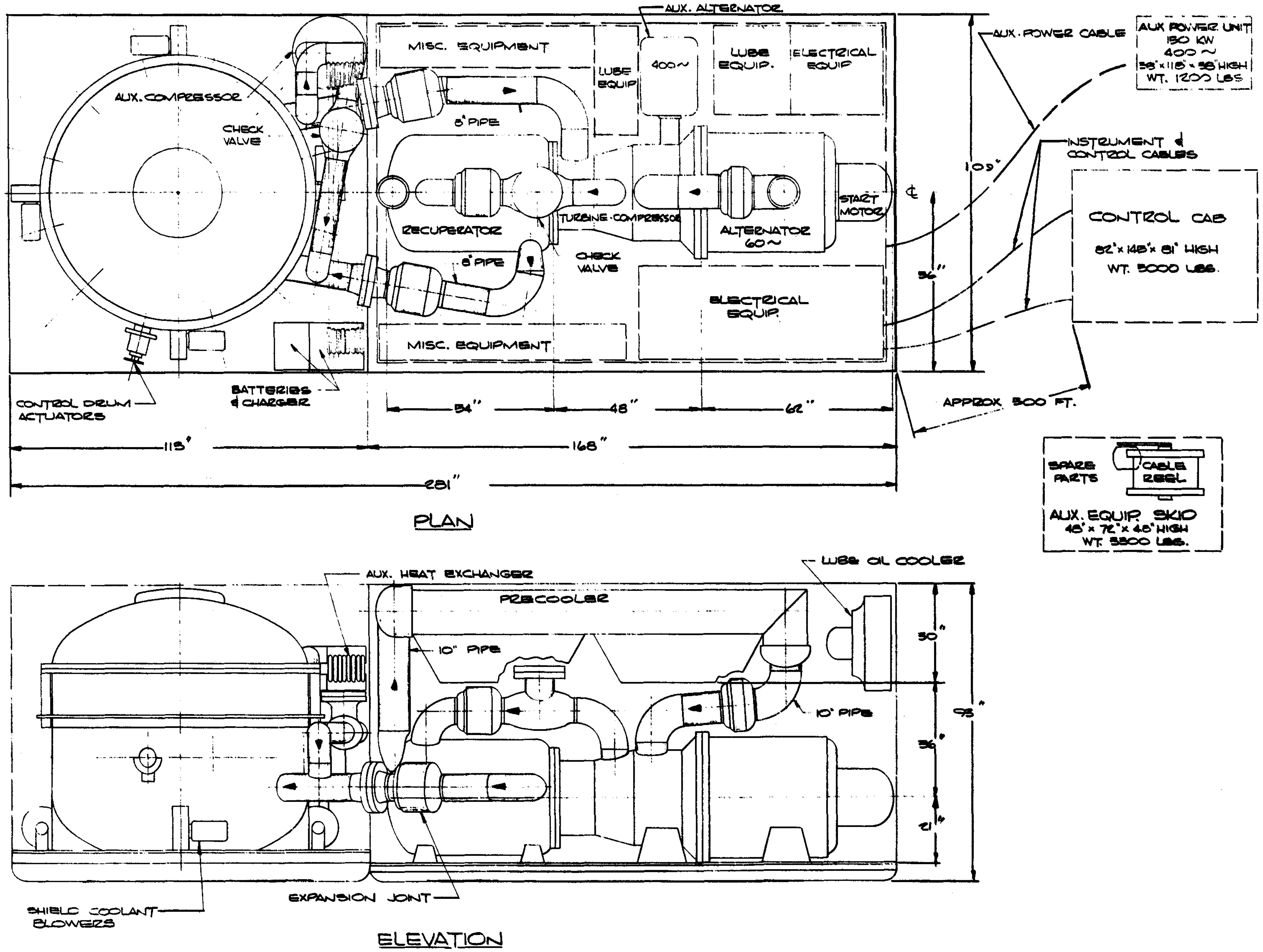
TABLE VI-1

TABULATION AND INDEX

FAST SYSTEM PLANT LAYOUT

The fast power plant consists of two major skids, a control cab, and two small auxiliary skids. The power plant is self-sufficient in the field for an operating period of one year. The two major skids can be separated for air transport or coupled for land transport. The truck convoy required consists of one tractor and trailer (M-172 or M-172-A-1) and three standard 2-1/2 ton trucks (M-35).

Sufficient radiation shielding is incorporated integrally on the reactor skid to permit operation from the control cab 500 feet away and to permit the plant to be transported 18 hours after shutdown following extended operation.



WEIGHT SUMMARY

REACTOR SKID		
SHIELD	18850	
PRESS VESSEL & CORE	5100	
CONTROL DRIVES & ACTUATORS	1200	
STRUCTURE	3700	
SHIELD COOLING BLOWERS	160	
AUXILIARY COOLING SYS.	1700	
		30710
POWER CONVERSION SKID		
TURBINE COMPRESSOR	3000	
RECUPERATOR	4000	
PRECOOLER	5700	
ALTERNATOR	6200	
START MOTOR	400	
LUBE SYSTEM	800	
AUX. ALTERNATOR	200	
STRUCTURE & ACC.	2800	
ELECTRICAL EQUIP.	3150	
PIPING & MISC.	2500	
		28460
CONTROL CAB		5000
AUX. POWER UNIT		1200
AUX. EQUIP. SKID		5500
TOTAL		68,660

FIGURE VI-1

FAST REACTOR PLANT LAYOUT

FAST SYSTEM FLOW DIAGRAM

The fast power plant uses air as a working fluid in a closed Brayton cycle with regeneration. The cycle state points and characteristics are listed below:

	Temperature (^{o}F)	Pressure (psia)
Compressor inlet	146	171
Compressor outlet	422	511
Reactor inlet	968	500
Reactor outlet	1450	463
Turbine outlet	1100	178
Precooler inlet	563	175

Core Δ P/P - 5%

Flow rate - 7.95×10^4 lb/hr

Reactor power (to gas) - 3.04 Mw

Recuperator heat load - 11.0×10^6 Btu/hr

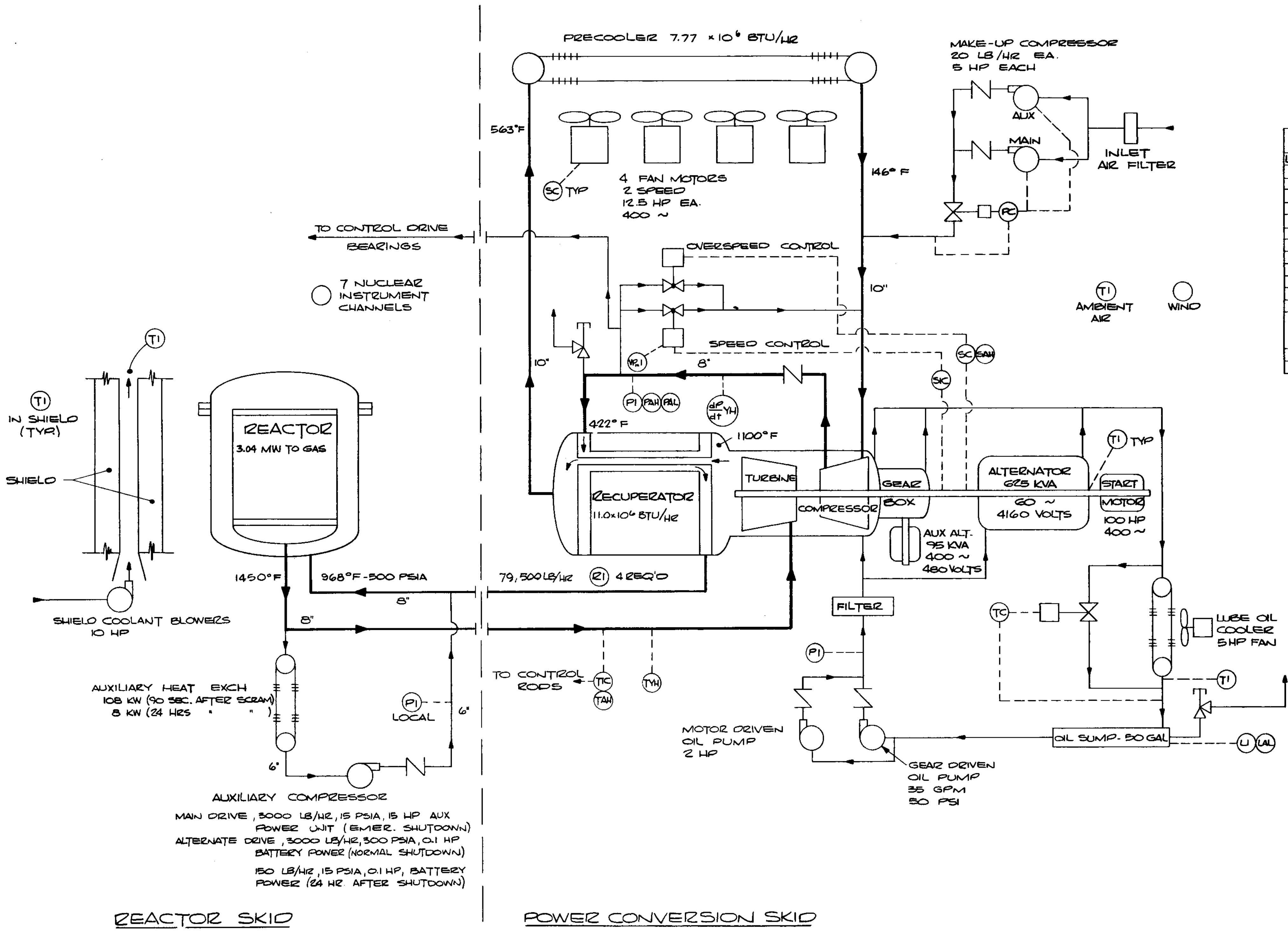
Precooler heat load - 7.77×10^6 Btu/hr

Power kw(e) - 575 gross; 500 net

Shield integral or separate - Integral

Reactor blower and power required - Emergency blower, 11 kw

Precooler fans and power required - Four 2-speed fan motors, 12.5 hp each, total 38 kw



INSTRUMENT SYMBOLS

LETTER	1ST LETTER	2ND LETTER	3RD LETTER
A		ALARM	
C		CONTROL	CONTROL
I		INDICATING	
L	LEVEL		LOW
P	PRESSURE		
P_o		POSITION	
R	RADIATION	RECORDING	
S	SPEED		
T	TEMPERATURE		
V	VALVE		
Y		SCRAM	SCRAM
H			HIGH
$\frac{dP}{dt}$	RATE OF PRESS CHANGE NEG.		
d	SUBSCRIPT REFFERING TO DIFFERENTIAL		
e	" " " ERROR		

FIGURE VI-2

FAST FLOW DIAGRAM

FAST REACTOR FUEL PIN

The basic element of the fast reactor core is a 0.35 inch diameter pin with a fueled length of 14 inches. The cladding is modified Hastelloy-X, 0.030 inches thick.

The fuel is UN ceramic in the form of pellets. The average fuel enrichment is 42%. A spiral spacer is provided on the outside diameter of the pin. This spacer contacts adjacent pins, maintains the correct core geometry for the proper coolant flow, and eliminates pin movement. The radial height of this spacer is 0.007 in. The pin is supported from the top.

Heat transfer parameters for the fuel pin are listed in Table VI-2.

FAST FUEL PIN

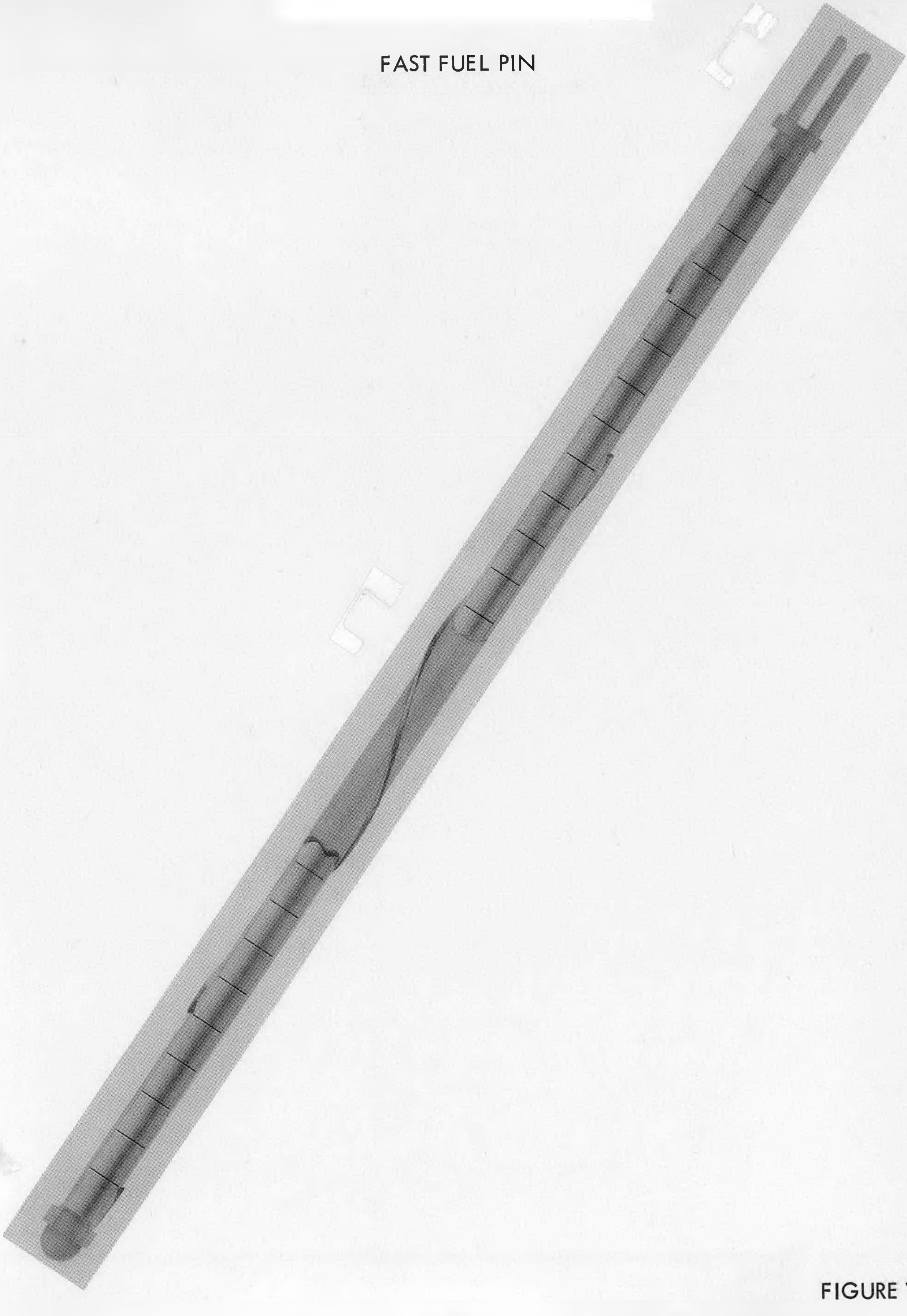


FIGURE VI-3

FAST PIN CLUSTER

The fuel pins in the fast reactor are supported in clusters. The major support members are rectangular cross-section beams to which the pins are fastened. Vertical support is provided only at the top where the pins are held to the beams by a welded joint.

The beams from which the pins are supported are formed in units, with several beams to a unit. These units are supported at the ends.

The pin diameter is increased at the lower end of the core to provide pin-to-pin contact. The core shroud contacts the outermost pins at operating temperature and provides lateral core constraint.

FAST PIN CLUSTER

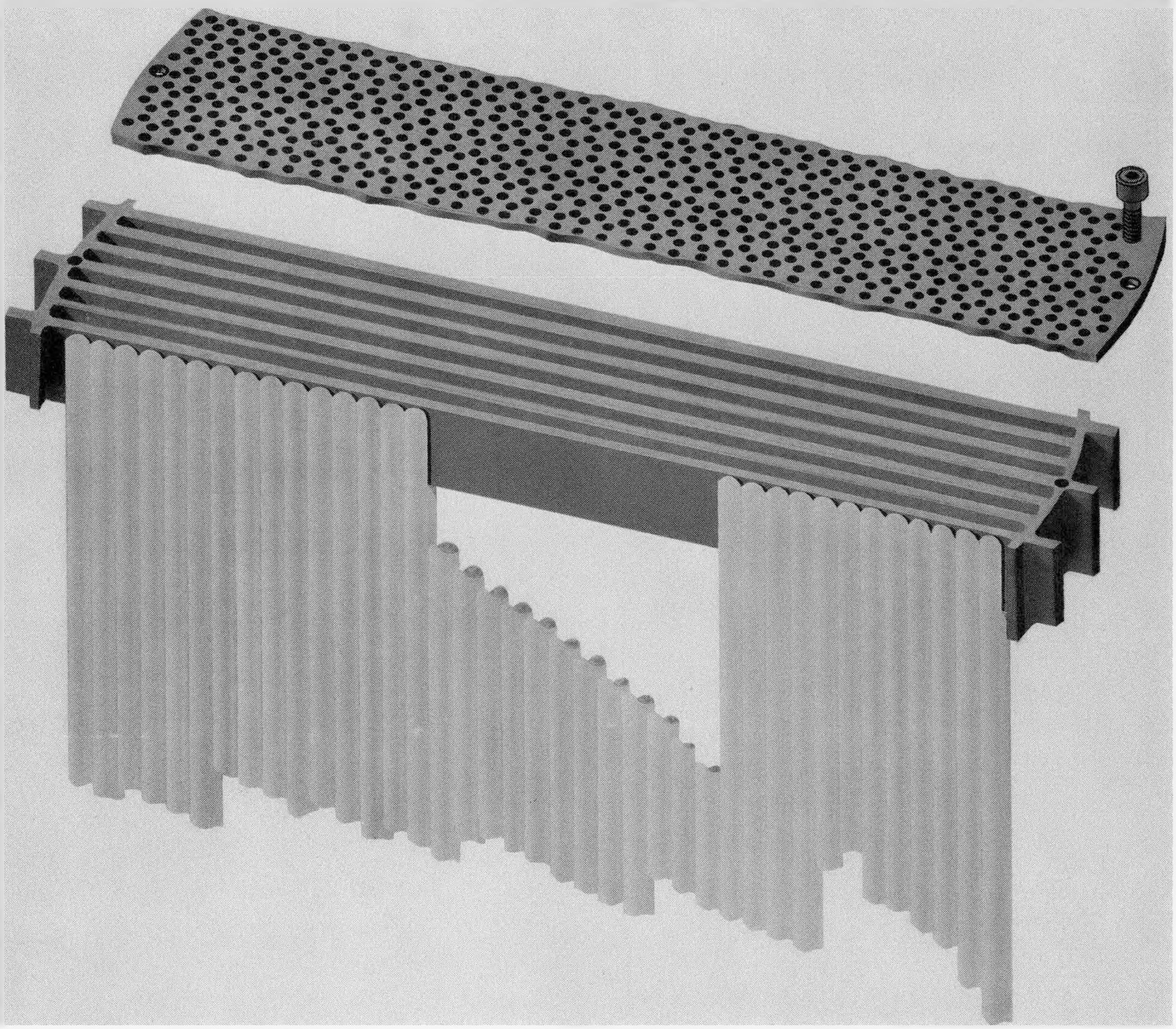


FIGURE VI-4

FAST REACTOR CORE

The fast reactor core is a cylinder 14 inches in diameter and height, composed of 1345 pins. A thin metal shroud separates the incoming and outgoing gas flows and surrounds the pin bundle.

A 4 inch thick radial reflector encloses the core and shroud. The reflector is composed of 2 inches of beryllia and 2 inches of nickel. Twelve control drums are contained in the reflector. The reflectors are supported by bolted tie rods and, in turn, support the pin clusters.

The control drums are identical with those in the HDMR.

FAST REACTOR CORE

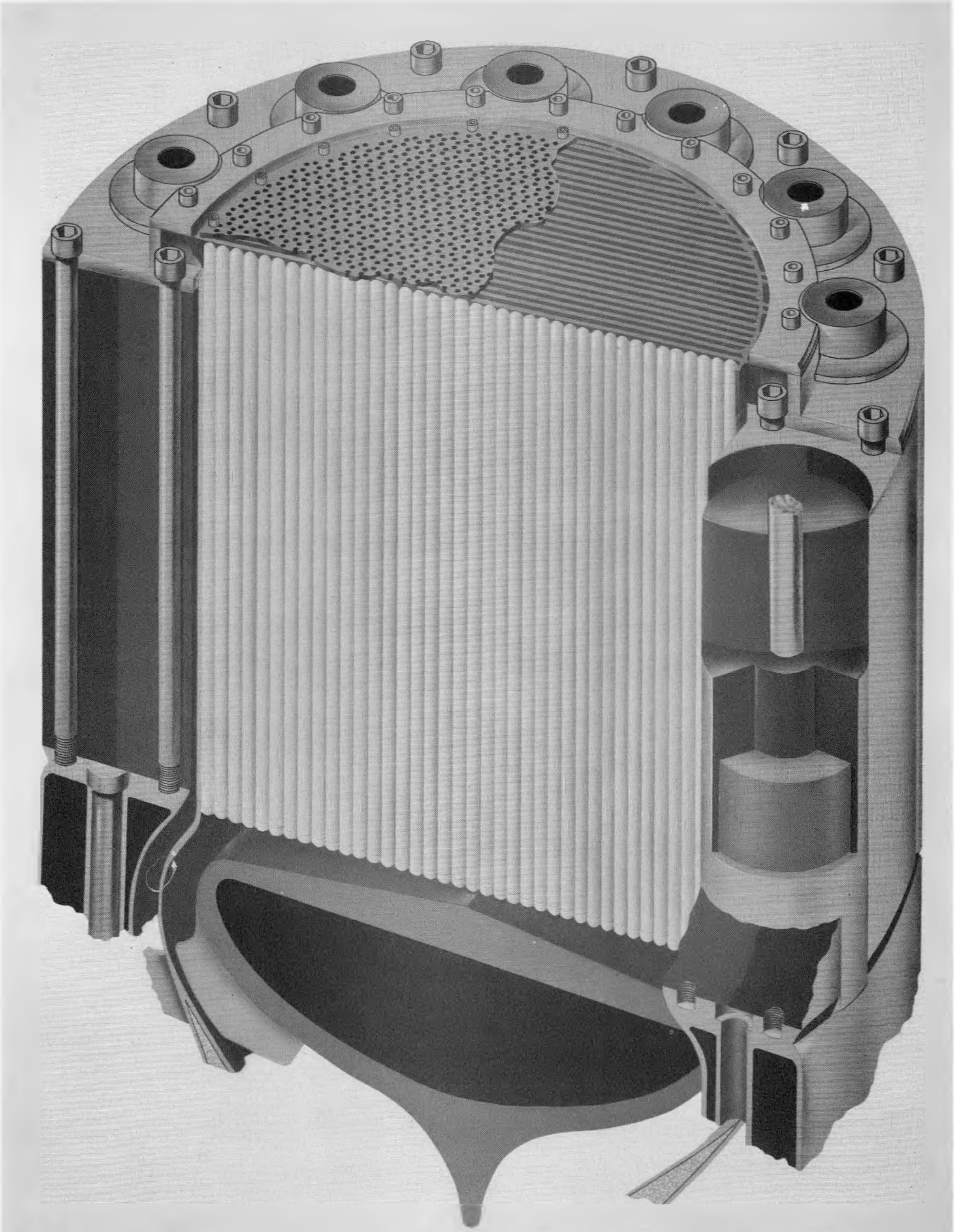


FIGURE VI-5

FAST REACTOR PRESSURE VESSEL

The fast reactor pressure vessel is fabricated from AISI Type 347 stainless steel. Axial tungsten shielding baffles are incorporated inside the vessel. The right-angle control drum drives are attached to the pressure vessel near the bottom. The pressure vessel closure flange is at the top; the inlet and exit coolant ducts are at the bottom.

Gas flow enters from the bottom and is diverted around the reflectors to provide cooling. The gas then flows downward through an orifice plate and the reactor core, around the lower baffle and out the internally insulated exit duct.

FAST REACTOR PRESSURE VESSEL

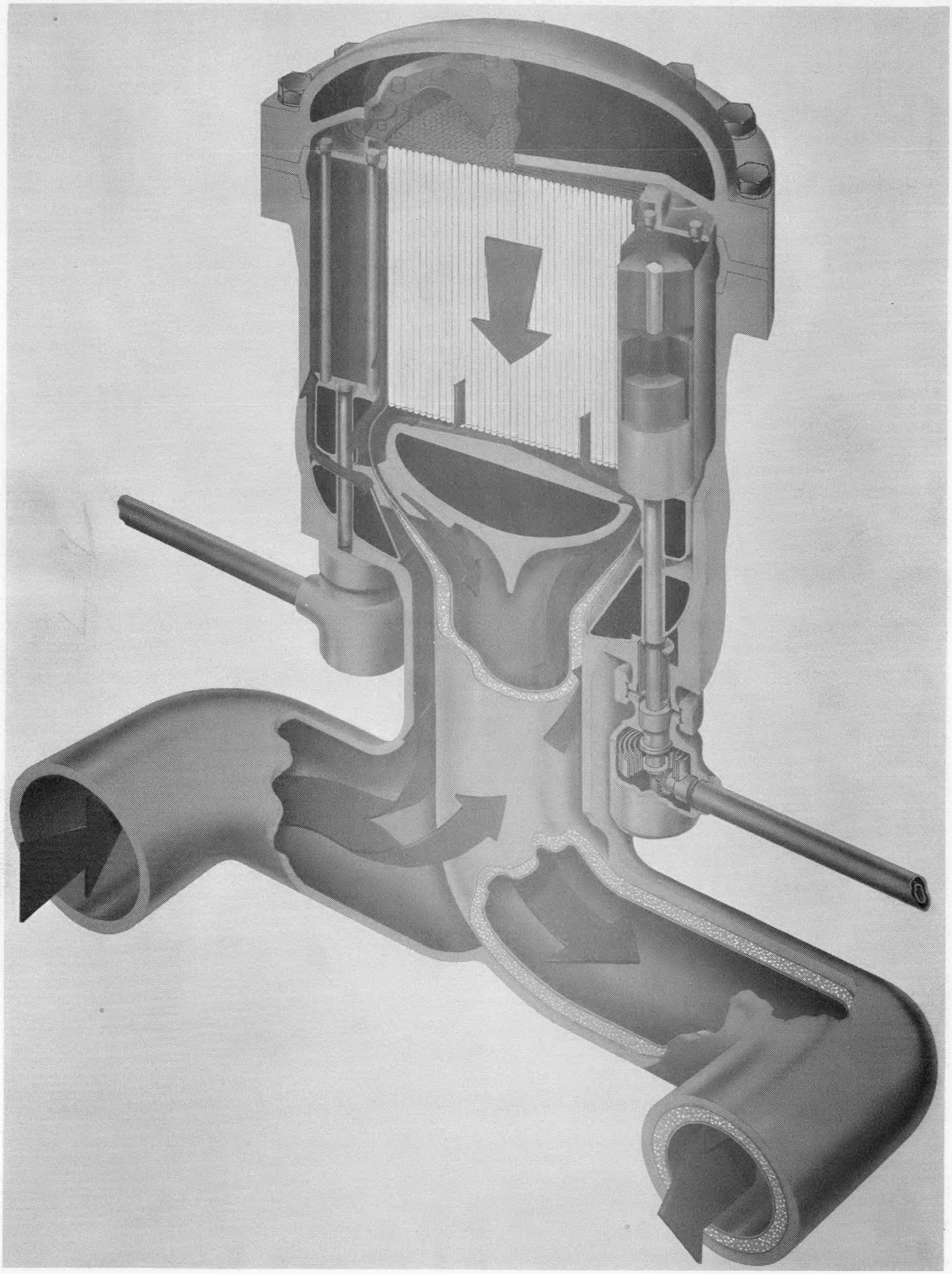


FIGURE VI-6

FAST REACTOR PACKAGE

Tungsten, the primary gamma ray shielding, surrounds the core, radially, adjacent to the pressure vessel. Lead is used outside of the tungsten shield in the regions where tungsten activation would present a shutdown activation problem.

Shielding of fission-born neutrons during operation and photoneutrons from the beryllia reflector after shutdown is provided by lithium hydride. The tungsten, lead and lithium hydride are cooled during operation by air delivered by three shield cooling blowers located at the bottom of the package. A fourth blower is provided as a spare. The air flows upward through the shield and is exhausted through vents in the top of the package.

Twelve electrically-energized actuators drive the twelve control drums through the right-angle drives. The mechanisms are located external to the shielding, as shown, for easy access.

The overall package dimensions are:

Length	113 in.
Width	109 in.
Height	90 in.

The package weighs 30,710 pounds.

FAST REACTOR PACKAGE

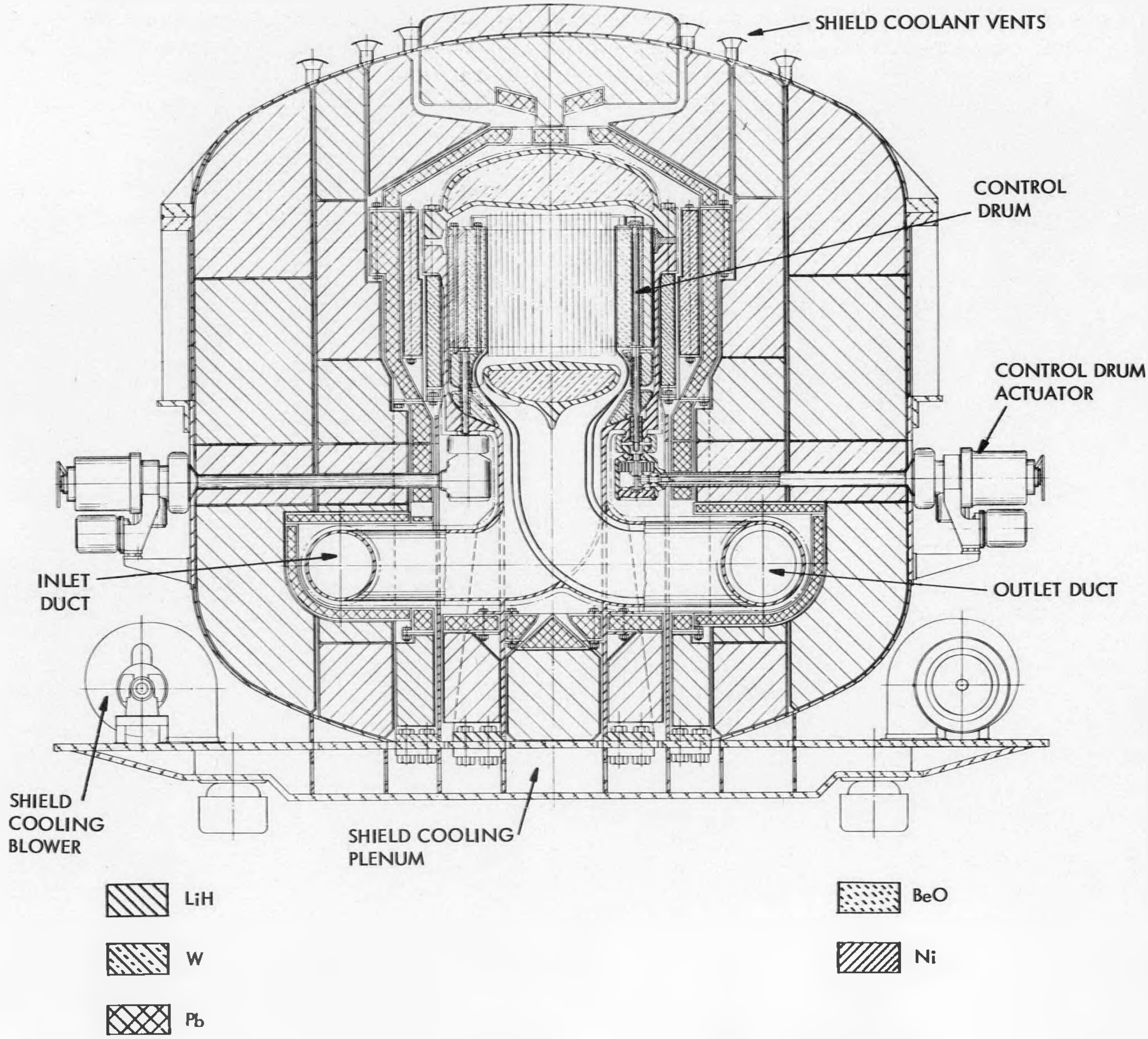


FIGURE VI-7

FAST SYSTEM FISSION SPECTRUM

The accompanying graph shows the spectrum of neutrons causing fission for the fast system. Virtually all fissions take place in the very high energy region. The mean energy of fission-causing neutrons is 300 Kev.

Under flooded conditions this spectrum is softened. Increases in U-238 pararitic absorption and the decrease in U-238 fast fission are insufficient, however, to compensate for the positive effect resulting from increased moderation and decreased leakage. The net effect is a positive reactivity change.

FAST SYSTEM NEUTRON FLUX

The neutron flux spectrum is normalized to 100 watts for comparison with other systems.

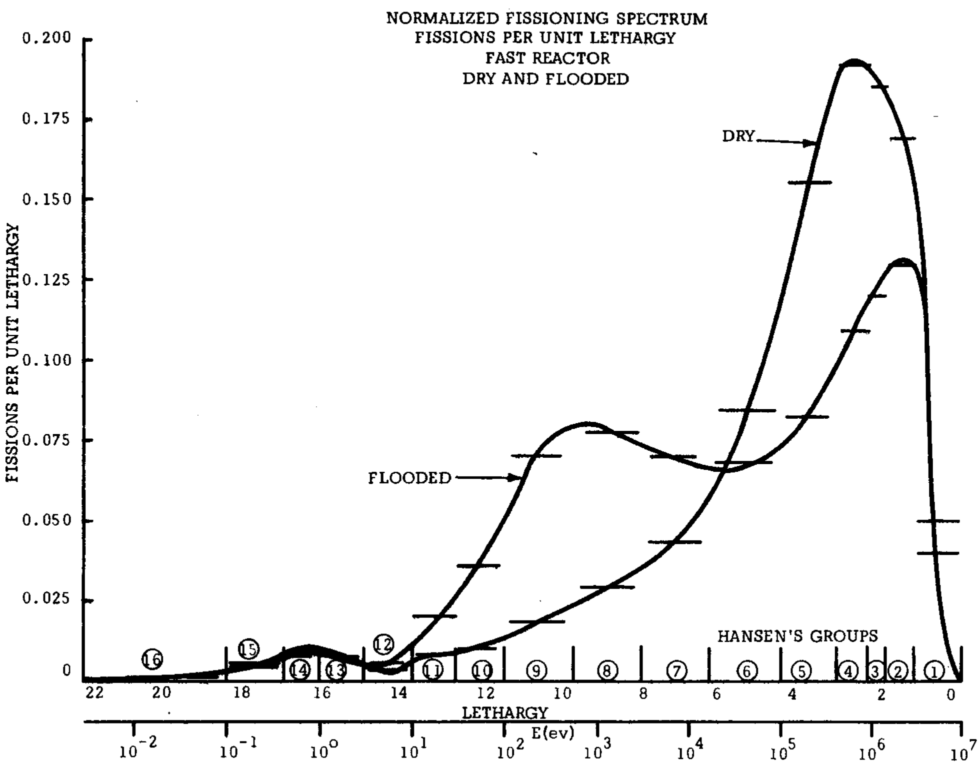


FIGURE VI-8

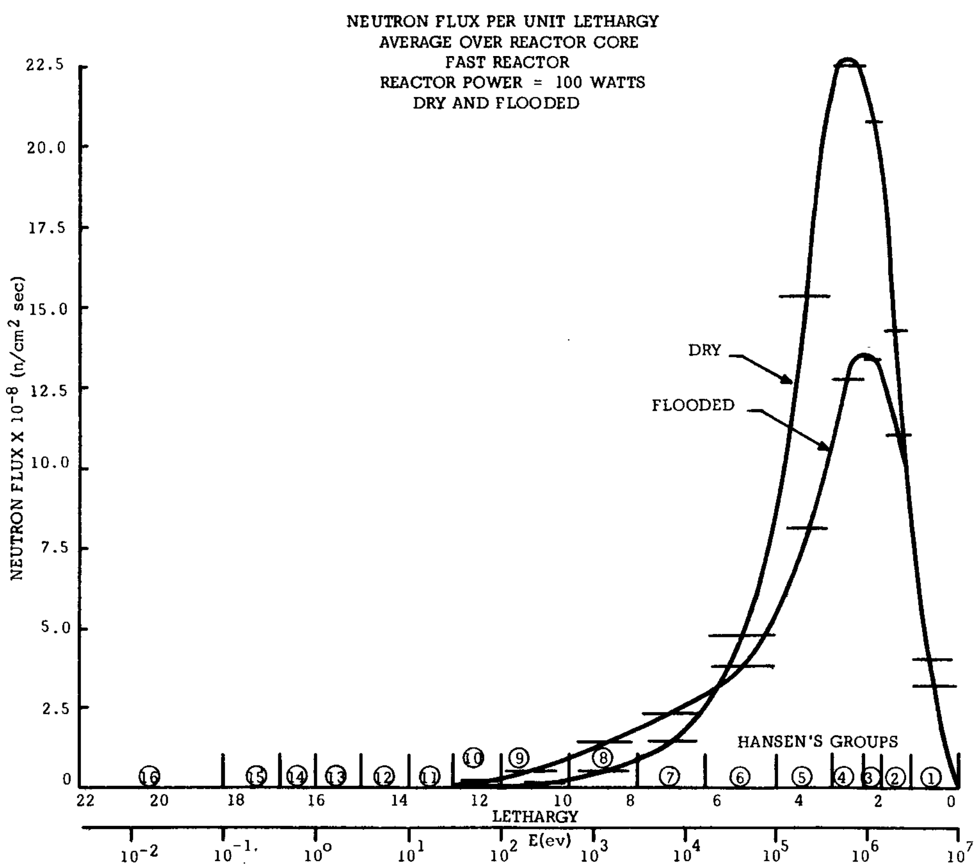


FIGURE VI-9

FAST SYSTEM CONTROL DRUM ACTUATOR

The control drum actuators for the fast system are identical with those for the HDMR with two exceptions:

1) Each mechanism drives only one drum.

2) The gear housings are joined to the pressure vessel with a Grayloc seal and, thus, the disassembly procedure for maintenance is slightly altered.

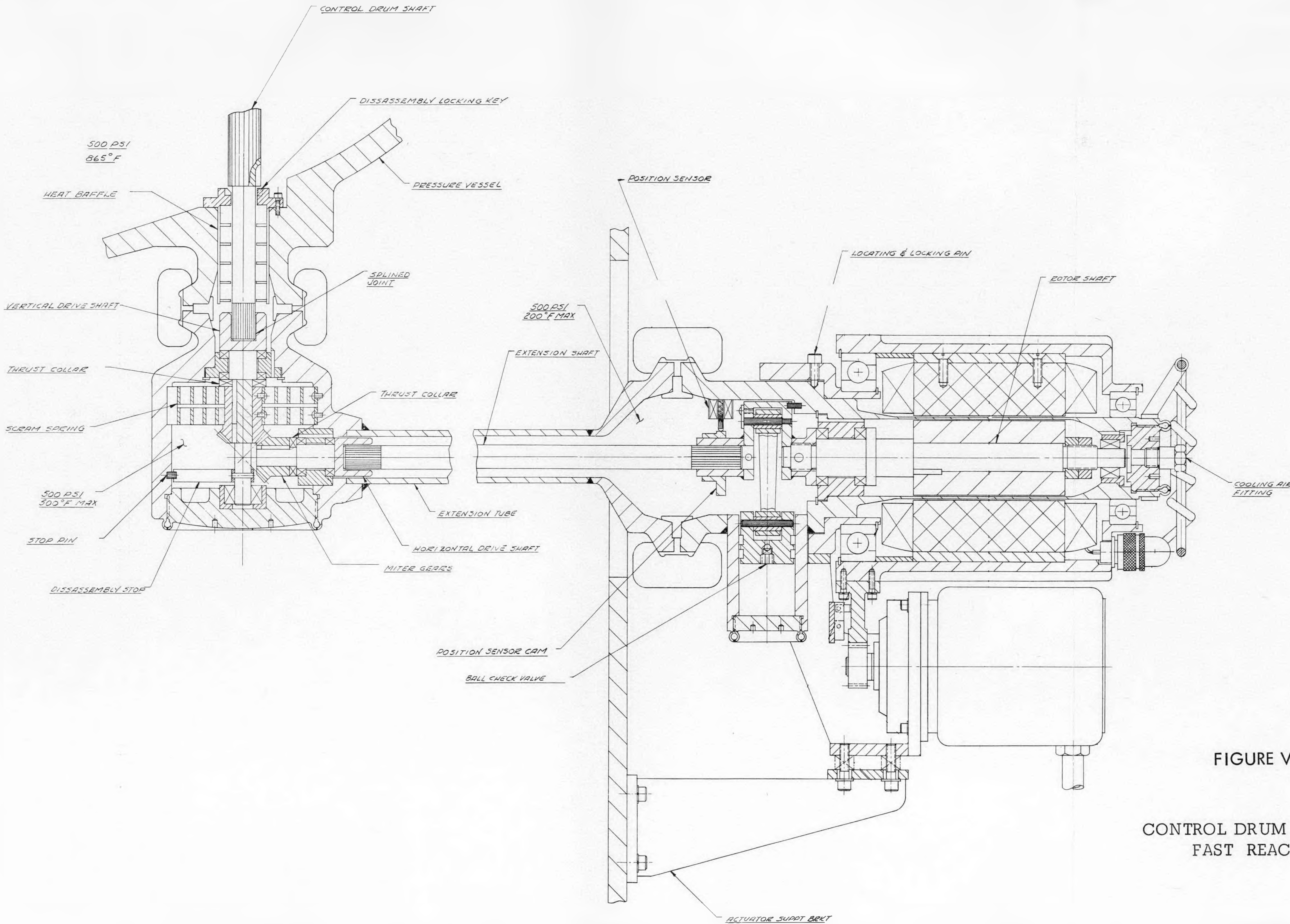


FIGURE VI-10

CONTROL DRUM ACTUATOR
FAST REACTOR

FAST SYSTEM NUCLEAR INSTRUMENTATION SYSTEM AND ELECTRICAL SYSTEM

These systems are identical with those described in the HDMR section of this report (Figures V-11 and V-12).

POWER CONVERSION SYSTEM PERFORMANCE CHARACTERISTICS SHIELDING PERFORMANCE CHARACTERISTICS

These characteristics are identical with those described in the HDMR section of this report (page 41).

TABLE VI-2

FAST CORE PERFORMANCE CHARACTERISTICS

1.	Thermal power (Mw)	3.75
2.	Bare core diameter (in.)	14
3.	Bare core height (in.)	14
4.	Coolant	Air
5.	Coolant flow rate (lb/hr)	79,500
6.	Core loading (kg U-235)	100
7.	Inlet gas temperature (^oF)	966
8.	Outlet gas temperature (^oF)	1450
9.	System pressure (psi)	500
10.	Core pressure drop (psi)	25
11.	Core void fraction (%)	13
12.	Cycle	Closed regenerative
13.	Maximum cladding hot spot temperature (^oF)	1690
14.	Average Δ T coolant-to-cladding (^oF)	150
15.	Average coolant velocity over fuel (ft/sec)	196
16.	Heat transfer surface area (ft^2)	149
17.	Average heat flux (Btu/hr/ft^2)	0.7×10^5
18.	Core flow area ($in.^2$)	20
19.	Volume fraction fuel (%)	57.7
20.	Core structural fraction (Vol%)	29.3

TABLE VI-3

FAST SYSTEM SELECTION CRITERIA

This table presents the primary criteria which were applied in the selection of the design concept in the several listed design areas.

Design Area	Selection	Primary Criteria
Moderator material	None	Minimum reactor size
Coolant	Air	Logistic advantages
Cycle	Closed-regenerative	Minimum reactor size and shield weight
Compressor ratio	3.0	Maximum cycle efficiency; Minimum reactor and heat exchanger size
Recuperator effectiveness	0.80	Minimum system weight
Precooler effectiveness	0.90	Minimum system weight
Turbine-compressor aerodynamics	Axial turbine centrifugal compressor	Maximum cycle efficiency; blade height requirements
Radiation criteria	Integral operational shield	Maximum mobility
Reactor active core size	14 in. x 14 in. active core	Minimum reactor temperatures consistent with shielding criteria
Duct location	Bottom inlet and exit	Minimum reactor shield weight
Reflector material	2 in. BeO - 2 in. Ni	Maximum reactivity, best core power distribution, acceptable shield properties
Reflector location	Inside pressure vessel	Maximum reactivity, easy cooling
Pressure vessel material	AISI Type 347 stainless steel	Developed technology
Operating control	Rotating drums in reflector	Best available environment for moving parts
Flooding control	Not practical	Inherent control
Core fuel geometry	All pins	Negative temperature coefficient; fission product containment, maximum reliability

FAST SYSTEM SELECTION CRITERIA (Condinued)

Design Area	Selection	Primary Criteria
Fuel materials	UN in Hastelloy-X	High temperature characteristics; high uranium density
Fuel dimensions	0.350 in. pin diameter	Maximum diameter for acceptable cladding temperature
Turbine inlet temperature	$1450^{o}F$	Minimum reactor power and flow rate for acceptable cladding temperatures
System pressure	500 psi	Minimum reactor temperatures within turbine blade height limitations
Reactor ΔP	5%	Minimum reactor power and flow rate
Shield material	Tungsten, lead and lithium hydride	Minimum reactor weight
Shield cooling	Open cycle air	Mechanical simplicity
Fuel distribution	Uniform	Minimum clad temperatures; simple fabrication

FAST SYSTEM PROGRAM SCHEDULE AND PROGRAM COSTS

The descriptive information presented in the HDMR section of this report (Figures V-15 and Table V-5) applies also to the schedule and cost estimate shown on the following pages. (Figure VI-11 and Table VI-4).

FAST PROGRAM SCHEDULE

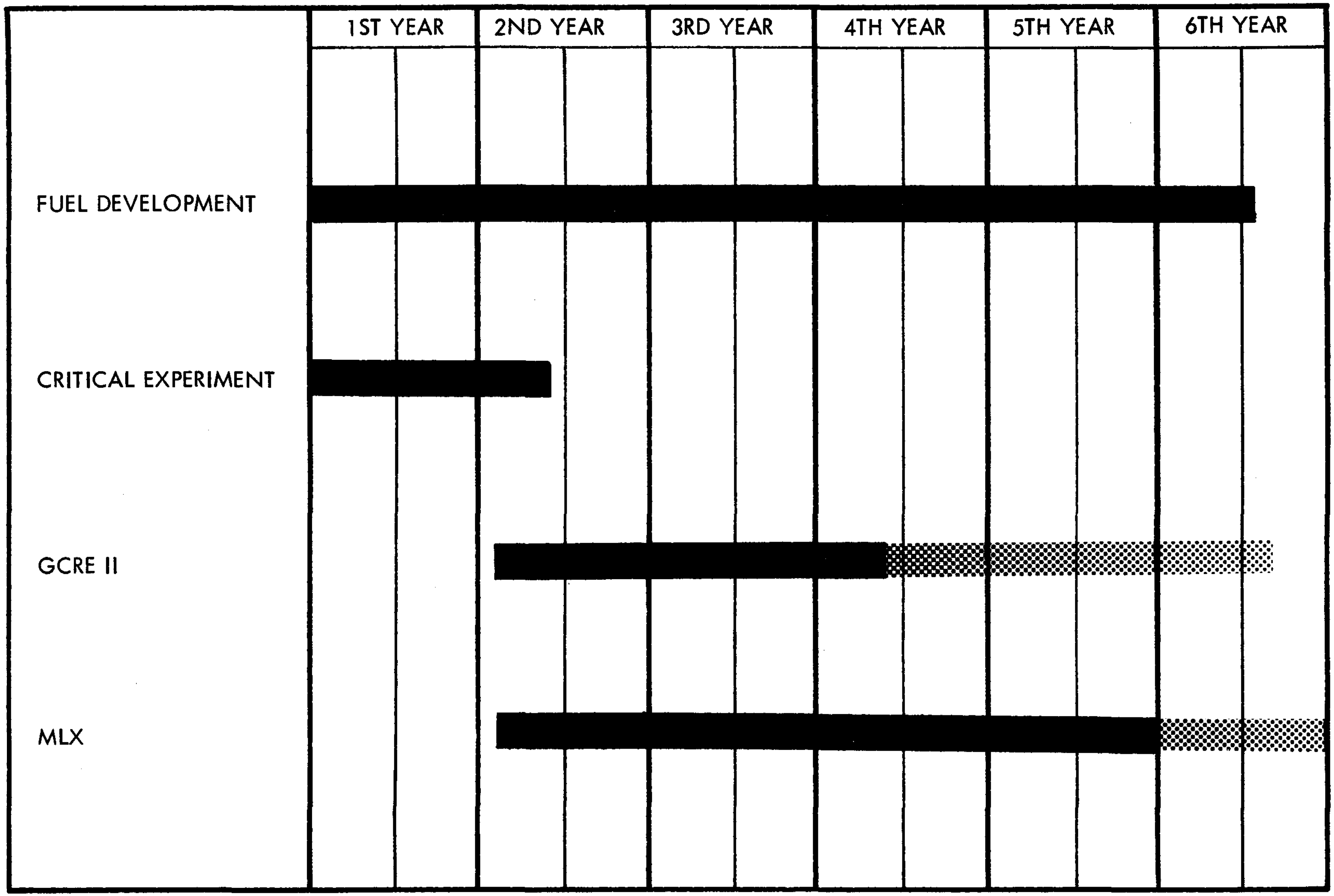


FIGURE VI-11

TABLE VI-4

FAST PROGRAM COSTS

(Thousands of Dollars)

DEVELOPMENT		
Fuel		$ 3600
Reactor		665
Power Conversion		6220
Controls		700
Critical		358
	Total Development	$ 11,543
GCRE II		
Facility		$ 2500
Reactor		1505
Fuel		515
Operations		1000
	Total GCRE II	$ 5520
MLX		
Reactor		$ 2095
Fuel		516
Power Conversion		1425
Controls		500
Auxiliaries		70
	Total MLX	$ 4606
	PROGRAM TOTAL	$ 21,700

VII. BeO PLANT DESCRIPTION

A. GENERAL

The MLX power plant designed around the BeO moderated reactor is similar in many respects to the HDMR and Fast plants described earlier. The power cycle and the power conversion equipment are identical except that temperatures are somewhat lower. The control cab and the auxiliary equipment skid are identical. The BeO plant includes an additional skid for storage and transport of the removable operational shield. The configuration of the reactor skid is different and the design of the reactor includes several significant deviations from the HDMR concept.

The reactor delivers 1300°F air to the turbine. The cycle efficiency is about 18% and the net plant thermal efficiency is 13.9%. The total plant weight, including the removable shielding is 85,500 lbs. The plant layout is shown in Figure VII-1 and the flow diagram, with state point data, in Figure VII-2.

The reactor core is composed of a bundle of fuel containing Hastelloy-X pins which form a right circular cylinder 20 inches in diameter and 20 inches high. The fuel, moderator and diluent are homogeneously mixed in the fuel pin pellets. The fuel is UO_2, the moderator is BeO and the diluent is Gd_2O_3.

Nickel is loaded into the top and bottom of each fuel pin to serve as an axial reflector. The radial reflector is nickel and beryllium oxide. Twelve rotating control drums are provided in the reflector. The shield is composed of tungsten, lead and lithium hydride. The shield is cooled by ambient air; the reflector and control drums are cooled by the working fluid entering the reactor.

The basic reason for the failure of the BeO system to qualify as the optimum MLX plant is the removable shield and the restriction this component places on the mobility of the plant.

B. DETAILED DESCRIPTION

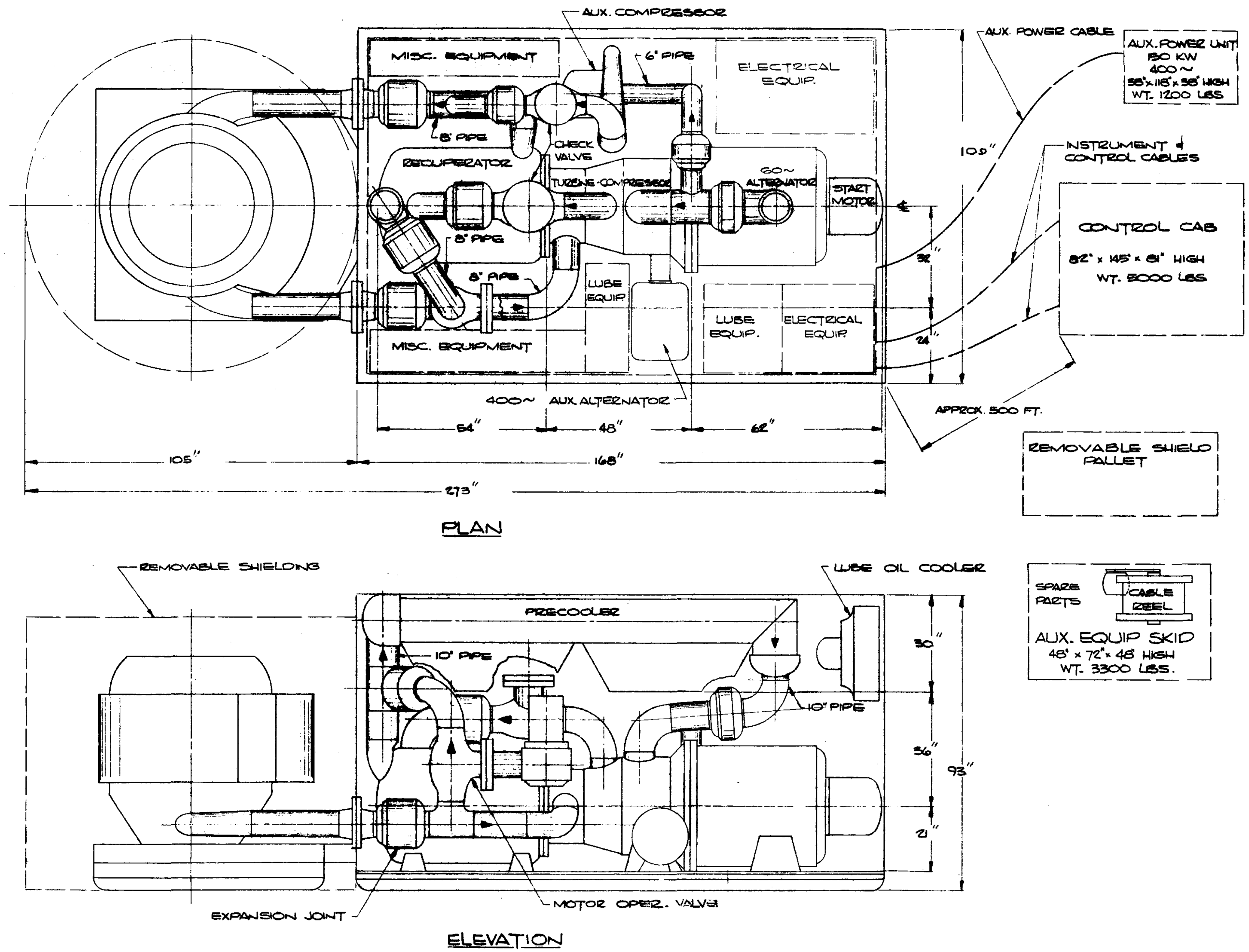
The pages which follow present detailed descriptions of the major systems, components and characteristics of the BeO power plant in the format described in Section IV. The following tabulation and index is provided for the convenience of the reader:

TABLE VII-1: TABULATION AND INDEX - BeO PLANT

BeO PLANT LAYOUT

The BeO plant consists of the two major skids, a control cab, two small auxiliary skids and the removable shielding pallet. The major skids can be separated for air transport or coupled for land transport. The truck convoy required consists of one tractor and trailer (M-172 or M-172-A-1), three 2-1/2 ton trucks (M-35) and one truck capable of transporting the 8.5 ton removable shield.

The reactor shielding is sufficient to permit relocation of the plant 36 hours after shutdown; with the removable shield installed, operation of the plant is possible from the control cab located 500 feet away.



WEIGHT SUMMARY

REACTOR SKID		
PERMANENT SHIELD	18,600	
PRESS VESSEL & CORE	7850	
CONTROL DRIVES & ACTUATORS	1200	
STRUCTURE	1100	
SHIELD COOLING BLOWERS	200	
AFTERGLOW COOLING SYS.	500	
		29450
POWER CONVERSION SKID		
TURBINE COMPRESSOR	3000	
RECUPERATOR	4000	
PRECOOLER	5700	
ALTERNATOR	6200	
START MOTOR	400	
LUBE SYSTEM	800	
AUX. COMPRESSOR	500	
STRUCTURE & ACC.	2600	
ELECTRICAL EQUIP.	3150	
PIPING & MISC.	3300	
AUX. ALTERNATOR	200	
		29 750
AUXILIARY EQUIP. SKID		3,300
CONTROL CAB		5000
REMOVABLE SHIELD PALLET		16,800
AUXILIARY POWER UNIT		1200
TOTAL		85,500

FIGURE VII-1

BeO PLANT LAYOUT

BeO PLANT FLOW DIAGRAM

The BeO power plant uses air as the working fluid in a Brayton cycle with regeneration. The cycle state points and characteristics are listed below:

	Temperature (^{o}F)	Pressure (psia)
Compressor inlet	143	171
Compressor outlet	418	511
Reactor inlet	865	500
Reactor outlet	1300	463
Turbine outlet	972	178
Precooler inlet	532	175

Core: $\Delta P/P$ - 5%

Flow rate - 1.065×10^5 lb/hr

Reactor power - 3.6 Mw (to gas)

Recuperator heat load - 12.1×10^6 Btu/hr

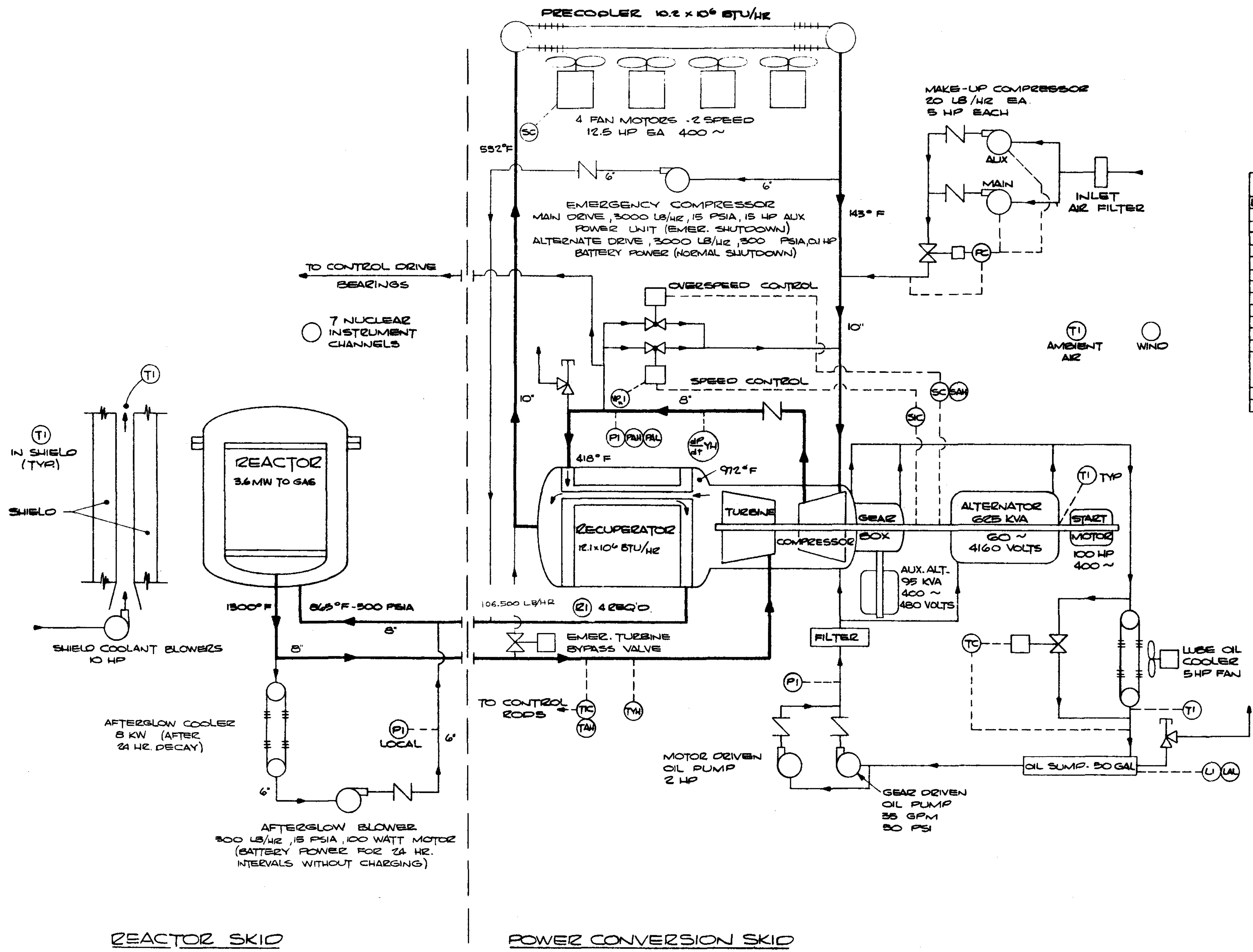
Precooler heat load - 10.2×10^6 Btu/hr

Power, kw(e) - 575 gross; 500 net

Shield integral or separate - partially separate

Reactor blower and power required - Emergency blower, 11 kw

Precooler fans and power required - Four 2-speed fans, 12.5 hp each, total 38 kw



INSTRUMENT SYMBOLS

LETTER	1ST LETTER	2ND LETTER	3RD LETTER
A		ALARM	
C		CONTROL	CONTROL
I		INDICATING	
L	LEVEL		LOW
P	PRESSURE		
P_n		POSITION	
R	RADIATION	RECORDING	
S	SPEED		
T	TEMPERATURE		
V	VALVE		
Y		SCRAM	SCRAM
H			HIGH
$\frac{dP}{dt}$	RATE OF PRESS CHANGE NEG.		
d	SUBSCRIPT REFERRING TO DIFFERENTIAL		
e	" " " ERROR		

FIGURE VII-2

BeO FLOW DIAGRAM

BeO FUEL PINS

The basic element of the BeO reactor core is a 0.76 inch diameter pin with a fueled length of 14 inches. The pin cladding is modified Hastelloy-X with 0.030 inches thick wall. Nickel is loaded in both ends of all pins to provide axial neutron reflection. The nickel is 4 inches thick at the inlet end and 2 inches thick at the outlet to shift axial power toward the inlet end and improve thermodynamic performance.

The fuel is a homogeneous mixture of BeO, UO_2 and Gd_2O_3 in pellet form. The uranium is 93.2% enriched. The weight fractions of the three constituents are: fuel, 26%; moderator,72.3%; diluent, 1.7%. The pin is supported at the upper end.

Heat transfer parameters are listed in Table VII-2.

BeO FUEL PIN

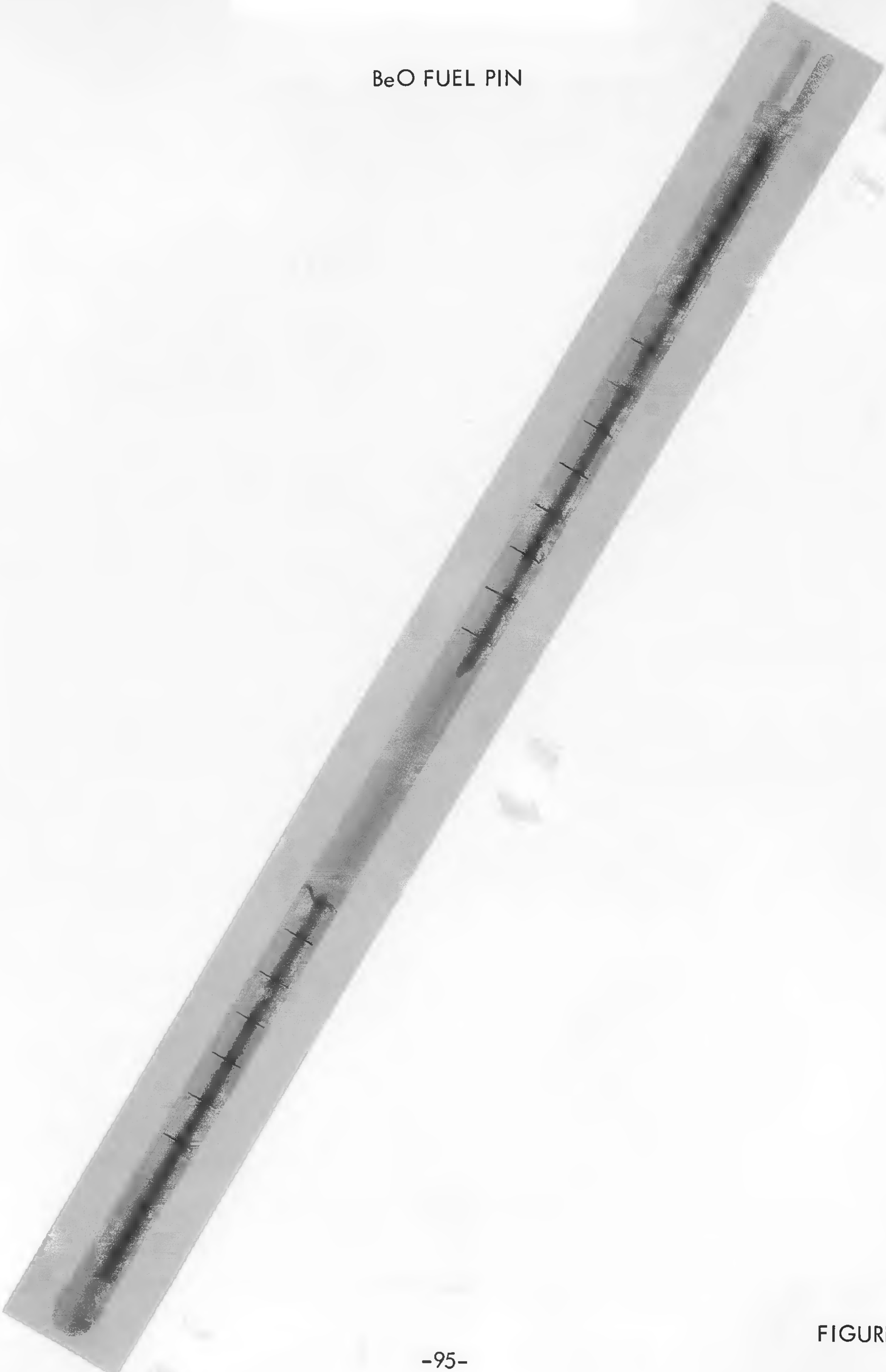


FIGURE VII-3

BeO PIN CLUSTER

The fuel elements in the BeO reactor are supported in clusters from the top of the core. Rectangular cross-section beams are provided to which the individual fuel pins are attached by a flexible joint. Several support beams, with the attached pins, are formed into units which are supported from the ends. The outer ring of fuel pins contacts the core shroud to provide lateral constraint for the pin bundle.

BeO PIN CLUSTER

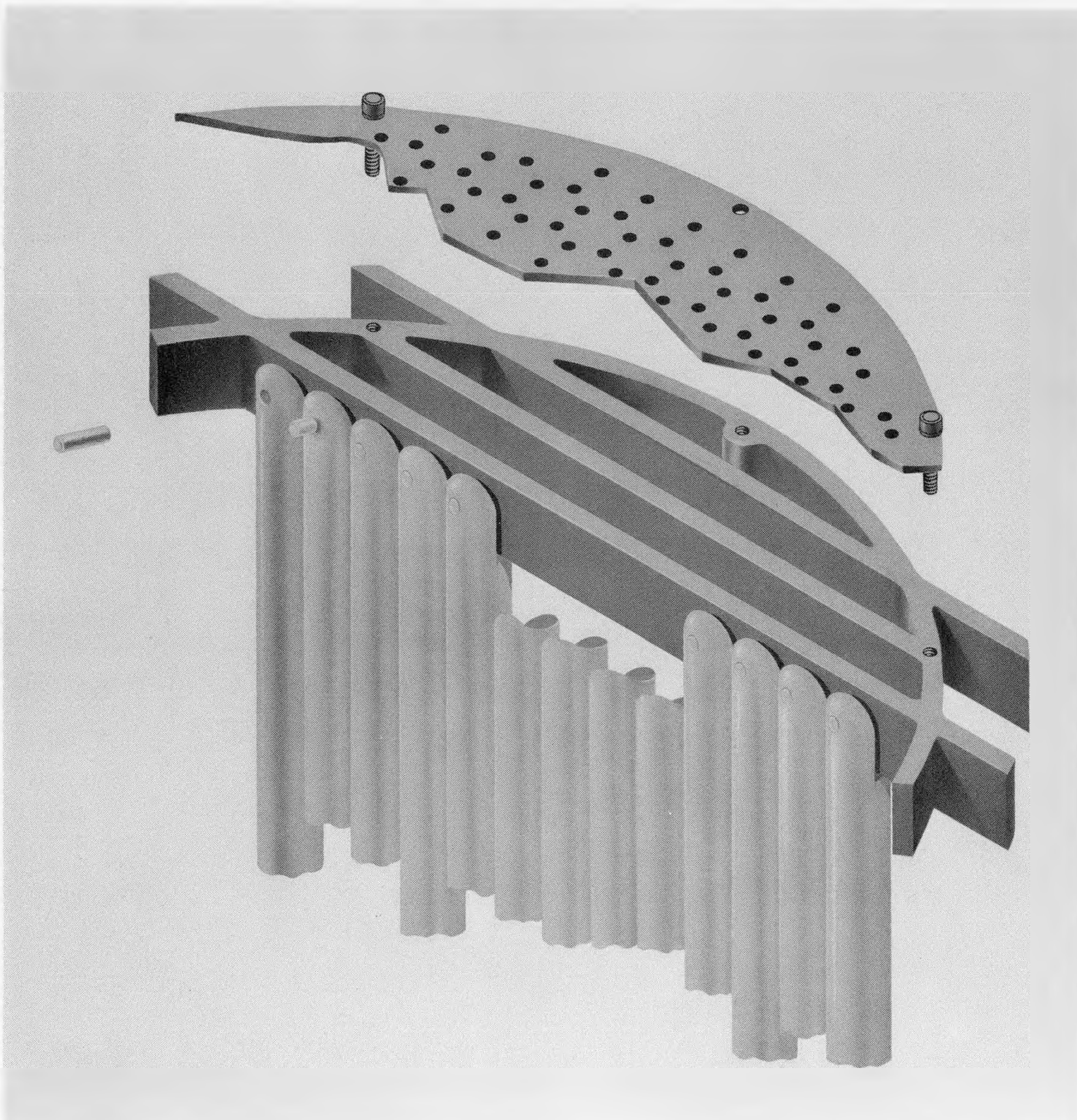


FIGURE VII-4

BeO REACTOR CORE

The BeO reactor core is a right circular cylinder, 20 inches in diameter and 20 inches high, composed of 571 modified Hastelloy-X pins containing pellets of homogeneously mixed BeO, UO_2 and Gd_2O_3. The core is contained in a thin metal shroud which provides lateral core constraint and also directs the gas flow. The core is reflected axially by four inches of nickel at the inlet and two inches of nickel at the outlet; the nickel is an integral part of each fuel pin. The radial reflector is composed of two inches of BeO and two inches of nickel. The reflector contains twelve control drums, four inches in diameter. The drums are clad and are of the same composition as the reflector; half of the cladding circumference contains B_4C absorber.

The top of the core is covered with an orifice plate. In this concept, the relatively large diameter pins with associated large flow passages, make possible the use of such a device to assist in controlling the temperature distribution within the core. The perforations in the orifice plate are of different sizes to distribute the coolant flow for optimum temperature distribution.

This reactor has a negative temperature coefficient, associated primarily with the overall dimensional change of the core caused by thermal expansion. This overall expansion coefficient is considered to be prompt and is approximately $-5 \times 10^{-6} \Delta k/k$°-C.

BeO REACTOR CORE

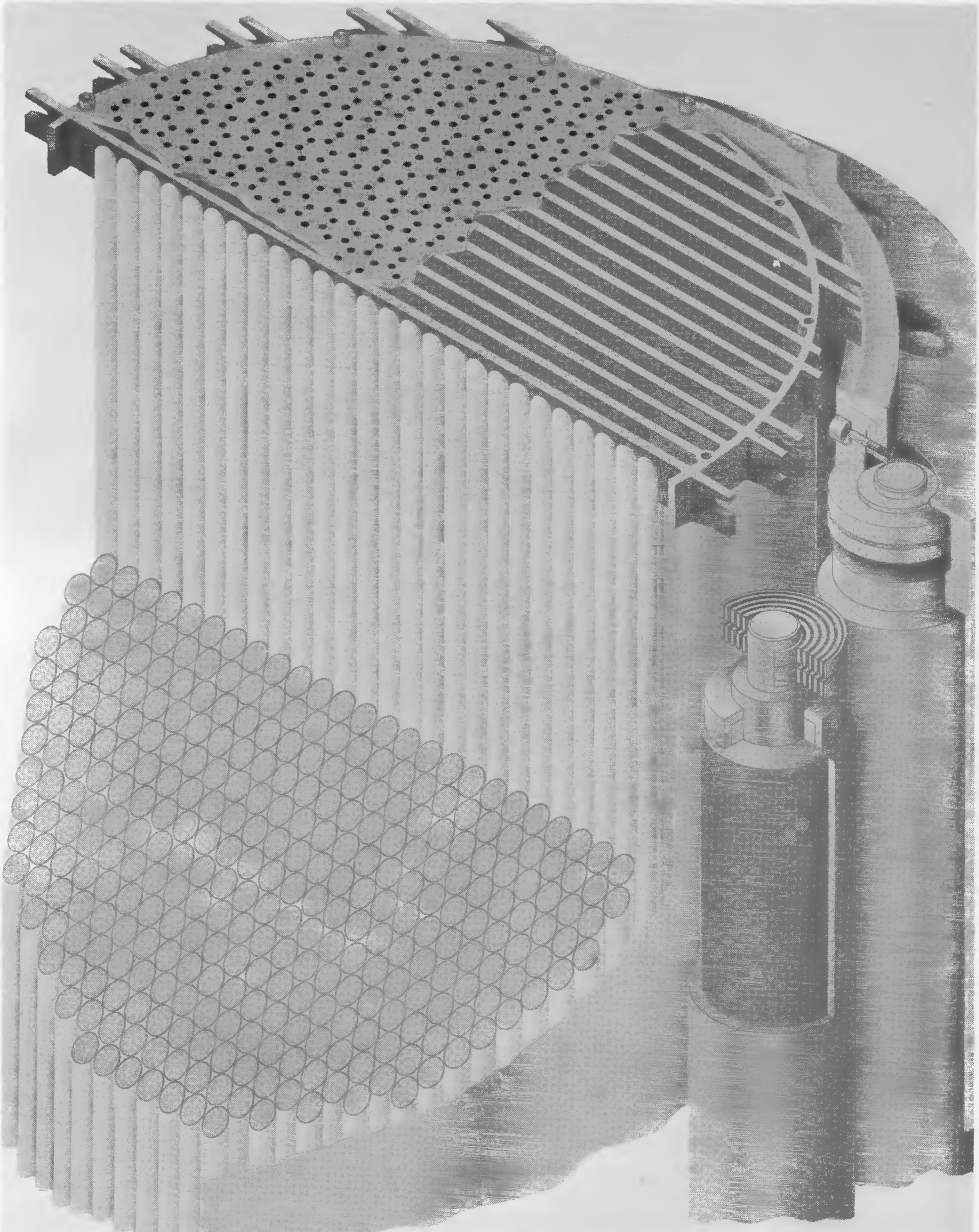


FIGURE VII-5

BeO REACTOR PRESSURE VESSEL

The BeO reactor core, reflectors and control drums are contained in an AISI Type 347 stainless steel pressure vessel. The inlet and exit gas ducts are located at the bottom of the vessel for minimum shield weight. Tungsten is placed inside the pressure vessel to provide axial radiation attenuation, at the bottom of the core in the form of a baffle plate to reduce duct streaming, and at the top in a slab just below the pressure vessel head.

Gas enters the system from the bottom, flows upward around the reflectors and control drums cooling these components as well as the pressure vessel. Flow through the reactor core is downward as shown. The pressure vessel surface temperatures are near the 865°F inlet gas temperature.

The control drum right-angle drives are located near the bottom of the assembly.

BeO REACTOR PRESSURE VESSEL

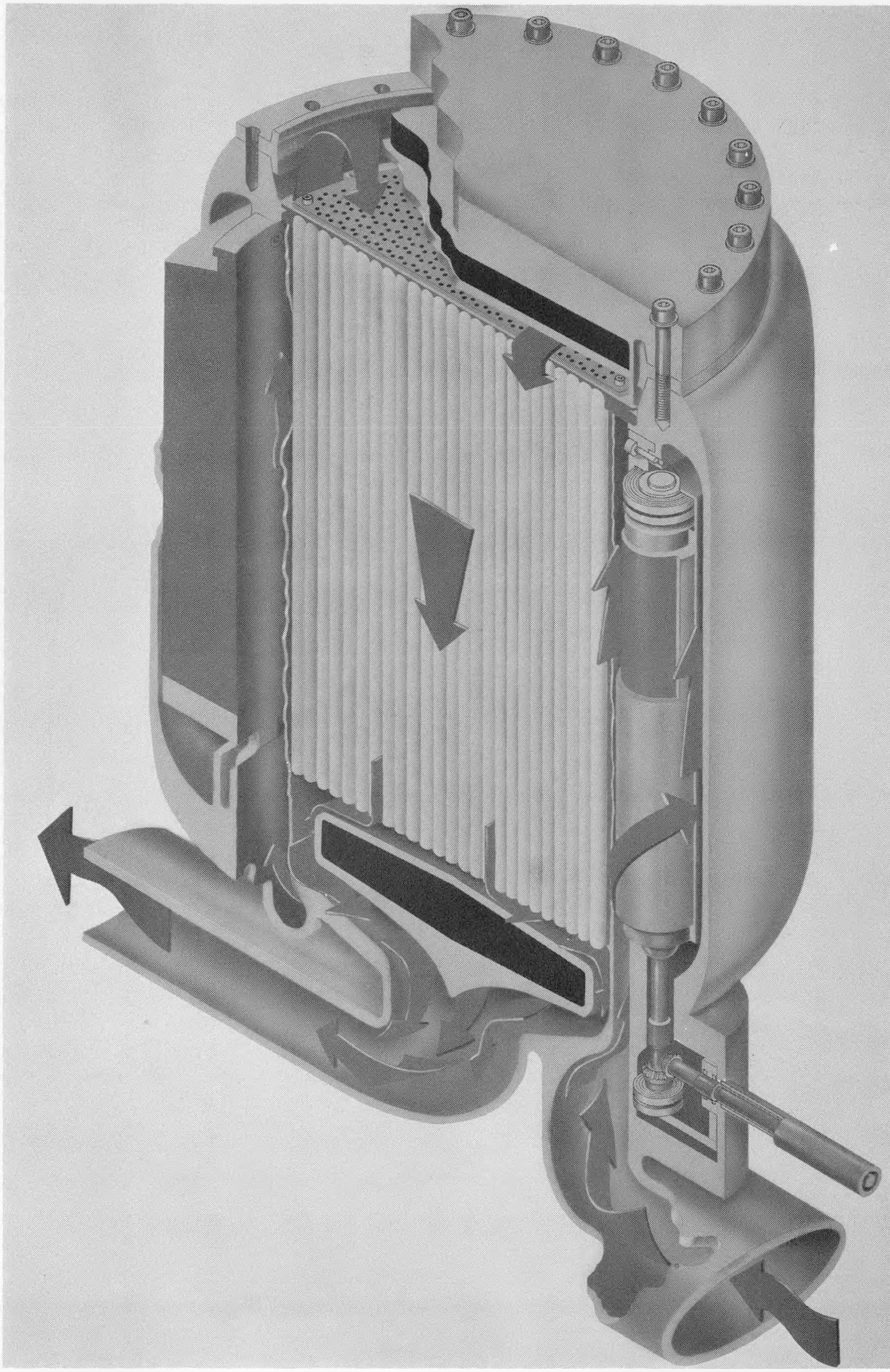


FIGURE VII-6

BeO REACTOR PACKAGE

The BeO system utilizes tungsten and lead for gamma ray attenuation and lithium hydride for the attenuation of neutrons. Tungsten surrounds the core radially outside the pressure vessel and is included as axial shielding inside the pressure vessel. The tungsten is enclosed by an annulus of LiH and both materials surrounded by a shell of lead. This shielding, with the additional thin annulus of LiH in the radial direction, comprises the shutdown shield. The remaining shielding required for operation is provided by removable LiH blocks. These units are stacked in place for operation and removed after shutdown but before transport to reduce the package weight to 15 tons.

The solid shield is air-cooled during operation by blowers mounted on the top of the package. Air is exhausted through vents located near the bottom of the package.

Twelve electrically energized actuating mechanisms drive the reflector control drums. These are located external to the integral shutdown shield for ease of access and maintenance.

The overall package dimensions are:

Length	105 in.
Width	109 in.
Height (for transport)	80 in.
Height (during operation)	95 in.

The package weighs 29,450 lbs and the removable shield weighs 16,800 lbs.

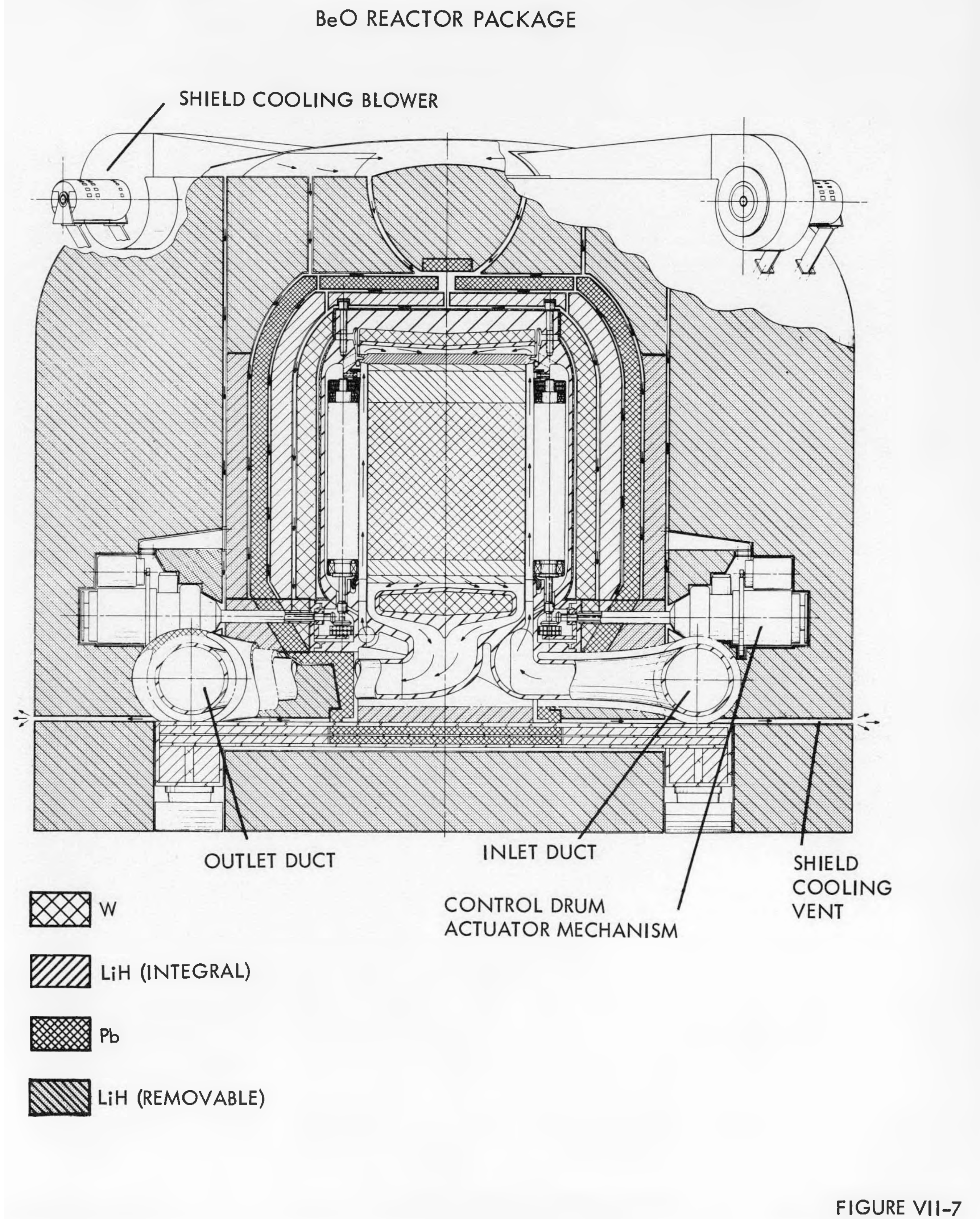

BeO REACTOR PACKAGE
SHIELD COOLING BLOWER
OUTLET DUCT
INLET DUCT
SHIELD COOLING VENT
CONTROL DRUM ACTUATOR MECHANISM
W
LiH (INTEGRAL)
Pb
LiH (REMOVABLE)

FIGURE VII-7

BeO SYSTEM FISSION SPECTRUM

Most fissions in this system are caused by neutrons in the resonance region (See Figure VII-8). The mean energy of neutrons causing fission is 640 ev.

Upon flooding of the reactor, the spectrum of neutrons in the system is appreciably softened. This shift to lower energies, particularly to thermal, coupled with the reduced neutron utilization at these energies due to the gadolinium in the system, results in what is referred to as "spectral shift control." The negative reactivity effect of this parasitic absorption overrides the positive effects of increased moderation and less core leakage associated with flooding. For this reason, the BeO reactor is inherently safe against flooding.

BeO SYSTEM NEUTRON FLUX

The neutron flux in the BeO system, normalized to 100 watts power, is shown for comparison with the other systems in Figure VII-9.

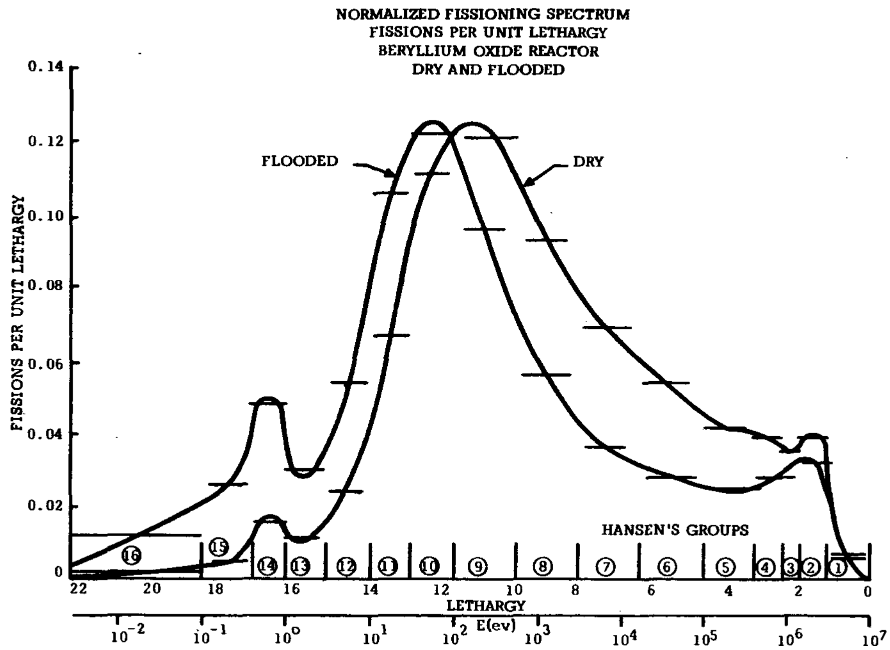


FIGURE VII-8

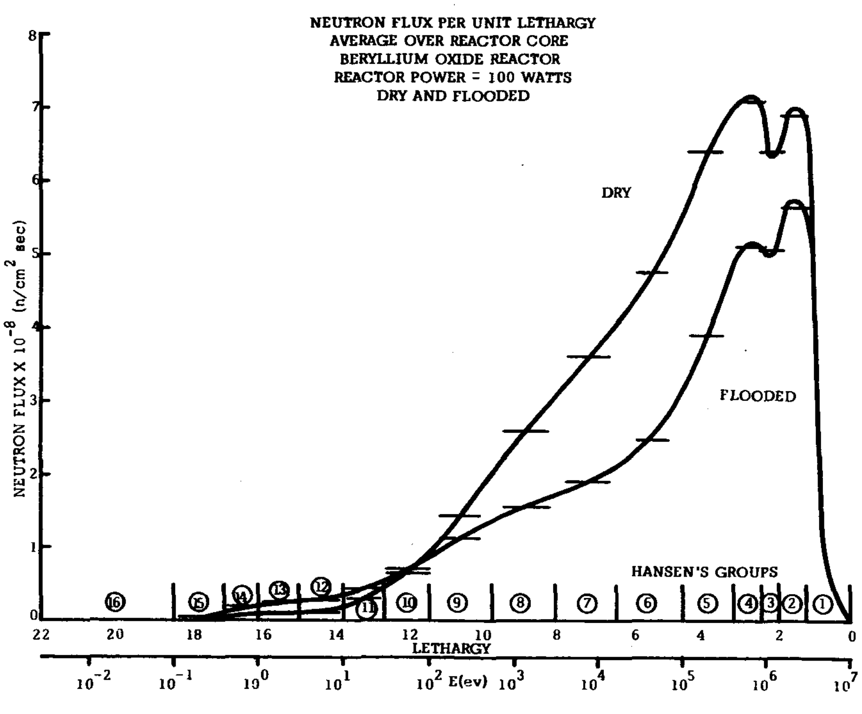


FIGURE VII-9

BeO REACTOR CONTROL DRUM ACTUATOR

The control drum actuators for the BeO system are identical with those for the HDMR system except for the inclusion of two additional scram springs on the extension shaft. These springs are provided to accommodate the inertia of the larger (than HDMR) control drums.

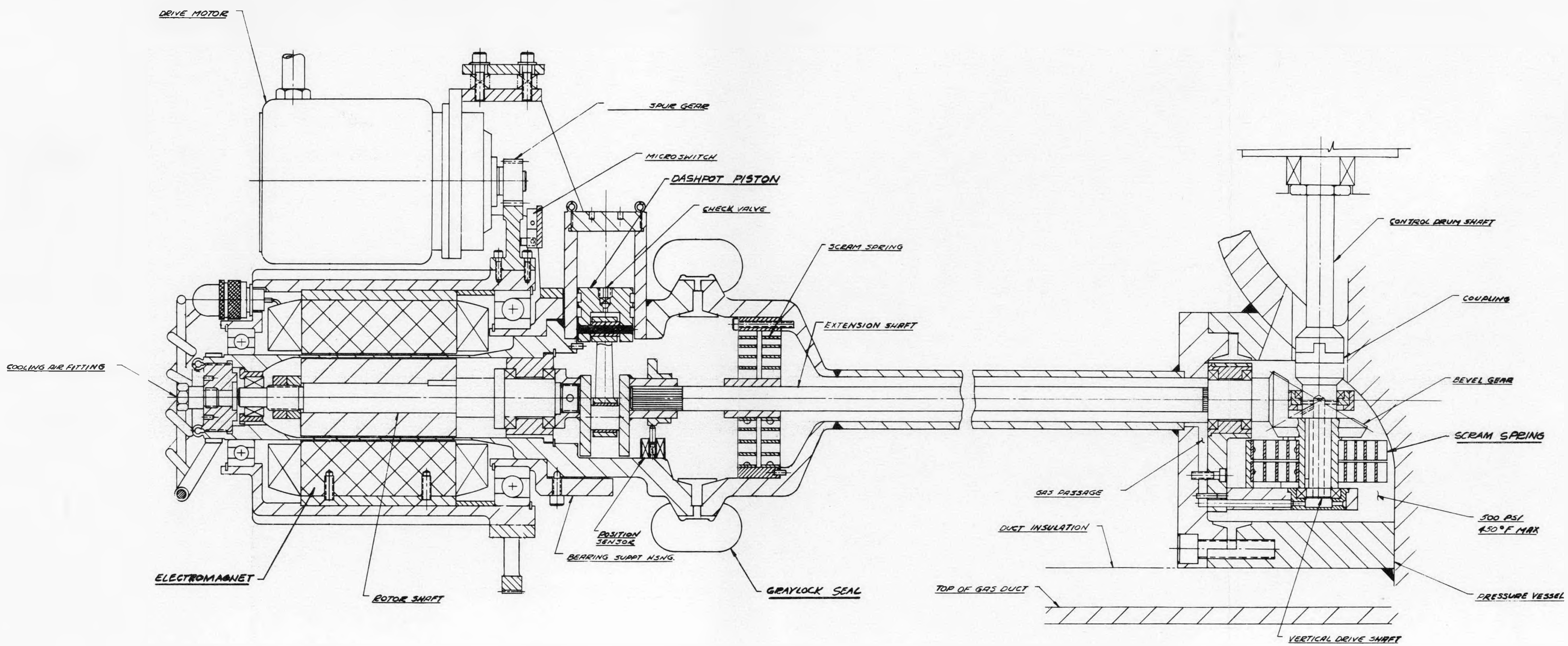


FIGURE VII-10

CONTROL DRUM ACTUATOR
BeO REACTOR

BeO SYSTEM NUCLEAR INSTRUMENTATION SYSTEM AND ELECTRICAL SYSTEM

These systems are identical with those described in the HDMR section of this report (Figures V-15 and V-16).

POWER CONVERSION SYSTEM PERFORMANCE CHARACTERISTICS

These characteristics are identical with those described in the HDMR section of this report.

TABLE VII-2: BeO CORE PERFORMANCE CHARACTERISTICS

1.	Thermal power (Mw)	3.76
2.	Bare core diameter (in.)	20
3.	Bare core height (in.)	20
4.	Coolant	Air
5.	Coolant flow rate (lb/hr)	106,500
6.	Core loading (kg. U-235)	55
7.	Inlet gas temperature (°F)	865
8.	Outlet gas temperature (°F)	1300
9.	System pressure (psi)	500
10.	Core pressure drop (psi)	20
11.	Core void fraction (%)	9.3
12.	Cycle	Closed regenerative air
13.	Maximum cladding hot spot temperature (°F)	1690
14.	Average Δ T coolant to cladding (°F)	1690
15.	Average coolant velocity through element	158
16.	Heat transfer surface area (ft^2)	200
17.	Average heat flux ($Btu/hr/ft^2$)	0.615×10^5
18.	Core flow area ($in.^2$)	28
19.	Volume fraction fuel (%)	6

TABLE VII-3: BeO SYSTEM

This table presents the primary criteria which were applied in the selection of the design concept in the several listed design areas.

Design Area	Selection	Primary Criteria
Moderator material	BeO	By definition
Coolant	Air	Logistic advantages
Cycle	Closed-regenerative	Minimum reactor size and shield weight
Compressor ratio	3.0	Maximum cycle efficiency; minimum reactor and heat exchanger size
Recuperator effectiveness	0.80	Minimum system weight
Precooler effectiveness	0.90	Minimum system weight
Turbine compressor aerothermodynamics	Axial turbine-centrifugal compressor	Maximum cycle efficiency; blade height requirements
Shield requirements	Integral shutdown shield; operational shield not feasible	Maximum mobility; radiation dose criteria in Military Characteristics
Reactor core size	20 in. diameter x 20 in. high	Minimum reactor temperatures consistent with shielding criteria
Duct location	Bottom entry and exit	Minimum shield weight, easy reflector cooling
Reflector material	2 in. BeO-2 in. Ni	Maximum reactivity and control, optimum core power distribution, acceptable shield properties
Reflector location	Inside pressure vessel	Maximum reactivity and control; easy reflector cooling
Pressure vessel material	AISI Type 347 stainless steel	Developed technology
Operating control	12 reflector control drums	Best available environment for moving parts; acceptable reactivity control

Design Area	Selection	Primary Criteria
Flooding control	Gadolinium spectral shift	Inherent control
Core fuel geometry	Bundle of pins containing fuel and moderator	Negative temperature coefficient; fission product containment; maximum reliability
Fuel materials	UO_2 in Hastelloy-X	High temperature characteristics; well-known technology
Fuel dimensions	0.76 in. pin diameter	Maximum diameter for acceptable cladding temperatures
Turbine inlet temperature	1300°F	Minimum reactor temperature
System pressure	500 psi	Minimum reactor temperature within turbine blade height limitations
Reactor ΔP 4%		Minimum reactor power and flow rate
Shield material	Lithium hydride, tungsten, lead	Minimum reactor weight
Shield cooling	Open cycle air	Mechanical simplicity
Fuel distribution	Uniform	Acceptable clad temperature with simple fabrication

BeO SYSTEM PROGRAM SCHEDULE AND PROGRAM COSTS

The descriptive information presented in the HDMR (Figures V-15 and Table V-5) section of this report applies also to the schedule and cost estimates shown on Figure VII-11 and Table VII-4.

BeO PROGRAM SCHEDULE

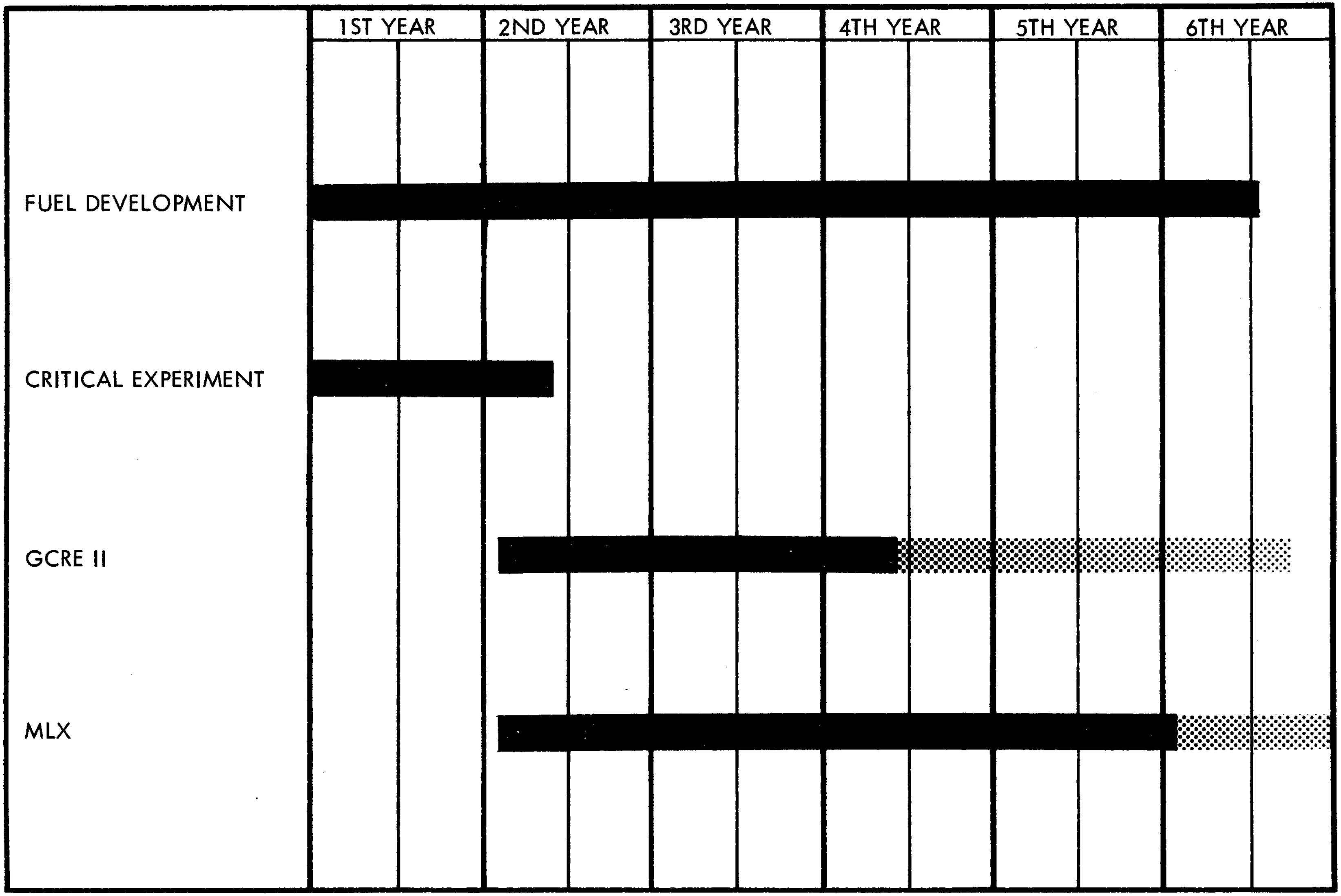


FIGURE VII-11

TABLE VII-4: BeO PROGRAM COSTS

(Thousands of Dollars)

DEVELOPMENT		
Fuel		$ 3500
Reactor		810
Power Conversion		6220
Controls		700
Critical		358
	Total Development	11,588
GCRE II		
Facility		2500
Reactor		1847
Fuel		396
Operations		1000
	Total GCRE II	5743
MLX		
Reactor		2957
Fuel		396
Power Conversion		1425
Controls		500
Auxiliaries		70
	Total MLX	5348
	Program Total	$22,700

VIII. MHX PLANT DESCRIPTION

A. GENERAL

The MLX plant designed around the homogeneous hydride moderated reactor is the most compact of all the reactors considered in this study. The power cycle and power conversion equipment are identical with the HDMR except that the compact (MHX) reactor design permits including the emergency cooling equipment on the reactor skid. An integral operational and shutdown shield is provided. The control cab and auxiliary equipment skid are the same as for the HDMR system. The configuration of the reactor skid is quite different, as is the design of the reactor, from any of the previously discussed plants.

The reactor delivers 1470^{o}F air to the turbine. The cycle efficiency is 23.2% and the net plant thermal efficiency is 17.85%. The total plant weight is 61,450 pounds. The plant layout is shown in Figure VIII-1 and the flow diagram, with state point data, in Figure VIII-2.

The core of the MHX reactor is composed of 37 fuel elements; each element is a cluster of 19 fueled pins (6 elements limited to 12 pins to accommodate control rods). The pins are loaded with a homogeneous mixture of UO_2 and yttrium hydride. The cladding is Fe-Cr-Al alloy.

The pin assemblies are constrained at the top and bottom by spiders.

The core is a cellular honeycomb structure in which the fuel elements are supported from the top. Six control rods enter the top of the core and move axially in the core. The reflector is $YH_{1.7}$, 1 in. thick on the periphery and 2 in. thick on the inlet end. No reflector is provided on the outlet end to optimize the power distribution. Coolant gas enters the core from the bottom, cools the pressure vessel and reflector on the upward pass and is heated in the reactor on the downward pass to the exit duct. The tungsten-lead-lithium hydride shield is cooled by ambient air.

The basic reason the MHX system fails to qualify as the optimum MLX plant is the relatively undeveloped state of the metallurgical technology of metal hydrides, at the operating temperatures, and Fe-Cr-Al cladding.

B. DETAILED DESCRIPTION

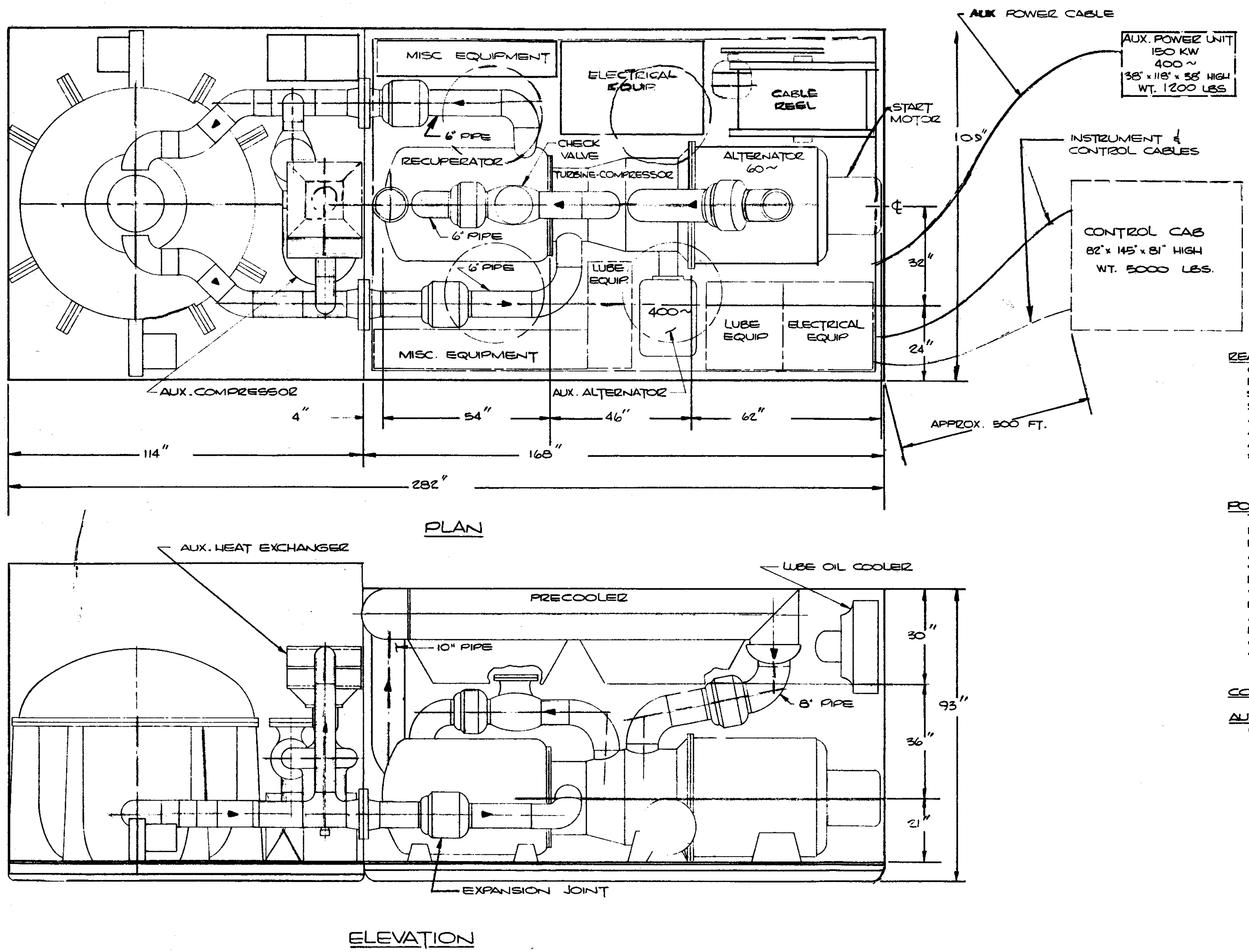
Following page 121 are detailed descriptions of the major systems, components and characteristics of the MHX power plant in the format described in Section IV. The following tabulation and index is provided for the convenience of the reader:

TABLE VIII-1: TABULATION AND INDEX

MHX PLANT LAYOUT

The homogeneous hydride moderated power plant consists of two major skids, a control cab, and one small auxiliary skid. The power plant is self-sufficient in the field for operating periods of 10,000 hours. The two major skids may be separated for air transport or coupled for land transport. The truck convoy required consists of one tractor and trailer (M-172 or M-172-A-1) and two standard 2-1/2 ton trucks (M-35).

Sufficient radiation shielding is incorporated integrally on the reactor skid to permit operation from the control cab 500 feet away and to permit the plant to be transported 18 hours after shutdown following long operation.



WEIGHT ESTIMATE

REACTOR SKID (SOLID SHIELD)	
CONTROL RODS & ACTUATORS	600
PRESS. VESSEL & CORE	2350
SHIELD	19450
STRUCTURE	1900
AUX. COMPR.	500
AUX. HEAT EXCH, FAN & PIPING	800
AUX. GAS ENGINE-GEN. SET	100
SHIELD COOLING BLOWERS	300
	26,000
POWER CONVERSION SKID	60 CYCLE
TURBINE-COMPR.	3000
RECUPERATOR	3000
PRECOOLER	4700
ALTERNATOR	6200
START MOTOR	400
LUBE SYSTEM	800
STRUCTURE & ACCESS.	2500
ELECTRICAL EQUIP.	3150
AUX ALTERNATOR	200
PIPING & MISC.	2500
CABLE REEL	2000
SPARE PARTS	800
	29,250
CONTROL CAB	5,000
AUX. POWER UNIT	
GAS TURBINE (RECIP) (3300)	1,200
TOTAL	61,450 LB.

FIGURE VIII-1

MHX PLANT LAYOUT

MHX FLOW DIAGRAM

The MHX power plant utilizes air as the working fluid in a closed Brayton cycle with regeneration. The cycle state points and characteristics are listed below:

	Temperature (^oF)	Pressure (psia)
Compressor inlet	147	171
Compressor outlet	423	511
Reactor inlet	975	500
Reactor outlet	1470	463
Turbine outlet	1123	178
Precooler inlet	567	175

Core $\Delta P/P$ - 2.5%

Recuperator heat load - 9.0 x 10^6 Btu/hr

Precooler heat load - 6.5 x 10^6 Btu/hr

Flow rate - 7.3 x 10^4 lb/hr

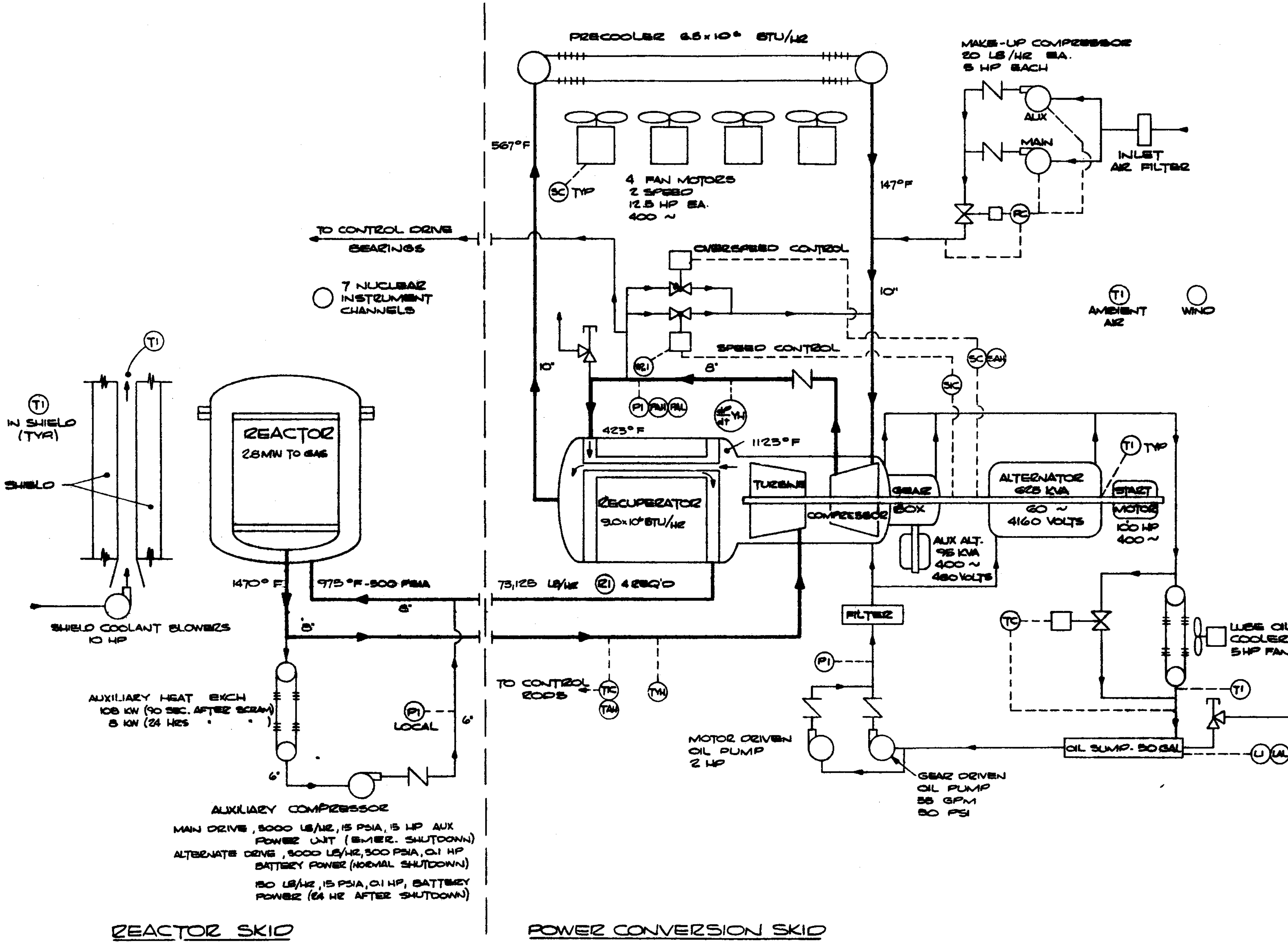
Reactor power (to gas) - 2.8 Mw

Power, kw(e) - 575 gross; 500 net

Shield integral or separate - Integral

Reactor blower and power required - Emergency blower, 11 kw

Precooler fans and power required - Four 2-speed fan, 12.5 hp each, total 38 kw



INSTRUMENT SYMBOLS

LETTER	1ST LETTER	2ND LETTER	3RD LETTER
A		ALARM	
C		CONTROL	CONTROL
I		INDICATING	
L	LEVEL		LOW
P	PRESSURE		
P_o		POSITION	
R	RADIATION	RECORDING	
S	SPEED		
T	TEMPERATURE		
V	VALVE		
Y		SCRAM	SCRAM
H			HIGH
$\frac{dP}{dt}$	RATE OF PRESS CHANGE NEG.		
d	SUBSCRIPT REFERRING TO DIFFERENTIAL		
e	" " " ERROR		

FIGURE VIII-2

MHX FLOW DIAGRAM

MHX PINS

The basic element of the homogeneous hydride reactor core is a pin 0.440 in. in diameter and 18 in. long. The upper 2 in. of the pin is a yttrium hydride reflector and the remaining 16 in. is fueled with UO_2 in an yttrium hydride matrix.

The UO_2 particles (approximately 200 microns) are distributed evenly in powdered yttrium, pressed into pins, chromium plated, and clad with 0.010 in. thick Fe-25Cr-4Al using pressure bonding technique. Hydrogen retention is provided by a very thin (0.0005 in.) oxide layer which forms on the outside of the cladding in the air coolant. All fuel pins have the same loading and are of the same size. A spiral spacer is provided to maintain a clearance between pins of approximately 20 mils.

The UO_2 is fully enriched. The weight fractions of fuel and moderator in the active (16 in. long) section are 11.3% and 88.7% respectively.

Heat transfer parameters are listed in Table VII-2.

MHX PIN

FIGURE VIII-3

MHX FUEL ELEMENT

Two types of fuel elements are provided to accommodate the in-core control rods. The first is composed of 19 of the pins as previously described. The pins are assembled into a hexagonal arrangement and each is welded to an upper spider which supports the bundle. A lower spider is welded to three of the pins to act as a guide for the remaining pins and as an assembly fixture. No external shroud is provided for the bundle, the shroud shown in Figure VIII-4 is part of the core structure.

The second type of element is similar to the first except that the seven center pins are removed and replaced by a guide tube for the control rod.

MHX FUEL ELEMENT

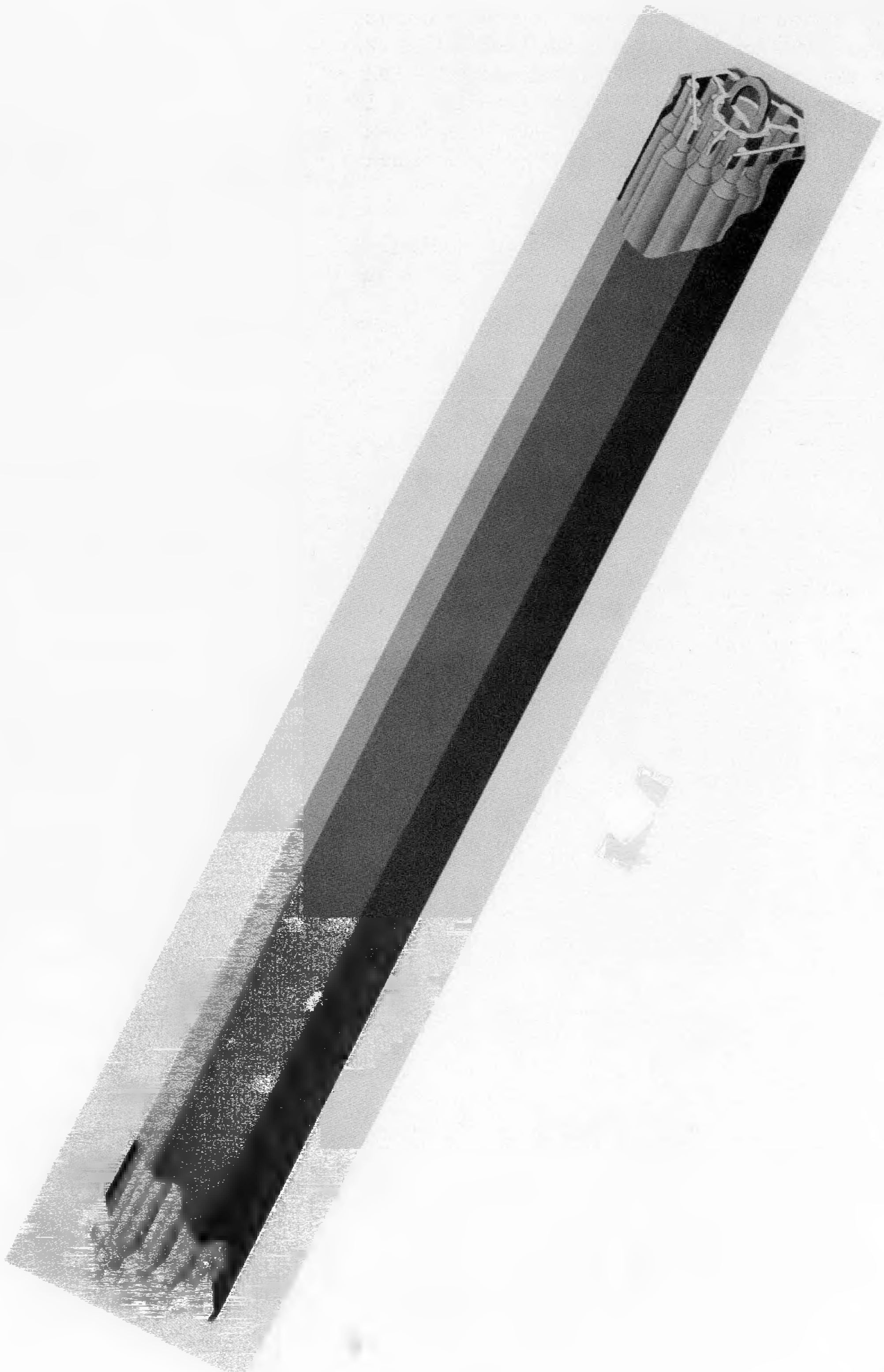


FIGURE VIII-4

MHX REACTOR CORE

The core is composed of 31 19 pin elements and 6 12 pin elements (total 661 pins). The fueled section of the core is 14 in. in diameter and 16 in. long. The core structure is a honeycomb fabricated from thin Hastelloy-X extending the full length of the core. This unusual construction permits near optimum distribution of the coolant flow pattern and provides passages which can be orificed to adjust the flow to obtain uniform fuel element temperatures. The core structure is surrounded by a 1 in. thick radial yttrium hydride reflector and a 2 in. reflector of the same material on the inlet end.

The prompt temperature coefficient of the core is small and probably negative. It is composed of a negative coefficient due to thermal expansion, a small negative coefficient associated with the neutron temperature, and a small positive coefficient resulting from Doppler broadening.

The MHX reactor is contained within an AISI Type 347 stainless steel pressure vessel. The inlet and exit ducts are located at the bottom, where radiation streaming causes the least problem, to minimize shielding weight.

Gas enters the bottom and is directed upward around the reflector to provide cooling for the reflector and pressure vessel. The pressure vessel operates near the 975°F inlet gas temperature. The gas is directed downward in the upper plenum, through the reactor core and out through an internally insulated duct to the turbine.

The pressure vessel is surrounded by a radial tungsten shield and tungsten shields are provided in each of the plenums. This shielding in turn is completely surrounded by a lead shield to aid in the direct shielding and to suppress the tungsten capture gammas. A lithium hydride shield encloses the entire heavy metal shield structure.

MHX REACTOR CORE

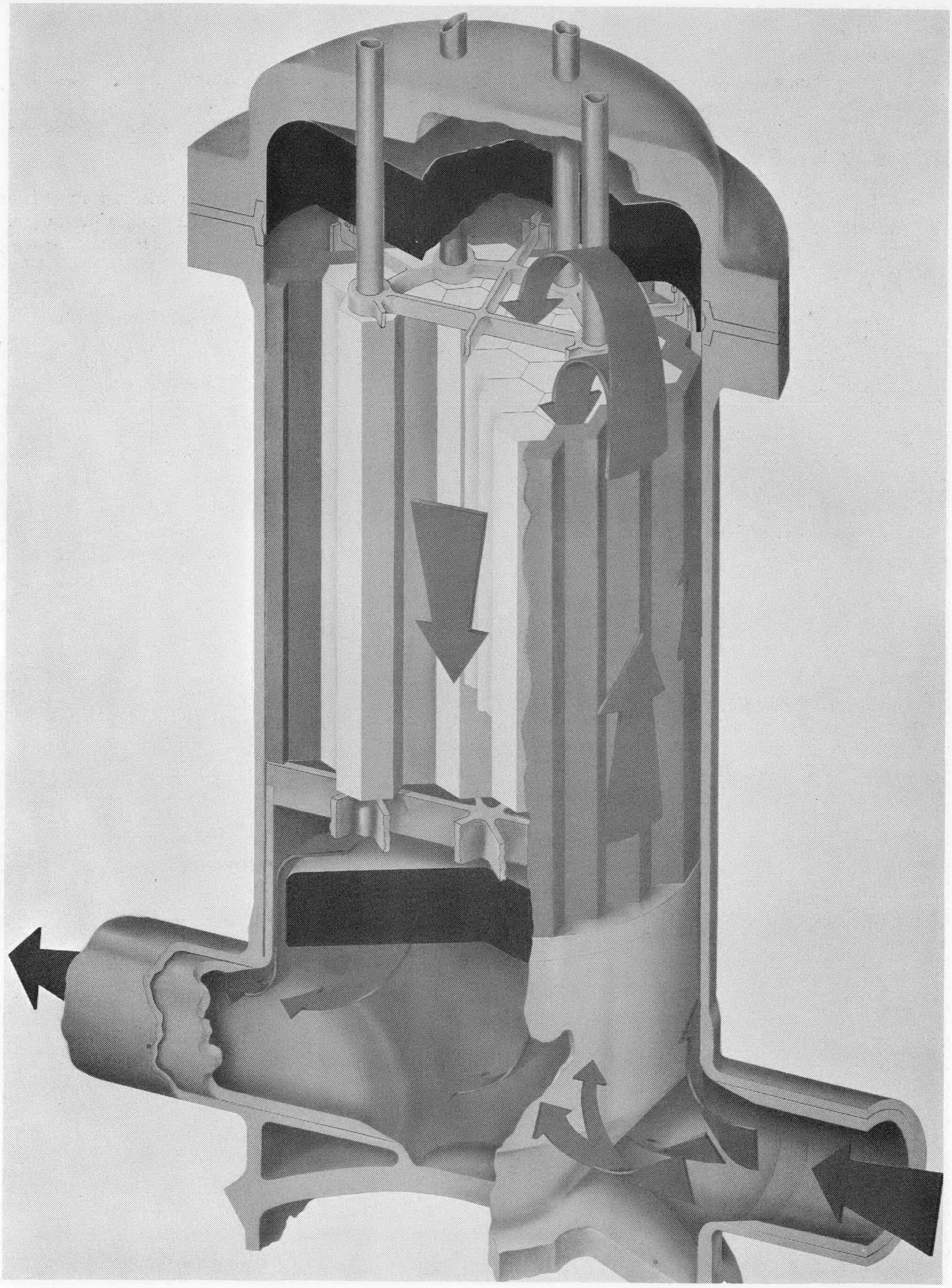


FIGURE VIII-5

MHX REACTOR PACKAGE

Tungsten, the primary gamma ray shielding, surrounds the core, radially, adjacent to the pressure vessel and within the upper and lower plenum. Lead is used outside of the tungsten shield to attenuate radiation from the activated tungsten.

Shielding of fission neutrons during operation is accomplished by lithium hydride. The tungsten, lead and lithium hydride are cooled during operation by air delivered by three shield cooling blowers located at the bottom of the package. A fourth blower is provided as a spare.

Six electrically-energized actuators drive the system control rods through the right-angle drives. These are located external to the shielding, as shown, for easy access. The rods incorporate samarium oxide absorbing material and enter the core region vertically from above.

An emergency blower is included on the reactor skid to provide coolant flow to the reactor in case of a coolant loss accident, following power plant shutdown and during transport.

The overall package dimensions for shipment are:

Length	- 114 in.
Width	- 109 in.
Height	- 80 in.

The package weighs 26,000 lbs.

MHX REACTOR PACKAGE

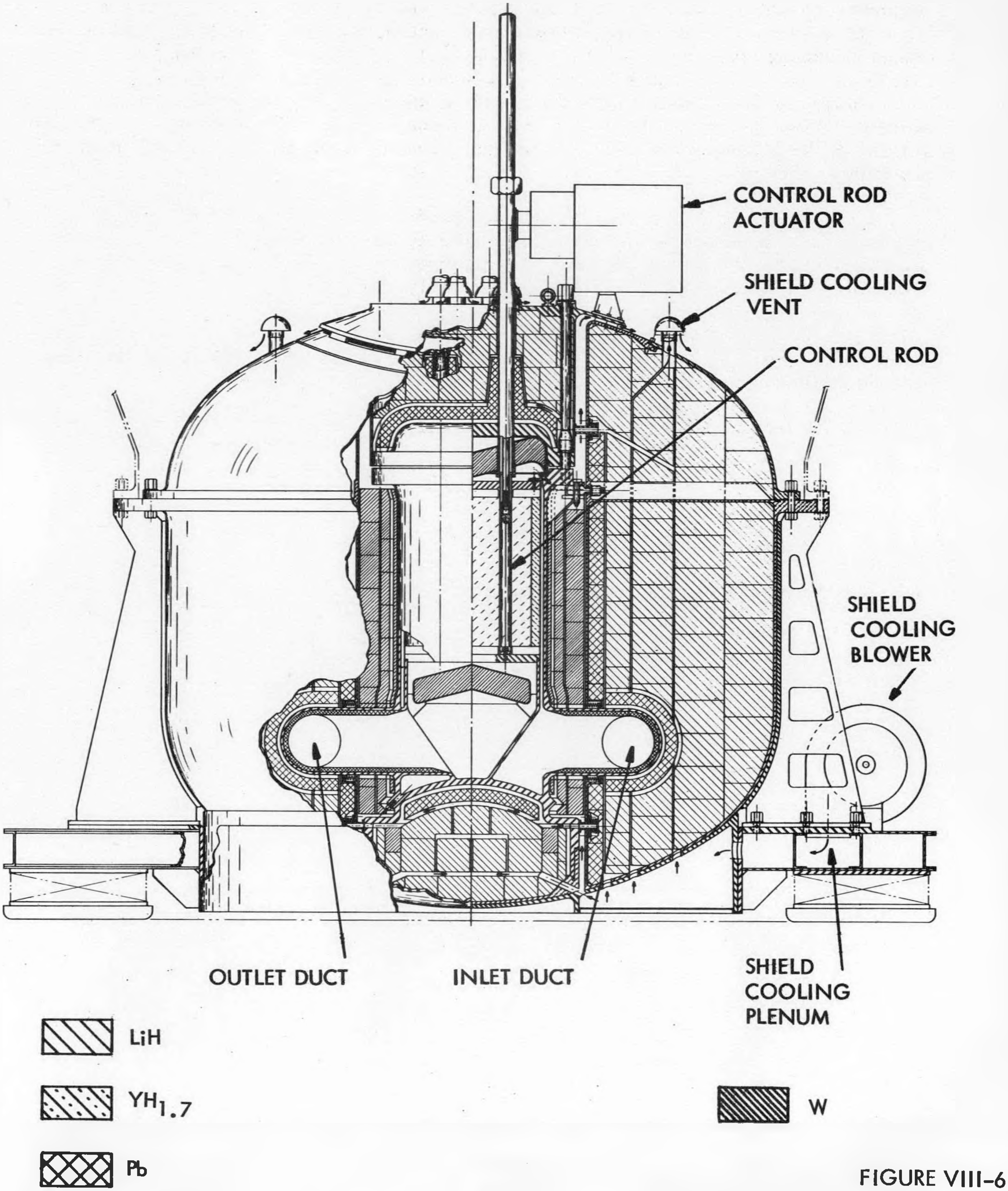


FIGURE VIII-6

MHX FISSION SPECTRUM

As expected in a hydrogen moderated system, most of the MHX fissions occur in the thermal region. When flooded, the neutron spectrum undergoes little change. Since the hydrogen percentage in the core is high, the addition of flooding water increases the moderation very little and the associated reactivity increase is only a few percent. The control rods control sufficient negative reactivity to prevent an excursion in case of accidental flooding.

MHX FLUX

The neutron flux, normalized to a reactor power of 100 watts, is shown on the facing page.

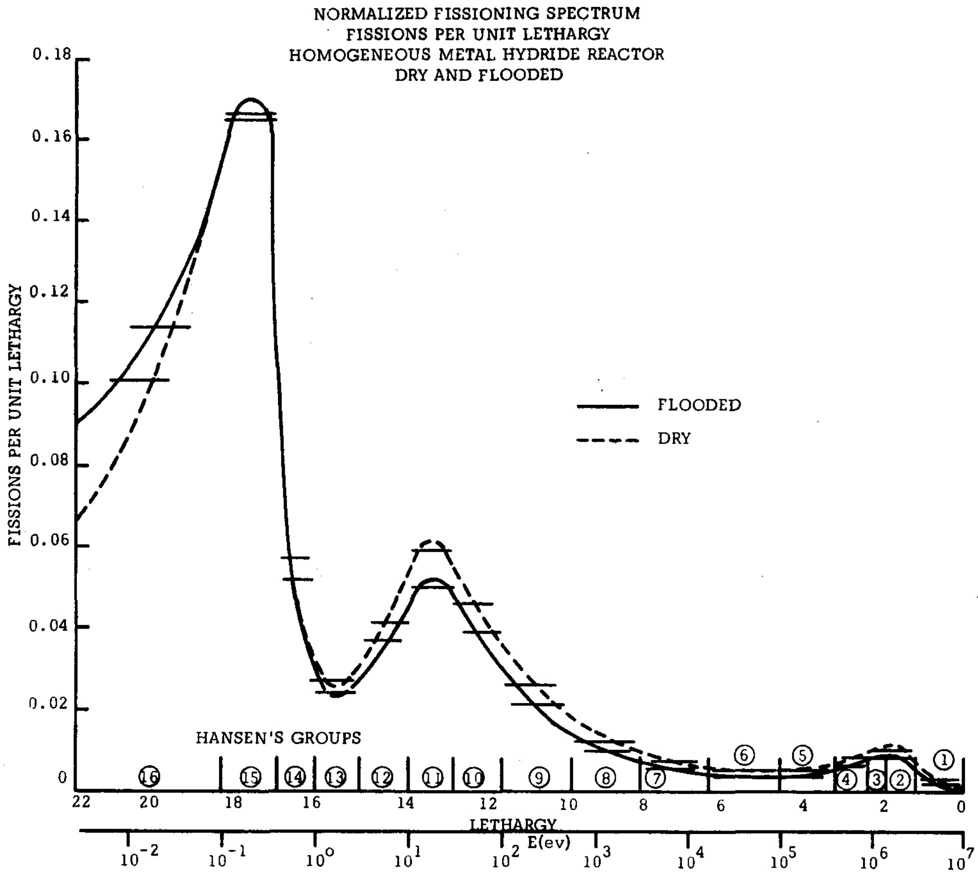


FIGURE VIII-7

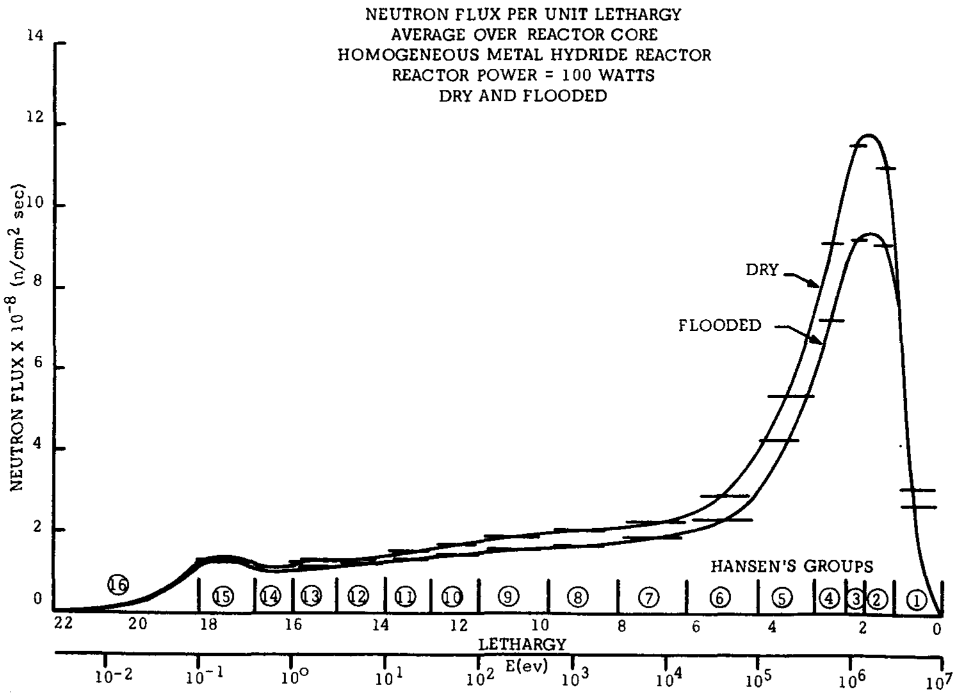


FIGURE VIII-8

MHX CONTROL ROD ACTUATOR

The control rods are positioned individually in the reactor by a rack and pinion drive mounted vertically above the core. A rotary actuator provides a right-angle drive through the pinion to a rack attached to the rod extension. A piston on the upper end of the rod extension serves as a linear air dash pot during scram action. A hermetically sealed electromagnetic coupling is used for the rotary actuator to eliminate the need for sliding or rotating shaft seals. All internal parts of the actuator are exposed to the reactor coolant which also serves as the working fluid for the dash pot. Two coiled springs, acting on the actuator shaft, provide the power for scram action.

The electromagnetic-coupled rotary actuator consists of a thin-walled pressure housing in which a solid steel rotor, supported by two radial bearings, is coupled directly to the drive shaft and pinion. The internal rotor is electrically coupled to an external rotating electromagnetic assembly. Rotary motion is induced in the drive shaft by the rotation of the electromagnet assembly by an electric gear motor. The electric gear motor uses a harmonic drive type gear reducer which is self-locking to holding the rod in position when no power is applied the drive motor. Scram release is accomplished by de-energizing the electromagnet, allowing the internal rotor and pinion to rotate and the control rod to be inserted under the force of gravity and the power of the coiled scram springs.

CONTROL ROD ACTUATOR
METAL HYDRIDE REACTOR

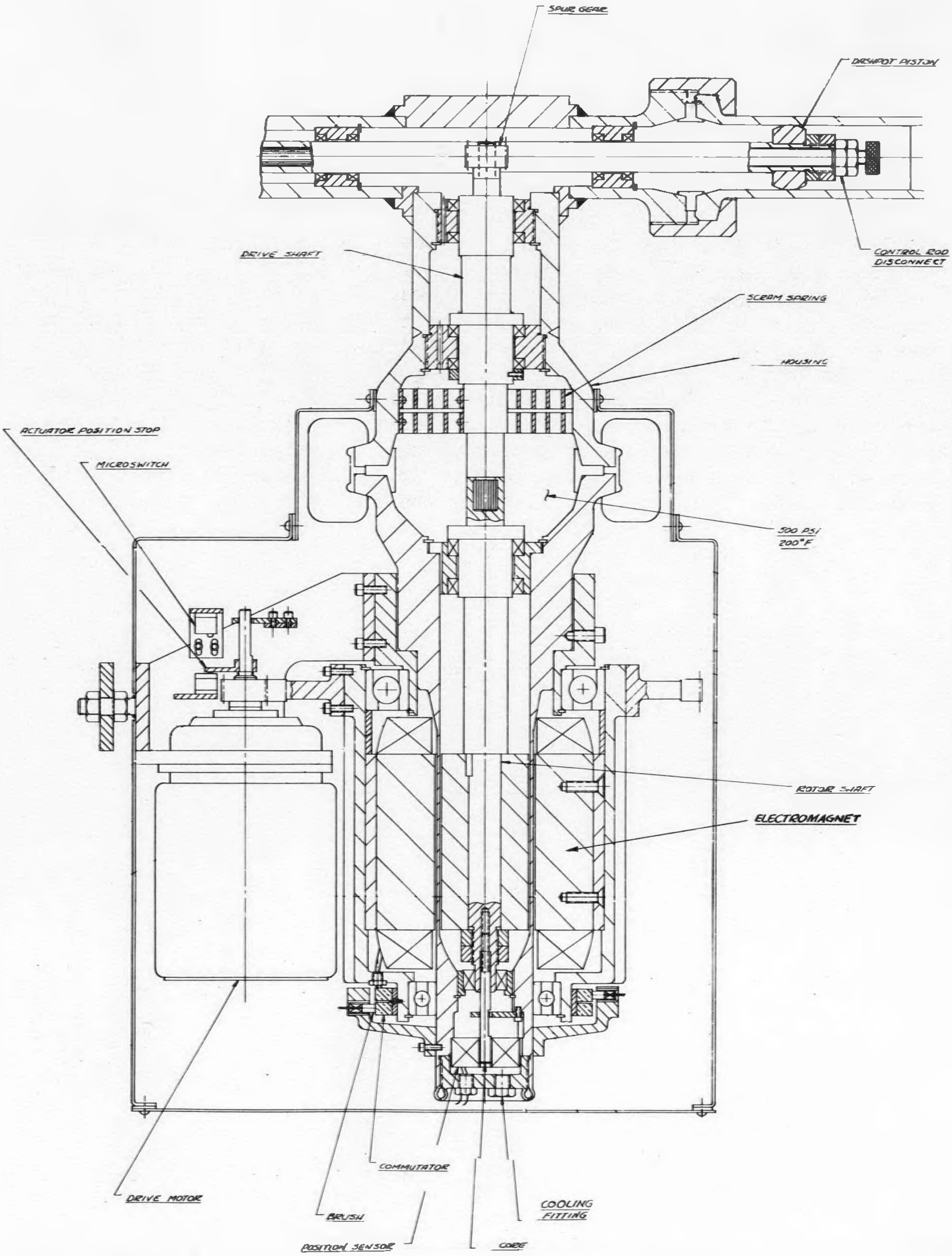


FIGURE VIII-9

MHX SYSTEM NUCLEAR INSTRUMENTATION SYSTEM AND ELECTRICAL SYSTEM

These systems are identical with those discussed in the HDMR section of this report (Figures V-11 and V-12).

POWER CONVERSION SYSTEM PERFORMANCE CHARACTERISTICS

These characteristics are identical with those described in the HDMR section of this report (page 41).

TABLE VIII-2

MHX CORE PERFORMANCE CHARACTERISTICS

1.	Thermal power (Mw)	2.96
2.	Bare core diameter (in.)	14
3.	Bare core height (in.)	16
4.	Coolant	Air
5.	Coolant flow rate (lb/hr)	73,000
6.	Core loading (kg. U-235)	12
7.	Inlet gas temperature (^{o}F)	975
8.	Outlet gas temperature (^{o}F)	1470
9.	System pressure (psi)	500
10.	Core pressure drop (psi)	10 (orificed)
11.	Core void fraction (%)	30.5
12.	Total core weight including moderator (lb)	348
13.	Cycle	closed regen.
14.	Maximum cladding hot spot temperature (^{o}F)	1728
15.	Average Δ T, coolant to cladding (^{o}F)	224
16.	Average nominal cladding temperature (^{o}F)	1340
17.	Average moderator temperature (^{o}F)	1430
18.	Average fuel temperature (^{o}F)	1728
19.	Average coolant velocity through element (ft/sec)	116
20.	Core structural fraction (vol%)	10
21.	Core moderator fraction (vol%)	54
22.	Heat transfer surface area (ft^2)	101.5
23.	Average heat flux (Btu/hr/ft^2)	0.94×10^5
24.	Core flow area (in.^{2})	33
25.	Volume fraction fuel (%)	3.5
26.	Moderator material	$YH_{1.7}$
27.	Moderator cladding material	Fe-25Cr-4Al
28.	Cladding thickness (in.)	0.010
29.	Total weight of moderator (lb)	235

TABLE VIII-3

METAL HYDRIDE SELECTION CRITERIA

This table presents the primary criteria which were applied to the selection of the design concept in the several listed design areas.

Design Area	Selection	Primary Criteria
Moderator material	Yttrium hydride$_{1.7}$	High temperature capacity
Coolant	Air	Maintenance of oxidation barrier for hydride; logistic advantages
Cycle	Closed regenerative	Minimum reactor size and shield weight
Compressor ratio	3.0	Maximum cycle efficiency, minimum reactor and heat exchanger
Recuperator effectiveness	0.80	Minimum system weight
Precooler effectiveness	0.90	Minimum system weight
Turbine-compressor aerodynamics	Axial turbine - centrifugal compressor	Maximum cycle efficiency, blade weight requirements
Radiation criteria	Fully operational shield	Maximum mobility
Reactor active core size	14 in. dia x 16 in. long	Minimum reactor temperatures consistent with shielding criteria
Duct location	Bottom entry and exit	Minimum shield weight; easy reflector cooling
Reflector material	$YH_{1.7}$	Minimum reflector thickness
Reflector location	Inside pressure vessel	Optimum power distribution
Operating control	6 in-core, axial rods	Minimum control required for operation and flooding
Flooding control	Same as operating	Inherent control not feasible
Core fuel geometry	Pins contained in 37 elements	Maximum reliability and ease of handling

Design Area	Selection	Primary Criteria
Fuel materials	Homogeneous $YH_{1.7}$ UO_2; Fe-Cr-Al clad	High temperature characteristics
Fuel dimensions	0.440 in. pin dia	Maximum diameter for acceptable fuel temperature
Turbine inlet temperature	1470°F	Minimum reactor power and flow rate
System pressure	500 psi	Minimum reactor temperatures within turbine blade height limitations
Reactor ΔP	2.5%	Minimum reactor power and flow rate
Shield material	Tungsten, lead, lithium hydride	Minimum reactor weight
Shield cooling	Open cycle air	Mechanical simplicity
Fuel distribution	(a) Homogeneous	Negative temperature coefficient
	(b) Uniform	Simple fabrication

MHX SYSTEM PROGRAM SCHEDULE AND PROGRAM COSTS

The descriptive information presented in the HDMR section of this report (Figures V-15 and Table V-5) applies also to the schedule and cost estimates shown on the following pages (Figure VIII-10 and Table VIII-4).

MHX PROGRAM SCHEDULE

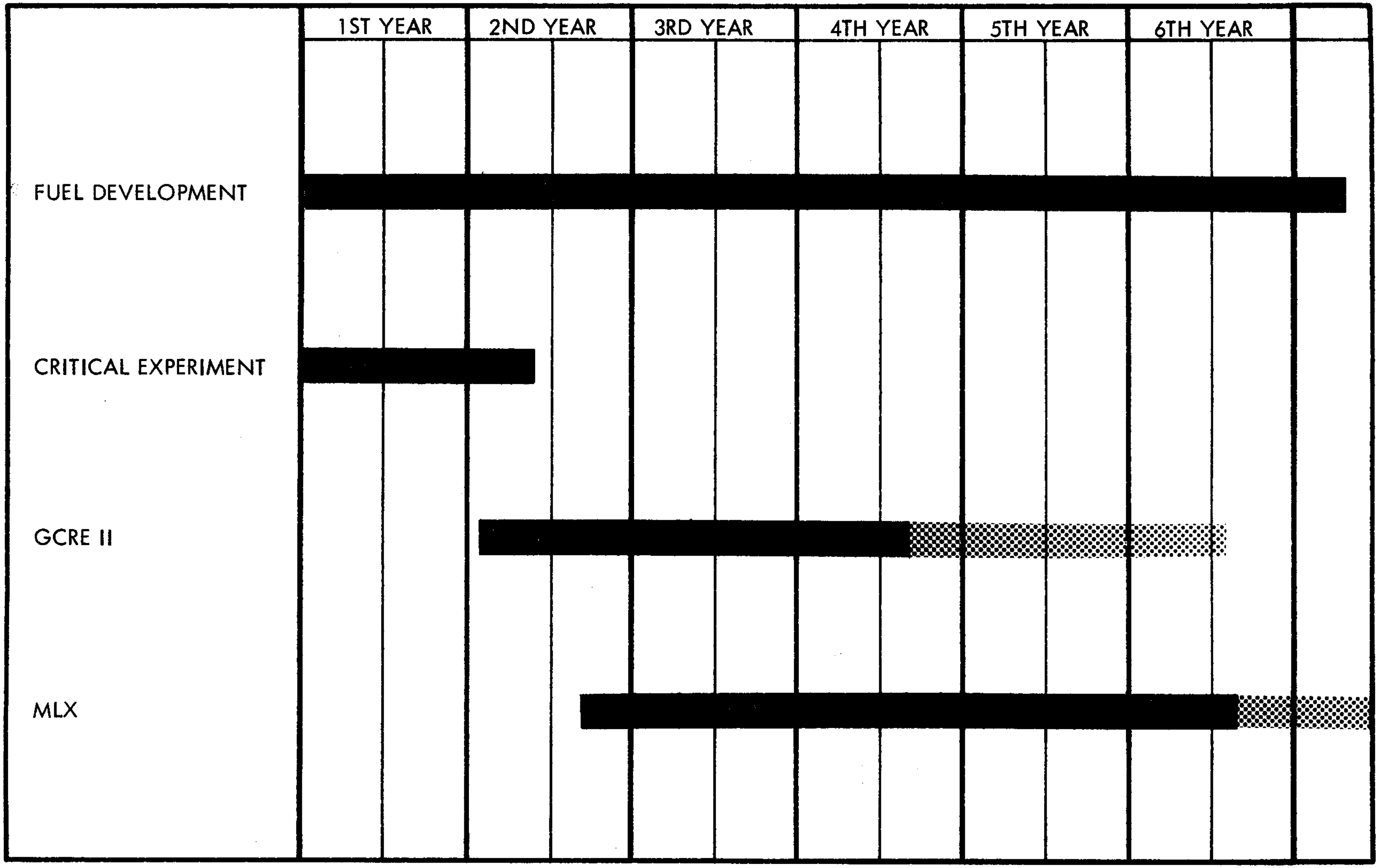


FIGURE VIII-10

TABLE VIII-4

MHX PROGRAM COSTS

(Thousands of Dollars)

DEVELOPMENT		
Fuel		$ 4,845
Reactor		526
Power Conversion		6,220
Controls		700
Critical		358
	Total Development	$ 12,649
GCRE II		
Facility		$ 2,500
Reactor		1,586
Fuel		380
Operations		1,000
	Total GCRE II	$ 5,466
MLX		
Reactor		$ 2,189
Fuel		380
Power Conversion		1,425
Controls		500
Auxiliaries		70
	Total MLX	$ 4,564
	Program Total	$ 22,700

IX. WMR PLANT DESCRIPTION

A. GENERAL

The MLX water moderated reactor power plant is designed to produce 500 kw(e) net plant output at 100°F ambient air temperature. The reactor coolant/power conversion working fluid is air at 500 psia (reactor inlet conditions). The plant consists of five packages: the reactor package; power conversion package; control cab; auxiliary equipment skid; and auxiliary power unit. The total weight is 69,050 pounds. All packages are designed for transport by standard military equipment. The plant layout is shown on Figure IX-1.

The plant flow diagram, Figure IX-2, illustrates the regenerative closed Brayton power cycle employed by the water moderated plant and lists the state points. At an ambient air temperature of 100°F, the cycle efficiency is 18.6% and the net plant thermal efficiency is 14.3%. The reactor outlet temperature is 1330°F.

The reactor pressure vessel is a dual plenum, pressure tube calandria with tube sheets internally cooled by moderator water. Annular layers of lead, tungsten, and borated zironium hydride surround the pressure vessel to provide the metal shield. A tank of tri-n-butyl-borate surrounds the metal shield. This fluid is cooled by the moderator water and by natural convective cooling to the atmosphere.

The reactor core is 19 in. diameter by 19 in. high and contains 55 fuel elements. The fuel elements are pin type; each element contains 19 pins. The pins are clad with Hastelloy-X and loaded with partially enriched uranium dioxide. The enrichment is nominally 40 wt% U-235; the loading is 40 kg of U-235. The partial enrichment results in a negative prompt temperature coefficient. Semiphore type control blades are utilized for in-core control. Provisions are made for removal of the blades.

The moderator water is circulated through the tube sheets, reactor core, organic shield cooler and through external piping, to two parallel forced air-cooled heat exchangers. The heat exchangers are used for afterheat removal as well as for control of moderator temperature during operation.

The power conversion skid is similar to the equipment proposed for the HDMR plant. The precooler is approximately 10% larger to reduce precooler fan power requirements. As in the case of the HDMR system, a two-speed, dual motor emergency blower is required for protection in the event of a loss of coolant.

Startup time of the water moderated plant is estimated to be 12 hours. The moderator system volume is 100 gallons. This small quantity of water is transported with the plant to eliminate the requirement for a water supply and water treatment. However, 6 hours is allowed for the placement of the supplementary expedient shield around the reactor package prior to startup.

Preparation for relocation of the WMR plant cannot begin until 24 hours after shutdown because of activation of the expedient shielding.

The basic reasons for the failure of the WMR plant to qualify as the optimum MLX plant are the general plant complexity, the requirement for an expedient shield during operation, and the small negative temperature coefficient.

B. DETAILED DESCRIPTION

Following on page 148 are detailed descriptions of the major systems, components and characteristics of the WMR power plant in the format described in Section IV. The tabulation and index in Table IX-1 is provided for the convenience of the reader.

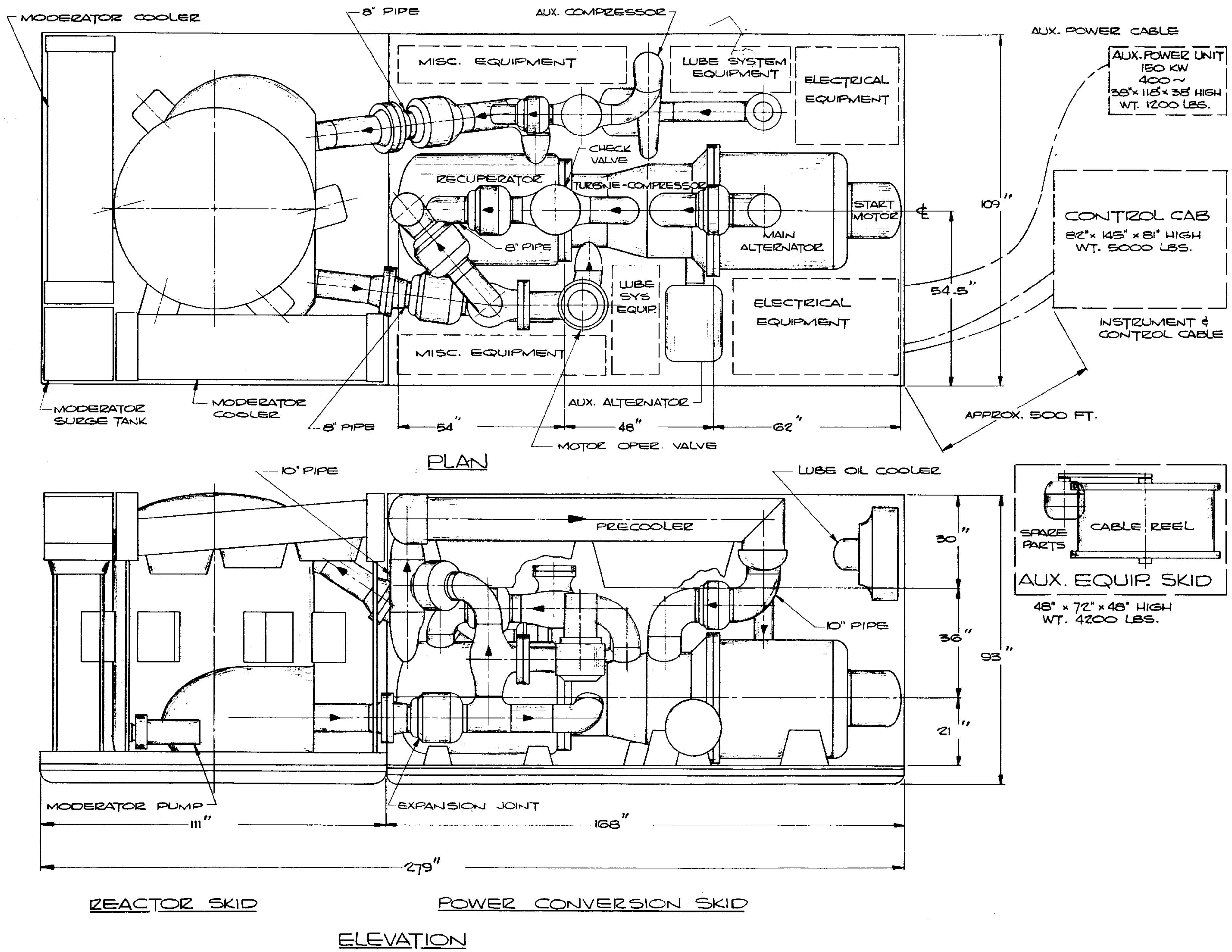
TABLE IX-1

TABULATION AND INDEX

WMR PLANT LAYOUT

The WMR plant consists of two major skids, a control cab, an auxiliary equipment skid and an auxiliary power unit. The truck convoy required for land transport is one tractor/trailer (M-172 or M-172-A-1) and three 2-1/2 ton trucks (M-35).

The reactor shielding is sufficient to permit relocation of the plant 36 hours after shutdown; with expedient shielding in place, operation of the plant is possible from the control cab located 500 feet distant.



WEIGHT SUMMARY

REACTOR SKID		
SHIELD	18300	
PRESS. VESSEL & CORE	4600	
CONTROL DRIVES & ACTUATORS	600	
STRUCTURE	3900	
MODERATOR COOLING SYS	1700	
INSTRUMENTATION	200	
WATER DURING TRANSPORT	200	
		29500
POWER CONVERSION SKID		
TURBINE COMPRESSOR	3000	
RECUPERATOR	3500	
PRECOOLER	5400	
ALTERNATOR	6200	
START MOTOR	400	
LUBE SYSTEM	800	
AUX. COMPRESSOR	500	
STRUCTURE & ACC.	2500	
ELECTRICAL EQUIP	3150	
PIPING & MISC.	3300	
AUX. ALTERNATOR	200	
EMER. BATTERY SYSTEM	200	
		29150
AUXILIARY EQUIP. SKID		4200
CONTROL CAB		5000
AUXILIARY POWER UNIT		1200
		69050

FIGURE IX-1

WATER MODERATED SYSTEM
PLANT LAYOUT

WMR PLANT FLOW DIAGRAM

The WMR power plant uses air as the working fluid in a Brayton cycle with regeneration. The cycle state points and characteristics are listed below:

	Temperature (°F)	Pressure, psia
Compressor inlet	144	171
Compressor outlet	419	511
Reactor inlet	887	500
Reactor outlet	1330	463
Turbine outlet	997	178
Precooler inlet	538	175

Flow rate - 101,000 lb/hr

Reactor power (to gas) - 3.5 Mw

Recuperator heat load - 11.85×10^6 Btu/hr

Precooler heat load - 9.73×10^6 Btu/hr

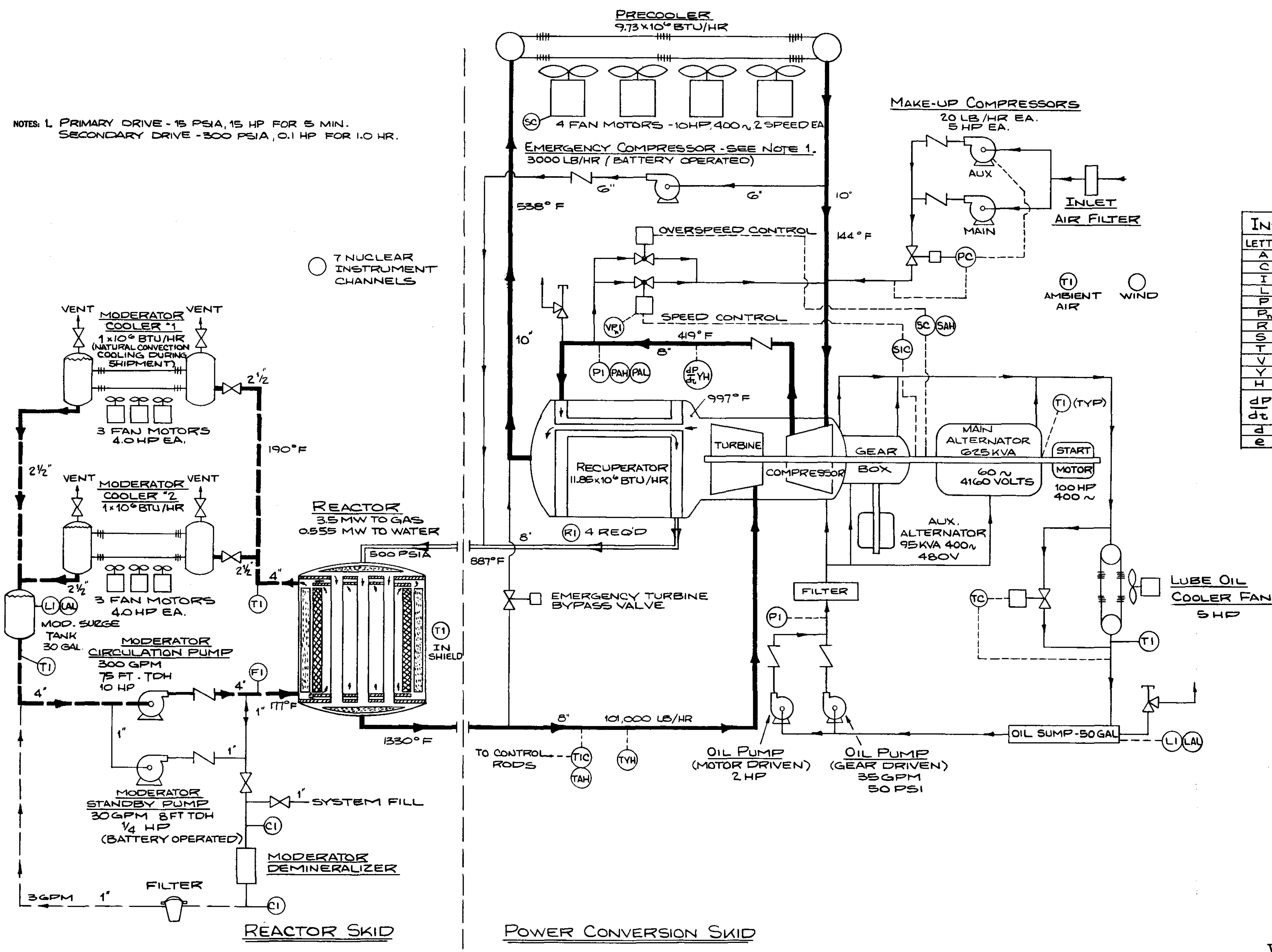
Power, kw(e) - 575 gross; 500 net

Emergency blower - 11 kw

Standby pump - 0.2 kw

Precooler fans - Four 2-speed fans, 10 hp each, 30 kw total

Moderator cooler fans - Six single-speed fans, 4 hp each, 18 kw total



INSTRUMENT SYMBOLS

LETTER	1ST LETTER	2ND LETTER	3RD LETTER
A		ALARM	
C	CONDUCTIVITY	CONTROL	CONTROL
I		INDICATING	
L	LEVEL		LOW
P	PRESSURE		
P_n		POSITION	
R	RADIATION	RECORDING	
S	SPEED		
T	TEMP		
V	VALVE		
Y		SCRAM	SCRAM
H			HIGH
$\frac{dP}{dt}$	RATE OF PRESSURE CHANGE NEG.		
d	SUBSCRIPT REFERING TO DIFFERENTIAL		
e	SUBSCRIPT REFERING TO ERROR		

FIGURE IX-2

WATER MODERATED SYSTEM
FLOW DIAGRAM

WMR FUEL ELEMENT

The WMR fuel element is a cluster of 19 pins inside a perforated insulated liner. The pins are separated by spacer wires. The fuel material is uranium dioxide enriched to approximately 40 wt% U-235. The enrichment is uniform over the entire core. The fuel is in the form of pellets loaded into a Hastelloy-X tube. The spacer wire, lower support spider and inner liner are Hastelloy-X. The outer liner is AISI Type 316 stainless steel and the insulation between liners is spiral wound, perforated Refrasil. Burnable poison (either boron or europium dispersed in a stainless steel matrix) is attached to the outside of the inner liner.

The 19 pin cluster is supported at the bottom by a single spider joined to the outer liner. A single spider minimizes core pressure drop and has several desirable mechanical characteristics. The fuel element is 23.68 inches long by 1.63 inches outside diameter. The fueled length of the pins is 19 inches; the overall length of the pin is 20 inches. The minimum cladding thickness is 0.020 inches. Turbulence promoters, 0.011 inches high, are provided over the lower 13 inches of the active length.

WATER MODERATED FUEL ELEMENT

FIGURE IX-3

WMR REACTOR

The WMR core is a cylinder 19 in. diameter and 19 in. high. The 55 fuel elements are hung from the top tube sheet in the pressure tubes which are surrounded by moderator water. The air coolant enters the core at the top and flows downward through the core. The moderator water flows up through the core.

The reactor pressure vessel is composed of AISI Type 347 stainless steel ducts and plenums and Inconel-X tube sheets and tubes. Coolant gas enters the upper plenum, passes through and around the upper tungsten axial shield, through the core, through the lower axial tungsten shield into the lower plenum and out through the gas duct. A 2 inch lead reflector surrounds the core; this reflector is, in turn, surrounded by the heavy shielding.

Reactor control is provided by six pairs of semaphore type control blades located in the moderator water. The neutron absorbing material for the five shim-safety blades is a rare earth in a stainless steel matrix. The control material for the regulating blade pair is a silver-indium-cadmium alloy.

WATER MODERATED REACTOR

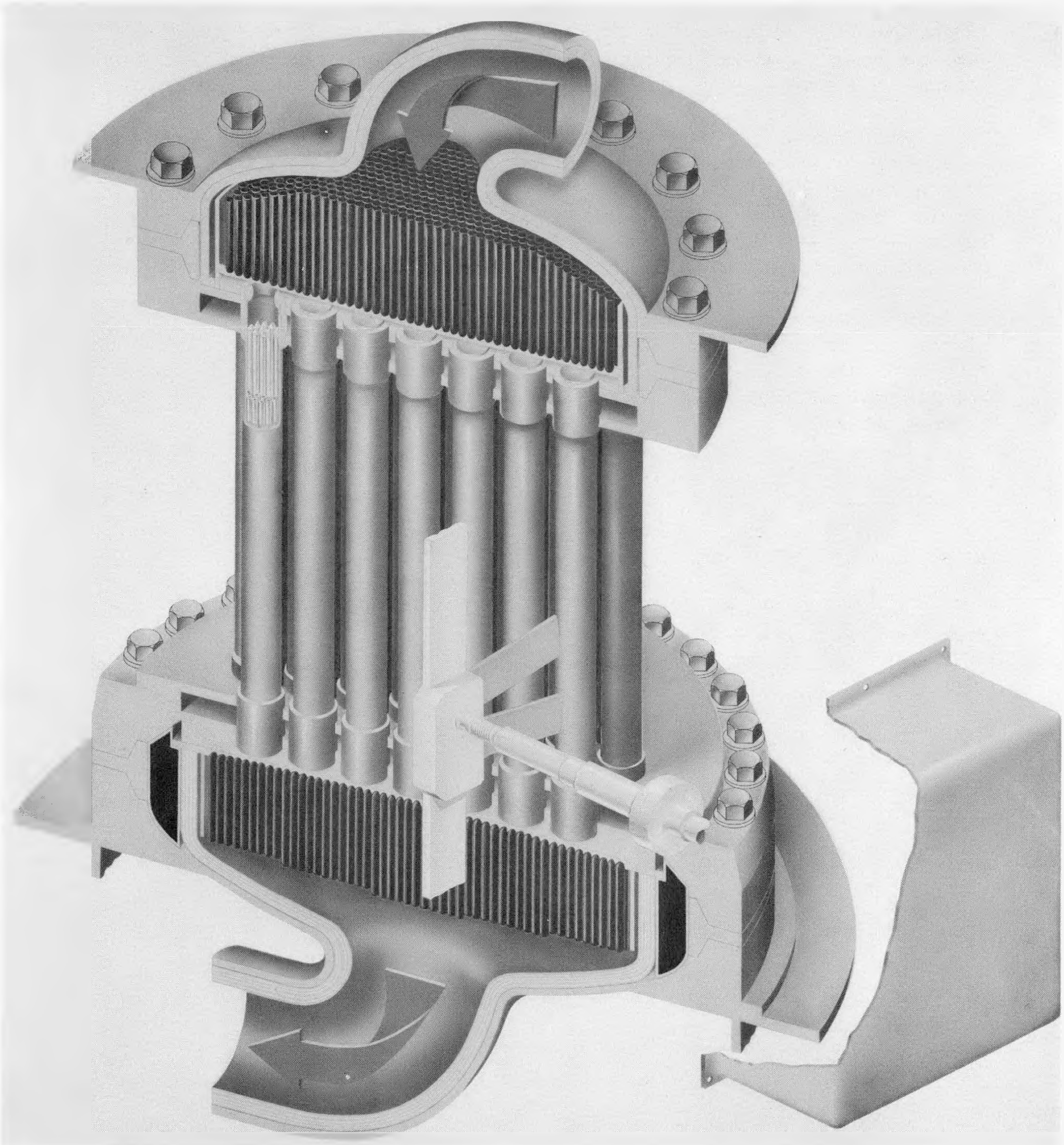


FIGURE IX-4

WMR REACTOR PACKAGE

The WMR reactor is a 19 in. diameter by 19 in. high single-pass core with partial operational shielding. The tube sheet and pressure type material is Inconel-X. The moderator water flows through and around the lower tube sheet, up through the core, through and around the upper sheet and out to the cooler.

The pressure vessel and heavy shield are supported by a stainless steel sheel welded to the lower cap flange which, in turn, is connected to the lower shield tank and skid support structure. The heavy shield consists of annular layers of lead, tungsten, and borated zirconium hydride. A tank of tri-n-butyl-borate surrounds the heavy shield. This fluid is cooled by the moderator water and by natural convection to the atmosphere. Heat exchange to the moderator cooler is accomplished through a coiled 1/2 in. finned tubing located in the shield fluid.

Two pumps are provided in the moderator system: a 300 gpm, 10 hp, "canned" centrifugal pump is used to circulate the moderator water during operation; a 30 gpm, 1/4 hp battery-operated pump is used during shutdown. Two heat exchangers are provided to remove the moderator heat. Each heat exchanger is equipped with three 4 hp fans to provide the required air flow. During shutdown, natural convective flow of the moderator from the hot core to the cool heat exchangers provides the required cooling for the core. The moderator system volume is about 100 gallons.

Reactor control is accomplished by six pairs of semaphore blades operating in the moderator water portion of the core. The six control actuators are mounted on the outer surface of the shield tank. The housings are equipped with doors for access and replacement.

The overall package dimensions are:

Length	-	111 in.
Width	-	109 in.
Height	-	93 in.

The package weight is 29,500 lb.

WATER MODERATED REACTOR PACKAGE

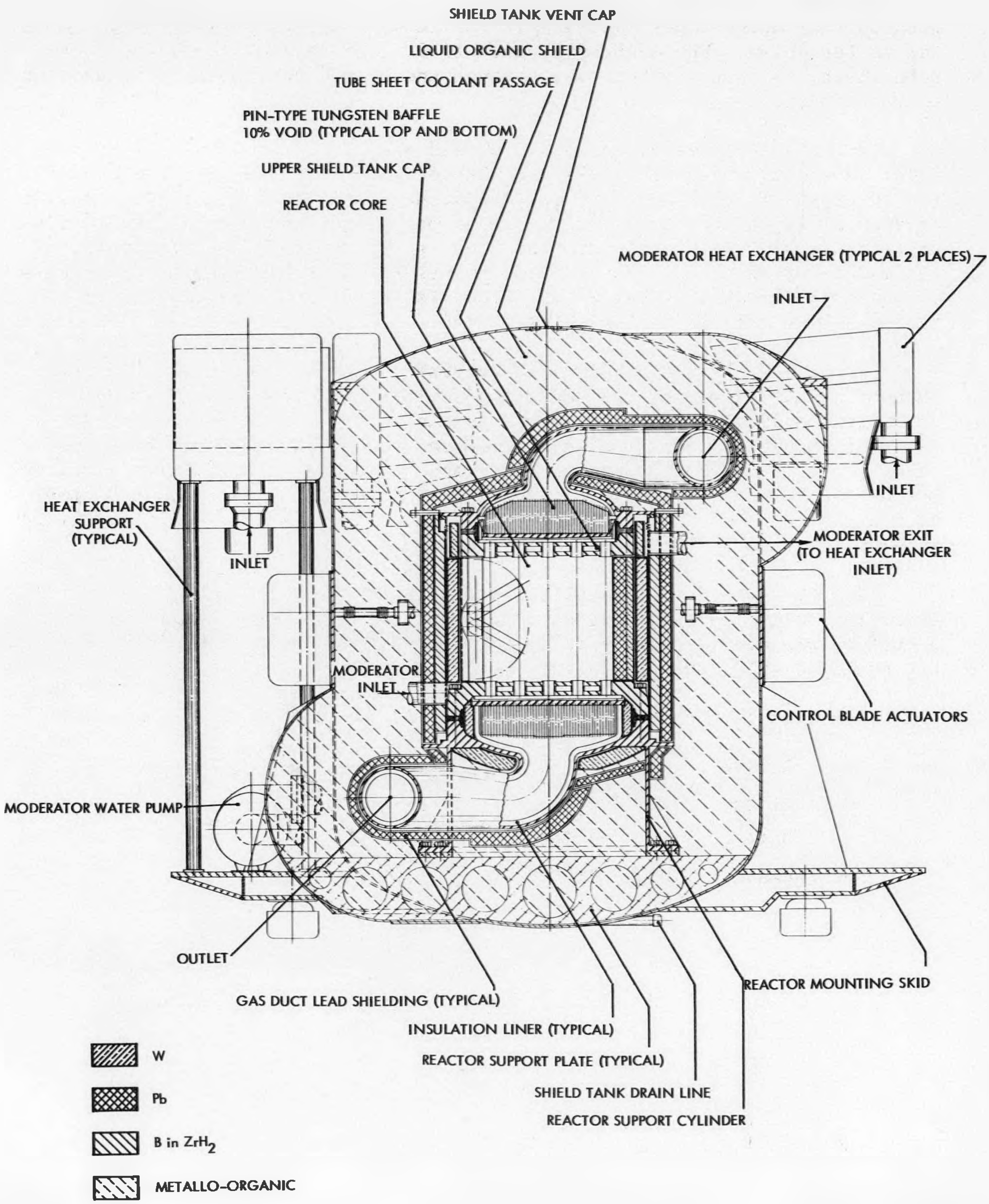


FIGURE IX-5

WMR FISSION SPECTRUM

Essentially all of the fissions occurring in the WMR reactor are caused by neutrons in the thermal region. The spectrum is not altered significantly by reactor flooding.

WMR NEUTRON FLUX

The neutron flux in the WMR system is shown on the facing page.

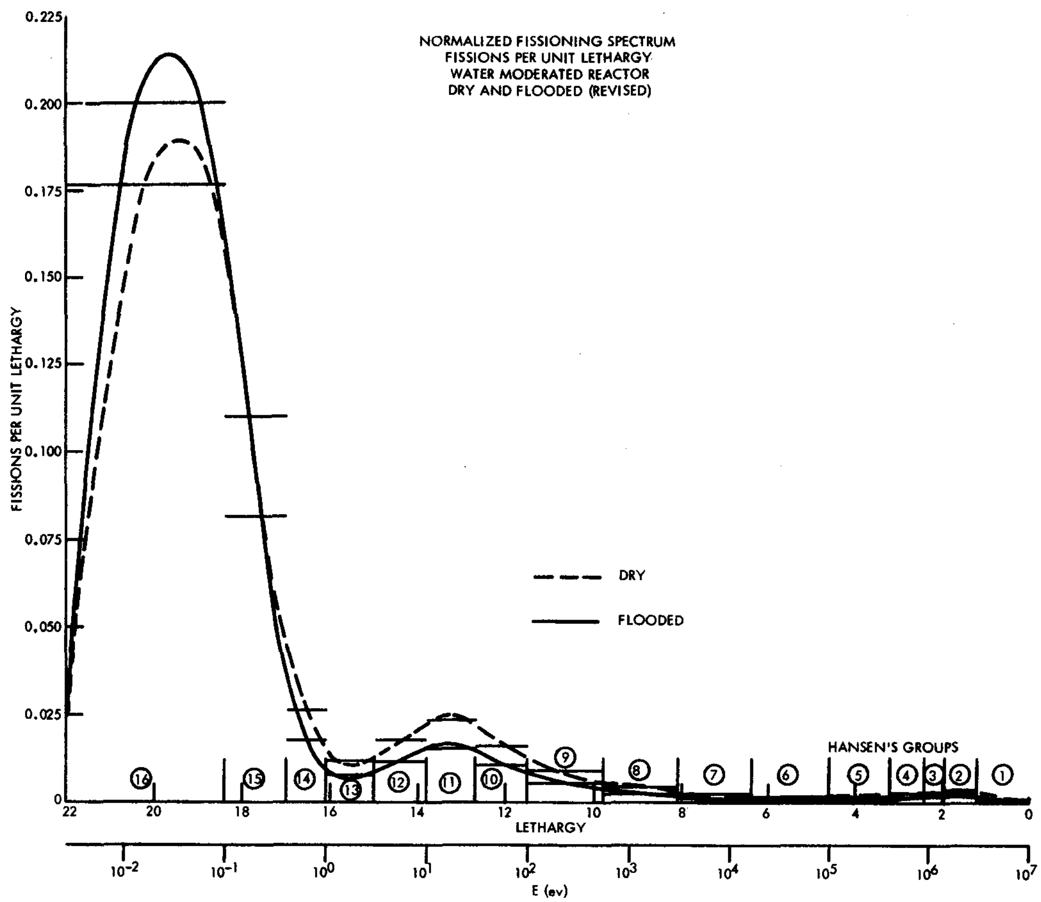


FIGURE IX-6

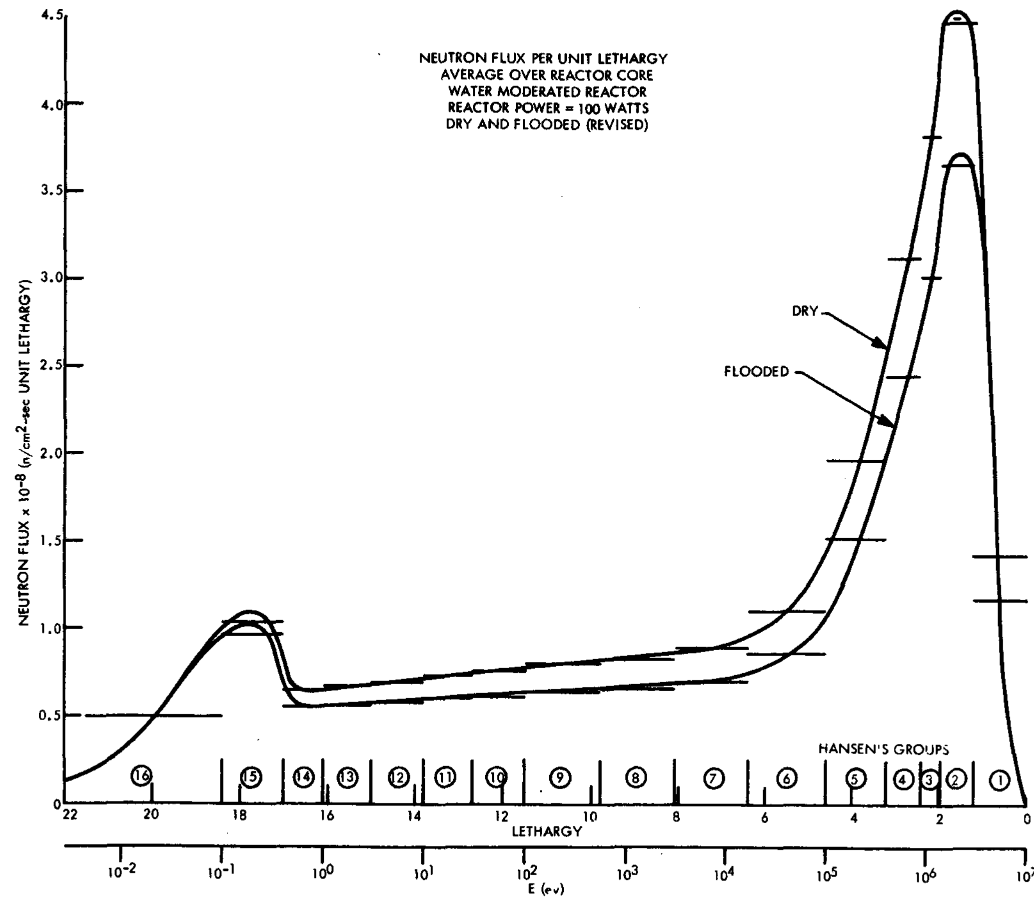


FIGURE IX-7

WMR CONTROL ROD

The WMR control rod consists of a pair of contra-rotating neutron absorbing blades of the semaphore type driven through a magnetic clutch and gear train by an electric motor.

The arrangement is similar to the ML-1 control rod system (See IDO-28550, "ML-1 Design Report"). Notable improvements include:

1) Use of an air dash pot to minimize corrosion and resultant malfunction.

2) "Bubble" mounting of actuator housing to permit actuator maintenance without removal.

CONTROL ROD ACTUATOR
WATER MODERATED REACTOR

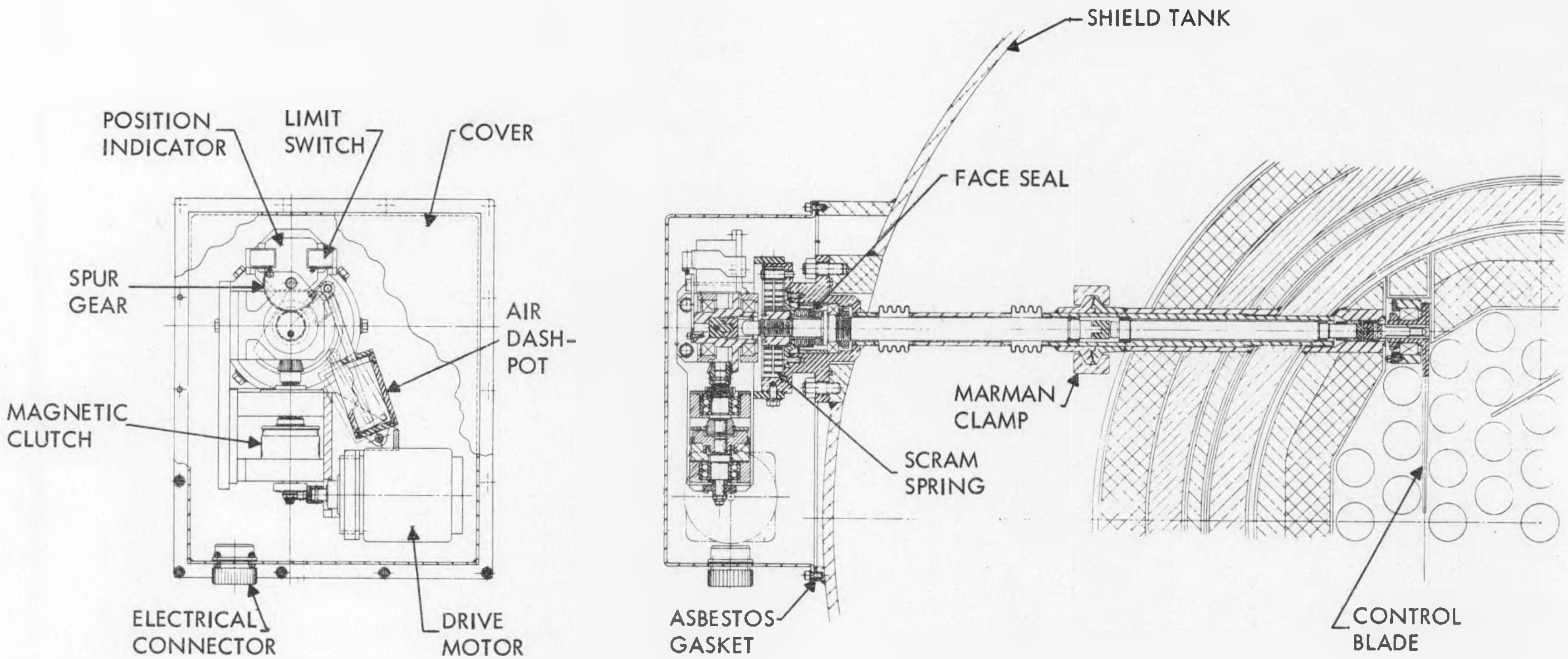


FIGURE IX-8

WMR NUCLEAR INSTRUMENTATION SYSTEM

The nuclear instrumentation system for the WMR is identical with that described in the HDMR section of this report (Figure V-11) in all respects but one. The actuators in the WMR design incorporate magnetic clutches instead of actuator electromagnets as called out for the HDMR.

WMR ELECTRICAL SYSTEM

The electrical system is identical with that described in the HDMR section of this report (Figure V-12) except that the plant loads on the 400 cycle system reflect the requirement for circulation and cooling of moderator water.

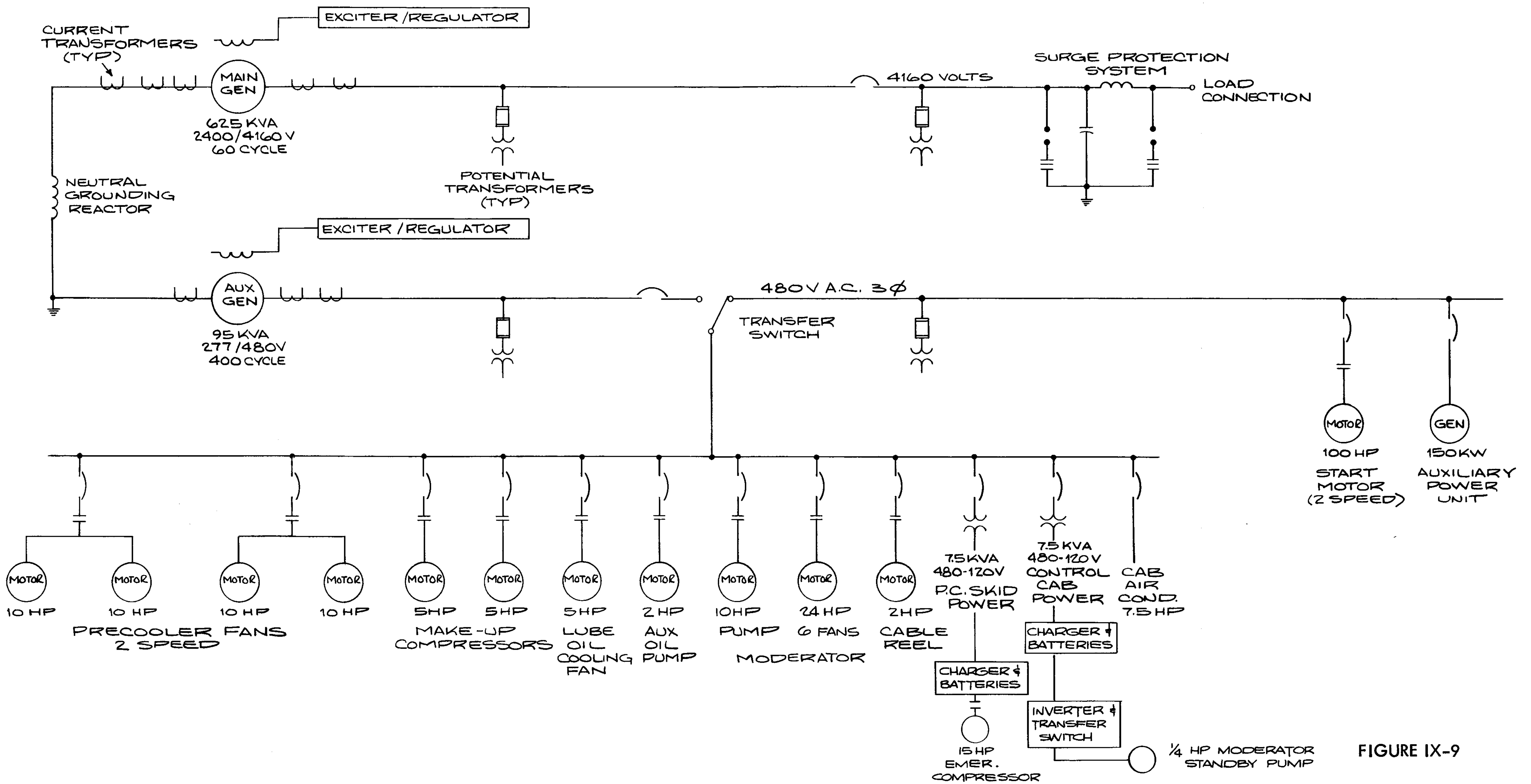


FIGURE IX-9

WATER MODERATED POWER PLANT
SINGLE LINE DIAGRAM

WMR POWER CONVERSION EQUIPMENT PERFORMANCE CHARACTERISTICS

The performance characteristics of the WMR power conversion equipment are identical with those described in the HDMR section, page 41 of this report.

TABLE IX-1 WMR CORE PERFORMANCE CHARACTERISTICS

1.	Thermal power (Mw)	3.78
2.	Bare core diameter (in.)	19
3.	Bare core height (in.)	19
4.	Coolant	Air
5.	Coolant flow rate (lb/hr)	101,000
6.	Core loading (kg. U-235)	40
7.	Inlet gas temperature (^oF)	887
8.	Outlet gas temperature (^oF)	1330
9.	System pressure (psi)	500
10.	Core pressure drop (psi)	25
11.	Core void fraction (%)	21.2
12.	Total core weight (lb) (including moderator)	1420
13.	Cycle	Closed regenerative
14.	Maximum clad hot spot temperature (^oF)	1765
15.	Average ΔT coolant to clad (^oF)	175
16.	Average nominal clad temperature (^oF)	1565
17.	Average moderator temperature (^oF)	183
18.	Average fuel temperature (^oF)	1600
19.	Average coolant velocity thru element (ft/sec)	97
20.	Core structural fraction (vol%)	11.8
21.	Core moderator fraction (vol%)	55
22.	Heat transfer surface area (ft^2)	108
23.	Average heat flux ($Btu/hr/ft^2$)	1.10×10^5
24.	Core flow area ($in.^2$)	29
25.	Volume fraction fuel (%)	12.0
26.	Moderator material	Demineralized water
27.	Total weight of moderator (lb)	850

TABLE IX-3

WATER MODERATED SYSTEM

This table presents the primary criteria which were applied in the selection of the design concept in the several listed design areas.

Design Area	Selection	Primary Criteria
Moderator	Water	By direction
Coolant	Air	Logistic advantage
Cycle	Closed regenerative	Minimum reactor and shield size
Compression ratio, turbine-compressor set	3.0	Maximum cycle efficiency, minimum reactor & heat exchanger size
Recuperator effectiveness	.80	Minimum system weight
Precooler effectiveness	.90	Minimum system weight
Turbine-compressor set aerodynamics	Axial turbine, centrifugal compressor	Maximum cycle efficiency, satisfy blade height requirements
Reactor active core size	19 in. diameter x 19 in. high	Minimum core size to utilize existing fuel technology
Duct location	Top entry, bottom exit	Minimum shielding weight and fuel cladding temperatures
Reflector material	Lead	Minimum fuel loading and package weight
Reflector location	Core perimeter	Minimum fuel loading and package weight
Pressure vessel material	Low cobalt Inconel-X tube sheets and pressure tubes; low cobalt CRES 347 plenums and duct	Maximum corrosion resistance and good mechanical properties; minimum contribution to shutdown dose
Reactor control	6 pairs of semaphore blades in moderator	In-core control required minimum package height
Flooding control	Control blades	Minimum reactivity increase with flooding with sufficient control in blades

WATER MODERATED SYSTEM (Continued)

Design Area	Selection	Primary Criteria
Core fuel geometry	Polygon pattern of fifty-five 19-pin elements	Negative temperature coefficient, fission product containment, maximum reliability
Fuel material	Uranium dioxide, partially enriched	High temperature characteristics, well-known technology
Pin dimensions	19 in. active length x 0.265 in. maximum outside diameter	Minimum fuel element cladding temperature within required fuel volume
Fuel element dimensions	23.68 in. overall length x 1.63 in. outside diameter (outer liner)	Minimum fuel element cladding temperature and tube sheet stresses
Turbine inlet temperature	1330°F	Minimum reactor temperature, power, and coolant flow
System pressure	500 psi	Minimum reactor temperature within turbine blade height limitations
Reactor Δ P	5%	Minimum reactor power and coolant flow
Shield material	Pb-W-borated ZrH_2 heavy shield surrounded by tri-n butyl borate fluid; supplemented by expedient shield	Minimum to meet military characteristics
Shield cooling	By moderator water and by natural convection of organic shield fluid	Minimum mechanical complexity, maximum reliability
Fuel distribution	Uniform	Minimum fabrication complexity, maximum reliability

WMR SYSTEM PROGRAM SCHEDULE AND PROGRAM COSTS

The descriptive information presented in the HDMR section (Figures IV-15 and Table IV-5) of this report applies also to the schedule and cost estimates shown on Figure IX-10 and Table IX-4.

WATER MODERATED PROGRAM SCHEDULE

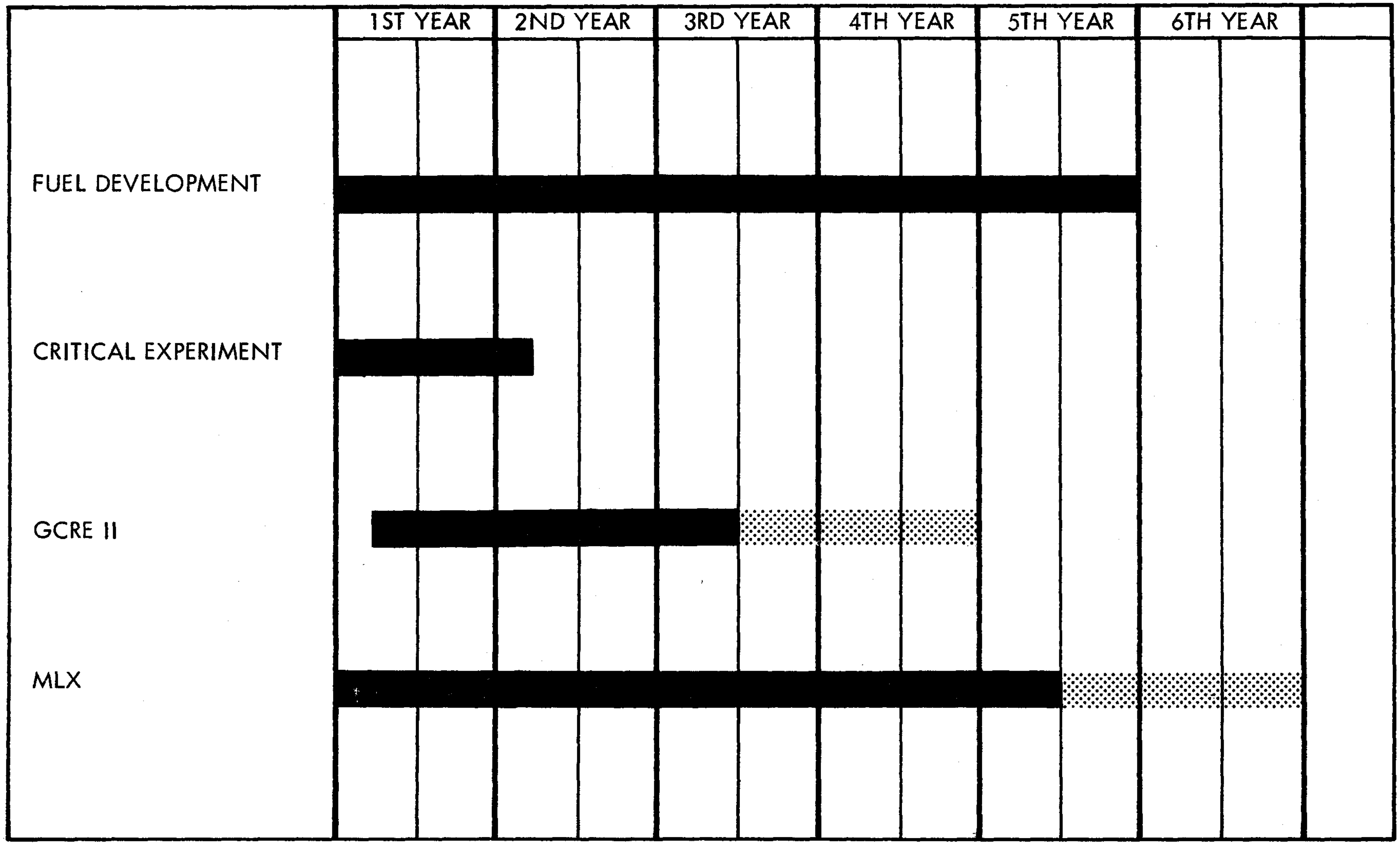


FIGURE IX-10

TABLE IX-4

WMR PROGRAM COSTS
(Thousands of Dollars)

DEVELOPMENT		
	Fuel	$ 3,540
	Reactor	190
	Power conversion	6,220
	Controls	700
	Critical	358
	Total Development	$ 11,008
GCRE II		
	Facility	$ 1,500
	Reactor	2,068
	Fuel	400
	Operations	1,000
	Total GCRE II	$ 4,968
MLX		
	Reactor	$ 2,200
	Fuel	400
	Power conversion	1,425
	Controls	500
	Auxiliaries	70
	Total MLX	$ 4,595
	PROGRAM TOTAL	$ 20,600