ABSTRACT

This is one of twenty-one volumes summarizing the Aircraft Nuclear Propulsion Program of the General Electric Company. This portion describes the XMA-1 which was the first developmental model of a power plant designed for operational applications.

The XMA-1 was designed to be a nuclear powered turbojet aircraft power plant consisting of a direct air cycle reactor, nuclear shielding, two parallel sets of X211 turbomachinery, and the required ducting, interconnecting structure and controls. Provisions were made for operation on either nuclear or chemical heat source.

Initially, the XMA-1 was to satisfy the requirements which included (1) cruise at Mach 0.9, 20,000 feet altitude; (2) low level attack at Mach 0.9, 500 feet altitude; and (3) sprint at Mach 2.5, 55,000 to 60,000 feet altitude. These were later changed to (1) cruise at 30,000 feet altitude at Mach 0.9 and (2) flight at Mach 0.9 at sea level.

The power plant proposed for first flight test was designated XMA-1A. The objective of the first power plant was a system that would represent as closely as possible the requirements and characteristics identified for the operational version. The operational version was designated XMA-1C.

This report presents a description of the XMA-1A design, design requirements, design data, and major test results, as well as the results of the studies directed toward selection of a reactor for the XMA-1C.

ACKNOWLEDGMENT

Acknowledgement is made of the contributions of J. I. Trussell.

PREFACE

In mid-1951, the General Electric Company, under contract to the United States Atomic Energy Commission and the United States Air Force, undertook the early development of a militarily useful nuclear propulsion system for aircraft of unlimited range. This research and development challenge to meet the stringent requirements of aircraft applications was unique. New reactor and power-plant designs, new materials, and new fabrication and testing techniques were required in fields of technology that were, and still are, advancing very rapidly. The scope of the program encompassed simultaneous advancement in reactor, shield, controls, turbomachinery, remote handling, and related nuclear and high-temperature technologies.

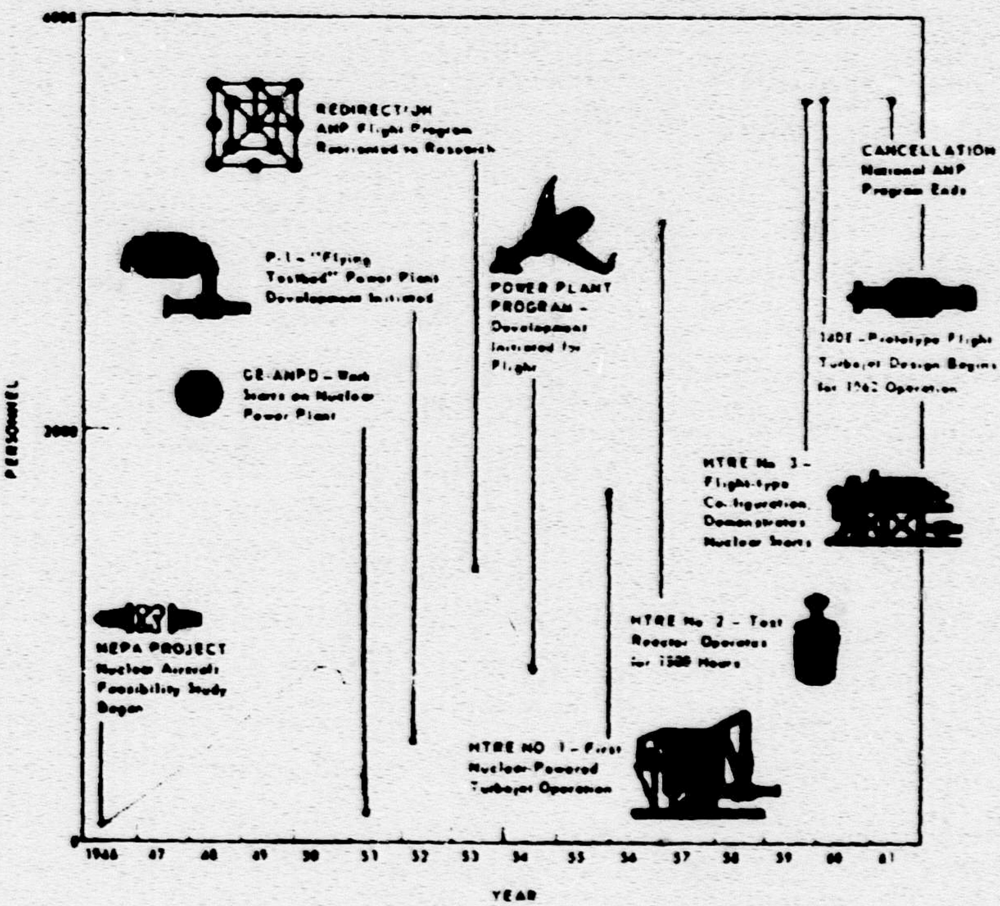
The power-plant design concept selected for development by the General Electric Company was the direct air cycle turbojet. Air is the only working fluid in this type of system. The reactor receives air from the jet engine compressor, heats it directly, and delivers it to the turbine. The high-temperature air then generates the forward thrust as it exhausts through the engine nozzle. The direct air cycle concept was selected on the basis of studies indicating that it would provide a relatively simple, dependable, and serviceable power plant with high-performance potential.

The decision to proceed with the nuclear-powered-flight program was based on the 1951 recommendations of the NEPA (Nuclear Energy for the Propulsion of Aircraft) project. Conducted by the Fairchild Engine and Airplane Corporation under contract to the USAF, the five-year NEPA project was a study and research effort culminating in the proposal for active development of nuclear propulsion for manned aircraft.

In the ensuing ten years, General Electric's Aircraft Nuclear Propulsion Department carried on the direct air cycle development until notification by the USAF and USAEC, early in 1961, of the cancellation of the national ANP program. The principal results of the ten-year effort are described in this and other volumes listed inside the front cover of the Comprehensive Technical Report of the General Electric Direct Air Cycle Aircraft Nuclear Propulsion Program.

Although the GE-ANPD effort was devoted primarily to achieving nuclear aircraft power-plant objectives (described mainly in APEX-902 through APEX-909), substantial contributions were made to all aspects of gas-cooled reactor technology and other promising nuclear propulsion systems (described mainly in APEX-910 through APEX-921). The Program Summary (APEX-901) presents a detailed description of the historical, programmatic, and technical background of the ten years covered by the program. A graphic summary of these events is shown on the next page.

Each portion of the Comprehensive Report, through extensive annotation and referencing of a large body of technical information, now makes accessible significant technical data, analyses, and descriptions generated by GE-ANPD. The references are grouped by subject and the complete reference list is contained in the Program Summary, APEX-901. This listing should facilitate rapid access by a researcher to specific interest areas or



Summary of events – General Electric Aircraft Nuclear Propulsion Program*

*Detailed history and chronology is provided in Progress Summary, APEX-901. Chronology information extracted from Aircraft Nuclear Propulsion Program hearing before the Subcommittee on Research and Development of the Joint Committee on Atomic Energy, 86th Congress of The United States, First Session, July 23, 1959. United States Government Printing Office, Washington 1959 sources of data. Each portion of the Comprehensive Report discusses an aspect of the Program not covered in other portions. Therefore, details of power plants can be found in the power-plant volumes and details of the technologies used in the power plants can be found in the other volumes. The referenced documents and reports, as well as other GE-ANPD technical information not covered by the Comprehensive Report, are available through the United States Atomic Energy Commission, Division of Technical Information Extension, Oak Ridge, Tennessee.

The Report is directed to Engineering Management and assumes that the reader is generally familiar with basic reactor and turbojet engine principles; has a technical understanding of the related disciplines and technologies necessary for their development and design; and, particularly in APEX-910 through APEX-921, has an understanding of the related computer and computative techniques.

The achievements of General Electric's Aircraft Nuclear Propulsion Program were the result of the efforts of many officers, managers, scientists, technicians, and administrative personnel in both government and industry. Most of them must remain anonymous, but particular mention should be made of Generals Donald J. Keirn and Irving L. Branch of the Joint USAF-USAEC Aircraft Nuclear Propulsion Office (ANPO) and their staffs; Messrs. Edmund M. Velten, Harry H. Gorman, and John L. Wilson of the USAF-USAEC Operations Office and their staffs; and Messrs. D. Roy Shoults, Samuel J. Levine, and David F. Shaw, GE-ANPD Managers and their staffs.

This Comprehensive Technical Report represents the efforts of the USAEC, USAF, and GE-ANPD managers, writers, authors, reviewers, and editors working within the Nuclear Materials and Propulsion Operation (formerly the Aircraft Nuclear Propulsion Department). The local representatives of the AEC-USAF team, the Lockland Aircraft Reactors Operations Office (LAROO), gave valuable guidance during manuscript preparation, and special appreciation is accorded J. L. Wilson, Manager, LAROO, and members of his staff. In addition to the authors listed in each volume, some of those in the General Electric Company who made significant contributions were: W. H. Long, Manager, Nuclear Materials and Propulsion Operation; V. P. Calkins, E. B. Delson, J. P. Kearns, M. C. Leverett, L. Lomen, H. F. Matthiesen, J. D. Selby, and G. Thornton, managers and reviewers; and C. L. Chase, D. W. Patrick, and J. W. Stephenson and their editorial, art, and production staffs. Their time and energy are gratefully acknowledged.

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November 6, 1961

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TABLES

1. INTRODUCTION AND SUMMARY

In 1954, General Electric Aircraft Nuclear Propulsion Department (GE-ANPD) planning included the development of components leading to the establishment of design specifications for a militarily useful aircraft power plant. A series of studies were performed considering various core configurations, shield configurations, types of moderator, and methods of control. Reactor-shield assemblies were coupled with various turbojet arrangements to determine the optimum engine configuration. Application studies were performed in conjunction with Lockheed, Boeing, and Convair to determine the design operating conditions for the nuclear engine. An analysis was performed to determine the engine requirements for the nuclear aircraft.

In March 1955, the Air Force issued requirements for a high performance, nuclear powered aircraft weapons system designated 125A.

The specific requirements called for (1) cruise at Mach 0.9, 20,000 feet altitude; (2) low level attack at Mach 0.9, 500 feet altitude; (3) sprint at Mach 2.5, 55,000 to 60,000 feet altitude; (4) uninterrupted cruise capability of 40 hours minimum; and (5) sprint distance of 2000 nautical miles.

Various power plant proposals were considered in determining the one to be used to meet the mission requirements; the AC-110 power plant was the one selected. The AC-110, described in detail in references 1 and 2, consisted of a reactor-shield assembly coupled and manifolded to two General Electric X211 turbojet engines (the turbomachinery designed to provide the basic air pump for the XMA-1). The reactor was a solid moderator, metallic fuel element, direct air cycle type. The design of the AC-110 power plant and the performance of the turbojet components were based on an assumed maximum turbine inlet temperature of 2000°F.

Convair Division of General Dynamics, Ft. Worth, Texas, performed the airframe work on the 125A Weapons Systems application. The designation of this aircraft was Model 25.[3*]

In June 1958, the all subsonic CAMAL mission replaced the 125A mission. The CAMAL requirements were: (1) cruise at Mach 0.9, 30,000 feet altitude, (2) low level penetration at Mach 0.9, 500 feet altitude, and (3) uninterrupted cruise of 120 hours. The design power plant was altered to suit the new requirements.

The configuration of the airframe to meet the CAMAL mission was designated the Convair Model 54.[4] The nuclear engines were mounted side by side in the aft fuselage in two separate nacelle areas. Each nacelle area had an oval shaped inlet located on the side of the fuselage just forward of the wing leading edge. The four-man crew compartment was located in the forward fuselage.

To minimize the total shield weight, the shielding was divided between the reactor and crew compartment. All components were located in regions of acceptable radiation levels

*Superscripts refer to the reference list that appears at the end of each section.

with a fuel tank located between the reactor and crew shield to augment radiation attenuation.

This volume presents: (1) the over-all design requirements including the performance goals and operating boundaries;[5] (2) a description of the XMA-1A, the first developmental model of the power plant, as it existed at the termination of the program; (3) a description of the design and testing of each of the major power plant components; (4) the proposed remote handling procedures and equipment to be used; and (5) performance requirements for reactor cores proposed for use for the XMA-1C. The XMA-1C was the growth version of the XMA-1A and the nuclear turbojet; it would have been installed in later (Model 54A and 54B) aircraft for operational use. The XMA-1C was designed to increase performance 10 percent[6] over that proposed in reference 2.

The analysis of the XMA-1 nuclear turbojet was the first significant instance in which the aircraft nuclear power plant requirements were determined on the basis of application to weapons system requirements (125A and CAMAL). Although the weapons systems requirements varied, the planning, design, development, and testing cycles for both engines were quite similar. Studies performed at GE-ANPD as well as at Convair and other contractors clarified the magnitude and complexities of the variety of research, development, testing, and operations involved. The component development and evaluation provided a good measure of the eventual practicalities of the nuclear system.

1.1 REFERENCES

1. "Preliminary Description of AC-110 Power Plant," GE-ANPD, APEX-208, November 1955.
2. "Preliminary Description of AC-110 Power Plant, Appendix A," GE-ANPD, APEX-210, November 1955.
3. "Convair Model 25 Preliminary Design Proposal - Weapons System Summary," Convair - Division of General Dynamics Corp., Ft. Worth, Texas, FZA-25-001, April 1956.
4. "CAMAL Proposal to USAF - Technical Summary," Convair - Division of General Dynamics Corp., Ft. Worth, Texas, FZP-54-001, (AEC 5113-CVAC), October 1958.
5. "Preliminary Performance and Installation Bulletin for the First Developmental XMA-1 Power Plant (Model XMA-1A)," GE-ANPD, APEX-380, June 30, 1958.
6. "Preliminary Performance and Installation Bulletin for the First Developmental XMA-1 Power Plant (Model C)," GE-ANPD, APEX-389, July 31, 1958.

2. POWER PLANT

2.1 OVER-ALL DESIGN REQUIREMENTS

2.1.1 GENERAL

The requirements presented in this section are those that were established for the over-all XMA-1A power plant.

2.1.2 THERMODYNAMIC PERFORMANCE

Component performance was designed for a level sufficiently high to provide minimum power plant performance as shown in Figures 2.26 through 2.35 based on a pressure loss characteristic presented in section 2.2.2.1.

2.1.3 MODES OF OPERATION

The XMA-1A power plant was designed to operate twin sets of turbomachinery on the nuclear flow path, chemical flow path, and a combination of nuclear and chemical flow paths.

The starting objectives were for starts on the chemical flow path or the nuclear flow path; none would be made with a combination of the two.

Accelerations were guarded (no rapid throttle movements). One minute accelerations and decelerations between idle and military power were required. The ability to make 15-second accelerations was an objective.

Minimum requirements were to transfer from the chemical to the nuclear flow path or from the nuclear to the chemical flow path with the power plant operating. No thrust was required from the power plant during this transfer.

2.1.4 OPERATING LIMITS

The basic XMA-1C Design Flight Limits, based on the requirements for the CAMAL weapons system, are presented in Figure 2.1.

The XMA-1A power plant and its components were designed to provide, as a minimum, satisfactory operation within the flight map presented in Figure 2.2.

The following design limits were established for the XMA-1A power plant:

1. Maximum compressor discharge pressure	204 psia
2. Maximum compressor discharge temperature	
a. Nuclear	727°F
b. Chemical	742°F

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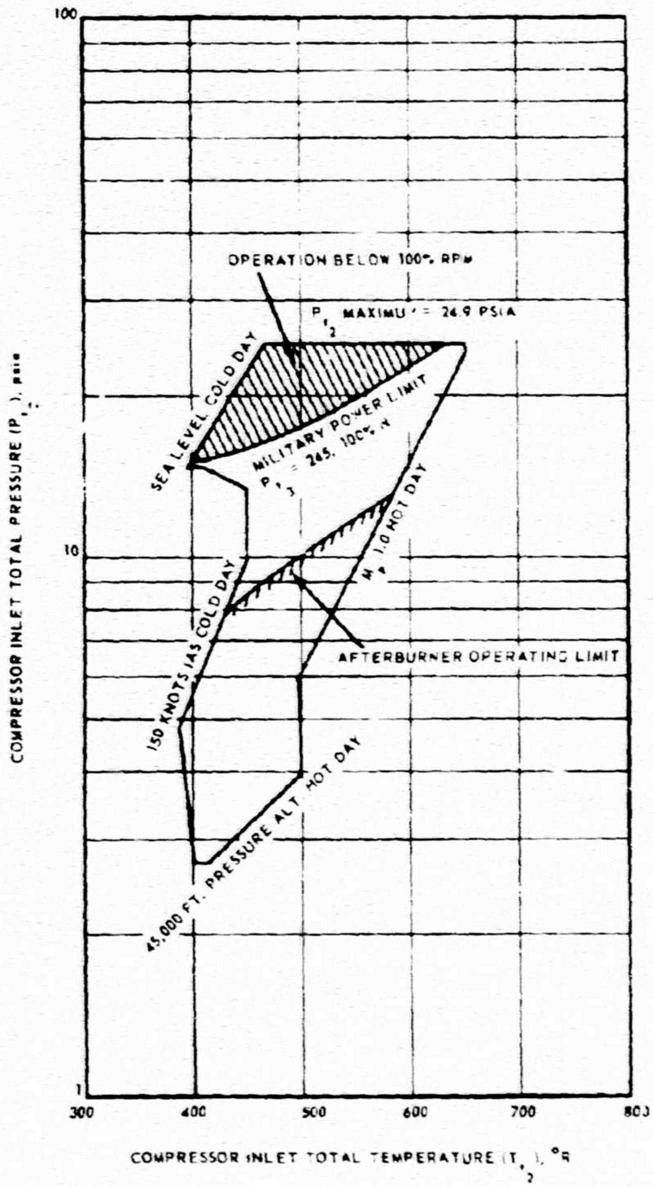

Fig. 2.1 – XMA-1C power plant estimated minimum performance flight limits

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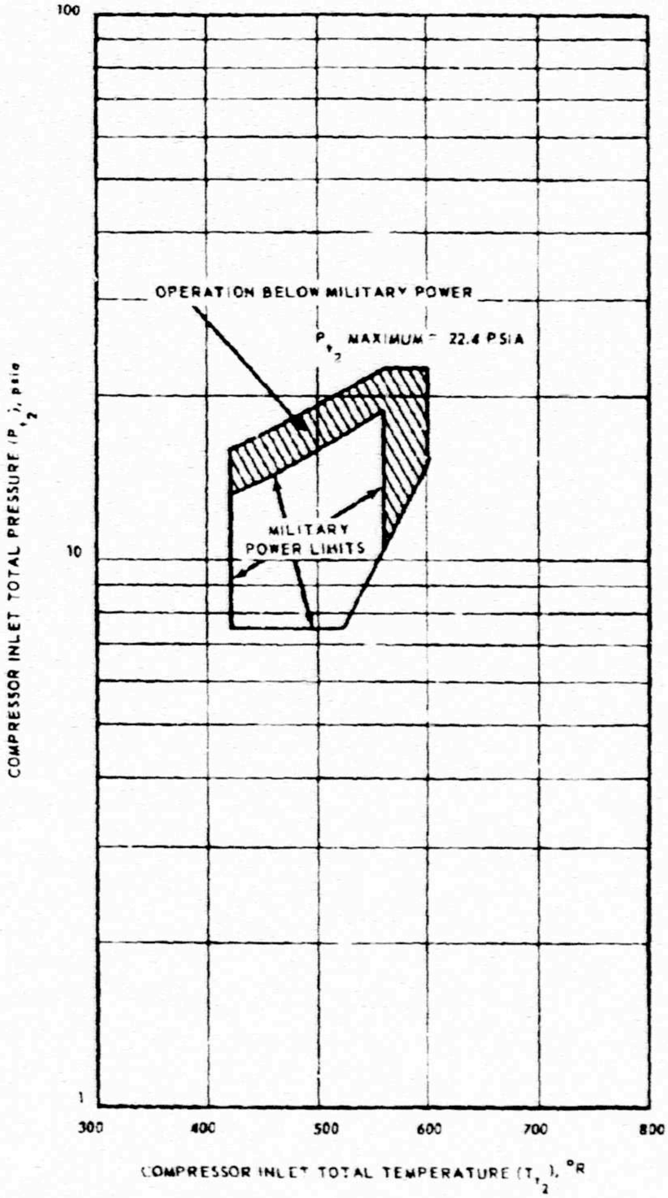

Fig. 2.2—XMA-1A power plant estimated minimum performance flight limits

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3. Turbomachinery rotational speed
   a. Design Military Power, nuclear — 4700 rpm
4. Turbine inlet temperature
   a. Design Military Power, nuclear — $1500^{\circ}F$
   b. Military power, chemical — $1550^{\circ}F$
5. Maximum reactor power — 205 mw

2.1.5 LOAD CRITERIA

The power plant structure was designed for the following loading conditions over the design life profile of the power plant. The applicable load factors for these conditions are presented in Table 2.1. All loads were assumed to act separately or in any combination so that the most severe stresses could be obtained.

1. Endurance. The weight loads, combined with the loads due to pressures and loads due to thermal gradients, were multiplied by 1.25.
2. Flight. The loads due to pressures and those due to thermal gradients were multiplied by 1.25 and inertial loads.
3. Ground Operation. The loads due to pressures and those due to thermal gradients were multiplied by 1.25 and inertial loads.
4. Ground Handling. Inertial loads only, at room temperature, were used.
5. Crash Landing. The loads due to pressure and those due to thermal gradients were multiplied by 1.25 and inertial loads.
6. Maximum Engine Speed. The structure and its supports were to withstand, without permanent deformation or failure, a gyroscopic moment imposed by a steady state angular velocity of 0.1 radian per second in yaw combined with a vertical load factor of plus or minus 1 for a period of 2 minutes.

TABLE 2.1

LOAD FACTORS FOR THE POWER PLANT STRUCTURE LOADING CONDITIONS

	Endurance	Flight[a]	Ground Operation[b]	Ground Handling[c]	Crash Landing	Maximum Engine Speed
Vertical load factor	1 down	2 up or 4 down	2 up or 2 down	2 up or 2 down		1 down
Side load factor		1 right or 1 left	1 right or 1 left	2 right or 2 left		
Axial load factor		1 fwd or 1 aft	2 fwd or 2 aft	2 fwd or 2 aft	5.33 fwd	
Pitching velocity		1.0 rad/sec				
Pitching acceleration		2.0 rad/sec^2				
Yawing velocity		0.1 rad/sec	0.5 rad/sec			0.1 rad/sec
Yawing acceleration		1.0 rad/sec^2				
Rolling velocity		40°/sec				
Rolling acceleration		1.25 rad/sec^2				

Note: Load factors, angular velocities and angular acceleration, should be taken at or about the center of gravity of the power plant. (The center of gravity of the power plant is located 78.5 ±4 inches aft of the front face of the reactor shield assembly forward flange and on the power plant centerline.) Down loads occur during pull-out. Fore loads occur during a braked landing.

[a]Flight includes landing up to and including touch down.

[b]Ground operation includes all operations on the ground including taxiing.

[c]Ground handling includes all conditions where the power plant is not running and is not installed in the aircraft and handling of power plant components.

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Additional requirements were:

1. The structure must not rupture before completion of operation over the full life profile endurance.
2. The structure must not yield when subjected for a short time (less than 1 minute) to flight, ground operation, and ground handling conditions.
3. The structure must not rupture when subjected for a short time (less than 1 minute) to flight, ground operations, ground handling, and crash landing multiplied by 1.5.
4. Minimum mechanical properties were used in all stress calculations.
5. When applicable test information was not available, the allowable ultimate or stress rupture values for welded joints were assumed to be 80 percent of the values for the unwelded material.

2.1.6 LIFE PROFILE AND STRESS CRITERIA

The power plant and its components were designed to provide, as a minimum, the operational life profile presented in Table 2.2.

Stress criteria for the design of the XMA-1A power plant is defined in reference 1.

2.1.7 DIMENSIONAL LIMITS

The installation envelope of the power plant, including over-all dimensions, mounting provisions, and piping connections, is shown in Figure 2.3. Clearance was maintained around the power plant to provide space for external wiring, piping, and secondary cooling airflow.

2.1.8 WEIGHT, CENTER OF GRAVITY, AND MOMENT OF INERTIA

2.1.8.1 Weight

The XMA-1A power plant weight objective was 100,000 pounds total. For design purposes the target weights, shown in Table 2.3, were established. These weights allowed for some weight growth.

2.1.8.2 Center of Gravity

The centers of gravity of the power plant and its major components are presented in Table 2.4.

2.1.8.3 Moment of Inertia

2.1.8.3.1 Polar Moment of Inertia - The polar moment of inertia of the rotor of each set of turbomachinery about its axis of rotation was not to exceed 6370 pounds per square foot.

2.1.8.3.2 Mass Moment of Inertia - The mass moment of inertia of the power plant and its major components were as shown in Table 2.5.

2.1.9 NUCLEAR RADIATION

2.1.9.1 XMA-1C Design Objective Nuclear Radiation Patterns

The XMA-1C power plant design objective gamma and neutron radiation patterns are presented in Figure 2.4. A shield diameter of 120 inches was used in the determination of these patterns for the XMA-1C. The XMA-1A power plant shield diameter was 105 inches.

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TABLE 2.2

XMA-1A OPERATIONAL LIFE PROFILE

Altitude, ft	Mach No.	Thrust Condition	T_{t2}, °R	P_{t2}, psia	N, rpm	W_a, lb/sec	P_{t3}, psia	T_{t3}, °R	T_{t4}, °R	Q, mw	Life,[a] hr
Nuclear Heat Source											
0	0	Military	560	14.7	4700	681	160	1186	1960	143	5
5,000	0	Military	501	12.22	4700	663	157	1127	1960	146	10
5,000	0	Normal	501	12.22	4625	646	153	1113	1910	136	100
5,000	0	Military	420	12.22	4700	841	193	1040	1960	206	10
6,000	0.6	Military	480	15.03	4700	866	205	1104	1960	189	5
10,000	0.6	Military	520	12.89	4700	664	157	1141	1960	143	20
Total Nuclear Power Life 21,640 mw - hr											
Operational Life, Nuclear Heat Source - 150 hr											
Chemical Heat Source										W_f, lb/hr	
0	0	Military	560	14.7	4890	736	162	1204	2010	31,200	3
5,000	0	Military	501	12.22	4890	713	155	1145	2010	33,200	7
5,000	0	Normal	501	12.22	4750	715	155	1115	1960	28,300	70
5,000	0	Military	420	12.22	4890	846	183	1036	2010	41,400	7
6,000	0.6	Military	480	15.03	4890	926	201	1120	2010	44,100	3
10,000	0.6	Military	520	12.89	4890	714	156	1166	2010	32,500	10
Operational Life, Chemical Heat Source - 100 hr											
Total Power Plant Operational Life - 250 hr											

[a]The power plant will be capable of 200 starts.

TABLE 2.3

XMA-1A POWER PLANT DESIGN WEIGHTS

Component	Design Weight, lb
Side shield	26,950
LiH	8,464
304 stainless steel (borided)	10,199
Structure	7,937
Be powder	350
Front shield plug	12,310
304 stainless steel (borided)	50
Be (borided)	6,100
Tungsten alloy (borided)	2,660
Structure and cladding	3,500
Rear shield plug	12,126
BeO (borided)	6,760
304 stainless steel	40
Structure and cladding	5,326
Reactor assembly	11,500
Reactor controls	3,545
Reactor valve	1,100
Power plant control equipment on airframe	425
Turbomachinery	30,000[a]
Power plant total	97,956 pounds[b]

[a]Design objective

[b]This total does not include the weight of the following equipment which is charged to the airframe manufacturer:

- Main or auxiliary oil tank
- Ducts to provide air for cooling of shield, power plant, and reactor afterheat
- Engine starters
- Airframe mounted control console
- Airframe - power plant disconnect panel
- Accessories supplied by airframe manufacturer

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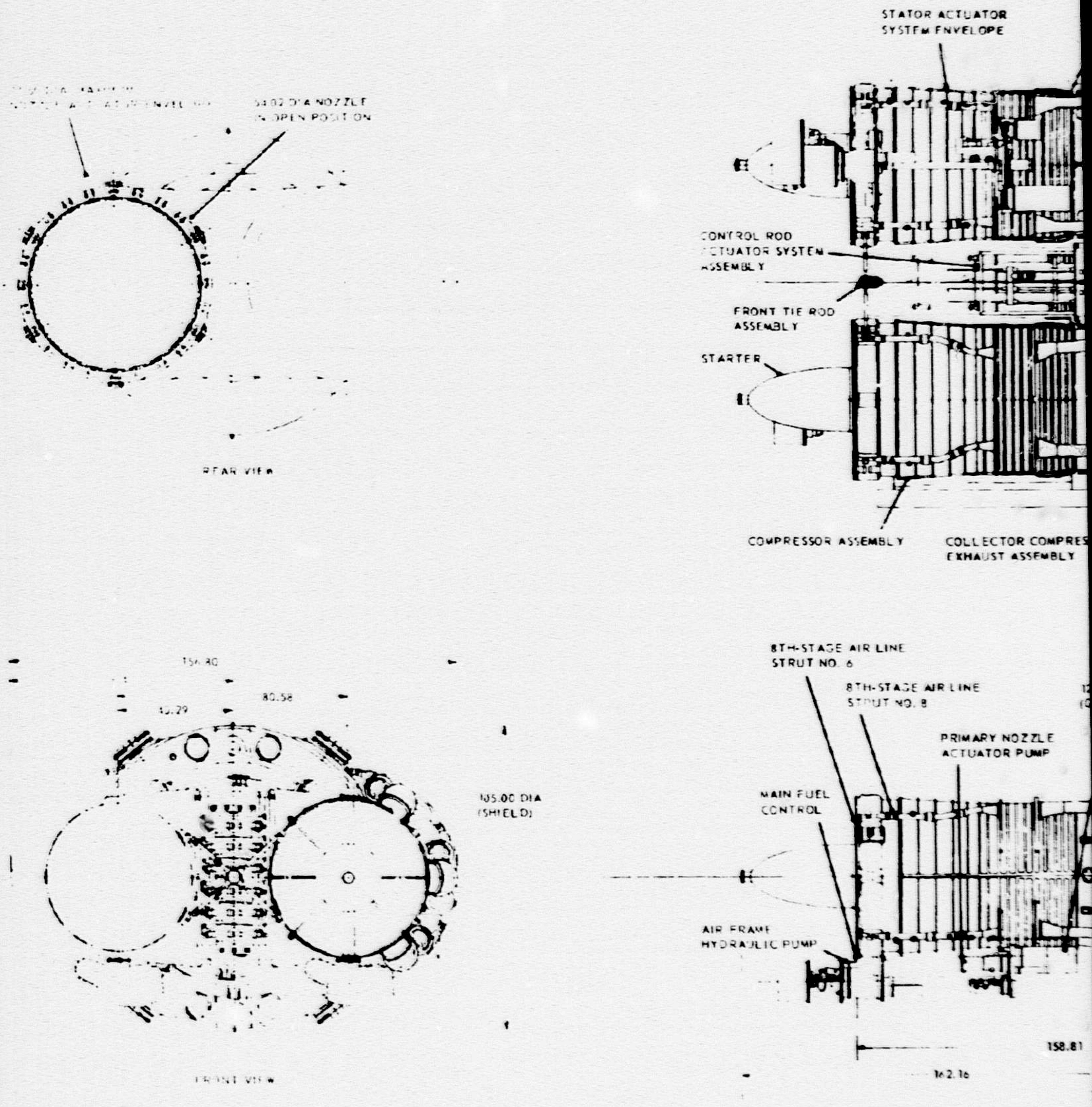

Fig. 2.3 – Installation XMA-1 po

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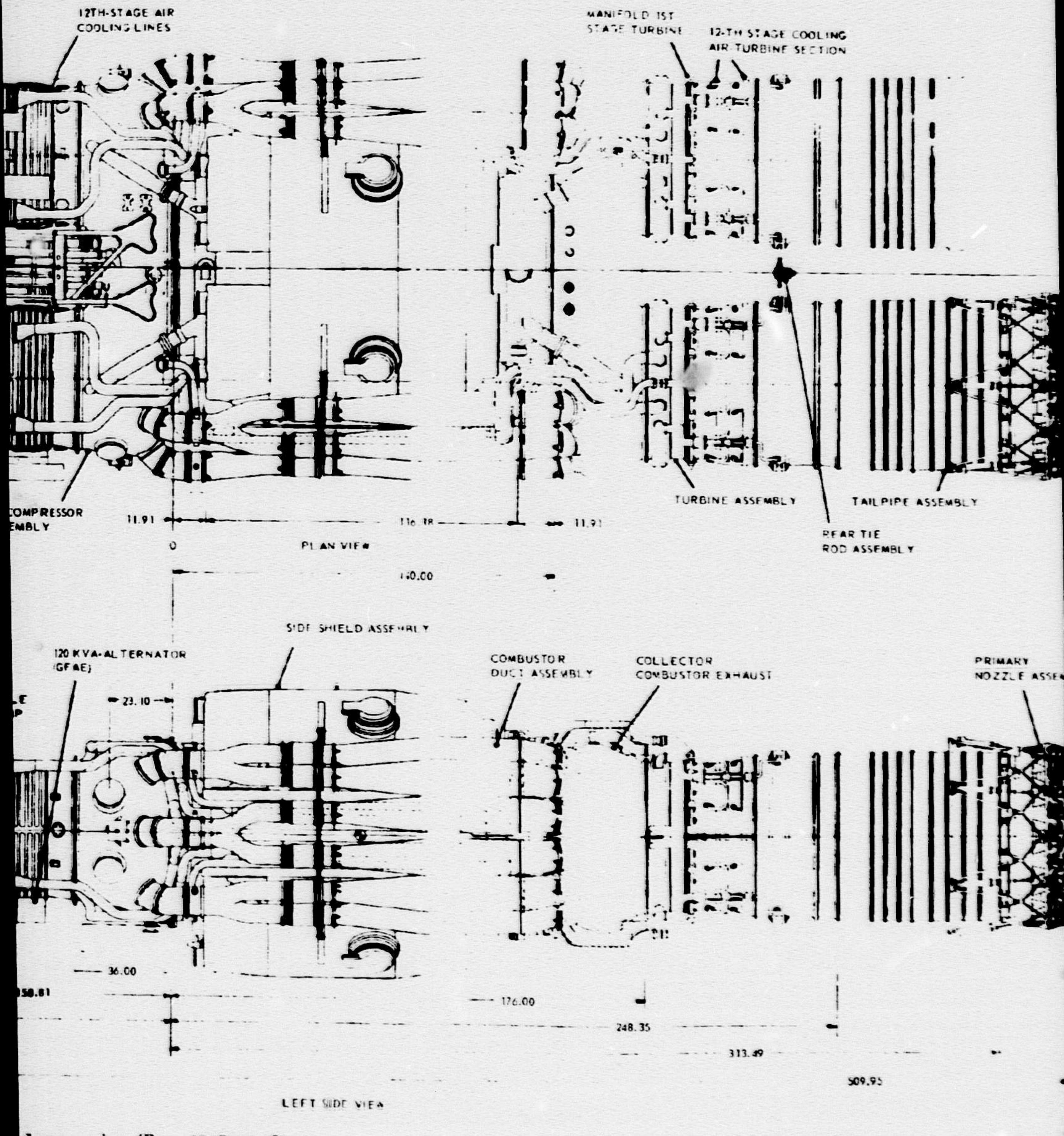

-1 power plant (Dwg. 176R490–Sh.1)

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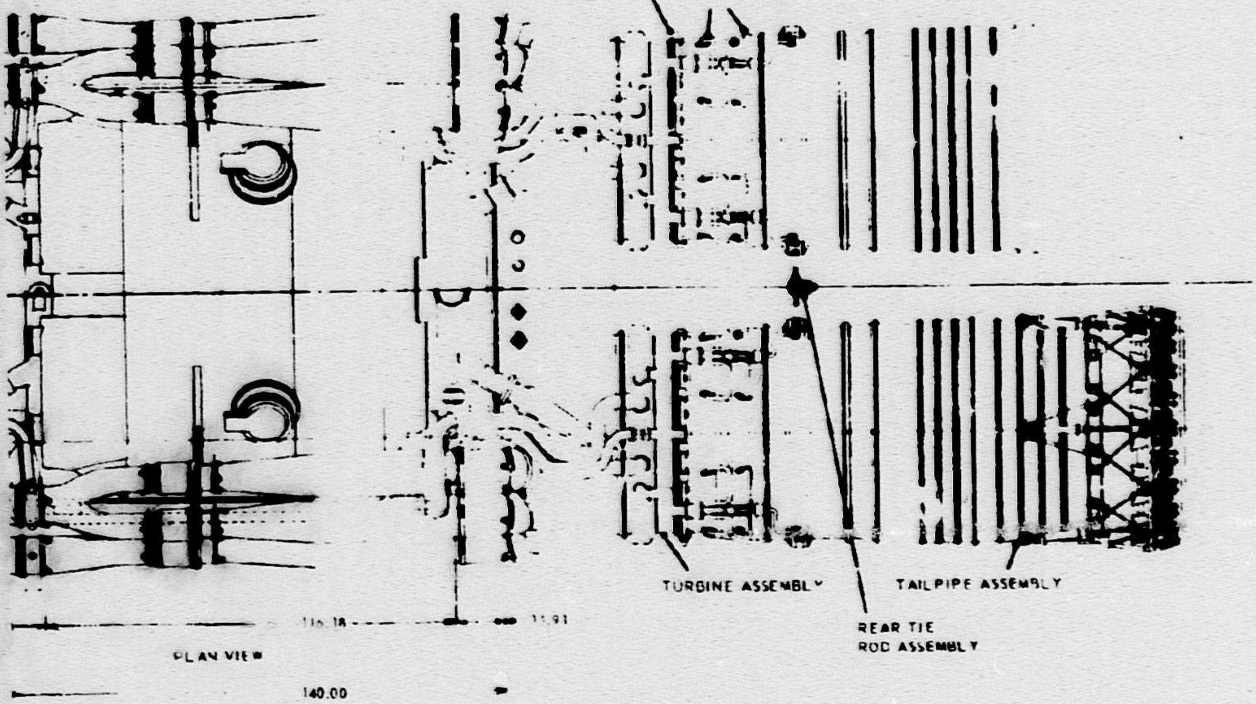

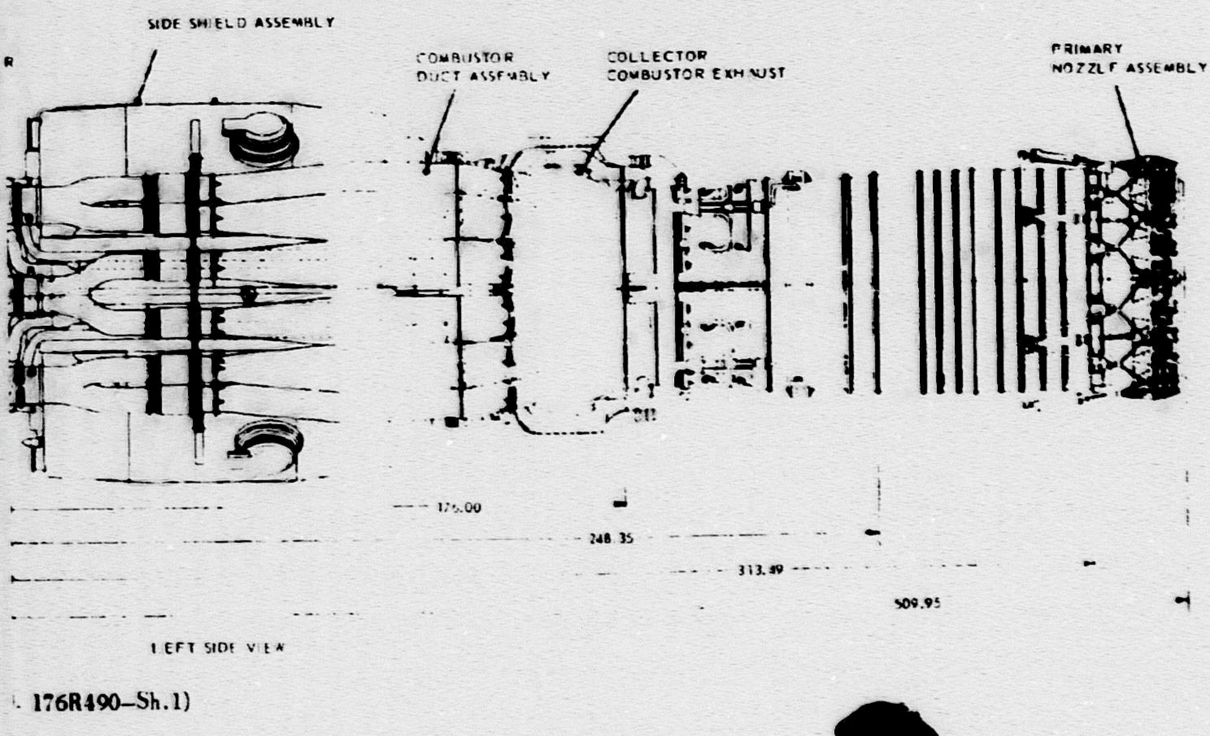

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TABLE 2.4

XMA-1A POWER PLANT CENTER OF GRAVITY

	Distance Of Center Of Gravity From The Front Face Of The Reactor Shield Assembly	Distance Of Center Of Gravity From The Longitudinal Centerline Of The Reactor
Turbomachinery components	93.7 ±4 in. aft.	0
Front section	71.7 ±4 in. forwd.	0
Center section	83.4 ±4 in. aft.	0
Rear section	243.6 ±6 in. aft.	0
Reactor shield assembly components	71.4 ±3 in. aft.	0
Front shield plug (includes reactor)	52.5 ±2 in. aft.	0
Side shield assembly	69.5 ±4 in. aft.	0
Rear shield plug	118.3 ±2 in. aft.	0
Power plant assembly	78.5 ±4 in. aft.	Approximately on the centerline

TABLE 2.5

XMA-1A POWER PLANT MASS MOMENT OF INERTIA

	About The Longitudinal Axis (I_x), lb-in^2 x 10^{-6}	About The Transverse Axis (I_y), lb-in^2 x 10^{-6}	About The Vertical Axis (I_z), lb-in^2 x 10^{-6}
Front shield plug and reactor	11	28	28
Rear shield plug	5	22	22
Side shield	59	60	61
Turbomachinery	57	815	869
Total power plant	132	925	980

Note: Measurements, in each case, taken through the power plant center of gravity.

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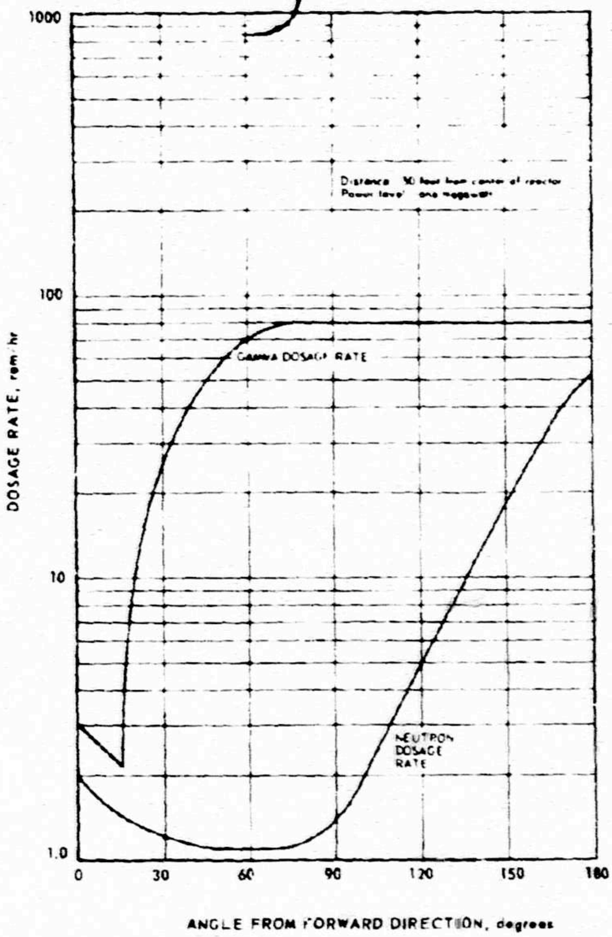

Fig. 2.4 -- XMA-1 model C objective nuclear radiation direct beam pattern

2.1.9.2 XMA-1A Design Objective Nuclear Radiation Levels

The XMA-1A power plant design objective gamma and neutron radiation patterns are presented in Figure 2.5. The radiation levels shown occur at a distance of 50 feet from the center of the reactor when the reactor is operating at a reference power level of 1 megawatt. These radiation levels are directly proportional to the power level of the reactor; correction of the values to other distances can be approximated within the accuracy of the predictions by the employment of a correction factor $1/x^2$, where x is the distance from the center of the reactor. Thus,

$$D_x = D_{50} \left(\frac{50}{x}\right)^2$$

D = dose rate at distance indicated by subscript
x = distance to point of interest in feet.

Note that the neutron radiation levels are given in units of rem per hour. Conversion to rep per hour should be made using the following equivalence:

1 rep per hour = 10 rem per hour

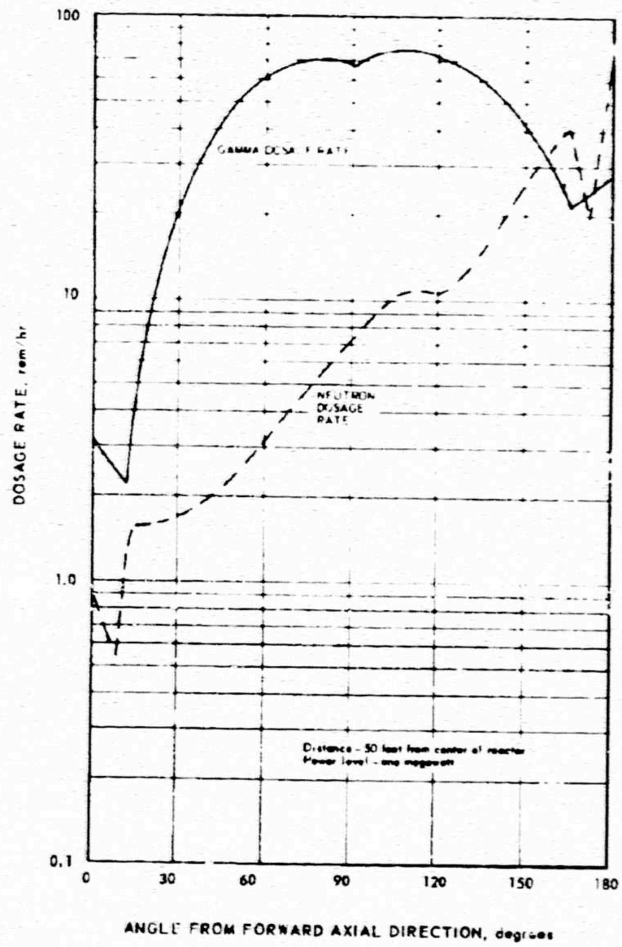

Fig. 2.5 – XMA-1A power plant objective nuclear radiation pattern

2.1.9.3 Radiation Patterns with Multiple Power Plants

Radiation patterns about one or more power plants in a multipower plant installation are considered to have the patterns about each individual power plant superimposed upon one another. These patterns are additive at the points of interest. Components should be designed for the radiation levels existing at their point of installation. Where the installation of a component at different locations in a multipower plant arrangement could result in different radiation levels, the highest radiation level should be used in the design. For flight application of either the XMA-1A or the XMA-1C it was planned that two power plants would be mounted side by side in the aircraft fuselage; therefore, dose rates for a single power plant should be multiplied by two.

2.1.10 MAINTENANCE AND HANDLING CRITERIA

The remote handling design requirements for the XMA-1A power plant were based on the fact that after testing at any substantial reactor power level, the power plant would be too radioactive to perform manual work on it until the core was removed. As a result of this radioactivity, shielded equipment such as the "Beetle" (a shielded personnel compartment, mounted on a wheeled vehicle, containing controls for manipulators, controls for vehicle propulsion, and a viewing system) would be used to perform minor maintenance and running repairs at the operating test facilities. The Beetle would utilize auxiliary fixtures and special equipment to accomplish its tasks. A shielded locomotive and transport vehicle would be used to remove the power plant from the test facility. For further detail see section 8. All attachments of the power plant to the test support structure and to the transport vehicle were to be remotely made and broken. The power plant would be transported to the hot shop, remotely removed from the transport vehicle and installed in the disassembly fixture. The disassembly of the power plant was pointed toward separation of the main components of the turbomachinery from the power plant and removal of them to a safe working area.

Basically, the power plant components were designed so they could be remotely handled with general purpose equipment such as cranes and manipulators. However, where it was not possible to provide adequate access and visibility for the equipment, suitable special equipment would be used. The operators would be assisted in the equipment operation by such aids as television and mirrors.

Parts to be handled by manipulators were designed within the weight capabilities of the manipulators involved. Where parts were fitted together remotely, the use of guide devices, such as tapered dowels, rabbeted flanges, and visual match marks, were used. In the handling of parts it is difficult to use manipulators simultaneously, thus, most operations were designed around one holding unit and one working unit. Complex operations required special fixturing.

In general, all parts that engaged with manipulator held tools were located so the engagement could be viewed directly by the manipulator operator. However, when this was not possible, suitable special equipment that would permit the automatic engagement of tools was used. Adequate tool clearance and access was provided wherever remotely operated tools would engage power plant components. All components that must be handled remotely had pickup points permitting remote assembly and disassembly with fixturing or handling brackets.

The assembly procedure for the power plant was as follows. Major assemblies were remotely carried from the component buildup stations to the power plant assembly stations, where they were remotely positioned and assembled into a complete power plant assembly. Disassembly was performed in similar fashion, in reverse order. The major assemblies of the power plant were the compressors, compressor exhaust collector, reactor bypass valve, front shield plug, reactor, side shield, rear shield plug, combustion exhaust collector, parallel combustion ducts, turbines, coupling shafts, tailpipes, and accessory assemblies.

The turbomachinery components (compressors, parallel combustion ducts, combustion exhaust collector, compressor exhaust collector, coupling shafts, turbines, tailpipes, and accessory assemblies) would be removed from the power plant and moved, by remote handling methods, to an area for storage. Induced activity would be permitted to decay to a level consistent with established standards. Those components would be decontaminated where possible. Manual maintenance and service could then be performed.

2.2 OVER-ALL POWER PLANT DESIGN

2.2.1 MECHANICAL

2.2.1.1 Configuration

The XMA-1 power plant consisted of two sets of X211 turbomachinery cantilevered from the reactor-shield assembly. A full-scale mockup of the power plant is shown in Figure 2.6. An artist's conception of the reactor-shield assembly is shown in Figure 2.7, and a lay-repairs at the operating test facilities. The Beetle would utilize auxiliary fixtures and special equipment to accomplish its tasks. A shielded locomotive and transport vehicle would be used to remove the power plant from the test facility. For further detail see section 8. All attachments of the power plant to the test support structure and to the transport vehicle were to be remotely made and broken. The power plant would be transported to the hot shop, remotely removed from the transport vehicle and installed in the disassembly fixture. The disassembly of the power plant was pointed toward separation of the main components of the turbomachinery from the power plant and removal of them to a safe working area.

Basically, the power plant components were designed so they could be remotely handled with general purpose equipment such as cranes and manipulators. However, where it was not possible to provide adequate access and visibility for the equipment, suitable special equipment would be used. The operators would be assisted in the equipment operation by such aids as television and mirrors.

Parts to be handled by manipulators were designed within the weight capabilities of the manipulators involved. Where parts were fitted together remotely, the use of guide devices, such as tapered dowels, rabbeted flanges, and visual match marks, were used. In the handling of parts it is difficult to use manipulators simultaneously, thus, most operations were designed around one holding unit and one working unit. Complex operations required special fixturing.

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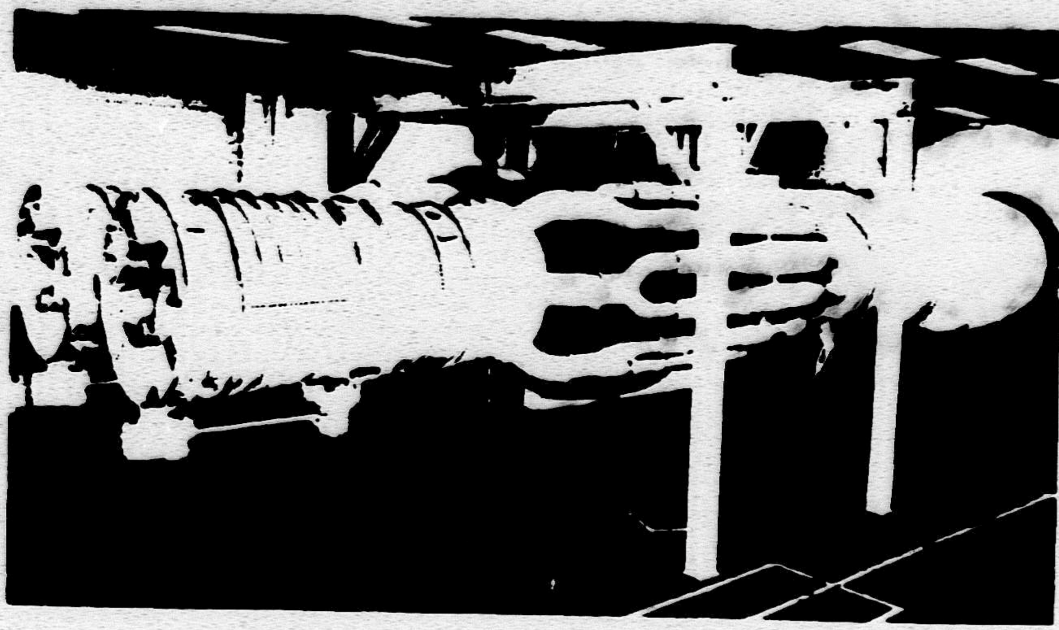

Fig. 2.6 – XMA-1A power plant mockup (Neg. C04781)

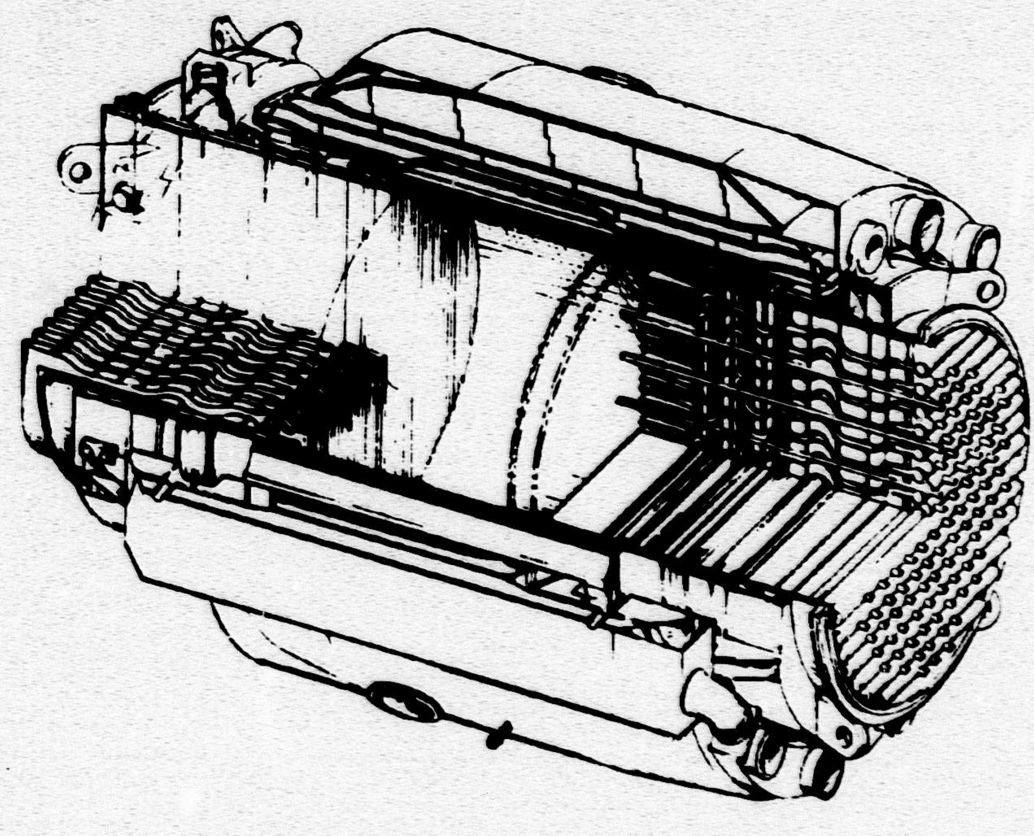

Fig. 2.7 – XMA-1A reactor-shield assembly

out control drawing of the reactor-shield assembly is shown in Figure 2.8. A drawing showing the mechanical arrangement of the turbomachinery is presented in Figure 2.9.

The compressor front-frame assembly consisted of the front frame, variable inlet guide vanes, No. 1 bearing sump and bearing, and the inlet accessory-drive gearbox. It was designed to provide: (1) the compressor with undistorted flow distribution, (2) structural rigidity for the compressor casing, (3) anti-icing of the struts, inlet guide vanes, and the inlet dome, and (4) air and oil seals to eliminate contamination of engine bleed air.

The front and rear compressor casings formed a cylindrical shell that served as the outer wall for the compressor air passage and provided mounts for the compressor front frame, 16 stages of stator vanes and their linkages, the outlet guide vanes, air-extraction hardware, and power plant accessories.

The variable stator vanes were designed to provide optimum compressor performance at the design point. The stage-16 vanes could be closed completely to act as a shutoff valve; leakage was not to exceed 6 percent at the above design point.

The compressor rotor was a 16-stage, axial-flow unit designed to operate under standard sea level static conditions, at a rated speed of 5,000 rpm, a pressure ratio of 14 to 1, and airflow of 425 pounds per second. Rigidity and reliability were incorporated into the rotor by use of the curvic coupling, axially split spacer rings, and single tang blade dovetails.

The compressor rear frame was designed to support the No. 2 bearing, which carried thrust and radial loads, provide an annular diffuser passage from the compressor to the compressor exhaust collector, provide customer bleed air free of contamination, provide structural rigidity for the compressor exhaust collector, and support the 16th-stage compressor air seal.

The compressor exhaust collector was designed as a twin scroll attached to the parallel compressor rear frames and to the reactor-shield-assembly forward flange. The compressor exhaust collector was capable of supporting, by itself, the compressor section and all of its attached parts for the loading conditions given in section 2.1.4.

The burners of the main combustion system consisted of six combustion ducts originating at the compressor exhaust collector and having a shutoff valve at its inlet. Each duct divided into two smaller ducts; each having a bellows, diffuser, combustion casing, combustion liner, fuel nozzle, fuel flow divider, cross fire tube, and a transition liner. The aft end of the combustion ducts attached to, and discharged into, the combustion exhaust collector.

The burner air-shutoff valve was capable of being actuated to, and holding, any desired position from full open to full closed.

The front shield plug assembly consisted of the reactor inlet valve, porous plug, and the mounting flange to mount it to the pressure shell. It was designed to be supported by the reactor main pressure shell, and to support the reactor shutoff valve and control rods.

The side shield assembly consisted of the pressure shell assembly, gamma shield, neutron shield, and shield cooling shroud. It was the main structural member of the power plant assembly; it contained the supports for shield mounting and supported the engine loads at its forward and aft flanges. It also provided the mountings for the No. 3 and No. 4 bearings which in turn supported the coupling shaft. It was designed to be supported by the airframe by means of the trunnion. The trunnion rings were used as plenums for side-shield cooling air.

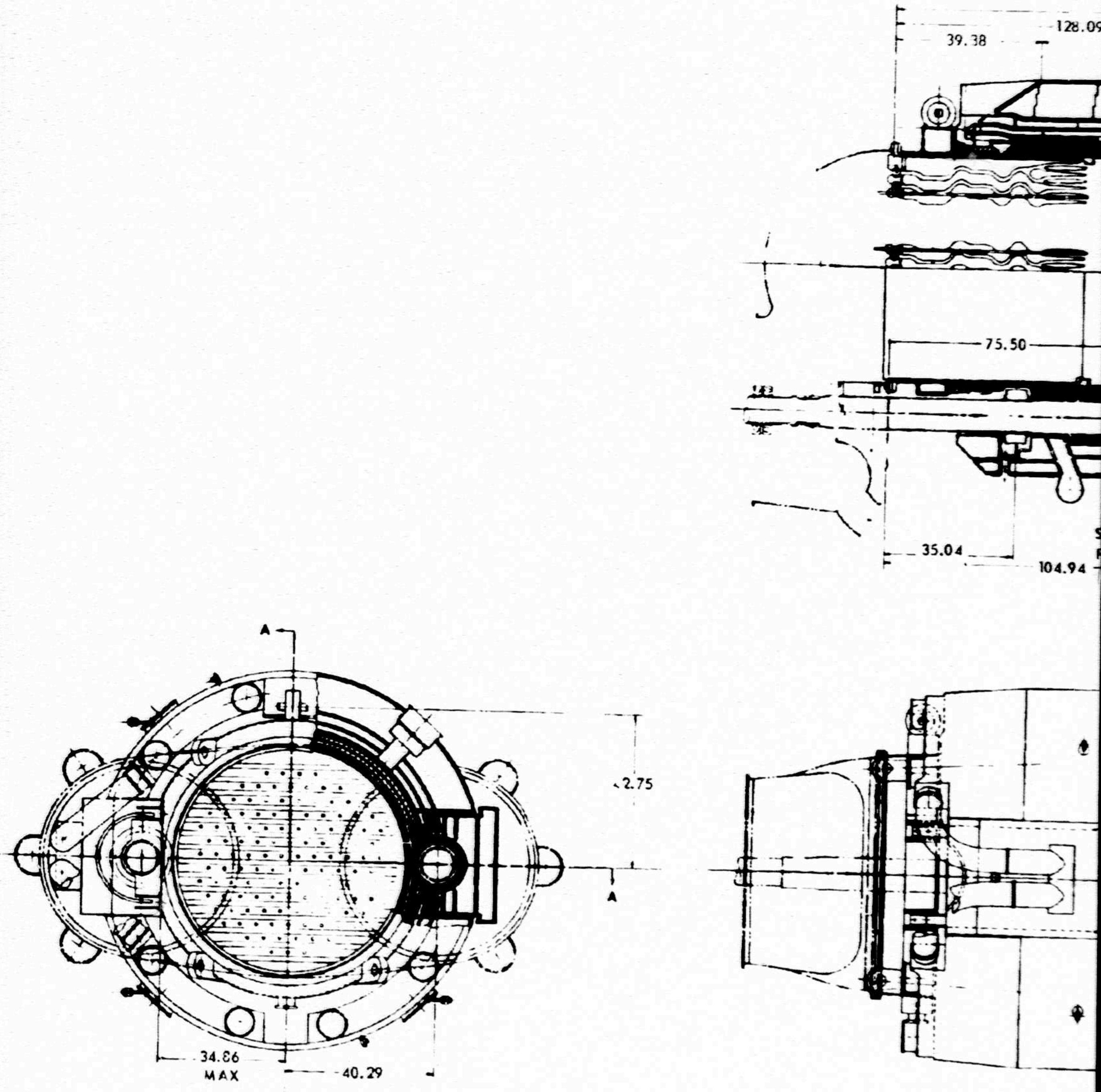

Fig. 2.8 – Reactor shiel

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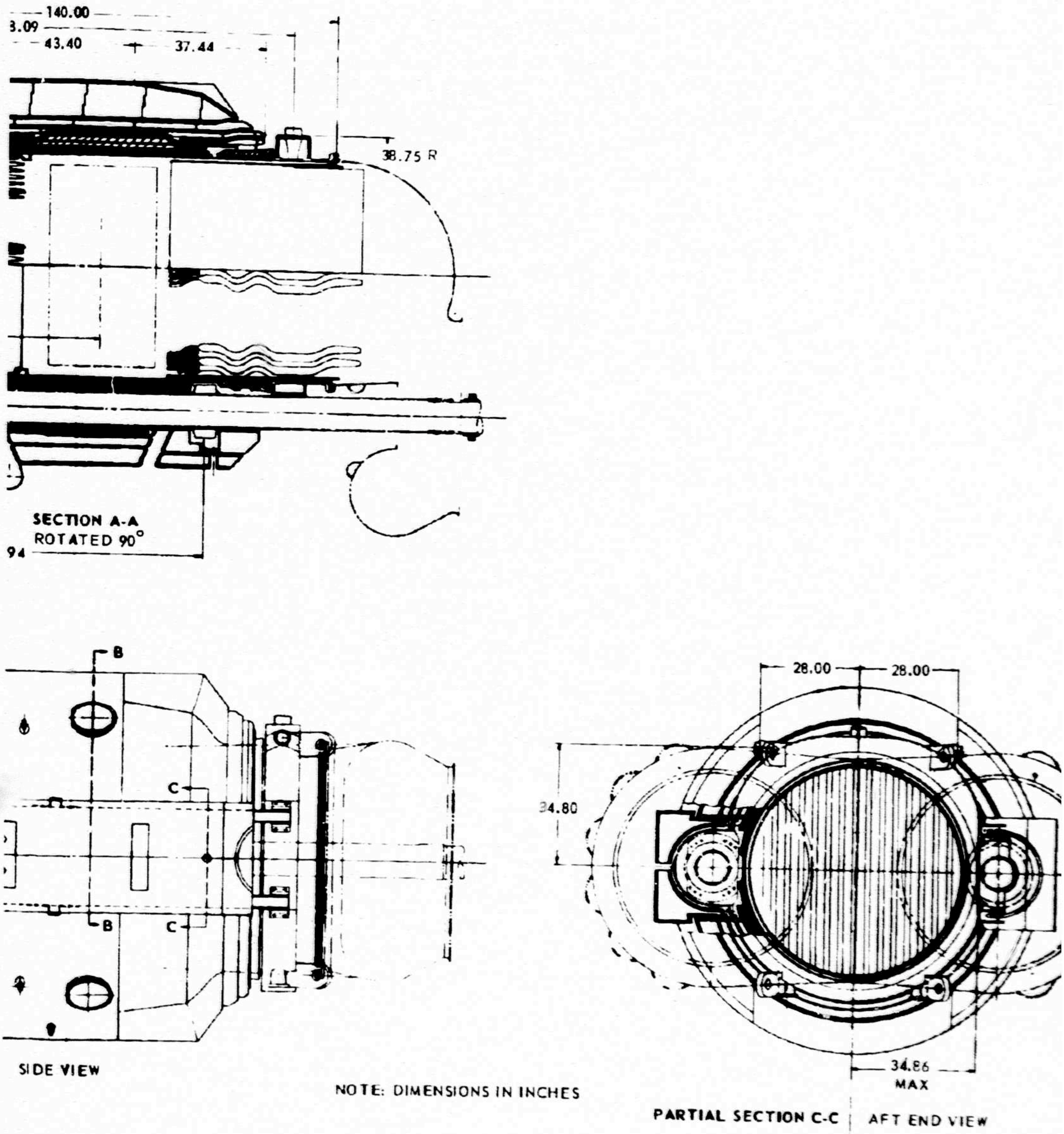

hield assembly (Dwg. 134R700)

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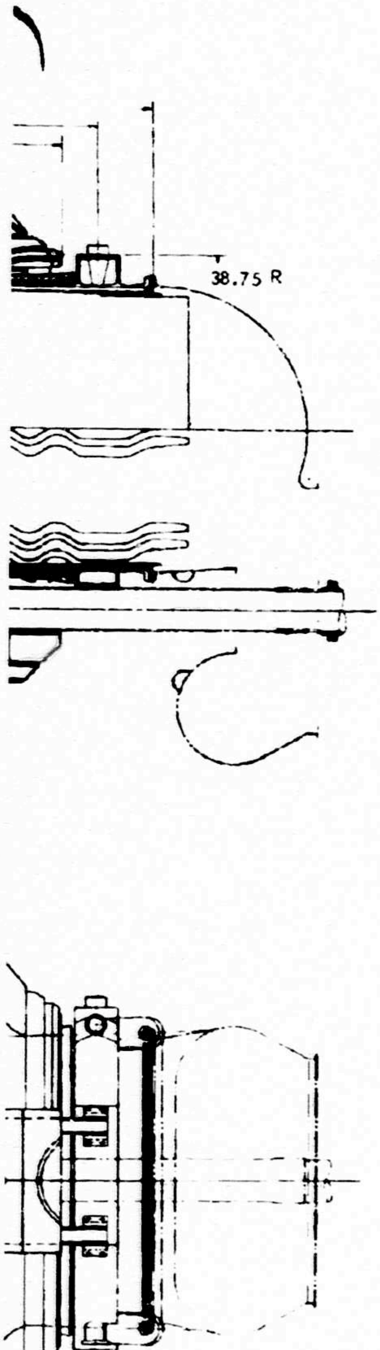

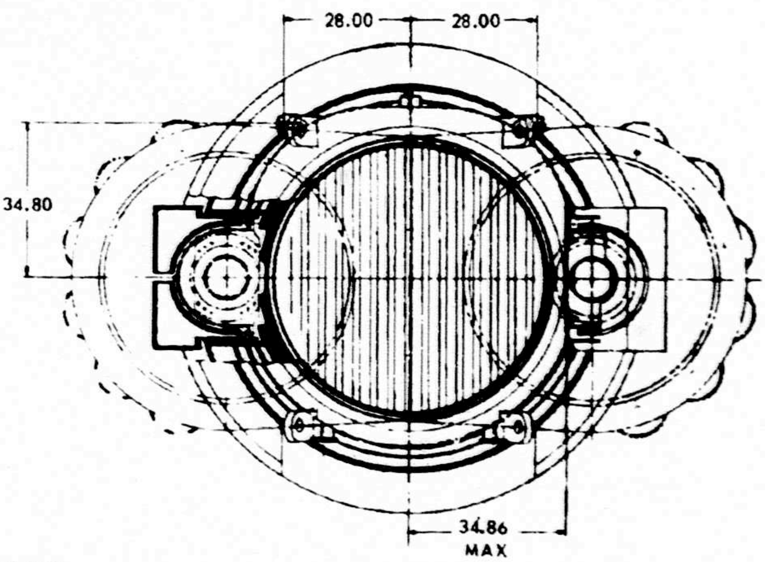

NOTE: DIMENSIONS IN INCHES

PARTIAL SECTION C-C | AFT END VIEW

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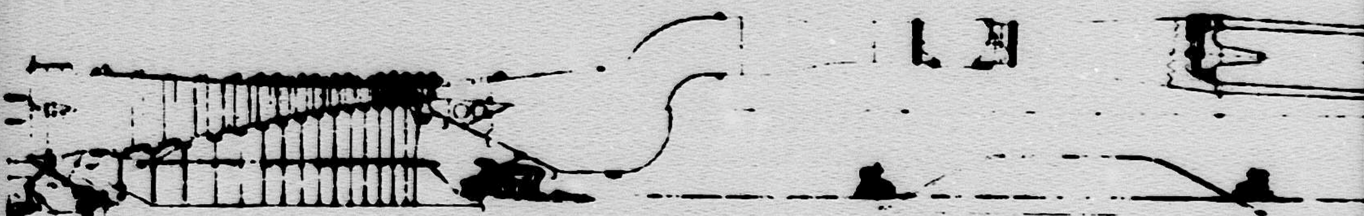

Fig. 2.9 – Cross section

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The gamma shield was attached to the pressure shell on both inside and outside diameters. It was designed to provide cooling passages for cooling the pressure shell and gamma shield material.

The neutron shield was mounted to the pressure shell, exterior to the gamma shield, and had shrouding and annular passages to provide for its cooling.

The reactor core assembly consisted of the tubesheet plate assembly, tubesheet, support plate, reflector, outer and center moderator, reflector backing plate, fuel elements, and control rods.

The tubesheet, tubesheet plate assembly and support plate were designed to accurately position and support the moderators under the load conditions stated in section 2.1.4.

The moderator tube was a hexagonal straight tube type. The reflector was BeO located on the exterior of the reactor core and restrained by the reflector backing plate.

Control of the reactor was provided by use of poison type control rods penetrating the moderator segments. These control rods were ganged into control frames in front of the front plug. Each of these control frames was activated by linear actuators located within the envelope between the compressors. The control rods traveled the full length of the reactor.

The fuel elements were concentric ring metallic ribbon type.

The rear shield plug assembly consisted of the porous plug and flange for mounting to the pressure shell.

The combustion exhaust collector was designed as a "twin scroll" attached at the forward flange to the rear flange of the heat exchanger and at the rear to the parallel turbine front frame. The combustion exhaust collector was capable of supporting the turbine, diffuser, afterburner, nozzle sections, and all their associated parts for the loading conditions given in section 2.1.4. These loads were completely transmitted to the reactor-shield assembly through the mating collector-reactor-shield assembly flange.

The combustion exhaust collector provided the mounting for the reactor discharge temperature sensors and allowed for passage of the two main coupling shafts.

Compressor cooling air was used for cooling the collector wall and turbine front-frame strut and walls.

The turbine front frame provided support for the No. 5 bearing, a diffuser passageway for turbine inlet, a pressure chamber for turbine shaft balance piston and contained the turbine isolation valves.

The turbine rotor assembly consisted of a conical shaft, three turbine discs, interstage torque rings, and turbine buckets. The turbine rotor assembly was designed for a maximum physical engine speed of 104 percent, and on chemical operation to withstand inlet temperature variation of $\pm 150^{\circ}$F from the average temperature and a total pressure variation of 3 to 5 percent.

The turbine stator assembly contained the turbine casing, the first stage turbine nozzle (mounted between turbine forward-frame aft flange and turbine-casing forward flange), the second- and third-stage turbine nozzles, the interstage air seals, and the first-, second-, and third-stage turbine shrouds.

The turbine stator assembly was designed to provide the proper aerodynamic passageway, provide structural support for all engine assemblies mounted aft of the turbine casing, and maintain close clearances with rotating parts for proper performance.

The afterburner consisted of the diffuser, tailpipe flameholder, spraybars, pilot burner, and tailpipe liner. It was designed to withstand wind loads and the actuator forces needed to actuate the jet nozzle and a collapsing pressure in the event of main combustor blow-out.

Provision was made to drain or purge the afterburner combustion system of fuel within 1 minute after shutdown of the afterburner.

The jet nozzle configuration was an aerodynamic converging nozzle with variable finger-type, adjustable area.

The accessory drive system consisted of the inlet gearbox, located in the front frame hub; transfer gearbox, located at the bottom of the front frame; and rear gearbox, located on the rear compressor casing at the bottom of the engine. It was designed to transmit power from the main engine rotor shaft to engine controls and customer accessories and to provide mounting pads for these components.

Each engine of the power plant had six main bearings, located to support the compressor rotor, turbine rotor, and dampers for the coupling shaft. The numbers 1, 3, 4, 5, and 6 bearings were roller bearings with outer race riding cages.

The lubricating oil for the power plant came from tanks, one per engine, mounted in the airframe. The lubricant, MIL-L-78080 lube oil, was pumped by the main engine lube pump to the six bearings and the gearboxes. The oil was scavenged by means of a scavenge pump on the front gearbox, a three-element scavenge pump driven by the engine turbine shaft and three elements of the main lube pump. Eductors were located at numbers 2, 3, 4, and 5 bearing sumps to assist in the scavenge of oil from the sumps to the elements of the above scavenge pumps.

In the design of the power plant, provisions were made for: (1) draining of the lubrication system quickly and easily in a horizontal position or with the nose elevated 15 degrees, (2) an oil filter at the engine outlet, and a safety shutoff device to prevent loss of oil in the event of constant speed drive and alternator package failure, and (3) for venting of the sumps through a common system.

2.2.1.2 Weights

A summary of the computed weights of the various XMA-1 power plant components is presented in Table 2.6. These calculated values do not include factors for either growth or omission. The reference axes are shown in Figure 2.10.

2.2.1.3 Vibration

A vibration analysis was performed to make analytical predictions of the XMA-1 power plant vibration amplitudes resulting from its environment.

The over-all natural frequencies and mode shapes of the power plant and the mobilities, M_{ij}, (velocity amplitudes at i per unit driving force amplitude at j) for an assumed value of damping of Q = 100 may be found in reference 2. The results of this analysis made possible the determination of the system response when the forces due to the rotating parts of the turbomachinery were known and the damping of the system was specified.

The "discrete mass" method of vibration analysis was used, wherein, the power plant was first approximated by a discrete number of masses. The number of mass points finally used was considered to be the best compromise between insuring prediction of all system frequencies in the power plant operating range and keeping the problem tractable. A system of nine rigid masses with appropriate connecting springs, as shown in Figure 2.11, was selected as the most suitable model by using rough calculations to indicate the magnitude of frequencies associated with various assumed mode shapes.

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TABLE 2.6

XMA-1A POWER PLANT COMPONENTS WEIGHT AND BALANCE SUMMARY

Components	Weight, lb	Balance Arm,[a] inches X Component	Y Component	Z Component
Front plug	12,075.50	227.3	0.0	100.0
Bypass valve	1 007.46	200.6	0.0	99.9
Core assembly	11,993.90	272.6	0.0	100.0
Side shield	26,842.00	264.5	0.0	100.0
Rear plug	11,988.74	316.4	0.0	100.0
Reactor shield assembly	(63,907.60)	267.8	0.0	100.0
Control rods and actuators	1,996.88	165.5	0.0	100.0
Dynamic rods	154.00	125.0	0.0	100.0
Control rod mounting	600.00	170.0	0.0	100.0
Reactor startups airframe mounted	120.00	270.0	0.0	100.0
Power range airframe mounting	92.00	270.0	0.0	100.0
Power plant cabling and junction boxes	150.00	270.0	0.0	100.0
Airflow control actuator system	500.00	195.0	0.0	100.0
Auxiliary electrical power supply	211.00	150.0	0.0	100.0
Starter system	200.00	60.0	+40.3	100.0
Airframe cabling	416.00	200.0	0.0	100.0
Airframe mounted component structure	250.00	270.0	0.0	100.0
Nuclear sensors	400.00	276.0	0.0	100.0
Temperature sensors	100.00	270.0	0.0	100.0
Total control systems	(5,189.88)	188.6	0.0	100.0
Compressor assembly	6,728.00	119.4	-40.3	100.0
Compressor assembly	6,728.00	119.4	+40.3	100.0
Turbine assembly	7,535.00	440.0	-40.3	100.0
Turbine assembly	7,535.00	440.0	+40.3	100.0
Shaft assembly	1,482.00	283.0	-40.3	100.0
Shaft assembly	1,482.00	283.0	+40.3	100.0
Turbomachinery	(31,490.00)	288.2	0.0	100.0
Shaft shielding	300.00	283.0	-40.3	100.0
Shaft shielding	300.00	283.0	+40.3	100.0
Total power plant	((101,187.48))	270.2	0.0	100.0

[a]Reference axes are shown in Figure 2.10.

In the analysis the engine was assumed to be free in space. From later studies it would be possible to obtain the influence on the response of the system caused by the attachment of the power plant to an airframe. The stiffness of the coupling shaft, being small compared to the other springs in parallel, and gyroscopic effects were not considered.

This preliminary analysis established the following:

1. The procedure used was feasible.
2. For the engine in free space, there were about 30 natural frequencies in the range of running speeds (i.e., natural frequencies which could be excited by a once-per-shaft-revolution excitation).
3. The order of anticipated steady-state vibration displacement amplitude due to rotating equipment unbalance excitation would only be excessive at a few frequencies in the running range.

The results of an investigation of the vibration response, of the XMA-1 power plant, caused by rotating unbalance excitation were reported.[3] In this analysis a 23-mass, 142 degrees of freedom representation of the power plant was used in contrast to the simplified 9-mass representation discussed in the previous section. Taking advantage of system symmetries, it was possible to uncouple the equations of motion so that the symmetric and antisymmetric problems could be handled separately. This reduced the necessary number of degrees of freedom to 71.

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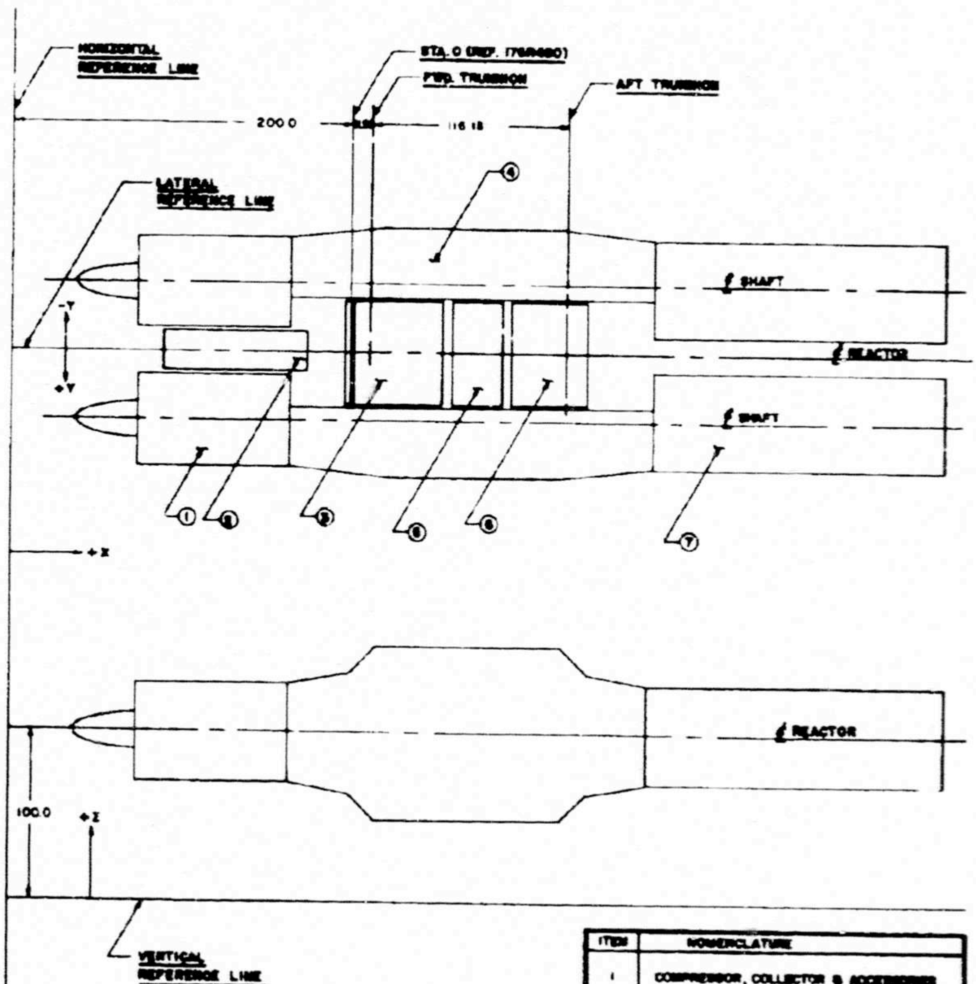

ITEM	NOMENCLATURE
1	COMPRESSOR, COLLECTOR & ACCESSORIES
2	CONTROL ROD ACTUATION SYSTEM
3	FRONT PLUG
4	SIDE SHIELD
5	REACTOR CORE
6	REAR PLUG
7	TURBINE, COLLECTOR & ACCESSORIES

Fig. 2.10 – Weight and balance reference axes

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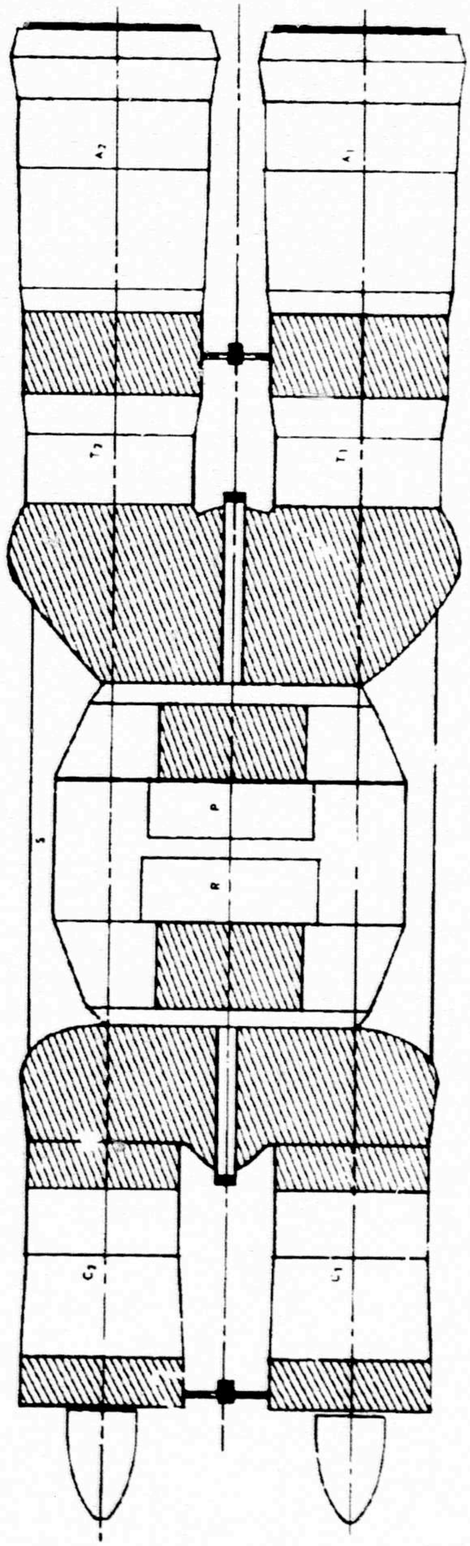

C_1, C_2 COMPRESSORS
S SHIELD
R FORWARD PLUG AND REACTOR
P REAR PLUG
T_1, T_2 TURBINES
A_1, A_2 AFTERBURNERS AND [illegible]ZZLES

Fig. 2.11 — Mass identification

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The gyroscopic effects of the rotating equipment were neglected. This was reported.[4]

The amount of damping in the system was estimated. Test cell analysis[5] and past experience indicate that the Q (mode amplification factor at resonance) was approximately 20 for the stationary equipment for all modes in the running range. Taking into account the lack of damping in the rotating equipment the Q was adjusted, using an infinite Q for the rotating equipment, to 25 as a reasonable value.

An additional study of the optimum value of viscous damping that should be used in the coupling shaft dampers was carried out and reported.[6] The optimum value of damping for each of the four shaft damper units was found to be approximately 400 pounds per inch per second. This value of damping was not critical as a $\pm$ 25 to 50 percent variation in actual value at any one or all of the bearings was allowable without changing the shaft displacements by more than 10 percent. For damper units with the above value to remain effective throughout the speed range, they must be supported by a structure whose stiffness was at least 0.2×10^6 pounds per inch. With 1 pound-inch unbalance at the above value of damping on both sides in the No. 3 and No. 4 bearings and with system damping included, the maximum unbalance displacement of the coupling shaft was predicted to be 0.007 inch peak at approximately 5500 rpm.

The forced vibration response was calculated for a sinusoidal force system acting on the system and consisting of only unbalanced forces. The unbalances assumed for the rotating equipment are:

Compressor (bearing 1)	50 gram-inches
Compressor (bearing 2)	50 gram-inches
Shaft (divided equally among five discrete masses)	2720 gram-inches
Turbine (bearing 5)	85 gram-inches
Turbine (bearing 6)	85 gram-inches

The phase of the unbalance forces were used to give the largest possible response.

The results of the analysis are presented in reference 3 in the form of graphs showing the response of portions of the system at their most critical resonances. The most critical response, from a displacement consideration, of the rotating equipment in the running range occurred at 74 cycles per second. This response was in the horizontal direction with a maximum displacement of the shaft of about 0.050-inch peak and an estimated maximum stress of about 3000 psi. From a maximum stress standpoint, the critical stress occurred at 80 cycles per second where the maximum displacement was about 0.036 inch caused by the deflected shape of the shaft; the maximum stress was about 5000 psi. Both of the modes represent motion in the horizontal direction with large motions occurring across the No. 3 and No. 4 bearings. The stiffness between the bearing beam and the shaft in the horizontal direction was much less than the corresponding vertical stiffness; hence, if the horizontal stiffness would be increased these two critical modes might take the appearance of the vertical modes whose response was much less.

In the running range, the pressure shell vibrated with amplitude of about 5 mils and had a maximum estimated stress of about 8000 psi at 68 cycles per second. The rear plug had a maximum displacement of 17 mils and an estimated stress of about 2000 psi at 53 cycles per second; the front plug reactor had a maximum displacement of 9 mils and an estimated stress of about 3500 psi at 80 cycles per second.

In the running range, it was predicted that the peak displacement of afterburner would be about 8 mils, the top and bottom shielding about 17 mils, and the control package about 11 mils.

2.2.1.4 Installation

Installation information for the XMA-1A power plant is included in references 7 and 8. The installation drawings are shown in Figure 2.3.

A study layout of the clearance between the power plant and nacelle envelope provided by Convair is shown in Figure 2.12.

2.2.1.5 Limits

Results of a study concerning reactor-shield internal clearances and limit dimensions were reported.[9] The first part of this study defines the maximum temperature differential between the pressure vessel, core, and plugs which would not cause interference. The second part defines the minimum clearance encountered when the core-plug assembly was in place in the pressure vessel in the assembly fixture. The third part defines the minimum clearance between the aft end of the core-plug assembly and the pressure vessel during assembly.

The reactor-shield assembly details affecting the design of the X211 engine are given in Figure 2.8. The assembly provides supports for the No. 3 and 4 damper bearings, which have a spring rate of 0.2×10^6 pounds per inch.

Using the location of the turbine rotor and stator at 70^0F and zero power or the reference location, the following were the maximum movements in inches of the first and third turbine rotor stages relative to the stator:

Condition	Direction	First Stage	Third Stage
Steady State	Forward	0.87	0.95
Steady State	Aft	0.02	0.02
Transient	Forward	--	--
Transient	Aft	--	--

2.2.1.6 Piping and Wiring

The piping, wiring, and manifold equipment on the X211 turbomachinery consisted of the piping and wiring which transports fluids and signals over the exterior of the engine, plus the bracketing which secured the equipment to the basic engine shell. The basic functions of this equipment were

1. To convey cooling, heating and/or pressurizing bleed air
2. To transport engine fuel, lubricating and hydraulic oil, and electrical power
3. To transmit pneumatic and electronic signals
4. To vent and/or drain engine cavities.

The over-all configuration of the X211 Turbomachinery was considerably different from that encountered on past turbojet engines. The main points of difference lay in the very nature of the power plant. The high temperature and radiation level ruled out the use of conventional organic substances for fluid transporting media and for sealing. The extremely long spans of large ducting between the two collectors created a special problem from the standpoint of thermal growth and structural support of equipment. Also, since the compressor and turbine section were separated by long distances, the weight of the equipment became very significant in the over-all weight analysis.

With the above problems in mind, a schematic was developed as illustrated in Figures 2.13 and 2.14. This schematic was essentially a 360-degree roll-out of the right set of turbomachinery; for the purpose of the schematic, the engine was considered to be a 56 inch drum with all the piping, wiring, accessories, controls, and other turbomachinery components located within the circumferential or peripheral surface of the drum. As

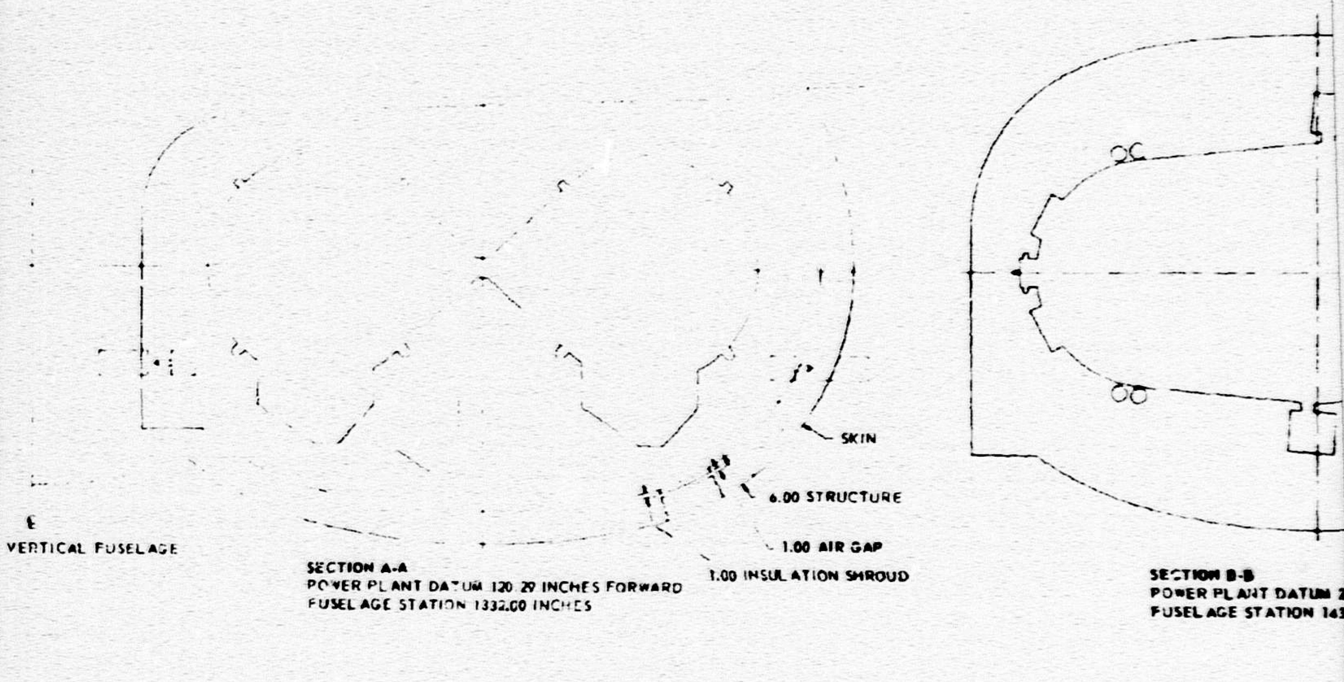

Fig. 2.12 – Clearance between the

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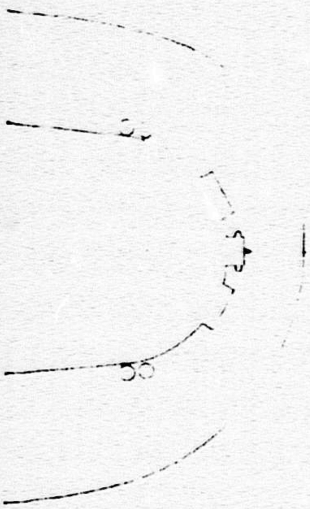

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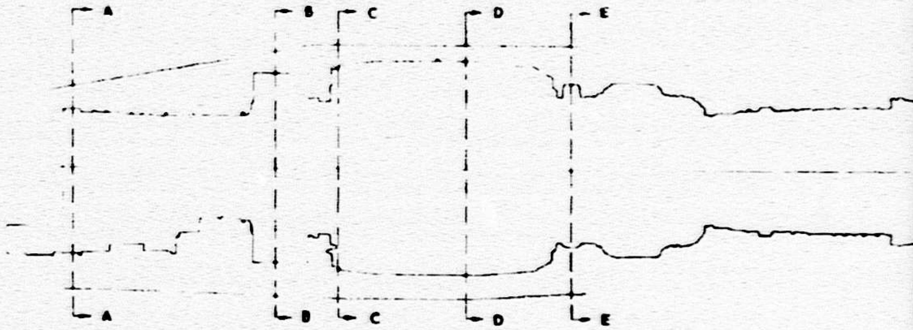
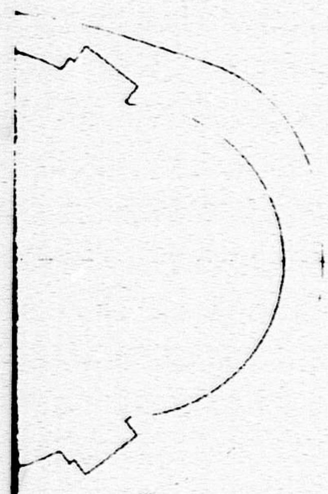
I INCHES



LEFT SIDE VIEW
SCALE 1/20



NCHES FORWARD
NCHES

SECTION E-E
POWER PLANT DATUM 128.09 INCHES FORWARD
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ver plant and nacelle envelope (Dwg. 175R979)

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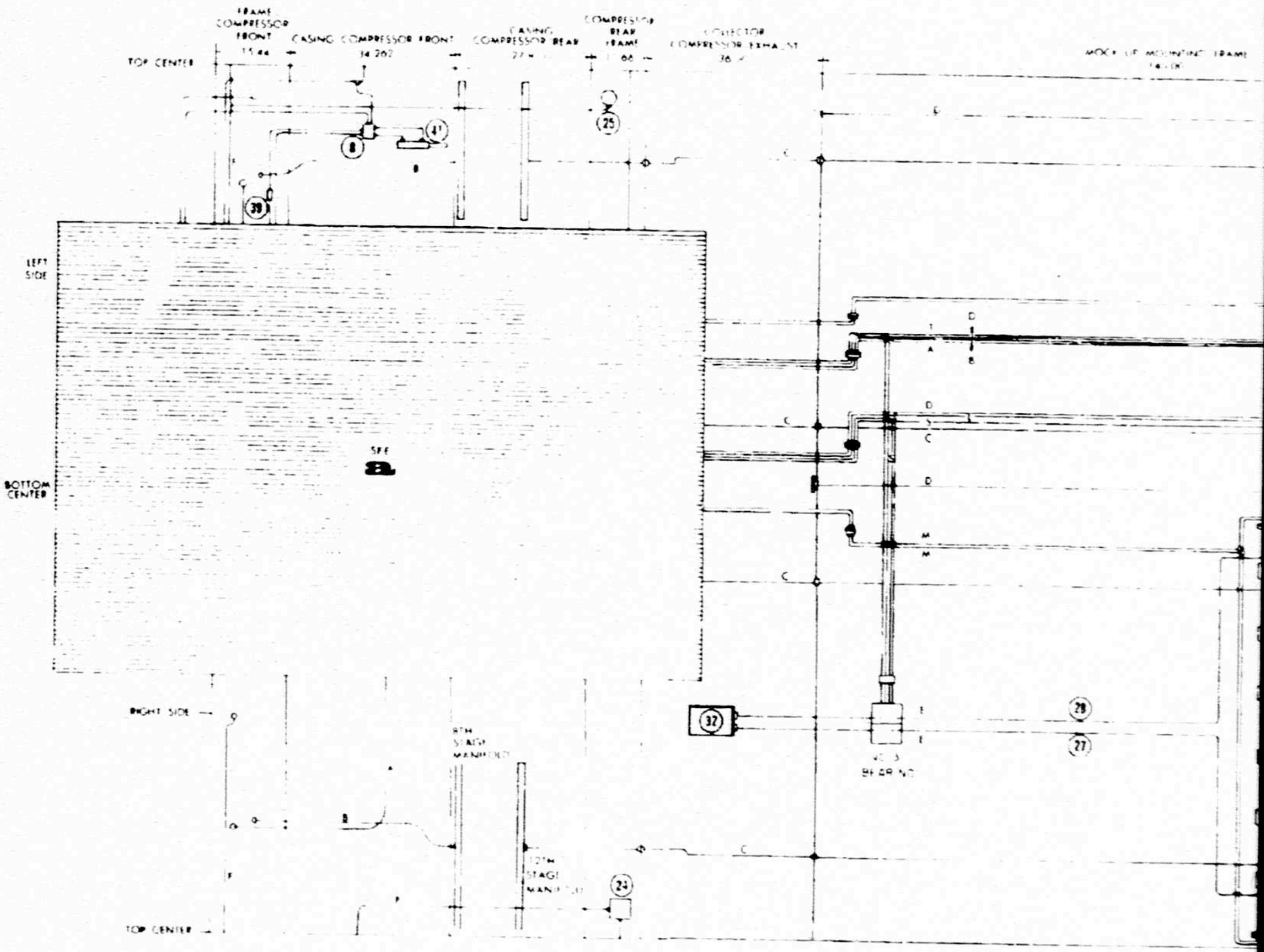

Fig. 2.13 – Piping and wiring

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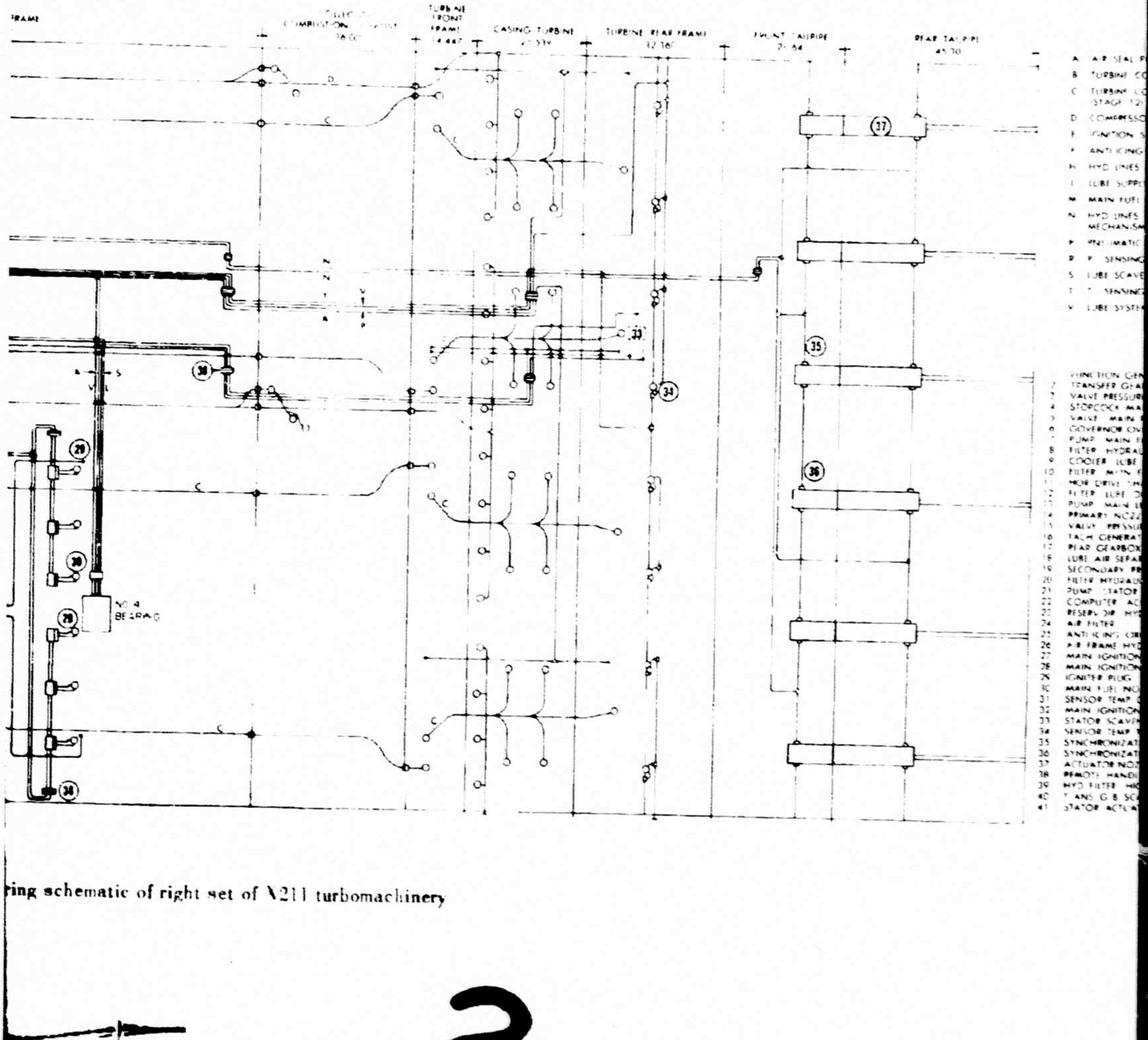

ring schematic of right set of X211 turbomachinery

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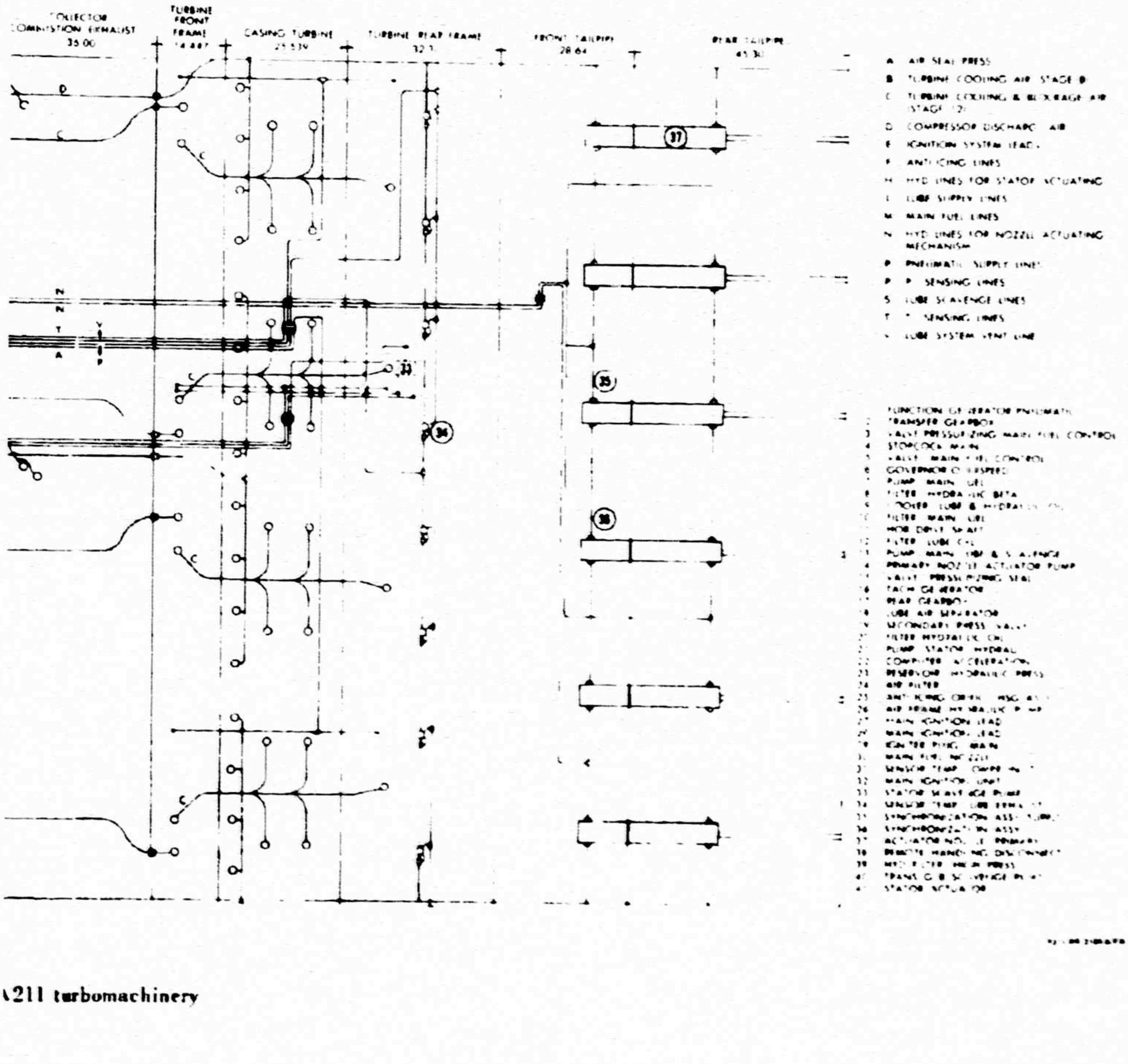

A211 turbomachinery

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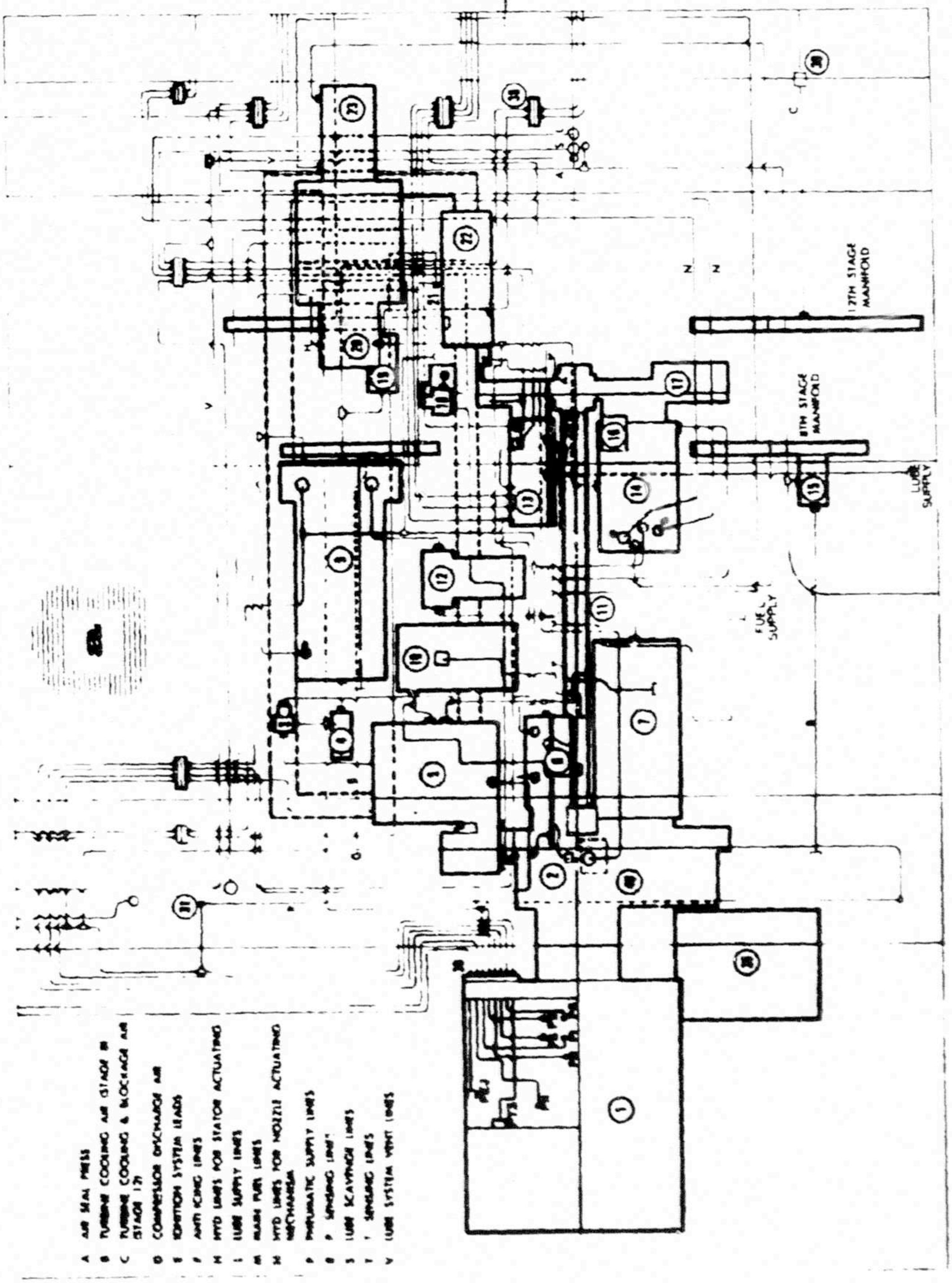

Fig. 2.14 – Piping and wiring schematic – blowup of compressor section X211 turbomachinery

shown, every effort was made to position all accessories and route lines in the most efficient manner. This schematic was used as the master plan for all layouts and drafting work. When the piping schematic was decided, a full-scale basic engine mockup was used to maintain a daily account of work progress in the configuration area. As tubing and accessory positions were decided, parts were procured and placed on the mockup to make a final check on the over-all system design.

The power plant external piping was designed with remote handling in mind. It was necessary, therefore, that the piping around the flanges for remote handling be readily accessible and removable. The design requirements were as follows:

1. Remote handling engine flanges must be made accessible.
2. Coupling shaft must be accessible vertically downward for shaft support mechanism during assembly and disassembly of the shaft and damper bearing assembly.
3. Heat exchanger girdles must be accessible for rollover supports.

The large cooling air ducts (supplying compressor 12th-stage and compressor discharge pressure air to turbine components) were capable of remote handling between the compressor rear frame and the turbine front frame. The tubes in this area were divided into three sections. A center section was located on the reactor-shield assembly and ran from forward of the No. 3 bearing, (as shown in Figure 2.13) to just aft of the No. 4 bearing. This section was fixed to the bearing supports and to the shield at the horizontal centerline of the reactor-shield assembly; it could be removed together with the coupling shaft and bearing assembly.

Removable sections allowed complete accessibility to the main components and prevented damage to the ducting from flange wrenching operations. These sections were attached to the center section, by remotely operated "V" band couplings, and extended forward and aft to the turbomachinery ports.

The small hydraulic lines were designed for handling in a manner similar to the air ducting. They were grouped together into removable "bundles" that extended from the compressor area to the reactor-shield assembly front girdle and from the reactor-shield assembly aft girdle to the turbine area. A group of remote-handling tube connectors were used at each end of the tube bundles to couple the lines to the turbomachinery component. The lines on the reactor-shield assembly extended aft from the couplings on the forward girdle through an area just below the lowest combustion duct connected to the aft girdle of the reactor. The lube and pneumatic service to the No. 3 and 4 bearings branched from this group of lines and loaded to a remote-handling tube connector near the center of the shell assembly. The above coupling joined the piping to the coupling shaft, bearing, and shield assembly which was a unit assembly designed for remote handling.

The main fuel lines (large slot and small slot) that led aft from the control component on the accessory tray were split aft of the front flange of the reactor-shield assembly; one set of lines ran under the coupling shaft and along the top of the reactor-shield assembly to a point opposite the No. 1 combustion casing diffuser. The other set ran near the bottom of the reactor-shield assembly and ended opposite the No. 6 casing diffuser. Two remotely handled harnesses of flexible metal hose, containing couplings for three casings, carried the fuel from couplings on the shield to the top three casings and bottom three casings respectively. From the couplings on the casings, permanently mounted tubes carried fuel to the nozzles.

It was necessary to design a mounting rack spanning the compressor flanges for the accommodation of the nondriven accessories and controls. This rack was capable of being handled by a manipulator at the same time that the gearboxes were handled (the simultaneous handling of the rack and gearbox set was necessary to eliminate the need for a large number of remote tube connections). The rack was mounted to the compressor by three captive bolts.

In designing the external piping and wiring configuration for the power plant, the remote handling requirement posed unique problems, since there were no standard couplings, connectors, or brackets designed for power plant remote handling. The design of these special fittings was broken down into three groupings as follows:

1. Small connectors - fluid couplings for lines through a 1.5-inch diameter
2. Large connectors - air duct couplings
3. Electrical connectors

Small Connectors

The philosophy for the design of small line connectors evolved from the need for a method of sealing joints during long exposure to radiation. Standard-type quick disconnects were found to be unsuitable for these purposes. Metal "O" rings, when properly applied, proved satisfactory as the sealing medium. From the choice of "O" rings, followed the design of lines in each coupling. The coupling took the form of a manifold with the halves clamped together by a single captive bolt; the "O" rings were retained between the manifold surfaces by a wafer plate as shown in Figure 2.15.

Large Connectors - Air Ducting

A comprehensive study of the means of joining large diameter ducts (4-inch diameter) revealed that an all-metal spring-flange "V" band joint offered the lowest weight, satis-

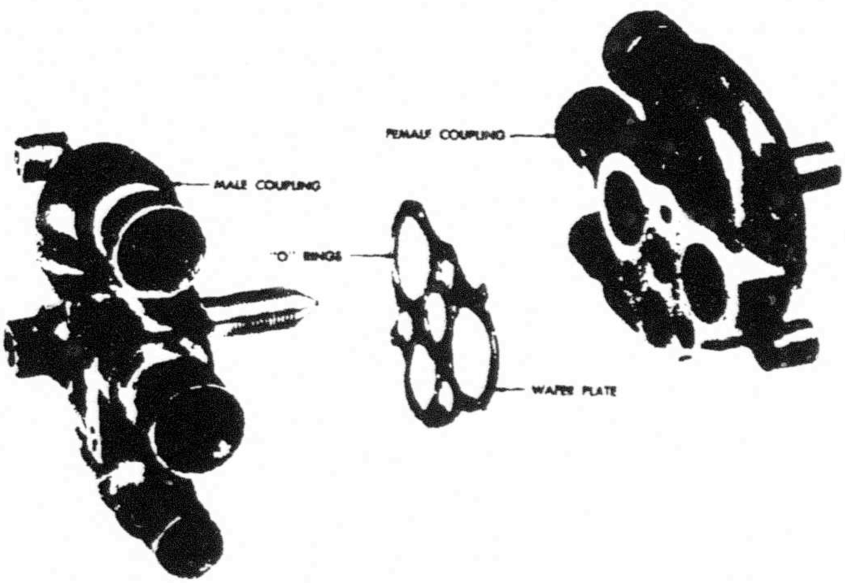

Fig. 2.15 – Remote handling tube connection

factory sealing characteristics, and a minimum of complex mechanism. The design of the standard spring-flange "V" band joint was modified by the addition to the "V" band of cams and followers plus a captive actuating bolt. These modifications positioned and retained the "V" band in relation to the duct so that it required a single wrenching action to open or close the joint.

Electrical Connectors

The electrical connector design was similar in concept to that employed in the small tube connector. The male and female housings supported and piloted radiation resistant multi-pin inserts of conventional design. The coupling was opened and closed by the manipulation of a single captive bolt providing an environmental seal in the housing (see Figure 2.16).

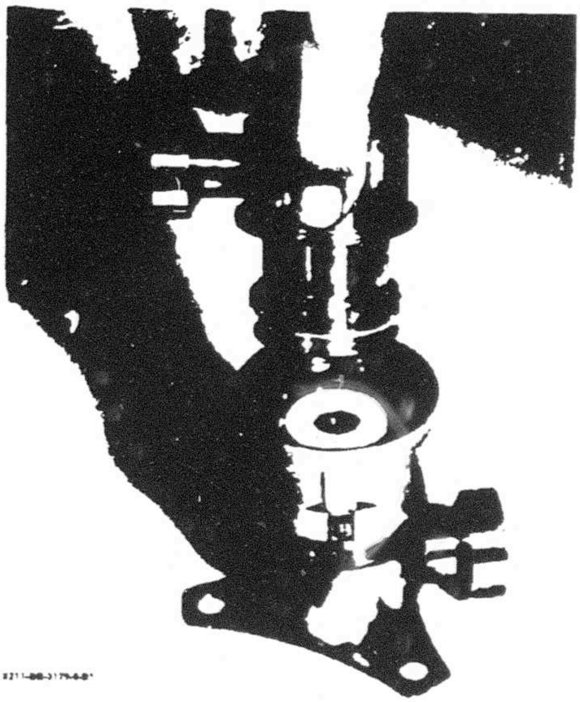

Fig. 2.16 -- Electrical connector -- parts

2.2.2 AEROTHERMAL DESIGN

2.2.2.1 Primary Cooling

Primary air is defined as all air that enters the compressor through the inlet diffuser. Primary cooling air is, therefore, any primary air which is utilized for cooling purposes. For convenience all leakage air from the cycle is listed with primary cooling.

An indication of the variation in pressure and temperature among the various parts of the primary circuit is given in Figure 2.17, the nomenclature for the components is also presented here.

Power plant stations are defined in Table 2.7.

The extraction of turbine cooling air was accomplished by bleeding 2 percent of the total inlet airflow from several stations within the compressor. This air was assumed to be re-

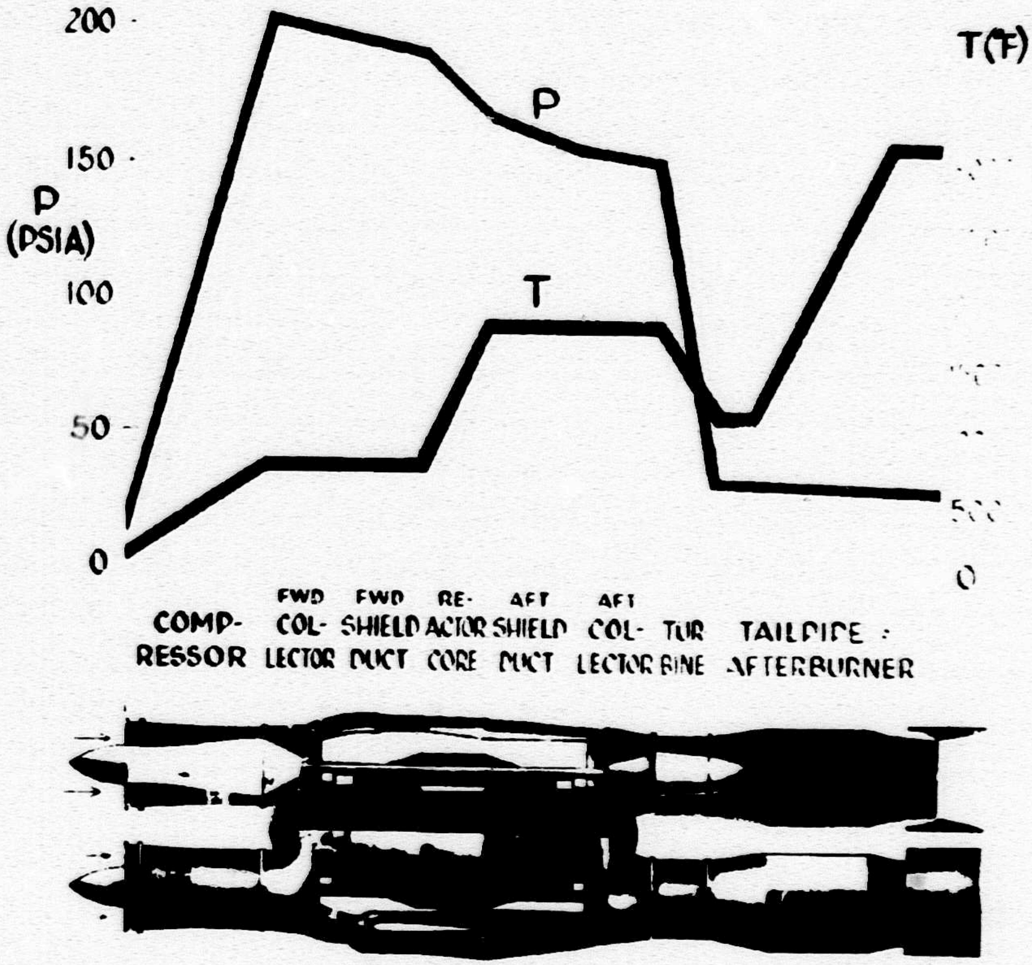

Fig. 2.17 – XMA-1 pressure and temperature variation (Dwg. 4012040-740)

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TABLE 2.7

POWER PLANT STATION DESIGNATIONS FOR THE XMA-1A

Subscript	Station	Effective Flow Area
R	Right set of turbomachinery as viewed from rear.	
L	Left set of turbomachinery.	
C	Nuclear flow system.	
O, am	Free stream.	
2 R, L	Plane of compressor inlet annulus.	15.0 ft^2/X211
3 R, L	Compressor discharge annulus.	2.23 ft^2/X211
3.1 C	Within compressor collector, immediately forward of control rod grate.	
3.1 R, L	Plane of interburner entrance from compressor collector.	1.62 ft^2/X211
3.2 C	Exit from compressor collector immediately forward of reactor bypass valve.	21.5 ft^2
3.2 R, L	Immediately aft of interburner valve.	
3.3 C	Constant area section of forward shield, immediately aft of reactor bypass valve.	4.46 ft^2
3.4 C	Plane of forward shield diffuser inlet.	4.46 ft^2
3.5 C	Reactor inlet plenum, immediately forward of reactor core.	21.5 ft^2
3.52 C	Immediately forward of first fuel element.	8.68 ft^2
3.54 C	Immediately aft of last fuel element.	8.68 ft^2
3.55 C	Plane of core diffuser inlet.	8.68 ft^2
3.58 C	Plane of core diffuser exit.	
3.6 C	Reactor discharge plenum, immediately forward of rear shield.	21.5 ft^2
3.7 C	Entrance of rear shield-triple vaned section.	7.51 ft^2
3.7 R, L	Immediately forward of interburner combustion liner.	1.68 ft^2/X211
3.74 C	Constant area section of rear shield aft of triple vaned section.	7.51 ft^2
3.8 C	Plane rear shield diffuser inlet.	7.51 ft^2
3.9 C	Entrance to turbine collector, aft of rear shield.	21.5 ft^2
3.9 R, L	Plane of interburner discharge to turbine collector.	4.82 ft^2/X211
4 R, L	Throat of first stage turbine nozzle diaphragm.	1.78 ft^2/X211
5 R, L	Exit from turbine.	
5.1 R, L	Entrance to tailpipe diffuser.	12.3 ft^2/X211
7 R, L	Entrance to exhaust nozzle.	
8 R, L	Throat of exhaust nozzle.	variable
x	Compressor bleed inlet.	

turned to the main stream just upstream of station 5.1. Leakage flow was assumed lost from the cycle downstream of station 3, and was assumed to be as follows:

$$\text{Leakage, percent of power plant air flow} = \frac{1.74}{\frac{W_a\sqrt{\theta_3}}{\delta_3}} \times 100.$$

For all conditions of operation above idle power, leakage flow was very close to 2.2 percent. The distribution of airflow during normal operation is shown in Figure 2.18, applicable to either nuclear or chemical operation.

On nuclear operation, up to 0.1 percent of the primary circuit airflow could leak through the closed valves at the inlet to the chemical interburner system. On chemical operation, up to 10 percent of the primary circuit airflow could flow through the reactor flow circuit for the removal of nuclear afterheat.

The pertinent parameters and estimated pressure loss characteristics of the primary flow system operating at the design point conditions for the XMA-1A are shown in Table 2.8.

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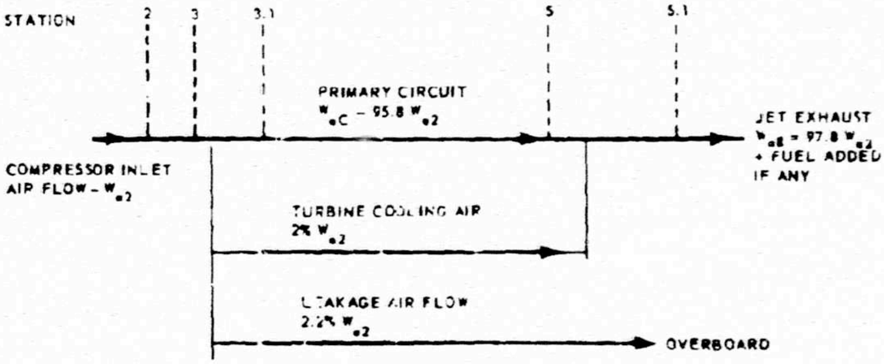

Fig. 2.18 – Airflow distribution

TABLE 2.8

PRIMARY FLOW PARAMETERS FOR THE XMA-1A POWER PLANT AT MACH NUMBER 0.6 AND AN ALTITUDE OF 10,000 FEET

Station,[a]	Design Criteria
W_a 3 R, L, lbs/sec	610.2
P_t 3 R, L psia	139.5
T_t 3 R, L °R	1143
P_t 3.3 C	136.0
3.3 C dynamic head psi	6.62
M 3.3 C	0.273
P_t 3.5 C/P_t 3.3 C	0.951
P_t 3.5 C	129.3
P_t 3.54 C/P_t 3.5 C	0.80
P_t 3.54 C	103.4
T_t 3.54 C	1910
P_t 3.7 C/P_t 3.54 C	0.986
P_t 3.7 C	102.0
M 3.7 C	0.280
3.7 C	5.22
P_t 3.9 C/P_t 3.7 C	0.974
P_t 3.9 C	98.8
P_t 4.0/P_t 3.9 C	0.986
P_t 4.0 R, L	97.3
M 4.0 R, L	1.0
P_t 4.0/P_t 3.0	0.698
A 3.0 R, L - sq. inches	642.2
A 3.3 C	642.6
A 3.54 C	1181
A 3.7 C	1082
A 4.0 R, L	521.6

[a]Definitions of power plant stations are given in Table 2.6.

The methods of determining the losses for the respective components are presented in Appendix A of reference 10 and may be used for computing loss characteristics at the operating conditions.

Losses were computed assuming a turbine nozzle diaphragm effective flow area of 521.6 square inches operating at choked conditions for the listed airflow and reactor discharge temperatures.

Over-all pressure losses used in the system performance calculations were based on the following empirical equation:

$$\frac{P_{t3.9C}}{P_{t3.1C}} = 1 - \left[\frac{W_{aC}\sqrt{\theta_{3.1C}}}{1000\ \delta_{3.1C}}\right]^2 \left[7.7 - 14.2\ \frac{T_{t3.9C}}{T_{t3.1C}}\right]$$

This equation represents the predicted reactor shield assembly pressure ratio within 1 percent throughout the range of possible operating conditions.

2.2.2.2 Secondary Cooling

Secondary cooling for the XMA-1A power plant is defined as all cooling for the power plant which does not enter the compressor inlet diffuser and includes external engine surface, side shield, and the lubrication system.

A final design for secondary cooling was incomplete at the time of the XMA-1 contract termination; however, a series of comprehensive studies were completed. The summary from reference 11 is repeated below:

"The best designs of secondary cooling systems, one for each of three modes of power operation, for the subsonic application of the XMA-1 power plant are evolved in this report. The first mode of operation assumes that the power plant will operate on either nuclear or chemical fuel over the complete subsonic flight spectrum. For this mode of operation, a system employing a variable cylindrical shroud ejector nozzle to pump both shield and turbomachinery cooling flows was recommended. A separate shield system with a simple cooling flow exit had a wide range over which inadequate cooling flows were pumped.

"The second mode of operation assumed that nuclear operation would be limited to ground operation and to Mach numbers of 0.6 or greater. Chemical operation was assumed permissible over the entire flight spectrum. For this mode of operation, the recommended system employed a short variable shroud ejector to pump turbomachinery cooling air, and a separate shield cooling path with a simple fixed exit for shield cooling. An auxiliary inlet was opened to draw in turbomachinery cooling flow at Mach numbers less than 0.2. On ground operation under nuclear power, the shield cooling air flowed in reverse through the system, being pumped by the lower than ambient static pressure existing at the compressor face.

"The third mode of operation assumed that both nuclear and afterburner-on powered flight was limited. Afterburner-on operation was assumed limited to Mach numbers less than 0.6 and altitudes less than 10,000 feet. Nuclear operation was restricted in the same manner as that for the second mode of operation. For this third mode, the system employing a short, fixed shroud ejector to pump turbomachinery cooling air, and a separate shield cooling path with a simple fixed exit for shield cooling was effective.

"Maximum system drags for the best systems of the first two modes was about 1.5 percent of the power plant primary gross thrust. For the third mode, a maximum system drag of about 3.7 percent of the power plant primary gross thrust is incurred. A nominal value of 30 pounds per second cooling air was used as the minimum required shield cooling flow at a plant power level of 300 megawatts. These systems will provide somewhat larger cooling flows. However, the maximum shield system pressure ratio is limited, for example, to about 0.86 at Mach number zero and 0.81 at Mach number 0.6."

The ducting requirements for the all subsonic application of the XMA-1A power plant was reported in reference 12 concluding that the nuclear radiation shield required eight ducts 8 inches in diameter. This was based on the requirement of a shield cooling flow of approximately 30 pounds per second at a reactor power level of 300 megawatts.

The lubricating oil heat exchangers for the XMA-1A were to be supplied by the airframe manufacturer. They were to provide cooling during all power plant operations. The design requirements were

M = 0.9 S.L. 96 percent N
  290,000 Btu/hr/set of turbomachinery
S.L.S. 100 percent N
  265,000 Btu/hr/set of turbomachinery
M = 0.9 30 K ft 96 percent N
  237,000 Btu/hr/set of turbomachinery

The heat load for the turbomachinery hydraulic system was 150,000 Btu/hr.

2.2.2.3 Aftercooling

The general scheme for afterheat removal was published.[13]

Motoring the turbomachinery with the starter to pump aftercooling air or to augment windmilling airflow in flight would be practical and desirable under normal conditions. Accordingly, provision was made in the starter system for extended periods of motoring and for the engagement of the starter during coastdown. However, there were numerous occurrences which could prevent the rotation of the turbomachinery (such as lubrication system failure) requiring a means of aftercooling not dependent on turbomachinery rotation.

Therefore, provision was made for the introduction of aftercooling air directly into the compressor collector through 10-inch ports. Each port was fitted with a check valve to prevent loss of air from the compressor collector during normal operation. Air in the aftercooling supply system was available when the power plant was operating on nuclear heat source at a pressure ratio of 2 to 1 or less (referred to ambient pressure) at the check valves. When the power plant was shut down and the pressure in the compressor collector fell below the aft[illegible] supply pressure, the check valves would open and allow air to enter the compre[illegible]llector, reactor, and hence, overboard through the turbines and tailpipes. The compressor discharge doors could be closed at speeds below 500 rpm minimizing aftercooling air loss through the compressor.

This scheme applied to both flight and ground test operation; however, the manner in which the aftercooling air was supplied varied. For ground tests a blower system was to be used and served as the source for power plant cooling air (including the side shield cooling) during normal operation as well as the source for aftercooling air. For flight, ram air was to be used, pressure augmented for low flight speeds and ground operation.

A detailed analysis of the reactor components' thermal behavior was published.[14] The operating conditions which were considered in this study were as follows:

1. The reactor would operate at 150 megawatts for 150 hours before shutdown with air being supplied by the compressor at a decreasing rate for a short period of time until its output reached 46 pounds per second, after which a constant flow of 46 pounds per second at 70°F was supplied by a blower.
2. The reactor would operate at 150 megawatts for 10 hours before shutdown. The airflow was the same as above.

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3. The reactor would operate at 150 megawatts for 0.1 hour before shutdown. The airflow was the same as above.
4. The reactor would operate at 150 megawatts for 150 hours with a sudden drop in airflow to 46 pounds per second, one second before the reactor was shut down.
5. The reactor would operate at 150 megawatts for 150 hours before shutdown with sudden reductions in airflow from 46 pounds per second after various periods of time after shutdown.
6. The reactor would operate at 203 megawatts for 150 hours before shutdown with air being supplied by the compressor at a decreasing rate until its output reached 46 pounds per second after which a constant flow of 46 pounds per second was supplied by a blower.
7. The reactor would operate at 203 megawatts for 0.1 hour with a sudden drop in airflow to 334 pounds per second at 640°F (40% of operating flow rate) one second before shutdown.
8. The reactor would operate at 203 megawatts for 150 hours with sudden reduction in airflow from 46 pounds per second to 7 pounds per second, 5 hours after shutdown.

Typical results of this study are shown in Figures 2.19 through 2.21.

The recommended minimum in-transit aftercooling requirements, including the core and side shield cooling flow, are given in Table 2.9.

The values given in the table are based on the most severe combination of cold day operating conditions prior to shutdown (100 hrs at 200 MW).

2.2.3 THERMODYNAMIC PERFORMANCE

2.2.3.1 Symbols

The symbols used throughout this report in describing thermodynamic performance are as follows:

A	Effective flow area - square feet
F_g	Power plant gross thrust for both sets of turbomachinery - pound
$F_n = F_g - F_r$	Power plant net thrust for both sets of turbomachinery - pounds
$F_r = \frac{W_a V_p}{g}$	Power plant ram drag for both sets of turbomachinery - pound
g	Gravitational constant, 32.2 feet per second per second
V_p	Airplane true velocity, feet per second
W_a	Power plant air flow for both sets of turbomachinery, pounds per second
W_{aC}	Nuclear flow system airflow, pounds per second
Q	Power plant heat rate to cycle air, megawatts
W_f	Power plant fuel flow for both sets of turbomachinery, pounds per hour
M_p	Flight Mach number
P_{am}	Atmospheric static pressure, psia
P_t	Total pressure at station indicated by subscript - psia
T_t	Total temperature at station indicated by subscript - °R
N	Engine mechanical speed, rpm
$\delta = P_t/14.7$	Relative pressure
$\theta = T_t/518.7$	Relative temperature
P_{t2}/P_{am}	Ram pressure ratio
q	Dynamic pressure, psi

2.2.3.2 Inlet Conditions

For convenience in the use of the generalized performance curves presented herein, compressor-inlet total pressure and total temperature based upon ICAO standard atmos-

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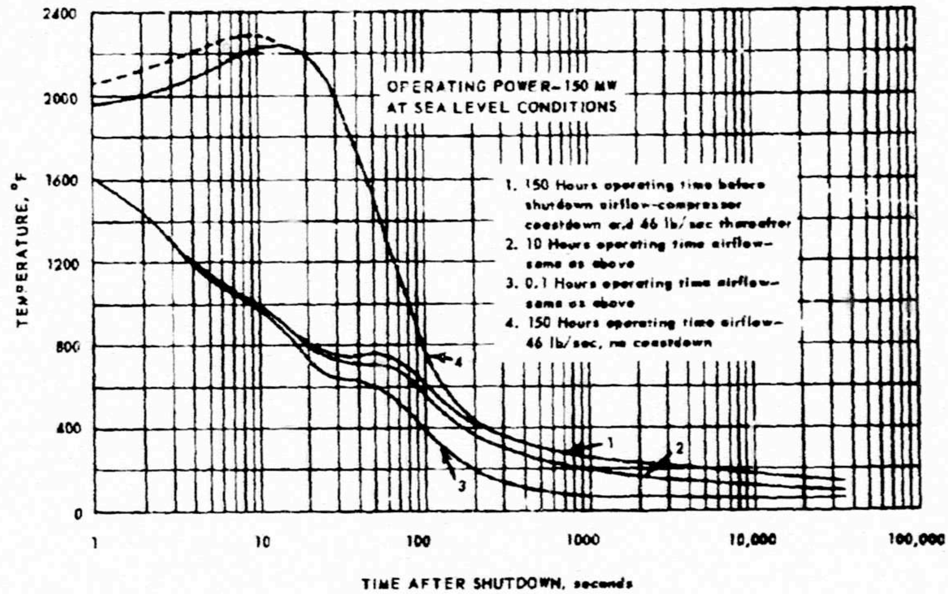

Fig. 2.19 – Fuel element exit temperature versus time after shutdown

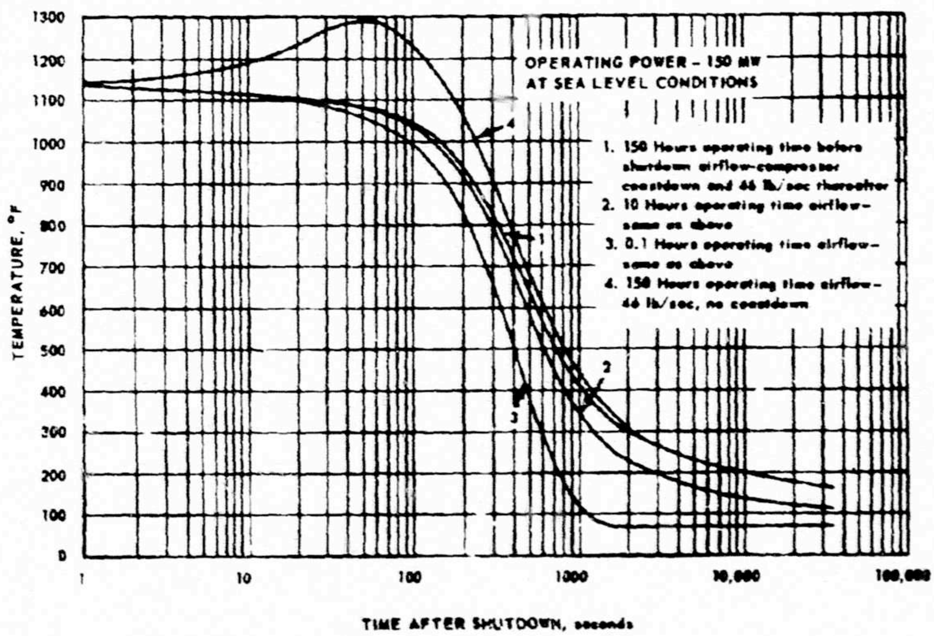

Fig. 2.20 – Moderator surface exit temperature versus time after shutdown

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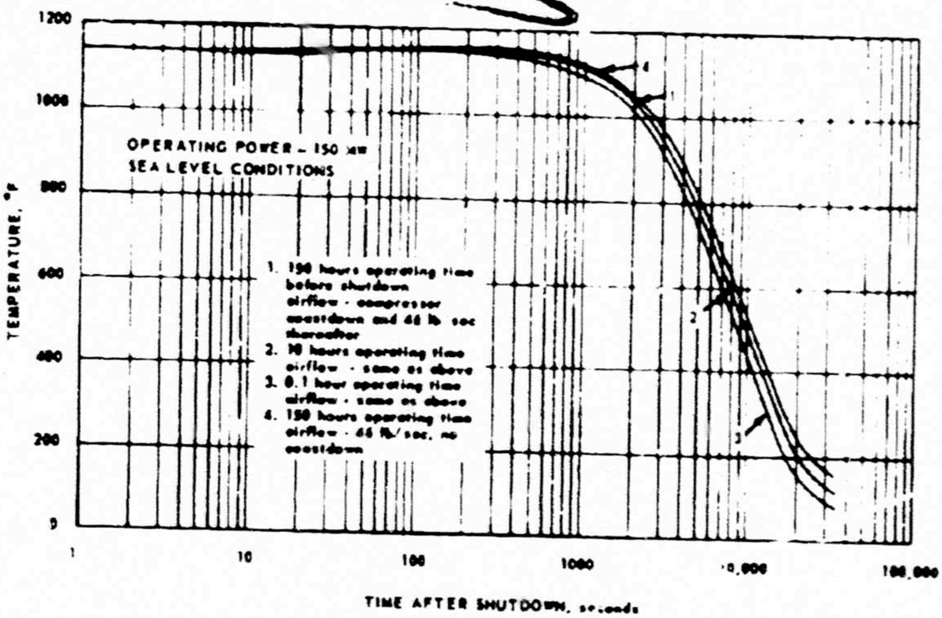

Fig. 2.21 – Reflector surface exit temperature versus time after shutdown

TABLE 2.9

MINIMUM IN-TRANSIT AFTERCOOLING FLOW REQUIREMENTS FOR THE XMA-1A

Time After Shutdown When Transfer From Initial To In-transit System Occurs, hr	Total Core Plus Side Shield After-cooling Flow Requirements, lb/sec
3	10
5	7
7	6
9	5

phere and 100 percent ram recovery are presented for various flight conditions in Figures 2.22 and 2.23.

2.2.3.3 Definition of Power Ratings

Design Military Power: The maximum power on nuclear heat source at which the power plant was capable of operating for periods up to 30 minutes. $T_{t4} = 1500°F$. N = 4700 rpm.

APEX 380 Military Power: The maximum power on nuclear heat source quoted for initial test purposes for the XMA-1A. $T_{t4} = 1450°F$. N = 4625 rpm.

Military Power: The maximum power on chemical heat source which the power plant was capable of operating for periods up to 30 minutes. $T_{t5.1} = 953°F$. N = 4890 rpm.

Normal Power: The maximum power on either heat source at which the power plant was capable of operating continuously.

Nuclear: $T_{t4} = 1383°F$. N = 4500 rpm.
Chemical: $T_{t5.1} = 865°F$. N = 4750 rpm.

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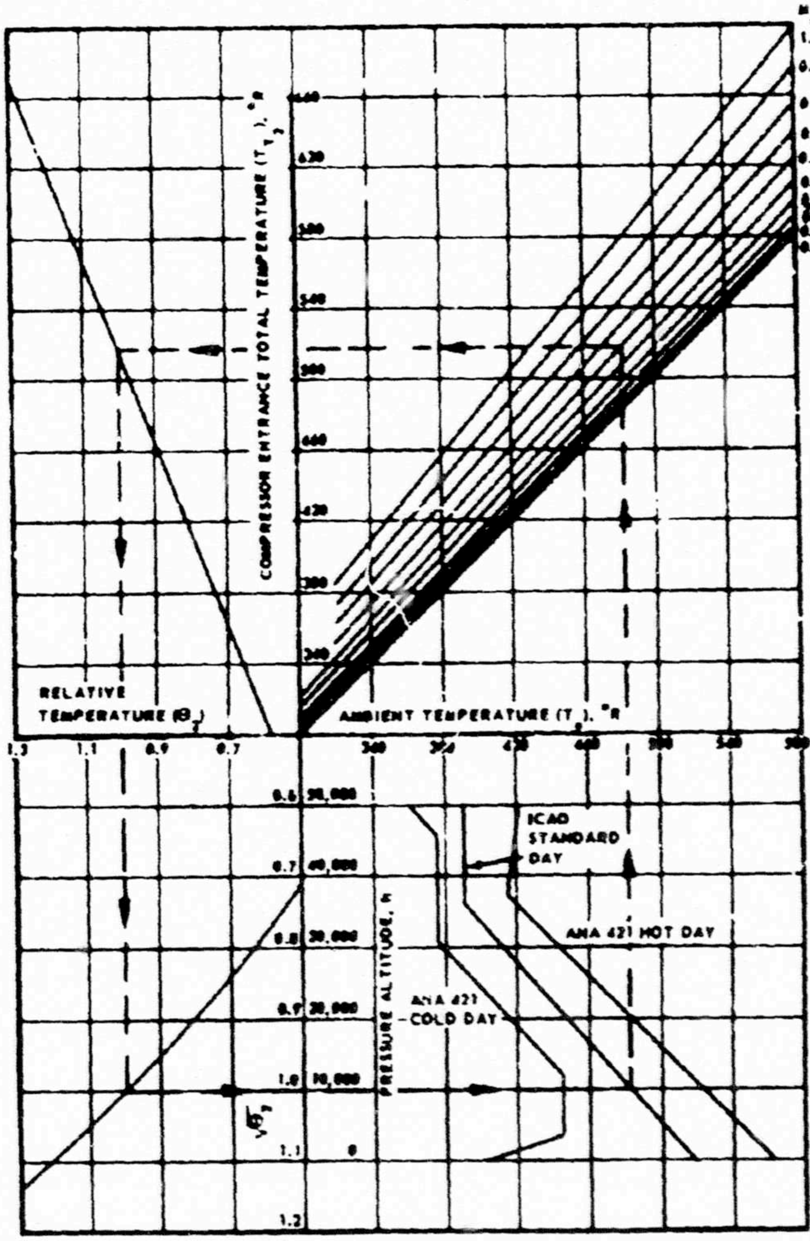

Fig. 2.22 – Engine inlet parameters as a function of pressure altitude and flight Mach number

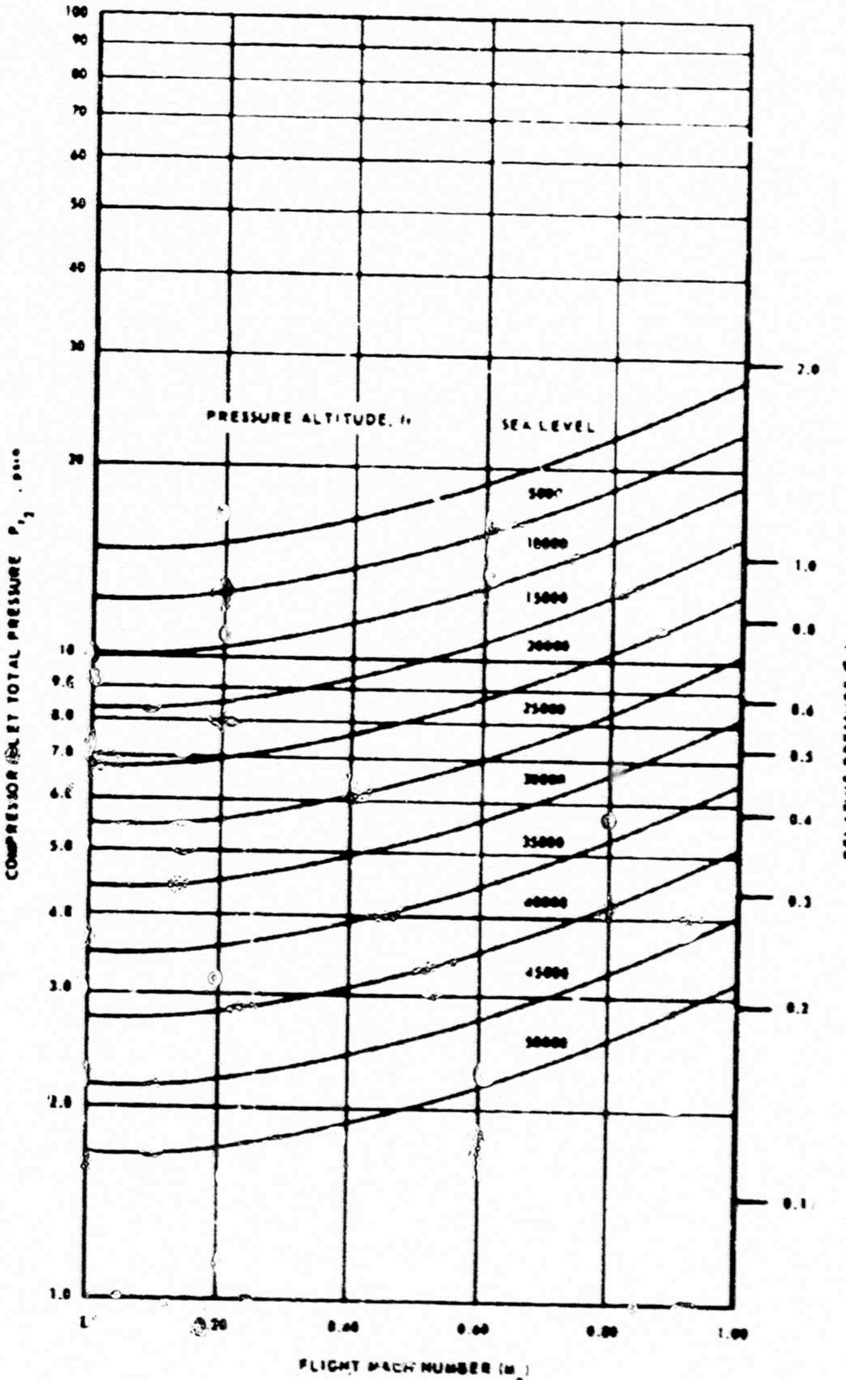

Fig. 2.23 – Engine inlet parameters as a function of pressure altitude and flight Mach number

2.2.3.4 Control Schedule

The nuclear heat source performance data are based on the schedule of turbine inlet temperature T_{t4} versus engine speed N shown in Figure 2.24. The chemical heat source performance data are based on the schedule of turbine discharge temperature $T_{t5.1}$ versus engine speed N given in Figure 2.25. These schedules were established to provide the engine speed resulting in the highest thrust for each turbine inlet temperature. The schedules optimized engine speed at M 0.6, 10,000 feet, standard day; however, the schedules yielded close to optimum thrust over the range of possible flight conditions.

2.2.3.5 Basis of Performance Calculations

Pressure losses through various components of the reactor-shield assembly flow path are presented in detail in section 2.2.2.1.

The calculations for the system performance data presented were made using a computer program developed by the General Electric Large Jet Engine Department for use with the IBM 704 computer. A description of this program is presented in reference 15. The detailed input for the cycle calculations was published in reference 16.

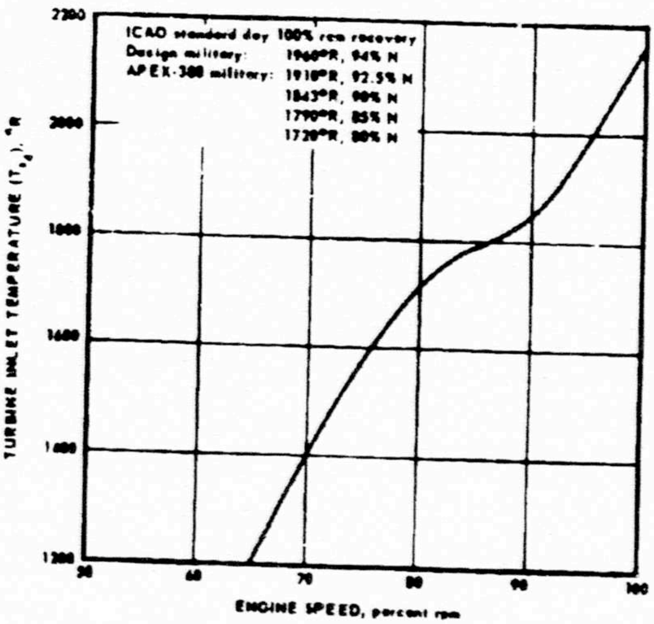

Fig. 2.24 – XMA-1A power plant estimated minimum performance – Nuclear heat source

2.2.3.6 Over-all System Performance

Military power thrust and heat addition data for standard inlet conditions are presented in Figures 2.26, 2.27, and 2.28. Other performance data are presented in the form of generalized curves.

Power plant corrected gross thrust and nuclear heat rate to cycle air and chemical fuel flow covering a broad range of power conditions for both modes of heat source operation are presented in generalized form in Figures 2.29 through 2.35. Airflow, nuclear heat rate to cycle air, and chemical fuel flow are presented in similar form in reference 7. Reynolds number corrections need not be applied to these generalized data within the lim-

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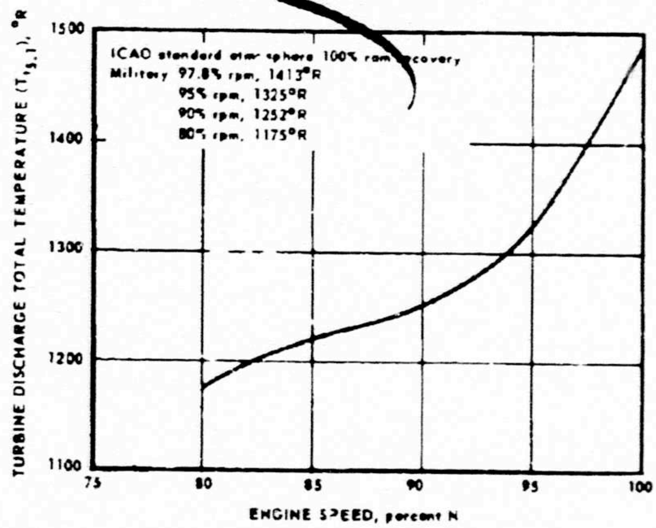

Fig. 2.25 – XMA-1A power plant estimated minimum performance – Chemical heat source

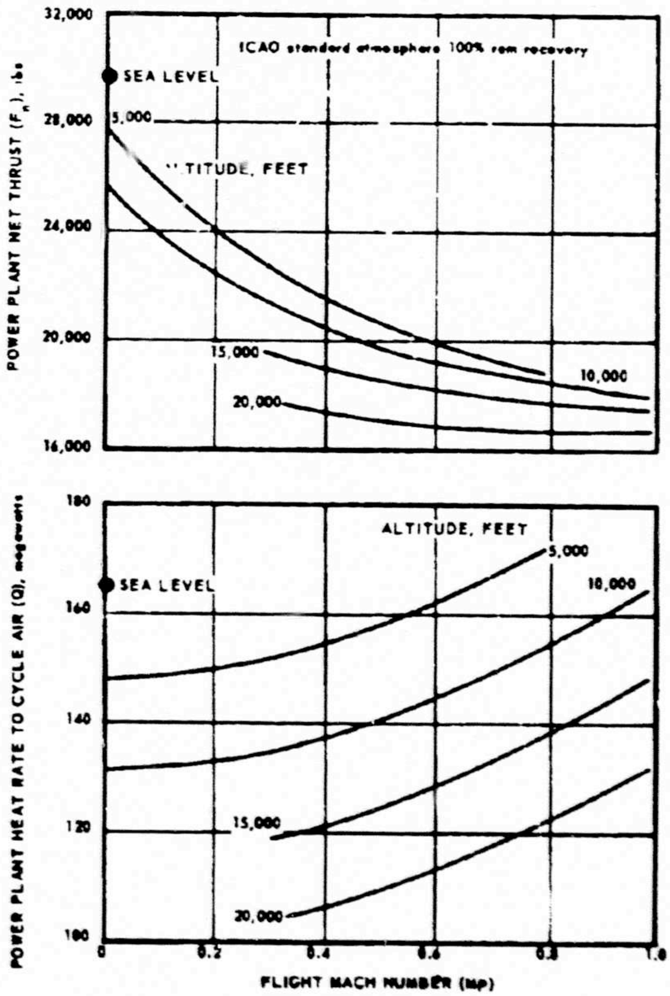

Fig. 2.26 – XMA-1A power plant estimated minimum performance for design military rating – Nuclear heat source

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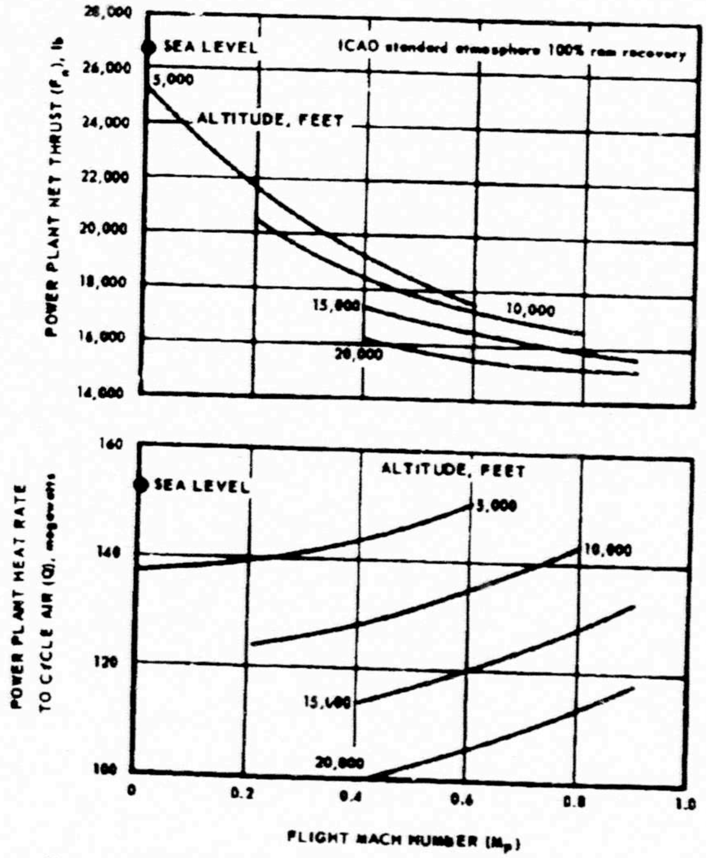

Fig. 2.27 – XMA-1A power estimated minimum performance for APEX-380 military rating – Nuclear heat source

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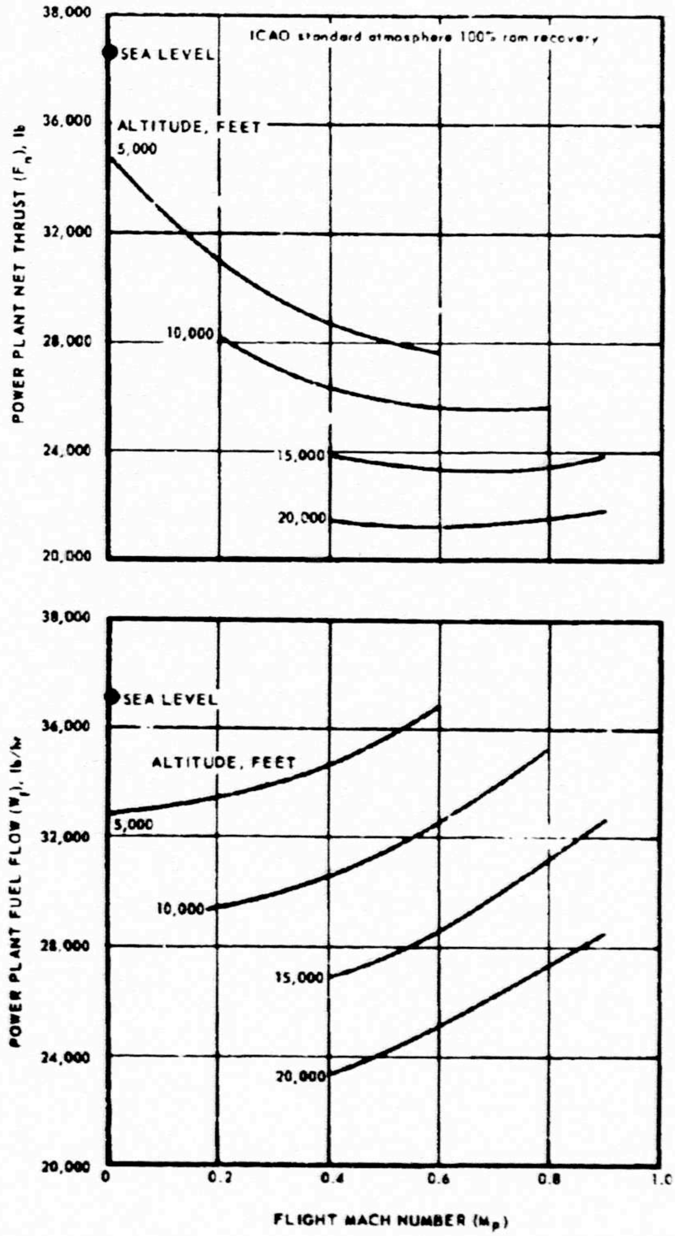

Fig. 2.28 – XMA-1A power plant estimated minimum performance for military design – Chemical heat source

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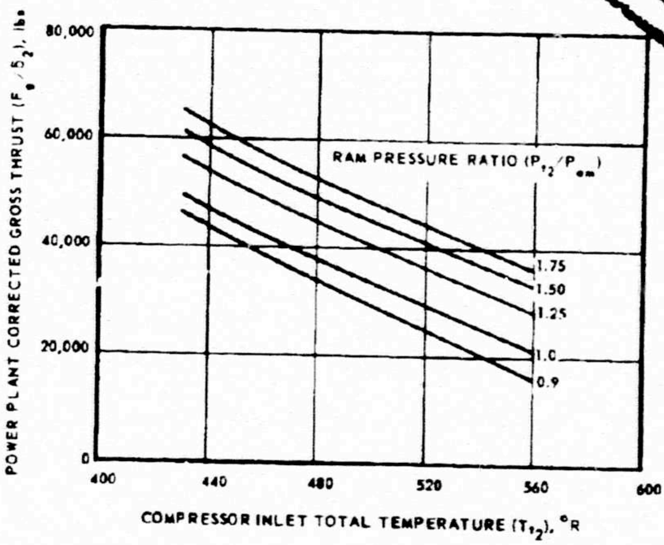

Fig. 2.29 – XMA-1A power plant estimated performance for design military rating – Corrected gross thrust – Nuclear heat source

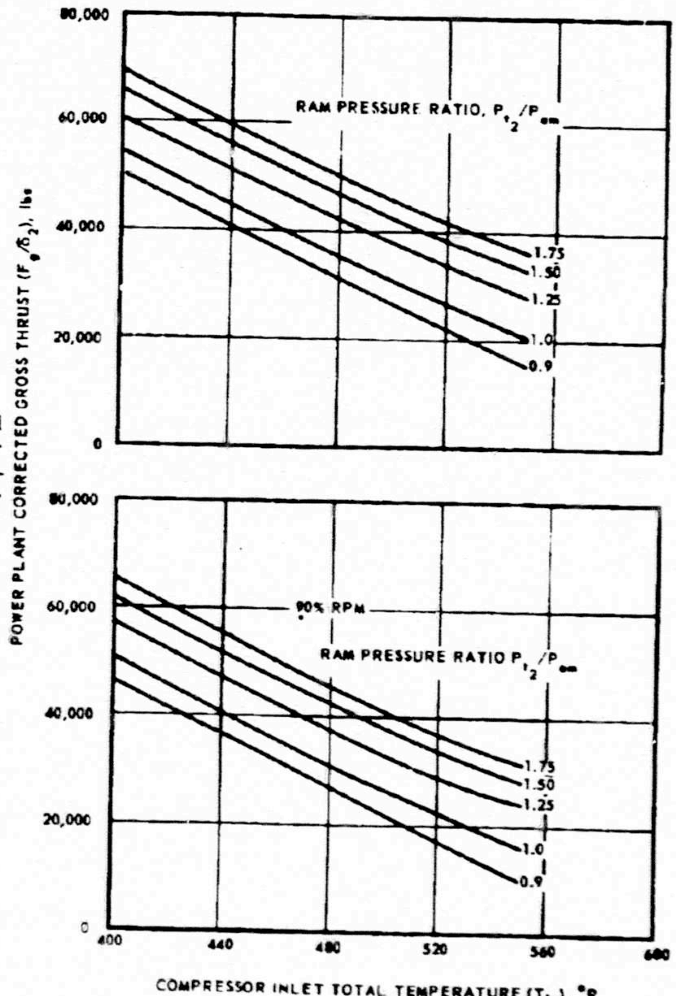

Fig. 2.30 – XMA-1A power plant estimated minimum performance for APEX-380 military rating – Corrected gross thrust – Nuclear heat source

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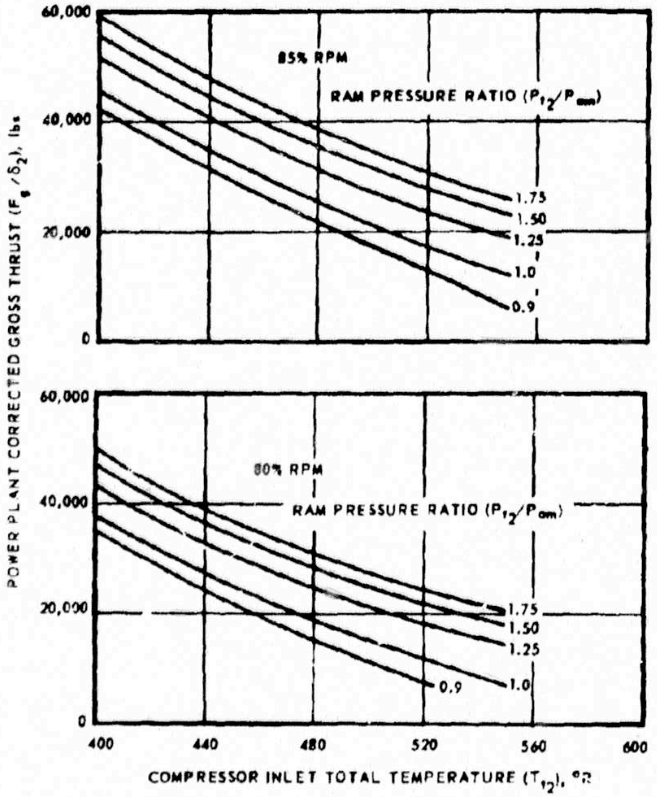

Fig. 2.31 – XMA-1A power plant estimated minimum for APEX-380 military rating – Corrected thrust – Nuclear heat source

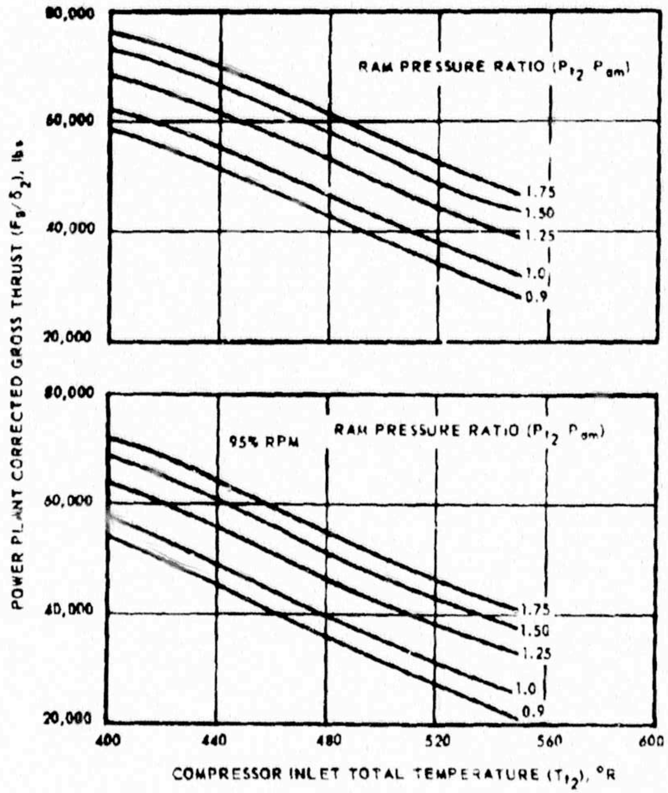

Fig. 2.32 – XMA-1A power plant estimated minimum performance for military – Corrected gross thrust – Chemical heat source

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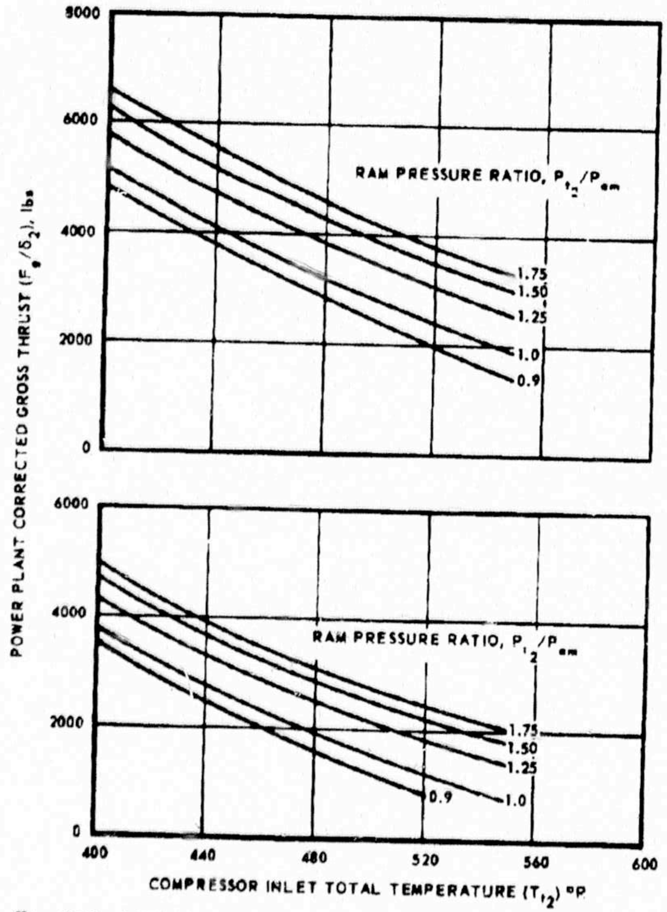

Fig. 2.33 – XMA-1A power plant estimated minimum performance for military rating – Corrected gross thrust – Chemical heat source

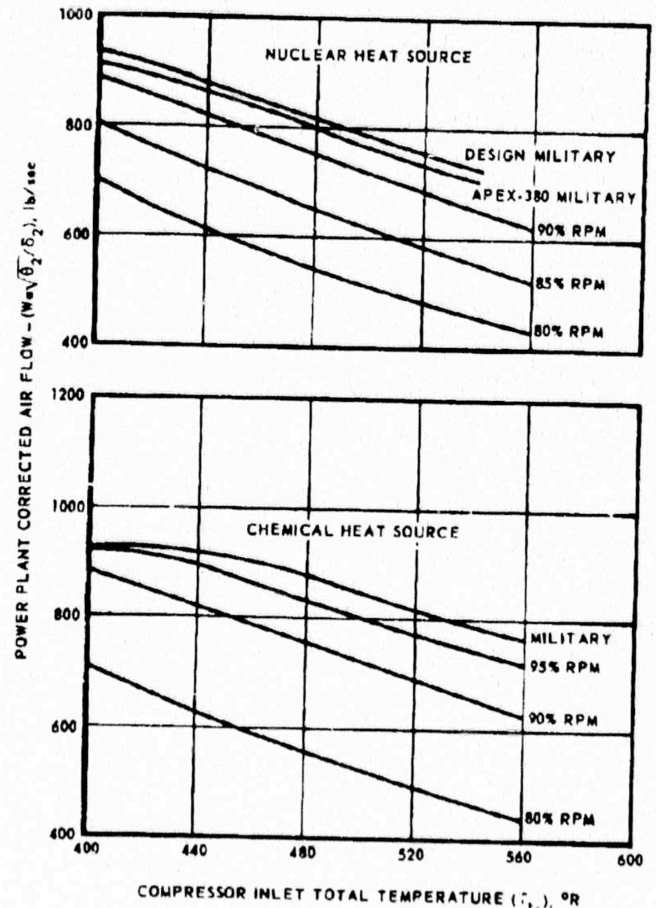

Fig. 2.34 – XMA-1A power plant estimated minimum performance – corrected air flow

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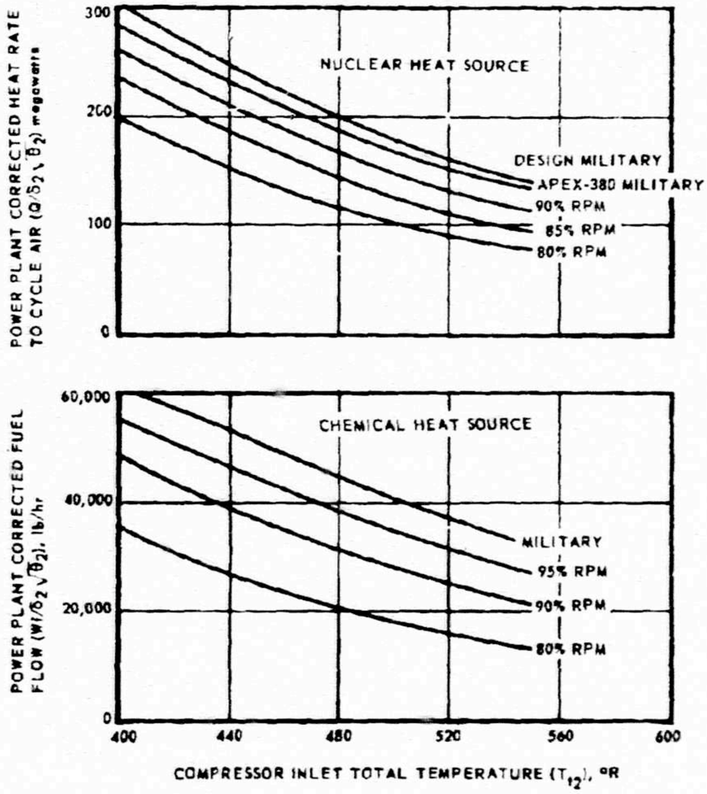

Fig. 2.35 – XMA-1A power plant estimated minimum performance

its of the XMA-1A flight envelope (section 2.1.3). Inlet duct losses can be taken into account by using the proper compressor inlet total pressure in entering the generalized curves. For convenience in working with the generalized curves, Figures 2.22 and 2.23 can be used to find standard, no-loss compressor inlet conditions.

2.2.3.7 Flow Conditions Within the Power Plant

Pressure, temperature, and corrected airflow at various stations within the power plant are presented in generalized form in reference 7. These data can be used to determine thermodynamic and aerodynamic loading conditions over the range of possible operating conditions.

2.2.3.8 System Optimization

A number of parametric system maps correlating reactor core parameters of fuel channel hydraulic diameter, maximum fuel element surface temperature and core or system pressure ratio with turbomachinery parameters of turbine inlet temperature, turbine nozzle diaphragm area or compressor stall margin, and engine thrust were published.[17] The maps resulting were useful for estimating XMA-1A system performance and in aiding in the visualization of trends and relationships between a limited number of engine and reactor variables. The more pertinent results are shown in Figures 2.36, 2.37, and 2.38.

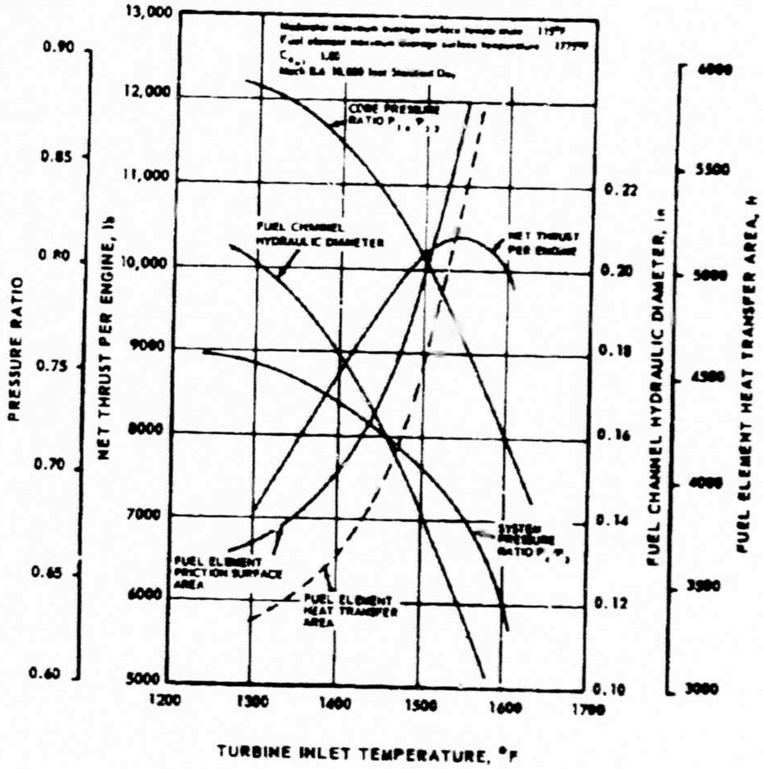

Fig. 2.36 – Engine thrust and core design parameters

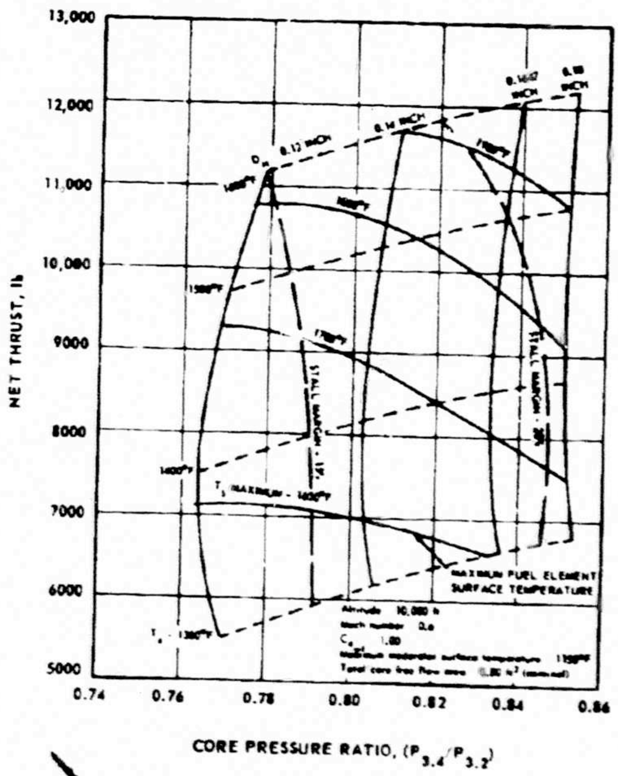

Fig. 2.37 – Net thrust versus core pressure ratio ($P_{3.4}/P_{3.2}$)

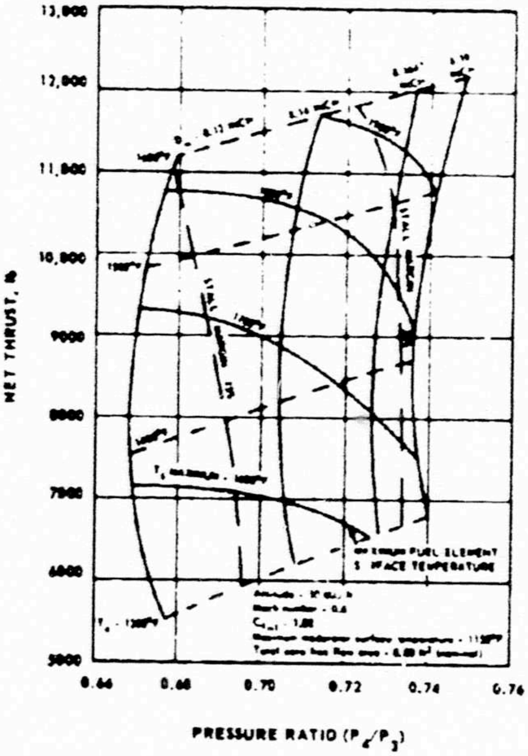

Fig. 2.38 – Net thrust versus pressure ratio (P_4/P_2)

2.3 XMA-1C POWER PLANT

The XMA-1A design and associated studies were directed toward the selection of a reactor and over-all engine for the XMA-1C. The XMA-1C was the designation for the operational version of the XMA-1A developmental power plant.

2.3.1 DESIGN REQUIREMENTS

2.3.1.1 Configuration

The XMA-1C engine was a nuclear turbojet system designed to operate on either nuclear or chemical power. It consisted of one reactor-shield assembly coupled with two sets of X211F turbomachinery. The two sets of turbomachinery were mounted from the forward and aft flanges of the reactor-shield assembly and arranged so that the compressor turbine coupling shafts passed through the outer portion of the reactor side shield with the chemical interburner combustion ducts on both sides of and parallel to the reactor side shield. In all respects, it is the same arrangement and configuration as the XMA-1A except for higher performance capabilities; therefore, the use of different materials was necessary. The reactor was designed to fit into the same reactor cavity as the XMA-1A.

The over-all power plant arrangement is shown in Figure 2.39. The weight objective of the power plant was 115,740 pounds as shown in Table 2.10. These weights were established for initial design objectives, and were subject to modification during the course of the preliminary design phase.

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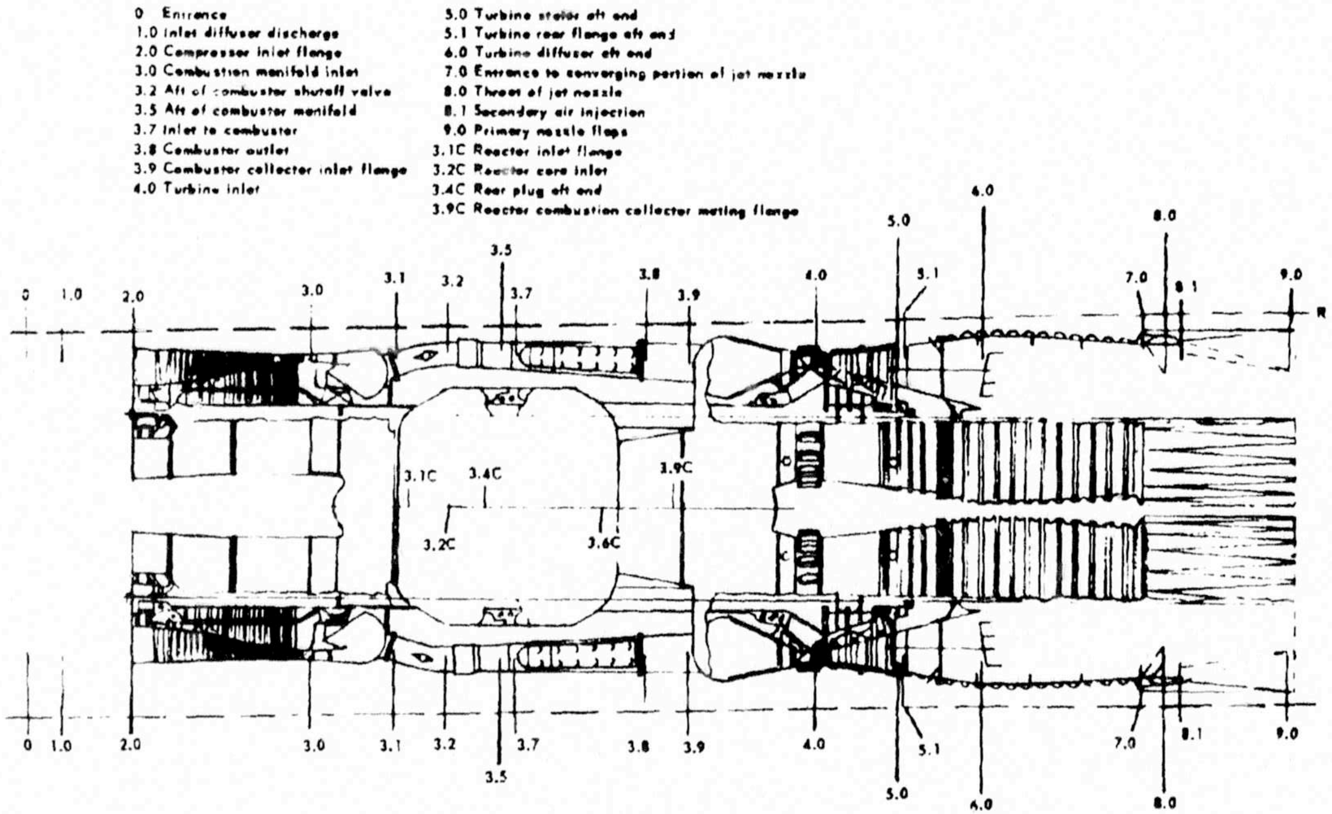

Fig. 2.39 – Over-all XMA-1C power plant arrangement

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TABLE 2.10

XMA-1C POWER PLANT WEIGHT OBJECTIVES

Reactor Shield Assembly		Weight, lb
Front plug		14,260[a]
Rear plug		14,605[a]
Side shield		32,085[a]
Core		14,950[a]
	Total	75,900
Control Installations		
Bypass valve		1,380[a]
Control rod and actuation		2,990[a]
Nuclear sensors		690[a]
Electronic and electrical controls		2,600[b]
	Total	7,660
Turbomachinery - X211F (2 Engines)		31,490
Shaft Shielding		690[a]
	Total power plant	115,740

[a]Approximate XMA-1A weights plus 15 percent growth factor.

[b]Approximate XMA-1A weights plus approximate 25 percent growth factor.

2.3.1.2 Application

Total lifetime requirements for the reactor was 1000 hours. For purposes of design, the tabulation in Table 2.11 itemizes the proportion of the total lifetime required at various flight conditions. Flight limits imposed upon the power plant were as follows:

P_{t3} = 245 psia maximum	T_{t2} = 655°R maximum
	400°R minimum
P_{t2} = 24.9 psia maximum	
2.58 psia minimum	Maximum altitude = 45,000 feet
P_{t2} = 20 psia minimum	Maximum speed = 1.0 Mach number
	Minimum speed = 150 knots

The application was further defined by the CAMAL mission. This mission was an all-subsonic operation consisting of 120 hours per mission, the majority of the time consisted of cruising at Mach 0.85 at 30,000 feet and included a penetration at Mach 0.9 at 500 feet. The duration of the penetration was to consist of from 3 to 6 hours. A flight profile considered to meet a typical CAMAL mission is detailed in Table 2.12.

2.3.1.3 Performance

The priority considerations that the Air Force specified in the statement of work for the CAMAL competition was as follows:

Payload	40,000 pounds
Sea level penetration speed	0.9 Mach number
Dose rate	0.020 rems per hour, maximum
	0.012 rems per hour, objective

TABLE 2.11

XMA-1C TOTAL LIFETIME REQUIREMENTS AT VARIOUS FLIGHT CONDITIONS

Altitude	Mach No.	Ambient Temperature	Thrust Condition	Primary Heat Source: Total Hours	Primary Heat Source: T_4, °F	Chemical Heat Source: Total Hours	Chemical Heat Source: T_4, °F	Primary Heat Source: W, lb sec	P_3, psia	T_3, °F	Q, mw	F_n, lb	N, %
Sea Level	0	Standard	Normal	20	1600	20	1550	760	181	804	190	36,700	97
Sea Level	0	Standard	Idle[a]	5		5							
Sea Level	0	Standard	Military - Afterburner			5	1660						
5000	0	Standard	Military[b]	775	1700			700	160.9	708	191.2	38,400	
Sea Level	0.9	Standard	Military	20	1700	3	1660	982	244.4	771	200.4	30,150	100
Sea Level	0.9	Hot	Military Sprint[c]	3	1700	1	1660	956	235.8	803	228.2	33,744	100
5000	0.6	Hot	Emergency Sprint[c]	5	1750			720	182	792	196.2	34,900	100
10,000	0.6	Standard	Emergency	(5)	1750			706	174	728	206	28,700	100
10,000	0.6	Standard	Military	35	1700	5	1660	706	172	728	180.4	28,300	100
30,000	0.85	Standard	Normal	810	1600	60	1550	414.4	98.5	642	110.8	17,200	97
Total Life				900		100							

[a]Nuclear checkout.

[b]Pre-installation checkout.

[c]Design is based on worst reactor operating condition. The 5000 feet is for aircraft with no payload and the 10,000 feet is for aircraft with payload (40,000 pounds).

TABLE 2.12

TENTATIVE FLIGHT PROFILE No. 1

Time, hr	Evolution	Altitude, ft	Mach No.	Power: Source	Power: Level, mw	T_4, °F
0-0:03	Start	0	0			
0:03-0:13	Checkout	0	0	Chemical military		
0:13-0:18	Taxi	0	0	Chemical idle		
0:18-0:19	Take-off	0	0-0.3	Chemical military plus afterburner		
0:20	Climb & acceleration	200	0.5	Chemical military plus afterburner		
0:21	Climb & acceleration	400	0.7	Chemical military plus afterburner		
0:22	Climb & acceleration	600	0.86	Chemical military plus afterburner		
0:25	Interrupt climb and shut off afterburner	10,000	0.86	Chemical military plus afterburner		
0:25-0:26	Transfer to nuclear	10,000	0.86-0.6		0 to 180.4	
0:26	Resume climb	10,000	0.6	Military nuclear	180.4	1700
0:40	Complete climb	30,000	0.85	Military nuclear	180.4	1700
0:40-96:20	Cruise out and on station	30,000	0.85	Normal nuclear	110.8	1600
96:20	Launch missiles	30,000	0.85	Normal nuclear	110.8	1600
96:20-96:40	Descend	30,000-200	0.9	Idle nuclear		
96:40-99:40	Penetration and escape	200	0.9	Military nuclear	200.4	1700
99:40-100:00	Climb	200-30,000	0.6-0.85	Military nuclear	150[a]	
100:00-119:33	Return home	30,000	0.85	Normal nuclear	110.8	1600
119:33-119:35	Transfer to chemical	30,000	0.85		110 to 0	
119:35-119:50	Descent	30,000-500	0.85-0.5	Chemical idle		
119:50-119:54	Final approach	500-0	0.5-0.2	Chemical idle		
119:54-119:55	Landing					
119:55-120:00	Taxi	0	0	Chemical idle		
120:00	Shutdown	0	0			

[a]Estimated average.

Emergency operation	Maintain 10,000 feet altitude with only one XMA-1C power plant in operation
Cruise altitude	Select the optimum for minimum dose rate but insure capability of penetration at any pressure altitude between sea level and 20,000 feet

Other general flight requirements included the following:

1. Take-off will be by chemical mode, augmented with afterburner.
2. Transfer from chemical to nuclear power was required without loss of altitude during transfer.
3. Ability to isolate one set of turbomachinery during take-off on chemical power was required, but single engine isolation after transfer to nuclear power was not required.
4. Xenon override after shutdown was not required since normal operations would need sufficient time for peak xenon to decay below equilibrium value during operation.

Radiation constraints are given in Figures 2.40 and 2.41. These dose rates were considerably different than those used in the design of the XMA-1A.[7] The radiation constraints were based on direct beam (no scatter) at a distance of 50 feet from the center of the reactor when operating at the cruise power level of 110 megawatts. The dose rates are given in terms of rems per hour for gammas and reps per hour for fast neutrons. Conversion should be made by the equivalence: 1 rep per hour = 10 rems per hour.

2.3.2 REACTOR TYPES STUDIED FOR APPLICATION WITH THE XMA-1C

Initial screening of reactor types for application with the XMA-1C power plant included various combinations of moderator materials in a straight-through-flow path. They specifically included fuel element-moderator combinations of: (1) ceramic-ceramic, (2) ceramic-metallic, (3) hydride-ceramic, (4) liquid-ceramic, and (5) liquid-metallic. The folded-flow reactor principle was also considered. A brief summary of the reactor types studied are presented in reference 18.

2.3.3 CONCLUSIONS

An evaluation of the significant data of the three reactors selected for consideration for application with the XMA-1C power plant showed an advantage, in terms of multiplication constant, fuel loading, and weight, for the P127B (ceramic core) reactor.[19] The higher weight of the P103B reactor[20,21] was attributed to the relatively large core diameter required and the high density of the materials used. The weight of the P123 (metallic core) reactor[22] was approximately the same as the P127B, but the P123 active core was much smaller in diameter so the effect of higher density material was cancelled.

The P127B, P103B, and P123 reactors are covered more extensively in reference 23.

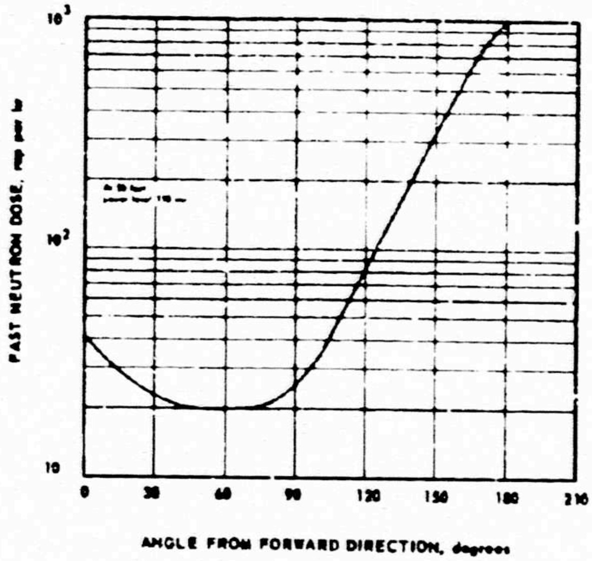

Fig. 2.40 – XMA-1C fast neutron constraint

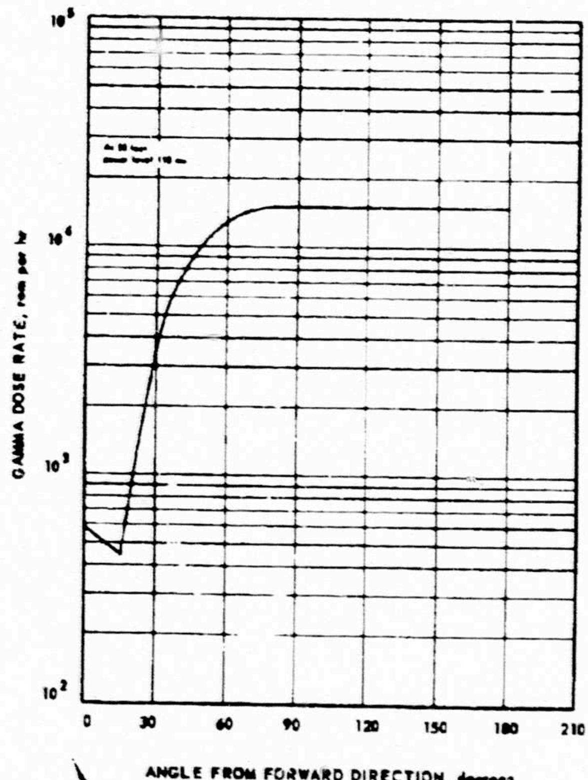

Fig. 2.41 – XMA-1C gamma radiation constraint

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3. XMA-1A REACTOR

3.1 GENERAL DESCRIPTION

The XMA-1 reactor was a cylindrical assembly 62 inches in diameter and 38.5 inches long. These dimensions encompassed the forward and side reflector plus the active core and core structure. The core consisted of 151 cylindrical metallic fuel cartridges in a matrix of unclad zirconium hydride moderator bars. This design permitted the air leaving the compressor to pass directly through the full length of the core in a single pass cooling the core components. A sketch of this assembly is shown in Figure 3.1.

The fuel sheet used in the cartridges consisted of a sintered sandwich of highly enriched UO_2 and nichrome with a nichrome clad on each side. The fuel sheet was fabricated into concentric rings 3 inches long that were assembled one inside the other to form a single fuel element having controlled area cooling passages. Nine fuel elements were assembled in line to make up the full length fuel cartridge.

The moderator bars of the XMA-1 reactor were constructed with a triflute cross section that permitted locating them at the interstices between the fuel cartridges. To provide additional moderation, round zirconium hydride bars were placed at the center of the fuel cartridges inside the smallest fuel ring. The individual fuel cells were 3.56 inches in diameter and were arranged in a triangular pattern with a 4.387-inch pitch.

Tubular members passed through the full length of the core at 129 positions. These tubes were used to accommodate the control rods and at some locations they provided the structural support between the forward and rear tube sheets.

The core was designed to operate in a horizontal position with the moderator bars and fuel cartridges supported by tube sheets at each end. The reflector assembly formed the support between the tube sheets and completed the cylindrical configuration. The complete assembly was cantilevered from the forward shield plug.

3.1.1 NUCLEAR CONCEPT

The experience gained and technology developed in the design and operation of the Heat Transfer Reactor Experiments (HTRE) was utilized to provide a highly refined nuclear design for the XMA-1A reactor.

For nuclear design purposes, the expected life of the power plant was specified at 21,640 megawatt hours, the design power level was 150 megawatts, and the excess reactivity was sufficient to override the xenon poisoning 1 hour after shutdown after reaching equilibrium at any part of the expected life cycle.

The fuel for the XMA-1 reactor was specified at 500 pounds of uranium-235, in the form of fully enriched uranium dioxide, contained in an 80Ni - 20Cr alloy. The fuel cart-

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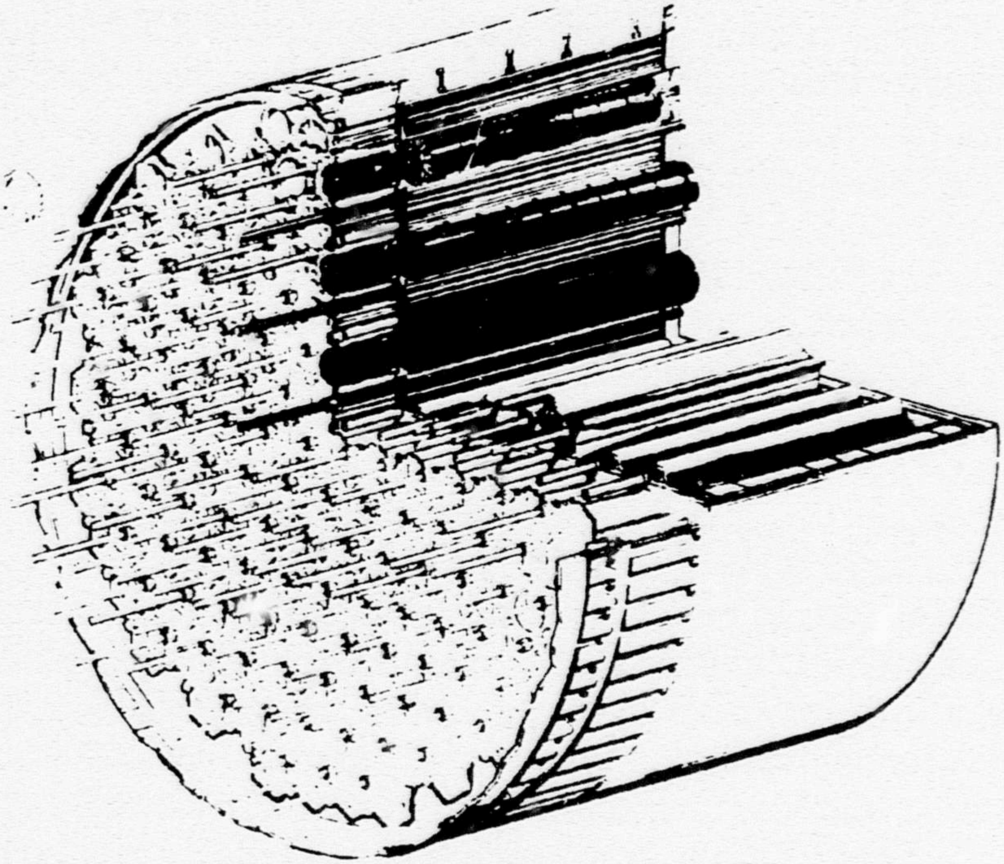

Fig. 3.1 – XMA-1A core (Neg. G1260A)

ridges were designed so that fuel concentrations varied both in the radial and longitudinal direction to provide the gross power flattening and longitudinal power shaping. A cross section of this assembly is shown in Figure 3.2.

Hydrided zirconium metal formed the matrix of the active core and provided the neutron moderation. The constant hydrogen density specification for this material was 4.0×10^{22} atoms per cubic centimeter.

A beryllium reflector was used on the front and sides of the core.

3.1.2 THERMAL CONCEPT

Thermal concept of the XMA-1A reactor design was similar to that of the HTRE No. 1 reactor with the exception that all reactor components were air cooled; in the HTRE No. 1 reactor only the fuel elements were air cooled.

In HTRE No. 1, heat generated in all nonfueled components was released to cooling water flowing in a closed circuit; this was subsequently transferred in a heat exchanger to a secondary water system. Utilization of a HTRE No. 1 reactor concept to an aircraft

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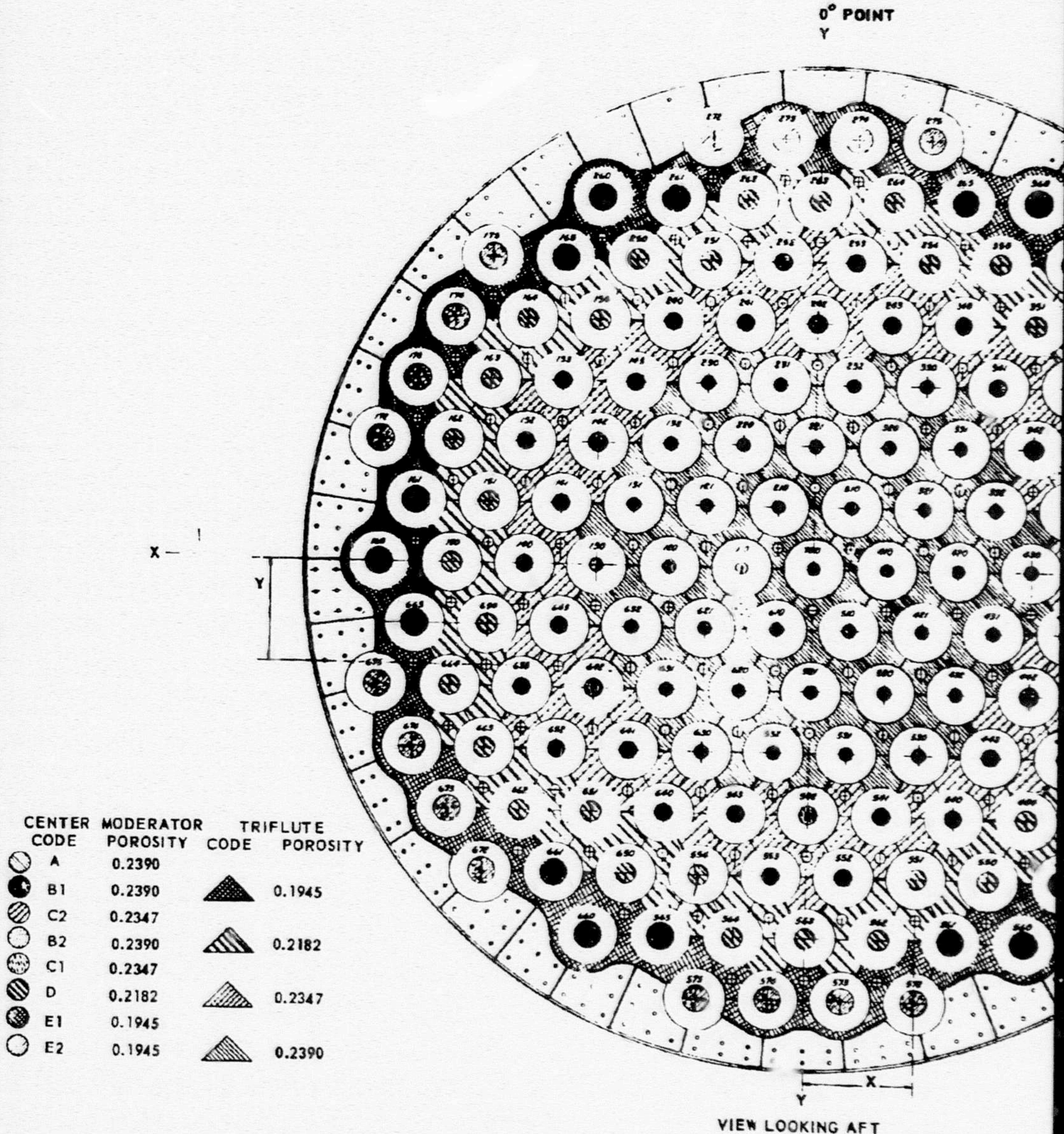

Fig. 3.2 — XMA-1A core cross section

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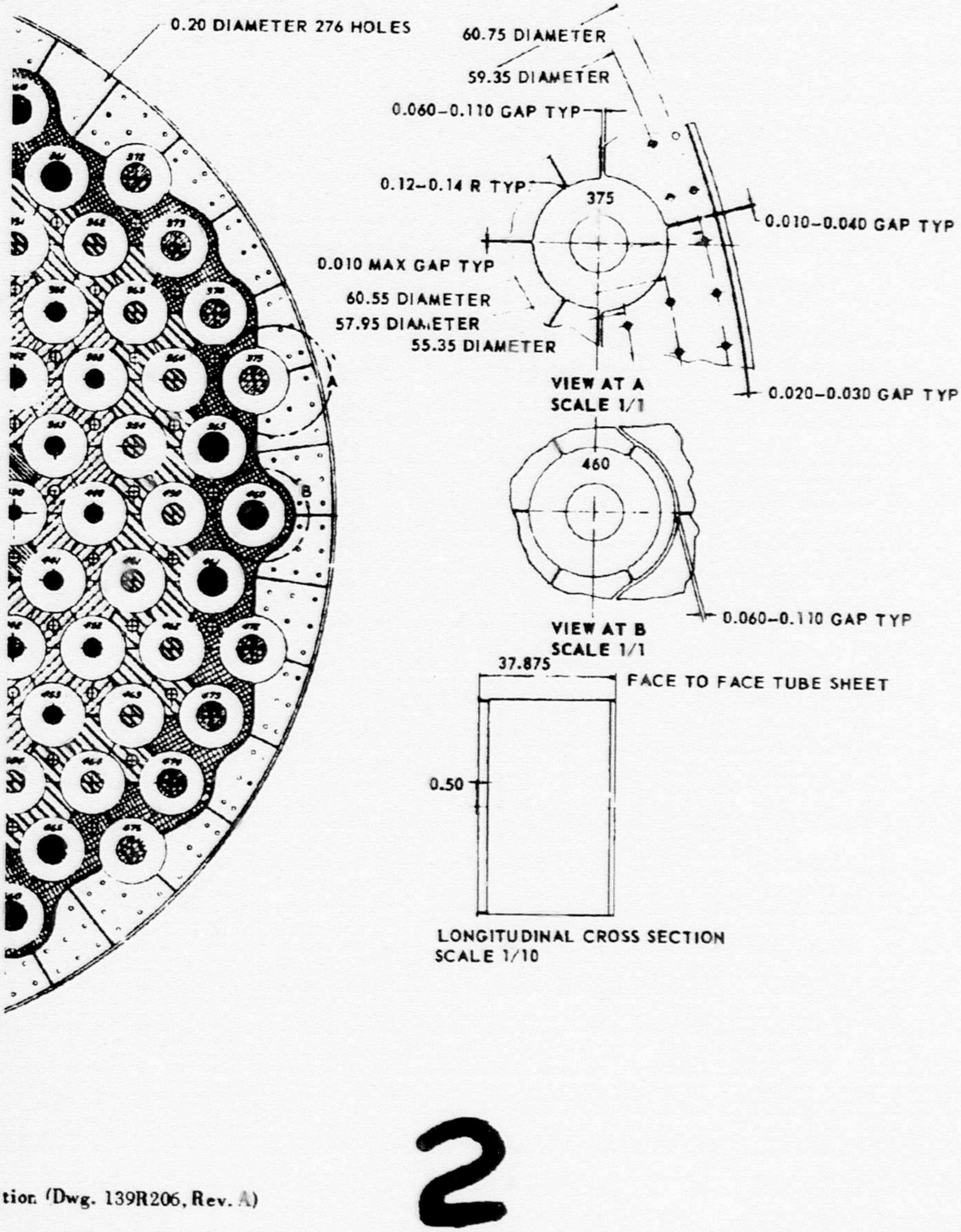

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power plant would probably have resulted in transfer of heat from the primary water system (or alternate liquid) to ram air by means of a liquid-to-air heat exchanger, or radiator. Addition of a radiator to the power plant system tends in itself to increase the power plant weight. However, air cooling of nonfueled reactor components with air from the primary turbojet cycle leads to increased reactor size and hence to increased power plant weight. A general choice of coolant for nonfueled reactor components cannot be made; it is necessary to make a choice for each power plant application with this choice being influenced by several factors, e.g., temperature of the ram air as determined by the mission requirements, temperature capability of the liquid coolant, and operating temperature limits of nonfueled reactor components. Extensive preliminary design studies led to a choice of air-cooled, nonfueled reactor components for the XMA-1 power plants. These studies were based on the HTRE No. 3 reactor test, which was a development tool for the XMA-1 system.

The XMA-1A reactor core components were air cooled like those in the HTRE No. 3 reactor, but several configuration details that influenced the thermal characteristics were different. Some of the more significant differences were:

1. The fuel element stages were 3 inches long instead of 1.5 inches to reduce effective friction factor and to reduce volume of poison material in support hardware.

2. The fuel element cartridges included a nonfueled ring to form the outer wall of the outermost annulus. By making this ring an integral part of the cartridge, it was possible to provide closer dimensional control of the annulus size than in the HTRE No. 3 design, where assembly clearances between the fuel cartridge rails and the insulation liner led to a relatively large eccentricity of the outermost annulus.

3. To reduce the maximum required fuel element temperature, the hydraulic diameters for the six rear stages were made smaller than those for the first three.

4. The number of fuel rings per stage was different for different radial regions of the core. This was the result of introducing several sizes of center moderator rods for gross radial power flattening. This introduction of central moderator rods in each cell led to a requirement for two insulation assemblies in each cell but eliminated several other problems which are discussed below.

5. The design for uniform ring-to-ring temperature distribution within a stage was achieved by varying the fuel loading. Attempts to do the same thing in HTRE No. 3 were unsuccessful because the required ring thickness for the innermost ring exceeded the fabrication capabilities. Therefore, both fuel loading and annulus size variations were required. The use of center moderator rods in the XMA-1A, by reducing the neutron flux variation and hence the required variation of ring thickness, avoided fabrication restraints and made uniform fine radial temperatures possible with fuel loading variation only.

6. The use of center moderator rods eliminated the center hole performance penalty associated with HTRE No. 3. In HTRE No. 3 the fabrication limitations fixed the minimum diameter of the smallest ring. This resulted in a center hole with a significantly larger hydraulic diameter, larger mass velocity, and lower exit-air temperature than for the annuli. Introduction of center rods in the XMA-1A resulted in a minimum required ring diameter well in excess of the fabrication limit.

7. The displacement of moderator volume from the area surrounding the fuel elements to the center rod, plus a lower moderator volume fraction than that associated with

HTRE No. 3, would have led to a hexagonal moderator design like HTRE No. 3. This would have been impractical because of the resultant thin wall thickness or web thickness. To alleviate this the triflute design was used.

There were some thermal advantages obtained from the choice of the internally cooled triflute moderator design. In the slotted hexagonal HTRE No. 3 moderator, the sink temperature for flow of heat from the fuel elements through the insulation was the moderator cooling-air temperature. For the triflute design, the sink temperature was that of the moderator itself which was higher than the coolant temperature. Therefore, for a given fuel temperature and insulation thermal resistance less heat, in addition to that generated in the moderator, was delivered to the lower temperature moderator coolant. All the wetted perimeter in the coolant channels of the triflute design was moderator heat transfer surface. In the hexagonal design only three-fourths of the wetted perimeter was heat transfer surface for the moderator.

8. The utilization of a deep forward structure section filled with loosely fitting forward reflector materials led to a thermal resistance between the reflector and the support structure that could not be accurately defined. In the final design, the reflector pieces were cooled by air flowing inside of the structure. This air subsequently was used to cool the moderator triflutes. With this series arrangement a cooling air excess was practical which reduced the criticality of cooling the component.

One of the optimizations reflected in the design point performance requirements was that of maximum power plant thrust versus fuel element heat transfer or hydraulic diameter. Heat transfer area was varied in an XMA-1A system cycle analysis[1] while holding fuel cell frontal area constant. For a fixed fuel element average maximum temperature, 1775°F, and fixed turbomachinery characteristics, the maximum power plant thrust was shown to be realizable when heat transfer area was adjusted to yield a turbine inlet temperature of 1540°F and a reactor pressure ratio of 0.77. The thrust associated with the XMA-1A design point, $T_{4.0}$, of 1500°F and reactor pressure ratio of 0.80 was within about 2 percent of the optimum value. The results of this study are shown in Figure 2.6 where net thrust, heat transfer area, fuel element hydraulic diameter, reactor pressure ratio, and system pressure ratio versus turbine inlet temperature are plotted.

These studies showed that near the design point, all other things being equal, an increase of 0.01 in reactor pressure ratio would yield a thrust increase of approximately 1.4 percent. Alternately, an increase of 10°F in turbine inlet temperature resulted in approximately 1.8 percent thrust increase. The additional parameters varied in the study were engine speed, turbine nozzle diaphragm area, and fuel element temperature. Compressor stall margins were reported as a function of turbine nozzle diaphragm areas and of fuel element heat transfer area.

3.1.3 FUEL

The XMA-1 fuel cartridge assemblies were designed as essentially right cylinders. The fuel cartridge consisted of a nose piece assembly, nine fuel elements, and a tail assembly. These components were joined together by girth-welds. A center moderator bar was mounted in the center of the assembly. The outside surface of the fuel cartridges were covered with 0.026 inch of duPont K.T. insulation having a density of 30 pounds per cubic foot and 0.005 inch of Type 310 stainless steel foil. The assembled fuel cartridge is shown in Figure 3.3. The center moderator bar is shown in Figure 3.4.

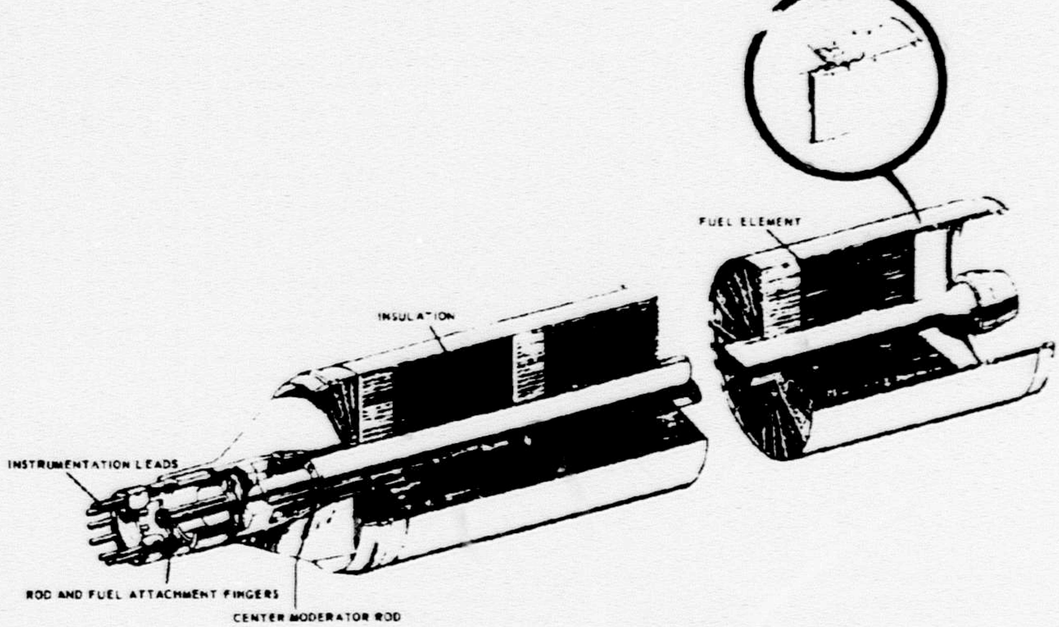

Fig. 3.3 – XMA-1A fuel cartridge (DI-37)

Fig. 3.4 – Fuel center-moderator (G-1477)

In the reactor assembly, the diameter of the center moderator bar incorporated in the fuel cartridge was varied in seven radial zones to effect gross radial power flattening. The individual fuel elements, therefore, in each zone had a different number of rings. The number of rings in the elements were also varied longitudinally to partially flatten the longitudinal temperature distribution.

The fuel cartridges were designed so that they could be remotely inserted and removed from the rear of the core. A fuel latch in the nose piece assembly was released by inserting a cartridge release rod through the center of the cartridge to actuate the latch. An instrumentation disconnect was provided on cartridges containing fuel or center moderator instrumentation to permit removal without destroying this instrumentation.

The total fuel content for the core was 500 pounds of uranium-235, in the form of fully enriched uranium dioxide, contained in an 80Ni - 20Cr alloy. The weight fraction of the UO_2 in this mixture varied from 0.42 to 0.27. As noted above, the front three stages of the core had a loading 1.5 times the average, the fourth and fifth stages had a loading of 0.9 times the average. Both of these variations were to allow the core to operate more isothermally. Provision was made for boron steel strips to be placed along the outside of the fuel support tube for the purpose of fine power shimming.

3.1.4 MODERATOR

The moderator sections for the XMA-1 core were designed as unclad zirconium hydride triflutes. The sections were pierced longitudinally by cooling passages to provide heat removal during operation. On the outer periphery, the triflute shapes were altered to partial triflutes and segmented to meet the minimum reflector material requirements and to permit the reflector to take a reasonable shape for manufacture. There were approximately two triflutes per cell in the core. The core was divided into three sections for the outer moderators, based on the porosity of the triflutes that was set by the radial temperature profile.

A complete triflute-moderator assembly is shown in Figure 3.5.

In the core assembly, the moderator cooling air passed through a series of four holes per section in the front tube sheet, through the cooling holes in the triflutes, and exhausted to a plenum area formed by the rear tube sheet and the end of the triflutes. The air from the rear plenum area was exhausted through a series of annular ducts formed between the rear tube sheet and the moderator support tube.

The moderator assemblies consisted of six full triflutes; or two full triflutes, two partial triflutes, and two arch segments clustered around a single support tube. There were 55 assemblies of this type in the core. Due to the core geometry, there were six assemblies of the arch segment assembled to the support tube and six assemblies of an arch segment and partial triflute assembled to a support tube respectively. The remaining cells were free tubes which supported the triflutes during operation but did not have moderators attached to them. The assemblies were designed to be remotely removed from the core.

To provide the moderator volume fractions required by the XMA-1A core specifications, extremely close tolerances were maintained in the design of the individual components and assemblies.

3.1.5 CONTROL RODS

In considering the problems of (1) nonuniform heating and/or cooling in the reactor control rod and (2) control rod guide tube deflection and distortion, a rod design was conceived that would move freely in a distorted guide tube even though it too was distorted.

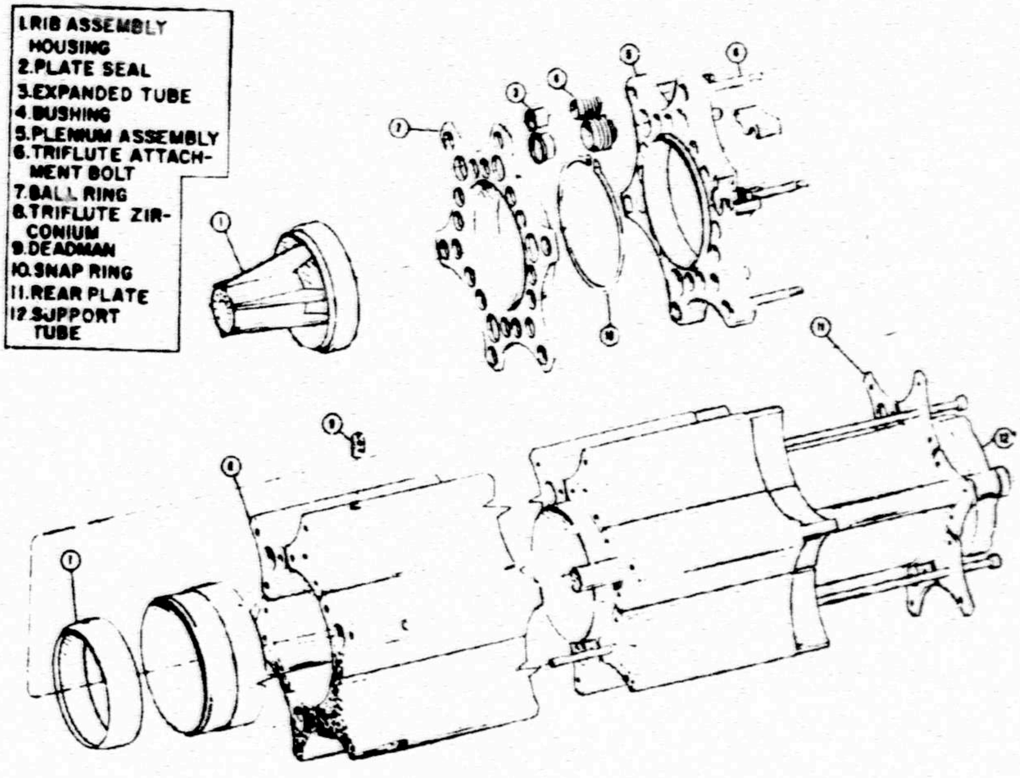

Fig. 3.5 – Triflute-moderator assembly (Dwg. G1472)

In this design, the length of a unit of poison-matrix clad assembly was limited to reduce the lever arm magnification of a local distortion that would occur in a long rod. Several of the short units were joined to form a flexible linkage of the required poison rod length. This design is shown in Figure 3.6.

The individual segments of the control rod were joined by straps, which act as flexing beams, and rigid columns to permit the rod to follow a misaligned and/or distorted guide tube with positive, slackless movement in an axial direction. Space between the poison capsules and their connecting straps were provided so that the individual segments could distort in any direction without affecting the rod as a whole. Further details on the design and development of the XMA-1 control rods are given in reference 2.

3.1.6 SIDE REFLECTOR

The XMA-1 side reflector was designed to be fabricated from unclad, reactor-grade beryllium. As shown in Figure 3.7, the reflector was constructed of 84 separate blocks for structural stability. Each block was supported by two bolts, one of standard design and one a special swinging type. The latter allowed for differential thermal expansion between the reflector material and the supporting shell. Each reflector block was internally cooled by the air that passed through longitudinal holes.

The reflector shell was a one-piece right circular cylinder with support flanges at each end. The shell was designed to cantilever from the forward tube sheet and thus support the aft tube sheet and side reflector. It also provided the air seal for the shell coolant and core void. The shell was fabricated from aged Inconel X for operation at a temperature of 1100°F.

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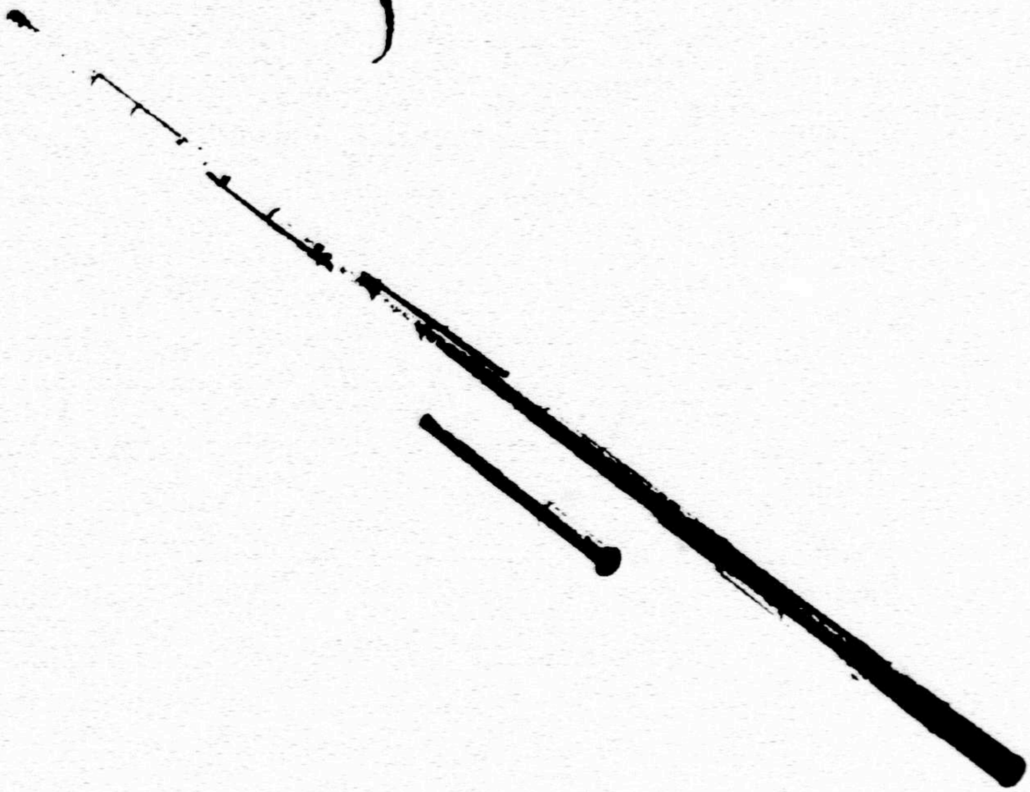

Fig. 3.6 – Control rod (Neg. U37171)

3.1.7 FORWARD TUBE SHEET

The purpose of the forward tube sheet was to provide a supporting structure for all core components against drag, acceleration loads, and shear loads. After several design studies, a two-plate construction separated by some type of webbing to transmit shear was selected. The final decision was to use tubes between the plates as the structural spacers, one being located at each control rod location and one at each similar location having no control rod. The two-plate design permitted beryllium metal blocks to be installed between the plates; this acted as a front reflector.

During the investigation of manufacturing methods for the structure, considerable difficulty was encountered in finding a method for joining the spacer tubes to the structural plates. Various welding techniques were investigated in detail; although some proved feasible they were very costly and time-consuming. Therefore, a mechanical means for making the tube-to-plate connection was selected. The final design layout of the forward tube sheet is shown in Figure 3.8.

3.1.8 REAR TUBE SHEET

The rear tube sheet was Inconel X plate, 0.500-inch thick, having a reinforced outside perimeter for high temperature operation. It was keyed to the reflector shell and supported by approximately one-half the control rod guide tubes. The tube sheet was capable of supporting the in-plane loads only on the aft end of the moderator support tubes. Loads normal to the structure were supported by guide tubes and the reflector shell flange. In-plane loads were transmitted through the shell to the forward grate. The final configuration of the rear tube sheet is shown in Figure 3.9.

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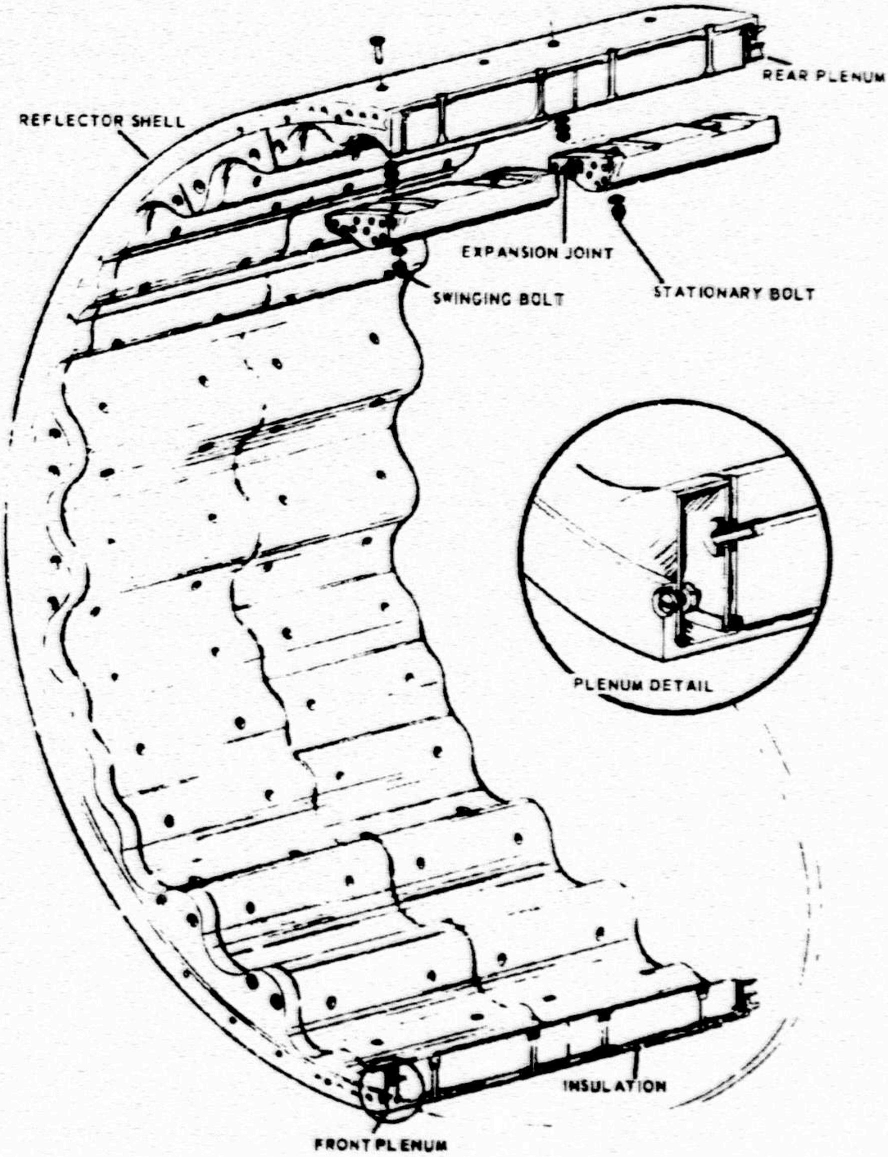

Fig. 3.7 – Reflector ass[illegible] (Dwg. G-1480)

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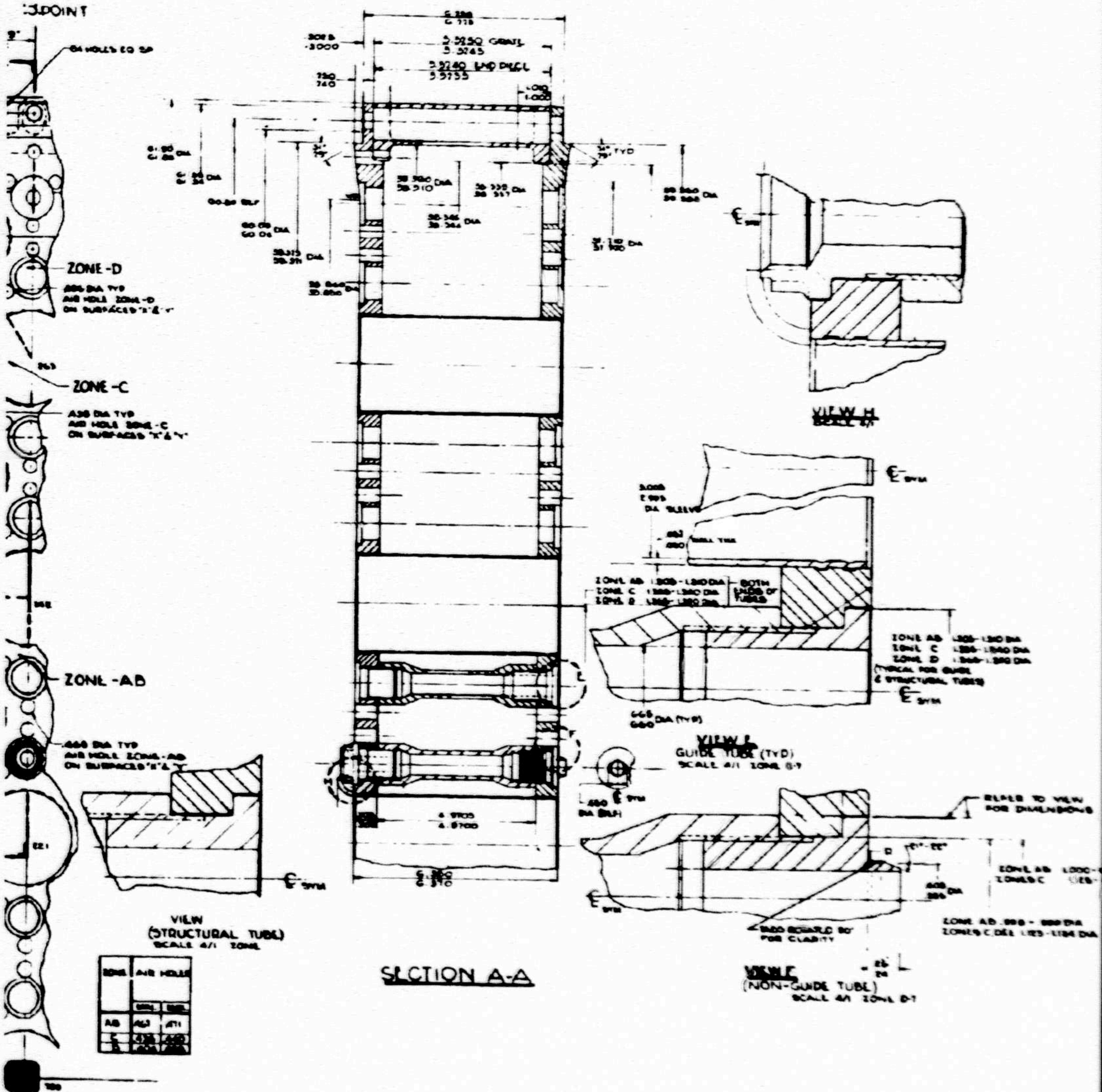

tube assy (Dwg. 195R705)

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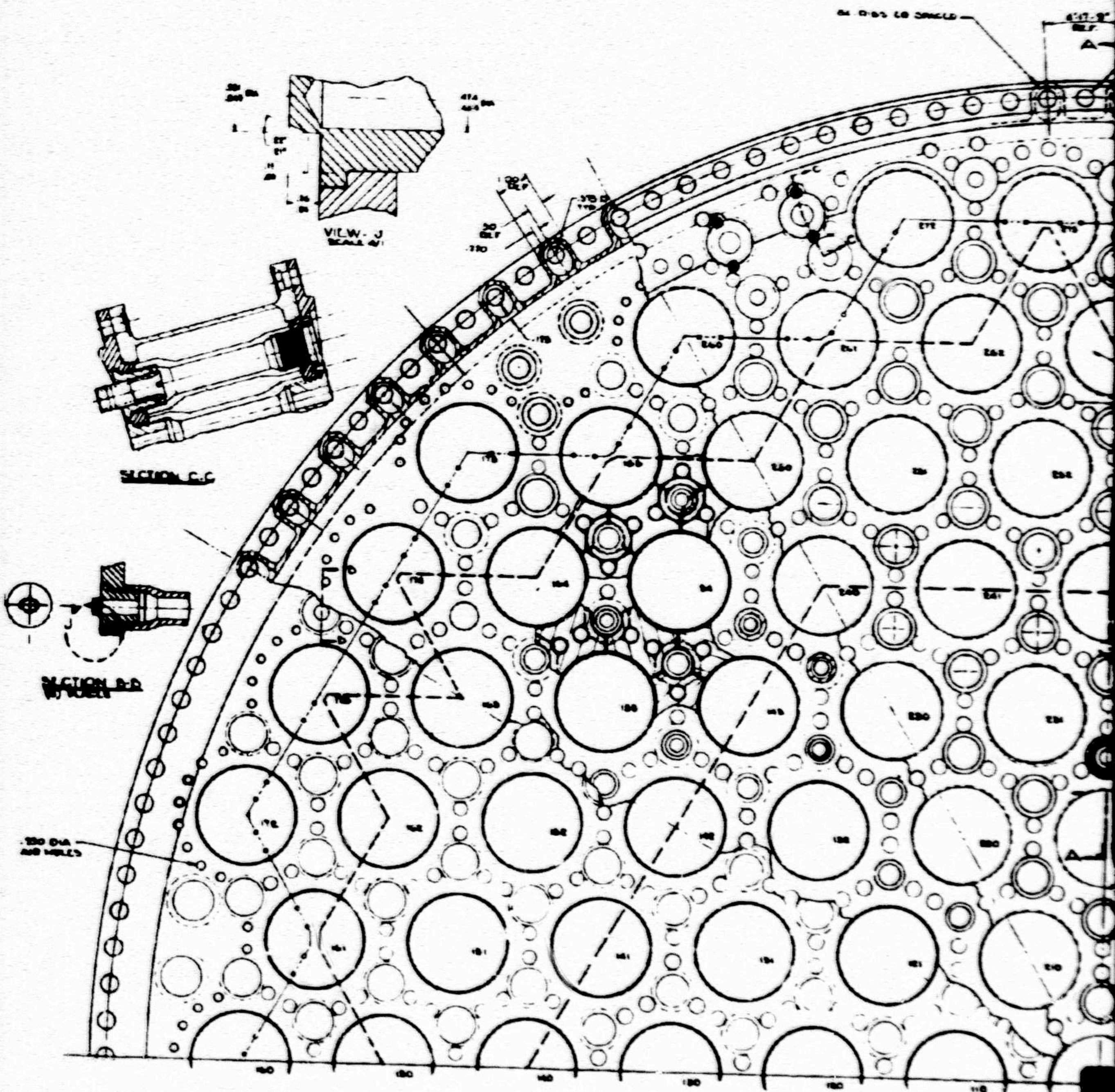

Fig. 3.8 – F[illegible]ward tub

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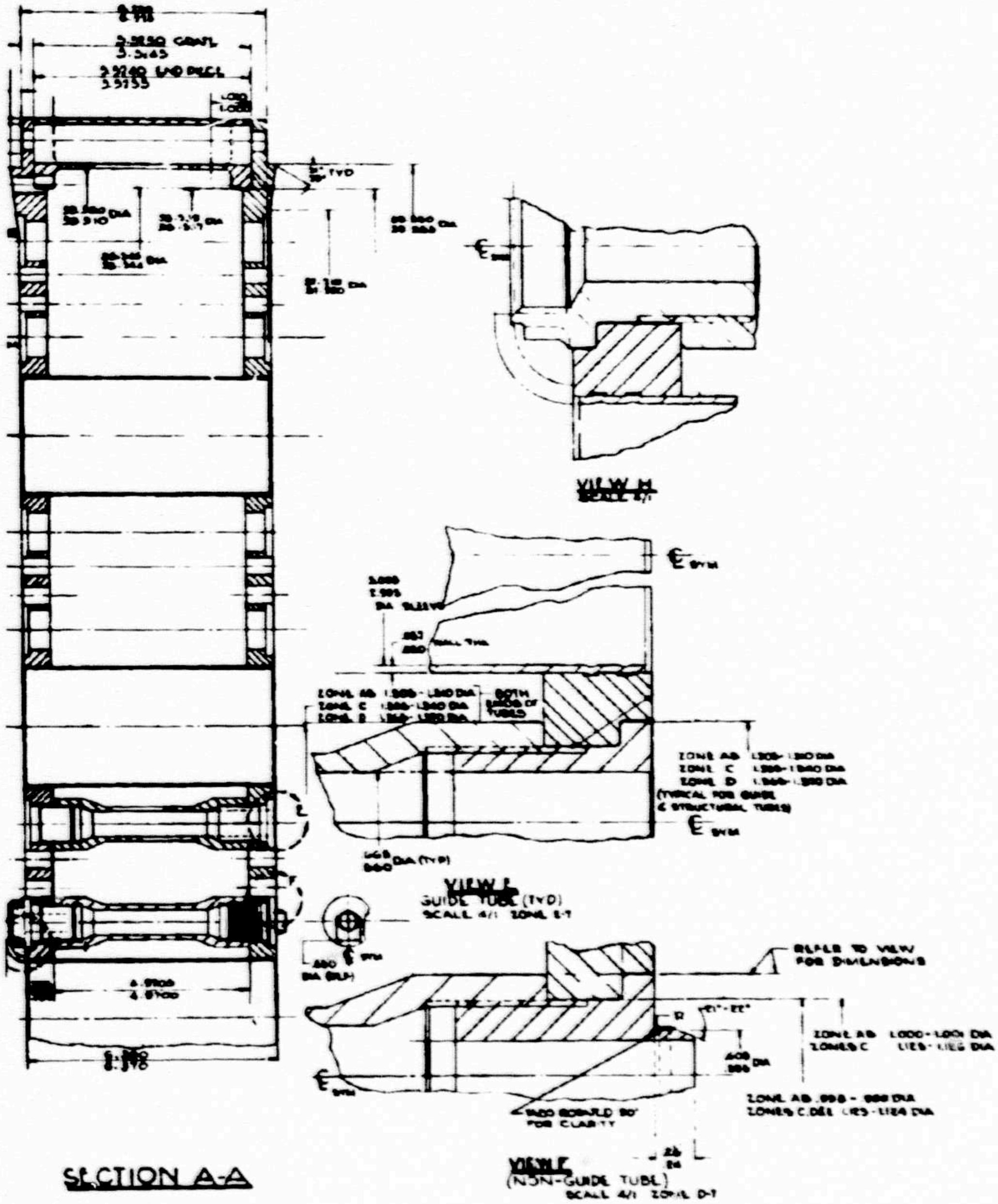
SECTION A-A
VIEW H
VIEW E
GUIDE TUBE (TYP)
REFER TO VIEW
FOR DIMENSIONS
VIEW F
(NON-GUIDE TUBE)

3

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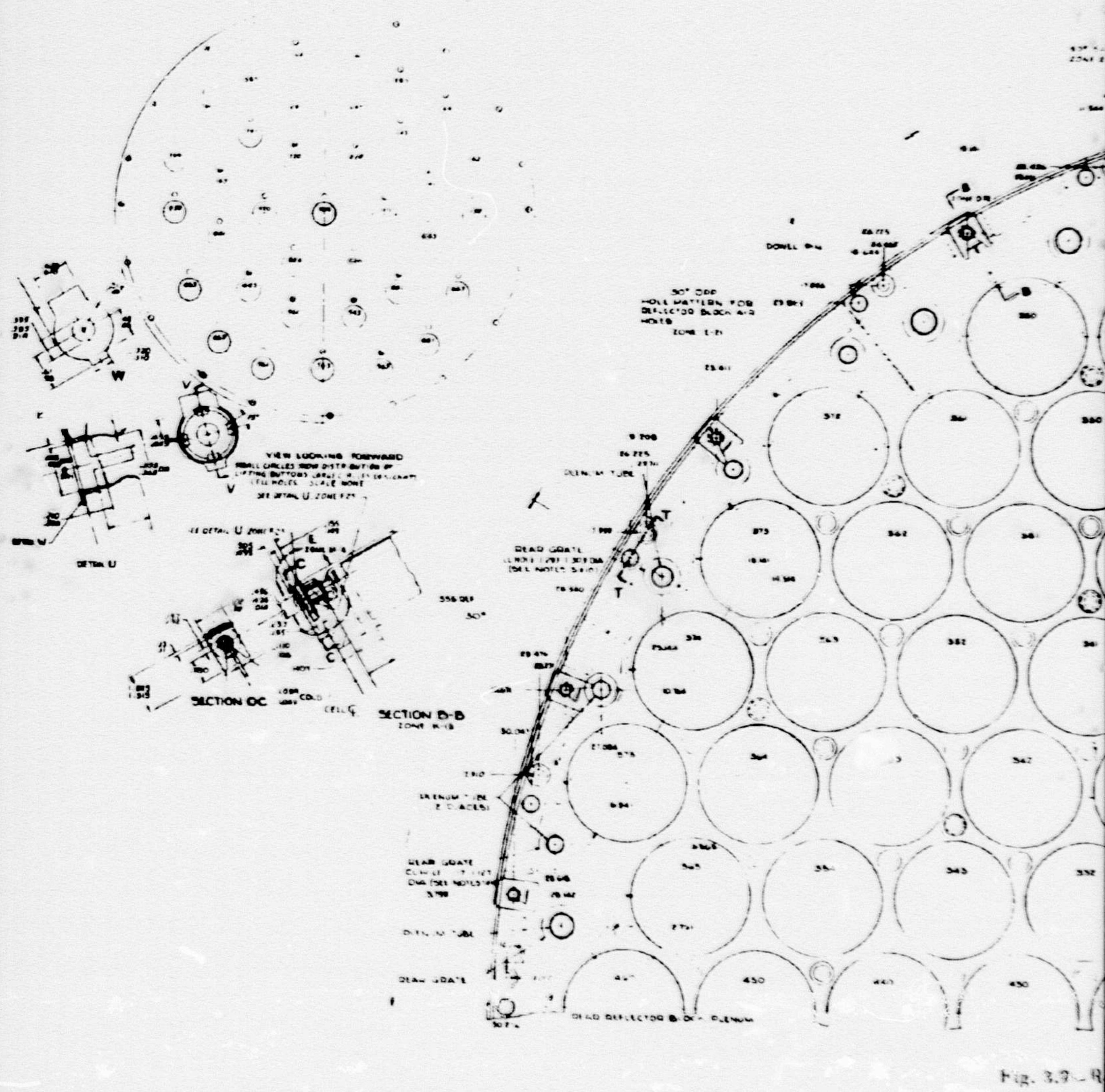
VIEW LOOKING FORWARD
DETAIL U
SECTION C-C
SECTION B-B
DOWEL
PLENUM TUBE
REAR GRATE
REAR REFLECTOR BLOCK PLENUM

Fig. 3.9—R

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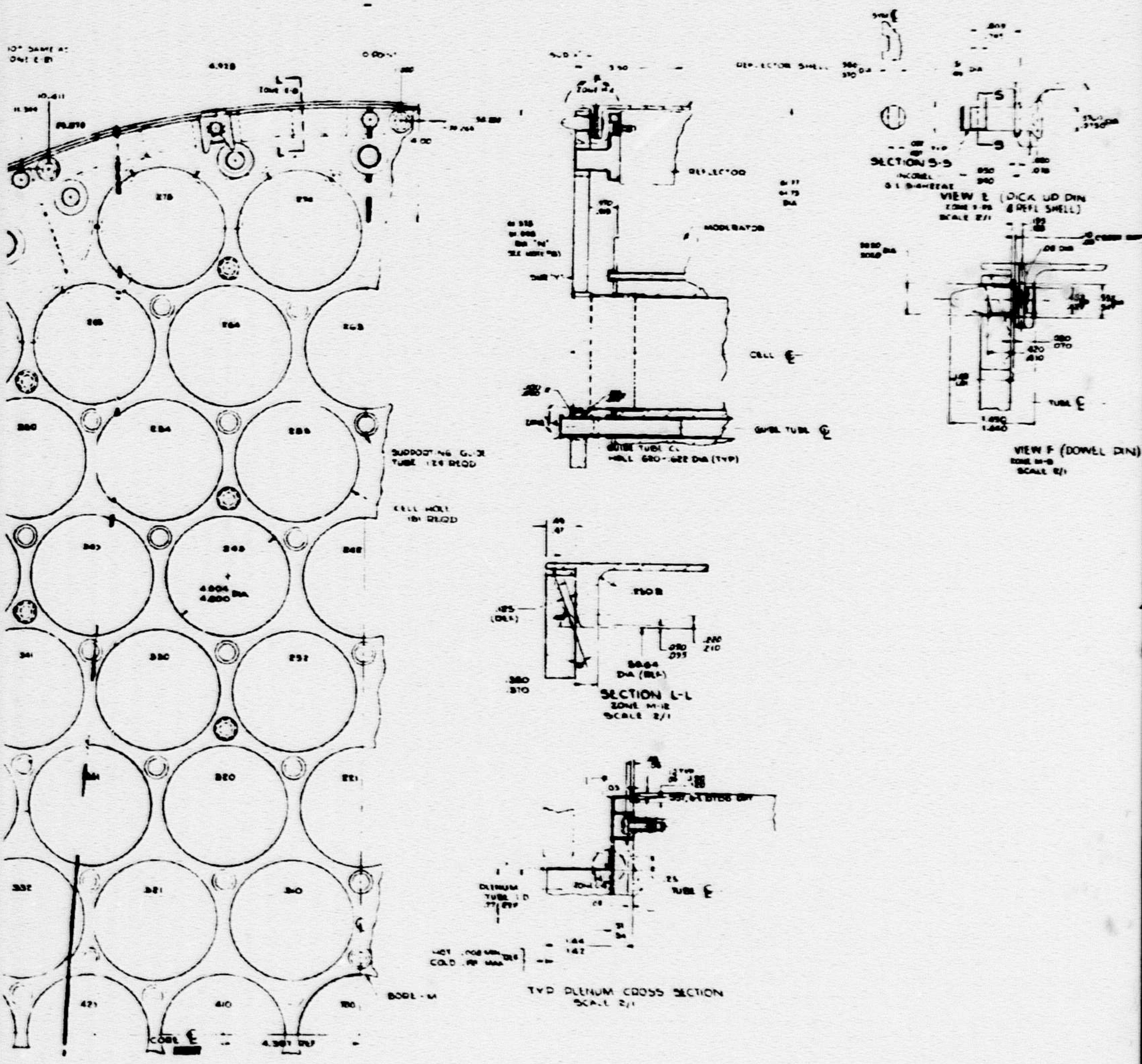

)– Rear tube sheet (139R284)

2

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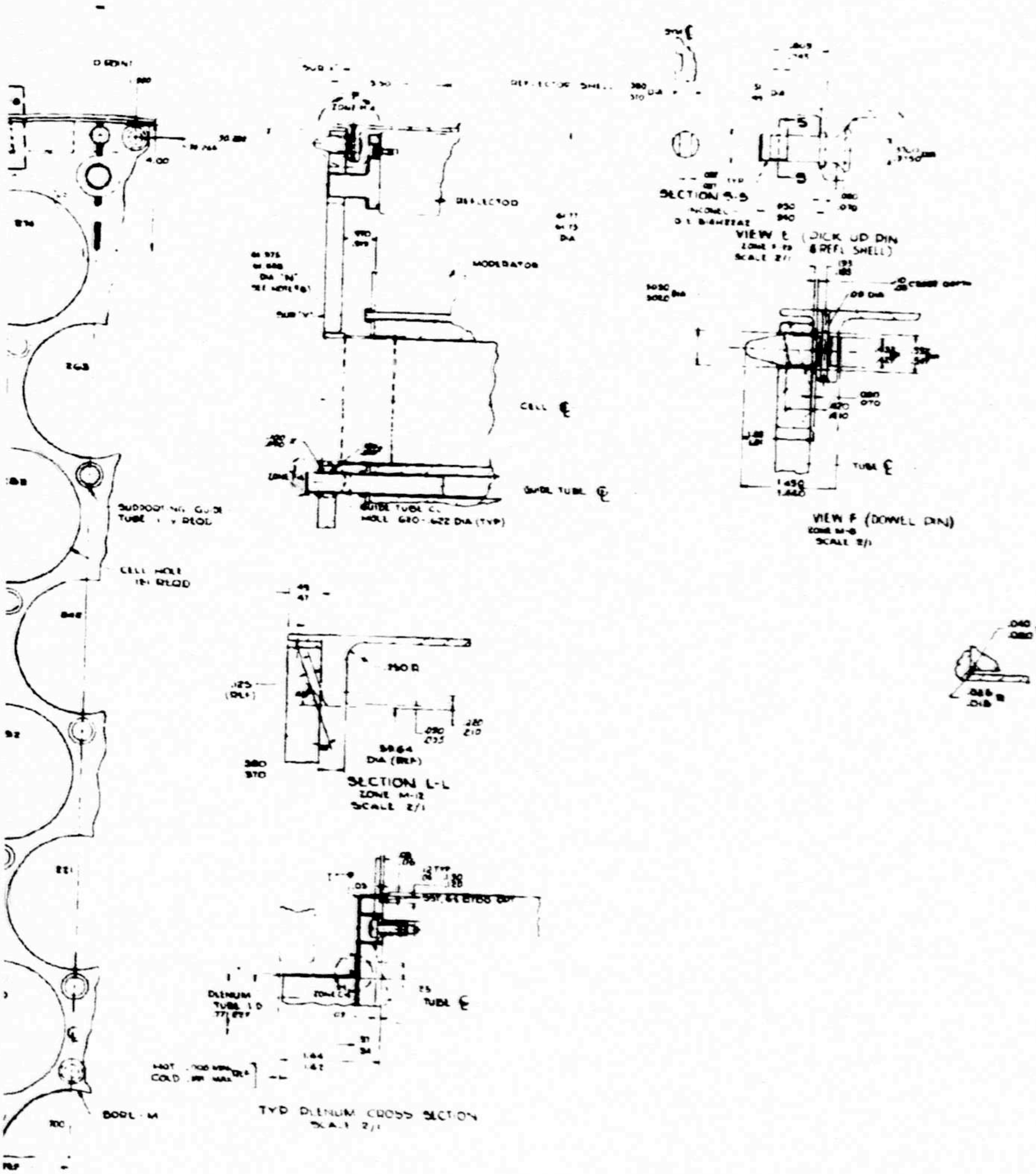
REFLECTOR SHELL
REFLECTOR
MODERATOR
CELL ℄
GUIDE TUBE ℄
SECTION S-S
VIEW E (PICK UP PIN & REFL SHELL)
VIEW F (DOWEL PIN)
SCALE 2/1
TUBE ℄
CELL HOLE IN PLUG
SECTION L-L
ZONE M-12
SCALE 2/1
TYP PLENUM CROSS SECTION
SCALE 2/1

3

1

3.1.9 CONTROL ROD GUIDE TUBE

The control rod guide tube provided a means for supporting and guiding the control rod within the reactor core. This component also carried axial loads from the rear tube sheet.

The assembled core contained 129 guide tubes having an inside diameter of 0.54 inch and an outside diameter of 0.60 inch. The tubes were constructed of Inconel X with chrome plate on the bore to reduce the friction between the control rod and guide tube during operation. Each guide tube was fixed to the front tube sheet by a friction latching device. One hundred twenty-two guide tubes were double flanged at the rear end to carry the axial loads of the rear tube sheet and provided a means to remotely disassemble these components from the core. The control rod installation can be seen in the XMA-1A cell sketch Figure 3.10.

3.1.10 BELLMOUTH

The bellmouth acted as an air guide for airflow entering into the fuel cartridge. It also served as (1) a cover for instrumentation which was routed across the top of the forward tube sheet and (2) a housing for the instrumentation disconnects and fuel cartridge latching mechanism. There were 151 bellmouths positioned on the upstream face of the forward tube sheet of the XMA-1 core, one at each fuel cartridge inlet. The bellmouth is shown in Figure 3.10.

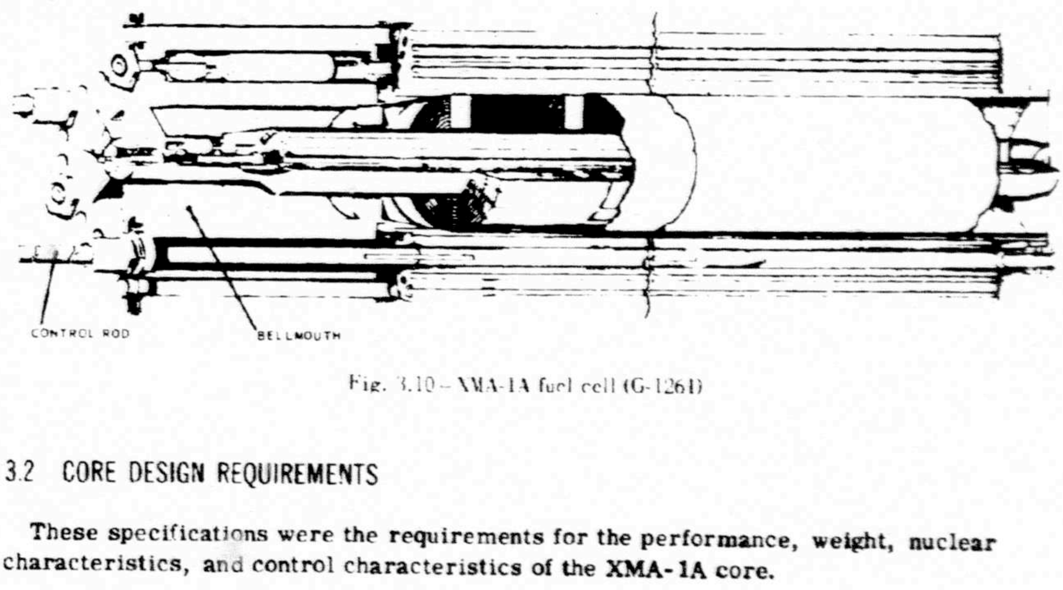

Fig. 3.10 – XMA-1A fuel cell (G-1261)

3.2 CORE DESIGN REQUIREMENTS

These specifications were the requirements for the performance, weight, nuclear characteristics, and control characteristics of the XMA-1A core.

For the purpose of these specifications, the core consisted of all the fixed hardware inside of and including the structural cylinder surrounding the reflector. This included tube sheets, flange and captive bolts for attachment to front shield plug, core inlet assemblies, instrumentation, and disconnects. Also included were the poison sections of the control rods. The core rear-plug seal was not considered in these specifications.

3.2.1 OVER-ALL PERFORMANCE REQUIREMENTS

Minimum core performance requirements at any time during the operating life of the power plant are given in Table 3.1 for the design points of Mach 0.6, 10,000 feet altitude and for the performance verification condition of ITS static, both for standard day and 100 percent inlet pressure recovery with operation at 95 percent engine speed (4750 rpm).

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TABLE 3.1

MINIMUM CORE PERFORMANCE REQUIREMENTS[a]

Core Variables	Conditions: ITS Static 5000 ft	Conditions: Mach 0.6, 10,000 ft
P_{t2} Compressor inlet total pressure, psia	12.2	12.9
T_{t2} Compressor inlet total temperature, °F	41	58
$P_{t3.2}$ Total pressure immediately upstream of bellmouth entry into reactor core, psia	144	144
$P_{t3.4}$ Total pressure at exit from reactor core does not include dumping losses, psia	115	115
$T_{t3.2}$ Total temperature at entrance to reactor core, °F	640	655
$T_{t3.4}$ Total temperature at exit from reactor core, assuming complete mixing of air streams from moderator, fuel elements, control rods, reflector, etc., °F	1500	1500
W_a Total airflow through core components, including reflector, lb/sec	630	642

[a]These performance requirements represented the minimum acceptable level. Deviations from nominal performance had to be anticipated and used in establishing the core design objectives.

3.2.1.1 Reactivity Requirements

The reactivity shall be sufficient for startup and operation within 1 hour after shutdown, following operation at 150 megawatts of power and after 20,000 megawatt-hours of operation. The system must be capable of startup with core temperatures 60°F to operating temperatures.

3.2.1.2 Performance Design Point

Performance of the core shall be optimized for military power, 95 percent engine speed on nuclear heat source at Mach 0.6, 10,000 feet, standard day.

3.2.1.3 Performance Verification Point

Performance of the core shall be verified at military power, 95 percent engine speed on nuclear heat source at ITS static, 5000 feet, standard day.

3.2.1.4 Structural Design Points

The core shall be designed to maintain structural integrity and full operability at the following structural design points:

	Point No. 1	Point No. 2	Point No. 3
Altitude	5000 ft	6000 ft	Sea level
Mach number	0	0.6	0
Engine speed, rpm	4750	4750	4750
T_2, °F	-40	+20	100
P_2, psia	12.2	15	15
$P_{3.2}$, psia	190	198	153
$T_{3.2}$, °F	560	640	700
$W_{a3.2}$, lb/sec	790	835	650
$T_{3.4}$, °F	1500	1500	1500
$P_{3.4}$, psia	152	158	122

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3.2.1.5 Reduced Power Design Point

The core shall perform and operate satisfactorily at the following condition over an extended period of time:

Altitude, ft	5000
Mach number	0
Engine speed, rpm	4650
T_2, °F	41
P_2, psia	12.2
$P_{3.2}$, psia	144
$T_{3.2}$, °F	620
$W_{a3.2}$, lb/sec	615
$T_{3.4}$, °F	1450
$P_{3.4}$, psia	115

3.2.1.6 Life Profile

The core shall operate and perform satisfactorily for the combination of the following operating times and conditions:

1. 20 hours at the performance design point.
2. 10 hours at the performance verification point.
3. 10 hours at structural design point No. 1.
4. 5 hours at structural design point No. 2.
5. 5 hours at structural design point No. 3.
6. 100 hours at the reduced power design point.

3.2.1.7 Transient Conditions

The reactor will be capable of withstanding, without damage, the transient conditions imposed by a scram.

3.2.1.8 Loading Criteria

The loading criteria for the reactor structure (tube sheets and shell) should be no less severe than those for the power plant requirements as described in section 2.1.5.

3.2.1.9 Limiting Surface Temperatures

The temperature of the reactor outer shell will be limited to a maximum of 1200°F.

3.2.1.10 Fuel-Air Velocity and Pressure

Fuel tube mass-velocity variation caused by flow characteristics external to the core shall not exceed 6 percent from the average.

3.2.1.11 Control System

The control system, consisting of the dynamic system, shim-scram system, and the source, shall have the following operational requirements:

1. The control system shall be capable of increasing power from idle to military in 1 minute.
2. The reactor core shall be capable of withstanding 100 scrams from any operating level.
3. The maximum friction load allowable is 15 pounds per rod.
4. The core structure shall be capable of withstanding a load of 1100 pounds applied to any single rod if it is the only one frozen, and up to a maximum of 3300 pounds total applied to the core. This 1100 pound maximum load per rod can be applied with any

distribution possible among the rods. These loads are in addition to the friction load imposed by the rods not frozen.

5. The travel life required of the control rod bearing is 60,000 feet of motion.

3.2.1.12 Structure Temperatures

1. The front tube sheet maximum temperature shall not exceed 1000°F.
2. The rear tube sheet maximum temperature shall not exceed 1500°F.
3. The maximum temperature of the rear flange face of the front shield plug shall not exceed 1000°F.

3.2.1.13 Remote Handling

The design remote handling requirements are described below.

Core Assembly - The core assembly shall be capable of being remotely removed and assembled from the front plug and side shield. The thermocouple instrumentation shall be remotely disconnected.

Fuel Cartridges - The fuel cartridges shall be capable of being remotely removed and inserted, including the center moderator rod and insulation, from the core. The instrumentation shall be remotely disconnected to allow cartridge removal.

Moderator Assembly - The moderator assembly shall be capable of being remotely removed and inserted from the core. The instrumentation shall be remotely disconnected to allow moderator removal. The flow orifices shall be remotely adjustable.

Reflector Assembly - The reflector assembly shall be manually removed and inserted. The flow orifices shall be remotely adjustable.

Control Rods - The control rods shall be capable of being remotely removed and inserted from the core and front plug. The poison tips shall be remotely removed from the extension rod. The guide tubes and instrumentation shall be manually removed and installed. The flow orifices shall be remotely adjustable.

Front Tube Sheet - The front tube sheet shall be manually removed and assembled.

Rear Tube Sheet - The rear tube sheet shall be capable of being remotely removed and assembled.

3.2.1.14 Configuration, Dimensions, and Weight

The core shall have: (1) a maximum weight (excluding the rear plug seal) of 11,980 pounds, (2) a right cylinder shape, (3) an over-all core length of 38.5 inches, (4) an outside diameter of 61.953 inches at maximum room temperature, (5) 151 fuel cells with a center-to-center distance of 4.387 inches, and (6) it shall be supported by a flange connected to the forward shield plug.

3.2.2 COMPONENT DESIGN SPECIFICATIONS

3.2.2.1 Fuel

The fuel requirements were as follows:

1. The longitudinal power distribution, fine and gross radial power flattening, and circumferential power scalloping shall be limited. The summation of heat added in a hot sector plus heat flux at a critical point in a fuel element sector shall not exceed 8 percent above the average. The total tube power shall not be greater than 5 percent below the average.
2. The fuel loading (UO_2) may be varied to ±5 percent, or the fuel plate thickness may be varied for adjustment of fine radial power, and for fine adjustment of gross radial power.

3. The maximum average fuel plate temperature shall be 1800°F. The maximum hot spot temperature shall not exceed 2020°F.
4. The gap-width tolerances, hot and cold, shall be held to a maximum of 20 percent under nominal. The total sum of under nominal gap widths in any one ansector shall not exceed 60 percent.
5. The fuel tube friction factor multiplier shall be 1.5 times a rough pipe.
6. The heat loss from fuel outer rings to moderator shall not be greater than 5 percent of moderator total heat load.

3.2.2.2 Moderator

The moderator requirements were as follows:

1. The local volumetric heating rates shall be within ±15 percent of that predicted.
2. The moderator volume fraction shall be the basic variable for adjusting gross radial power distribution.
3. The moderator N_H range may be varied for fine adjustment of power distribution as a last resort.
4. The moderator hydrogen loss shall not exceed 5 percent for 100 hours operation at maximum power.
5. The moderator hydrogen migration shall not perturb fuel element power above the limits specified under fuel specifications.
6. At the maximum temperature region in the moderator, the maximum temperature shall not exceed 1250°F and the minimum internal temperature shall not be less than 1100°F.
7. The variation in heat transfer coefficient will be assumed to be ±10 percent of the nominal predicted value.
8. The internal temperature rise from surface to maximum shall not exceed 30°F.
9. The moderator hydraulic diameter tolerances, hot and cold, shall not exceed ±3 percent.
10. The inlet and exit pressure losses (excluding orifice loss) shall not exceed 20 percent of the total moderator pressure loss.
11. The moderator orifices must permit adjustment after power operation.
12. The free flow area, hot and cold, shall be sized for a flow 15 percent above nominal.
13. The leakage past the moderators shall not exceed 0.5 percent of the total reactor flow.
14. Oxidation shall not increase total moderator pressure drop more than 5 percent.
15. The moderator erosion shall not exceed 1 percent of the total moderator volume after 100 hours of operation.
16. The surface area shall not vary more than ±3 percent from nominal.

3.2.2.3 Control System

The control system specifications were as follows:

1. The maximum surface hot-spot temperature of the poison tip shall be 1650°F. The maximum average temperature shall be 1500°F.
2. The maximum guide tube hot-spot temperature shall be 1250°F.
3. The cooling air weight flow shall not exceed 20 percent above nominal.
4. The flow area shall not exceed 5 percent under nominal.
5. The orifices shall be adjustable, following power tests.
6. An intimate contact between the poison core and clad shall be required for good thermal conductivity.
7. Oxidation shall not increase the total pressure drop by more than 5 percent.

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3.2.2.4 Reflector

The specifications for the reflector were as follows:

1. At the maximum temperature region in the reflector, the maximum temperature shall not exceed 1200°F and the minimum temperature shall not be less than 1000°F. The maximum internal temperature rise shall be 50°F.
2. The cooling air weight flow, for operation, shall not exceed 20 percent above nominal.
3. The cooling hole size tolerances, hot and cold, shall not exceed ±3 percent of nominal.
4. The inlet and exit configuration losses, excluding orifice losses, shall not exceed 25 percent of the total core.
5. The orifices shall be adjustable after power tests.
6. The free flow area, hot and cold, shall not exceed ± 5 percent of nominal.
7. The heat transfer surface area shall not exceed ± 5 percent of nominal.
8. Leakage past the reflector shall not exceed 0.1 percent of the total core flow.
9. Erosion shall not exceed 1 percent of the total reflector volume.

3.2.2.5 Structure

The structure specifications were:

1. The front tube sheet maximum allowable temperature shall be 1000°F. The gross radial temperature difference shall not exceed 200°F. The local temperature gradient shall not exceed 10°F per inch. For a split tube sheet design, the difference in temperature from one sheet to the other shall not exceed 100°F.
2. The rear tube sheet maximum temperature, at any point, shall not exceed 1500°F. The gross radial temperature difference shall not exceed 200°F. The local temperature gradient shall not exceed 10°F per inch. The maximum pressure drop shall not exceed 2 pounds per square inch.

3.3 NUCLEAR DESIGN

This section presents the nuclear design of the XMA-1A reactor. It includes a description of the reactor, nuclear representation, pertinent analysis work, and a discussion of the expected differences between the XMA-1A and the final critical experiment, the Advanced Solid Moderator Reactor Experiment No. 3 (ASM-III).

3.3.1 HISTORY OF THE DESIGN SEQUENCE

The design sequence of the XMA-1A represented a series of compromises between the nuclear, mechanical, and thermodynamic requirements. Because of this, and also because of the information obtained from the ASM critical experiment, the design evolved from its preliminary form into the final design presented in this report.

As originally conceived, the XMA-1A reactor had an active core length of 30 inches, four radial regions, a uniform longitudinal fuel loading of 400 pounds of uranium-235, a solid forward tube sheet (about 3 inches thick), and control rods in the center of each fuel cell. The core diameter and over-all length was fixed by the size of the radial shield. The first major change involved moving the control rods to the triflutes and fixing their number, size, and mode of operation. This was done early in 1958 and remained fixed throughout the design. A study was then initiated to investigate the longitudinal power profile. This resulted in a redistribution of fuel longitudinally to shift the power forward in the core. The new design also incorporated a divided forward tube sheet containing beryllium reflec-

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tor material between the two sections. With the redistribution of fuel, the active core length became 27.5 inches. In addition, the number of radial fuel cell types was increased from four to seven and preliminary values of moderator porosity were established.

Critical experiment measurements were performed. The results indicated that the reactivity of the system and the longitudinal power distribution were unsatisfactory, due to the effect of the shields. To correct this the fuel loading was increased and redistributed. The new, and final, loading was 500 pounds of uranium-235 with a larger loading in the forward end. This was the last gross change in the reactor, and at this point the fuel element fine structure design was started.

During this period, minor changes were evaluated as they occurred. Typical changes which occurred were (1) a change in insulation from Thermoflex (a mixture of aluminum and silicon dioxide) to duPont K. T. (pure potassium titanate), (2) a gradual reduction in the side reflector due to mechanical and thermodynamic requirements, and (3) the removal of beryllium from the center bar extensions.

3.3.2 NUCLEAR REPRESENTATION AND METHODS OF ANALYSIS

Most of the analysis on the XMA-1A reactor was performed using IBM 704 digital computer Programs GEORGE[3] and G-2.[4] These programs required that an analytic model of the reactor be constructed. This model was constructed by reducing the three-dimensional geometry of the actual reactor to a set of one-dimensional representations. This required a set of homogenized regions in which the fine structure and perpendicular material variations were taken into account.

In the fueled core, five different radial regions were used to account for the variation in fuel and moderator concentrations; three longitudinal regions were used to account for the fuel loading variation.

3.3.3 REACTIVITY ANALYSIS

The XMA-1A reactivity prediction is presented in Table 3.2. These values were based on the information derived from the three critical experiments conducted, ASM-I, -II, and -III.

3.3.3.1 Required Reactivity

The estimated required reactivity for the XMA-1A reactor is shown in Table 3.3. The total reactivity required was based on the combination of a number of unrelated items, each with an estimated uncertainty. These uncertainties were estimates of the reliability of the various requirements and were considered to be, very approximately, the limit of about 70 perc... confidence. These values were then combined just as though they were statistically meaningful, a process which was theoretically incorrect but nevertheless useful. This gave a total net change from a cold, clean condition to a hot, dirty one with an assigned uncertainty of about 30 percent. This uncertainty was added to the total value to give the probable maximum expected change, -6.1 percent $\Delta k/k$. It was expected that this value would have about an 85 percent confidence limit of being sufficient for the core life required.

3.3.3.2 Xenon-135 Override Requirement

The basic requirement on the XMA-1A with respect to xenon-135 was the reactor could be started 1 hour after shutdown, after reaching equilibrium.

The following sequence was followed to find this effect: A Program GEORGE cross match was run at 1000°F to determine the base reactivity at operating temperature. Program G-2 cases were then run, using the savings found from the GEORGE case, in both

TABLE 3.2

REACTIVITY PREDICTION OF THE XMA-1A DESIGN

	$\Delta k/k$, %
ASM-III D reactivity	8.63
N_H difference	-0.4
Boration of radial shield compared to boral plug steel shield of the ASM-III	-0.2[a]
LiH radial shield	+0.2[a]
Inconel X in support and guide tubes	-0.2
Increased thickness of center moderator support ring	-0.4
Foil and insulation	-0.3
Front plug discrepancy (maximum)	-0.4
Difference in front reflector	+0.2
Reduced Be radial reflector	-0.2[a]
Excess reactivity	7.73

[a]Analytical value.

TABLE 3.3

REQUIRED EXCESS REACTIVITY

Requirement	Change From Cold-Clean, $\Delta k/k$, %
Xenon-135 override, 1 hour after shutdown after reaching equilibrium and at 500°F	-2.8 ± 1.0
Hydrogen loss, 6.4 percent after 100 hours operation at 150 mw	-1.8 ± 1.0
Temperature, 68° to 1000°F (moderator)	+0.5 ± 0.5
Fuel burnup, 21,640 mw hours	(negligible)
Fission product poisoning, stable and transient, excluding xenon-135	-0.5 ± 0.3
Net change, cold-clean to hot-dirty	-4.6 ± 1.5
Probable maximum expected change	-6.1
Allowance for the addition of boron liners	-1.5
Total change from cold-clean	-7.6
Required excess reactivity	+7.6

the radial and longitudinal directions at 1000°F. This gave the flux distribution and magnitude in each longitudinal stage, nine in all, and in each radial region, five in all. Using a digital computer program written for this purpose, the concentration of xenon-135 in each region was found as a function of time. This procedure accounted for the difference in flux spectrum and power level in each region of the core and would be more accurate than a calculation for a homogeneous core. These xenon-135 concentrations were placed in the Program GEORGE and the cross match re-run, both at 1000°F and at 500°F; this latter temperature was assumed to be a reasonable value for the moderator 1 hour after shutdown. To compensate for the change due to the xenon-135 being produced solely in the fuel, the cases used cell corrections at three levels.

The change in reactivity between a 1000°F clean core and a 500°F xenon-135 poisoned core was considered to be the desired value. This was -2.08 percent $\Delta k/k$, to which a correction factor of 1.35 was applied, based upon HTRE No. 1 correlation work. This gave a value of -2.8 percent $\Delta k/k$. The assigned uncertainty accounted for the questionable validity of the correction factor and for all other errors in the analytical procedure.

3.3.3.3 Hydrogen Loss

It was expected that the hydrided zirconium moderator would lose some hydrogen during operation. The value of total loss presented in Table 3.2 was an estimate used for this analysis. The analysis assumed a nonuniform longitudinal loss of hydrogen with most of the loss taking place in the rear stages.

3.3.3.4 Temperature Coefficient

The reported temperature coefficient (Table 3.2) was based on analytical work that was modified to reflect HTRE No. 3 and our high temperature critical experience. The calculated reactivity change, using cross matched Program GEORGE cases at 68°F and 1000°F, was ±0.76 percent $\Delta k/k$. Since the experimental data available indicated that this method overpredicted the temperature coefficient, a value of +0.5 ± 0.5 $\Delta k/k$ was chosen. This value reflected the thinking that the temperature coefficient would be positive and fairly small.

3.3.3.5 Fuel Burnup

The fuel burnup for the XMA-1A reactor was defined as the loss of uranium-235 through all processes, non-fission capture as well as fission. The total fuel burnup for 21,640 megawatt hours was 3.0 pounds, or 0.6 percent of the total loading of 500 pounds. Since this amount was about the same value as the tolerance on total loading, and since the addition of 100 pounds of uranium-235 was only worth about 4 percent $\Delta k/k$, the reactivity effect was negligible in comparison to the other long term effects.

3.3.3.6 Fission Product Poisoning (Excluding Xenon)

This value of the fission product poisoning represented a reasonable estimate of the effect of all stable and transient fission products on reactivity.

3.3.4 NUCLEAR POWER DISTRIBUTIONS

During the course of the design work on this reactor, it was found that the analytical methods in use did not always predict nuclear power distributions accurately. This required the use of the critical experiment information (ASM-III) rather than the analytical as the basis for aerothermal design work. However, the analytical power distribution of the design reactor was compared with that of the critical experiment to see what the differences was between the two systems. These differences were interpreted by one of three explanations and were taken into account in the aerothermal performance predictions.

These three major categories were as follows:

Analysis Differences - An attempt was made during the design effort to use identical procedures in the analysis of both the ASM and the XMA-1A. As a result only one difference existed. This occurred in the analysis of the fuel elements. In the critical experiment analysis the fuel elements were contained in three to five cylinders; each cylinder was considered as a separate region in Program I_2.[5] part of the Program GEORGE computer sequence. The XMA-1A reactor fuel elements were treated as homogeneous regions. This difference in the fuel element analysis showed up as a different cell correction factor for the fuel, approximately 7 percent.

Material Difference - The major material differences between the two reactors were in the core structural material and in the core supports and shielding. The moderator support tubes in the ASM were constructed of stainless steel rather than Inconel X, as in the design reactor, and were not insulated; the Inconel X pressure and reflector shells of the design reactor were mocked up by a mild steel shell in the ASM. These differences were not expected to affect the power distribution, but would affect the over-all assembly reactivity.

Configuration Differences - The differences within the actual core and the critical experiment mockup that would have contributed significantly were mostly in the fuel region, where the multiring fuel element of the XMA-1A was replaced in the ASM by three to five fueled cylinders. Outside the active core, the biggest differences between the two reactors was in the wavy-wall configuration of the XMA-1A shield plugs. An exact mockup was not made in the ASM-III.

3.3.5 REACTOR KINETICS

Figure 3.11 shows the reactivity ($\Delta k/k$ in percent) as a function of reactor period. This graph and the tabulated data in Table 3.4 were calculated using IBM 704 Program G-5[6] which used a bare reactor perturbation theory method.

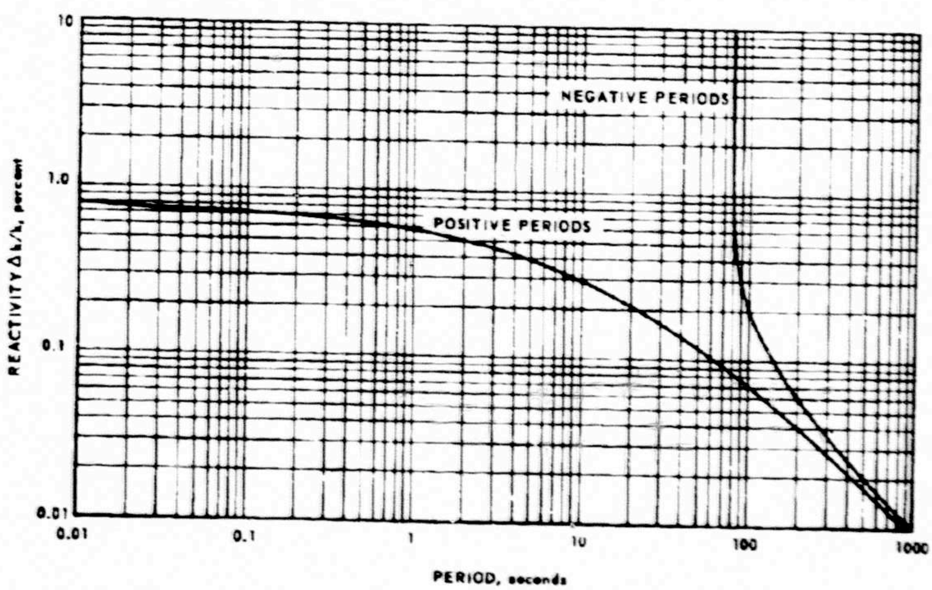

Fig. 3.11 – Reactivity versus reactor period

TABLE 3.4

REACTOR KINETICS

Group No.	Actual Fraction	Effective Fraction	Decay Control
1	0.00023	0.00026	0.0126
2	0.00142	0.00160	0.0311
3	0.00126	0.00144	0.1134
4	0.00264	0.00298	0.3060
5	0.00080	0.00091	1.253
6	0.00022	0.00025	3.381

Note: Average neutron generation time
1. 68°F: 9.181×10^{-6} second
2. 1000°F: 7.418×10^{-6} second

3.3.6 SECONDARY HEATING

Gamma heating measurements were made in the ASM-III. The analysis reported was for a core containing a fuel loading of 400 pounds of uranium-235, a configuration with 100 pounds less fuel and a slightly different fuel distribution. Based upon previous analysis this difference had little effect upon either heating rates or distribution. However, the experimental data was used when available to correct the analytic distributions in the core, especially at the core boundaries, and to verify that the reported analysis was still applicable.

The gross secondary heating, in percent reactor fission power for the principal components of the XMA-1A power plant, is presented in Table 3.5. Figures 3.12 and 3.13 give the longitudinal heating and radial heating throughout and show the consistency in heating rates from one component to another.

Afterheat distributions in the principal reactor components, corresponding to the steady-state values of Table 3.5, are shown in Figures 3.14, 3.15, 3.16, and 3.17.

TABLE 3.5

NUCLEAR HEATING IN PERCENT OF FISSION POWER

Component	Neutron Moderation	Core Gammas	Extra Core Gammas	Fission Fragment Kinetic Energy And Beta Absorption	Total
Core					
Moderator	0.993	4.490			5.483
Support tubes and insulation liners		0.851			0.851
Fuel elements		3.070		89.744	92.814
Rod guide tubes		0.089			0.089
Radial Be reflector	0.086	0.142	0.008		0.236
Reflector shell and pressure vessel		0.057	0.032		0.089
Forward ZrH and plenum region	0.029	0.158	0.032		0.219
Rear grate		0.046	0.023		0.069
Forward Be reflector	0.060	0.065	0.032		0.157
Front grate		0.017	0.023		0.040
Rear ZrH	0.007	0.017	0.001		0.025
Rear tube sheet		0.059	0.008		0.067
					100.139

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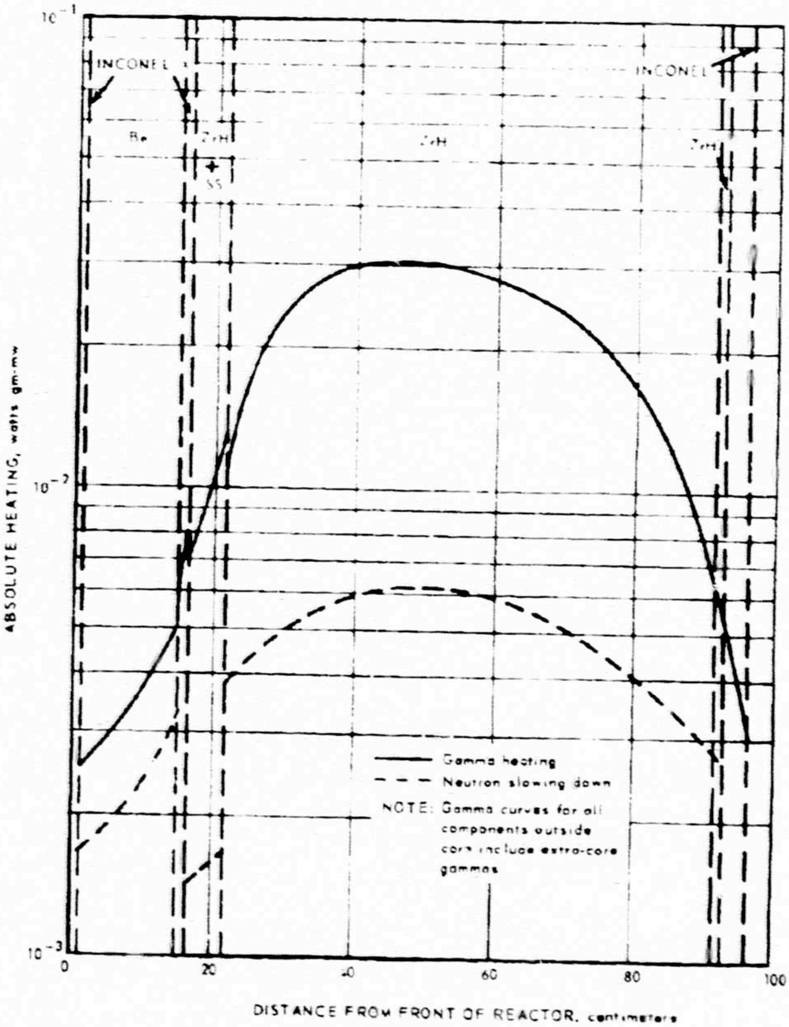

Fig. 3.12 — Longitudinal heating traverse

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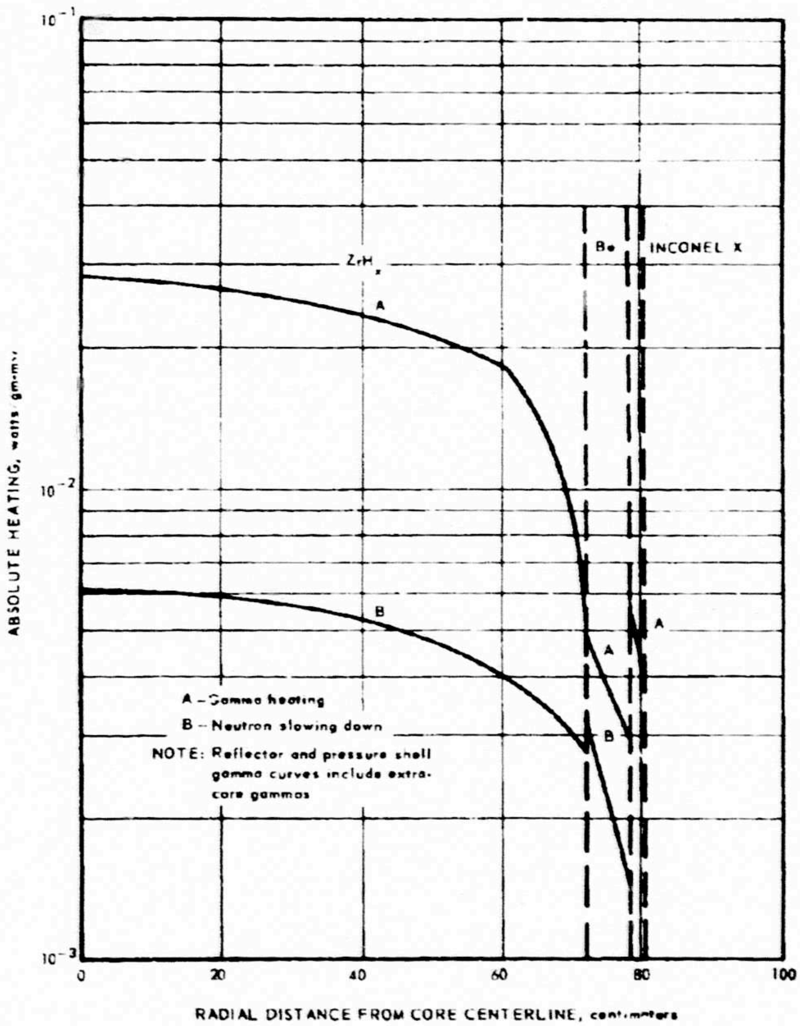

Fig. 3.13 – Radial heating traverse

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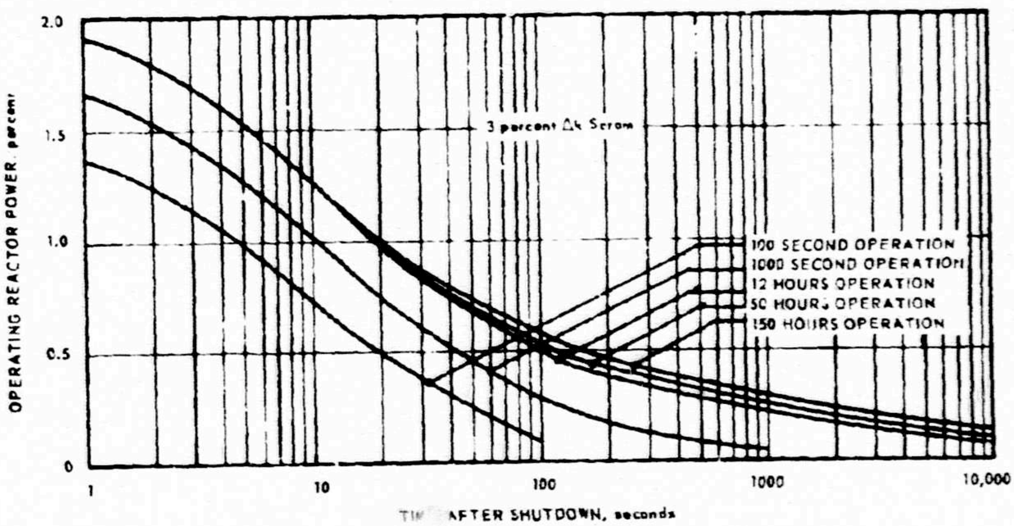

Fig. 3.14 – [illegible]erheat distribution in moderator

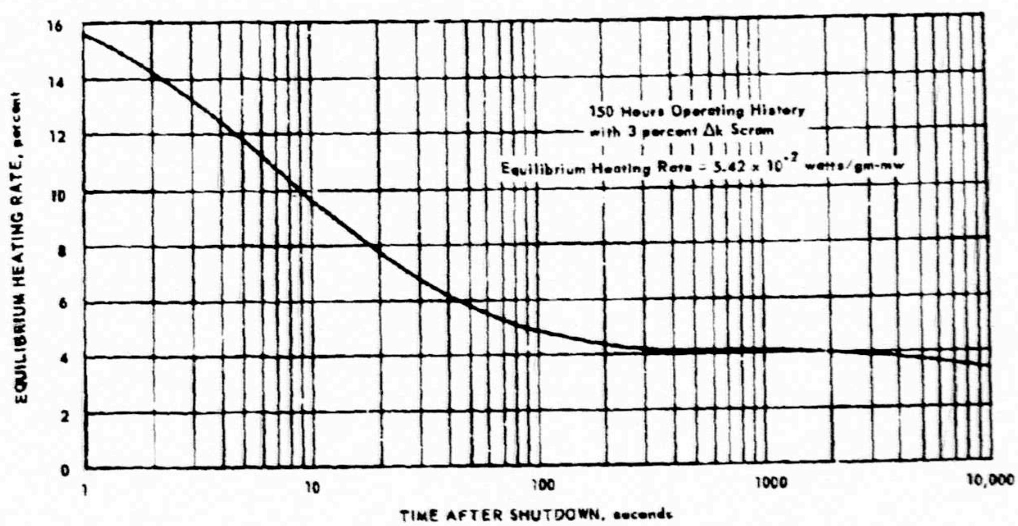

Fig. 3.15 – Afterheat distribution in control rods

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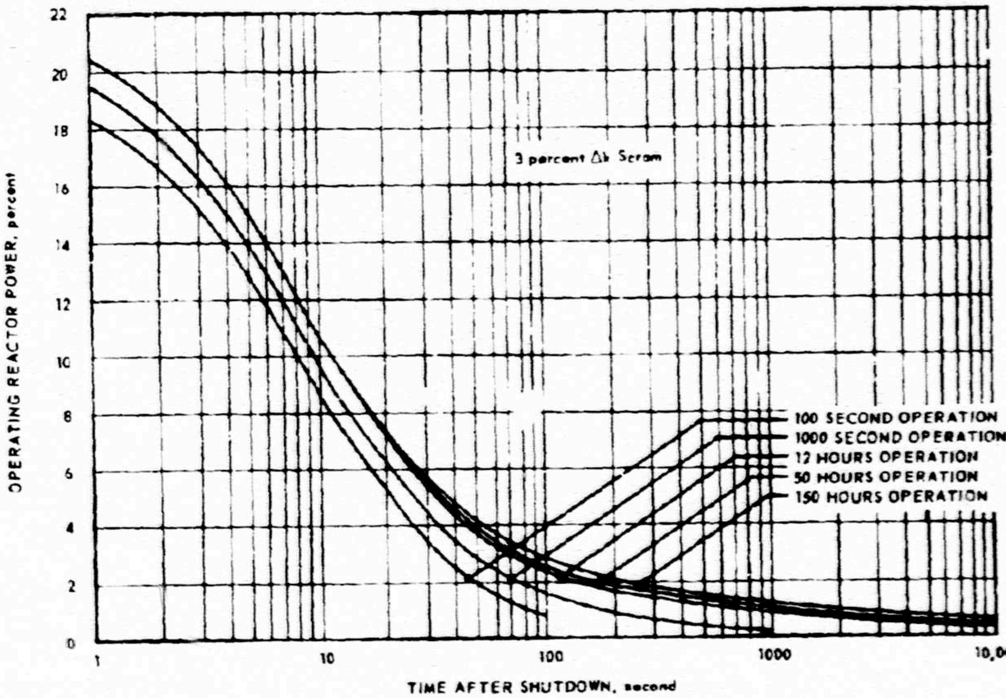

Fig. 3.16 – Afterheat distribution in fuel elements

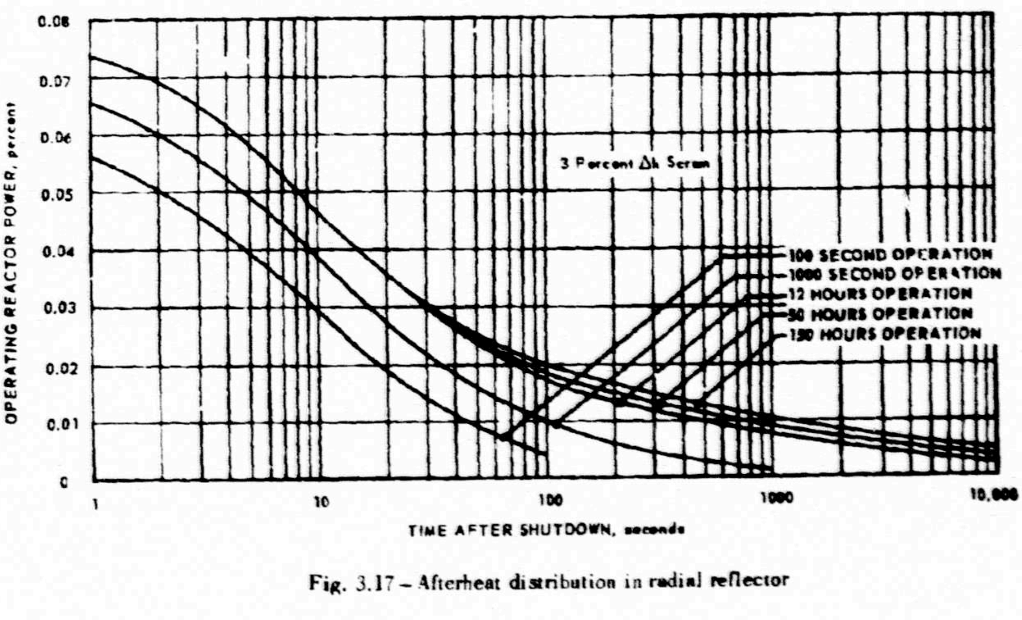

Fig. 3.17 – Afterheat distribution in radial reflector

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3.4 AEROTHERMAL DESIGN

The objectives of the aerothermal design of the XMA-1A reactor, in addition to providing a reactor that would meet the performance requirements of section 3.2, were to minimize the void required for airflow and the volume of poison or inactive materials, such as insulation assemblies and fuel element clad. The volume of the fuel element clad for a given clad thickness was directly proportional to the heat transfer area, which in turn was inversely proportional to the film temperature difference for convective heat transfer. The insulation volume requirements were determined by (1) choice of cell size (surface area of insulation), (2) the requirement to limit heat flow from fuel elements to lower temperature moderator (insulation thickness), and (3) fabrication limitations.

The void volume for the airflow was determined by the pressure loss allocated to the reactor and by the heat transfer area. In the XMA-1A reactor, the fuel elements operated at a higher temperature than the other reactor components. To compensate for temperature dilutions arising from mixing with cooler air from other components, the air had to be heated by the fuel elements to a temperature in excess of that required by the turbine. This resulted in a larger heat transfer area and hence an increase in the flow area requirement. For the first-of-a-kind reactor, the flow areas in the nonfueled components were made over-size to allow for initial uncertainties involved in temperature predictions and then orificed, if required. Operating temperature limits for the fuel element and the allowances for "hot channels" or fuel element temperature perturbations were a strong influence on heat transfer area requirements and hence, on flow area requirements.

3.4.1 REACTOR GEOMETRY

Consideration of the above factors led to a reactor configuration characterized by the following dimensions:

	Stage 1-3	Stage 4-9
1. Flow Areas, square feet		
Fuel elements	6.09	6.67
Moderator	1.41	1.41
2. Hydraulic Diameter, inches		
Fuel elements	Variable 0.125 to 0.133	0.126
Moderator	0.125	0.125
3. Heat Transfer Area, square feet		
Fuel elements	4980 total	
Moderator	1310 total	

3.4.2 REACTOR PERFORMANCE

The core performance parameters were evaluated for the XMA-1A specified design operating points. In the course of the evaluation, the reactor-shield assembly and the X211 engine match points were recomputed factoring in the latest applicable design parameters.

The results obtained are tabulated in Table 3.6. The values shown were based on the latest fuel element design and included the assumptions presented in Table 3.7.

It should be noted that the data in Table 3.6 reflects some longitudinal isothermalization of the fuel elements by hydraulic diameter variation and fuel loading variation. This led to a lower pressure ratio and average maximum temperature than originally listed as a requirement for the performance design point. In addition, more recent data indi-

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TABLE 3.6

PERFORMANCE AT VARIOUS DESIGN POINTS

Operating Point	ITS Static Standard Day,[a] 5000 ft	Mach Number 0.6 Standard Day,[a] 10,000 ft	ITS Static Standard Day Reduced Power,[b] 5000 ft	Sea Level Static, Hot Day[a]	Static, $-40^{\circ}F$ Day,[a] 5000 ft		Mach Number 0.6 Cold Day,[a] 6000 ft	
					Design	Revised[c]	Design	Revised[c]
Compressor inlet pressure, (P_{T2}), psia	12.2	12.9	12.2	15	12.2		15	
Compressor inlet temperature, (T_{T2}), °F	41	58	41	100	-40		20	
Core inlet pressure, (PT_{in}), psia	141	142	135	142	178	173	184	181
Core discharge pressure, (PT_{ex}), psia	107.6	107.9	102.9	107.9	139	135.1	143.2	142.5
Ratio of core inlet pressure to core discharge pressure, (PT_{ex}/PT_{in}), psia	0.763	0.764	0.762	0.760	0.781	0.781	0.778	0.787
Core inlet temperature, (T_{in}), °F	666	684	649	728	580	563	645	636
Fuel element maximum average surface temperature, (T_s), °F	1741	1737	1682	1725	1777	1717	1759	1729
Fuel element maximum-maximum surface temperature, (T_{sms}), °F	2020	2020	1950	1985	2100	2025	2060	2020
Moderator maximum average surface temperature, (T_{sm}), °F	1139	1147	1103	1157	1110	1073	1137	1118
Fuel element average discharge air temperature, ($T_{ex\ fe}$), °F	1585	1584	1532	1580	1593	1540	1589	1561
Moderator average discharge air temperature, (T_{exm}), °F	1078	1087	1045	1102	1036	1002	1068	1051
Turbine inlet temperature, (T_4), °F	1500	1500	1450	1500	1500	1450	1500	1475
Engine speed, rpm, %	94	94	92.5	94	94	92.5	94	93.25
Total core flow rate, (W_T), lb/sec	634	636	615	638	799	785	827	803
Fuel element flow rate, (W_{fe}), lb/sec	532	534	510	536	671	659	694	674
Moderator flow rate, (W_m), lb/sec	90.9	91.1	88.1	91.4	114.5	112.5	118.5	115.1
Fuel element exit dynamic head, (q_{ex}), psi	4.8	4.8	4.6	4.8	5.9	5.7	6.1	5.7
Total reactor power, (Q_T), mw	149	146.5	138.4	139.4	206	194.5	199	189.5
Net engine thrust (2 engines), (F_s), lb	28000	19300	25300	21100	43500	41300	29500	28200

[a] Engine power 94 percent rpm and turbine inlet temperature 1500°F.

[b] Engine power 92.5 percent rpm and turbine inlet temperature 1450°F.

[c] Revised turbine inlet temperature and rpm in order to reduce maximum-maximum fuel element temperature to its design value.

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TABLE 3.7

ASSUMED VALUES FOR XMA-1A DESIGN POINTS

	Fuel Element	Moderator
Flow distribution, %	83.96	14.33
Power distribution, %	92.36	6.85
Friction factor multipliers based on rough pipe	1.5	1.0
Film heat transfer coefficient	$Nu = 0.0217\ N_{Re}^{0.8} N_{Pr}^{0.4}$	Same as F.E.
Hot channel factor:		
Applied to average bulk temperature rise	1.18	
Applied to film temperature drop at location of maximum-maximum temperature	1.52	

cated that the friction factor multiplier was 1.25 rather than 1.5 and the fuel element perturbations were less than that assumed in this analysis.

Working curves useful for estimating pressure ratios, and fuel element and moderator temperatures for operating points other than those shown previously are presented in reference 7. Pages 19 through 21 explain these curves fully.

3.4.3 REACTOR THERMAL TRANSIENTS

A series of calculations were made using the reactor core transient temperature computer program[8] to determine the temperatures that would exist in the fuel elements, moderator, and reflector of the XMA-1A core after it was shut down. The operating conditions considered were as follows:

1. The reactor was operated at 150 megawatts for 150 hours before shutdown; the cooling air was supplied at a decreasing rate by the compressor for a short period of time until its output reached 46 pounds per second, then a constant flow of 46 pounds per second at 70°F was assumed to be supplied by a blower.
2. The same as above after 10 hours of operation.
3. The same as above after 0.1 hour of operation.
4. The reactor was operated at 150 megawatts for 150 hours, then the airflow was suddenly dropped to 46 pounds per second, 1 second before reactor shutdown.
5. The reactor was operated at 150 megawatts for 150 hours before shutdown; the airflow was suddenly reduced from 46 pounds per second after various periods of time after reactor shutdown.

The assumed compressor cooling airflow coastdown is shown in Figure 3.18. The associated compressor discharge pressure and temperature curves are shown in Figure 3.19 and Figure 3.20, respectively.

Curves of heat generation versus time after reactor scram for the moderator, fuel elements, and reflector are shown in Figures 3.14, 3.16, and 3.17, respectively.

The results of the analysis are presented in the individual component sections of this volume: fuel elements, section 6.2.6; moderator, section 6.2.7; and reflector, section 6.2.8.

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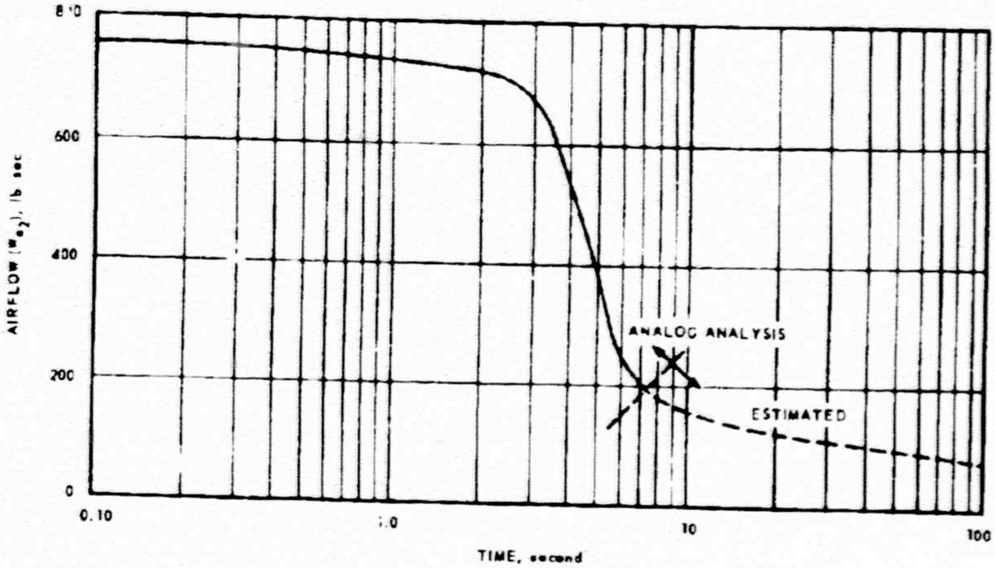

Fig. 3.18 – Compressor airflow following scram – sea level static

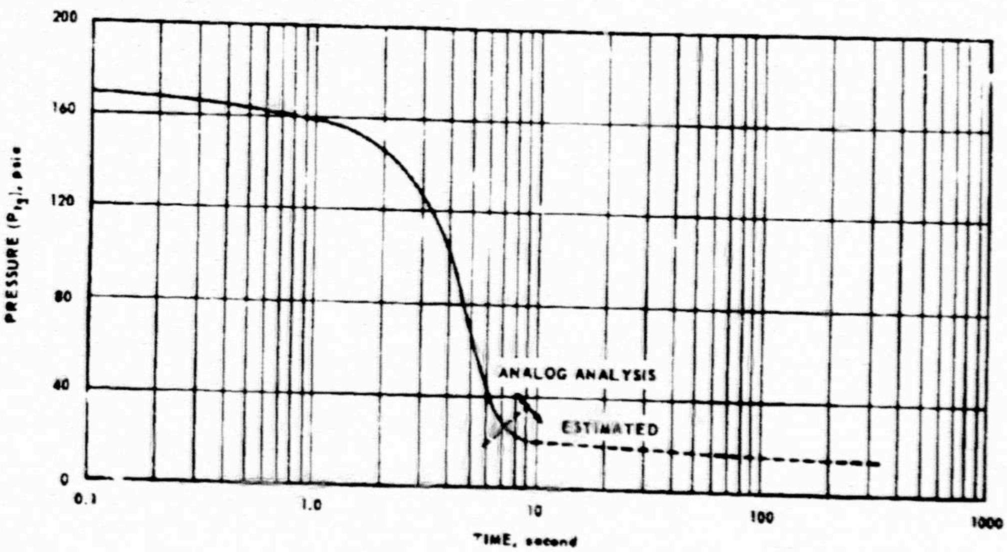

Fig. 3.19 – Compressor discharge pressure following scram – sea level static

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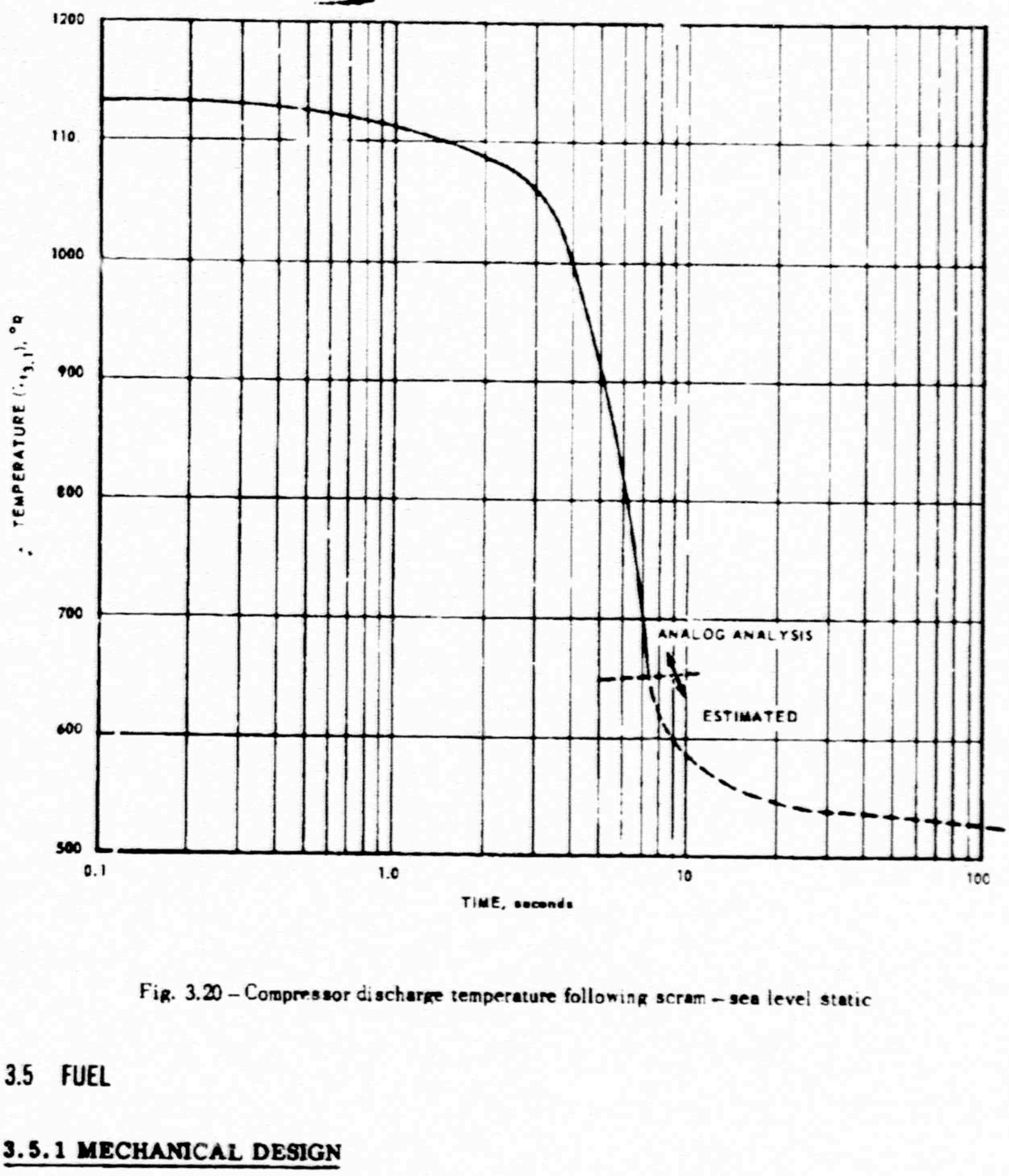

Fig. 3.20 – Compressor discharge temperature following scram – sea level static

3.5 FUEL

3.5.1 MECHANICAL DESIGN

The XMA-1A fuel cartridge assemblies were essentially right cylinders consisting of either an instrumented or noninstrumented nose piece, nine fuel element assemblies, a tail assembly joined together by girth welds, and a moderator rod inserted into the center of the assembly. The outside diameter of the fuel element and tail piece assemblies were covered with 0.0265 inch of duPont K.T. insulation and a 0.005 inch Type 310 stainless steel foil.

The diameter of the center moderator was varied in seven radial zones to effect gross radial power flattening. Therefore, the fuel elements in each zone had a different amount of rings. The number of rings in the elements were also varied longitudinally to partially isothermalize the cartridge.

The fuel cartridge was capable of being remotely inserted and removed from the rear of the core. The fuel latch was released by inserting a cartridge release rod through the cen-

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ter of the cartridge. An instrumentation disconnect was provided on cartridges containing fuel or center moderator instrumentation to permit removal without destroying the instrumentation.

After the fuel cartridge was removed from the core, the center moderator was remotely removed from the fuel cartridge by actuating the center moderator latch clip on the nose. There was no instrumentation disconnect between the center moderator and the fuel cartridge. Therefore, if a center moderator having instrumentation had to be removed from the fuel cartridge the instrumentation would be destroyed. The center moderator coolant orifice could be changed after it was removed from the cartridge.

The nose piece assembly (instrumented and noninstrumented) consisted of a center housing, three ribs, and an outside ring. The material selected for its construction was Type 310 stainless steel to insure that the coefficient of thermal expansion was compatible with GE-Specification B50T2026A (the material of the outer shell of the fuel element assembly). The function of the nose piece was to orientate the cartridge to the core radially and longitudinally. It also provided a passage for the center moderator coolant and a clip latch to retain the center moderator in the cartridge when it was outside of the core. In addition, the instrumented nose piece provided a retainer for the instrumentation disconnect and appropriate passages to accommodate the thermocouple wiring.

The fuel element assemblies consisted of an outer structural shell, an inner support ring, 6 major comb ribs, 6 intermediate comb ribs, 12 minor comb ribs, 6 pads, and a varying number of rings as explained above. A typical element is shown in Figure 3.21. The material selected for the structure of the fuel element assembly, the outer shell, comb ribs, pads, and inner support ring was a nickel-chrome alloy GE-Specification B50T2026A. It was selected for its strength and oxidation resistance at the design temperature of 1650°F. The function of the structure was to support the fueled rings yet impose a minimum load on them.

The fueled ring core was the standard matrix of nickel, chrome, and UO_2. The fuel ring cladding material was a nickel-chrome alloy, GE-Specification B50YA13, hot finished for improved creep and oxidation resistance properties at the design temperature of 1800°F.

The tail piece assembly consisted of an outer structural shell, six major ribs, and an inner support ring. The material selected for this assembly was a nickel-chrome alloy GE-Specification B50T2026A; selected for its strength, oxidation resistance, and to match coefficients of thermal expansion with the fuel element assembly outer shell. Its function was to support the rear face of the last fueled element outer shell and to provide appropriate notches to insure the remote handling capability.

The center moderator assembly consisted of a nose piece containing the latch fingers, a zirconium hydride rod with an N_H of 4.1, a tail piece brazement, and a center rod assembly. This assembly is shown in Figure 3.4. The outside diameter of the zirconium hydride rod was covered with 0.0265 inch thick duPont K. T. insulation that in turn was covered with a 0.005 inch Type 310 stainless steel foil. A center moderator coolant orifice fitted over the nose piece. The latch finger material was Inconel X, heat treated to obtain good spring properties at the design temperature of 1000°F. The function of the latch fingers was to retain the fuel cartridge assembly in the bellmouth latch. The nose piece was made from Type 310 stainless steel selected for thermal expansion compatibility as well as oxidation resistance and strength at the 1000°F design temperature. The nose piece retained the zirconium bar and located it longitudinally in the core. It also provided an entrance for the coolant and a plenum to distribute it to the coolant passages in the zirconium bar. The center rod assembly material was Type 310 stainless steel selected for its oxidation resistance at the design temperature of 1300°F. This assembly provided the passage for the cartridge release rod; it also tied the assembly together. The center moderator

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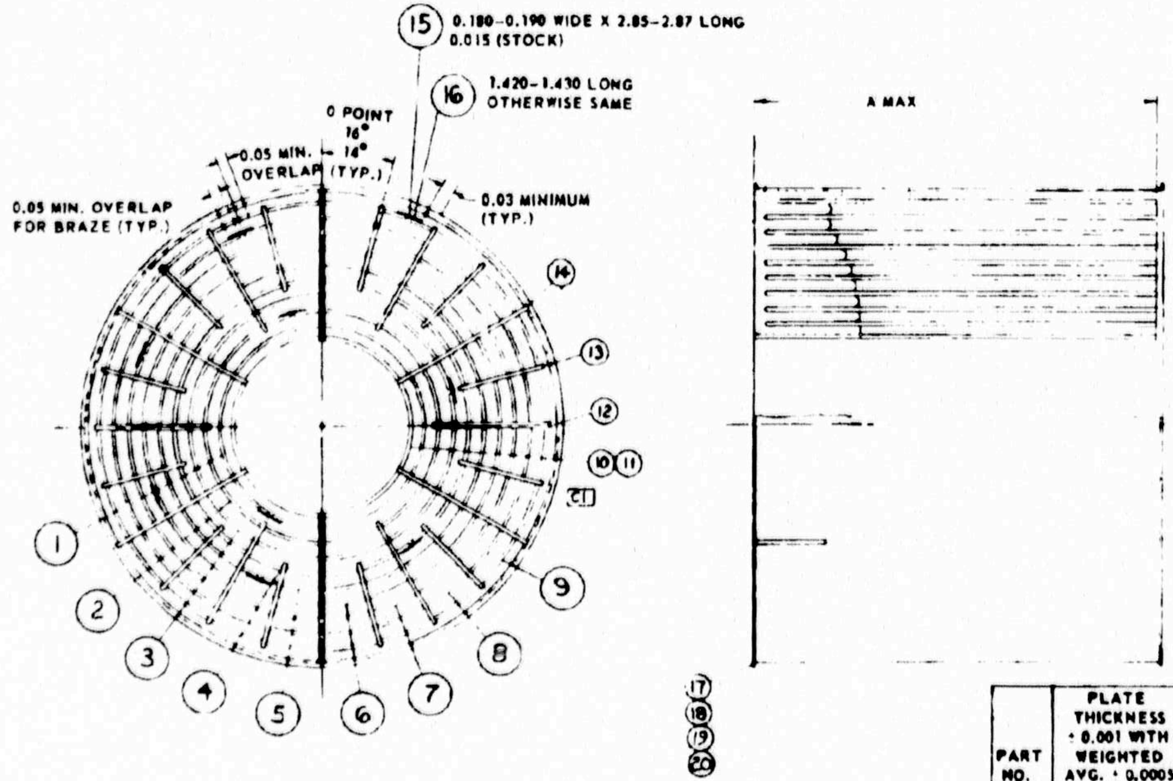

	GROUP NO.	A DIM.
B4	1 AND 3	3.053
	2 AND 4	1.614

PART NO.	DESCRIPTION OR NAME
1	RING NO. 1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	RING NO. 9
10	RING - SUPPORT
11	RING - SUPPORT
12	RIB - SMALL
13	RIB - SMALL
14	RIB - LARGE
15	STRIP - JOINT
16	STRIP - JOINT
17	SHELL
18	SHELL
19	SHELL
20	SHELL

PART NO.	PLATE THICKNESS ± 0.001 WITH WEIGHTED AVG. ± 0.0005	OUTSIDE DIAMETER (REF.)	CUT LENGTH ± 0.015	INTER RING GAP ± 0.005
				0.0645
1	0.025	1.538	4.667	0.088
2		1.764	5.377	
3		1.990	6.087	
4		2.216	6.796	
5		2.442	7.506	
6		2.668	8.216	
7		2.894	8.925	
8		3.120	9.635	0.088
9	0.025	3.346	10.345	0.0645

FREE FLOW AREA 75.04 PERCENT

Fig. 3.21 – Fuel element assembly (Dwg. 567D°70)

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assembly was mechanically held into the nose piece, and the tail piece was welded to this assembly. The tail piece was fabricated from nickel-chromium alloy, GE-Specification B50T2026A, selected for its oxidation resistance. The tail piece centered the center rod assembly. It also provided for 0.375 inch permanent growth of the zirconium hydride bar.

To complete the design and all factory drawings, the following work would have to be completed:

1. The outer shell girth weld development program must be completed. This program was to determine the exact joint design, weld procedure, process specification details, and the longitudinal weld shrinkage. It was to determine also the short time tensile tests of the welded joint at 800° to 1800°F in 200°F intervals. The preliminary work performed indicated the joint design shown on the drawings was satisfactory. The length of the outer shell was such that it accommodated 0.015 weld shrinkage. If the exact weld shrinkage is determined this length may have to be adjusted as well as other components (the nose and tail assemblies) to maintain the centerline of the active core.
2. The material development program to obtain enriched boron for power shimming must be completed. Radial space for the boron shim material was extremely limited; therefore, enriched boron was required to give the desired neutron absorption capability in the specified thickness, AMS-Specification 552 or GE-Specification B50T2026A. The materials were required for oxidation resistance and to match coefficients of thermal expansion with either the outer shell material or the outer foil material.
3. The stress analysis of the cartridge and the components must be completed. The stress analysis was completed on the individual components for zone AB_1 of the cartridge assembly. The stress levels were acceptable; however, the tail assembly should be redesigned to reduce the stress levels. This might require the remote handling equipment to be redesigned. The stress levels in the entire cartridge assembly should be examined; including stress levels during remote handling. The length of the intermediate and minor combs on the remaining zones should be evaluated from a stress viewpoint.
4. A fuel element development program should be completed to optimize the design. Specific items under evaluation were vacuum melted hot rolled materials, with a 0.020 inch minimum ring thickness established for the core, and, if at all possible, placing the pads on the inside diameter of the outer shell. This would permit full insulation on the outside diameter of the outer shell and prevent local hot spots on the moderator support tube. In the current design, the pads were located on the outside diameter of the shell. There they lay against the moderator support tube increasing the local temperature to a point that stress levels were greater than those allowed.
5. Fuel cartridge instrumentation design must be completed. The fuel plate and air thermocouple and the center moderator surface thermocouple specifications were in preliminary form and must be completed. A design layout must be completed to determine a method of routing, etc. The instrumented elements, center moderator, and cartridges must be completed.
6. The center moderator extrusion drawings must be completed so that they can be cross referenced on the factory detail drawings.
7. The details of the center moderator orifices will have to be completed.
8. The center moderator temperature profiles were assumed for the design. The design should be reviewed for proper clearances both radially and longitudinally.
9. A checking layout of an instrumented moderator and a noninstrumented fuel cartridge must be prepared to check clearances. Preliminary work indicated that there were no interferences.

10. Fuel element specifications must be completed and the fuel element drawings must be checked to insure compliance with these specifications.
11. Remote handling equipment must be checked to insure it will fit the fuel cartridge and work with component de-igns.
12. An insulation specification must be written and referenced on the cartridge assembly drawings. An instruction manual for applying the insulation to the cartridge must also be completed and referenced on the cartridge assembly drawing.

3.5.2 AEROTHERMAL DESIGN

Each fuel cartridge was formed of nine 3-inch fueled stages of which stages 1, 2, and 3 were identical, 4 and 5 were identical, and 6 through 9 were identical. There were six variations of the fuel cartridges in the core; regions "A" and "B1" (identical), "B2" and "C1" (identical), "C2," "D," "E1," and "E2." Region "C3" was an alternate design proposed for use in flattening the gross radial power profile if needed. Region A was located at the center of the core and B2, C1, C2, D, E1, and E2 were located progressively farther from the center with E2 at the outer edge. This arrangement is shown in Figure 3.2.

The fine radial temperature profile in each cartridge was flattened by adjusting fuel ring thickness and fuel concentration on a ring-to-ring basis as a function of fine radial power profile. Fine radial profiles of volumetric power are shown in Figure 3.22; this curve is for regions A and B1. The other regions show similar patterns and are in reference 9. Additional details are also covered in the reference.

3.6 MODERATOR

The moderator segments for the XMA-1A core were unclad zirconium hydride, hydrided to an N_H of 3.95 to 4.05. They were shaped in the form of triflutes and cooled by a series of internal cooling holes. On the outer periphery, the shapes were altered to partial triflutes and were segmented to meet the minimum reflector material requirements and to

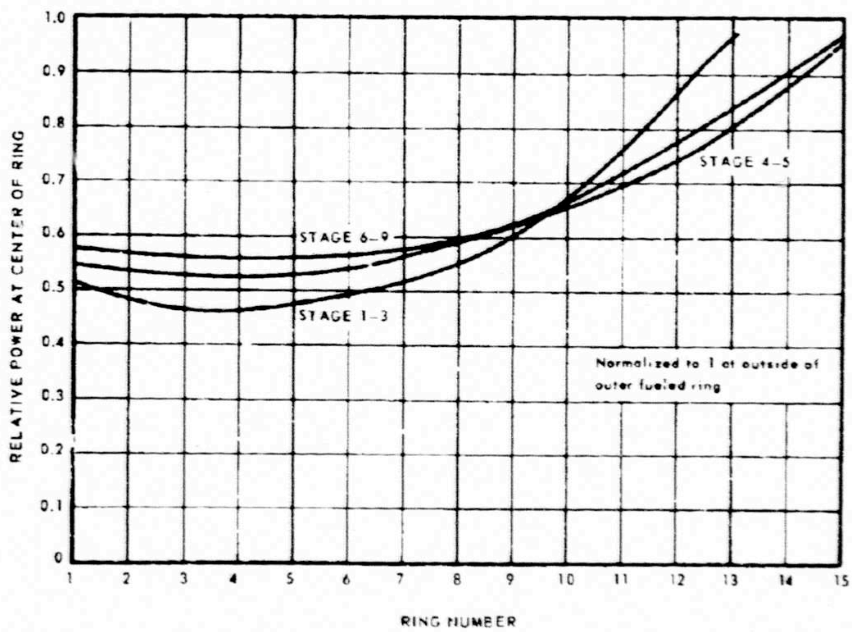

Fig. 3.22 – Fine radial power distribution – Region A and B1

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permit the reflector to take a reasonable shape for manufacturing. There were approximately two triflutes per cell in the core. The core was divided into three zones for the outer moderators, based on the porosity of the triflutes that were set by the radial temperature profile. There were 96 triflutes in zone AB, 120 triflutes in zone C, and 42 full triflutes, 42 partial triflutes, and 48 arch triflutes in zone D. Figure 3.5 shows a triflute-moderator assembly.

The moderator cooling air entered through a series of four holes per triflute in the front tube sheet, through the cooling holes in the triflutes, and was exhausted to a large plenum area formed by the rear tube sheet and the end of the triflutes. The air from the rear plenum area was exhausted through a series of annular ducts formed between the rear tube sheet and the moderator support tube.

The moderator assemblies consisted of six full triflutes; or two full triflutes, two partial triflutes, and two arch segments clustered around a single support tube. There were 55 assemblies of this type in the core. Due to the geometry of the core, there were six assemblies of an arch segment and six assemblies of an arch segment and partial triflute assembled to a support tube. The remaining cells were free tubes which supported the triflutes during operation but did not have moderators attached to them. The assemblies were designed to be remotely removed from the core. To meet the moderator volume fractions required by the XMA-1A core, extremely tight tolerances were maintained on the individual components and assemblies.

3.6.1 MECHANICAL DESIGN

A major criteria in formulating the mechanical design of the XMA-1A moderator was to minimize the air leakage between the moderator blocks. Seals were installed in the areas of cooling air leaving the tube sheet, cooling air entering the triflutes, and where the support tube attached to the tube sheet separating the fuel and moderator air.

The moderator cooling air leaving the front tube sheet was sealed from the moderator cavity by an 0.085-inch-thick seal plate bolted to the tube sheet through the rib support assembly.

The moderator mechanical design is covered more thoroughly in reference 10.

3.6.2 AEROTHERMAL DESIGN

The moderator thermodynamic design analysis was carried out in two phases. The first phase consisted in establishing the basic parameters of required free flow areas and hydraulic diameter on the basis of the given reactor operating conditions, average heating rate, and moderator volume fraction. The second phase consisted of establishing the required porosities for each moderator piece, consistent with the local heating rates and minimum internal temperature gradients.

The average moderator design and thermodynamic parameters as well as the assumptions on which they were based are summarized in reference 11.

3.7 REFLECTOR

The nuclear function of the reflector material was to limit the neutron loss from the core periphery and thus enhance core reactivity. Material specifications required the use of unclad reactor grade beryllium and defined the volumetric fractions that set the cell pitch and in turn the reflector thickness.

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Additional specifications were:

1. The reflector component shall not be remotely removable.
2. The shell shall be internally cooled by a specific flow channel.
3. The reflector material shall overlap fuel at both ends.

The assembly is shown in Figure 3.23.

3.7.1 MECHANICAL DESIGN

The reflector for structural stability consisted of 84 blocks of beryllium. Each block was supported by two bolts, one of standard design and one a swinging type to allow for differential thermal expansion of the supporting shell and beryllium. Each block was internally cooled by 0.187-inch diameter longitudinal holes - 492 in the total core cross section. The amount of cooling air entering through the holes was set by the forward orifices, to hold the maximum beryllium temperature between 1000°F and 1200°F. Six blocks in the core cross section had parallel rather than radial sides to enhance assembly of the blocks.

Additional design data of the reflector can be found in reference 12.

3.7.2 AEROTHERMAL DESIGN

The reflector airflow passed through coolant holes in the periphery and flanges of the front tube sheet, and then entered a plenum behind the tube sheet. The airflow then divided, one part passing through the reflector and the remainder through the coolant annulus between the reflector and reflector shell. At the end of the reflector, the annulus air was mixed with moderator air and exhausted through holes in the rear tube sheet and around the rim of the rear tube sheet. The reflector air bypassed the rear tube sheet by collecting in a can or plenum attached to the end of each reflector block, and passing through holes in the rear tube sheet by means of short lengths of tube attached to the collector cans or plenums. This was necessary because the reflector had a slower transient response than the moderator, as a result of a smaller flow rate per unit volume and the higher heat capacity of the beryllium metal. During cooling, after a reactor scram, the reflector discharge air could be 400° to 500°F higher than the moderator discharge air. This temperature difference would impose excessive temperature gradients in the rear tube sheet if the rim of the rear tube sheet were exposed directly to the reflector air and the center part of the tube sheet exposed directly to moderator air.

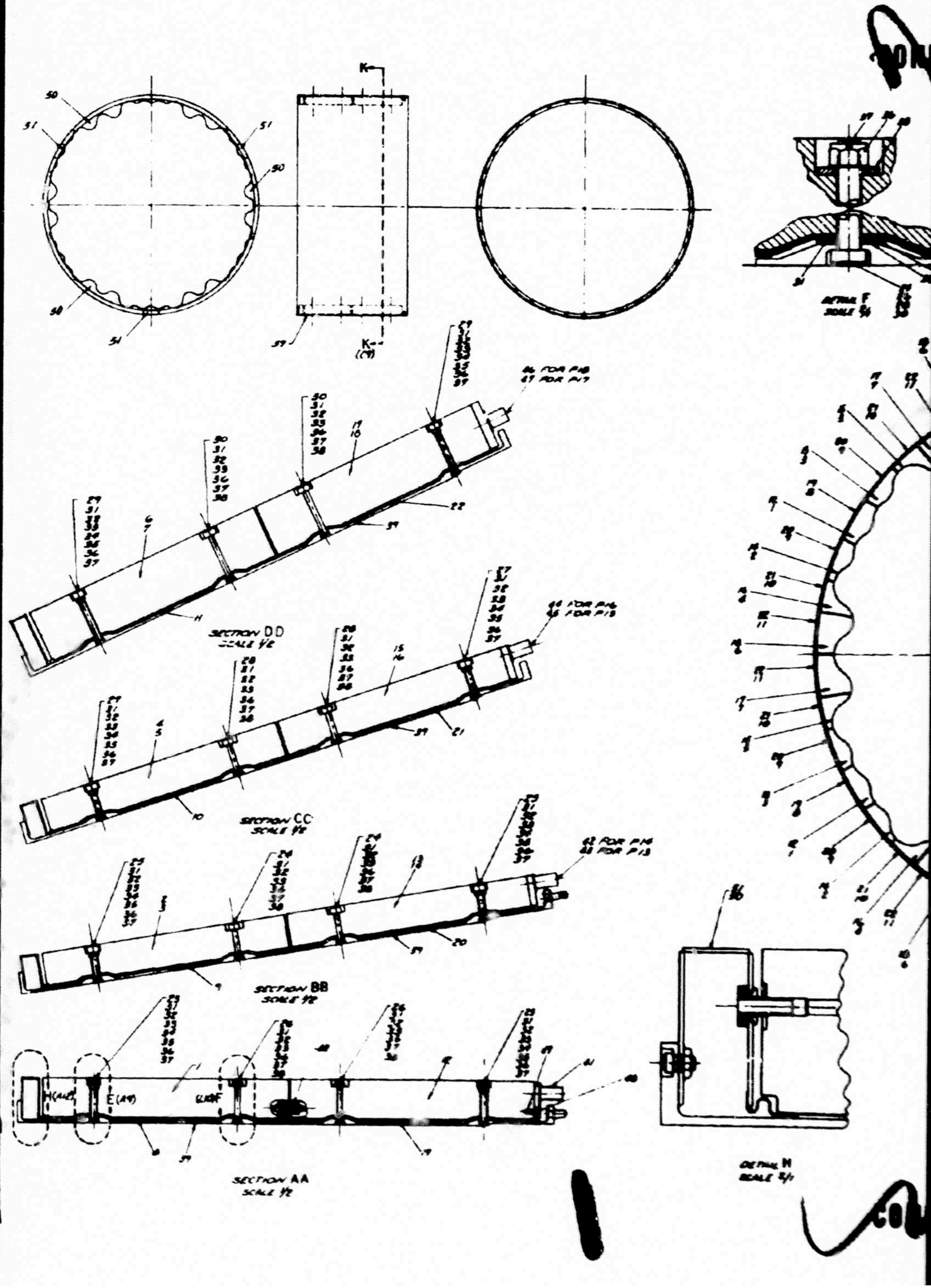
Additional aerothermal design data of the reflector can be found in reference 13.

3.8 FORWARD TUBE SHEET

The design requirements stipulated a forward structure supported at its perimeter and in turn supporting all other core components against drag and aft acceleration loads, and all shear loads of cantilevered core and core components.

In addition, certain specific tasks were assigned to the component as follows:

1. To provide the air distribution for cooling all core components together with the capability of adjusting airflow to the moderators and reflectors by means of variable orificing.
2. To provide a forward reflector to aid in bringing the power profile peak farther forward.
3. To provide an accurate and positive means for locating all core components at their forward ends during initial assembly and remote reassembly.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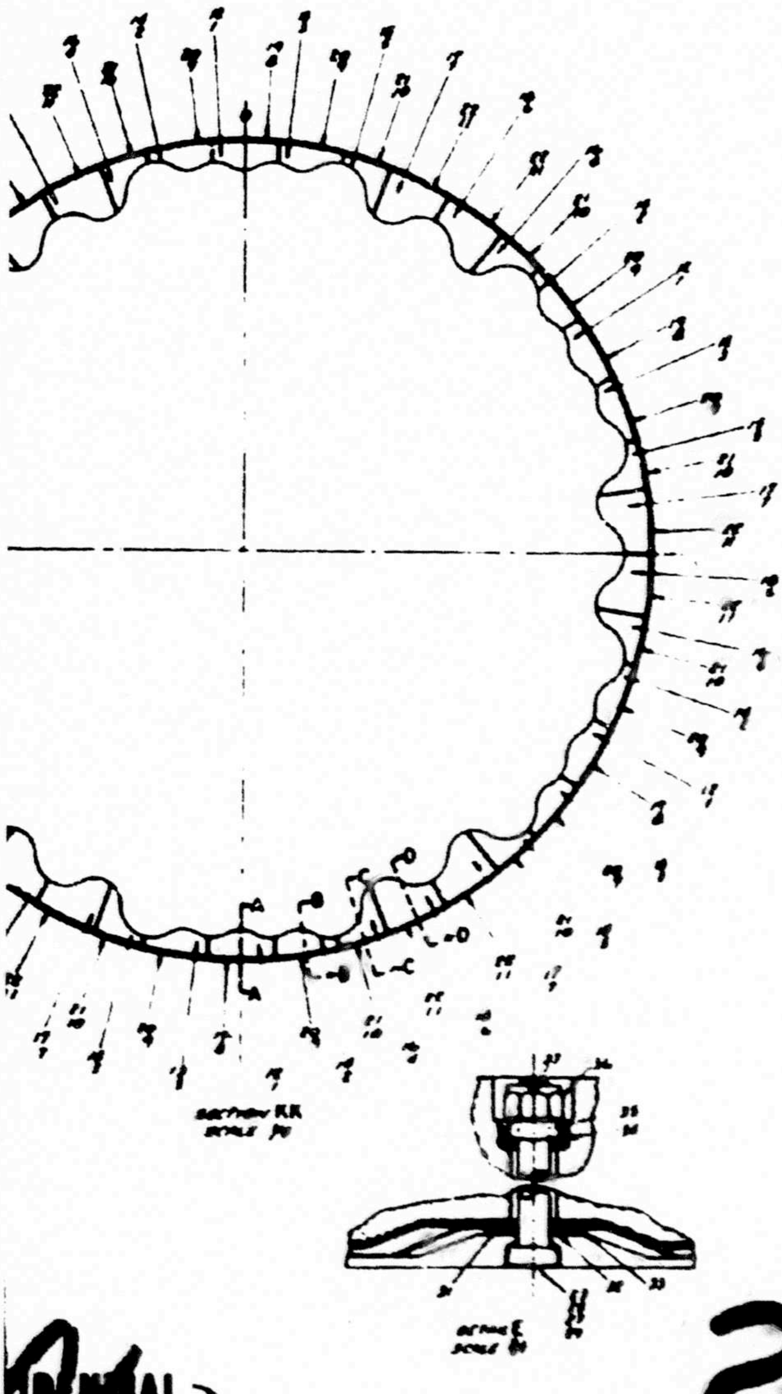

PART NO.	DESCRIPTION OR NAME
1	BLOCK – 4L
2	BLOCK – 5L
3	BLOCK – 3L
4	BLOCK – 6L
5	BLOCK – 2L
6	BLOCK – 7L
7	BLOCK – 1L
8	INSULATION ASS'Y – FWD
9	INSULATION ASS'Y – FWD
10	INSULATION ASS'Y – FWD
11	INSULATION ASS'Y – FWD
12	BLOCK – 4R
13	BLOCK – 3R
14	BLOCK – 5R
15	BLOCK – 2R
16	BLOCK – 6R
17	BLOCK – 1R
18	BLOCK – 7R
19	INSULATION ASS'Y – AFT
20	INSULATION ASS'Y – AFT
21	INSULATION ASS'Y – AFT
22	INSULATION ASS'Y – AFT
23	BOLT – SWING
24	BOLT
25	BOLT – SWING
26	BOLT
27	BOLT – SWING
28	BOLT
29	BOLT – SWING
30	BOLT
31	WASHER
32	SHIM
33	PAD
34	BEARING SEAT
35	BEARING
36	NUT
37	LOCKWIRE
38	WASHER
39	SHELL
40	EXPANSION JOINT
41	PLENUM ASS'Y – 4R
42	PLENUM ASS'Y – 5R
43	PLENUM ASS'Y – 3R
44	PLENUM ASS'Y – 6R
45	PLENUM ASS'Y – 2R
46	PLENUM ASS'Y – 7R
47	PLENUM ASS'Y – 1R
48	FIL. HD. MACH. SCR. NO. 8 – 32 UNC X 0.62 LG
49	THREAD INSERT HELI-COIL CORP. DANBURY, CONN. OR EQUAL
50	PLENUM ASS'Y – LARGE
51	PLENUM ASS'Y – SMALL

Fig. 3.23 – Reflector assembly (Dwg. 176R105)

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4. To support the core components under maximum longitudinal loading conditions so that differential deflection, center to perimeter, would not exceed 0.2 inch.
5. To provide a means of routing the instrumentation wiring from the forward ends of the core components to the aft perimeter of the front plug.

Of the 38 inches over-all core length, a nominal 6.375 inches at the forward end was allotted for these purposes. In order to obtain maximum depth of structure, two plates were proposed, separated by some type of webbing to transmit shear. Beryllium reflector material was selected to fill the voids between the plates.

The geometry of the core components dictated the sizes and locations of cooling-air passages, which in turn, defined the remaining space available for the shear ties and reflector. After several iterations it was decided to use tubes between the plates as structural spacers, one being located at each control rod location and one at each similar location having no control rod, i.e., at the centroid of the triangle drawn between any three mutually adjacent cell hole centers. In addition, a heavy rim and flange section was used for the same purpose at the perimeter.

With the geometry established, all members were sized and the structure defined. At this point nuclear, thermal, and stress analysis was begun. A simplified version of the structure was fabricated. This was to be used in manufacturing trials and experimental stress analysis. In addition, a program for the physical development of the structure was outlined in reference 14 to answer questions dealing with manufacturing, structural integrity, inspection, performance, etc.

Additional design data of the forward tube sheet can be obtained in reference 15.

3.9 REAR TUBE SHEET

The design conditions called for a rear tube sheet of a very thin structure capable of supporting the in-plane loads only at the aft end of the moderator support tubes. Loads normal to the structure would be supported by guide tubes and the reflector shell flange. In-plane loads were to be transmitted through the shell to the forward grate.

Differential expansion between the grate, which sees primarily moderator discharge air, and the shell flange, which sees primarily reflector discharge air, made it necessary to provide for a relative radial motion between the two, while maintaining a load path for in-plane loads to the shell. Furthermore, it was imperative that the grate and shell remain concentric regardless of their relative thermal expansion because of the alignment of internal components. Temperature differentials were further compounded during transient conditions of operation in both radial and longitudinal directions.

Additional design data of the rear tube sheet can be found in reference 16.

3.10 COMPONENT RELEASE MECHANISM

The component release mechanism consisted of three subassemblies: the support assembly-rib, the plunger assembly, and the bellmouth assembly. The component release mechanism assembly is shown in Figure 3.24. The primary functions were to remotely latch and unlatch the fuel cartridge, latch and unlatch the moderator assembly, provide a smooth entrance for air into the cell, and maintain a seal between the moderator plenum and the forward plate. The structure of the release mechanism was designed to meet XMA-1 flight conditions.

Additional design data of the component release mechanism is contained in reference 17.

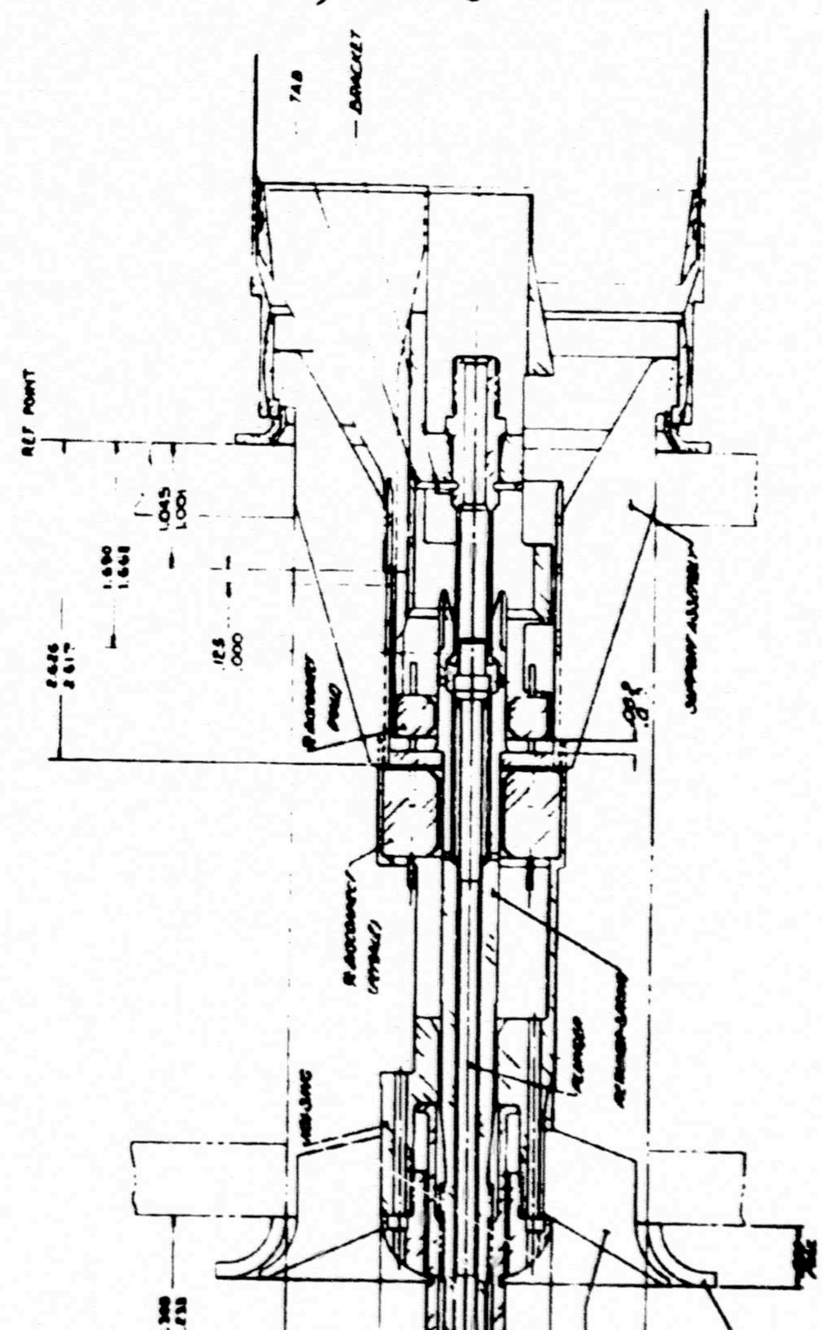

Fig. 3.24 — Component release assembly (Dwg. 665D257)

3.11 CONTROL RODS

The control rods designed for the XMA-1 power plant consisted of five segments, each 4.00 inches long by 0.406 inch diameter, joined together with Inconel X tie straps. The segments were composed of 38 weight percent Eu_2O_3 dispersed in a nickel matrix and clad with a low silicon 80Ni - 20Cr alloy. The specific dimensions and details of this design are shown in Figure 3.25. Seven of these rods were used for dynamic control of the reactor and 122 rods were used for combined shim-scram operation.

The operational requirements for the control rods were 1000 hours useful life at a maximum surface temperature of 1650°F in air. During their lifetime, the rods were required to travel 60,000 feet with a maximum friction load of 15 pounds per rod.

The segmented design of the control rods was required to reduce the bowing that occurred when the rod was eccentric in its guide tube which caused nonuniform cooling, and also to impart sufficient flexibility to the rod so that the rod would negotiate a bowed guide tube. The guide tubes would be bowed from longitudinal differential thermal expansion of the reactor core and also from misalignment of the core and shield assemblies.

By dividing the rod into a series of short lengths, the bowing caused by nonuniform cooling occurred separately over each segment length rather than cumulatively over the entire length. By this means, the magnitude of the bowing was reduced to a level where it could be accommodated by increasing the guide tube clearances. Dividing the rod into several short lengths also provided the needed flexibility, if the segements were joined together properly. Joining the segments was accomplished by attaching straps near the midplane of each segment and then leaving a gap both between segments and between the segments and the straps to provide room for the segments to pivot about the point of strap attachment.

The tie straps provided a simple means of centering the rod in the guide tube and became the bearing surfaces in contact with the guide tube.

The poison was dispersed in a metallic matrix to improve thermal conductivity and, thus, reduce the operating temperature of the poison core. It was also used to increase the workability and thermal shock resistance of the core. The cladding was required to protect the nickel matrix from oxidation and to carry all the loads to which the control rod would be subjected.

The control rods were fabricated by a process very similar to that used for the HTRE No. 3 control rods, the only differences being caused by the change in diameter from 0.720 to 0.406 inch and a change in composition from 42 to 38 weight percent Eu_2O_3. The fabrication procedure and the material specifications are presented in reference 18.

A series of XMA-1A control rod segments were tested in a nonnuclear environment. The condition and results of these tests are shown in Table 3.8.

These tests demonstrated that the control rods had a useful life of over 1000 hours at 1800°F in air and a nonnuclear environment. Previous tests on HTRE No. 3 control rods indicated that friction and wear of the Inconel X tie straps was not a problem. The major factor limiting the useful life of these control rods was the thermal-cycle induced growth.

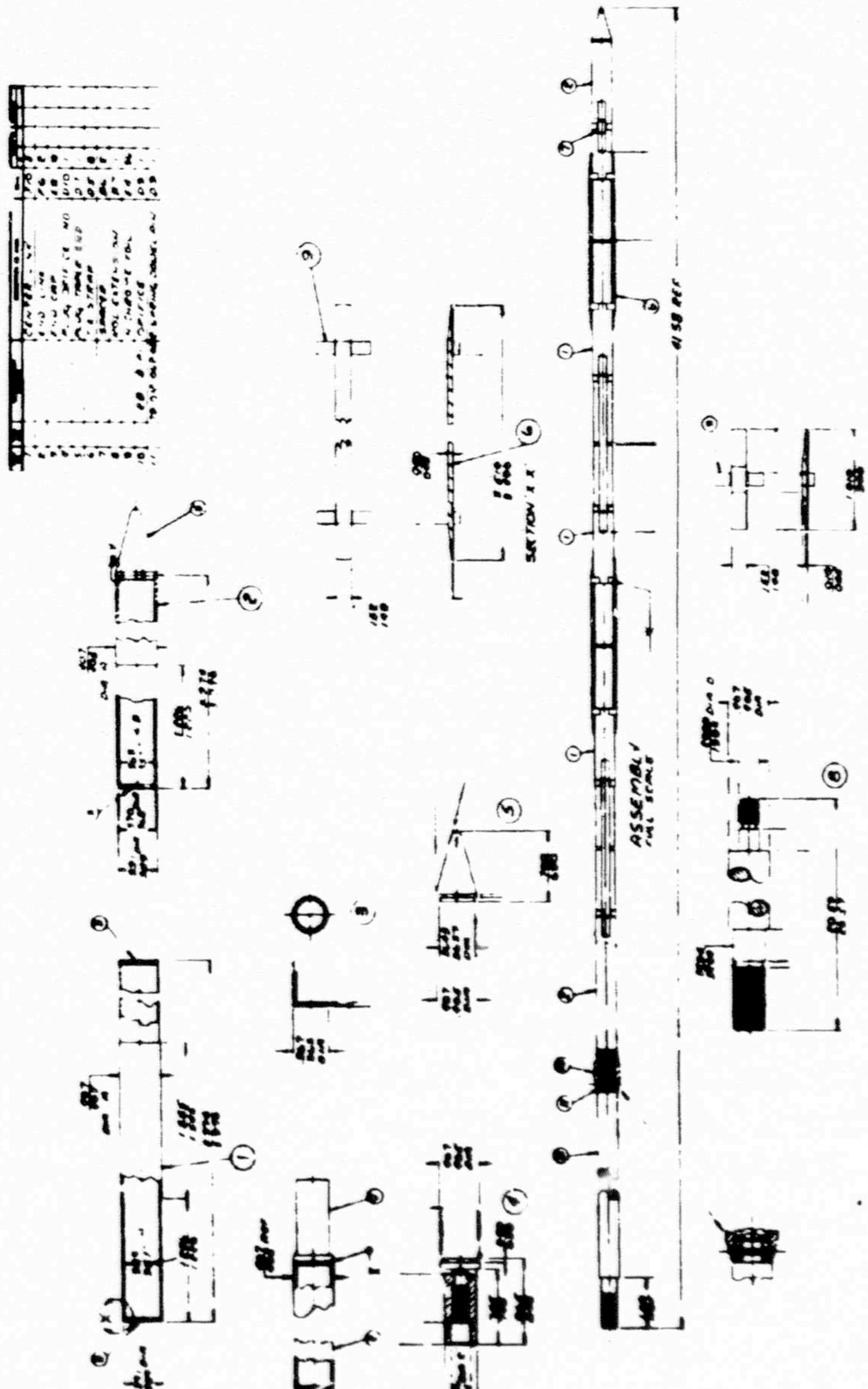

Fig. 3.25 – Control rod assembly (Dwg. 6650611)

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TABLE 3.8

THERMAL CYCLE TESTING OF CONTROL ROD ASSEMBLIES[a]

Test Number	Temperature Range, °F	Test Time, hr	Number Of Thermal Cycles	Time At Maximum Temp/Cycle, min	Cooling Time, min	Longitudinal Growth, in./in.	Radial Growth, in./in.	Growth Rate, in./in./~ 10^{-6}		Comments
								Longitudinal	Radial	
H-1	1650-500	300.9	498	30	1	0.0006	0.0053	1.2	11	
H-7	1650-500	1248.2	1673	30	1	0.0023	0.0180	1.4	11	0.060 inch bow in 8 inch span
HI-8	1800	641	6		static air cooled	-0.0014	0.0010	-230	170	Isothermal test
H-6	1800-1000	1040.9	919	60	1	0.0070	0.0260	7.6	27	0.030 inch bow at end of segmen due to pin-hole leak in end cap weld
H-9	1800-1000	1022.9	476	120	1	0.0010[b]	0.0078	2.1	16	
H-12	1800-1000	1002.1	254	120	[illegible]	0.0024[b]	0.0091	9.5	36	
H-10	1900-1000	1016.3	491	120	1	0.0059[b]	0.0240	12	49	0.030 inch gap closed after 856 hours

[a]An assembly consists of two 4 inch long x 0.46 inch diameter 80Ni - 20Cr clad, 38 weight percent Eu_2O_3 - 62 weight percent Ni core, control rod segments suspended vertically in a furnace. Samples H-1, H-6, and H-7 had a 1000 psi load on the straps. HI-8 was a single segment held horizontally.

[b]X-ray indicates longitudinal shrinkage of the core material.

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3.12 CONTROL ROD GUIDE TUBE

The XMA-1A control rod guide tube provided a path for supporting and guiding the control rod and carried the axial loads of the rear tube sheet. The tube was deflected within the core by the interaction of forces from the following conditions:

1. Differential thermal expansion between front and rear tube sheet.
2. Air loads on the front and rear tube sheet.
3. G loading on the reflector shell and tube sheet.
4. Tolerance stackup of parts throughout the core.

The core contained 129 guide tubes each having an outside diameter of 0. 60 inch, an inside diameter of 0. 54 inch, and 99. 8 inches long. The tubes were constructed of Inconel X, chrome-plated on the inside to reduce the sliding friction between the control rod and guide tube and to reduce the possibility of seizing and galling (Figure 3. 26). Each guide tube was fixed to the front tube sheet by a friction latching device. One hundred and twenty-two guide tubes were double flanged at the rear end to carry the axial loads of the rear tube sheet and to provide a place for the remote handling equipment to grasp the tube during remote disassembly of the core.

To disassemble the core after the fuel cartridges were removed, the guide tube latch was released and the tubes along with the rear tube sheet were pulled away from the assembly permitting the moderator assemblies to be remove.

The complete analysis of the guide tube system was published.[19]

The control rod guide tube latch was designed to maintain proper guide tube position in the core by securing the tube to the front grate. The requirements for the latch were:

1. In the event of a jammed control rod the latch must withstand a short-time axial load on the guide tube of 2170 pounds.
2. It should conform to dimensional limits of 1. 25 inch length forward of the front grate and 1. 5 inch diameter at the bellmouth level.
3. To provide a bushing for the integrated part of the front grate assembly.
4. To provide the flow of cooling air outside the guide tubes for core moderators.
5. To allow remote handling assembly and disassembly of the guide tubes.
6. To provide positive locking of the latch bushing to the front grate and the latch nut to the latch bushing.

The final design of the guide tube latch is shown in Figure 3. 27. The gripping action of the latch was provided by the friction of fingers against the guide tube. The radial force pushing the fingers against the guide tube was provided by interference between the fingers of the latch bushing and the space available between the guide tube and the inside of the latch nut. This interference varied between 0. 0015 inch and 0. 0025 inch on the radius providing a radial gripping force of 3120 to 5200 pounds.

In order to conform to dimensional limits, the length of contact of the fingers on the guide tube had to be limited to slightly under 0. 5 inch. A compromise was made between the total length available and the excessive tangential stress in the guide tube due to concentration of the radial load of the fingers against the guide tube. A length of 0. 75 inch had to be allowed for slotting the fingers in order to provide flexing in the radial direction. The remainder of the 1. 25 inches of length allowed forward of the front grate was allotted to the threads and tool relief. The outside diameter of the latch nut was limited to 1. 15 inches in order to provide clearances with adjacent bellmouth assemblies.

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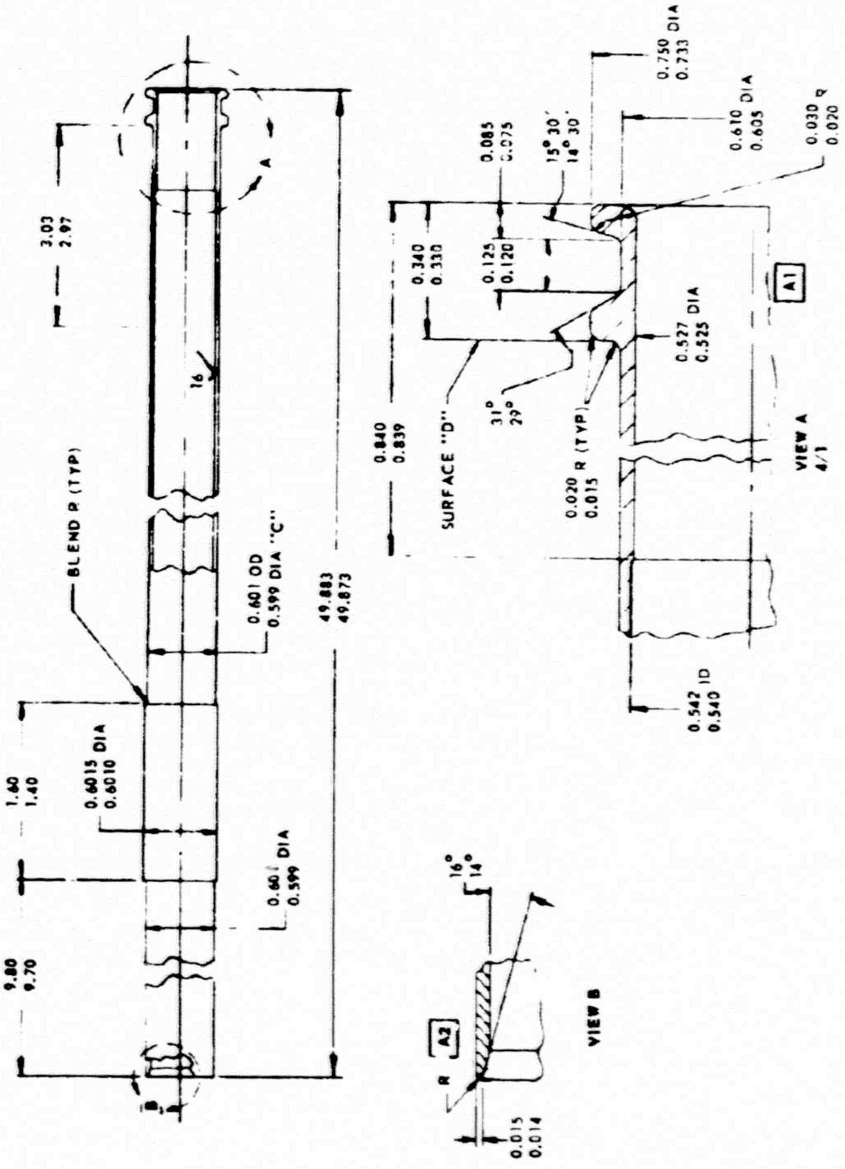

Fig. 3.26 – Control rod guide tube (101B6393)

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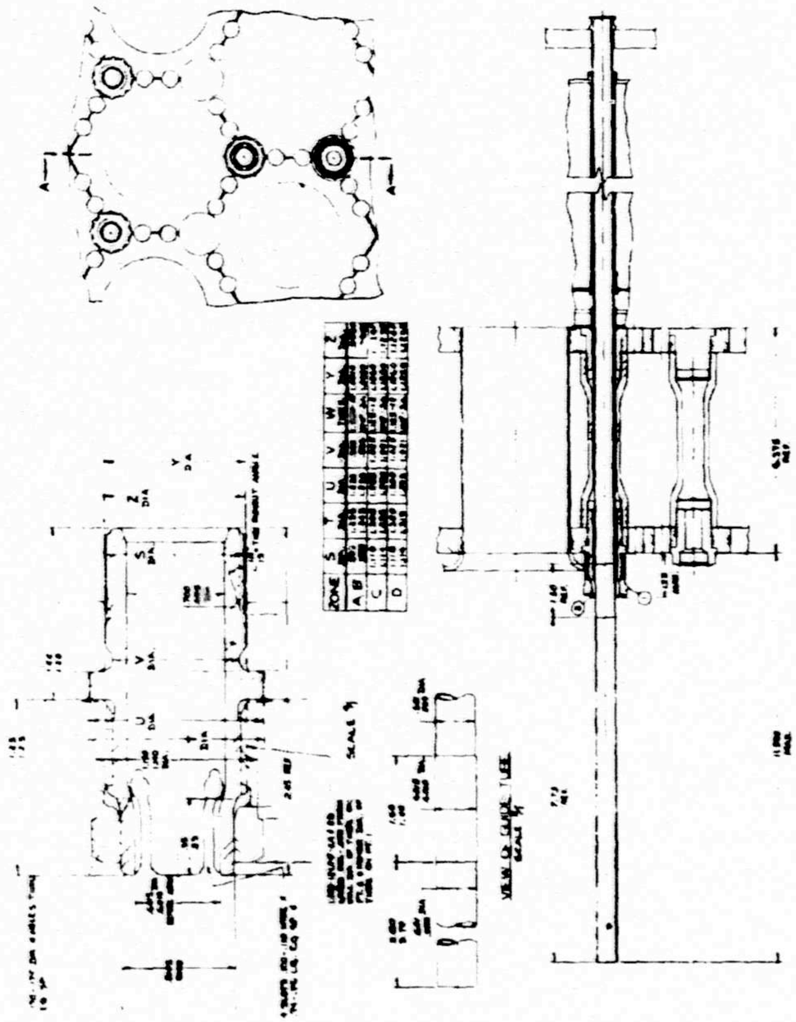

Fig. 3.27 – Guide tube latch design (Dwg. 656E547)

In addition, it was necessary to incorporate the latch and front grate bushing into one part. Thus, the latch bushing had a latch configuration on its forward end and a threaded rear end similar to the guide tube bushings of the front grate assembly.

Since the latch had to be a permanent part of the front grate, it was necessary to select a material that was harder than Inconel X to reduce wear of the latch fingers during the replacement of the guide tubes. In addition to the hardness requirement, this material had to have oxidation resistance properties for use in an environment of 800°F, rapidly moving air. Vasco Jet 1000 was selected for its hardness of R_c 50 (room temperature) and its resistance to oxidation. It also had a coefficient of thermal expansion similar to that of Inconel X.

Another design requirement was the provision of passages for airflow to augment and improve distribution of cooling air to the moderators. Use of fingers provided air passages for the moderator cooling air (a flow area of 0.096 to 0.109 square inch). Holes were provided to improve the flow at the transition point where the airflow path changed from between the fingers, to the annulus between the guide tube outside diameter and bushing inside diameter.

Design of the latch parts had to provide remote handling capabilities. Lead-in was provided on the latch nut and the forward end of the fingers on the latch bushing.

Locking of the latch bushing was a problem that had not been completely solved. Locking pins between the flange on the latch bushing and the front plate of the front grate was a possible solution. Half of the holes accommodating the pins could be machined in the edge of the latch bushing flange. These half-holes would provide a means of torquing the bushing into the front grate assembly.

3.12.1 CONTROL ROD AND GUIDE TUBE AEROTHERMAL

An analysis was made to determine the cooling flow required in the annulus between the control rod and guide tube so that a maximum control rod surface temperature of 1650°F and/or a maximum guide tube surface temperature of 1200°F was not exceeded. The study was based on the following conditions and assumptions:

Geometry

1. Control rod diameter, 0.36 inch.
2. Rod cladding thickness, 0.02 inch.
3. Guide tube inside diameter, 0.54 inch.
4. Guide tube outside diameter, 0.60 inch.
5. Active core rod insertion, 20.0 inches.

Conditions and Properties

1. Reactor power, 147 megawatts.
2. Inlet air temperature, 694°F.
3. Rod and cladding thermal conductivity, 0.36 Btu/hr-in-°F.
4. Guide tube thermal conductivity, $0.653 + 0.347 \times 10^{-3}$ Btu/hr-in-°F.
5. Cladding and guide tube emissivity, 0.7.
6. Rod average longitudinal heating rate, 4431 Btu/hr-in.^{3}.
7. Cladding average longitudinal heating rate, 2072 Btu/hr-in.^{3}.
8. Guide tube average longitudinal heating rate, 2050 Btu/hr-in.^{3}.

Assumptions

1. Only the active core portions of the guide tube and control rod were considered.
2. All heat generated in the control rod, cladding, and guide tube was assumed to pass to the cooling air in the annulus.

3. No allowance was made for radial power deviation.
4. The same longitudinal power profile was used for the control rod, cladding, and guide tube.

It was determined that the cooling flow required in the annulus was 0.0333 pound per second or a total flow of 129 x 0.0333 = 4.3 pounds per second. Under these flow conditions, the maximum control rod surface temperature was less than the maximum allowable 1600°F. Calculations indicated that the resulting flow would produce a turbine inlet dilution penalty of approximately 2°F.

The resulting longitudinal temperature profiles of the center of the control rod, surface of the control rod, surface of the guide tube, and cooling air are shown in Figure 3.28.

An additional analysis was made to determine the weight flows and resulting steady-state temperature profiles when an orificed, average control rod was withdrawn from an initial insertion in the active core of 20 inches to insertions of 10 and 5 inches.

When the control rod was withdrawn from 20 inches to 10 inches, the weight flow in the annulus increased from 0.0333 to 0.0368 pound per second. When withdrawn to 5 inches, the flow increased to 0.0383 pound per second.

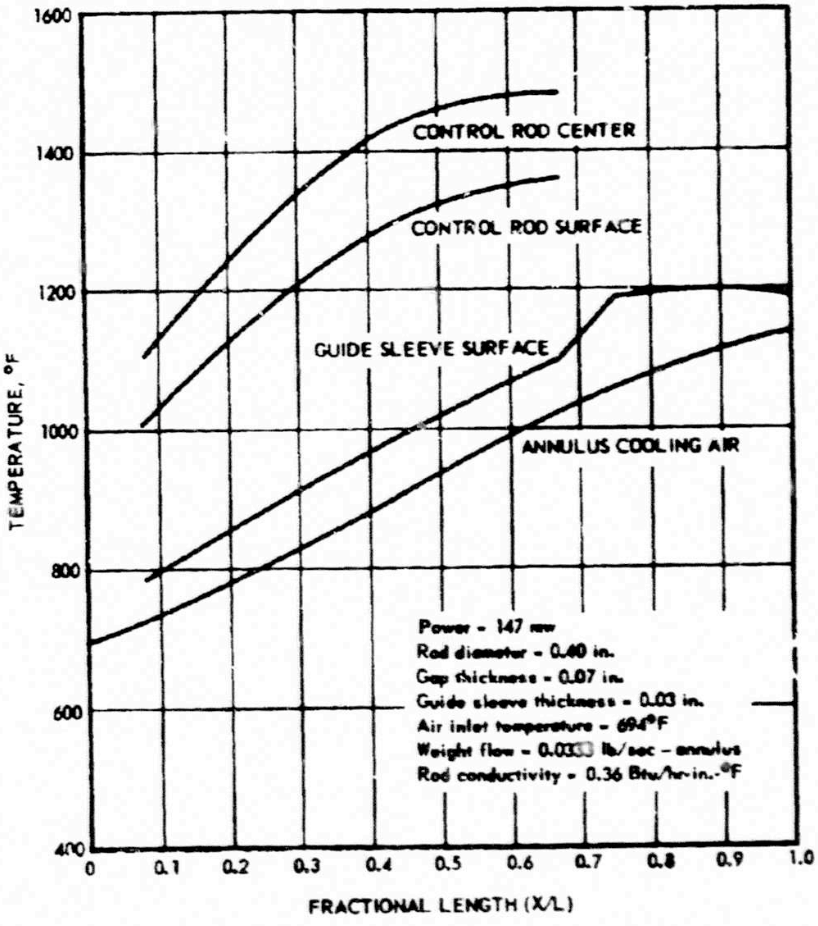

Fig. 3.28 – Control rod and guide tube temperature profile – rod inserted 20 inches

The resulting longitudinal temperature profiles are shown in Figures 3.29 and 3.30 for 10 inch and 5 inch insertions, respectively.

3.13 EXPERIMENTAL DATA

3.13.1 NUCLEAR

The ASM reactor was a critical assembly designed to mock up the XMA-1A. The reactor was mounted in a horizontal position as shown in Figure 3.31. A detailed description of the test cell in which the reactor was located and the hydraulic lift which effected closure of the two halves of the reactor is contained in reference 20.

3.13.1.1 Advanced Solid Moderator Reactor Experiment No. I

The specifications for the initial buildup of the ASM had to be issued before the XMA-1A reactor moderator volume fraction and distribution was finalized. Therefore, the specified moderator volume fraction for the ASM-I was higher than the design reactor and it was assumed that a moderator reboring operation would be completed after the criticality of the core was established.

The ASM-I was an assembly of 151 hexagonal cells approximating a cylinder, 56.28 inches in diameter and 27.5 inches in height. A cell was composed of a moderator hex surrounding an annular fuel region with a central moderator rod. The side and front reflectors were beryllium. The moderator volume fraction was equal to 0.3230 and the fuel region loading was 400 pounds of uranium-235 and 2422 pounds of nichrome. At that time there was a longitudinal variation in heat transfer area in the design reactor which was mocked up in the ASM-I by varying the nichrome loading, i.e., stages 4 through 8 had an equivalent 2573 pounds of nichrome and stages 1 through 3 and 9 had an equivalent 2232 pounds of nichrome.

3.13.1.2 Advanced Solid Moderator Reactor Experiment No. II

The second buildup of the ASM incorporated a more accurate mockup of the design reactor moderator volume fraction and distribution. Due to a change in twelve of the outermost moderator hexes, the effective core diameter was increased to 56.61 inches. The moderator volume fraction was reduced to 0.2980 by reboring the moderator hexes and changing the moderator rods. Although the total fuel loading remained at 400 pounds of uranium-235, the longitudinal distribution was such that stages 1 through 3 had an equivalent 550-pound loading, stages 4 through 6 had an equivalent 400-pound loading, and stages 7 through 9 had an equivalent 250-pound loading. The nichrome loading was increased to 2481 pounds with stages 1 through 3 having an equivalent 2154 pounds, stages 4 through 6 having an equivalent 2573 pounds, and stages 7 through 9 having an equivalent 2717 pounds.

Shield mockups were added to the assembly. The radial shield was mocked up with 3.5 inches of Type 304 stainless steel. To mock up the front plug, beryllium plugs, 3.5 inches in diameter by 1.85 inches in length, were located flush against the forward ends of each fuel element support inside the fuel element support tubes. The rear plug mockup was constructed of beryllium oxide and mild steel slabs placed on shelves outside the rear tube sheet. The front reflector region was also modified to include a mockup of the split tube sheet of the design reactor.

3.13.1.3 Advanced Solid Moderator Reactor Experiment No. III

The most significant difference between ASM-III and its predecessor, ASM-II, was the addition of 100 pounds of uranium-235 bringing the total core loading to 500 pounds of uranium-235. The fuel distribution was changed so that stages 1 through 3 had an equivalent

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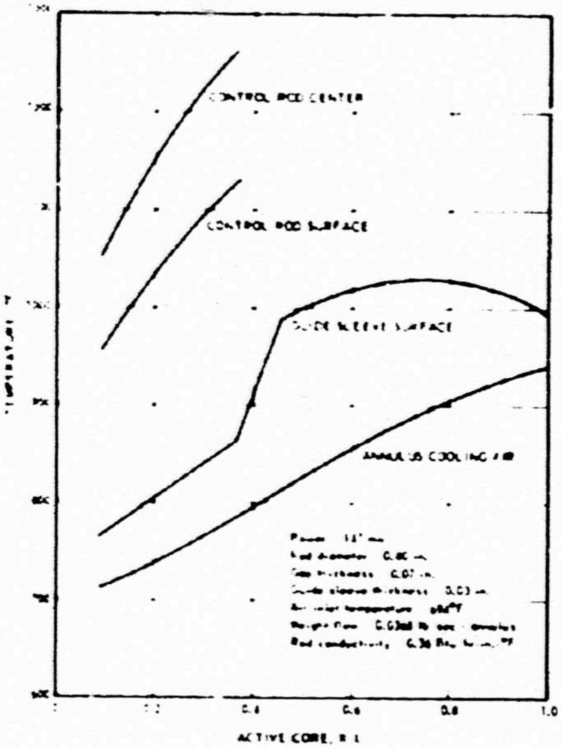

Fig. 5.29 – Control rod and guide tube temperature profile – rod inserted 10 inches

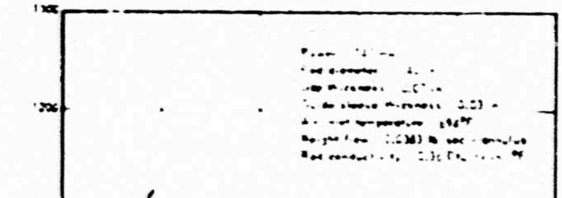

Fig. 5.30 – Control rod and guide tube temperature profile – rod inserted 5 inches

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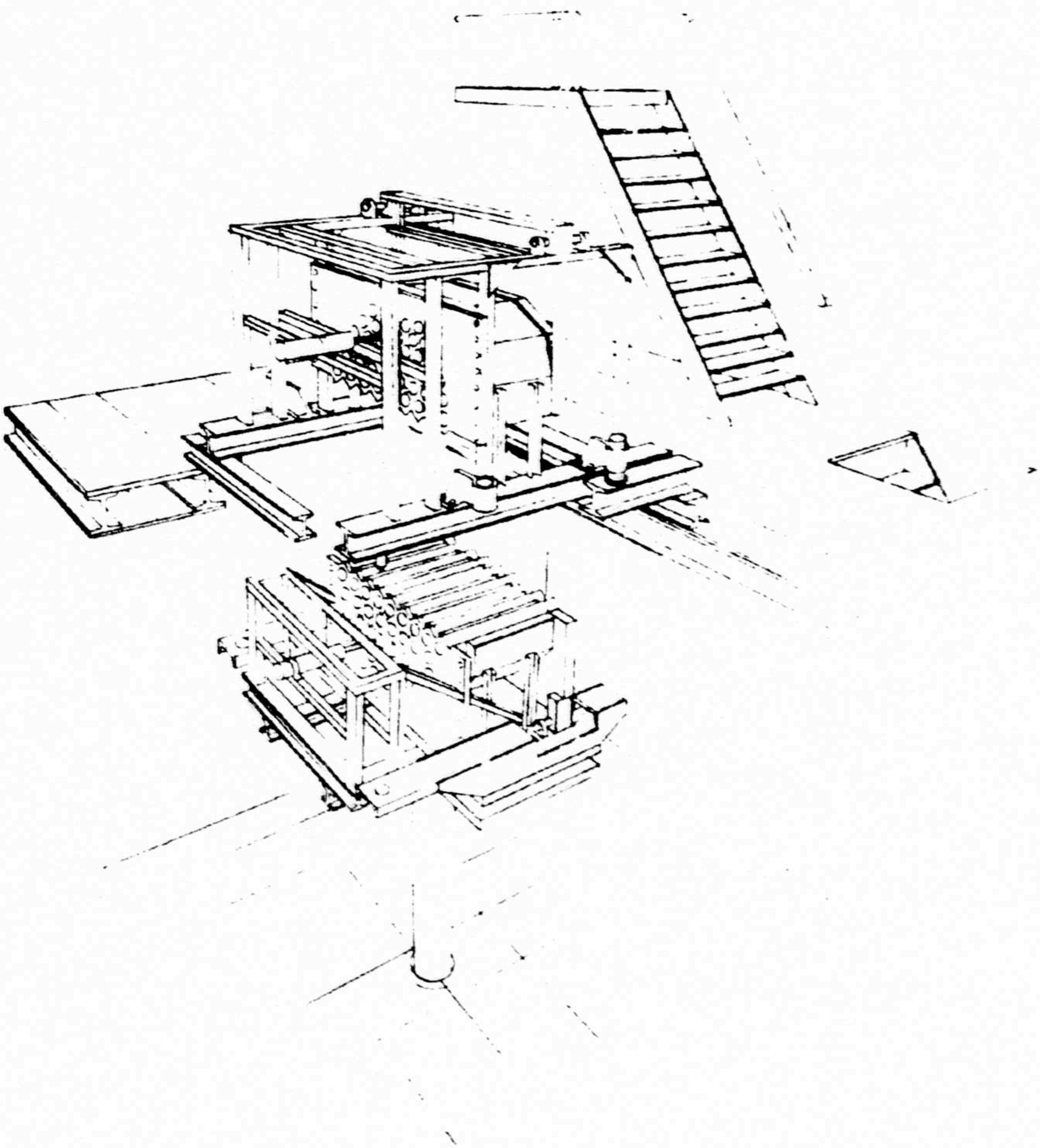

Fig. 3.31 – ASM assembly

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750-pound loading, stages 4 and 5 had an equivalent 450-pound loading, and stages 6 through 9 had an equivalent 337.5-pound loading. The nichrome loading remained approximately the same, i.e., 2478 pounds, with an equivalent 2667 pounds in stages 1 through 3, an equivalent 2303 pounds in stages 4 and 5, and an equivalent 2425 pounds in stages 6 through 9.

The thickness of the radial shield mockup was reduced from 3.5 to 2.87 inches. Nickel and boral were added to the rear plug mockup to more nearly mock up the design plug materials.

The core was divided into five radial regions to account for eight variations of the moderator rod size, five variations of the inner bore diameter of the moderator hex, and seven variations in fuel and nichrome loadings. Longitudinally there were five core regions which accounted for moderator variations and three different fuel and nichrome loadings.

Program I_2 (multiregion P_3 approximation to transport theory) and C_2 (bare reactor calculation) of IBM 704 Program GEORGE[3] were used to determine the two-group constants required by Program F_2[21] (one-dimensional, two-group diffusion calculation). Clean core excess reactivity was calculated by the consistent reflector savings method.

Cell corrections were applied to the 16th, 17th, and thermal groups in Program C_2.[22] The Behren's correction option which calculated $f_{n,r} = f_{n,z}$ was used in the analysis. The diffusion coefficients incorporating two-group buckling were utilized by Program F_2 which calculated the bucklings for each region. For dimensions the regions of the active core utilized the height and diameter of the active core. The radial reflector and shield regions assumed the height of the active core and an infinite (10^6 centimeter) diameter. The longitudinal reflector and shield regions assumed an infinite (10^6 centimeter) height and the diameter of the active core.

3.13.1.4 Analysis Results

The clean core excess reactivities for the three ASM assemblies are given in Table 3.9. The experimental values are also given for comparison purposes.

The predicted gross radial power for eighteen typical cells of the three ASM configurations are given in Table 3.10. The one-dimensional predictions are based on Program F_2[21] power curves. The two-dimensional prediction for the ASM-II was obtained from Program CURE. The measured values are also presented in the table for comparison purposes.

The method (referred to as G_2[4] - I_2[5]) used for correlating the fine radial power of the ASM-III was the same as the method for predicting fine radial power incorporated in the first stages of the XMA-1A fuel element design. $G_2 - I_2$ utilizes one Program G_2 (multi-energy multiregion one-dimensional neutron-diffusion theory) and one Program I_2 (non-energetic P_3 approximation to neutron transport theory). $G_2 - I_2$ assumes that diffusion theory represents a good approximation to the fine radial power distribution except for the

TABLE 3.9

ASM REACTIVITY VALUES

Experiment	Analytical, Δk/k %	Experimental, Δk/k %
ASM-I	5.2	3.9
ASM-II with radial shield	3.7	2.0
ASM-III with all shields	10.6	8.6
ASM-III with radial and front shields	7.6	7.0
ASM-III with radial shield	6.7	6.2
ASM-III with front shield	5.0	5.8

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TABLE 3.10

GROSS RADIAL POWER DISTRIBUTION

Measurement Element	ASM-I One-Dimensional Prediction	ASM-I Measured	ASM-II One-Dimensional Prediction	ASM-II Two-Dimensional Prediction	ASM-II Measured	ASM-III One-Dimensional Prediction	ASM-III Measured
700	1.122	1.205	0.950	0.912	1.006	0.970	1.058
210	1.112	1.180	0.942	0.906	0.966	0.964	1.002
220	1.067	1.110	0.923	0.869	0.939	0.924	0.972
221	1.072	1.118	0.928	0.892	0.993	0.962	1.013
230	1.023	1.081	0.950	0.903	0.979	0.914	0.943
231	1.030	1.065	0.906	0.863	0.935	0.939	0.938
240	1.028	1.012	0.979	0.940	0.950	0.989	0.962
241	1.042	1.069	0.957	0.952	1.002	0.969	0.941
242	1.058	1.064	0.933	0.898	1.003	0.932	0.981
250	0.932	0.962	1.058	1.028	1.009	0.967	0.968
251	0.948	1.002	0.997	1.048	1.021	1.004	0.987
252	0.963	1.031	0.936	0.903	0.928	1.026	1.005
260	0.931	0.906	1.100	1.147	1.103	1.074	1.149
261	0.991	1.005	1.107	1.150	1.087	1.092	1.129
262	0.942	0.885	1.032	0.975	0.976	0.984	0.962
263	0.874	0.870	0.997	0.973	0.968	0.954	0.935
272	0.971	0.782	1.086	1.147	1.057	1.102	1.064
273	1.011	0.892	1.175	1.145	1.084	1.116	1.046

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thermal contribution which is represented by transport theory. Thus the fine radial power becomes

$$P(r) = P(r) - N\, \nu\Sigma f_{th}\, \phi^1_{th}(r)\, \phi^2_{th}(r)$$

where

$P(r)$ = fine radial power density output of G_2 normalized to 1 at the outermost radius of the fuel region

$\nu\Sigma f_{th}$ = thermal fission cross section (G_2 output)

$\phi^1_{th}(r)$ = G_2 thermal flux at radius r

$\phi^2_{th}(r)$ = I_2 thermal flux at radius r normalized to the G_2 thermal flux at the outermost radius of the fuel region

N = normalizing factor which satisfies the following relationship at the outermost radius of the fuel region

$$N\left[\sum_{n=1}^{18} \left(\nu\Sigma f_n \phi_n + \nu\Sigma f_{n-1} \phi_{n-1}\right)\frac{\Delta u}{2} + \nu\Sigma f_{th}\phi_{th}\right] = 1.$$

In the above definitions the outermost radius of the fuel region is the outermost radius at which a power density is given in the G_2 output.

3.13.2 AEROTHERMAL

A program of XMA-1A component cold-flow tests was initiated to determine possible problems in pressure drop and flow distribution, and to test the validity of assumptions made in the course of the design. The series of tests indicated that the pressure losses in the various flow passages and the distributions of the flow within various components were such that the core performance could have exceeded that specified in the design, after only minor design changes.

Results of primary interest are summarized in reference 23.

3.13.2.1 Fuel Elements

As reported in reference 24, the fuel element friction factor for Reynolds numbers ranging from 3.4×10^4 to 8.0×10^4 was determined to be $f = 0.057\, R_e^{-0.183}$. This implied a multiplier of 1.25 times the standard rough pipe relation, compared with the 1.5 multiplier assumed in the design. These data were obtained for ETR cartridges consisting of 3-inch-stage lengths employing rounded leading edges.

Various tests were conducted to determine the effect of rounded leading edges on friction factor. Reference 25 reports that the pressure loss for the fuel element section of a 6-stage (1.5 inch lengths) MTR cartridge was reduced approximately 10 percent when the leading edges were rounded. Tests of a 19-stage (1.5 inch lengths) XR-27 cartridge, as reported in reference 26, indicate a 16 percent reduction in friction factor by rounding the leading edges.

Fuel element flow distribution measurements were made as a part of the experimental program. At the design point condition, variations in mass velocity between annuli at the exit of the second stage were as large as ±20 percent. The velocity profile entering the first stage was seriously perturbed by the diffuser section immediately upstream (weight flow profile exhibited a peak-to-minimum ratio of 2.0). In addition, variations in flow rate within the center moderator rod introduced appreciable changes in the flow distribution entering the inner annuli of the fuel element. Although the experiments were not completely analyzed at the time XMA-1A effort was terminated, studies indicated that a redesign of the entering flow passages would suffice to reduce the above variation to within ±5 percent.

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3.13.2.2 Moderator

Experimental measurements of friction factors for moderator triflutes were reported in reference 27. The friction factor was determined to be $f=0.0435\ R_e^{-0.165}$ which implied a multiplier of 1.15 times the rough pipe relation, compared with the 1.0 multiplier assumed in the design.

Based on the over-all pressure drop measured during the above test from the inlet of the front tube sheet to the exit of the rear tube sheet, the predicted pressure drop at the design point was 22 psi with no restrictor. Four restrictors were tested and covered the range up to 49 psi. Thus, from these data, the correct restrictor design could be chosen to selectively control the moderator flow.

Additional tests were conducted to determine whether the short entrance plenum to the moderator triflute would allow the entering cooling flow to distribute itself reasonably among the triflute holes. An additional factor affecting the flow distribution was the wide variation in hole geometries (size and shape). The measured ratio of local-to-average mass flow covered a maximum range of 0.962 to 1.172 for two runs at Reynolds numbers of 3.02×10^4 and 3.91×10^4. Excluding the flow in the center hole, the ratio ranged from 0.962 to 1.085.

3.13.2.3 Control Rods

The friction factor for flow in the annulus between the guide tube and the strapped or poison portion of the control rod was determined to be $f=0.089\ R_e^{-0.233}$, based on a hydraulic diameter calculated from a weighted average value of free flow area and wetted perimeter.

During the above test, it became obvious that the restrictor design would require modification prior to use. Pressure drops for most of the restrictors were too large to be of practical interest in operating the XMA-1A reactor. The use of two restrictors in series was suggested as a solution to the problem.

3.13.3 ETR TESTING

An in-pile testing program utilizing the Engineering Test Reactor (ETR) 6 by 6 facility at the Idaho Test Station (ITS) was established to support the fuel design for the XMA-1A reactor. Modifications were made in the program at various times because of facility availability problems and program redirection. The two major shortenings of the testing program were the result of the XMA-1A cancellation and the suspension of the 80Ni - 20Cr evaluation program.

The purpose of these tests was to obtain data on the mechanical, aerodynamic, thermodynamic, and nuclear characteristics of the fuel under XMA-1A design conditions. In particular, the following were investigated:

1. The feasibility of 3-inch-stage design and a comparison with 1.5-inch-stage design.
2. The effect of dead edge size.
3. The effectiveness of various thicknesses of cladding.
4. The feasibility of the unfueled outer ring concept.
5. The effect of time, temperature, and dynamic head.
6. The adequacy of the final XMA-1A design.

Seven cartridges were tested. The last, specimen 66F55, was the first of a series utilizing a new method of ring forming. It demonstrated excellent characteristics until it was damaged during an unscheduled reactor shutdown. No further tests were run since the 80Ni - 20Cr evaluation program was terminated at the end of that test. Significant advance had been made in the 80Ni - 20Cr design and good progress was in view at the time of cancellation.

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Seven XMA-1A type fuel cartridges were tested in the ETR. Samples 66F5 and 66F7 were of the 1.5-inch stage-length 17-stage type. The remaining were all of 3-inch, 9-stage configuration.

The purpose of the tests was to demonstrate the ability of the cartridges to operate satisfactorily for 100 hours at the conditions required for XMA-1A performance. These conditions were as follows:

1. Cartridge total power, 0.88 megawatt.
2. Inlet air temperature, 692°F.
3. Bulk outlet air temperature, 1600°F.
4. Weight flow, 3.45 pounds per second.
5. Inlet pressure, 151 psia.
6. Exit dynamic head, 4.7 psi.
7. Maximum predicted plate temperature, 1790°F.

3.13.3.1 Specimen 66F5

The first XMA-1A test cartridge run in the ETR was specimen 66F5. This was a 1.5-inch 17-stage cold-rolled cartridge. It was run for 100 hours at less than design conditions. Unsatisfactory neutron flux distribution accounted for the inability to reach the design point. The main contribution of this test was data for the fixture of boron poison shims to later test cartridges.

The average exit air from the sample was 1223°F. At this temperature there was no significant deformation of the rings.

3.13.3.2 Specimen 66F7

Specimen 66F7 was similar to 66F5 except that the ring dead edge (rear) was increased and the boron steel liner thickness was increased from 0.020 to 0.053 inch to reduce the circumferential scallop seen in the earlier test. Specimen 66F7 ran for 100 hours with an average exit air temperature of 1475°F.

The design test conditions were not reached with this sample because of power scalloping. With the highest plate temperature at maximum allowable, the average plate temperature and resultant exit air temperature were low.

When the test was concluded it was found that pieces of stainless steel foil had lodged between the orifice plate and the first stage of the cartridge. This caused two cartridge sectors to operate at higher temperatures.

Following 80 hours of endurance running the ETR core was reloaded and the sample operated in the new core for 20 hours. Very little change in the scallop was noted.

No blisters occurred during the test but ring deformation was noted at two angles on nearly every stage.

3.13.3.3 Specimen 66F6

The third test in the series was specimen 66F6. This was the first 3-inch 9-stage cartridge and the first cartridge to operate at XMA-1A design condition. The scallop evident in the previous test was reduced to 1.07 by the use of a 0.077-inch-thick boron liner.

After 68 hours of testing at design conditions, ETR control rod 12 was withdrawn for improved testing conditions. This withdrawal was finished at 75 hours of testing. At 82 hours a fission product release was noted. Rod 12 was reinserted at 85 hours and the test terminated at 95 hours because of ETR fuel depletion.

Inspection of the cartridge showed extensive blistering and gross ring deformation. The major cladding break was on the portion of the sample affected by the rod 12 withdrawal.

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3.13.3.4 Specimen 66F4

Specimen 66F4 was the same design as 66F6, except, it had a shorter ring rear-dead-edge and used a boron liner 0.060-inch thick to reduce scalloping.

The specimen was run for 120 hours with an average exit air temperature of 1600°F and maximum plate temperature varying between 1800°F and 1900°F throughout the test.

In the course of the test, three ETR core loadings were used. The cartridge was operated for a total of 188 hours at ETR power levels over 30 megawatts. Fission products were released at 116 test hours and at 120 hours reached a level that indicated the location of the cladding break could be easily discovered in the inspection.

Inspection of the cartridge showed extensive ring deformations. The major cladding break was on stage 6 at an angle corresponding to rod 15 (which had been withdrawn several times during the test). The general appearance was better than specimen 66F6.

In achieving the performance level indicated, specimen 66F4 had higher maximum plate temperatures and larger gradients than would exit in the hottest XMA-1A cell. In the final design, the maximum plate temperature necessary to produce a hot streak of 1670°F air, as seen in specimen 66F4, was 1875°F in the sample but only 1830°F in the final core design. In the XMA-1A the hot streak would occur in a cell having power above the average for the core, and the temperature gradient would be lower than in specimen 66F4, which had a power equal to core average. Thus, the maximum material temperature magnitude and gradient were higher than would have been required in the XMA-1A to reach the performance goal.

Specimen 66F4 and 66F6 were not of the quality which would have existed in the XMA-1A. Edge seal blistering was virtually eliminated since these tests were run, and the introduction of hot roll formed rings greatly improved the strength of the element.

3.13.3.5 Specimen 66F22

Specimen 66F22 was originally built as a spare cartridge for 66F4. It was tested to provide data for use in the selection of operating parameters for a later series of tests which were to be conducted to demonstrate life temperature capability of the material.

The ETR data system was not operating properly during the test and accuracy was questionable. A 20.2-hour endurance test was conducted at 1700°F average exit air temperature by the use of two separate ETR core loadings. The first core loading was for 17.2 hours. A fission product release during the second core loading terminated the test.

A great deal of test time was run at a power level in excess of 100 megawatts, but short of test conditions and may have affected the life capability of the cartridge.

3.13.3.6 Specimen 66F23

Specimen 66F23 was similar to 66F6. It operated at an average exit air temperature of 1600°F for 89 hours.

Termination of testing was due to fission product release.

3.13.3.7 Specimen 66F55

Specimen 66F55 was the first of a scheduled series of tests designed to investigate the functional dependence of cartridge life on performance level. Based on the XMA-1A core final design, the sample consisted of warm-finished hot-roll-formed 80Ni - 20Cr rings. It was expected to exhibit a life of a factor three times greater than the cold finished material, operated at the same conditions.

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Specimen 66F55 ran for 202.5 hours at conditions approximating the XMA-1A design point without any detected fission product release. This was twice the life exhibited by specimens 66F4 and 66F23. The specimen could possibly have accomplished 300 hours of testing if the facility liner had not failed.

Aside from the physical damage resulting from the specimen assembly sticking in the liner tube, the cartridge, thermocouples, insulation, and stages were in good condition.

3.13.3.8 Test Design Discussion

Orificing - Each specimen to be tested in the ETR was given a cold flow test to calibrate the flow orifice for the determination of weight flow and dynamic head. The orifice was designed to divide the flow through the facility hole between the cartridge and its liner. It was apparent after the ETR data were analyzed that the cold flow calibration for the orifice was inconsistent with the data taken under elevated temperature conditions. This was attributed to the change in the inlet velocity ratio at the entrance of the cartridge and the consequent change in orifice calibration.

Redesign of the entrance air passage was completed in time for introduction into the 66F55 hardware design. The improvement consisted of lengthening the inlet and installing a perforated plate flow straightener. This change made the orifice calibration independent of the flow split.

Operation Below Design Power - The first six specimens achieved the desired testing conditions for only about 60 percent of the ETR operating time. Specimen 66F4, for example, to accomplish its 120 testing hours was in the ETR for a total of 188 hours at ETR powers above 33 megawatts. Specimen 66F55, however, was at design conditions for 95 percent of the operating time it was in the ETR.

It is felt that the earlier samples were affected to some degree by the near-test conditions.

Power Scallops - ETR control rods 12 and 15 were adjacent to the 6 by 6 facility. Since the positions of these rods affected the sample's flux environment, the test specifications limited the position of the rods to either full-in or full-out. Either position had to be specified before testing to permit the addition of boron-lining in the proper amount to reduce the circumferential power scallop.

During testing, it sometimes occurred that the control rods in question were inserted or removed. Normal removal rate was approximately 7 hours for the stroke.

Post-inspection of samples that encountered the control rod changes showed ring deformation in the sectors oriented toward the rods. With the removal of rod 12 in the specimen 66F6 test there was a subsequent fission product release from the rings in that rod's sector.

3.13.3.9 Test Evaluation

Life Expectancy - The purpose of the ETR program for 80Ni - 20Cr fuel testing was to develop a fuel element capable of delivering 1600°F exit air temperature for 100 hours or more at XMA-1A design inlet conditions.

The final test demonstrated a substantial increase in life capability. Based on these data and burner rig test information it was felt that the later design fuel cartridges could be operated for 300 to 400 hours or more at design conditions.

This increase was mainly due to the introduction of the hot-rolling warm-finishing method of ring fabrication.

Ring Deformation - Ring deformation was greatest in stages 7 and 8 at the peak temperature location. The outer rings at the unsupported aft end of the fuel stage became deformed most readily. In some cases there was contact between rings, causing flow blocking, hot-spots, and blisters.

Blisters - Blisters in the fuel rings of the earlier specimens were the result of openings in the fuel cladding which allowed the UO_2 to oxidize to U_3O_8. The volumetric change resulting in the core material caused blisters to raise.

The cladding openings were caused by ring deformation that blocked airflow and allowed burning of the clad. The later improvements in the ring stability greatly reduced deformation and blisters.

Fission Product Release - Tests, when run to failure, were terminated upon fission product release causing radioactivity of 100 milliroentgens per hour in the ETR cubicle. This level was set for personnel protection and because it permitted release to continue to a point where the cladding penetration point could be detected when the specimen was inspected.

Cartridge performance was relatively unaffected by fission product release, except, it generally meant that hot spots had formed because of ring deformation and that deterioration of the ring would increase at a faster rate.

Warm-Finished Hot-Rolled Rings - The warm-finished hot-rolling fuel-ring fabrication process was the greatest single contribution to increased life and strength capabilities in the 80Ni - 20Cr development program. With the introduction of this method the life expectancy of the fuel rings was increased by 2 to 4 times.

Specific data concerning the increased capabilities of the material are not available since there was only one test made in the ETR and only a few burner rig samples run before the program was cancelled.

Unfueled Ring Concept - All specimens had unfueled outer and inner rings to which the major ribs were brazed. This design was the result of HTRE No. 3 experience which indicated better tolerance control was needed at the outer ring passage to allow the nominal power to be increased in this area. The use of the unfueled ring allowed better tolerance control and thus eliminated hot and cold spots in the outer channel.

Instrumentation - Thermocouple reliability was less than desired in the ETR testing program. The most persistent problem was the difficulty of maintaining the thermoelement attachments to the fuel plate. Several designs were tested but none proved completely satisfactory.

A new thermocouple system was developed for high temperature use and was utilized in testing specimen 66F55. The thermoelements were Chromel A (nickel-chromium) and Hoskins 875 (iron-chrome-aluminum). The new system had the advantages of cost, sturdiness, and ease of fabrication over the platinum platinum-10 percent rhodium type that had been in use on previous cartridges. When the thermocouples were subjected to in-pile testing in the 66F55 it was found that all the Chromel A-Hoskins 875 thermocouples were erratic, due to faulty installation, and so were disregarded. A combination of thermocouple types had been used, the new type being in the sample high temperature areas. Since these were unreliable the sample temperature was inferred from the platinum platinum-10 percent rhodium thermocouples that had been mounted in the cooler areas of the specimen.

The conclusions reached from the ETR test data were:

1. No failures resulted from stress oxide penetration.
2. Fission product releases were due to ring deformation and resulting localized increase in temperature.

3. Ring deformation was directly related to the ETR 6 by 6 hole flux pattern. Boron shimming reduced, but did not eliminate power scallops caused by the facility.
4. Hot spot temperatures exceeded highest measured temperatures since thermocouple locations never coincided with the hot spots.
5. Warm-finished rings showed considerable increase in ring stability and life.
6. Thermocouple life was greatly improved by the flattened thermocouple design but faulty installation caused erroneous readings.
7. Failures were only small breaks in local areas of the fuel ring. Fission products released were not sufficient to require power plant shutdown.

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4. SHIELD

The shielding was divided between the reactor and crew compartment. Studies were made both at GE-ANPD and at Convair, Ft. Worth to arrive at the minimum shield weight for the installed nuclear power plant. Considerations were made to assure that crew, airframe, power plant, and the operational as well as maintenance problems were not over compromised.

The reactors were shielded to a level to allow personnel handling of the airframe after removal of the nuclear engines. All power plant and airframe components were located in regions of acceptable radiation levels. A fuel tank was located in the fuselage between the reactor and the crew shield to augment radiation attenuation.

4.1 DESCRIPTION

4.1.1 OVER-ALL SHIELD

The reactor shield for the XMA-1A power plant is shown in Figure 4.1. It consisted of a front shield, rear shield, side shield, and bypass valve. The front and rear shields and the bypass valve were cooled by the primary air flowing through them. Cooling of the side shield was accomplished with ram air in flight and an auxiliary air supply on the ground. The shield assembly was 140-inches long, had an outside diameter of 105 inches, and weighed 52,000 pounds.

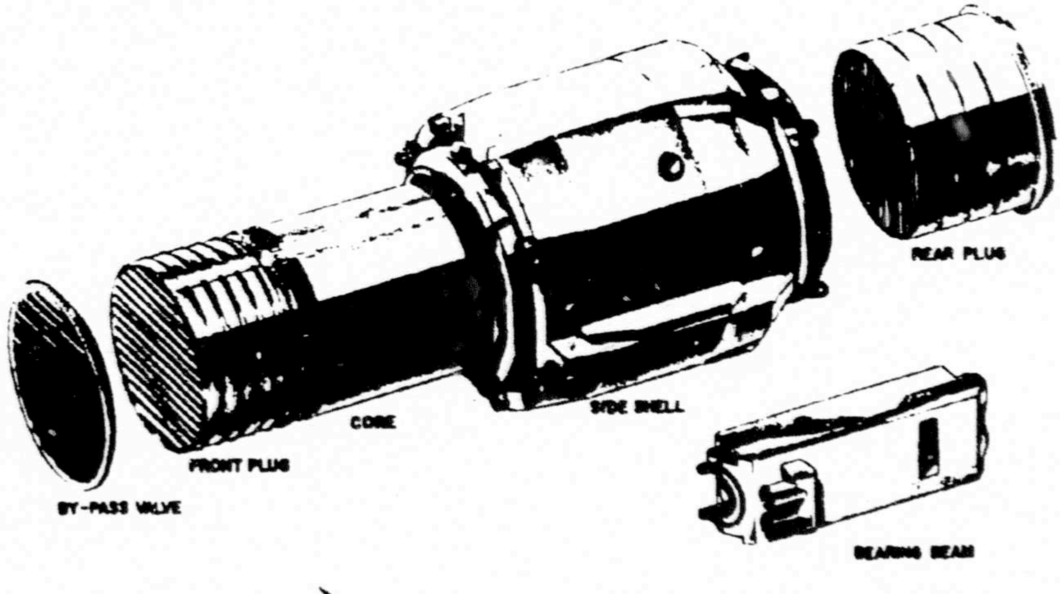

Fig. 4.1 – Reactor shield assembly (Dwg G-1211)

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4.1.2 FRONT SHIELD

The front shield, shown in Figure 4.2 consisted basically of a cylinder assembly, which was the main structural assembly, and wavy walls, which were inside of and supported by the cylinder assembly.

4.1.2.1 Cylinder Assembly

The cylinder assembly consisted of the forward flange ring, aft flange ring, and four intermediate rings, all connected by a cylindrical shell.

Each wavy wall was supported at the forward flange, the four intermediate rings, and the bypass valve. The connections at the forward flange carried only longitudinal loads; they were designed to allow distortion of the flange ring, due to thermal differences and mechanical loadings, without affecting the alignment of the wavy walls. The supports at the intermediate rings were designed to react vertical loads only and provided for motion, due to thermal expansion, in the longitudinal and lateral directions. Side load was transferred from a wavy wall to its related bypass valve element by a pin located at the center of the leading edge of the wavy wall.

The forward flange ring of the cylinder was used to attach the plug to the compressor-collector rear flange and to attach these parts in turn to the forward flange of the side shield. Four splines, located on the plug forward flange, were used to position and support the bypass valve. The splines were required to allow thermal and load distortion of the flange relative to the valve.

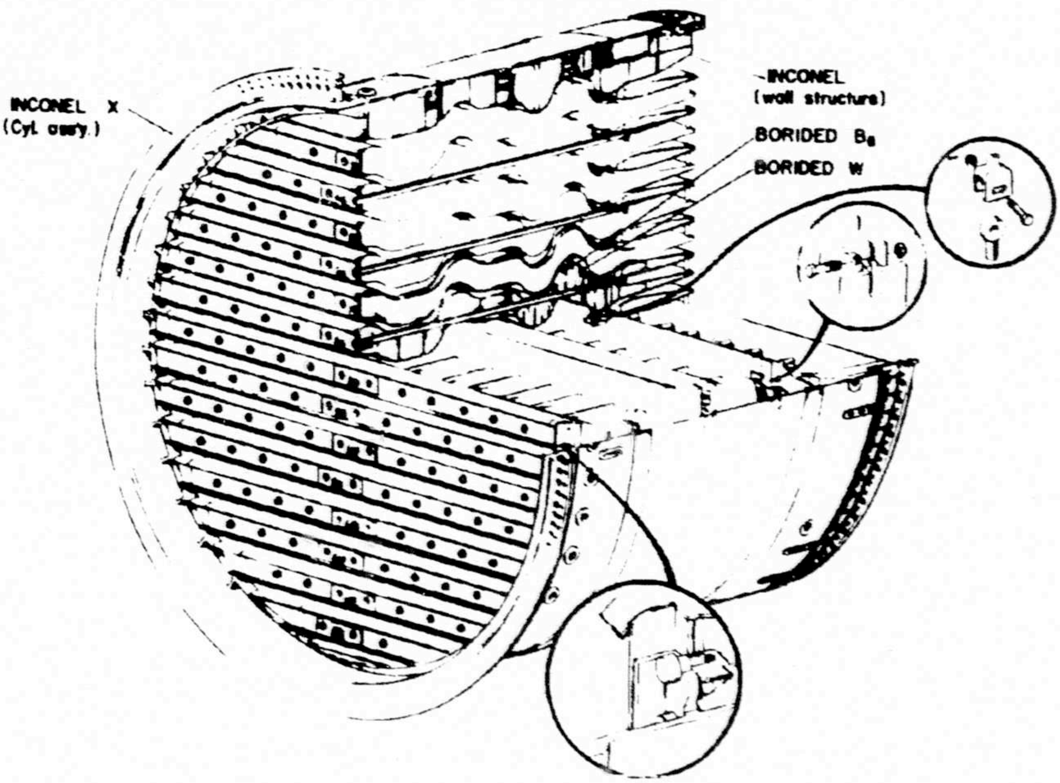

Fig. 4.2 – XMA-1A front shield (Dwg G-1284-A)

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The rear flange of the cylinder located and attached the reactor to the front shield by means of a rabbet and dowel pins. The flange was offset to match the smaller diameter of the core. Tubes, which carried cooling air from inside the plug, through the flanges, and into the core reflector area were located between the bolt holes in the flange.

The cylinder shell extended from the front to the rear flange and was stiffened by 4 H-section intermediate rings (to which the wavy walls were attached). To obtain optimum tolerance control, the shell sections, stiffening rings, and shell splice joints were made with mechanical, blind lock-bolts instead of welding.

In the final design stage of the front plug, thermal analysis indicated that during transient conditions severe temperature gradients existed within the cylinder assembly. To overcome this condition, a series of sheet metal baffles were designed to insulate the inside surface of the cylinder. These baffles prevented the direct flow of primary air on the cylinder and thereby reduced the temperature rate of change. The final thermal analysis data indicated that the baffles caused an increase in the maximum temperatures of the cylinder during steady-state operation but reduced the thermal gradients during shutdown or startup conditions.

4.1.2.2 Wavy Walls

The general arrangement of the wavy walls within the cylinder is shown in Figure 4.3. At the trailing edge of each wavy wall, the basic wall thickness was reduced and a diffuser strut was attached in order to better diffuse the primary air from the front shield into the plenum chamber ahead of the reactor. There were 14 walls, each about 3-inches thick, spaced approximately 0.86 inch apart. The resulting void-volume ratio of the front shield was 0.28.

The basic structure consisted of a gridwork of ribs and stiffeners to which wavy skins were spot-welded.

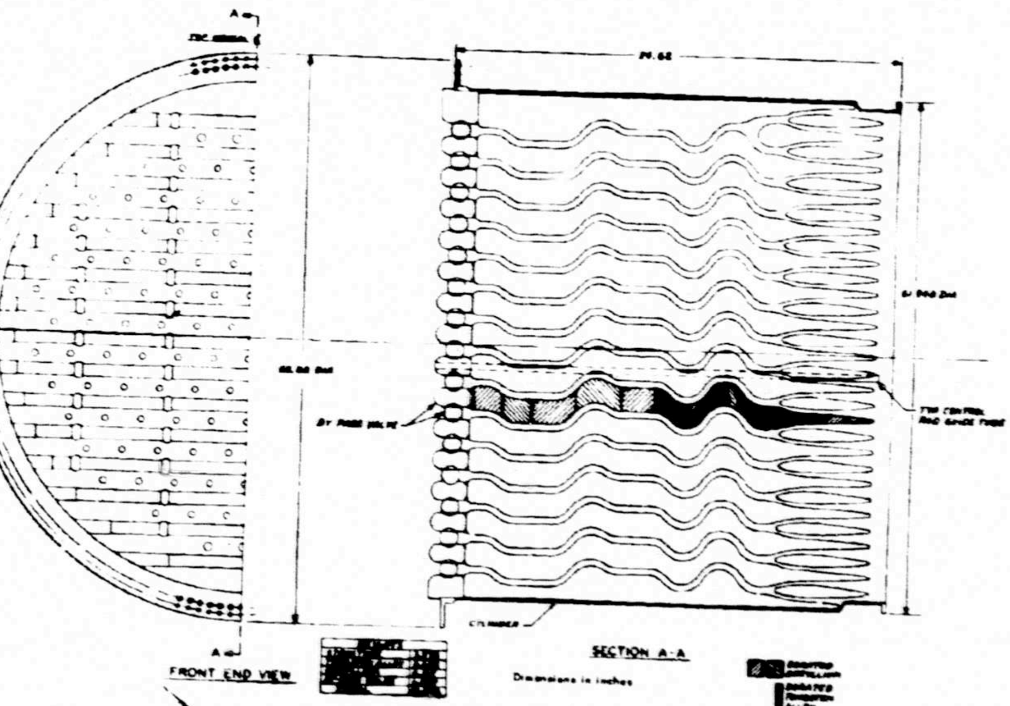

Fig. 4.3 – Schematic of XMA-1A front plug (Dwg SK645D631)

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The rear flange of the cylinder located and attached the reactor to the front shield by means of a rabbet and dowel pins. The flange was offset to match the smaller diameter of the core. Tubes, which carried cooling air from inside the plug, through the flanges, and into the core reflector area were located between the bolt holes in the flange.

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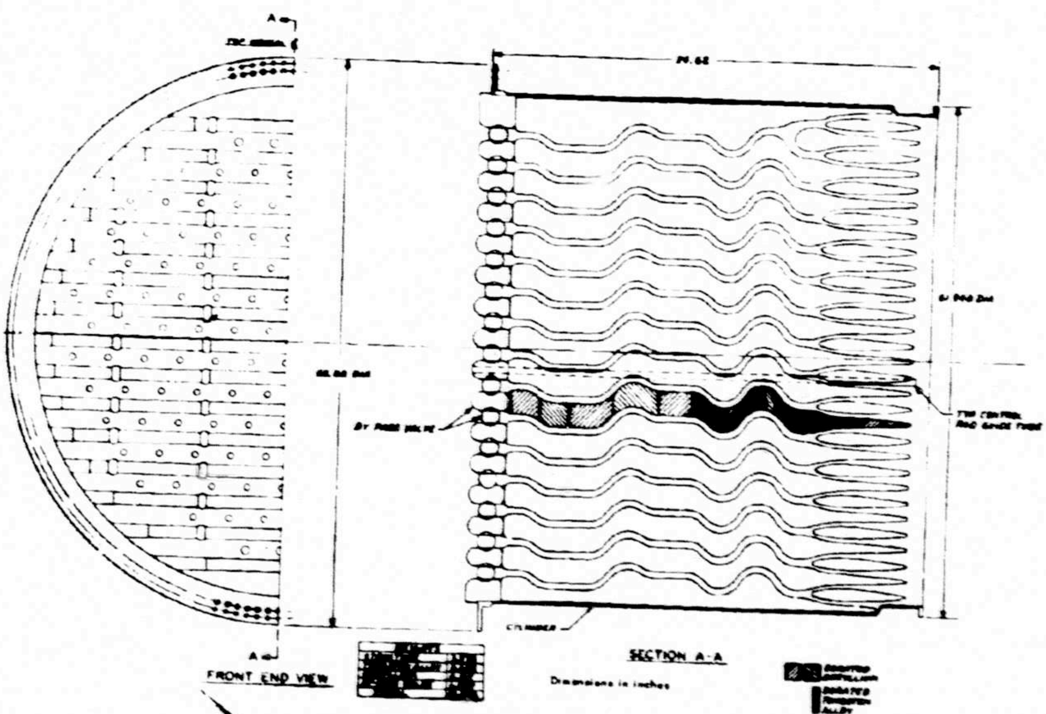

[illegible]g. 4.3 – Schematic o[illegible]-1A front plug (Dwg SK645D631)

In the final design of the stiffeners, the transient thermal conditions that occurred during startup and shutdown of the powerplant were major considerations. These conditions produced high stresses because of the temperature differences between the stiffener webs and the combination of stiffener flanges and outside skin. Thermal analysis and thermal tests of stiffener-skin test specimens showed that solid-web stiffeners yielded under the thermal stresses produced. To overcome this problem, material was removed from the webs in such a way as to minimize continuity in the spanwise direction.

Access for the control rods was provided by a series of axial holes spaced every 4 inches across the span of each wall. The control rod guide tubes passed through these holes and were welded into the wall structure at both ends to provide both a seal and structural continuity. Clearance for the control rods in the aft diffuser section was provided by internal beads in the bottom surface of the diffuser strut.

The wavy walls were filled with blocks of beryllium and tungsten alloy as shield material. These were considered nonstructural except for their ability to transmit compression loads. The interior of the walls were vented to the atmosphere (by means of a system of tubes) so that during powerplant operation the external air pressure produced maximum pressure on the skins of the walls.

The vent system also bled off any air that might enter the wall as a result of weld cracks, porosity, etc. Design of the walls to operate under large external pressure required that the blocks of shield material be well-fitted so that pressure loads could be transmitted through the skins to the blocks without excessive deflection of the skin. This close-fit requirement, in combination with the external pressure, would result in optimum contact conditions, and thus optimum heat-transfer conditions between the skin and the blocks.

4.1.3 REAR SHIELD

The rear shield, shown in Figure 4.4, consisted of 15 wavy walls assembled in a cylindrical shell with a flange at the aft end. The wavy walls were attached vertically to the inner surface of the cylinder to provide constant-width air passages between the walls through the length of the plug, except for approximately the first 10 inches. In that portion of the plug, each wall thickness was reduced; the resulting void was filled by narrow baffles, one attached to each side of the thinned-down section of the wall. The width of the air passages for the first 10 inches, between the baffles, was 0.50 inch. Behind the first 10 inches, the passage width was 1.50 inches, carrying the air from three of the 0.50 inch passages between baffles. The rear shield was cantilevered from the rear flange of the side shield through the cylindrical shell flange.

4.1.3.1 Wavy Wall

The wavy wall consisted of a forward transition baffle and an aft wide baffle. Due to the high heat generation rate at the forward end of the rear shield, the thickness of the transition baffle was reduced to approximately 0.078 inch. This baffle was machined from a solid piece of metal and had a series of internal holes that were filled with beryllium oxide rods. In order to minimize the temperature gradient through the baffle, fins were added to the leading edge and the gaps between the beryllium oxide rods and baffle holes were held to a minimum and filled with helium gas under pressure. The wide baffle portion of the wavy wall was constructed of sheet metal (Figure 4.5); the shielding material that it contained was in the form of contoured beryllium oxide blocks (Figure 4.6). To permit adequate heat transfer, the maximum allowable gap between the shielding materials and the structure was limited to 0.030 inch on a side. Horizontal and vertical channels were placed internally to stiffen the skin structure. The shielding blocks were staggered and attached to the horizontal channels to eliminate radiation-streaming gaps. At the trailing edge of the wavy wall, a hollow streamlined tail section was attached and was used to diffuse the flow from the 1.50-inch air passageway to the aft collector.

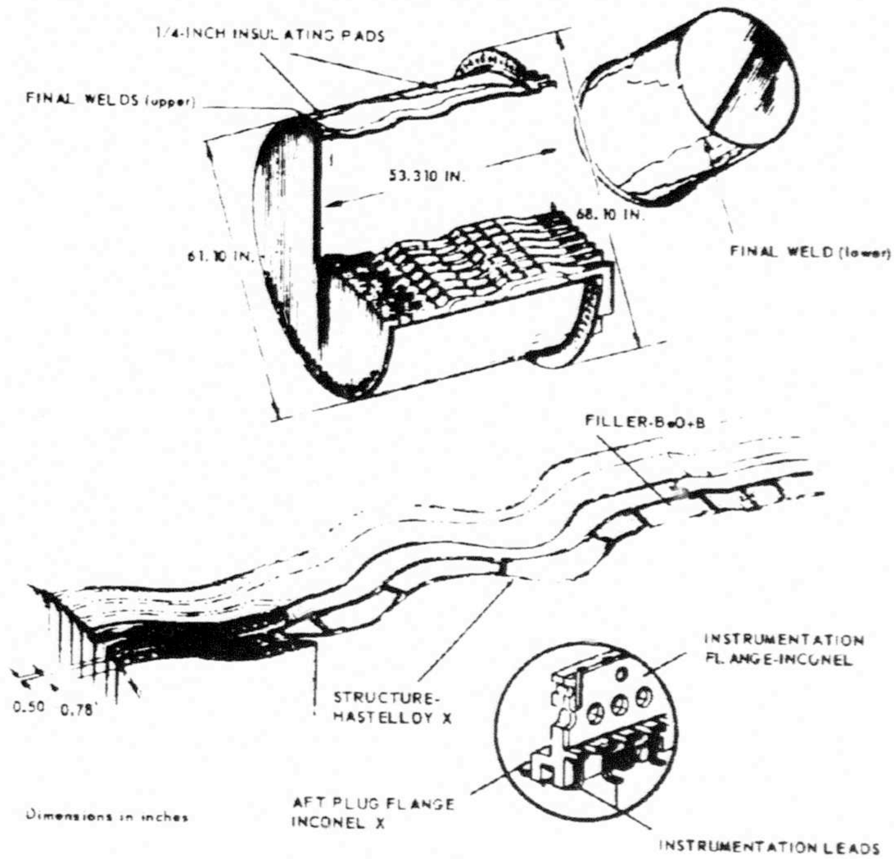

Fig. 4.4 – Rear shield assembly (Dwg G-1286-Rev. A)

4.1.3.2 Narrow Baffle

The narrow baffles, similar in construction to the transition baffles, were 10.00-inches long; they were located adjacent to the transition baffles at the forward portion of the plug. These baffles were welded to the shell and tied to the transition baffles by a series of tie bolts at their forward and aft ends.

4.1.3.3 Shell

The cylindrical shell consisted of a thin cylinder which supported the wavy walls and a flange that attached the rear shield to the rear flange of the side shield. The cylinder was supported by the flange through splines which accommodate differential thermal expansions.

4.1.4 SIDE SHIELD

The side shield, shown in Figure 4.7 consisted essentially of a pressure shell and shielding materials that were attached to the pressure shell. Passages were provided within the shielding material for cooling with an external air supply. The bearing beam sections of the side shield, shown in Figure 4.8, housed the engine coupling-shafts and their bearings.

4.1.4.1 Pressure Shell

The pressure shell was a thin wall cylinder with flanged ends. It served as the power plant carry-through structure, connecting the turbojet compressor and turbine assemblies

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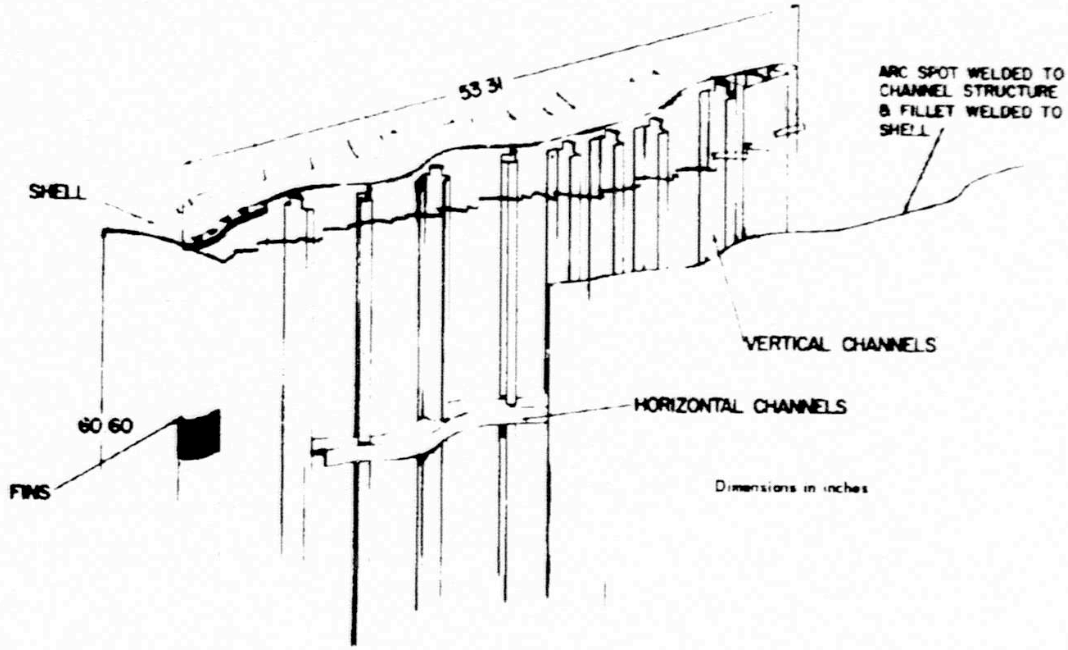

Fig. 4.5 – Rear shield wavy wall - partial sub-assembly and shin (Dwg G-1390 Rev. A)

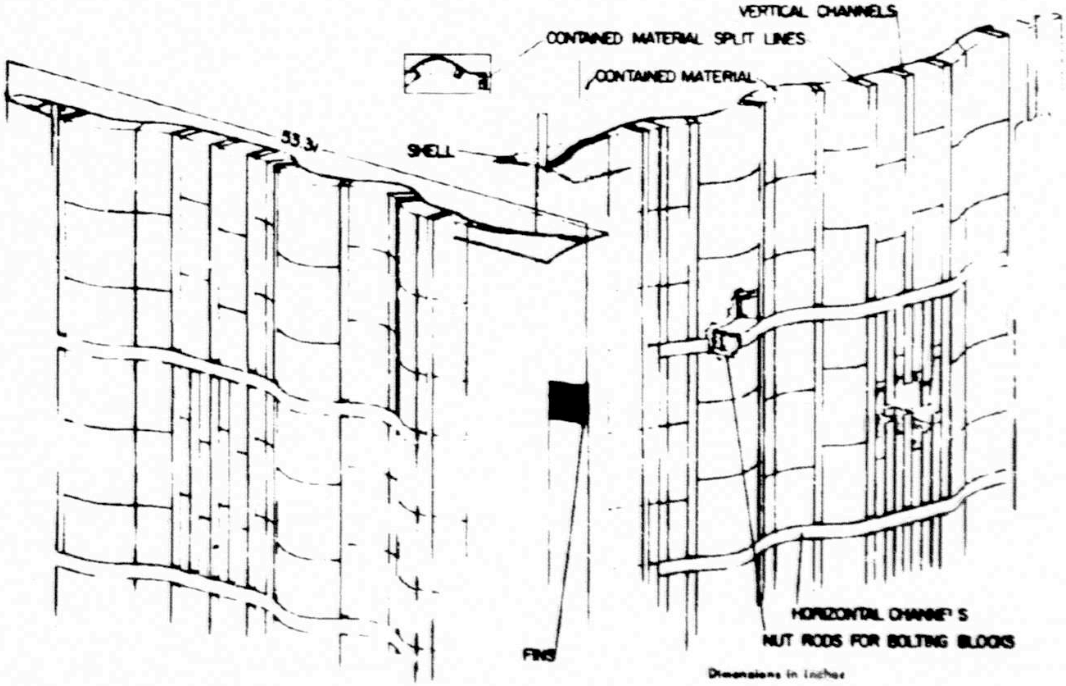

Fig. 4.6 – Partial wall with contained material (Dwg G-1391 Rev. A)

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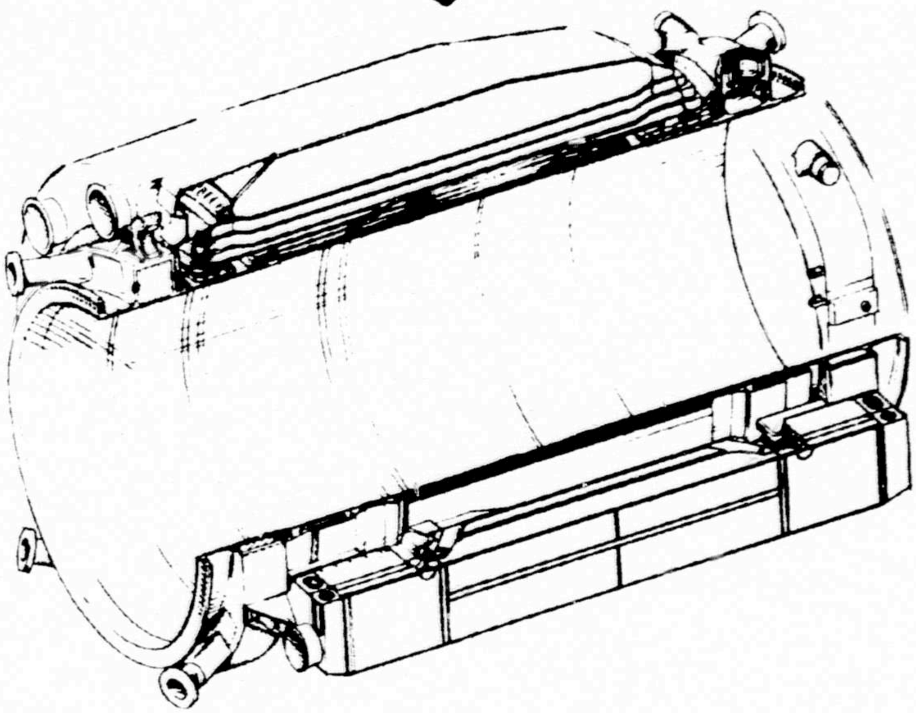

Fig. 4.7 – Side shield assembly (Dwg G-1445)

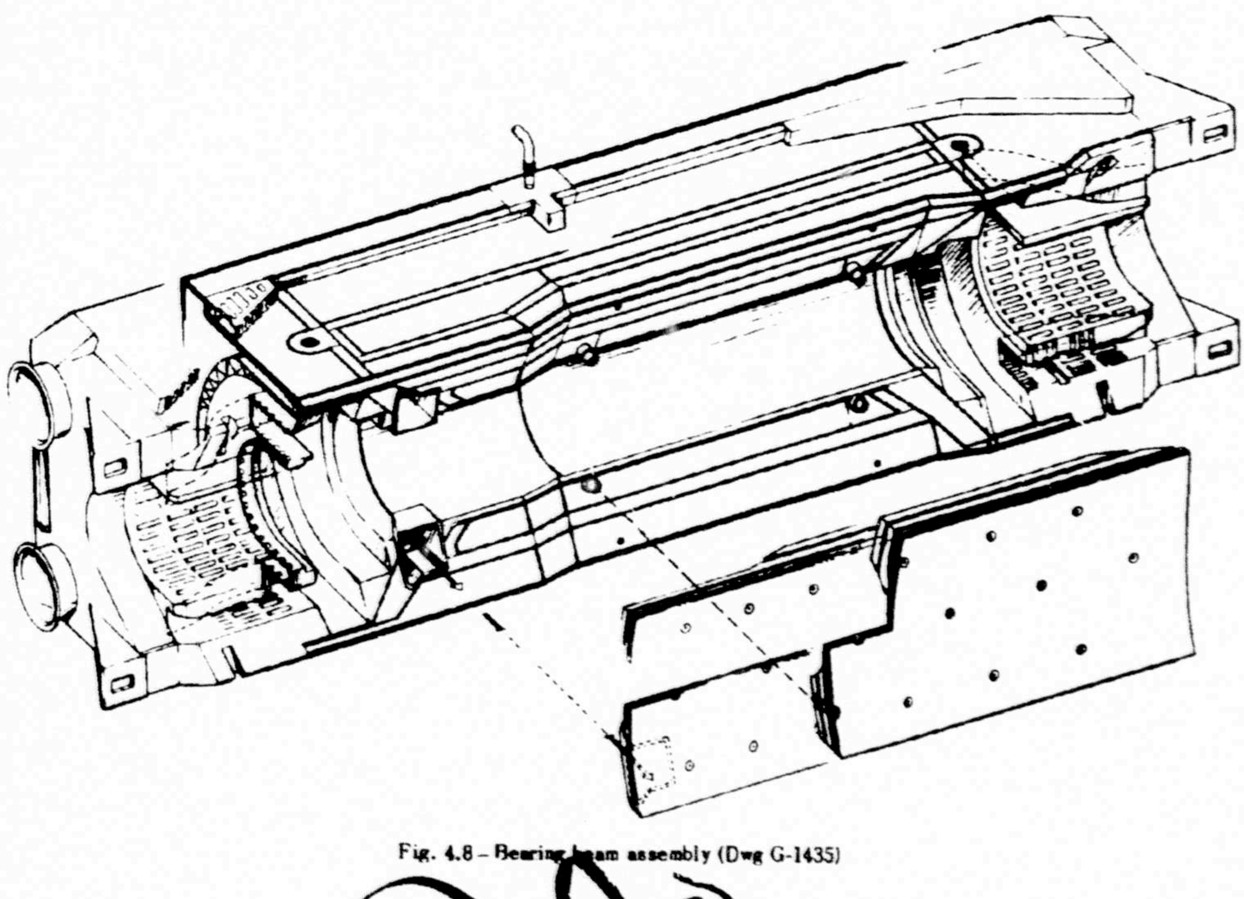

Fig. 4.8 – Bearing beam assembly (Dwg G-1435)

and contained the primary airflow in the reactor shield. The front-shield assembly was mounted to the forward flange and the rear shield was mounted to the rear flange. Reinforcing rings (trunnion rings) at the ends of the shell contained the power plant mounting fittings and the fittings that supported the collector struts.

4.1.4.2 "A" Shells

The "A" shells were the major neutron shielding sections; they consisted of pressed-and machined-blocks of lithium hydride canned in corrugated-sheet-metal sandwich structures. The sandwich construction served the dual purpose of providing air passages and a lightweight high-strength structure. The A shells were joined to the pressure shell by connections that could accommodate differential thermal expansions. These connections consisted of a bellows at the forward end and splined fittings at the aft end.

4.1.4.3 Gamma Shielding

The gamma shielding ("B" material) was divided into 4 layers in the reactor region and 3 layers in the front-and rear-shield areas. Circumferentially, each layer was divided into slabs, similar to barrel staves; each slab subtending an arc of 15 degrees. Each layer was made up of three sections in the longitudinal direction. In the A shell areas of the shield, the gamma shielding slabs were supported by the pressure shell with pins that securely held the slabs but permitted relative motion between them.

4.1.4.4 Bearing Beam

The bearing beam basic structural design and materials were the same as those of the A shells. The general arrangement was the result of studies to develop a sound structure that would permit servicing of the engine-coupling-shaft bearings and would be compatible with the required shielding disposition and cooling system. The gamma shielding slabs in the bearing-beam sections of the shield were attached to the beam in the same manner as the slabs in the A shell areas were attached to the pressure vessel. The beam was cooled by external air flowing through passages that extended through the length of the beam.

4.1.5 BYPASS VALVE

The bypass valve, shown in Figure 4.9, was located forward of the front shield. Its purpose was to bypass the compressor discharge air around the front shield and reactor into the parallel combustors during operation on chemical heat. The valve consisted of nose sections for the front-shield wavy walls, slotted cylinders, and struts assembled in a flange ring. The cylinders rotated between the wavy-wall nose sections through an angle of 90 degrees from full close to full open. This design permitted a very low pressure drop across the valve in the open position because the valve was built into the front shield. The valve was supported by the front shield through connections between the nose caps and shield wavy walls and four splines on the valve flange ring that engaged matching fittings on the front-shield front flange.

The bypass valve was actuated by a push-pull linkage system (Figure 4.10). Two sets of tie bars and rocker arms were housed in a strut that was located on the valve vertical center line and split the valve into two sections. Each set of rocker arms and tie bars operated the cylinders in the valve section adjacent to it and was driven by a separate actuator through a linkage system extending forward from the valve and piercing the compressor collector. One actuator was located at the top of the collector and the other was located at the bottom.

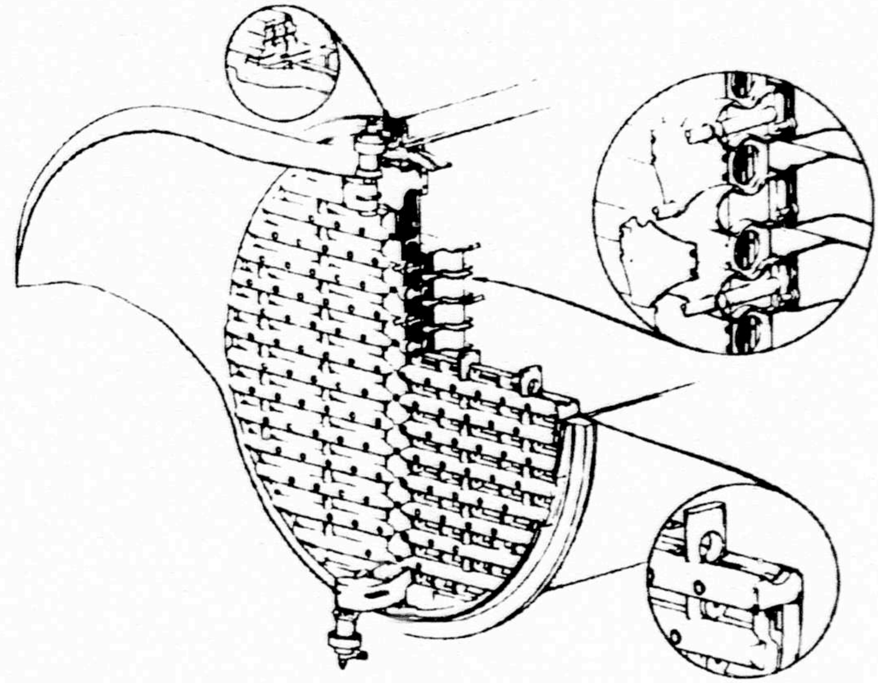

Fig. 4.9 – Bypass valve (Dwg G-1419)

4.2 DESIGN REQUIREMENTS

4.2.1 NUCLEAR

The nuclear design criteria for the shield were based on radiation constraints such as crew dose rate, airframe-component life, and airframe personnel maintenance accessibility. In addition, the physical size limitations placed on the shield confined the degree that the above parameters could be varied to achieve a compatible system. After analysis of these factors the radiation environment of the XMA-1 was evolved. Gamma ray and neutron radiation patterns around the power plant are shown in Figure 4.11. The radiation levels, as shown, occurred at a distance of 50 feet from the center of the reactor when the reactor was operating at a power level of 194 megawatts. The neutron-radiation level depicted was based upon the probability of neutron leakage penetrating the crew compartment. The neutron leakage was determined as a function of magnitude, solid angle subtended, and probability of penetrating the crew compartment. The gamma radiation level was based primarily on radiation damage constraints on airframe components.

4.2.2 MECHANICAL

In addition to reducing the radiation escaping from the reactor, the shield assembly served as the primary power plant structure that connected the turbomachinery components and supported the reactor.

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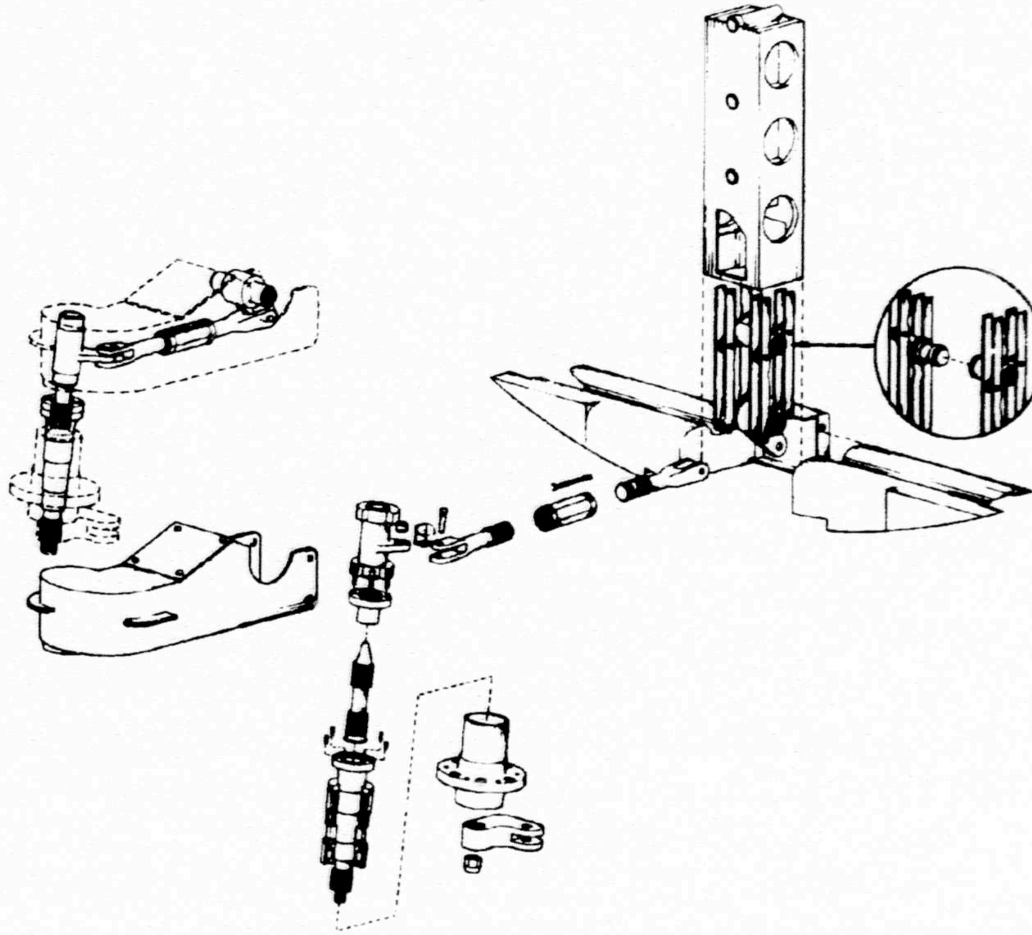

Fig. 4.10 – Bypass valve actuation system (Dwg G-1433)

4.2.2.1 General Design Requirements

The design requirements for six loading conditions (1) flight endurance, (2) accelerated flight, (3) ground operation, (4) ground handling, (5) crash landing, and (6) flight are covered fully in section 2.1.2. Table 2.1 presents the inertial load factors.

The maximum shield weights are presented in Table 2.3, section 2.1.2.

4.2.2.2 Component Design Requirements

1. Front Shield
   a. The shield shall be designed for a life of 1000 hours.
   b. Figure 4.12 presents maximum, normal air-turning incremental pressures and the resulting loads on the wavy walls which could occur during nuclear power operation with the bypass valve open. During chemical operation, with the bypass valve closed, the air-turning loads are negligible.
   c. Average maximum operating temperatures for the exposed structure range from 640^{o} to 740^{o}F. Details are presented in reference 2.
   d. Beryllium parts shall be assumed to have only compressive strength.

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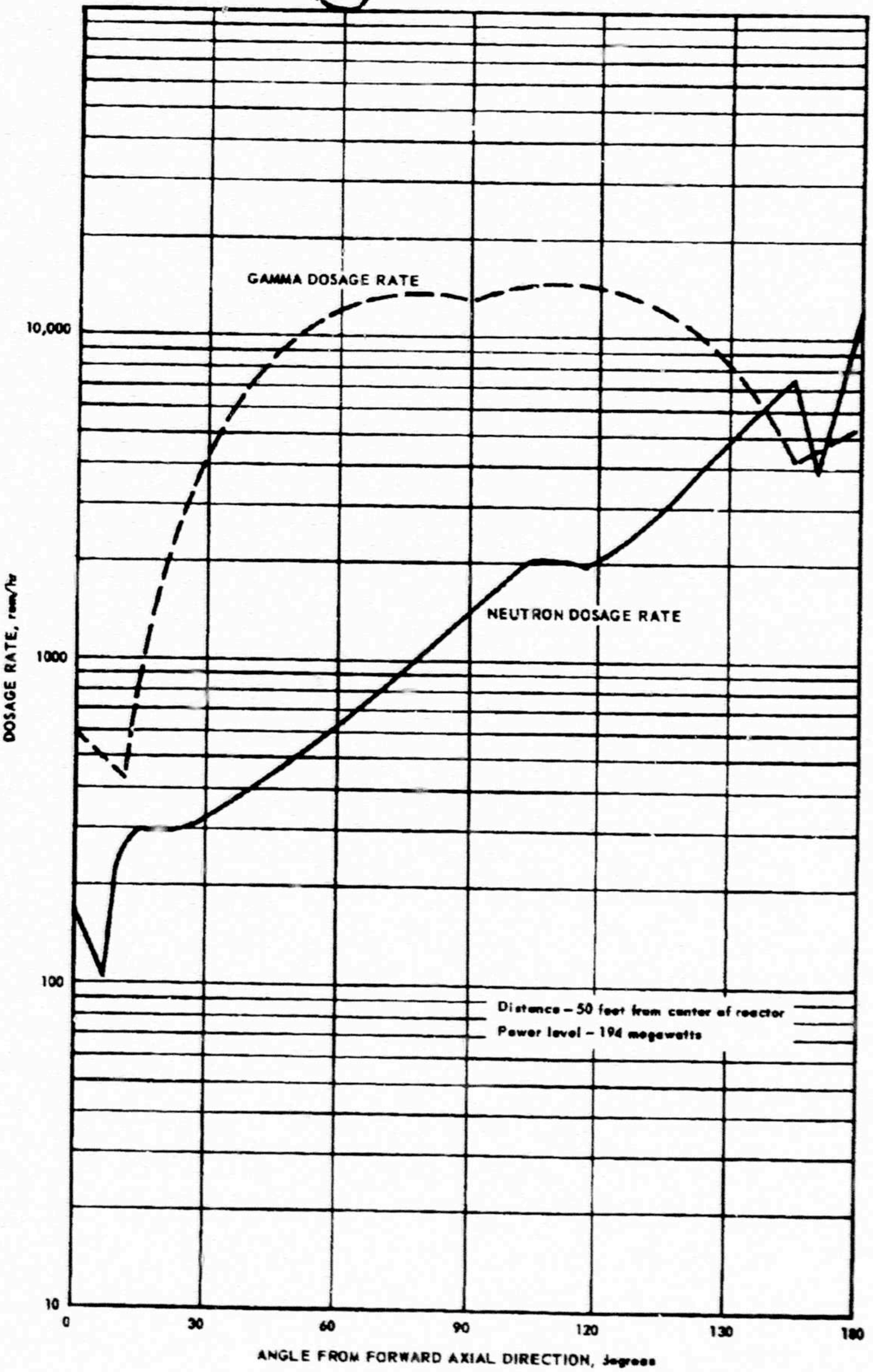

Fig. 4.11 – XMA-1A power plant estimated nuclear radiation pattern

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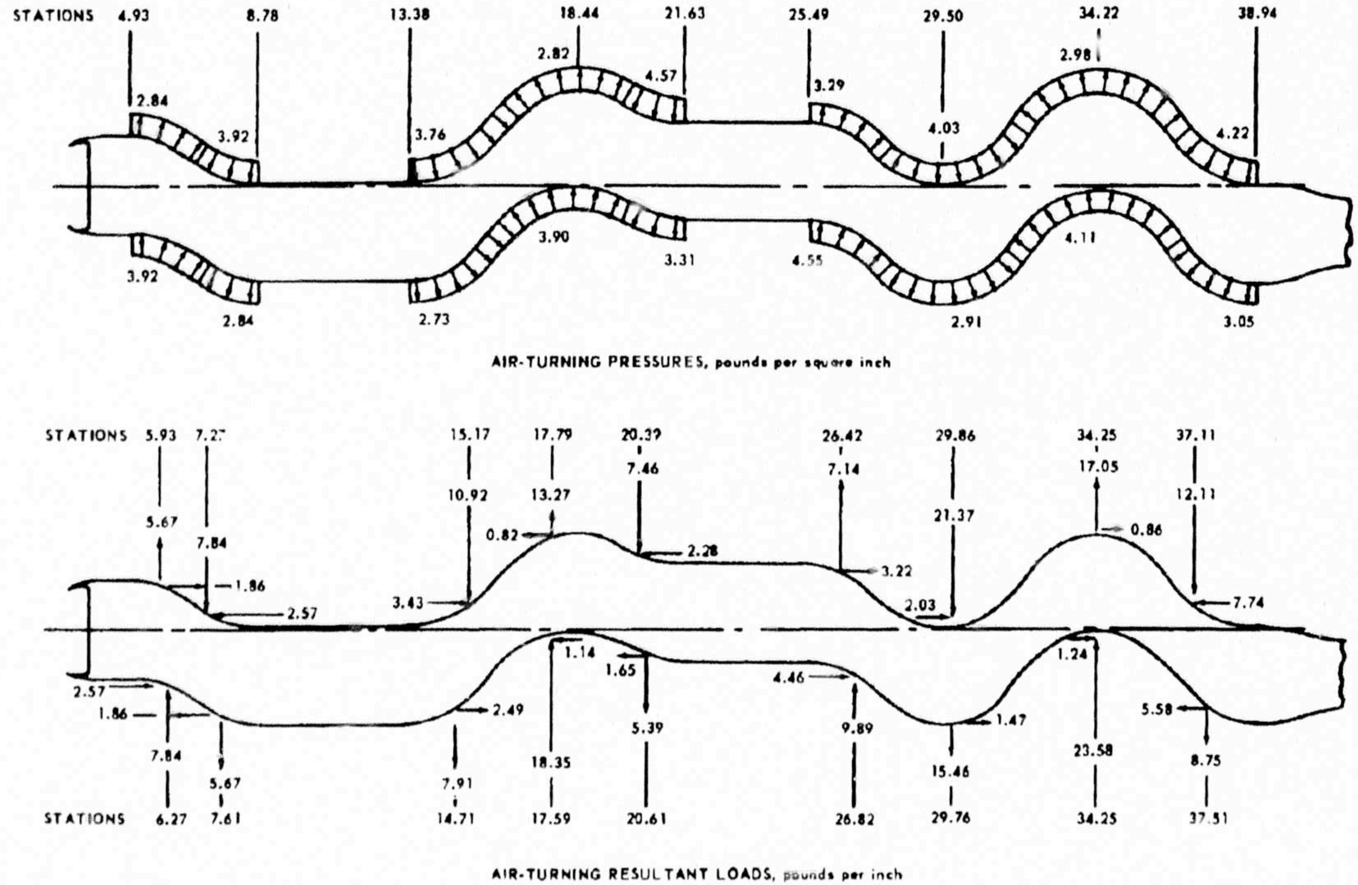

Fig. 4.12 – Design air-turning loads on wavy walls of XMA-1A front plug

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2. Rear Shield
   a. Due to the very high operating temperature of its structure, 1800°F, a design life of 100 hours shall be acceptable for the rear shield.
   b. The design pressures are shown in Figure 4.13.
   c. A regulatory system shall be provided to maintain the gas pressures in the transition and narrow baffles at 1 to 2 psi higher than the ambient pressure.
   d. Beryllium oxide parts shall be assumed to have only compressive strength.
3. Side Shield and Bearing Beams
   a. The side shield shall be designed for a life of 1000 hours.
   b. Weights and moments of inertia of the power plant components attached to the side shield are shown in Figure 4.14.
   c. The pressure shell shall be designed for a collapsing differential pressure of 10 psi and an internal pressure of 235 psia.
   d. The engine coupling-shaft critical-speed requirements dictate that the bearing-beam structure shall support the shaft bearings with a spring rate of 0.2×10^6 pounds per inch in any direction in the plane through the bearing center line.
   e. A pressure-regulation system will limit the gas bursting pressure in the A shells and bearing beams to 5 psi.
   f. The lithium hydride blocks are to be assumed to have only compressive strength.
4. Bypass Valve
   a. The bypass valve shall have (1) a life of 100 hours in the closed position, (2) a life of 900 hours in the open position, and (3) a pressure drop across the valve, in the open position, of 3 psi.
   b. The torque applied to the valve by the air flowing through it is given in reference 3.

4.2.3 AEROTHERMAL

The requirements for the aerothermodynamic analyses were to assure that all materials in the shield were cooled so they could be maintained within permissable temperature levels and to assure thermomechanical integrity with respect to (1) thermal gradients, (2) differential thermal expansions resulting in interference between members, and (3) distortion effects.

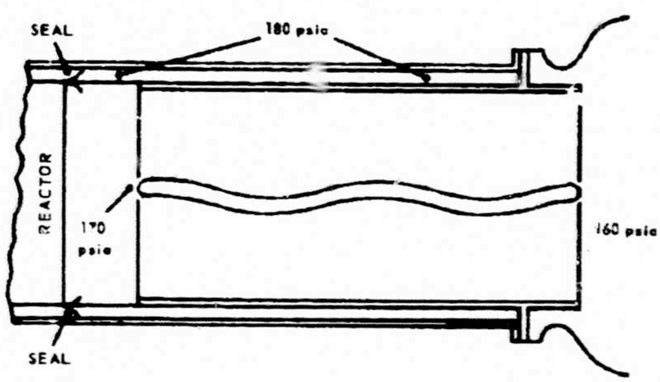
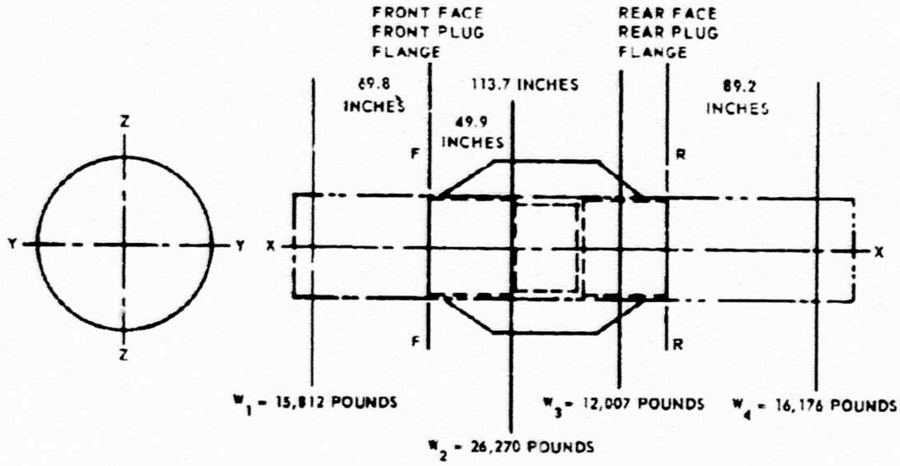


Fig. 4.13 – Rear-shield design pressures



Mass moment of inertia at center of gravity of mass
for W_2 $I_{YY} = I_{ZZ} = 66,136$ lb/in.-sec^2
for W_3 $I_{YY} = I_{ZZ} = 14,620$ lb/in.-sec^2
Mass moment of inertia at front face of frong plug flange (F-F)
for W_1 $I_{YY} - I_{ZZ} = 470,666$ lb/in.-sec^2
Mass moment of inertia at rear face of rear plug flange (R-R)
for W_4 $I_{YY} = I_{ZZ} = 887,190$ lb/in.-sec^2
Polar moment of inertia of rotating parts forward of F-F
$I_p = 3109$ lb/ft^2-per side
Polar moment of inertia of rotating parts aft of R-R
$I_p = 3030$ lb/ft^2-per side
Speed of rotating parts = 5000 rpm

Fig. 4.14 – Weights and moments of inertia

These requirements applied to conditions anywhere within the power plant operational envelope and considered the factors of design clearances, manufacturing tolerances, and misalignments. Thermodynamic conditions, in fact, were the major criteria for adjusting limits to these factors.

4.3 DESIGN DATA

The design data for the reactor-shield assembly is covered fully in reference 4.

4.4 COMPONENT TESTING

The XMA-1A shield design and development was subjected to a variety of component tests to verify that they met the design requirements. The test program was established for the front shield components, side shield components, rear shield components, and the ducting involved. These tests are summarized in reference 5.

4.5 FABRICATION STUDIES

Paralleling the engineering design effort were fabrication feasibility studies. These were being carried out at the time of program termination. Potential vendors were being evaluated in preparation for manufacture of the components of the shield assembly. Manufacturing methods being considered, tooling and equipment requirements, schedules, cost estimates, and results obtained from fabrication studies are covered in references 6 and 7.

4.6 REFERENCES

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4. "XMA-1 Shield Design Data Summary," GE-ANPD, DC 61-11-23, April 1962.
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6. Kilb, E. P., "Qualification of Beryllium Alloy Vendor," GE-ANPD, DC 59-9-115, September 1959.
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5. TURBOMACHINERY

The XMA-1 power plant utilized two sets of X211 turbomachinery that consisted of the following: (1) two compressor assemblies, (2) a compressor exhaust collector, (3) two chemical combustion systems, (4) a combustion exhaust collector, (5) two turbine assemblies, (6) two tailpipes, (7) two exhaust nozzles, (8) two turbine compressor coupling shafts, and (9) controls and accessories for each set.

The turbomachinery was coupled to the reactor-shield assembly through the compressor and combustion exhaust collectors which attached to the fore and aft pressure shell flanges and through the collector braces which connected to the pressure shell fore and aft trunnion rings. Coupling shaft vibration damper bearings and combustion system dampers were supported from the side shield.

The turbomachinery configuration is shown in Figure 5.1. This figure is a photograph of one of the early factory test engines assembled in the Engine Test Burner (ETB). The ETB simulated the reactor-shield assembly for engine test purposes. The engine test assembly had only one operable set of turbomachiner; a dummy engine was installed on the left side (aft looking forward) to simulate an actual engine. Much of the external piping, wiring, and structure was associated with instrumentation and special test systems.

The objectives for the turbomachinery were based on requirements for the operational power plant (XMA-1C). The initial goals were (1) to provide hardware suitable for ground testing the XMA-1A and (2) to provide hardware suitable for flight-test operation of the XMA-1A. This section presents a discussion of all the component parts except controls, which are discussed in section 6, as they existed at the termination of the XMA-1 program.

5.1 DESCRIPTION

5.1.1 COMPRESSOR

5.1.1.1 Compressor Front Frame

Functions - The front frame assembly was a fabricated sheet metal (Chromoloy) structure designed (1) to provide a smooth aerodynamic air passage; (2) to limit stator casing distortion; (3) to support the variable inlet guide vanes, the forward main engine bearing, front and transfer gearboxes; and (4) to provide engine tie-bar and damper-support mounts. In addition, passageways were provided for lubricating oil and scavenge oil, No. 1 sump vent, air pressure for the carbon oil seal, inlet-guide-vane anti-icing air, and turbine cooling-air.

Components - The compressor front frame housed the No. 1 bearing assembly, the variable-pitch inlet-guide vanes, eight support struts, the radial accessory-drive shaft, and served as a support for the inlet gearbox. The transfer gearbox, with various engine accessories, was suspended from the compressor front frame. The outer shell of the frame also provided pin-type mounts for interengine tie bars and engine-airframe damper-supports.

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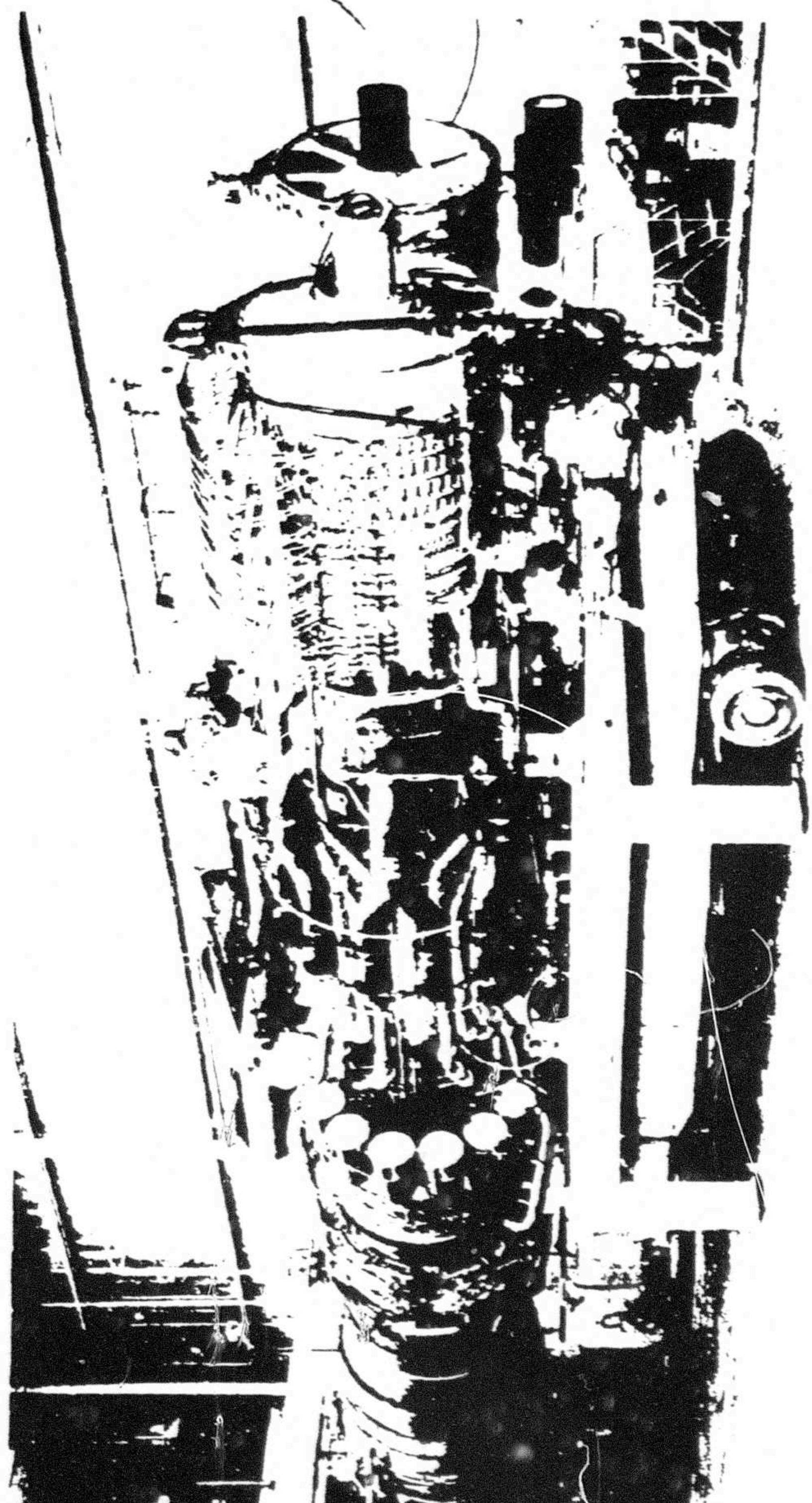

X211-DR-2245-0-D2

Fig. 5.1 – First X211 engine

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The variable inlet-guide-vane design consisted of a wrap-around sheet metal airfoil, contour brazed to an internal corrugated stiffener. The 48 variable inlet-guide-vanes were supported by spherical bearings located in the front frame, and were actuated by a linkage system connected with the variable-stator linkage mechanism.

Anti-icing of the inlet-guide-vanes and front-frame struts was accomplished by a dual system. Compressor discharge air was brought forward to the strut pads at the 3 and 9 o'clock positions on the frame. The discharge from those struts was manifolded for the distribution of anti-icing air to the 48 inlet-guide-vanes. The air passed internally through the vanes and was discharged into the compressor inlet at the top pressure side of the inlet-guide-vane. Anti-icing of the eight struts in the front frame was accomplished by piping the eighth-stage compressor discharge air (turbine cooling air) to strut pads 2, 4, 6, and 8. The air was then manifolded to the leading and trailing edge passages of all eight struts (see Figure 5.2). A line was provided from the internal anti-icing inlet-guide-vane manifold to de-ice the bullet nose.

Interengine Tie Rods - Interengine tie-rod assemblies were located between the compressor front frames and the turbine rear frames. Their function was to restrain the cantilevered engine sections against horizontal angular deflections. The design would allow thermal expansion of the collectors, damp engine vibration, and limit horizontal deflection. The tie-rod assembly consisted of four links with paddle-like clevises which joined to form a sandwich of plates at the power plant centerline. Two clevises were slotted to compensate for thermal growth, and two concentric helical springs bore against the clevises to provide the necessary friction force for damping action until full extension was obtained. The tie rods could be remotely assembled and disassembled to the frames and incorporated spherical rod ends at the frame attachment points to aid in maintaining alignment.

5.1.1.2 Compressor Stator

Function - The compressor stator consisted of two casings that housed the 16 stages of stator vanes and one set of outlet-guide-vanes. The first 10 stages were variable and were ganged, along with the inlet-guide-vanes, into a single system. The other stages were in-

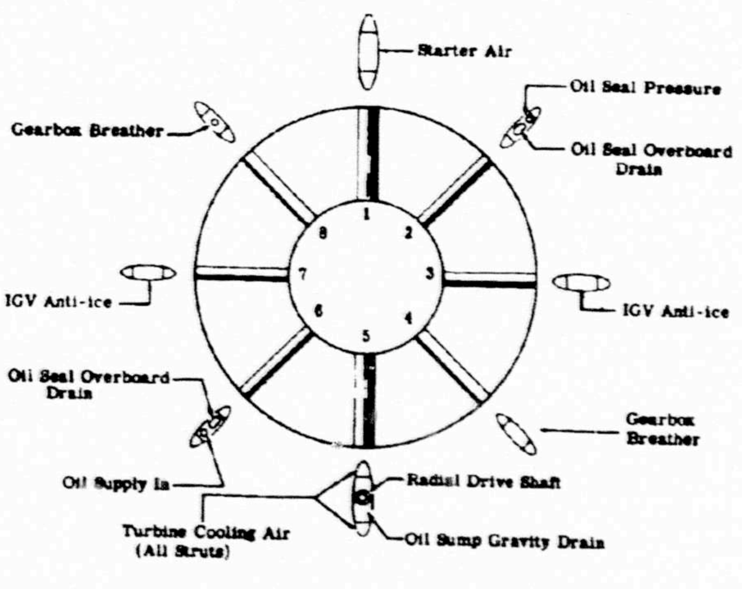

Fig. 5.2 – Compressor front frame – strut piping

dividually variable for purposes of testing. The sixteenth-stage vanes performed a dual function, serving as conventional vanes and as compressor shutoff valves if one of the twin engine power plants had to be shut down in flight. The number of vanes per stage varied from 54 to 200. Air bleed was provided at the eighth-stage for turbine cooling and No. 5 bearing seal pressurization. A section through the stator assembly is shown in Figure 5.3.

Components - The complete casing was made up of front and rear sections, with the front casing housing stages 1 through 6 and the rear casing stages 7 through 16. Each casing was split horizontally and had three body-bound bolts in each flange to ensure alignment during machining, assembly, and subsequent buildups. The compressor casings were roll forged and machined from Chromoloy.

The front casing was conical on the inside diameter. Slots were provided to retain the filled honeycomb linings. The use of these linings permitted the holding of closer rotor tip-to-casing wall clearances, because there was no damage to the linings or rotor blades if interference did occur. External stiffening ribs at stages 1 through 5 and an internal stiffening rib at stage 6 were provided to prevent excessive casing deflections due to compressor inlet distortions. Bosses were located at each stage to support the stator vane actuating mechanism. The cylindrical compressor rear casing contained internal stiffening ribs. This casing also had an inner wall, formed by the casing linings. The dead air space between the inner and outer walls served as insulation providing lower structural wall temperature and reducing the heat losses from the casing.

Air-bleed manifolds to handle the discharge air were located over the eighth and twelfth stages of the rotor. A 360 degree slot was provided to extract air from the casing into the manifold air passage. From there, it flowed through holes in the outer wall into four external manifolds as shown in Figure 5.4.

5.1.1.3 Compressor Rotor

Function - The function of the compressor rotor was threefold: (1) to provide the inner air passage wall, (2) to support the rotating blade rows, and (3) to transfer kinetic energy from the blade rows to the air passing through them. The rotor was a sixteen-stage axial-flow unit with the first two interstage areas designed for stator shrouds. The rotor was designed to pass 425 pounds of air per second at 5000 rpm, sea level static, and a pressure ratio of 14 to 1.

Discs - The assembled discs formed a tube that served as the main structural member to resist bending. This tube also transmitted torque and positioned the discs radially and axially.

The discs, blades and airfoils, dovetails, spacers, and front and rear shafts are described in reference 2.

5.1.1.4 Compressor Rear Frame

Function - The major structural function of the compressor rear frame was to provide support for the No. 2 thrust bearing which absorbed the axial thrust of the rotor and the radial reactor load. In addition, this frame supported the compressor components that (1) provided diffusion at the compressor outlet, (2) supported the stationary portion of the compressor discharge seal, (3) served as an integrated structural and aerodynamic member of the frame-compressor collector section of the engine, and (4) provided attachment points for assembly and handling of the compressor unit.

The rear frame components, design features, and sump features are described in reference 3.

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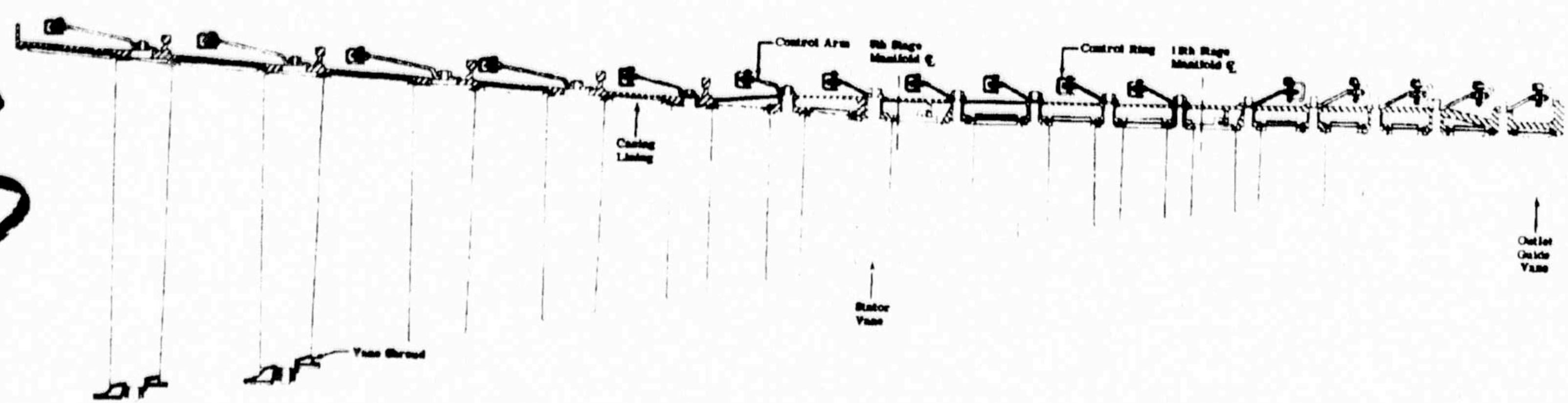

Fig. 5.3 – Compressor stator assembly

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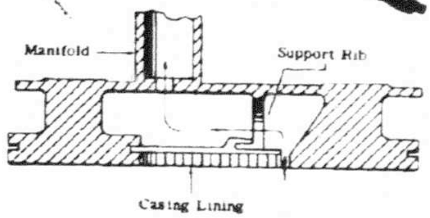

Fig. 5.4 – Compressor stator – air bleed manifold

5.1.2 CHEMICAL COMBUSTION SYSTEM

The chemical combustion system was located between the compressor exhaust collector and the combustion exhaust collector and was parallel and external to the reactor (Figure 5.5). The combustion system included three shut-off valves attached to outlets on the compressor exhaust collector followed by three Y-duct air manifolds. Expansion ducts were attached to the manifold outlets to provide for thermal expansion and manufacturing stackup of the system's parts when assembled. Interconnections between expansion ducts served as vibration dampers and limited the maximum displacement of the combustion-system components.

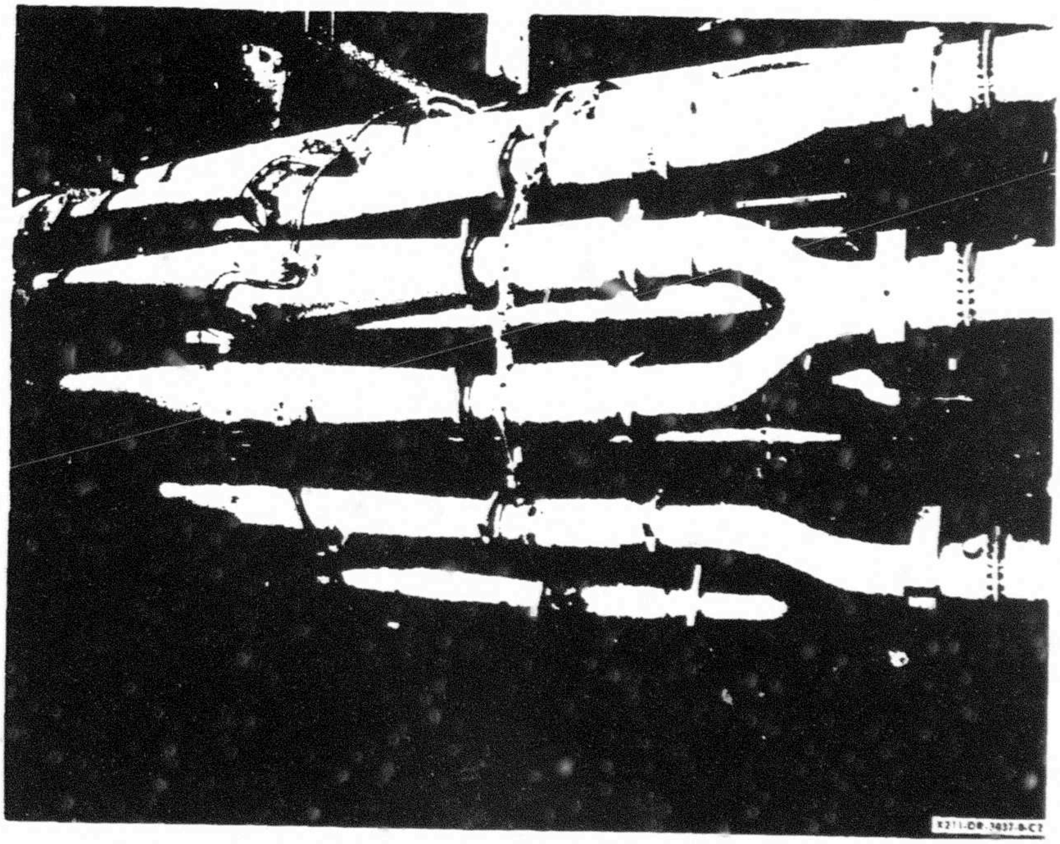

Fig. 5.5 – Mockup – X211 combustion system

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5.1.2.1 Function

Combustion Intake Air Butterfly Valve - The purpose of the butterfly valves was to prevent airflow into the combustion system during reactor operation. The valve blade was designed to minimize airflow distortions while operating chemically. One end of the valve shaft had a splined extension to receive the actuating lever, and had an actuator mounting pad on the valve housing.

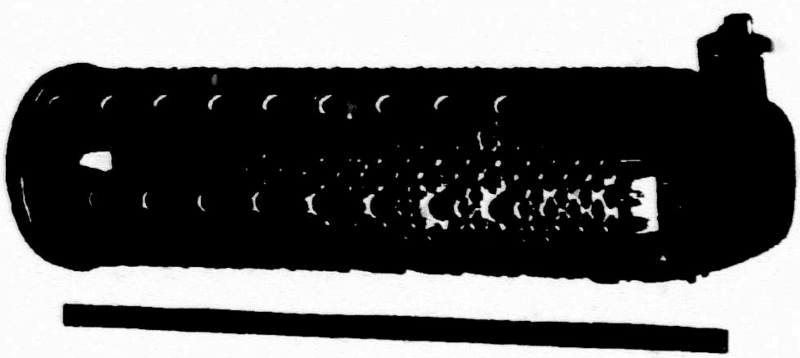
Combustion Air Intake Manifold - The manifold was used to distribute the airflow from each intake valve to the combustion casings.

Expansion Duct - The expansion duct was designed to compensate for the expansion and manufacturing tolerances of the combustion system components.

Combustion Duct Dampers - The combustion duct dampers were attached to the expansion ducts and, at the end points, to the reactor-shield assembly. They damped out combustion duct vibration by the use of spring-loaded friction plates, and limited the maximum deflection of the combustion ducting.

Rear Combustion Liner - The rear combustion liner served as a hot-wall liner, ducting the combustion discharge gases into the combustion exhaust collector. The liner was cooled by airflow over the outer surface.

Combustion Liner - The combustion liner, shown in Figure 5.6, was fabricated of Inconel 702. The skirt of the combustion liner had thimble holes to permit entry of combustion and mixing air; crescent type louvers were used for film cooling. Louvers were also used in the dome for cooling and combustion-air entry. Ignitors were installed in the end liner domes, and ignition to the center liners was accomplished by means of cross ignition tubes passing between the combustion liner skirts and through the combustion casings. The combustion liner was supported at the upstream end by the fuel injector and at the downstream end by the rear combustion liner.



X211-DR-2120-0-F1

Fig. 5.6 – Combustion liner and fuel injector

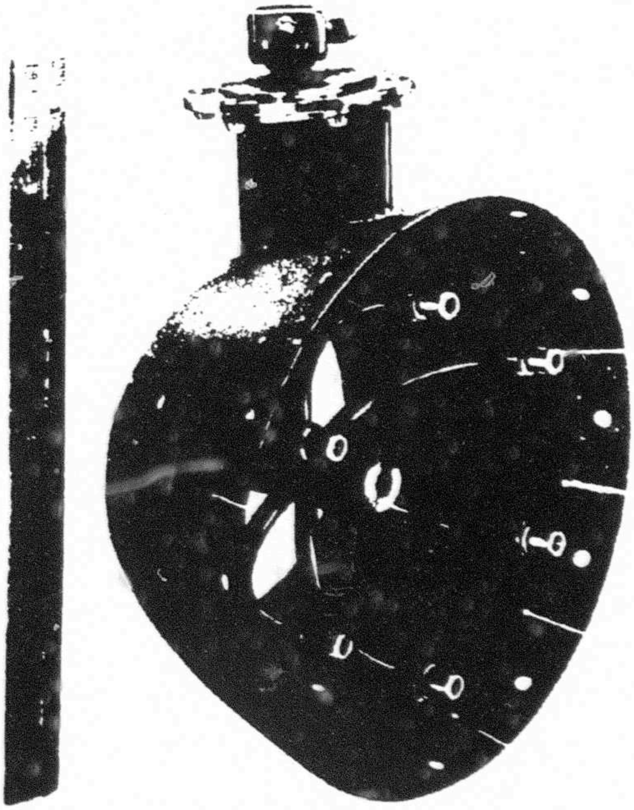
Fuel Injector - The fuel injector consisted of dual-cone nozzles, a support strut, and a mounting plate as shown in Figure 5.7. It was attached to the front end of the combustion liner and the combustion casing.

5.1.2.2 Design Considerations

The main combustion system was designed to fit within the space bounded by the outer contour of the reactor-shield assembly and a 38.25-inch radius from the centerline of the turbomachinery. All components in the combustion system were designed for 1000-hour life under the operating conditions stipulated by the design requirements.

The combustion system was designed for assembling in, or removing from, the power plant without disturbing any of the other major subassemblies. In addition, combustion-system components could be removed and replaced individually. The combustion system was designed for remotely assembling or disassembling the ducting and ignitors.

Remote handling requirements necessitated separating the combustion-system stub ducts, on the collectors behind the plane of main-flange faces, for access to the bolts on the main collector flange. All remote handling flanges had tapered rabbets to aid assembly. Since internal locating pins were found to be unsatisfactory for remote handling, large external pins were developed. These pins were located at each remote handling flange except the expansion duct aft flange.



X211-DR-2121-0-D1

Fig. 5.7 – Fuel injector

5.1.3 COLLECTORS

5.1.3.1 Function

The compressor and combustion collectors (Figures 5.8 and 5.9) were fabricated structural components that connected two separate sets of X211 components to the reactor and the shield assembly. Both collectors had the multiple functions of providing support for the cantilevered X211 components, serving as the pressure vessel that ducted gas flow between the engines and reactor-shield assembly, and providing inlets and outlets for the external chemical-combustion system. Additional functions resulting from remote handling requirements and growth developments were as follows:

1. Compressor Collector
   a. Provide support for the control rod actuator package and access ports for control linkages.
   b. Provide means of introducing after-cooling air (from an external source) when the X211 components were inoperative.
   c. Provide mounting pads for the reactor-shield-assembly components during assembly and disassembly of the power plant.
2. Combustion Collector
   a. Provide mounting ports for reactor discharge temperature sensors.
   b. Provide means of supporting internal reactor shield assembly components during assembly and disassembly of the power plant.

5.1.3.2 Compressor Collector Design

The compressor collector was fabricated of A-286 sheet-metal plus bar-stock weldment. The openings cut into the shell for combustion ducts and bleed parts were reinforced by sheet-stock patches and machined rings.

The external supports were semi-tubular sections with integral fingers for distributing the loads over greater areas of the shell surface. Openings through the shell, underneath each end of the tubular section, allowed compressor discharge air to circulate; this maintained the support-skin temperature at approximately the same level as the shell temperature.

The five main flanges and the four external brace flanges were designed for remote handling by providing captive bolts and nuts.

The collector flange, which mated with the reactor-shield assembly, was designed so that the internal components of the reactor-shield assembly remained attached to the collector during remote disassembly and assembly of the X211 components. There were three flanges in the joint between the collector and the actuator shield assembly (1) the collector flange, (2) the internal components flange, and (3) the shield assembly flange. In addition, an instrumentation spacer ring and a lip for supporting the bypass valve were provided. The collector flange was bolted to the internal components flange with captive bolts and nuts. These flanges were then bolted to the reactor-shield-assembly flange as the internal components were inserted into the reactor-shield assembly.

5.1.3.3 Combustion Collector Design

The basic shell and external supports of the combustion collector were the same as those of the compressor collector except for difference in size. Twelve combustion ducts formed entrances for the discharge of the chemical combustion system. The shaft opening area was surrounded externally by a cooling air manifold and internally by an air guide. Air from the manifold flowed through holes in the structural shell, then between the air guide and structural wall around the cavity. The air continued through an air guide section on the turbine front frame to provide cooling for the internal cone, and finally discharged at the turbine inlet.

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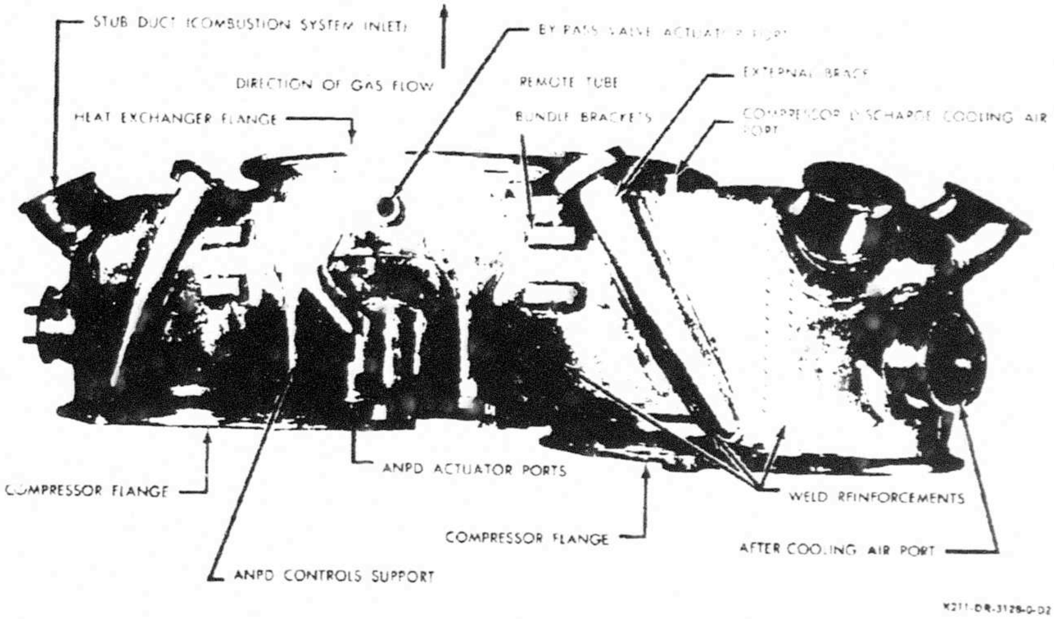

Fig. 5.8 – Compressor collector

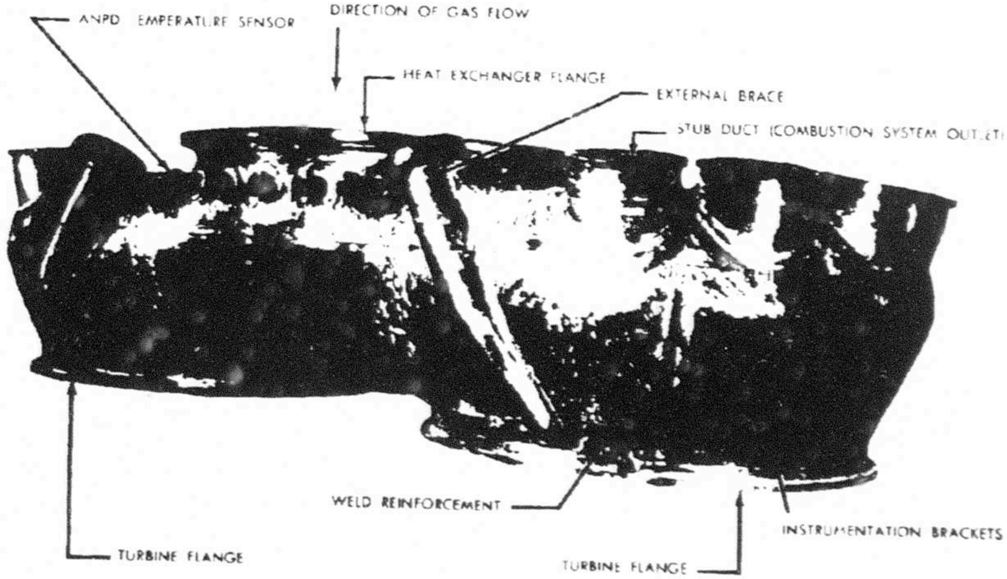

Fig. 5.9 – Compressor collector

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The combustion-collector skin was insulated on the gas side of the structural walls to prevent it from operating above permissible temperature limits. This insulation consisted of a foil covered quartz or silicate blanket protected by a 0.032-inch thick Inconel 702 liner. The methods studied for attaching the insulation liner to the structural walls are covered in reference 3.

5.1.3.4 Material

As engine operation and collector fabrication experience was gained, it became evident that A-286 was not a satisfactory collector material. Principle problems were:

1. Extensive weld cracking was encountered during fabrication.
2. A-286 structures of this type were prone to cracking during engine operation. Since there were no alternate load paths, this was dangerous on the collectors.
3. Repair welding was difficult.
4. Extreme care had to be exercised with joint fitup during fabrications.
5. Parts could not be controlled dimensionally during fabrication because of excessive distortion in heat treatment.

A better material for the compressor collector may be Type 410 stainless steel. A better material for the combustion collector may be N155 sheet metal with L605 flanges.

5.1.4 TURBINE

5.1.4.1 Turbine Front Frame

Function - The turbine front frame was a fabricated sheet metal structure mounted between the combustion exhaust collector and the turbine casing. It provided a bearing support through eight radial struts that extended from the inner box section to the outer shell. A turbine inlet-gas passage was formed by the frame outer shell and a conical inner body that extended forward into the combustion exhaust collector (Figure 5.10).

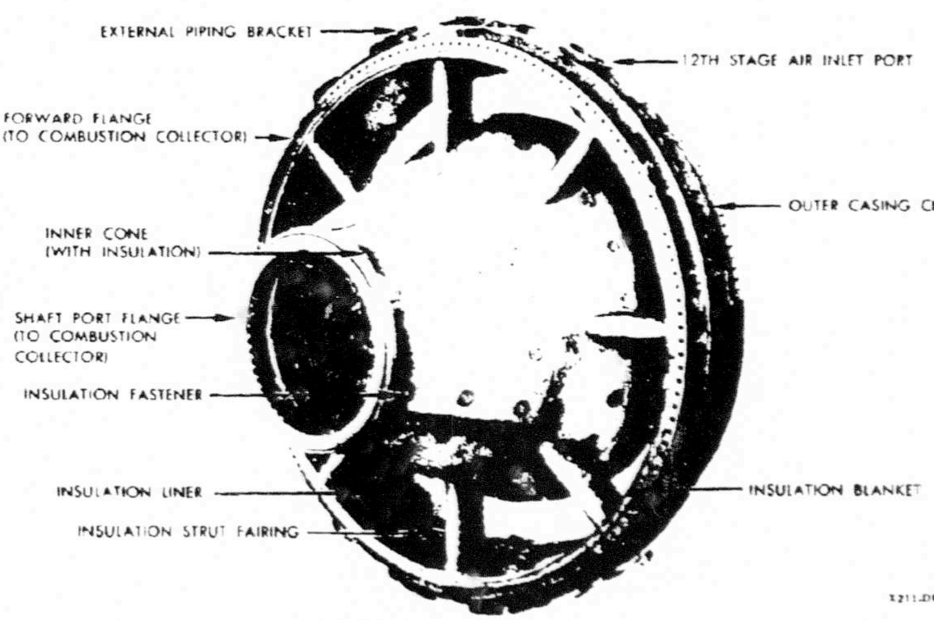

Fig. 5.10 – Turbine front frame

The primary purpose of the turbine front frame was to achieve a turbine-unit assembly with a bearing at the turbine forward end. This was required to permit disassembly of the X211 aft end without external support for the rotor. A bearing was also required at the turbine forward end due to the increased length of the compressor drive shaft over that of a conventional turbojet shaft. Other functions were as follows:

1. Carry the No. 5 bearing sump and sump service lines.
2. Provide an annular convergent turbine inlet from the combustion exhaust collector.
3. Provide structural rigidity for the turbine forward end.
4. Supply a bulkhead for the rotor balance piston.
5. Supply rotor balance piston with compressor bleed air at a low pressure loss.
6. Support turbine isolation valves.
7. Support the cantilever loading of the engine aft end.
8. Provide attachment points for assembly and handling of the turbine unit.

Outer Casing - The outer casing was a cylindrical shell reinforced about its circumference with a 2.61-inch high channel. This channel supported the casing against the radial load of the struts, provided a manifold to distribute balance-piston air from the external piping to the struts, and acted as a manifold to supply cooling air to the second- and third-stage nozzle diaphragms.

Struts - Eight radial struts connected the outer casing and channel to the inner strut support. To reduce thermal stresses, the struts were not attached to the inner cone, but a close fit eliminated axial movement between the strut and inner core. They carried the radial load of the No. 5 bearing, served as piping for balance-piston air from the outer channel, and provided passages for four sump-service pipes.

Inner Strut Support - The inner strut support was a ring with a box-shaped cross-section. This support transmitted the radial load from the bearing support cone to the struts, and served as a manifold for balance-piston air from the struts to the piston area. The box shape was chosen to fulfill the dual purpose of a rigid structure and an air manifold.

Sump - The sump area consisted of a bearing support cone, an aft cone to support the balance-piston air seal, and two cones that supported bearing oil seals.

5.1.4.2 Turbine Stator

Casing - The turbine casing was a fabricated cylindrical structure mounted through its forward circumferential flange to the turbine front frame; it provided an aft circumferential mounting flange for the turbine rear frame. The casing was split at the horizontal flange line and provided internal supports for the second- and third-stage turbine nozzles, the spacers, the turbine shrouds, and the interstage air seals.

Nozzle - One of the most important considerations in the design of the turbine nozzle was the maintenance of their axial positions in the gas passageway with minimum deflection from gas loading under all engine operating conditions. This was accomplished in the first stage by securing the turbine nozzle at both the inner and outer diameters. The second and third turbine nozzles, cantilevered from the turbine casing, required a design rigid enough to resist deflection yet flexible enough to avoid the buildup of thermal stresses. Cooling air for each stage was introduced through eight external tubes, one for each nozzle sector, into the eight outer bands that acted as manifolds for the sectors. The cooling air flowed through the inner band that held a thin sheet metal throttling section to control the amount of air that could flow through the leading, center, and trailing edge portions of each partition before being discharged into the gas chamber.

Seals - Nozzle seals consisted of lightweight open Inconel honeycomb brazed to a supporting framework of formed sheet metal. The honeycomb mated with machined teeth, incorporated in rotor parts, to provide the labyrinth-type seal. On the first stage, the honeycomb was mounted on a simple cone and rigidly attached to the turbine front frame. Second- and third-stage seals were attached to the nozzle diaphragm inner bands by using pins, and tongue and groove couplings. The seals could thus tolerate diaphragm growth and was self-centering to a limited degree.

The nozzle seals also exhausted the nozzle cooling air in such a manner that hot combustion gas was purged from the bucket shanks preventing overheating. Baffles on the seals controlled this purge air. The labyrinth design minimized leakage so essentially there was no flow of combustion gas around the nozzles.

5.1.4.3 Turbine Rotor

Function - The turbine rotor, shown in Figure 5.11, was connected to the compressor rotor by a long, hollow coupling shaft that transmitted the power, supplied by the turbine rotor, necessary to drive the compressor.

The three-stage turbine rotor was characterized by a large-diameter conical turbine-shaft, large-diameter interstage torque-rings, and outboard bearing supports. This arrangement permitted a high critical speed and facilitated the passage of cooling air through the interior in such a manner that the critical areas of the wheel, torque rings, and turbine shaft were effectively cooled. Each component of the turbine rotor was designed with the

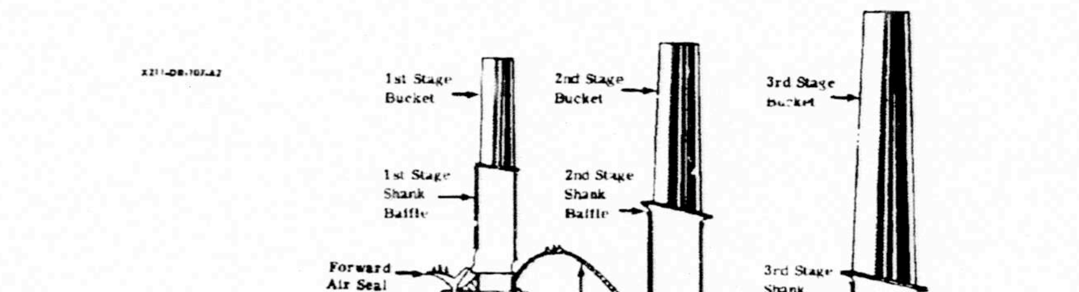

Fig. 5.11 – Turbine rotor assembly

cognizance that parts must operate in as cool an atmosphere as possible to achieve optimum utilization of the materials.

Turbine Buckets - The turbine buckets were designed to use 100 percent of their life during one complete 1000 hour mission. The design criteria for the turbine buckets, discs, and dovetails are presented in reference 3.

Turbine Shaft - The turbine shaft was a long conical shaft bolted to the first stage turbine wheel. It transmitted the torque, developed by the turbine, through a splined connection to the coupling shaft. The turbine shaft was designed to maintain the turbine-rotor critical speed above the engine operating speed, to transmit cooling air, carry the forward rotating air seal, and to transmit turbine torque through the coupling shaft to the compressor rotor. At the forward end, the turbine shaft was underneath the No. 5 bearing; it carried the sump and seal rotating components, thus, moving the cone portion aft. It was externally splined to accept the internal spline of the coupling shaft.

Turbine Spacers - The turbine spacers performed three functions. They (1) transmitted stage torque to the turbine shaft, (2) provided separation and support between the wheels, and (3) served as interstage gas seals. The catenary seal, a catenary-shaped outer seal ring, served as the primary interstage seal between the first and second stages and as a heat shield for the second-stage spacer. The seal and spacer configuration is shown in Figure 5.11.

Turbine Map - The thermodynamic characteristics of the turbine is shown in Figure 5.12.

5.1.4.4 Turbine Rear Frame

The turbine rear frame, shown in Figure 5.13, was a structural member constructed of welded, formed sheet metal parts. It consisted of an outer ring, eight radial struts, and an inner ring with a bearing support cone. Surrounding this structure was an aerodynamic envelope consisting of an outer gas passage, fairings around each strut, and an inner diffuser cone.

The primary purpose of the rear frame was to support the No. 6 bearing. It also supported the diffuser and tailpipe and kept the turbine casing round. The radial struts, in addition to their structural capacity, served as passageways to transmit the piping that serviced the No. 6 bearing, oil supply, air supply for the sump seal, and the sump air vent.

5.1.5 TAILPIPE AND JET NOZZLE

5.1.5.1 Afterburner

Description - The turbine discharge gases exhausted through the tailpipe and the exhaust nozzle. The forward portion of the tailpipe and the aft portion of the inner cone formed a continuation of the turbine rear frame diffuser passage. Afterburner fuel, which was injected through spray bars, was ignited by a catolytic ignitor located in the flameholder. The flameholder was mounted on the inner cone. The tailpipe was protected from the high temperature of afterburner combustion by a continuous-slot liner and cooling gas flow.

Fuel System - A simplex fuel system was planned for the subsonic takeoff afterburner. The spray bar consisted of two tubes welded together and projecting radially inward into the gas stream. Each tube had a number of orifices for injecting the fuel into the air stream.

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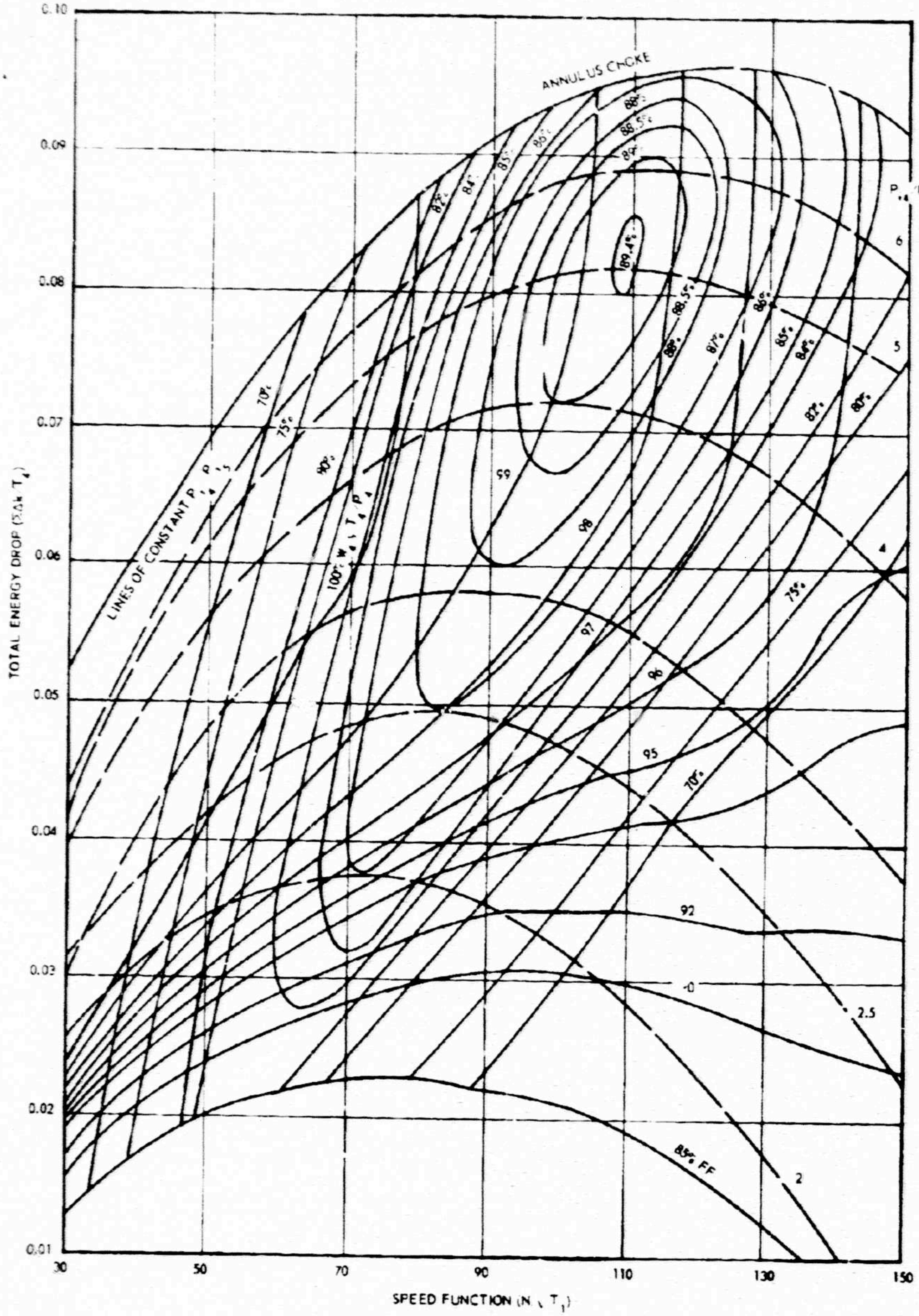

Fig. 5.12 – XMA-1A power plant – X211 – A, D and E turbine map

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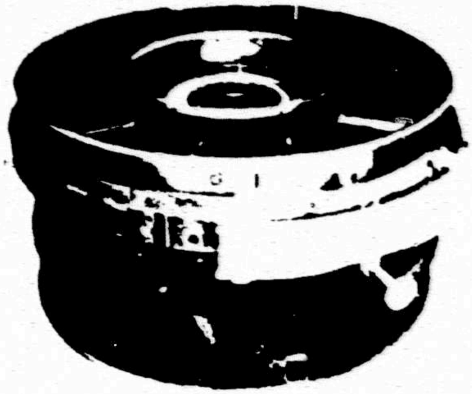

Fig. 5.13 – Turbine rear frame

Flameholders - The flameholders consisted of four V-gutters connected by 0.25 inch rods. The rods were pin connected to the gutters to provide freedom for thermal expansion. The flameholders were mounted from the outer wall of the tailpipe.

Liners - The tailpipe liner, a spot welded sandwich type structure, had a number of circumferential slots for introducing a film of cooling air at various axial locations. It was supported from the tailpipe by "piano hinge" type hangers. The hangers were designed to accommodate the thermal expansion of the liner with respect to the tailpipe.

5.1.5.2 Jet Nozzle

Function - The X211 jet nozzle provided the correct engine exit area and controlled engine speed at all operating conditions. Provisions were incorporated to provide secondary cooling air for the afterburner section during reheat operation.

The design considerations are presented in reference 2.

The complete nozzle assembly is shown in Figure 5.14.

5.1.6 OTHER MECHANICAL COMPONENTS

5.1.6.1 Coupling Shaft

The coupling shaft transmitted turbine power to the compressor. This shaft also provided transmission of compressor air for the turbine disc, seal, and torque ring cooling. It was supported at the ends by the compressor and turbine and at two intermediate points by damper bearings; these in turn were supported by the reactor-shield assembly.

5.1.6.2 Accessory Drives

General - The accessory-drive system transmitted power from the main-engine rotor shaft to the engine and customer accessories such as lubrication and fuel pumps, alternators, etc. It also provided mounting pads for these components. The system consisted of three basic gearboxes:

1. The inlet gearbox located in the front frame hub.
2. The transfer gearbox located at the bottom of the compressor front frame.
3. The rear gearbox located on the bottom of the gear compressor casing.

These gearboxes are described in reference 3.

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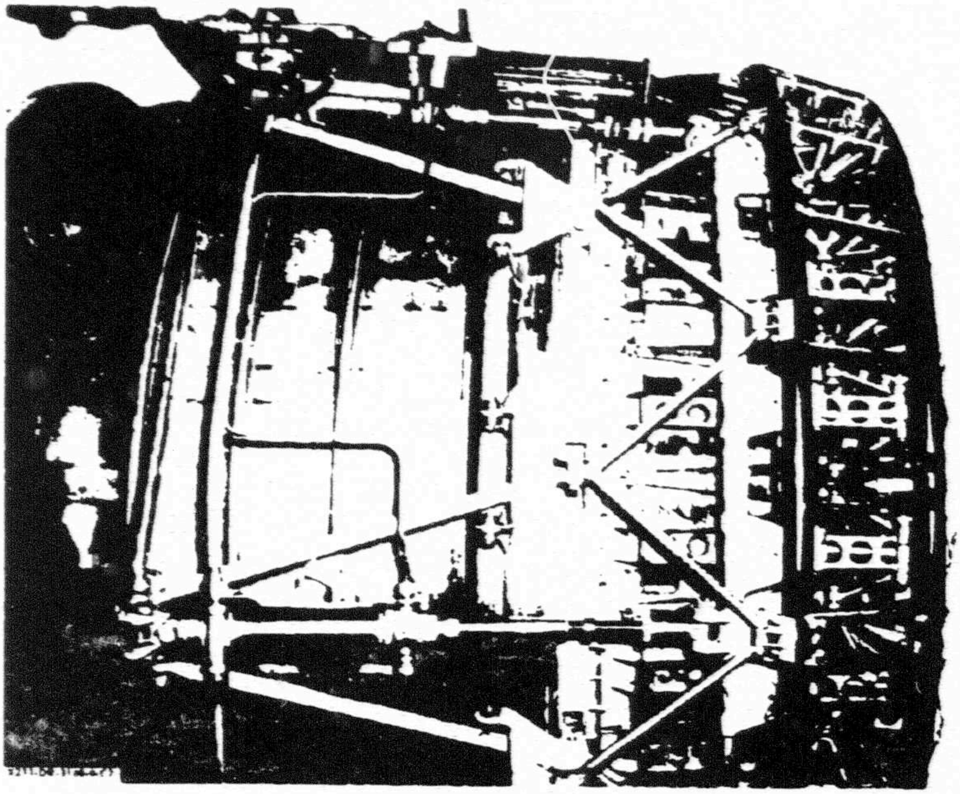

Fig. 5.14 – Exhaust nozzle and jet nozzle assembly

5.2 TURBOMACHINERY DESIGN REQUIREMENTS

5.2.1 GENERAL

The turbomachinery models for use as a part of the XMA-1A power plant were designated X211-A and X211-E. The X211-A was the first model and was used in the ground development of the XMA-1A power plant. The X211-E was an improved version for use in the XMA-1A power plants.

Both the X211-A and the X211-E were major development steps toward the X211-F which was the designation for the turbomachinery to be used in the operational model power plant (XMA-1C).

5.2.2 REQUIREMENTS

Both the X211-A and X211-E were designed essentially in accordance with the requirements presented in section 2.1.

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5.3 TESTING

Significant testing of X211 components and buildups for the XMA-1A took place between September 1957 and early 1960. (The first firing on ETB was performed on March 3, 1958.) Testing beyond that time was directed toward contemplated program and power plant changes and was primarily used for the XNJ140E power plant. These tests are described in APEX-908. The nuclear aspects of the development of materials for the turbomachinery are described in APEX-917. Full scale testing of the X211 assembly took place in the X-1 cell, Figure 5.15.

More complete descriptions of X211 testing and evaluation are given in references 1, 2, 3, 4, and 5.

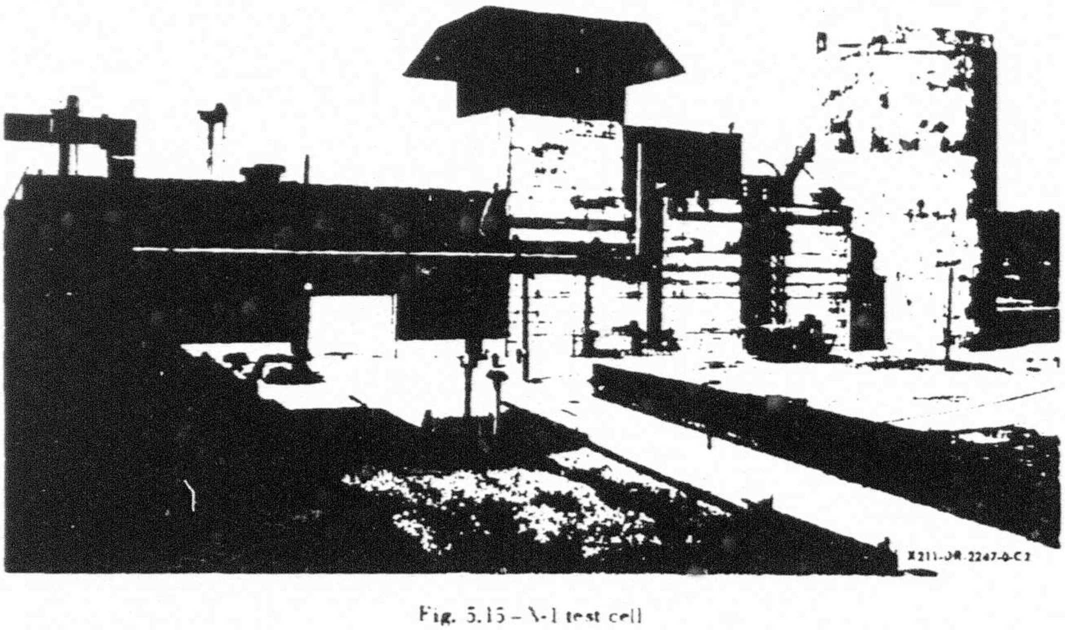

Fig. 5.15 – X-1 test cell

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5.4 REFERENCES

1. Felber, M. A., "Design Data Book XMA-1A Power Plant Section 2.0 - Turbomachinery," GE-ANPD, DC 59-4-200, April 1959.
2. "X211 Engine Development During Contract Year 1958" GE-FPLD, R58AGT767, September 1958.
3. "X211 Engine Development During Contract Year 1957" GE-FPLD, R57AGT579, September 1957.
4. "X211 Engine Development During Contract Year 1959," GE-FPLD, R59FPD494, September 1959.
5. "XMA-1A Power Plant - X211 Turbomachinery Testing Summary," GE-ANPD, DC 61-11-25, April 1962.

6. CONTROLS

The original XMA-1 power plant objectives were the design and development of controls and accessories to meet requirements imposed by Weapons System 125A. The high ambient temperature resulting from the high flight speeds (Mach 2.5 with possible growth to Mach 3) coupled with nuclear radiation effects on materials were too severe for conventional jet engine control systems. Because of the environment, pneumatic controls were chosen for the power-plant-mounted engine controls. Hydraulic actuators were chosen for all actuation except for shim-scram and dynamic actuators; these were originally electromechanical. An attempt was made to minimize the use of power-plant-mounted electrical components although some, such as feedback elements and torque motors, were required. Magnetic amplifiers were selected as the basic mechanization for those reactor and engine control components which could be located off the power plant.

When the CAMAL mission was established, the design environmental temperature requirements were reduced as a result of lowering the flight speed to Mach 0.9. The only operational requirement dropped was chemical afterburner operation on nuclear power.

The system was required to control the power plant in all modes of operation; on either chemical or nuclear power, to transfer between the two without shutting down, and to operate a single engine on nuclear power in the event of one engine failure. The initial development system was a fully integrated automatic control with the jet nozzle area controlling speed, the fuel flow controlling turbine discharge temperature, the reactor power controlling reactor discharge temperature, and the compressor-stator position being controlled as a function of engine speed and inlet temperature.

Late in the program, it was decided to provide a control that would demonstrate sufficient performance and reliability for accomplishing early flight in a test bed aircraft. The program emphasis, at that time, changed from an automatic to a manual fuel control. Effort was continued on the automatic speed control and increased on a variable stator control. Work was started on a manual jet nozzle area control and on an automatic slave stator system. The reactor control remained essentially the same. Design work was begun on a power plant control console for use with both ground test and flight test operation. This control was under development at the end of the XMA-1 program.

6.1 SYSTEM DESCRIPTION

6.1.1 ENGINE CONTROL SYSTEM

The objective of the engine control program was to design an engine control that would, in combination with the reactor control, provide a high performance integrated power plant control system. The engine control system required was for the stator, the fuel, and the rotor speed. A detailed description of this system may be found in references 1 and 2.

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6.1.1.1 Speed Control

The speed control system is shown in Figure 6.1. Details of the hydraulic components are shown in Figure 6.2. Speed control was obtained by automatic control of the nozzle area. A manual control loop was also provided for the nozzle area to accommodate power plant performance mapping during initial operation.

In operation, the demand speed was compared with the actual engine speed. After amplification, the speed error was fed through variable gain and stabilizing networks where lead-lag circuits compensated for the phase lag due to the polar moment of inertia of the rotor. The output of the stabilizing networks constituted a demand for nozzle servopump stem position. Stem position was detected with an electromagnetic transducer and fed back for comparison with the reference. Stem position error was fed through networks that compensated for variations in torque motor impedence due to temperature changes and culminated as an input to a torque-motor-operated servovalve. The torque motor controlled a flapper valve which directed fluid to two stem positioning pistons operating through the torque balance of a rocker arm.

The rocker arm served as a cam which was followed by the servopump stem and supplied stem position information through mechanical linkage to a differential transformer. The stem positioning pistons also served as metering valves which directed the flow of fluid to the nozzle actuators. The pump stem was connected to the sleeves of the nozzle pump pistons. Variations in piston sleeve position corresponded to variations in the effective length of the piston stroke and, consequently, to the fluid flow rate to the nozzle actuators.

There were six synchronized piston-operated hydraulic actuators. The actuators were operated in parallel with common extend and retract manifolds. The flexible synchronization cable and cable assembly was integral to the extend manifold. The rod sides of the actuators connected to an actuator ring. The head side of the actuators were mounted to an actuator mounting ring cantilevered off the tailpipe aft flange.

A change in nozzle servopump area, operating through the turbomachinery dynamics, produced a change in rotor speed which was sensed and fed back for comparison with the speed reference.

The pneumatic speed sensor detected mechanical speed with a conventional system of flyweights operating against a calibrated spring. The spring displacement drove a pneumatic pressure divider whose output was amplified and used to drive a piston. The position of the piston was fed back through a "square law" cam and compared with the spring position. When the position error was zero the piston output was proportional to speed.

In summation, the automatic speed control operated as follows: a speed error positioned the nozzle servopump stem which established the delivery of fluid to the nozzle actuators, thus, changing nozzle area. The area change reduced the speed error to zero by driving the actual speed to correspond with the scheduled value.

6.1.1.2 Fuel Control

The fuel control system is shown in Figure 6.3. The block diagram shows the facility fuel supply system and the main ignition system as well as the engine control system.

A description of the various components of the fuel control system is presented in reference 2.

6.1.1.3 Stator Control

The stator control system is shown in Figure 6.4. This figure shows two possible control arrangements. In one arrangement each of the variable stator stages would be indi-

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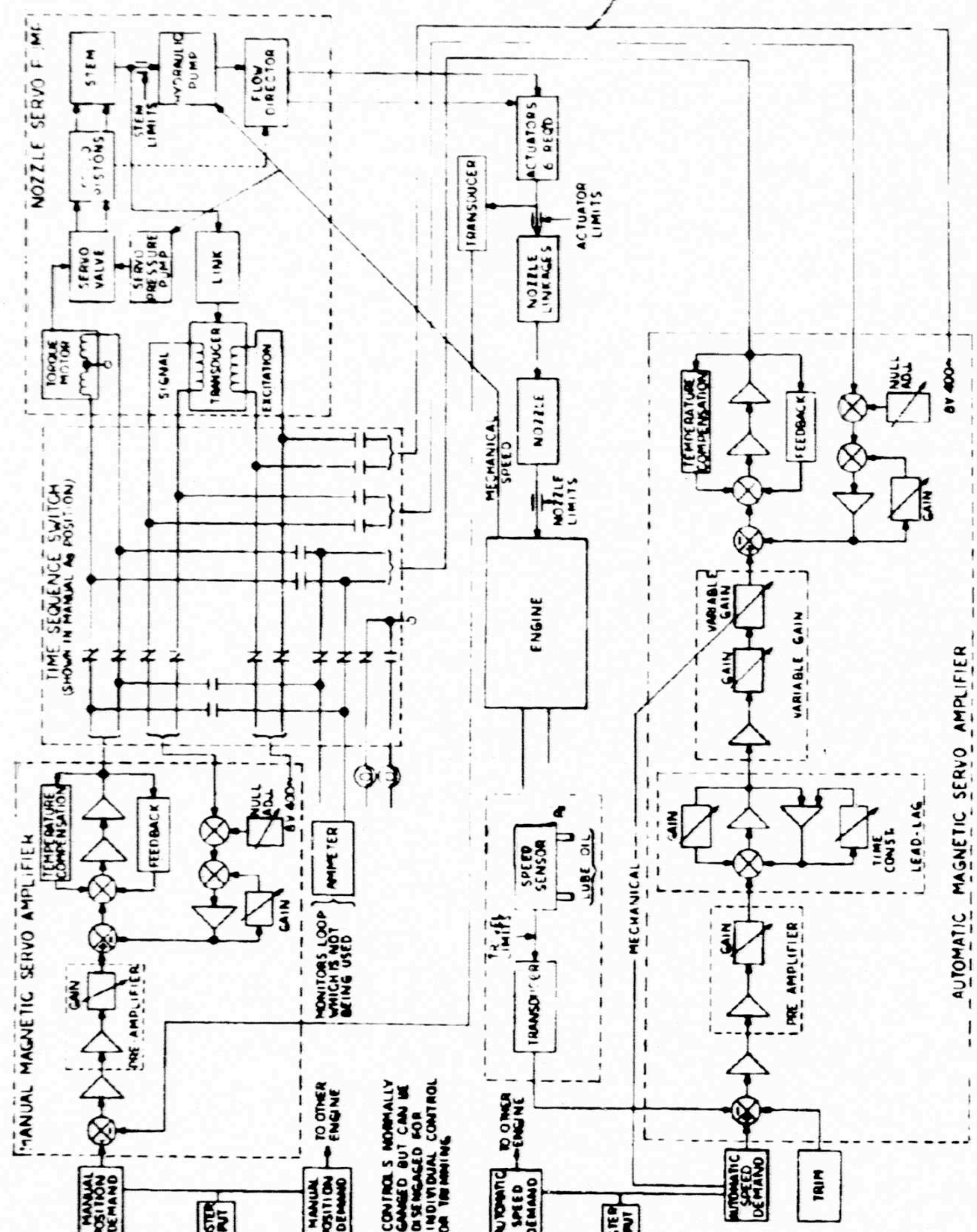

Fig. 6.1 – XMA-1A jet nozzle control system

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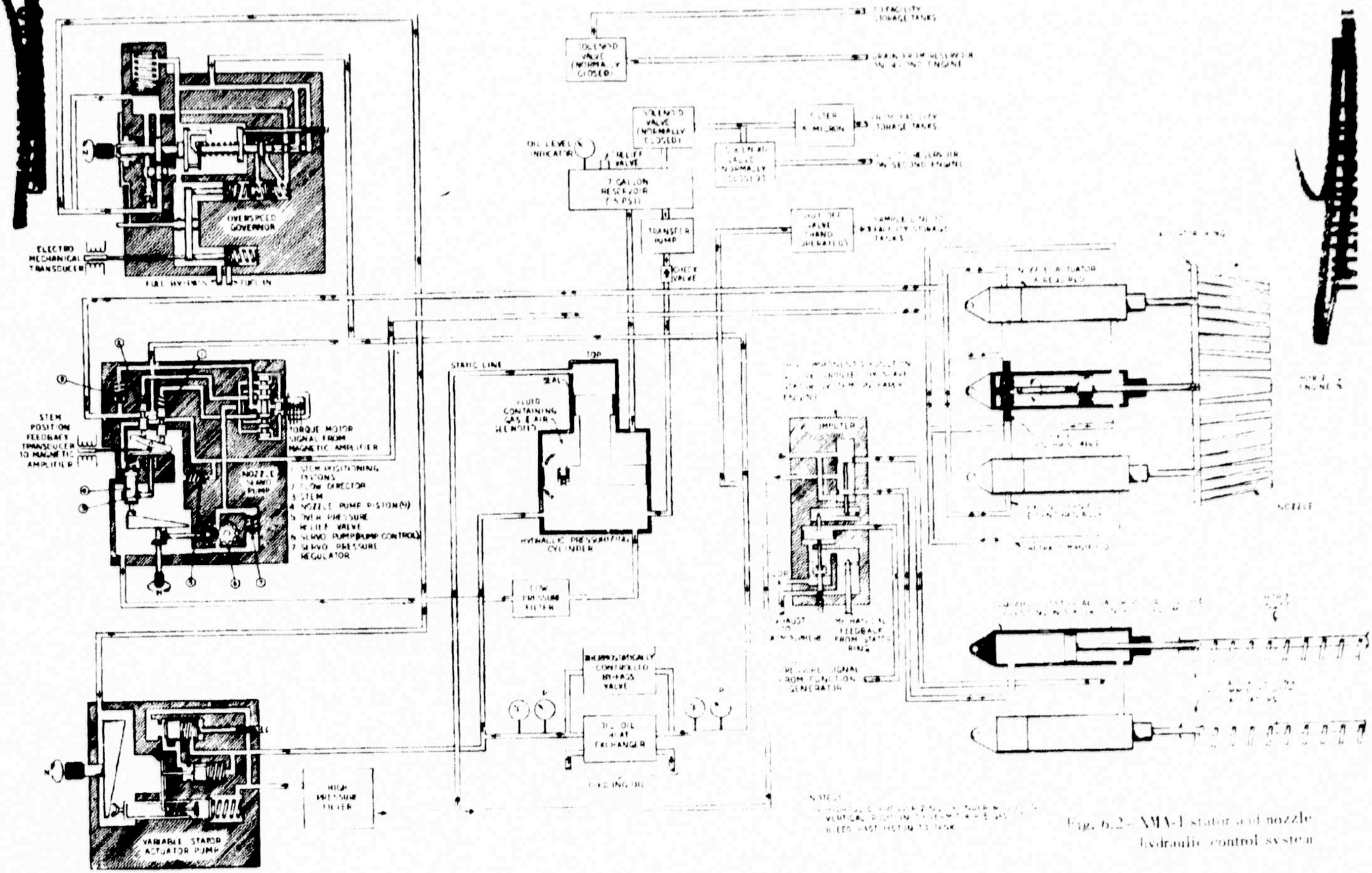

Fig. 6.2—XMA-1 stator and nozzle hydraulic control system

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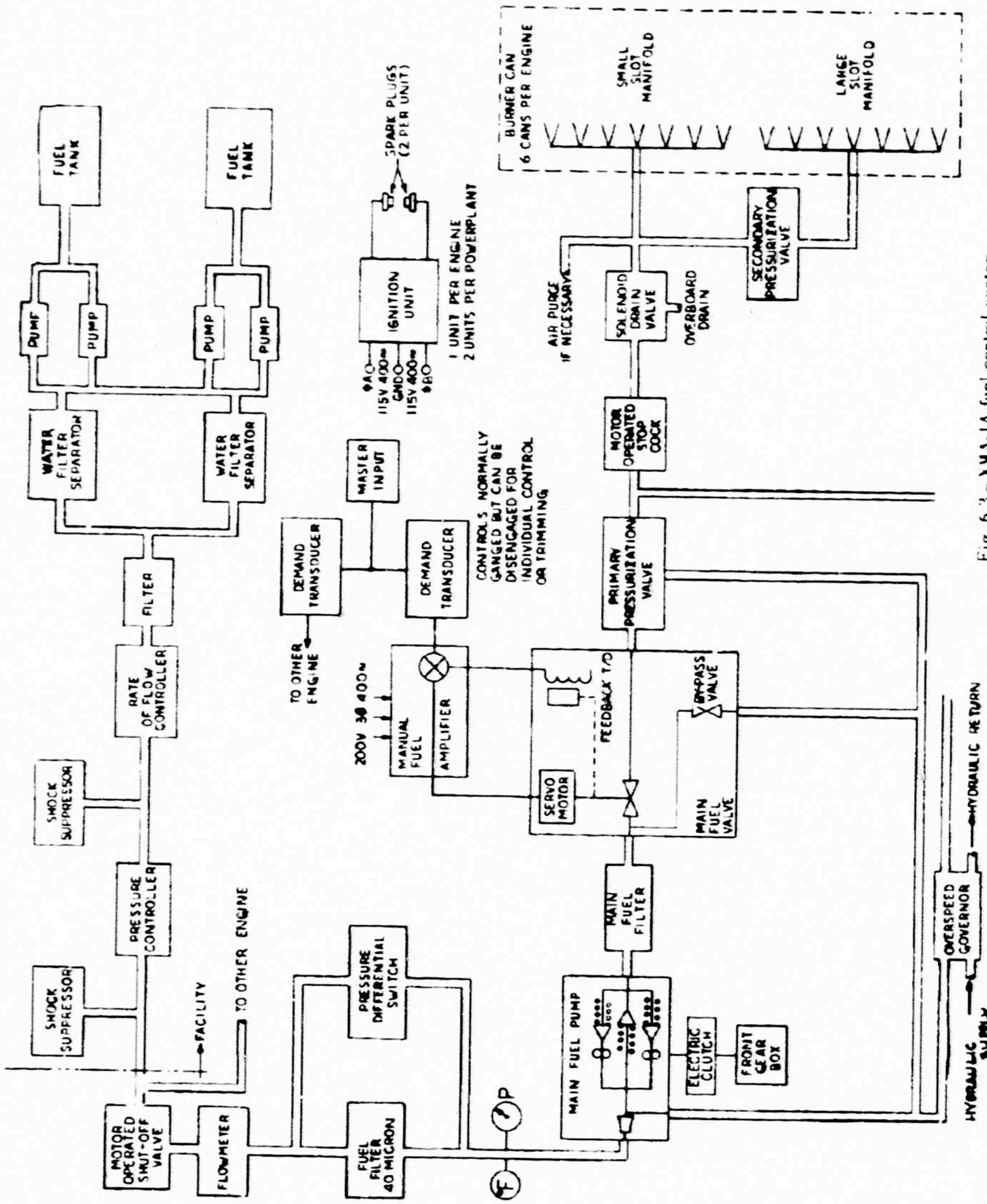

Fig. 6.3 – XMA-1A fuel control system

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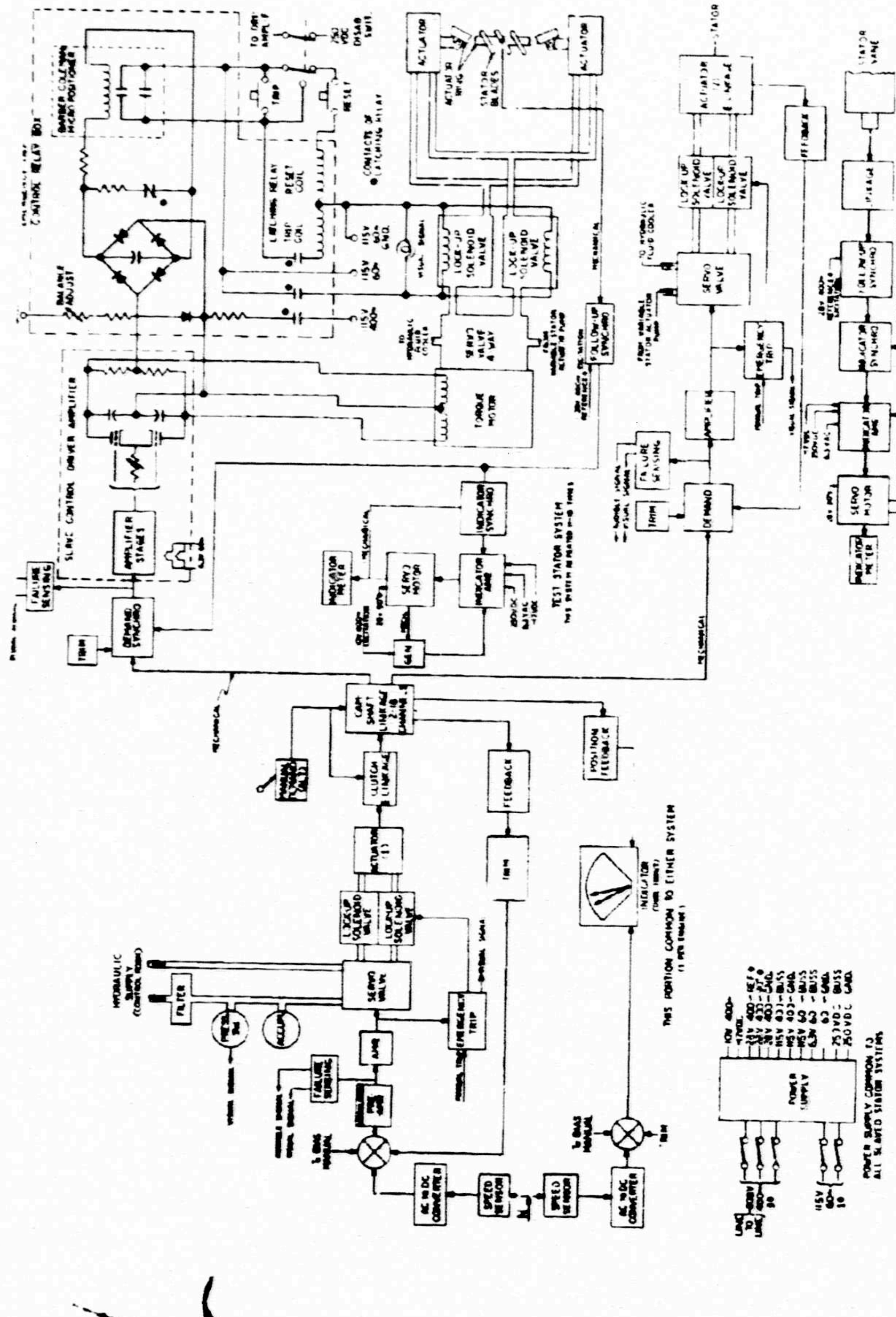

Fig. 6.4 – XMA-1A stator control system

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vidually activated. In the other, the 11 to 18 variable stages would be divided into two groups with each of the stages linked together. At the termination of the XMA-1 program it appeared that the individually actuated system would be the one used and the following discussion is applicable to that system.

The variable stator control system was sufficiently flexible to provide a means for determining the optimum stator schedules for steady state, starting, and semitransient operation. It could substantiate the performance of various stator schedules and explore regions of 90 to 103 percent corrected speed during operation of the turbomachinery.

Actual engine speed was sensed by a tachometer generator whose a-c output was converted to a d-c proportional signal. The d-c signal was used as a demand for cam shaft angular position. The angular position of the shaft was sensed with a potentiometer and compared with the speed proportional signal. The shaft error was amplified and fed to a conventional torque-motor servovalve actuator combination which drove the cam shaft to an angular position proportional to the turbomachinery speed. Actual speed was corrected by the manual T_2 bias adjustment at the speed error detector.

The stator control components and their function are presented in reference 2.

6.1.1.4 Pneumatic Control System Development

The technology acquired in this work is described in reference 3. The pneumatic controls utilized compressor discharge air as the operating fluid. The pneumatic pressure divider was the basic building element of the control. In its simplest form, it consisted of two orifices in series; one was a fixed orifice and the other a variable area orifice.

The compressor discharge air entered the compressor-signal pressure chamber through the fixed orifice. The pressure in the signal chamber was established by the area of the variable area orifice which exhausted to ambient pressure. The pressures from each divider's signal pressure chamber, when fed to the two sides of a pressure sensitive piston, would (if the pressures are unequal) move in the direction of the lower pressure, causing a servovalve or similar device to take corrective action. Bimetallic temperature elements effectively set the variable area in a pressure divider. An error sensing piston then determined if a second divider used to establish a reference had matched this pressure. If the pressure in the second divider matched that of the temperature sensor, the divider needle had to be at the desired position. Thus, a mechanical motion as a direct function of temperature was created at a remote location. This motion could move cams or fuel flow computing devices.

Many refinements and adjustments were added to this simplest divider and power piston arrangement to perform stabilizing functions as shown in the functional schematic drawing of the development control, Figure 6.5.

In operation, the pneumatic control sensed compressor inlet temperature (T_2) by means of two parallel bimetallic sensors. The pneumatic signal was transmitted to the T_2 amplifier whose mechanical output positioned three-dimensional cam-racks as a function of T_2. The control sensed engine speed (N) by means of a governor flyweight system; the governor output went to a pneumatic amplifier which positioned the three-dimensional cam-racks as a function of N. The cam-rack system generated (1) acceleration fuel-to-air ratio demand, (2) the stator vane positions required, and (3) acceleration power-to-airflow ratio.

Maximum compressor case limit pressure was generated as a function of T_2 only. The output displacements from the three-dimensional cams displaced pneumatic dividers whose pressure-ratio signal outputs were demand signals for other components. Signals defining N and T_2 were extracted for electrical transmission to nonengine mounted controls; these mechanical displacement signals were used to energize electromechanical transducers.

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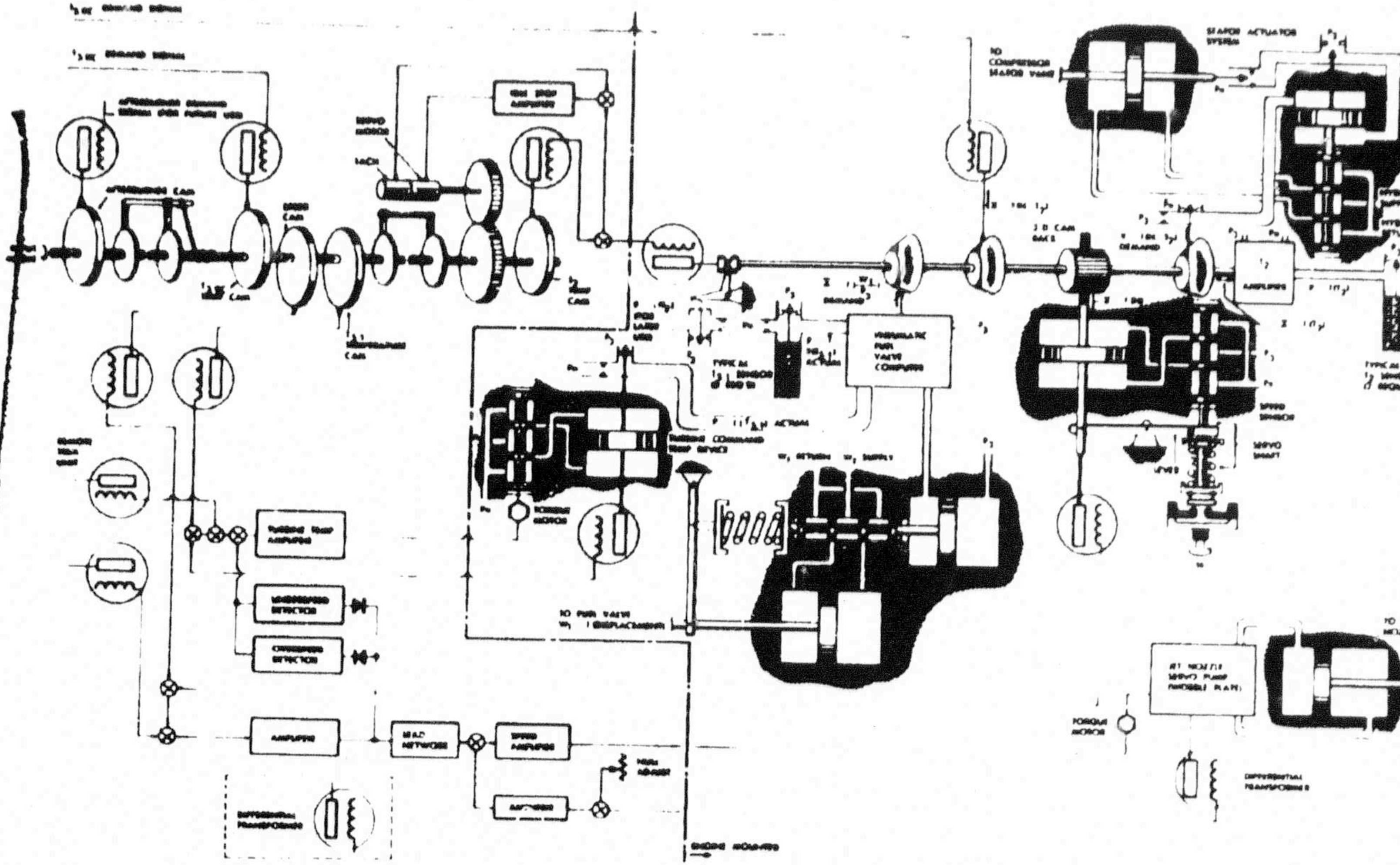

Fig. 6.5 – Schematic of development pneumatic control system

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Stator-vane position-demand pressure ratios were fed from the function generator package to the stator computers. Mechanical-displacement-feedback devices positioned the pressure divider within this computer in a way similar to the divider in the function generator. If the positions, and therefore the pressures, were dissimilar the error-sensing piston displaced a servovalve. High-pressure oil flowed to the stator actuators until the stator vanes and the feedback divider were correctly positioned.

During an acceleration, the acceleration fuel-to-air ratio demand displacement moved a pressure-divider needle whose pressure was transmitted to the fuel-control valve. A piston in this valve was loaded in one direction by compressor discharge pressure (P_3) and in the other direction by the demand pressure (a function of fuel-to-air ratio W_f/P_3) and a calibrated spring. The displacement of the spring was then a function of the required fuel flow.

A fuel servomechanism was provided to position the calibrated variable area fuel-to-engine metering valve. Another fuel servomechanism maintained a constant pressure drop across the metering valve by controlling the fuel returned to the fuel pump inlet. This provided the fuel flow necessary to meet the fuel-to-air ratio demanded by the function generator. In a similar manner, the acceleration power computer received a pressure which was a function of engine energy required. In conjunction with a calibrated spring, this pressure was compared to compressor discharge pressures to produce displacements proportional to energy (Q). This displacement energized a transducer sending a proportional electrical signal to other controls.

The steady-state temperature-demand signal was achieved by recreating the demand signal generated in the thrust selector located in the off-engine. An electrical current was received by the engine mounted turbine discharge-temperature ($T_{5.1}$) command device whenever its output pressure divider was not in the proper position. Actual divider position was sensed by a linear transducer, and existance of positional error was determined by the electrical devices located in the off-engine control compartment. The turbine discharge-temperature command amplifier received the error current and, by means of an electrical torque motor and servovalve, pneumatically positioned the demand pressure divider until the error current disappeared.

The pressure ratio of the demand divider was compared by a pressure-sensitive piston with the pressure ratio developed by the eight parallel turbine discharge-temperature sensors. If the pressures, and therefore the temperatures (actual versus demand), were not identical the error sensing piston moved the output needle of the fuel computer in the direction that would establish corrective fuel flow and eliminate the temperature error.

A piston, cylinder, and orifice were added to the fuel computer to give proportional plus integral action. These first limited instantaneous response to a large error (proportional) and then gradually permitted the divider needle to move to the required position (integral). Acceleration or deceleration fuel flows were established in response to swamping electrical signals to the $T_{5.1}$ demand device. A continuous swamping current to the torque motor of the $T_{5.1}$ demand device caused the $T_{5.1}$ demand divider to create a pressure. When this pressure was compared with the pressure from the $T_{5.1}$ temperature sensors, the error drove the fuel computer follower against the three-dimensional cam of the function generator. The output needle of the fuel computer was positioned during the accelerations as a scheduled function of N and T_2 as described earlier. A continuous swamping current of polarity opposite to that of the torque motor drove the fuel computer in the opposite direction and against a mechanical stop. The engine then accelerated on this fixed minimum fuel-to-air ratio until a minimum fuel flow (W_f) was reached in the fuel valve.

6.1.2 REACTOR CONTROL SYSTEM

The XMA-1A reactor control system was designed to control the reactor power generation of a metallic core reactor, directly coupled to twin X211 gas turbines, to effect aircraft nuclear propulsion.

The control regulated reactor exit-air temperatures ($T_{3.9}$) as a basic control parameter. A closed logarithmic flux loop and closed shim and dynamic rod position loops were enclosed by the temperature loop to obtain the required performance and reliability. In addition to the power-range temperature control, an automatic startup control was available; it was capable of performing a period controlled reactor startup. An extremely low-level power holding capability was obtained through use of a count rate control.

A single line block diagram of the power-range control, startup control, and safety circuitry is shown on Figures 6.6 through 6.8.

Detailed design objectives were:

1. To provide a means of automatic reactor startup from subcritical to 1.5 percent of full power.
2. To provide low-level flux regulation and holding from subcritical to 1.5 percent of full power.
3. To provide reliable control of the reactor exit-air temperature within ±25°F from 1100° to 1500°F.
4. To provide transient performance for acceleration from idle to military thrust in not more than 60 seconds.

Complete system design and analysis information may be found in references 4, 5, and 6. Requirements for control system mechanisation are presented in references 7 and 8, and the results of an extensive component evaluation program may be found in references 9 and 10.

6.1.2.1 Startup

The startup control involved the use of two primary sensor packages, each containing three fission chambers and a power-range ion chamber. The three fission chambers in each sensor package were varied in size and location to produce continuous detection, spanning some 10 decades change in thermal neutron density. Associated with each chamber was the electronic circuitry required to compute log count rate and period. The former was a measure of the reactor power level and the latter a measure of its rate of change.

Automatic Period Control - The six fission chambers together with their associated period computing circuitry were arranged in two instrument systems of three channels each. Each system provided continuous log count rate and period information throughout the 10 decade operating range. The period output from one instrument system was compared with a reference period and the error was used to position the shim-rod grates, reducing the period error to zero while driving the actual reactor period to correspondence with the reference.

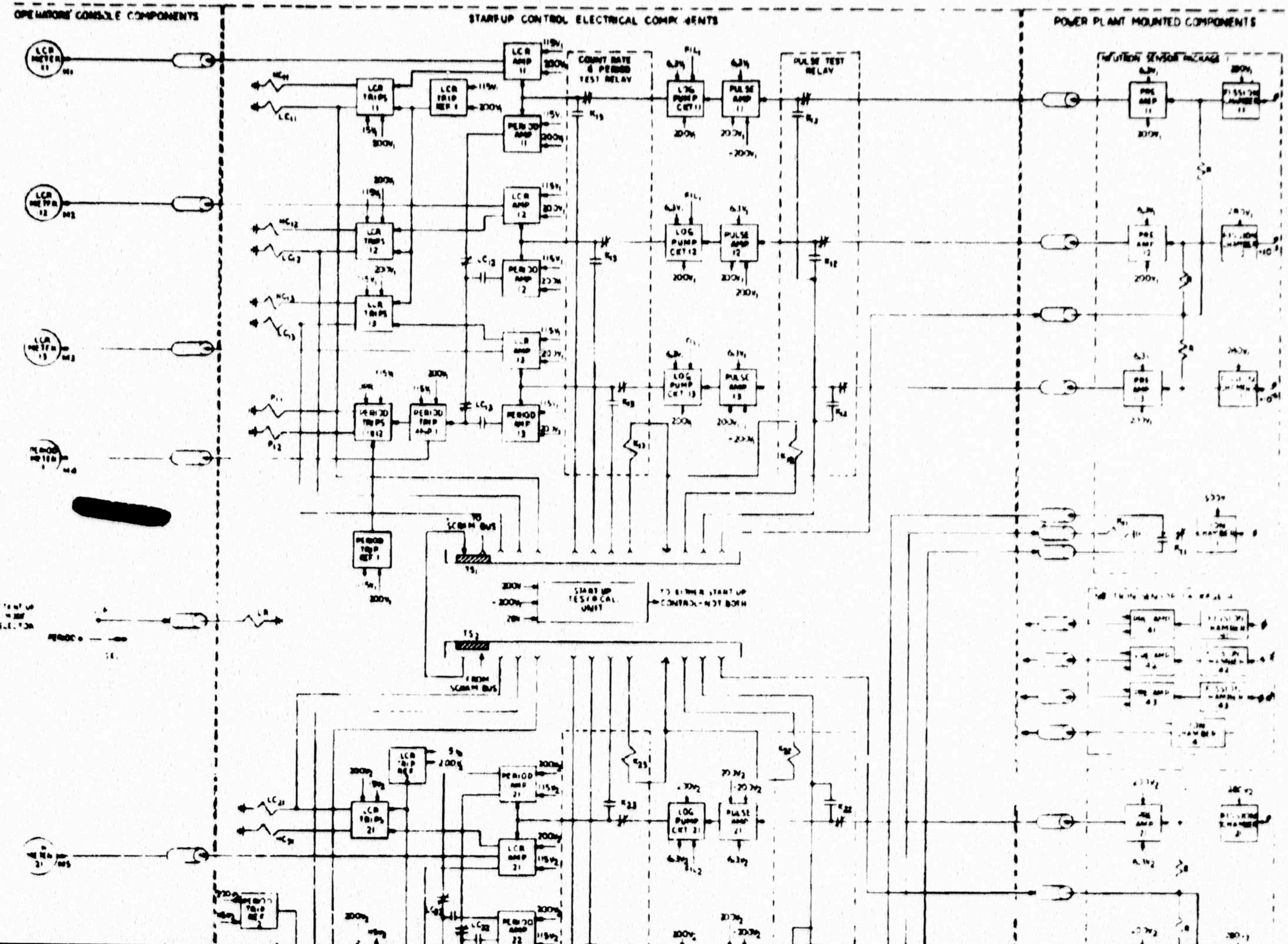
A bode plot (straight line attenuation frequency diagram) of the period control is shown in Figure 6.9. Two curves were used to show the effect of the variable time response of the logarithmic count-rate circuit. The solid line shows a case in which the variable time response had a negligible effect upon the loop. This condition occurred at high counting rates. The dashed curve includes the effect of the time response at minimum count rate (100 pulse per second). The attenuation curves were drawn in a normalized fashion with the crossover points indicated for one-quater, one-half and full gain. This figure shows the adverse effect of the time response of the low counting rates and indicated the need for a small lead time constant at the higher gains.

KEY TO FIGURES 6.6, 6.7, AND 6.8

Symbol	Reference
A	Alarm drop relay
AI	Actuator, insert
AW	Actuator, withdraw
AL	Alarm bus relay
AT	Annunciator, test
AR	Annunciator, reset
D	Demand pots or controls
DL	Dynamic limit switch relay
DM	Dynamic actuator, on manual
DS	Dynamic actuator, on servo
EA	Exit air temperature trip
EQ	Equipment continuity trip
ES	Emergency engine shutdown trip
FE	Fuel element temperature trip
FM	Facility monitors, all fuel element rupture, radiation, and other trips
HC	High count trip, startup
HF	High frequency, 400 cycle bus
HP	High power level trip
HV	High voltage, 400 cycle bus
I_{cx}	Constant current supply output
K	Test relay
LA	Latch indication relay
LC	Low count trip, startup
LF	Low frequency, 400 cycle bus
LV	Low voltage, 400 cycle bus
LP	Lamp pulsing relay, shim
LR	Log count rate mode, startup

Symbol	Reference
M	Meter
N	Speed trip
P	Period mode, startup
PB	Pushbutton
PD	Power demand interlock relay
PW	Power mode
R	Resistor, bridging
S	Scram drop relay
SC	Scram bus relay
SE	Selectors or operator's manuals
SM	Shim actuator, on manual
SS	Shim actuator, on servo
SR	Scram reset
TE	Temperature mode
TS	Test set connector trips
1φ	Single phase a-c power
3φ	Three phase a-c power
3 mw	3 mw transfer trip
15 mw	4-15 mw low power trip
6.3 V	6.3 volts, a-c filament voltage
Fil	6.3 volts, a-c filament voltage biased
115 V	115 volts, a-c, 400 cycle, isolated bus
400~	115 volts, a-c, 400 cycle, unisolated bus
12 V	12 volts, a-c voltage reference
25 V	25 volts, a-c voltage reference
37 V	37 volts, a-c voltage reference
28 V	28 volts, d-c power bus and trip
200 V	200 volts, d-c safety trip
(+ or -) 200 V	200 volts, d-c power buses, plus or minus
280 V	280 volts, d-c safety trip
+280 V	280 volts, d-c power bus
1500	1500 volts, d-c power bus and safety trip

KMAHA REACTOR CONTROL SYSTEM



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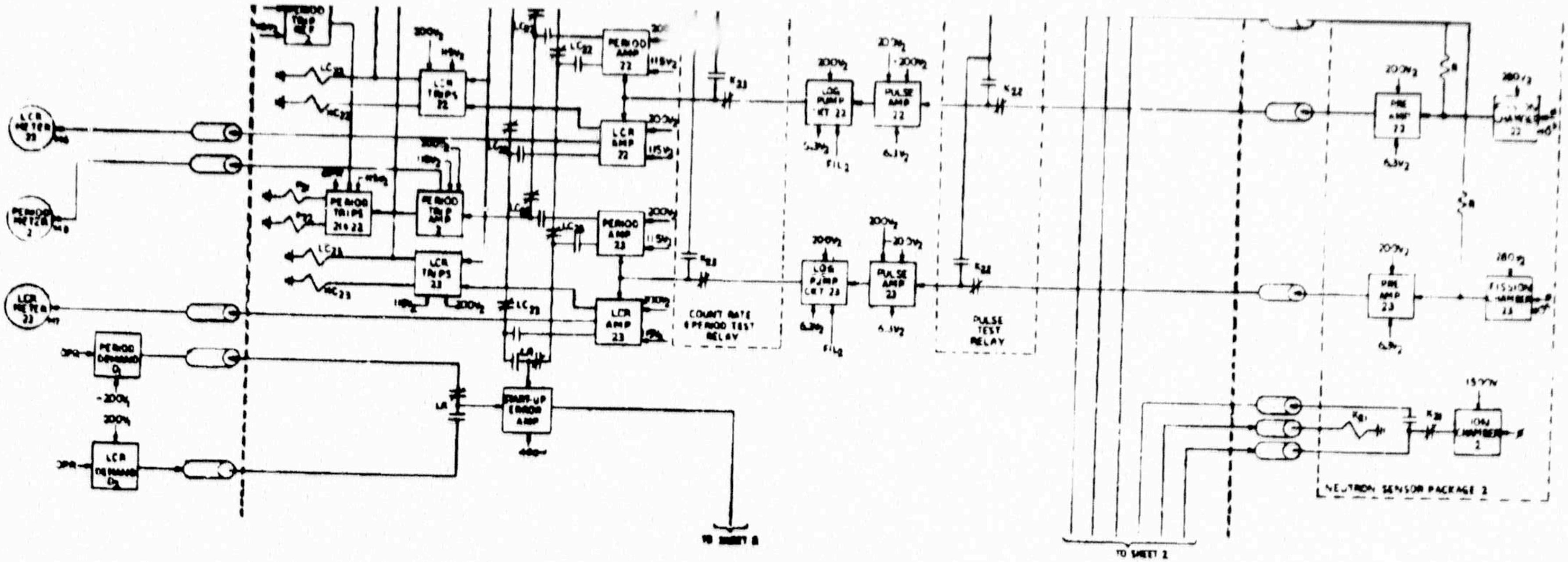

Fig. 6.6 – XMA-1A reactor control system (Dwg. 168HR197, Sh. 1)

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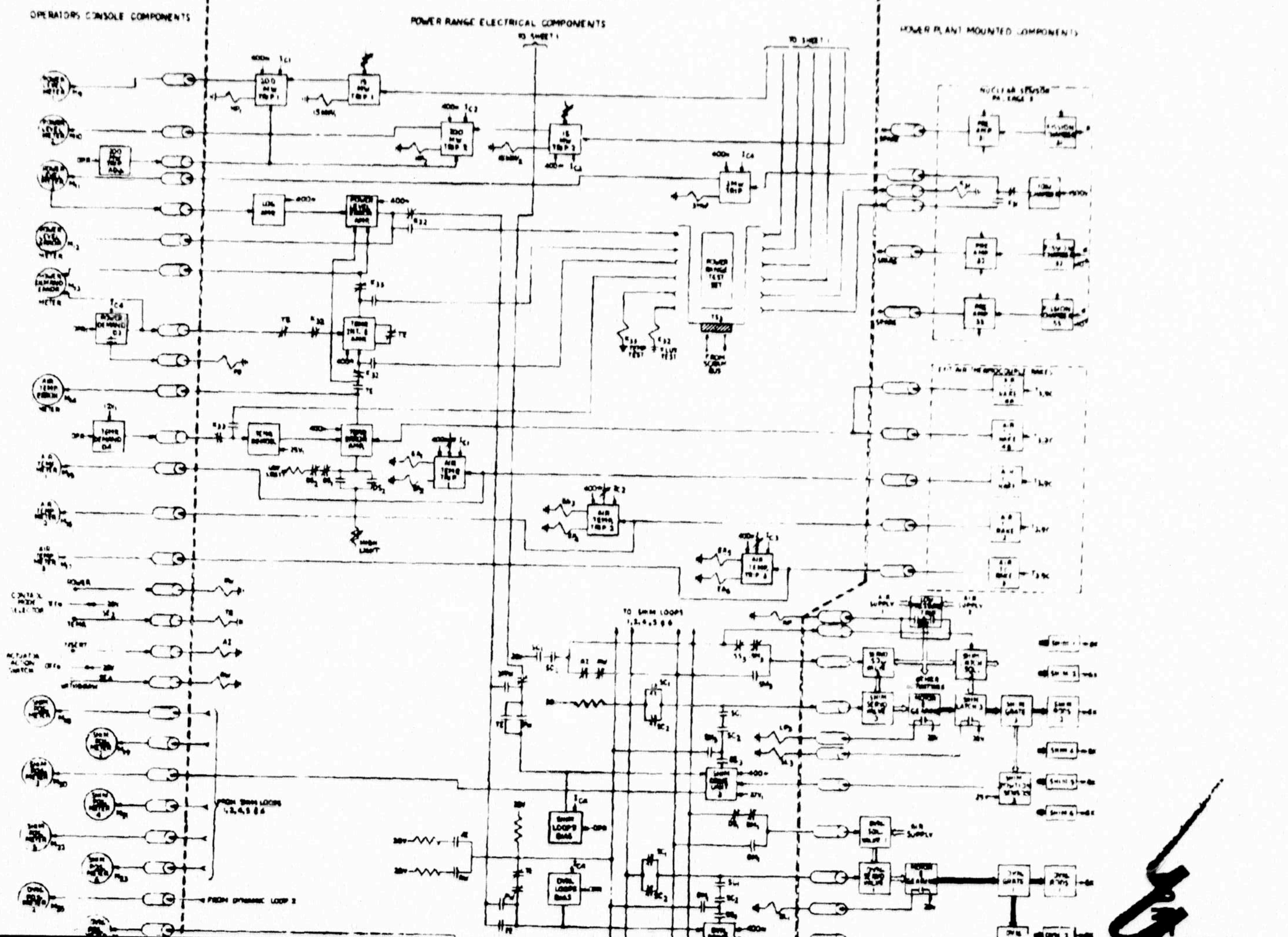
XMA-1A REACTOR CONTROL SYSTEM



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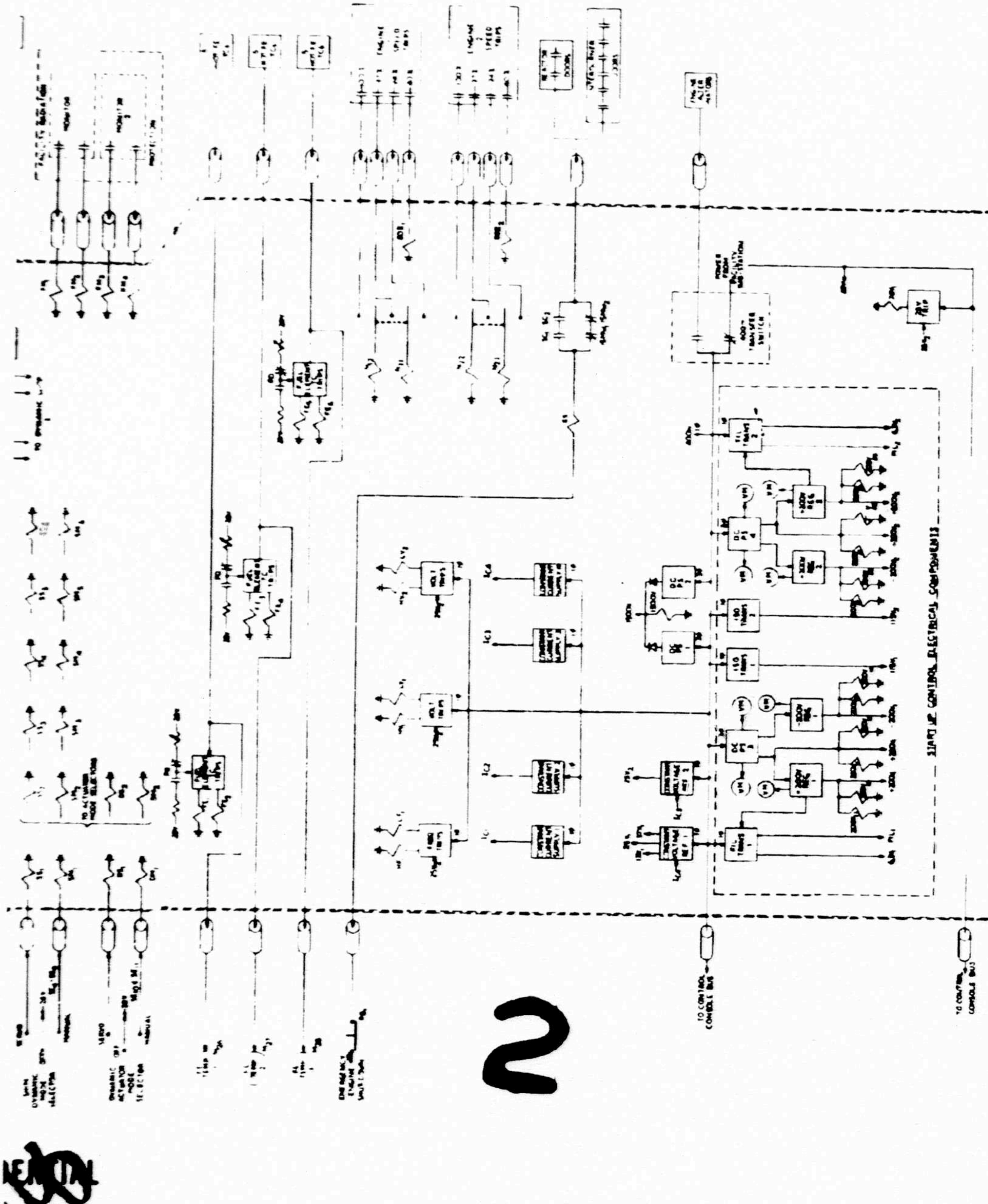

Fig. 6.7 – XMA-1A reactor control system (Dwg. 168HR197, Sh. 2)

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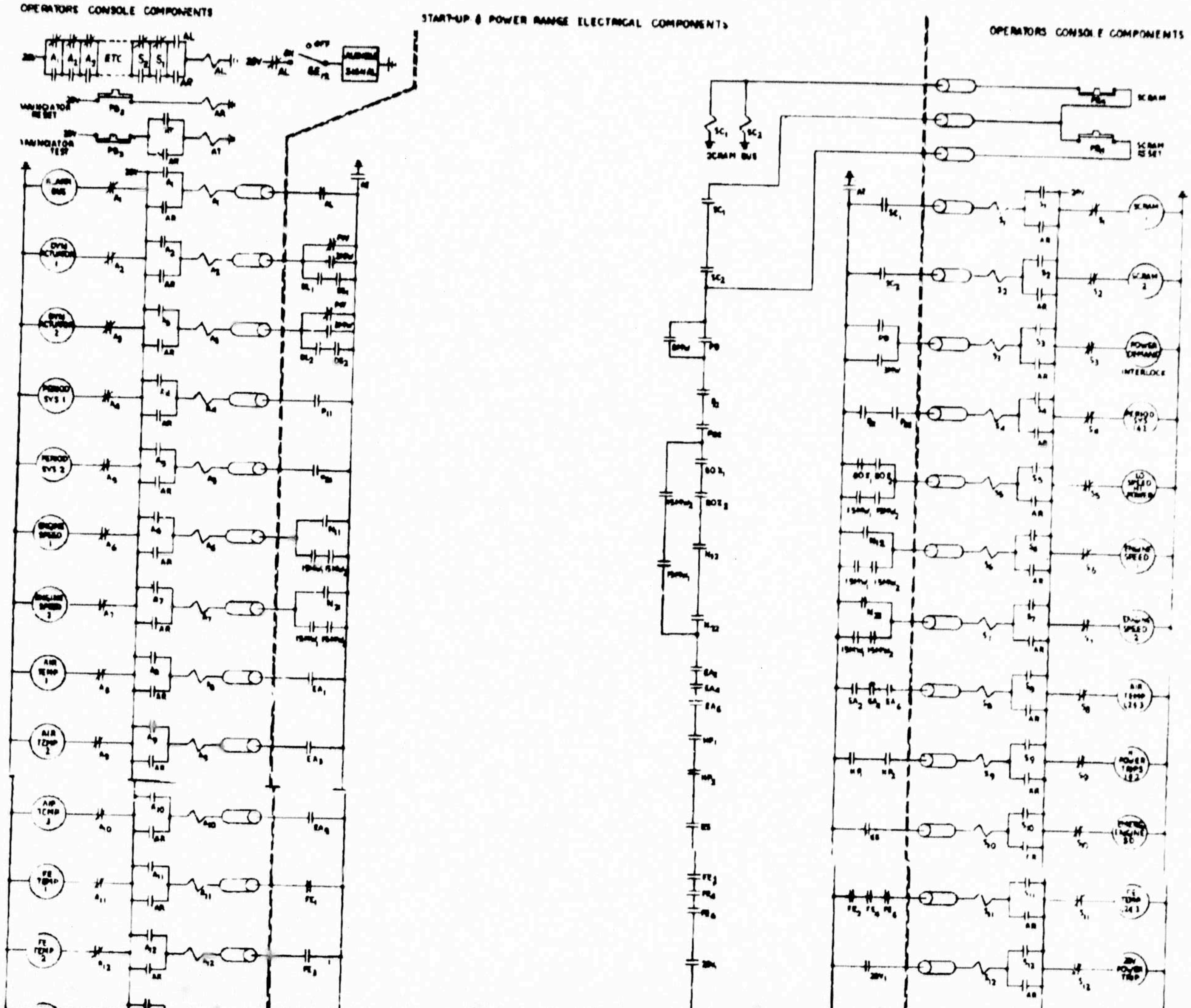
XMA-1A REACTOR CONTROL SYSTEM



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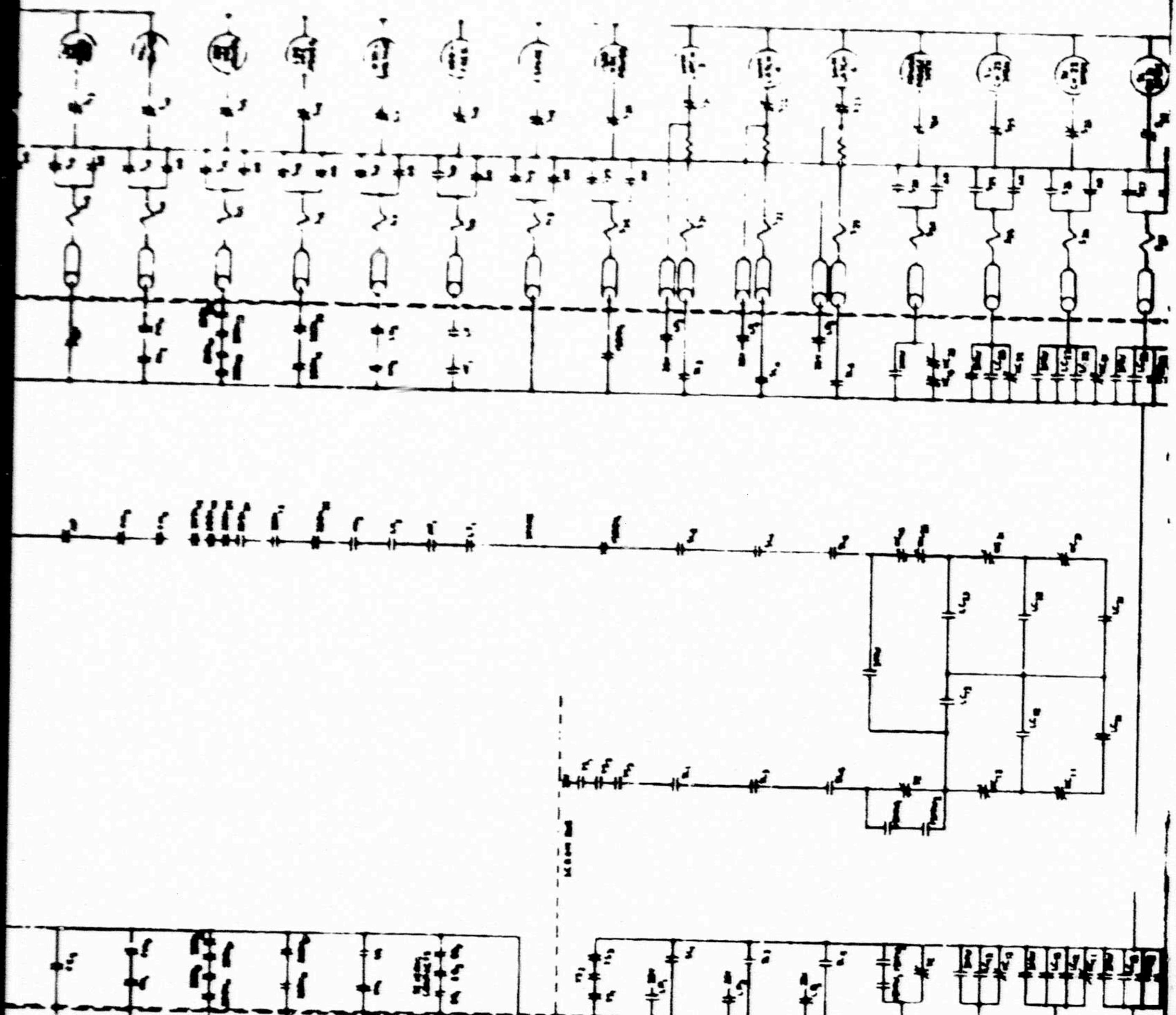

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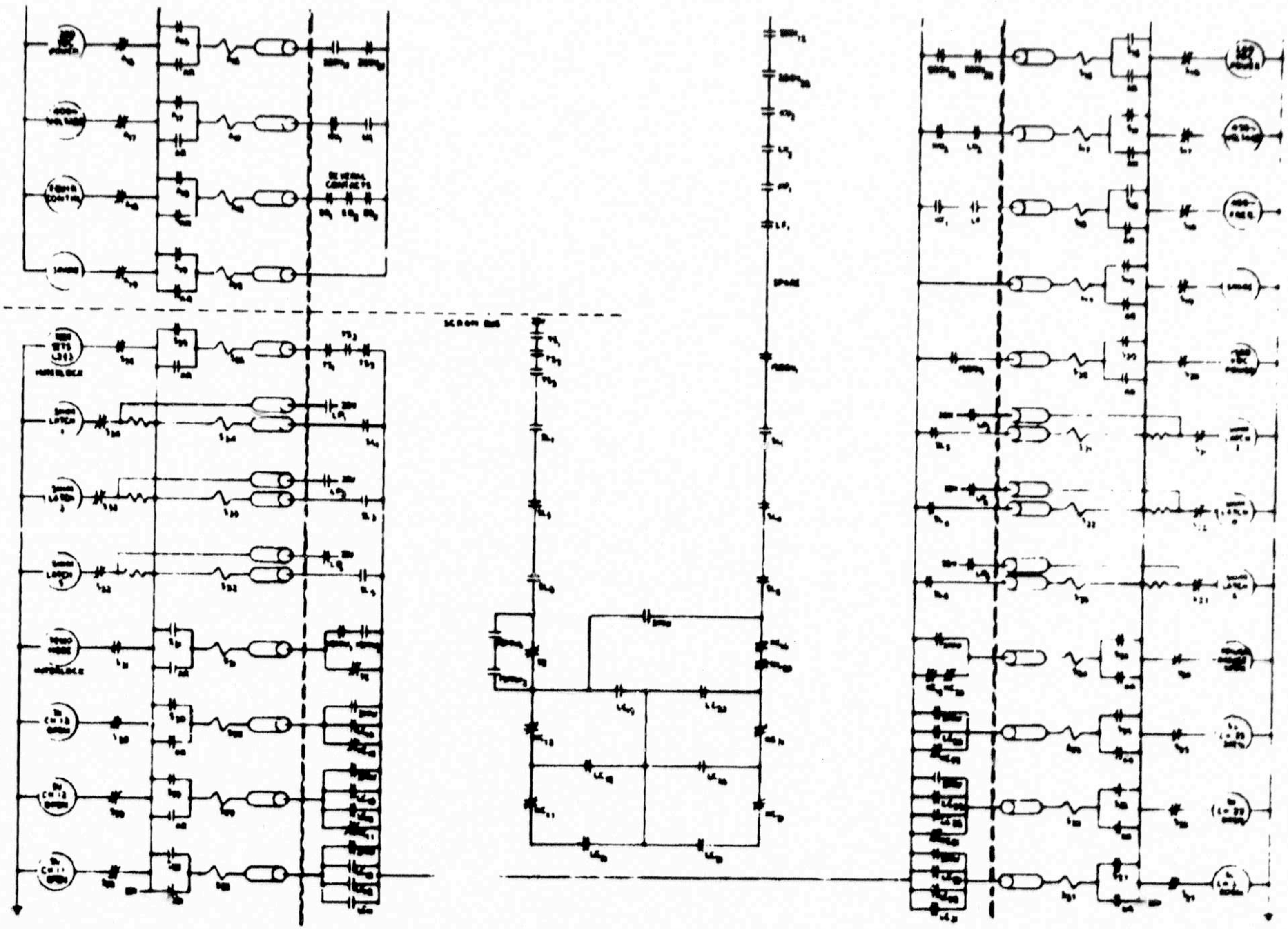

Fig. 6.8 – XMA-1A reactor control system (Dwg. 168HR197, Sh. 3)

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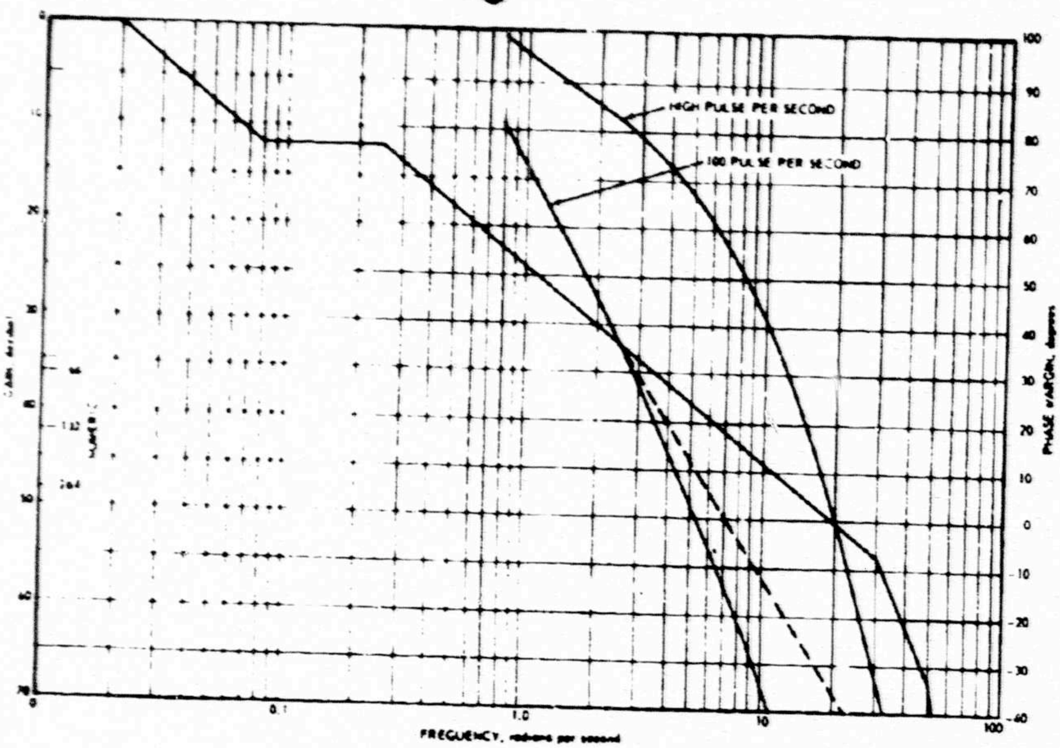

Fig. 6.9 – Period control bode plots

The indicated gains were selected on a basic of period accuracy depending upon the relative position of the shim rods and electrical neutral. The full gain case yielded a 10 percent period error for a demanded 30-second period when the relative position was at a maximum. The desired period was obtained either by increasing the period-demand potentiometer setting or by changing the position of the electrical neutral of the shim loops with a bias potentiometer.

Low-Power Level Regulation - Automatic power level regulation was accomplished in the startup range by utilizing the majority of the period control components. It required only a log count rate reference for comparison with the computed value obtained from the proper instrument channel. Power level control was effective within the upper seven of eight decades of startup range operation.

6.1.2.2 Power-Range Reactor Control

The power-range reactor control system maintained scheduled reactor power by modulating reactivity, and maintained constant reactor exit-air temperature by modulating reactor power.

Reactor Power Control Description - The reactor power-control system was a multiple-loop system consisting of two dynamic-rod position loops, six synchronized shim-scram-rod position loops, and reactor power and temperature loops.

The dynamic-rod position loops were used to regulate reactor power and to improve system transient response. The shim rods compensated for fuel depletion and assisted the dynamic rods. The control system could operate satisfactorily with either shim or dynamic rods exclusively.

The demand for dynamic rod position consisted of the difference between either the temperature loop error or scheduled power reference and the logarithmically amplified output of the ion chamber. In either case, the rods position themselves to reduce the power error to zero, thus, driving reactor power output in correspondence with the demand.

Although the reactor-power loop had a logarithmic output-input characteristic, the power reference was compensated to allow linear power demands. As the mode selector was switched between power and temperature control, the operating loop was stabilized accordingly. The transfer function block diagram of the flux loop is shown in Figure 6.10.

A logarithmic amplifier was employed in the feedback to linearize the open loop gain. A similar logarithmic transducer operated on the demand signal to maintain a constant closed loop gain characteristic. This compensation was required when the flux loop was employed as a forward element of the temperature control. The modified logarithmic feedback and demand signals were compared at the error amplifier and the resulting error was used to position dynamic and shim rods, operating in parallel position loops, to obtain the demanded power level.

The dynamic response characteristics of the flux loop is shown in Figure 6.11. A slightly overdamped response was indicated with a steady state accuracy greater than ±0.5 percent of the operating point. A more complete discussion of the operating characteristics of the flux loop can be found in reference 10.

Reactor Exit-Air Temperature Control Description - The temperature reference was compared with a sensed value from the exit-air thermocouples. Any discrepancy between the demand value and the actual value repositioned the shim-scram and dynamic rods to reduce the power error to zero and, thus, drove the actual reactor exit-air temperature to correspond with the temperature reference. The temperature loop block diagram is shown in Figure 6.12. More detailed temperature control characteristics may be found in reference 10.

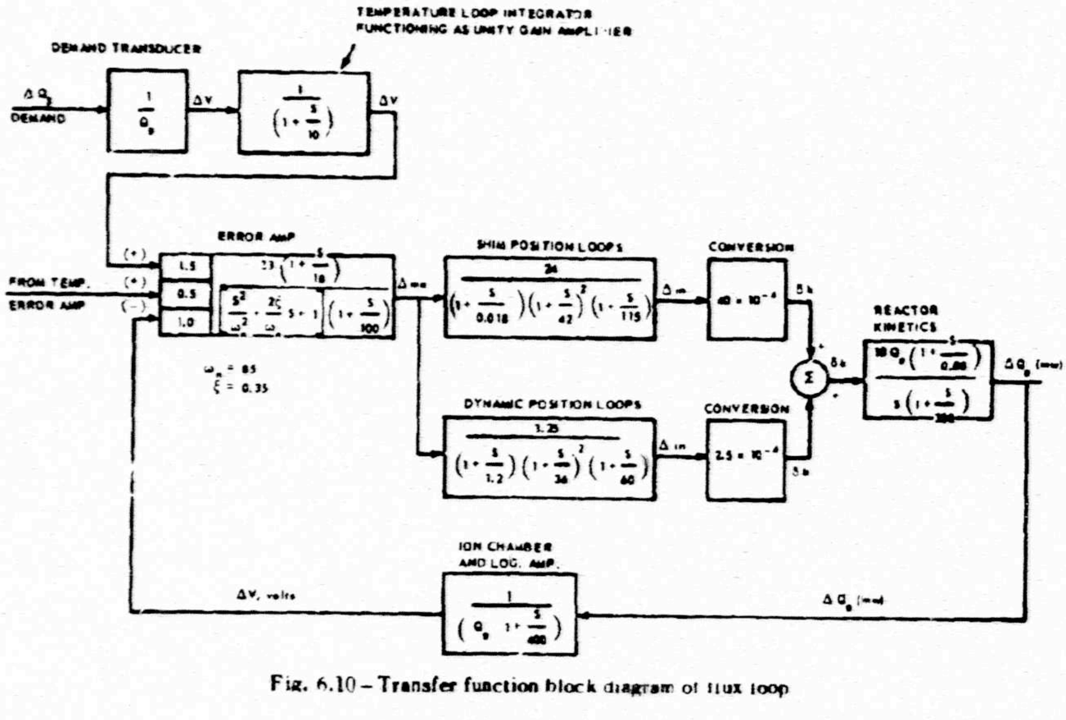

Fig. 6.10 – Transfer function block diagram of flux loop

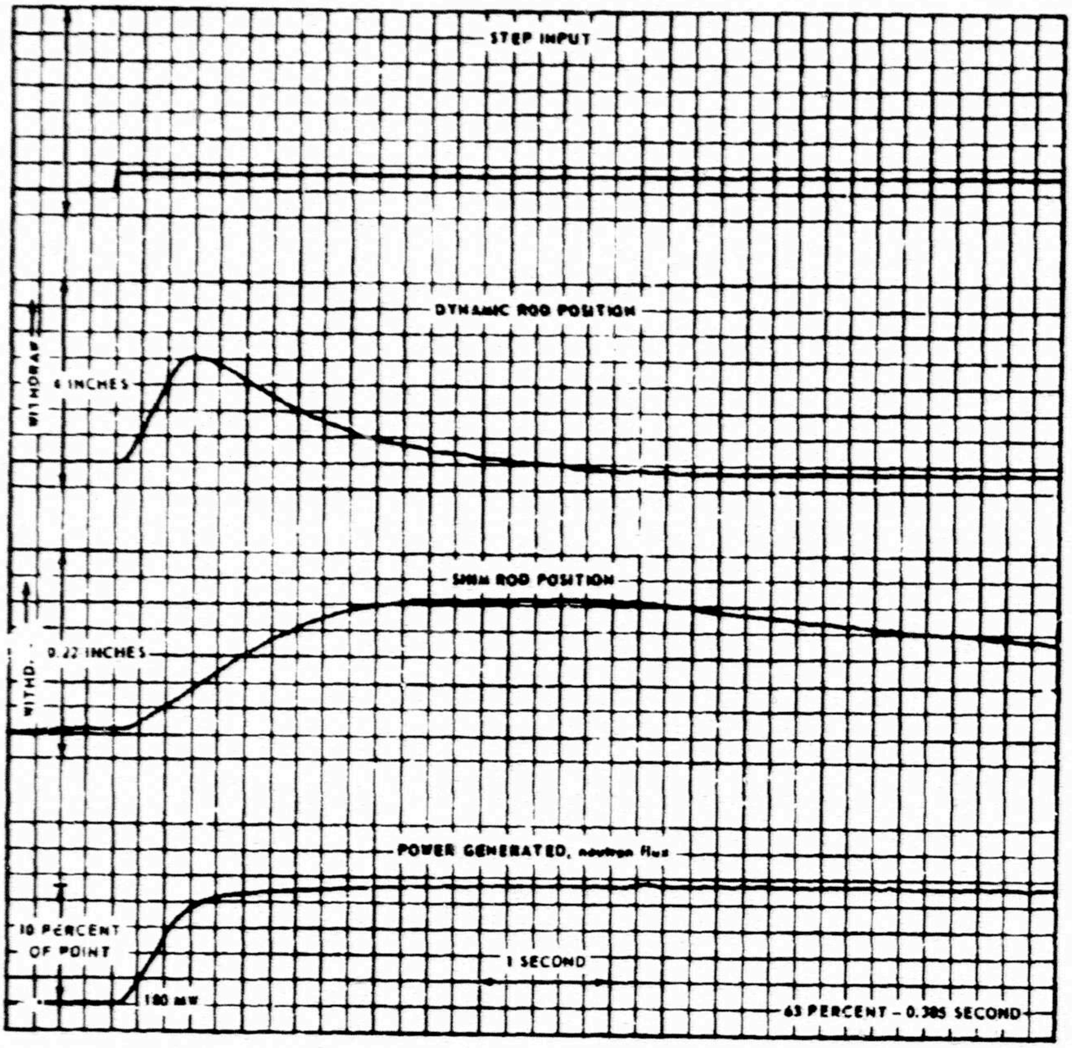

Fig. 6.11 – Step response of the flux loop for a 10 percent demand

6. 1. 2. 3 Safety Circuits

The XMA-1A power plant required an extensive reactor safety system because of its high-power and rapid response characteristics. The safety system consisted of two basic safety actions, i.e., alarm and scram. The alarm response was initiated when critical power plant parameters exceeded normal operating limits and was safely correctable through operator action. The scram response was initiated whenever parameter excursions endangered power plant safety.

Complete requirements for safety circuit mechanization are covered in references 7 and 8.

6. 1. 3 ACCESSORY CONTROLS

6. 1. 3. 1 Air Transfer Systems

The power plant valve actuation system is shown in Figure 6. 13. This system included the actuators for the two halves of the reactor bypass valve and the six interburner valves.

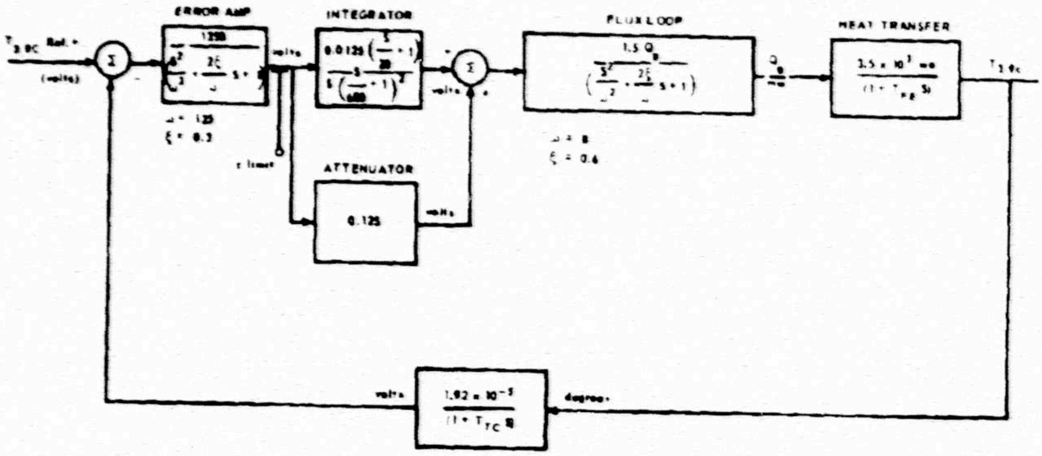

Fig. 6.12 – Temperature loop transfer function block diagram

Not shown on this diagram are the limit switches attached to the actuators which would shutdown the power plant unless both sets of combustor inlet valves or the reactor inlet valves were fully open. Another set of limit switches would shut off fuel to both engines whenever the combustor inlet valves were closed more than a specific number of degrees.

The reactor inlet valve had duplicate controls for its two valve halves. The input to the two controls was provided by two ganged synchronized control transformers. The output of the control transformer represented the error between the demand and the actuators actual position. Any error present was amplified and fed to the torque motor of the servovalve. The servovalve then fed hydraulic fluid through the three-way solenoid valves to reposition the actuators and reduce the error to zero. The control operation of the combustor inlet valve control system was basically the same.

In the event of an emergency shutdown or scram, the three-way solenoid valves would de-energize allowing hydraulic fluid to be ported to the actuators. This placed the valves in their cooling position, i.e., reactor inlet valve open and the combustor inlet valves closed. Hydraulic latches were installed on the actuator to lock the actuator in case of failure in the hydraulic system. For additional information see references 1, 12, and 13.

Valve Control Hydraulic Power Supply - The hydraulic supply for transfer valve actuation is presented schematically in Figure 6.14. The boot strap reservoir consisted of a boost pump which pumped hydraulic fluid through a check valve to a low-pressure piston cavity and back to a boost reservoir in an amount equal to the leakage flow past the low-pressure piston. The low-pressure piston cavity was connected to the high-pressure piston cavity through a low-pressure filter and the main hydraulic pump. This placed the double ended piston in a force balance, and the main pump and the boost pressures in fixed ratio. This arrangement provided two advantages: the boost pressure was continuously presented to the main pump inlet and the pressure was regulated at its outlet.

From the main pump, hydraulic power was fed through a high-pressure filter with high-pressure bypass to the three combustion system inlet valves and one reactor inlet half-valve actuation system. Provision was made for manually connecting the hydraulic supply to the other reactor half-valve actuation system. Accumulators were provided with the transfer valve actuation system to insure two cycles of actuation following hydraulic power supply failure. The fluid was returned from the actuating systems through a heat-exchanger, with a 60,000 Btu per hour capacity, and a shutoff valve to the low-pressure piston cavity of the boot strap reservoir.

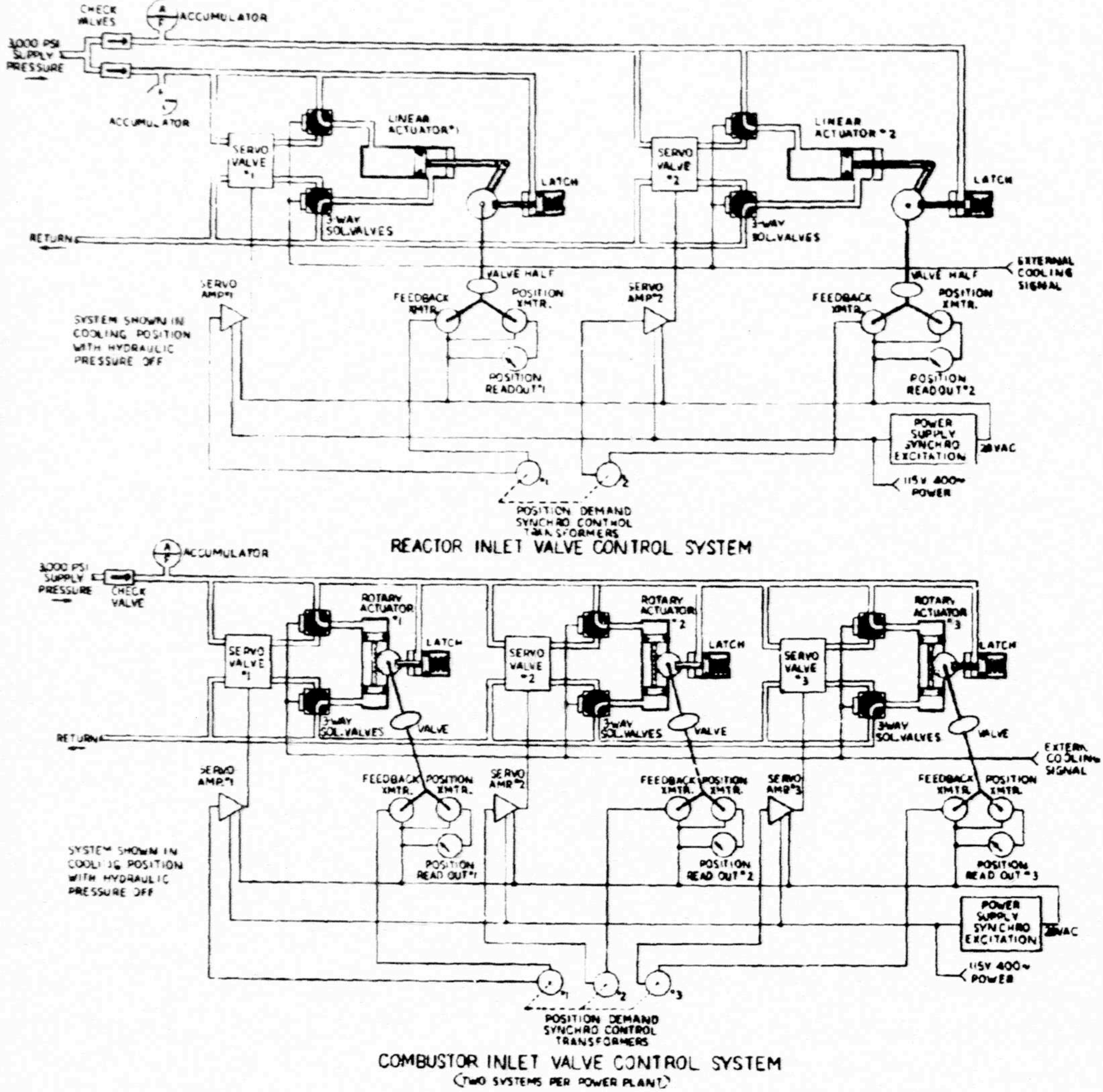

Fig. 6.13 – XMA-1A power plant valve control system

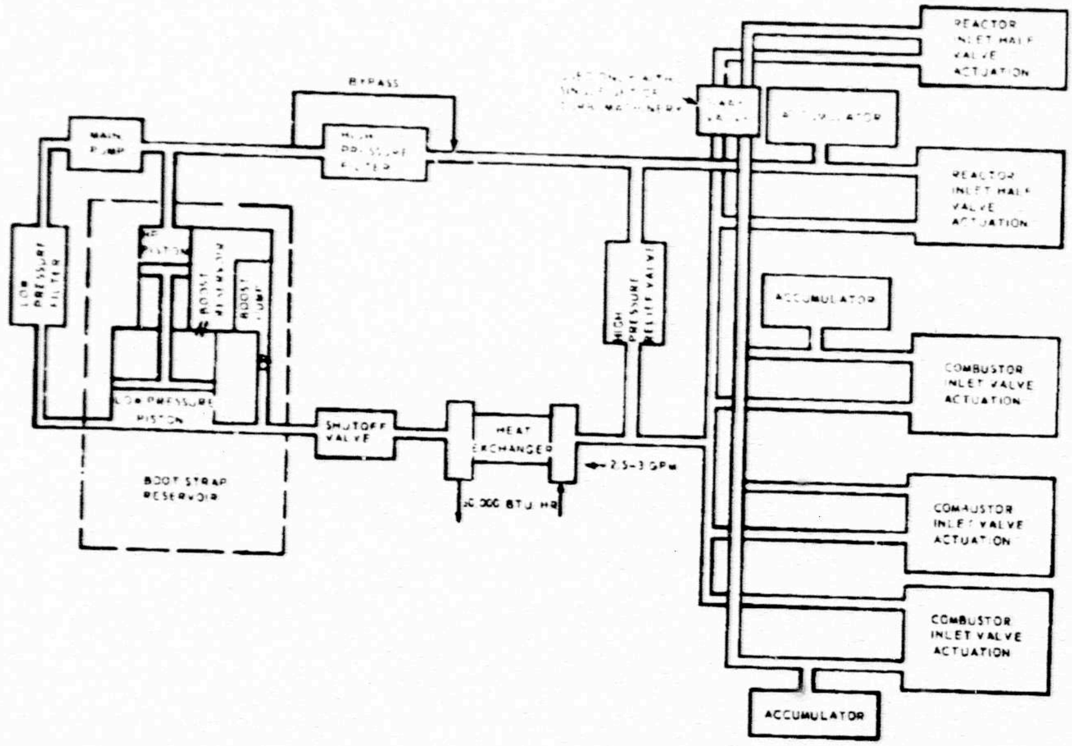

Fig. 6.14 – Transfer valve hydraulic power supply

Sixteenth-Stage Stator-Vane Controls - The final-stage compressor-stator-vane control was a two-position open-closed control that would be closed when aftercooling air was supplied to the nuclear flow-path and the turbomachinery speed was less than 500 rpm.

6.1.3.3 Electrical Power Supplies

Electrical power for the XMA-1 power plant was to be initially supplied by facility d-c power motor generator sets. When turbomachinery-driven constant-speed drives and alternators became available, startup power was still supplied by facility power. At 3000 rpm, power could be transferred from the facility supply to one of two turbomachinery driven alternators, frequency regulated by their associated constant speed drives. The transfer could be accomplished manually. Since the facility generator and turbomachinery driven alternators were momentarily paralleled, their outputs had to be reasonably well matched in frequency, voltage, and phase.

From the transfer switch, electrical power was fed to a bus where current, active, and reactive power were monitored. From the bus, power was fed to the reactor controls and the turbomachinery controls through isolation switches to allow operation of the turbomachinery controls only when operating the power plant on chemical power exclusively.

Power for operation of the transfer valves was fed directly from the bus to assure valve operating capability independent of the power plant operating mode. A more detailed description of the power supply system was published.[14]

6.1.3.4 Primary and Secondary Consoles

The control console consisted of a primary and a secondary panel. It was designed so that with only slight modification it would be adequate for airframe installation.

Flight test bed operation with a single power plant would require two operators; one operating the primary panel and one monitoring at the secondary panel. Flight test bed operation with twin power plants would require one operator at the primary panel of each power plant. Secondary panels would not be installed in the twin power plant version.

Primary Panel - The primary panel mounted the levers, switches, and indicators necessary for operator manipulation of the power plant controls and auxiliary systems. It identified variables approaching limiting value, requiring operator execution of immediate corrective action. In addition, it displayed the history of any automatic safety response culminating in scram. The primary design details and requirements are presented in references 3, 15, and 16.

Secondary Panel - The secondary panel was basically a flight-type console containing 207 data points. It was located on the port side of the aircraft adjacent to the primary console, and was similar in shape to the primary console. Of the 207 monitored parameters, 20 percent were critical and were, therefore, located in the vicinity of the operators horizontal line of vision. The panel provided continuous monitoring of selected engine and reactor parameters and, on demand, continuous monitoring of less critical parameters. Additional details can be found in references 17 and 18.

6.2 MECHANIZATION DESCRIPTION

6.2.1 ENGINE CONTROL

The initial mechanization approach for the X211 engine controls placed primary emphasis on development of the pneumatic control system described in section 6.1.1.4. The general theory and some of the general problems associated with pneumatic components are discussed in reference 3. A more detailed description of these components is presented below.

6.2.1.1 Pneumatic Components

Speed Sensor - The speed sensor was an engine rpm-to-position transducer with compressor discharge air as the flow medium. A change in engine rpm changed the rotational forces on the speeder-head flyweights, as shown in the schematic and functional block diagram of Figure 6.15. This in turn transmitted a force through a linkage to the speed sensor spring resulting in a displacement of the servovalve from its null position. Displacement of the servovalve permitted airflow to the compensating and power pistons; these in turn were displaced. The compensating piston was displaced before the power piston; its primary function was to produce an opposing or stabilizing force on the speeder-head force table during engine acceleration and deceleration conditions. Displacement of the power piston proceeded to develop an opposing force on the speed-sensor feedback spring through the use of a square law cam linkage. In essence, a change in engine rpm resulted in a change in power piston position until the forces on the speed-sensor feedback spring were balanced and the servovalve was restored to its null position. The power-piston output shaft then had rotated the schedule generator cams to a new position. Simultaneously, a transducer which was connected to the speed sensor through appropriate linkage, developed a voltage proportional to the power piston position. This voltage was a function of engine speed and was fed back to the electronic power-lever command system. If the

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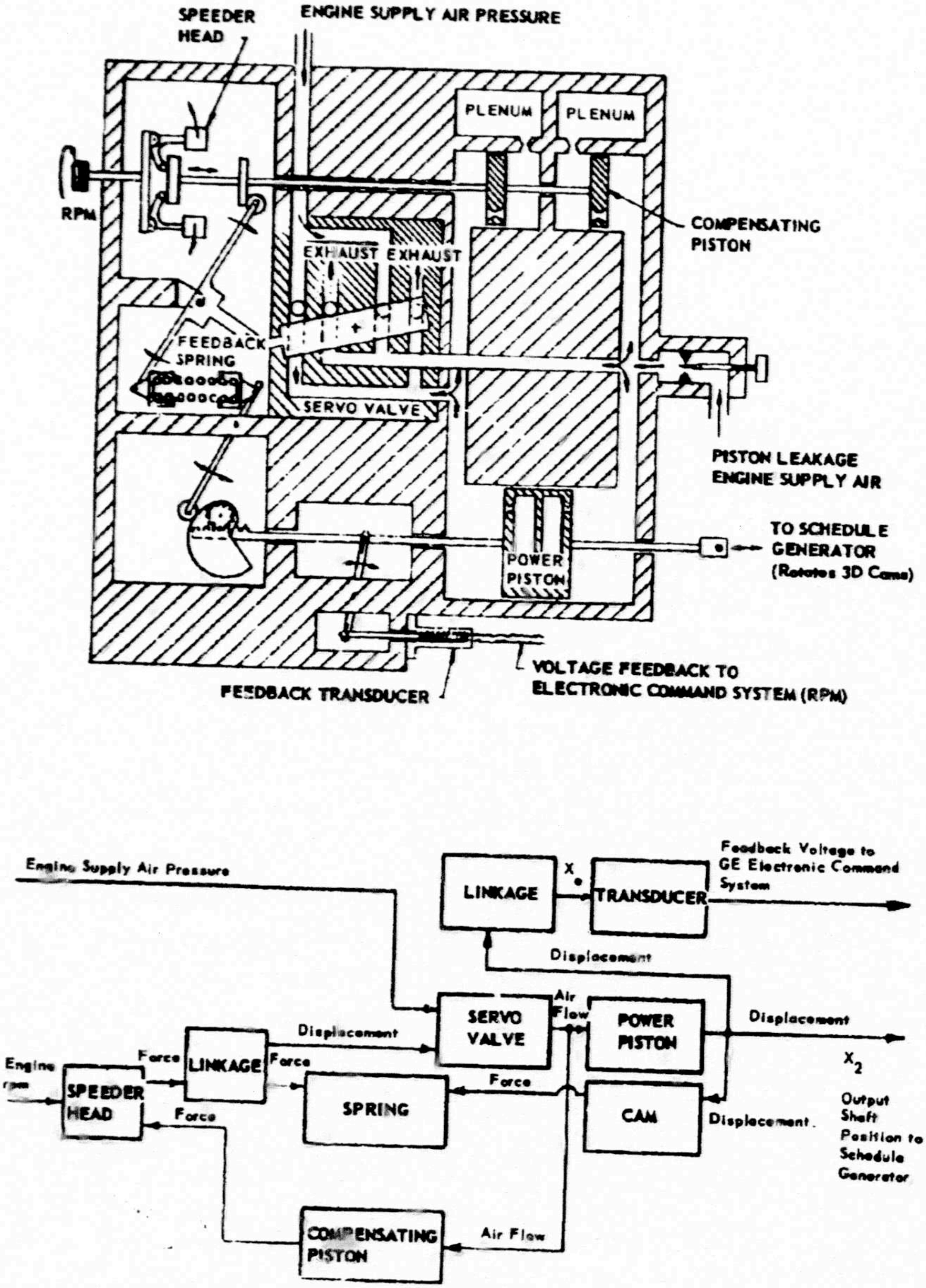

Fig. 6.15 – Speed sensor – schematic and functional block diagram

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existing engine speed varied from the command value by a preset amount, the electronic command system delivered an electrical signal to an exhaust nozzle area control which adjusted the engine nozzle area to restore the commanded rpm.

T_2 Temperature Sensor - The T_2 temperature sensors were similar in construction and operation to the $T_{5.1}$ temperature sensors. The basic difference was the bimetallic element materials used and the temperature range to which they were subjected. Two manifolded T_2 temperature sensors transmitted a pressure divider output signal (P_1) as a function of engine inlet air temperature to the T_2 pneumatic amplifier. A schematic and functional block diagram is shown in Figure 6.16.

T_2 Pneumatic Amplifier - The T_2 pneumatic amplifier contained a pressure sensing piston (Figure 6.17) that received a signal pressure (P_1) from two manifolded T_2 temperature sensors. A change in P_1 moved the sensing piston and displaced its attached servovalve; the pressure-divider inlet needle caused the same change in its pressure-divider output signal as that which had taken place in the P_1. This new feedback pressure was then fed back to the sensing chamber and stopped further movement by acting as an air spring. Under this condition, the servovalve was displaced from its null position and permitted the passage of air to the power piston. One end of the power piston shaft was connected to the schedule generator; the other end mounted the pressure-divider exhaust needle. Movement of the power piston, therefore, displaced the pressure-divider exhaust needle. Displacement of this needle, in turn, developed a change in the pressure divider output signal. This signal was fed back to the sensing piston chamber. The change in the signal pressure induced a change in the position of the sensing piston. When this occurred, the servovalve was displaced once again toward its null position. Airflow to the power piston was then partially cut off, and movement of the exhaust needle began to slow down in an integrating fashion while the inlet needle gradually returned to its original position. This process continued until an equality of the sensed signal pressure and the feedback pressure was accomplished. The result was the output shaft had moved to a new position, and subsequently, positioned the schedule-generator three-dimensional cams as a function of compressor inlet temperature.

Schedule Generator - The schedule generator consisted essentially of four 3-dimensional cams which were rotated through appropriate gearing by the speed sensor output and translated by the T_2 pneumatic amplifier output as shown in Figure 6.18.

One of the four cams was designated as the $T_{5.1}$ cam and contained a contoured schedule that displaced a cam follower. Its purpose was to provide a scheduled voltage feedback to the electronic command system as a function of compressor inlet temperature and engine rpm. The second cam was designated as the engine-acceleration fuel flow cam and was utilized through a cam follower to position the exhaust needle in the fuel computer during engine rpm acceleration conditions.

The remaining two cams contained stator guide-vane-angle schedules, and positioned their associated pressure-divider exhaust needles. This changed the ratio of the pressure-divider output signal, P_{17} or P_{15}, to engine compressor-discharge pressure. Each of these output-signal pressures was sent to its appropriate stator guide-vane control and represented a scheduled engine-stator guide-vane angle as a function of compressor inlet temperature, compressor discharge pressure, and engine rpm.

Fuel Computer - The fuel computer sensed two signal pressures which were designated as P_2 and P_3. The P_2 pressure was supplied by eight manifolded $T_{5.1}$ temperature sensors, and P_3 was supplied by the $T_{5.1}$ command amplifier. The pressure divider on this component (Figure 6.19) utilized an engine air-supply pressure as its working medium. This supply pressure was also fed to both the $T_{5.1}$ temperature sensors and $T_{5.1}$ com-

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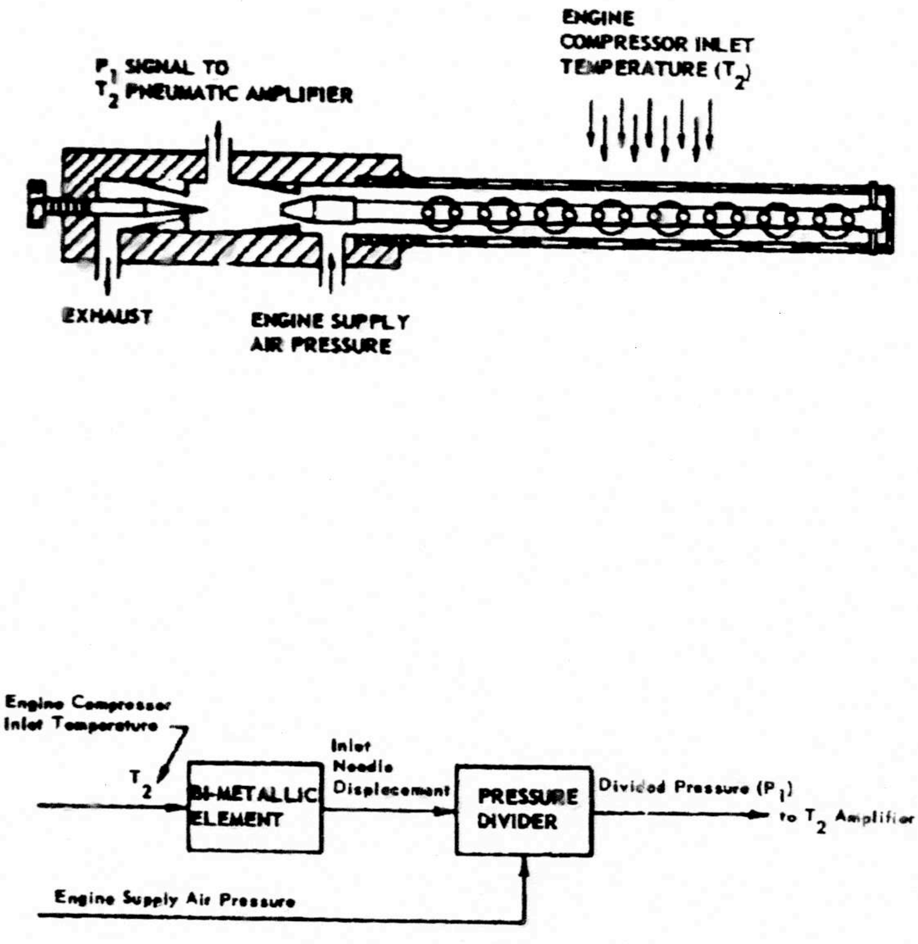

Fig. 6.16 – T_2 temperature sensor – schematic and functional block diagram

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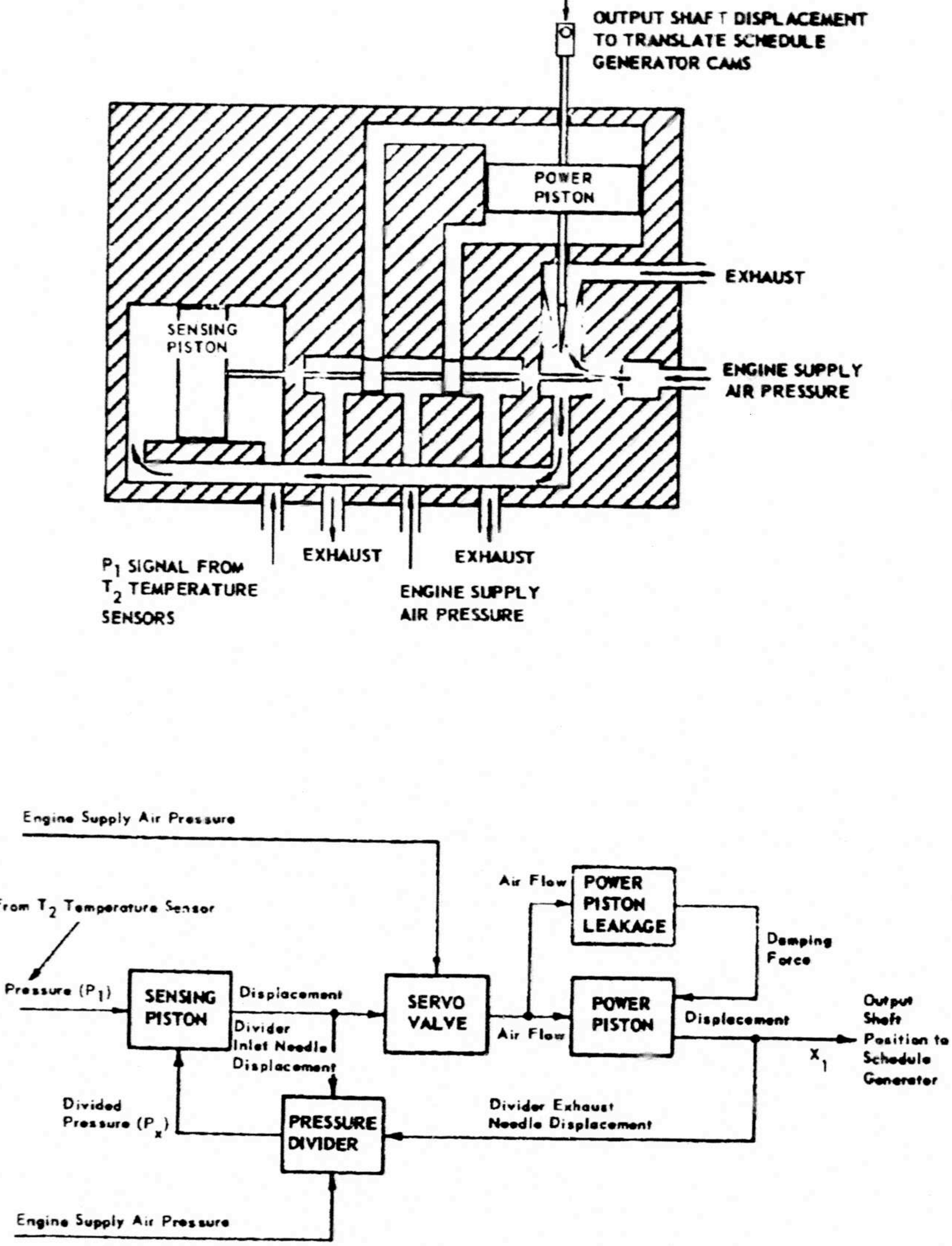

Fig. 6.17 – T_2 pneumatic amplifier – schematic and functional block diagram

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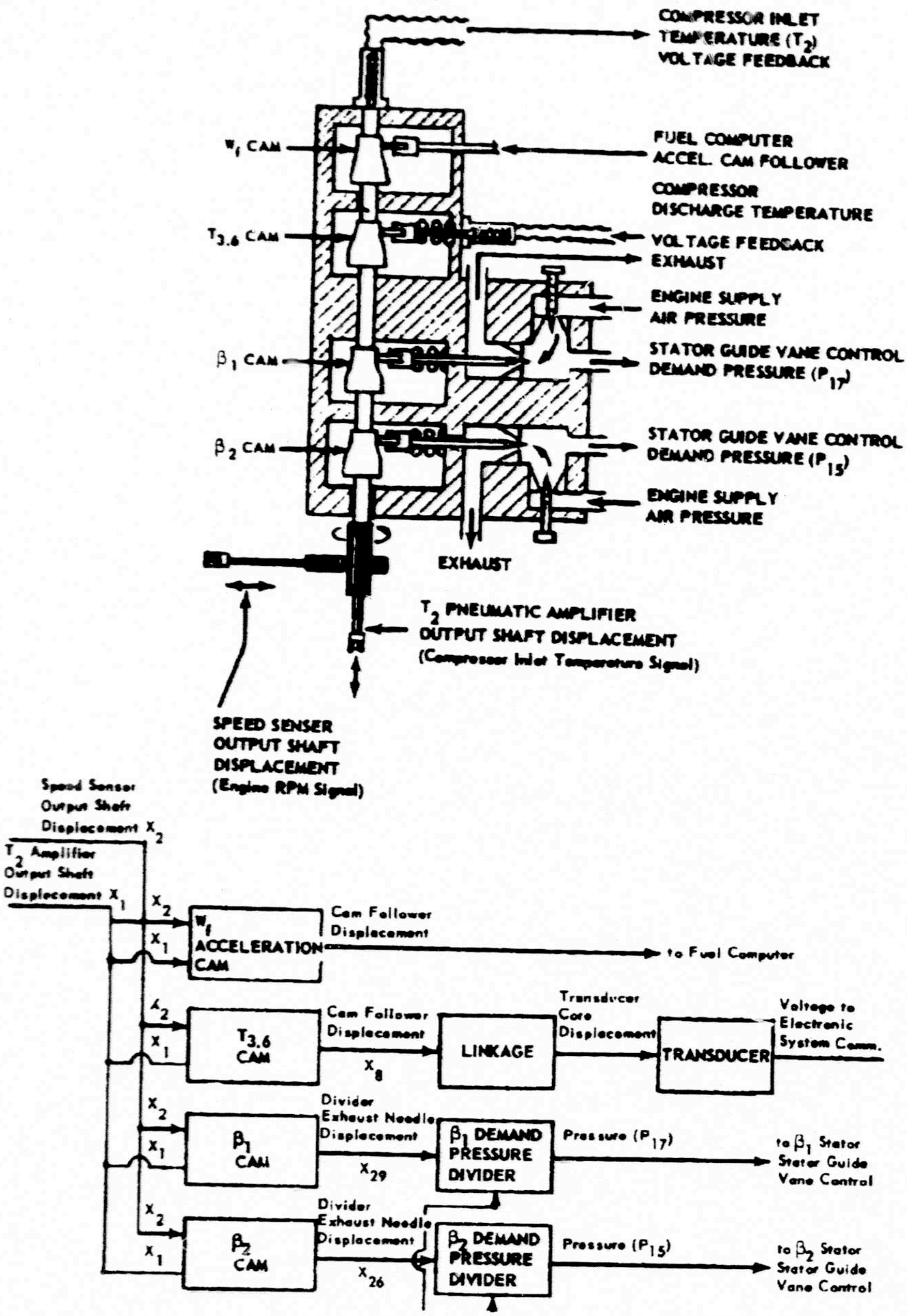

Fig. 6.18 – Schedule generator – schematic and functional block diagram

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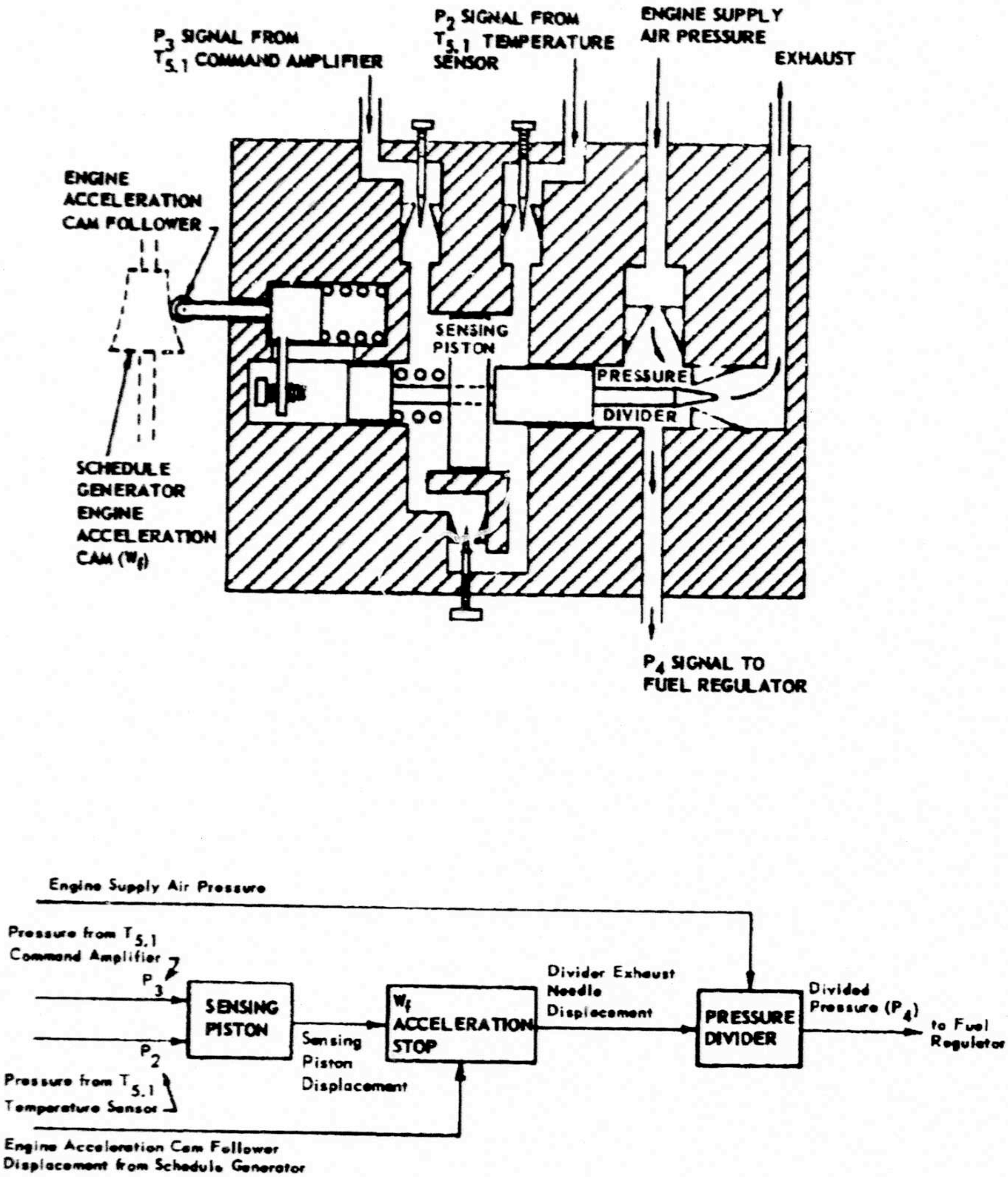

Fig. 6.19 – Fuel computer – schematic and functional block diagram

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mand amplifier. Both pressure dividers on the $T_{5.1}$ command amplifier and the $T_{5.1}$ temperature sensors were adjusted so that they produced the same output pressures for a given supply air pressure and power lever $T_{5.1}$ condition.

The signal pressure, P_3, represented a commanded engine turbine exhaust temperature ($T_{5.1}$), while the signal pressure, P_2, represented the existing engine turbine exhaust temperature. Any pressure difference sensed between the commanded and existing temperatures resulted in a displacement of the fuel-computer sensing piston, its shaft, and the pressure-divider exhaust needle which was attached to the end of the shaft. A displacement of this exhaust needle caused a change in the signal pressure, P_4, which was generated by the pressure divider. This generated signal pressure, P_4, was then fed to the fuel regulator. Two additional functions were accomplished by the fuel computer: the computation and control of fuel flow to the engine during engine acceleration and deceleration.

<u>$T_{5.1}$ Temperature Sensor</u> - The $T_{5.1}$ temperature sensors were temperature-to-pressure transducers. Differential expansion of an inner tube with respect to an outer tube took place, as shown in the schematic of Figure 6.20, due to a change in engine turbine exhaust-gas temperatures.

The expansion of the inner tube displaced a pressure-divider inlet needle which was mounted on the end of the inner tube. Displacement of the inlet needle changed the ratio of the signal pressure, P_2, to the compressor discharge pressure. Eight of the $T_{5.1}$ temperature sensors were manifolded and subjected to essentially the same change in engine turbine exhaust-gas temperature. Each of the new resulting P_2 signal pressures were averaged caused by the manifolding and fed on to the fuel computer for closing the steady-state engine-exhaust temperature loop.

<u>$T_{5.1}$ Command Amplifier</u> - The $T_{5.1}$ command amplifier was a current-to-pressure transducer and amplifier. A change in current, supplied by the electronic power-lever command system, was imposed upon the torque motor as shown in Figure 6.21. This caused the torque motor armature to be displaced and, through an attached linkage, displaced a flat-plate type servovalve from its null position. Engine-supply air pressure was then ducted through the servovalve and on to one side of the power piston, resulting in a displacement of the power piston. Displacement of the power piston resulted in a displacement of the transducer core and the inlet needle which was mounted on the end of the power piston. The subsequent transducer voltage change was fed back to the electronic command system and nullified the current flow being fed to the torque motor. As soon as the torque motor current had been nullified, the servovalve returned to its normal position and airflow to the power piston was cut off. The result was that the power piston and its attached pressure-divider inlet needle assumed a new position. This new inlet-needle position produced a change in the pressure-divider output pressure, P_3, which was sent to the fuel computer.

<u>Fuel Regulator</u> - The main function of the fuel regulator was to maintain a given ratio of fuel flow to engine-compressor discharge pressure (fuel-to-air ratio) for engine acceleration, steady state, and deceleration conditions. It accomplished this by sensing different variations between engine compressor discharge pressure and a signal pressure, P_4, which was received from the fuel computer. When this difference was varied, a sensing piston was displaced as shown in Figure 6.22. This sensing piston was connected through a force-balance type linkage, to both the metering servovalve and the metering-loop feedback spring. Displacement of the sensing piston resulted in the displacement of the metering-loop servovalve and its feedback spring. Displacement of the metering-loop servovalve permitted fuel flow to be ported to the power piston. Displacement of the power piston subsequently took place in a direction that produced an opposing or balancing type

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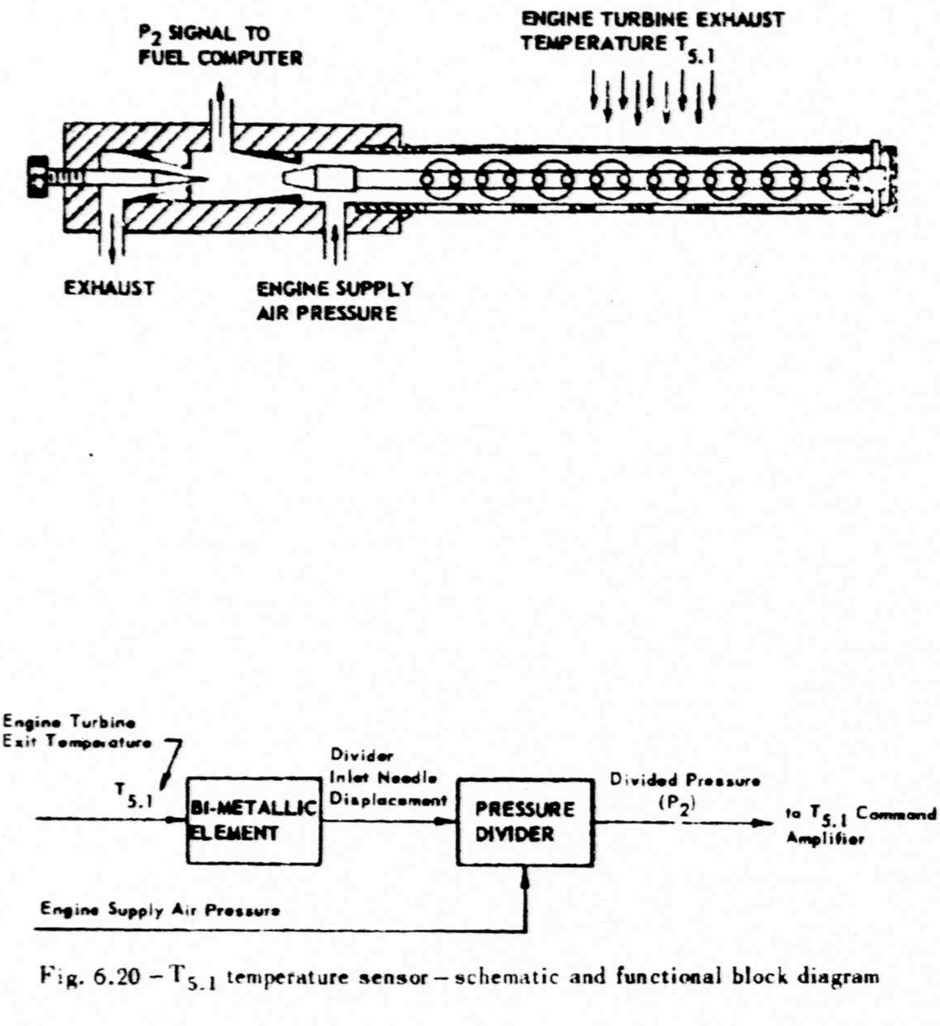

Fig. 6.20 – $T_{5.1}$ temperature sensor – schematic and functional block diagram

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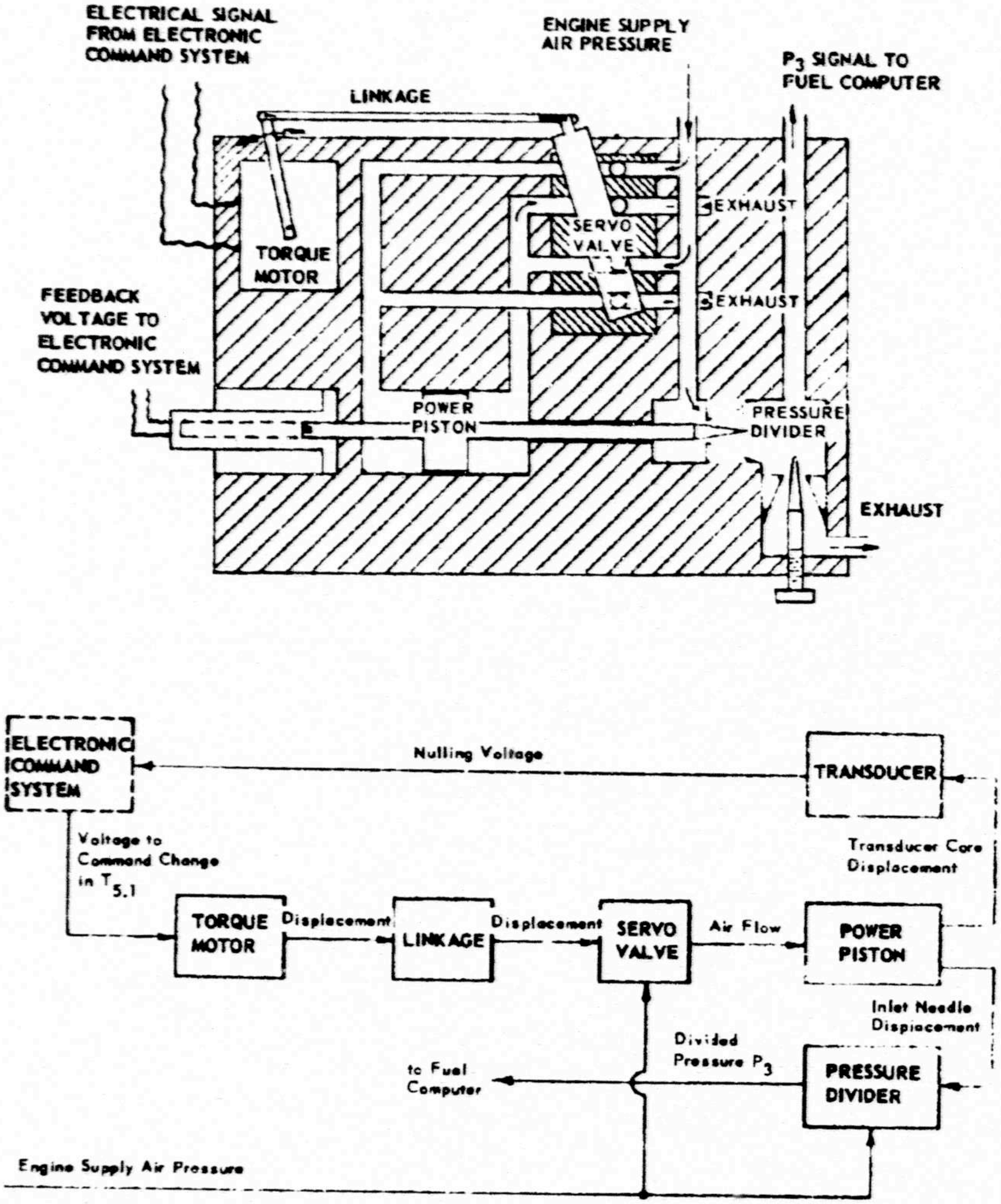

Fig. 6.21 – $T_{5.1}$ command amplifier – schematic and functional block diagram

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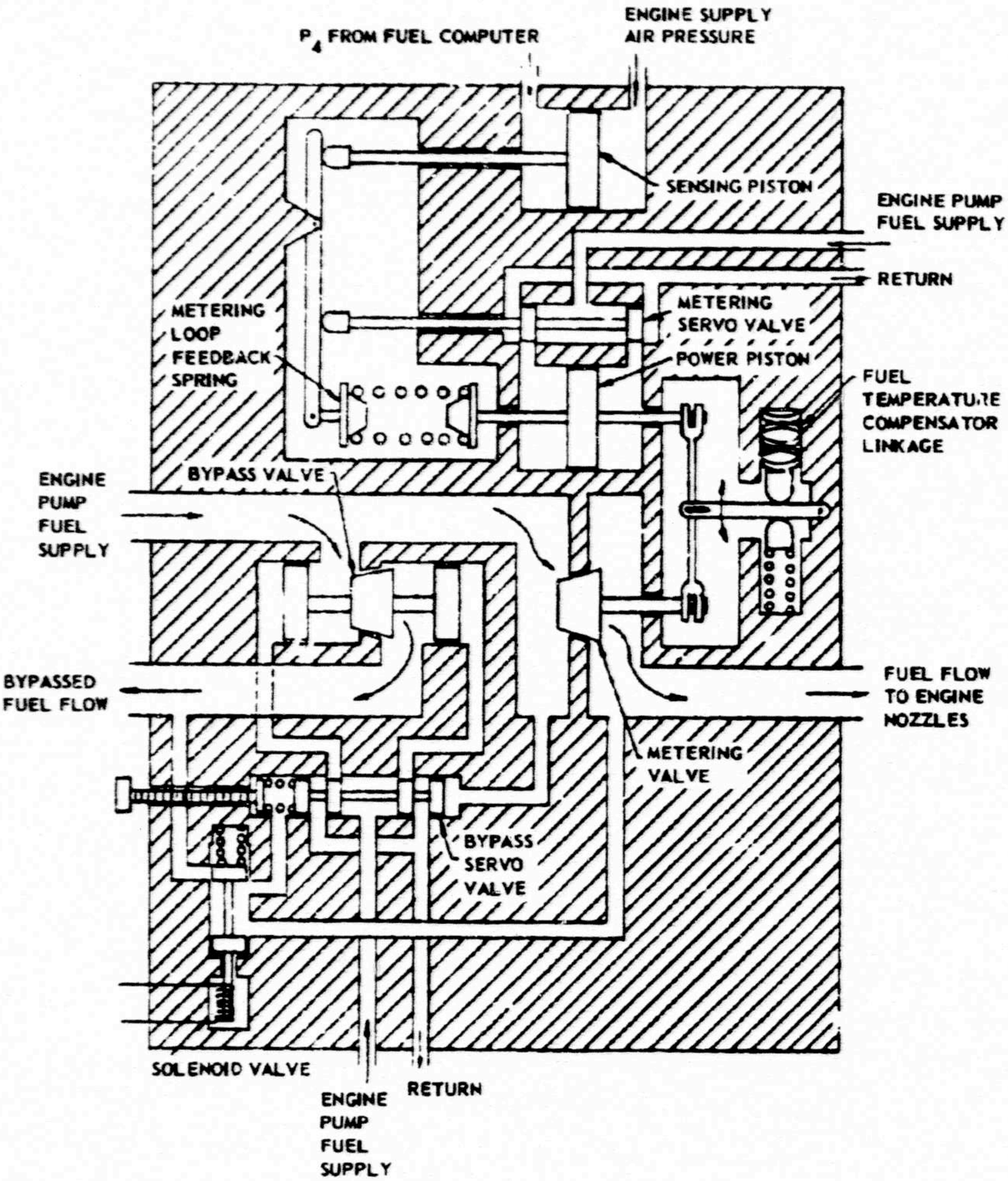

Fig. 6.22 – Schematic of fuel regulator

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displacement on the metering-loop feedback spring. This developed the required force on the force-balance linkage so that it returned to its original position.

The opposite end of the power piston shaft was connected to a fuel-temperature compensating linkage. This compensating linkage was a stacked assembly of bimetallic discs which changed the lever ratio between the power piston and the metering valve to compensate for fuel density changes, as a function of the fuel temperature in which the discs were immersed. The linkage, being directly coupled to the metering valve, produced a proportionate power-piston-to-metering-valve displacement.

Pressures upstream and downstream of the metering valve were sensed and maintained at a fixed differential by the bypass servovalve. In the event the pressure differential was not in accord with the prevailing value, the pressures from each of the sensing points caused a displacement of the bypass servovalve. The displacement was such that the bypass valve opened, allowing more fuel to be bypassed if the pressure difference was too high, or closed if the pressure difference was too low. The required pressure was set by adjusting a spring load that was axially applied to the bypass servovalve spool. This spring load was set or adjusted to conform with the various fuel densities encountered in the different batches of aircraft engine fuel utilized.

Auxiliary equipment was provided to facilitate fuel flow cutoff to the engine nozzles. This was accomplished by energizing the solenoid valve which resulted in switching the downstream pressure sensing point from the metering valve to that of the bypass valve. Because the pressure of the latter downstream sensing point was considerably lower than that of the metering valve downstream pressure, the bypass servovalve and bypass valve were displaced. This bypassed the total fuel flow back to the engine fuel pump. Simultaneously, a minimum pressure poppet type valve, included in the fuel metering line, closed and cut off all fuel flow to the engine nozzles until the minimum pressure was once again exceeded.

Stator Guide-Vane Control - The stator guide-vane controls were used to position the engine compressor-stator guide-vane angles in accordance with a given schedule as a function of both engine rpm and compressor inlet temperature. It performed this function by receiving either the P_{15} or P_{17} signal pressure, fed to it by the schedule generator, and comparing this pressure with an existing one on the opposing side of a sensing piston. In the event they were unequal, a displacement of the sensing piston took place. A simultaneous displacement took place in the contained two-stage servovalve. The motion of the sensing piston displaced the pressure-divider inlet needle, raising the feedback signal to a value that balanced the existing signal being fed to the sensing chamber. When the two-stage servovalve was displaced hydraulic fluid was transmitted to the power piston, causing it to be displaced. This rotated the stator guide vanes to their proper angle. A positional feedback connection was attached to the engine linkage so that a displacement of the pressure-divider exhaust needle would take place. This displacement occurred in a direction that produced the required feedback pressure to return the sensing piston and its connected servovalve back to their normal positions. The schematic and functional block diagram for this component is shown in Figure 6.23.

6.2.2 REACTOR CONTROLS

6.2.2.1 Electronic Components

The reactor control system was divided into three basic categories; the start up range, the power range, and the safety circuits. The components developed to perform these functions can also be divided into two distinct classes, i.e., vacuum tube circuits and magnetic amplifier circuits. With the exception of a portion of the start up range, which used vacuum tube circuits, the bulk of the components used in the control system were magnetic ampli-

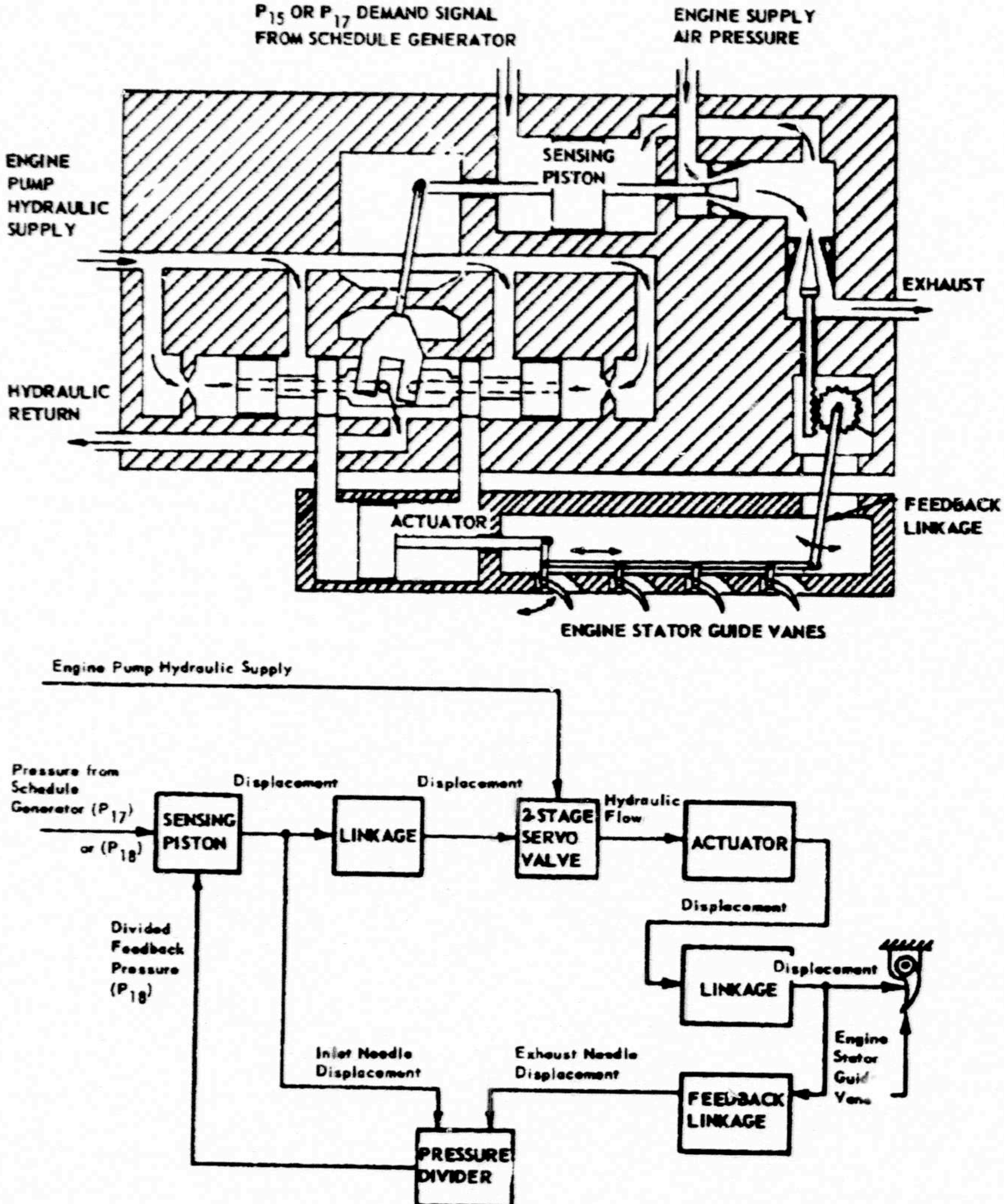


Fig. 6.23 – Stator guide vane control-schematic and functional block diagram

fiers. For a development history of the control system see reference 19. A functional block diagram showing the component composite of the control system is contained in Figures 6.24 and 6.25.

The block diagrams show that magnetic amplifiers were used from the count rate computer on through the start range, power range, and safety circuits. The high reliability of these amplifiers made their use desirable in the entire control system, but their limited frequency response excluded their use in pulse circuitry.

Vacuum tubes were used for the pulse signal functions. These circuits were conventional except for the pulse preamplifiers. To reduce the signal-to-noise ratio of the fission-chamber signals the pulse preamplifiers were located as close to the sensors as possible. In the XMA-1A design they were located on the reactor shield radially outward from the fission chambers. The temperature and radiation environments in that location were severe and required the use of a specialized electronic design. Since the preamplifier was mounted on the reactor shield, it was subject to vibration and acoustical noise as well as the high temperature and radiation fields. In addition to these environmental effects, it was necessary to make the unit suitable for remote handling. The design which met all these conditions was quite unique in the electronics field. The preamplifiers used ceramic tubes, welded connections, high temperature mica condensors, resistors, and mechanical hardware appropriate for the severe environment. For detailed discussion on electrical performance, packaging, and test results see reference 20.

As stated previously, the preferred circuitry and/or components for the XMA-1A control system were magnetic amplifiers. When reliability was the foremost design consideration, a so-called static system resulted; that is, a minimum of moving parts, sliding contacts, and switching contacts were used. A control system in a nuclear engine would be subjected to conditions that include radiation, high-temperatures, high acoustic noise levels, shock, and vibration. Either magnetic amplifier or transistor mechanization of power-range control could satisfy the requirement for a static system. A hybrid system was, of course, possible. However, transistors did not prove sufficiently tolerant of a radiation environment. The magnetic amplifier thus appeared to be a logical choice for mechanization of the control system, where feasible.

In addition to the reliability aspects of the device, several other salient features substantiated its use for the reactor control system. The size and weight of a magnetic amplifier system could be equal to or less than an equivalent electron tube implementation since no d-c power supply was needed. Extremely high power gains could be realized in one stage. This gain was proportioned between voltage and current gain by proper choice of turns to meet the requirements.

As for environment, the magnetic amplifier was quite tolerant of conditions that would be encountered in a nuclear aircraft. Vibration would not damage an encapsulated magnetic amplifier with suitable core cushioning. A problem encountered with turbojets was high-level acoustic noise. Because of its inherent ruggedness, the magnetic amplifier was not affected by the forces produced and frequencies encountered. However, the design of the amplifier had to include a solid mounting and a low center of gravity.

The most serious environmental problems of a nuclear aircraft control system were radiation and heat. The semiconductor diodes were the components most affected by radiation. A great deal of testing was done to establish the performance of these devices under radiation, to improve their tolerance, and to design the magnetic amplifier circuits to be more tolerant of the radiation-produced diode changes.

In general, the magnetic system could be packaged in half the volume of a corresponding electron-tube system with power supplies.

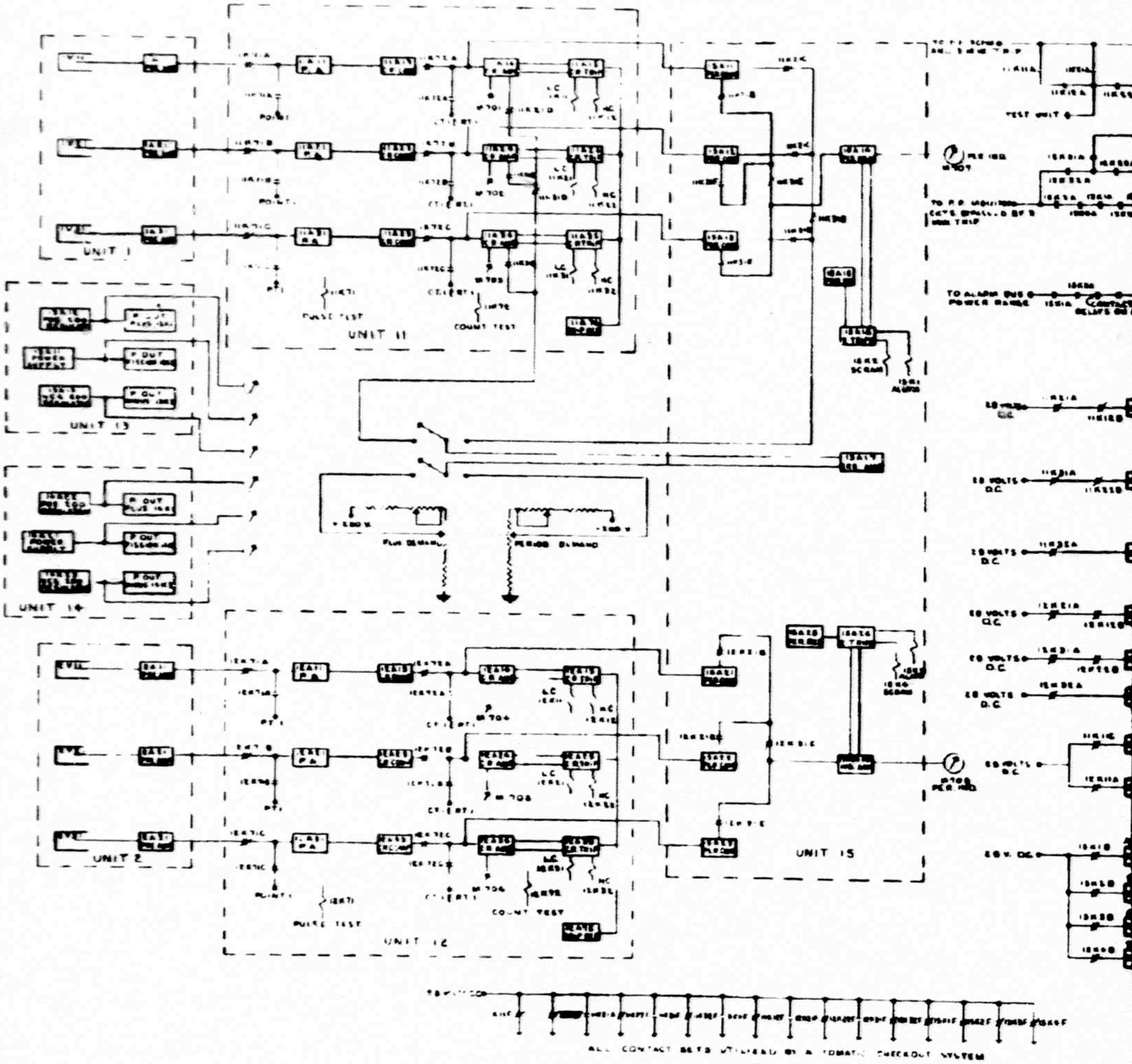
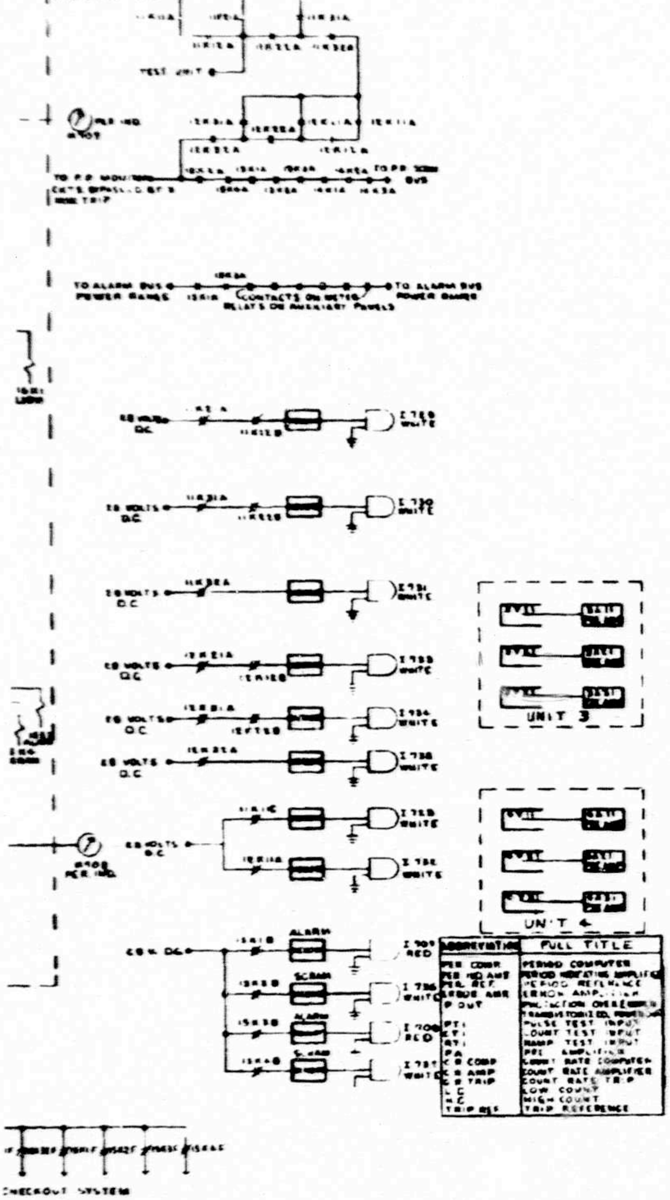


Fig. 6.24 – Startup system functional block diagram (Dwg. 665E366)



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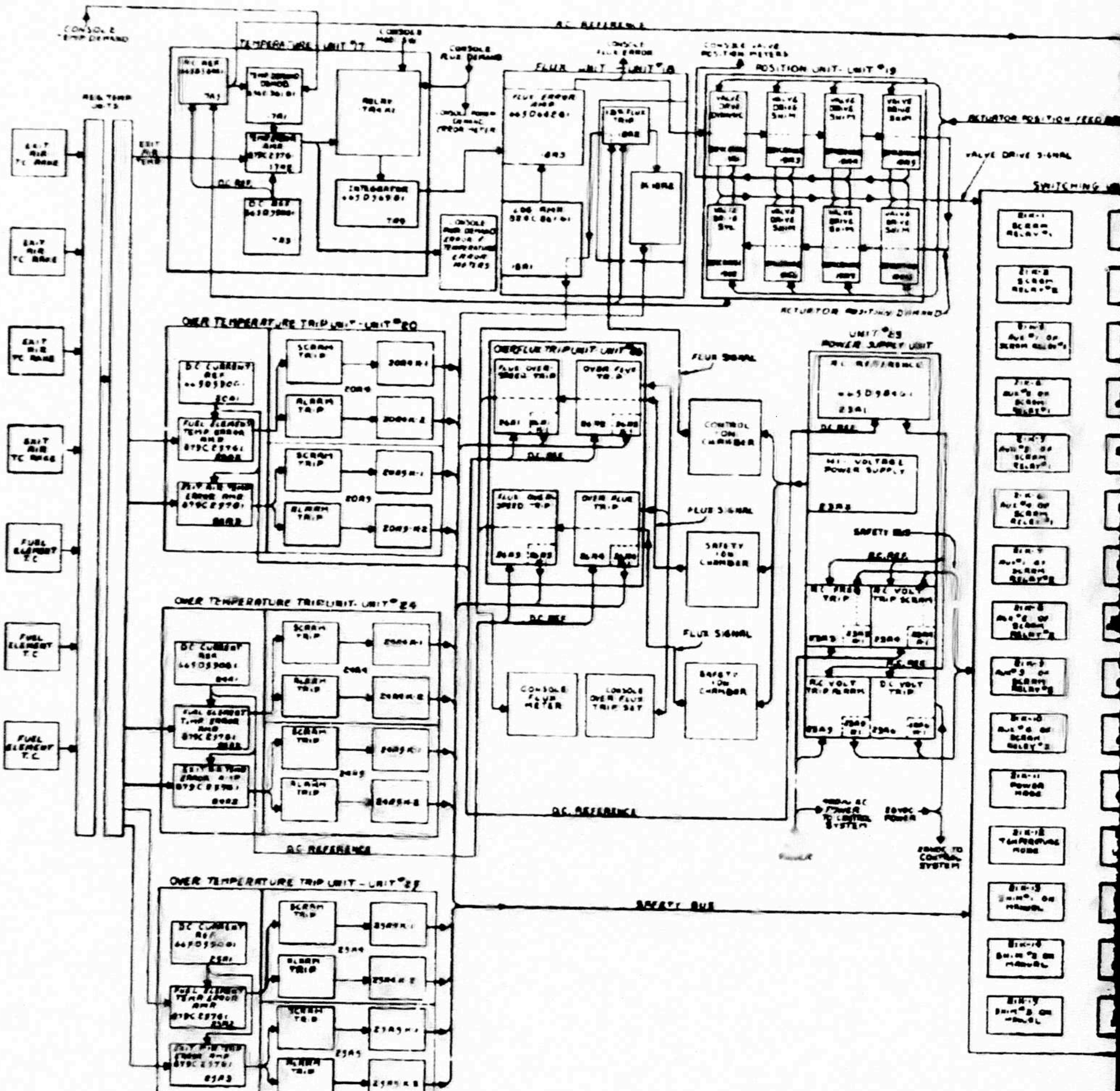

Fig. 6.25 – Power range functional block diagram (Dwg. 682E460)

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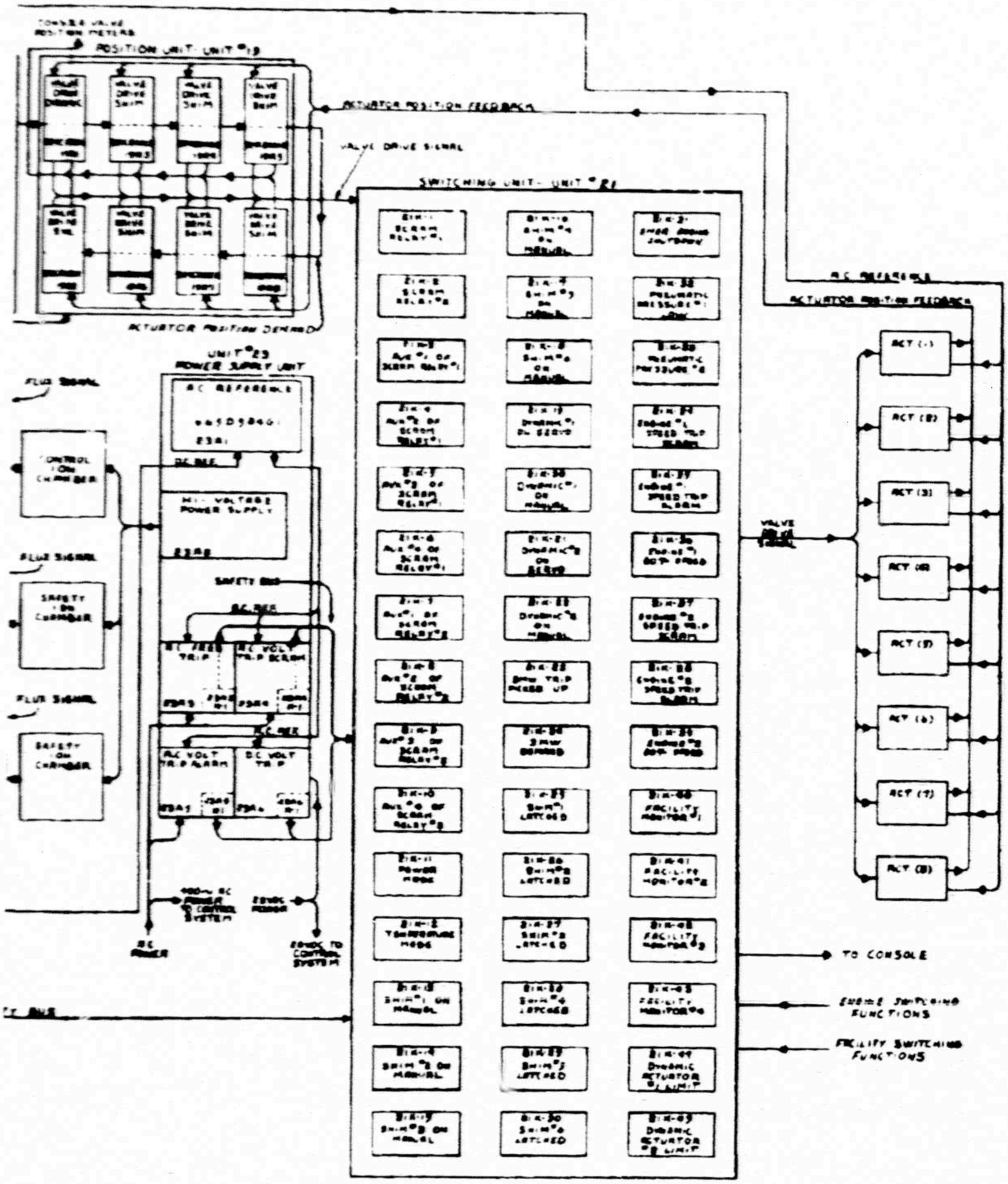

functional block diagram (Dwg. 682E460)

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There were two general types of magnetic amplifier circuitry used in this system: (1) power devices and linear amplifiers and (2) computing amplifiers and devices.[21] The last group was fairly new to the servomechanism field. These new devices would be made to perform integration, differentiation, logarithmic computation, and conventional lead-lag computation. Most of the development engineering hours were devoted to these computing devices.

There were some unusual circuit features of magnetic devices that were put to use in this system. First, it was possible to have multiple, electrically isolated inputs to an amplifier. This arrangement was used in the flux amplifier, the temperature amplifier, and the feedback amplifier around the integrator. Each of these amplifiers was at a summing point in the circuit. Through the use of these multiple inputs, the summing could be done without danger of interaction between the various signal circuits. Another feature was the possibility of having feedback around an amplifier and still have the input isolated electrically from the output. This method of feedback was used in many places throughout the system.

Magnetic amplifiers had very low input resistance; this made them excellent thermocouple amplifiers because good impedance matching could be achieved. This property was used in the temperature loop.

Another useful feature of one type of magnetic amplifier, a half-wave amplifier, was that it could sum a-c and d-c signals at the same time. Thus, a-c position feedback around the position loop amplifiers was summed with the d-c demand, and the necessity of demodulating the a-c transducer signal was eliminated.

The developmental model of the reactor control system, after accumulating approximately 2500 hours of operation, experienced only one electrical component part failure. The fault (an over-heated resistor) was located and corrected during this period. This excellent record was the result of attention given to part selection, circuit design and development, and the rule of operating parts at 50 percent or less of the manufactures rating.

6.2.2.2 Actuators

The control rod actuators under development for the XMA-1 power plant were of two types: a shim-scram actuator and a dynamic actuator. Six shim-scram and two dynamic rod actuators were mounted on the actuator support structure in front of the compressor exhaust collector, within the envelope defined by the compressor section, and centered on the power plant vertical and horizontal centerlines. A test mockup of this mounting sharing the eight actuators can be seen in Figure 6.26.

Shim-Scram Actuator - A shim-scram actuator consisted of an air motor, slip clutch, ball screw, latch mechanism, cross-head, drive rods, nested spring assembly, compensating cylinders, position transducers, and actuator-support structure quick disconnects. A photograph of the development model shim-scram actuator is shown in Figure 6.27.

The air motor drove a gear train that transmitted power through a slip clutch to a ball screw mechanism and subsequently to cross-head, drive rods, grate, extension, and control rods. The maximum force output of the system at the grate was 2000 pounds. The control rods moved through 20 inches of travel at a rate of 5 inches per minute.

The drive rods passed through the wall of the compressor collector, where carbon seals served as air seals and attached to the grates. The grates were located inside the collector in front of the reactor bypass valve.

The position transducer, attached to the cross-head bar, provided sensed position information for automatic shim position control as well as position instrumentation.

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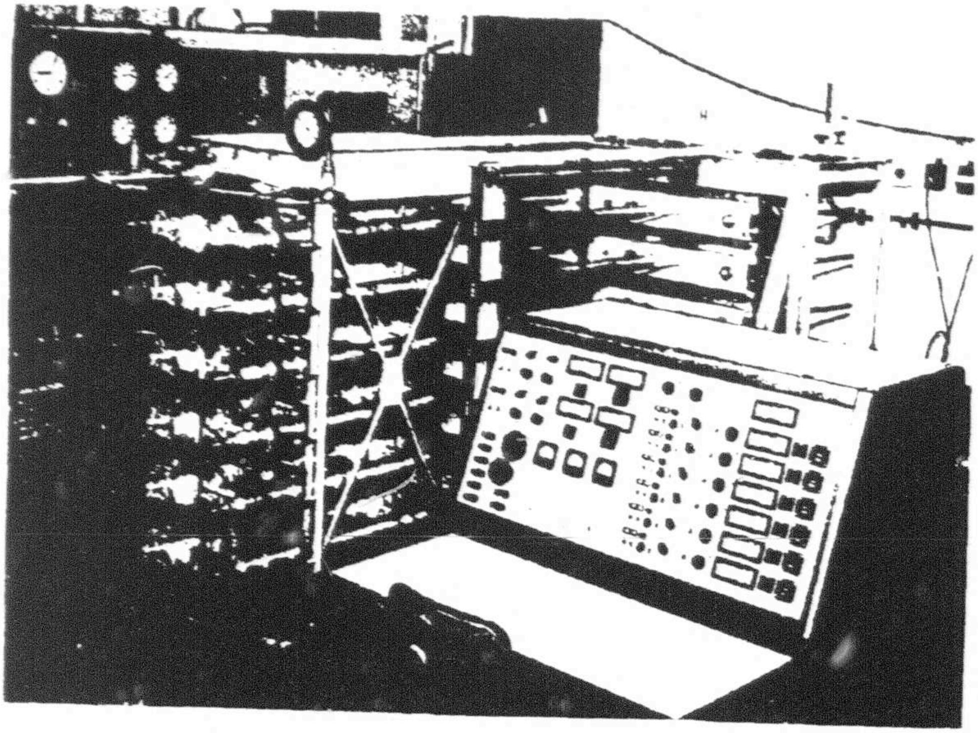

Fig. 6.26 – Test setup for development model actuators (Neg. 1-38331)

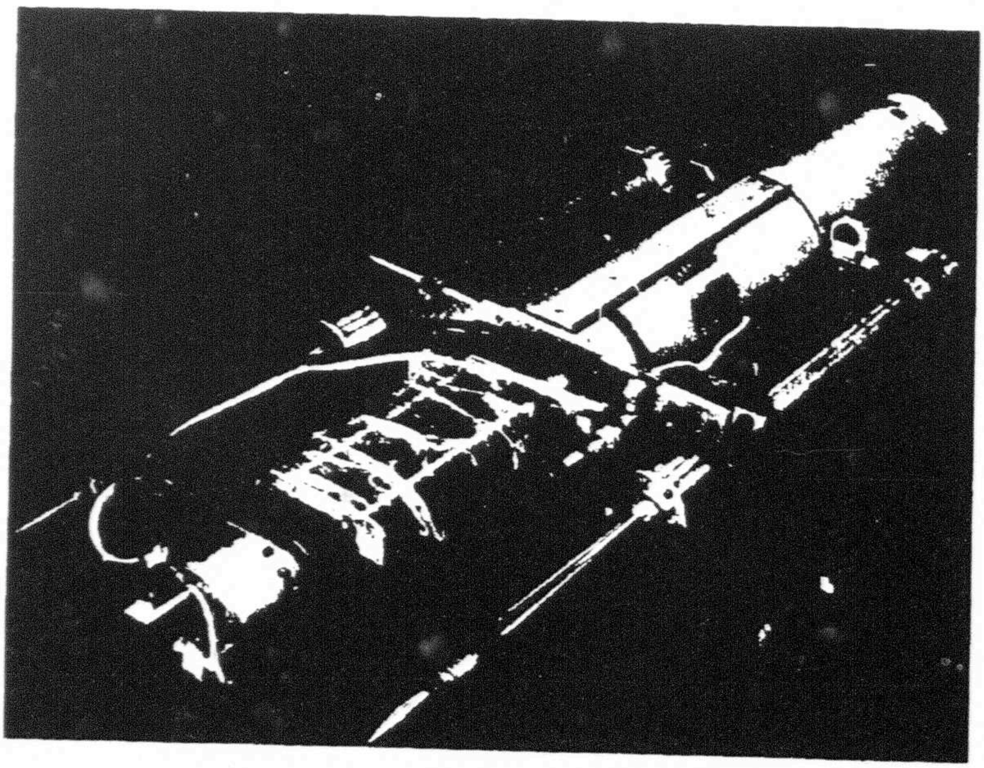

Fig. 6.27 – Development model shim-scram actuator (Neg. 1-38097-B)

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To effect scram, springs were arranged to quickly insert the shim-scram control rods into the reactor. During scram, the 20 inches of rod travel was traversed in 650 milliseconds. Entrapped air assisted the rubber cushioning in absorbing the momentum of the actuator system during scram. An electrically-operated air-actuated latch mechanism was used to trigger scram.

The compensating cylinders counteracted static air loads on the control drive rods, imposed by pressures in the compressor exhaust collector, by bleeding collector air to a piston of larger area than the total drive rod area. A resultant force was produced on the actuator system in the insert direction.

Remote handling provisions were incorporated into each shim-scram actuator to permit individual replacement. This provision was incorporated at the nut, holding the drive rod to the cross bar, the air actuated disconnects on the compensating cylinder, the electrical fitting disconnects, and the pneumatic fitting disconnects. This installation and removal technique permitted positive location of the grate system with respect to the actuator cross-head.

A summary report of the work accomplished on the shim-scram actuator was published.[22]

Dynamic Rod Actuator - The actuators associated with the dynamic control rods were mounted at the top and bottom of the actuator-system support structure. Figure 6.26 shows one dynamic actuator mounted at the top structure. The air motors, position transducers, and compensating cylinders were essentially the same as those associated with the shim-scram actuators.

The grates for the dynamic control rods were outside the compressor exhaust collector at the top and bottom of the actuator support structure. The top grate mounted four extension rods, the bottom grate mounted three. Extension rods passed from the grates to the control-rod poison tips in the same manner as in the shim-scram system.

The dynamic actuator system operated through 20 inches of travel at a maximum rate of 5 inches per second. The actuator could exert 500 pounds maximum force on each grate.

The air for operation of the motors and latch mechanisms was bled from the compressor exhaust collector or was facility supplied. A photograph of the development model dynamic actuator is shown in Figure 6.28.

The dynamic actuator used the same air motor and servovalve to drive it as the shim-scram actuator used. It had a 10.1 gear reduction and drove only three or four control rods. Therefore, its speed was much faster than the shim-scram actuator.

Both the shim-scram and the dynamic actuator design had progressed to the development hardware stage when the project was cancelled.

Testing - Although very little testing was accomplished on the XMA-1A development model actuators, extensive work was accomplished on components intended for use on the XMA-1A control actuators.[22,23]

The following component tests or evaluations were performed to check the feasibility of the designs:

1. The pneumatic motor proposed for both the shim-scram actuator and the dynamic actuator was a two-gear type rotary motor. Extensive testing and development was accomplished on this motor.[24,25]
2. One of the major structural parts involved in the design of the shim-scram actuator was a cross-head that tied the two ends of the push rods together. This part was an

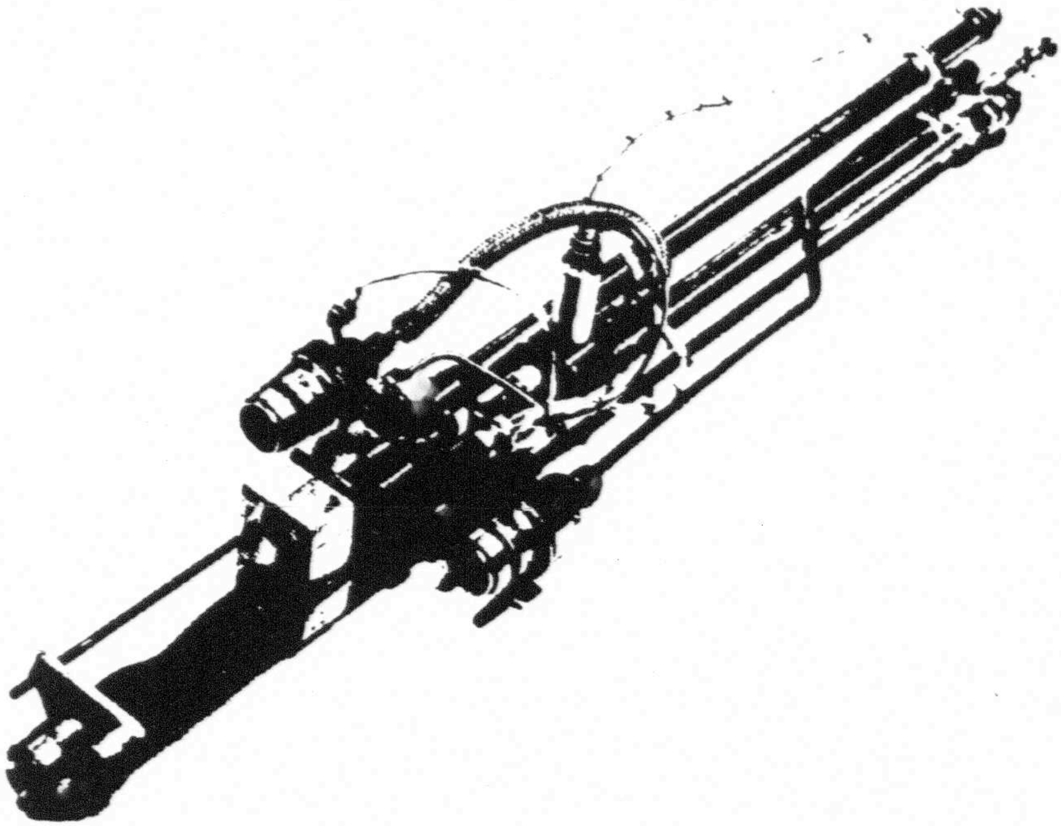

Fig. 6.23 – Development model dynamic actuator (Neg. U38254-B)

aluminum casting for lightness; it was tested for deflection stress, concentration, and ultimate load capability. No serious stresses or deflections were encountered and an ultimate safety factor of four was determined.[26]

3. The XMA-1A control actuators represented a new concept in control drives in that low-pressure air controlled by a 4-way two-stage servovalve was the prime mover.[27] Although the valves were operated unlubricated, at no time did excessive wear appear between the main spool and the sleeve it operated within. There were indications that because of the lesser viscosity of the air, as compared to hydraulic fluid, enough air was passing by the spool to give an air bearing effect. This would account for the lack of wear.

4. Both the shim-scram and the dynamic actuators were mated to the power plant at an interface that was operating between 400° and 500°F under nuclear radiation. The disconnects that performed the mating were not capable of sealing through a metallic O-ring due to lack of force (1500 pounds required). An effort was initiated to find an elastomeric O-ring for this application. After many elastomers had failed because of temperature alone, an investigation of silicon O-rings was initiated and a suitable silicon O-ring was obtained.[28]

5. During the course of designing and developing the XMA-1A actuator, calculations indicated a ratio of force level of 16:1 between stall torque of the actuator and running

torque. This would be 25,000 pounds of force at the push rods for the stall condition. It was quite evident that in order to protect the core from damage if several rods became stuck in their guide tubes, it would be necessary to limit the torque at some point in the drive train. A slip clutch was selected as a method of doing this and a limiting value of 1700 pounds was imposed. The clutch would be slipped continuously and consequently involved considerable development effort on the selection of materials.[29]

6. Vibration, G loading, and static load tests had been started on a single actuator when the XMA-1A power plant was cancelled.[30,31]

7. The most severe problem encountered with the XMA-1A dynamic actuator was the development of a suitable dashpot to absorb the kinetic energy at the end of the rod travel. A partial solution existed in that part of the original design was a balance piston that compensated for the back pressure on the push rods passing into the pressure chamber. However, attempts to use this cylinder as a pneumatic buffer were not successful and other methods were evaluated. One method was the use of Belleville washers as a shock absorber; this particular design was successful.[32]

6.2.2.3 Control Sensors

Nuclear Sensors - The nuclear sensors used for control in the XMA-1A power plant were located in the side shield sensor wells. They were located on a plane through the vertical center of the active core and at an angle of 42 degrees 32 minutes from the vertical centerline of the power plant. This located two packages in the top half and two in the bottom half of the power plant. Details of analyses and tests performed to arrive at these locations were reported.[33,34,35,36]

The nuclear sensor package (Figure 6.29) consisted of the outer skin, nuclear sensors, nuclear sensor leads, shield block, and fission-chamber preamplifiers. The outer skin was the enclosure into which all components of the package were assembled. It consisted of several sections each having a different diameter. The outer skin was assembled in this way to minimize radiation streaming from the side shield. There was an elliptical section at the lower end of the assembly which contained the nuclear sensors, shield material, and air passages for the flow of cooling air. Detailed analyses of the cooling requirements for the sensor assemblies was published.[37]

The shield block of the sensor package was located in the central portion of the assembly. It consisted of four sections containing grooves for the leads and slots for cooling-air passage. The four sections were held together by the assembly of the upper and lower covers. At the lower end of the shield block the chambers were connected to their respective leads and held in place by bolting the sensor baskets to the block.

The side shield provided a cooling-air manifold. To facilitate cooling, a 0.25 inch gap was maintained between the sensor well wall and the outer skin of the sensor package. The air flowed down through the gap into the bottom of the sensor package, up through the package, and exhausted into a plenum. The plenum discharged into the nacelle flow path.

The uncompensated ion chamber and the large fission chamber were located in the elliptical section of the sensor package with centerlines on the major axis. The two small fission chambers were located with centerlines on the minor axis.

The ionization chamber consisted of a can containing a voltage tube and a signal tube. These tubes were coated on the insides with boron-10. The chamber was filled with dry nitrogen gas at a pressure of one atmosphere.

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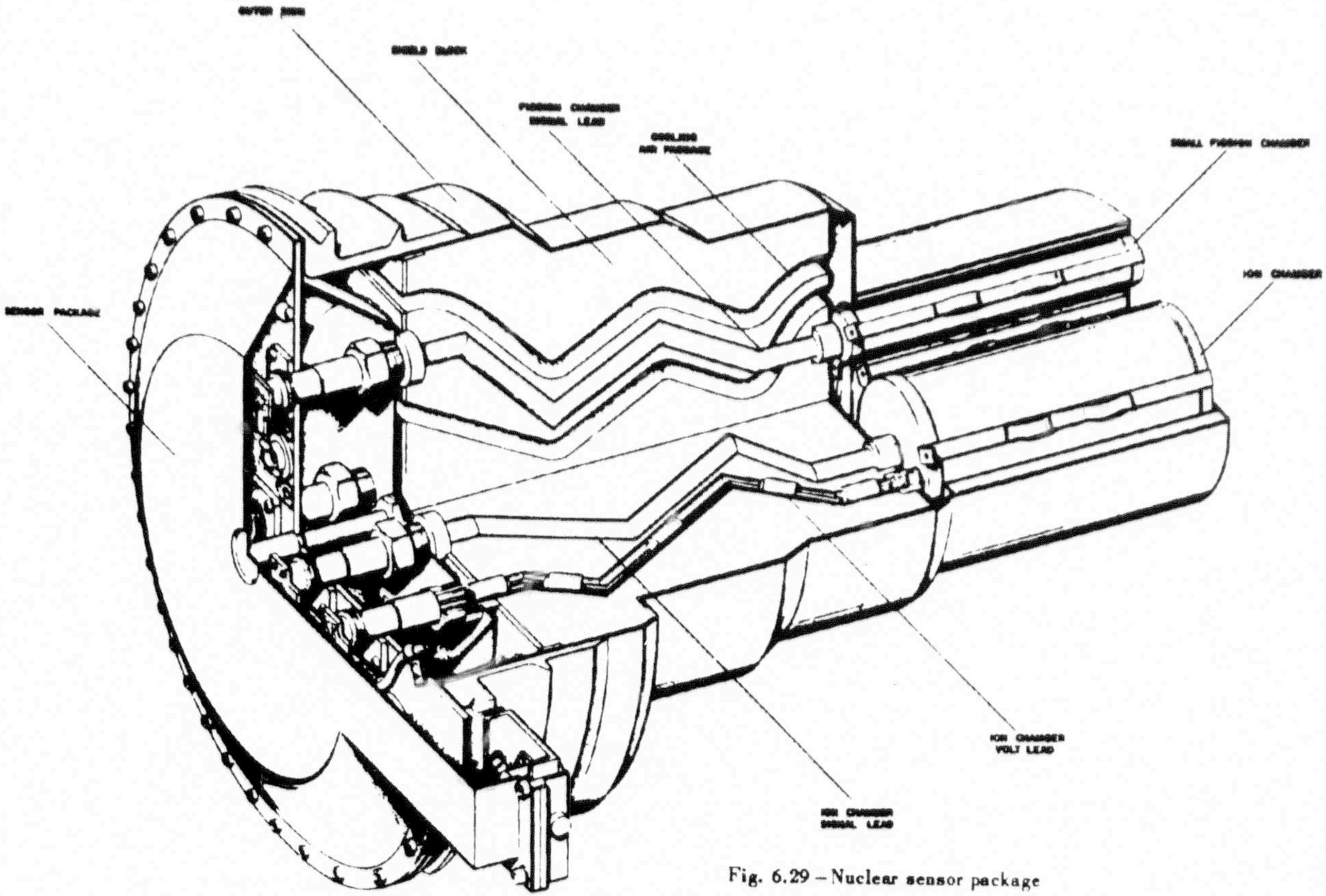

Fig. 6.29 – Nuclear sensor package

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The large fission chamber consisted of four concentric tubes spaced at 0.125 inch intervals. Each tube was coated with enriched uranium-235. The inner and outer tubes were coated on one side only. The other tubes were coated on both sides. The chamber was filled with 99 percent argon and 1 percent nitrogen gas at a pressure of one atmosphere.

The two small fission chambers consisted of two concentric tubes spaced 0.125 inch apart. These chambers were also filled with 99 percent argon and 1 percent nitrogen at a pressure of one atmosphere.

Leads were attached to each sensor, one to each fission chamber, and two to each ionization chamber. They were designed in several angled sections to keep radiation streaming to a minimum. The leads were fitted into the shield block with chambers connected to one end and the preamplifier package plugged onto the other end. The leads were evacuated and filled with an inert gas to a pressure of one atmosphere.

The amplifier package plugged onto the leads from the chambers and carried the signals to the assembly connector. The signals from the ionization chamber were carried direct to the connector while those from the fission chambers passed through the preamplifiers and then to the connector. The preamplifiers increased the amplitude of the output pulses from the fission chambers for transmission to the instruments located in the control room.

A detailed description of the nuclear sensors was published.[38]

Reactor Discharge Temperature Rakes - Provisions were made in the design of the power plant for installation of five reactor discharge temperature rakes on the combustion exhaust collector. Two of the rakes were used for reactor control; the remaining three for reactor safety.

The rakes were 5-feet long and 1.2 inches in diameter. Thermocouple pairs were placed at 9.5 inch intervals along the rake. Each rake contained two temperature sensing groups of five paralleled thermocouples each.

The rakes were inserted through a flange in the combustor discharge collector and were contained in tubes mounted at the aft end of the rear shield plug. Air from between the walls of selected wavy plates was collected and directed over thermocouple pairs inside the rake's sensor orifices. The air-temperature sensing system was developed to measure maximum temperatures between 1900° and 2300°F.

For a detailed discussion of the technical details and test results see reference 39. The following are the most significant conclusions derived from the temperature sensor development program.

1. By melting high-purity heats of Pd / Pt - 15Ir it was predicted that thermoelements reproducible to within ±0.25 percent could be made.
2. Pd / Pt - 15Ir possessed acceptable thermoelectric stability in moving and dynamic air at 1200°F and 2000°F.
3. The Tophet C / Ni - 4.3Si leadwires were also stable and oxidized very slightly at 1200°F. They could be platinum plated if necessary for pins and jacks.
4. V-junction breakage occurred with Pd / Pt - 15Ir because of differing coefficients of expansion and tensile strengths. The possibility of failure was reduced to a low level by using the machined-loop configuration.
5. Stress-relief heat treatment of 24 hours at 1000°F appeared to be adequate for bringing Pd / Pt - 15Ir, swaged to 25 percent reduction in area, within ±0.25 percent of its calibration curve.
6. Average temperatures measured with the rakes and their attached leadwires were usually within ±3°F (between 1100° and 1800°F) of true furnace temperature.

7. One rake was vibration tested and successfully passed all qualification tests according to the requirements with the sensor operating at 1800°F.
8. The time response of the bare Pd / Pt - 15Ir thermocouples was about 1.75 seconds at 8 pounds per square foot per second. Incorporating these junctions into a rake and diffusor mounting increased time response 220 percent when airflows remained at 8 pounds per square foot per second past the total assembly.

6.3 DESIGN REQUIREMENTS

The requirements and data essential to the design, development, and mechanization of the XMA-1 power plant controls and accessories are presented in detail in reference 2.

6.4 SYSTEMS ANALYSIS

6.4.1 SIMULATION

In order to provide a complete power plant in the shortest possible time, it was necessary to carry out essentially parallel design programs on all parts. This required that control components be designed and built before operation of any of the basic mechanical components such as compressors or turbines.

With early turbojet engines, it was fairly easy to describe the transient behavior of the power plant in order to study the control characteristics because there was only one control variable, i.e., fuel flow. In the XMA-1 system, however, there were a great many controlled variables: reactor power level, interburner fuel flow, jet nozzle area, compressor stator-vane angles, and afterburner fuel flow in addition to values that proportioned the airflow between the two heat sources. With such a complicated power plant, it was not sufficient to study the dynamic behavior by using linear differential equations only, since these could not adequately describe its behavior. Because of this, it became necessary in designing the XMA-1 control system to use nonlinear equations and other more accurate relations to represent the power plant dynamics.

Since the best possible method of solving nonlinear differential equations is to use an electronic analog computer, a simulator was developed utilizing general purpose analog computing equipment. This provided a simulator which was capable of continuous dynamic operation of the power plant over a range of corrected speed sufficient to permit studies of idle to military operation for the full range of flight conditions. Corrected parameters were used throughout the simulation to minimize changes required in going from one flight condition to another.

A detailed discussion of the simulator may be found in references 40, 41, and 42. Development of a reactor heat transfer simulator for use with a power plant simulation is described in reference 43. Earlier work done on studying a reactor and its controls utilizing analog computer techniques is presented in reference 42.

6.4.2 ANALYSIS

The simulator proved to be an even more valuable design tool than was originally anticipated. Its three main areas of use were stability analysis, failure analysis, and development of operating procedures.

The system was evaluated for stability in all its various operating modes, i.e., fully automatic, various combinations of automatic and manual, and all manual. These evaluations were carried out over the idle to military speed range for a wide range of flight conditions. They also included introduction of engine asymmetries to evaluate their effect. Acceleration and deceleration rates in the range between idle and military for both nuclear and chemical power were studied. Detailed discussion of all these investigations may be found in references 44, 45, and 46.

The simulator was used to study various single failures that could result in power plant damage. Failures that could result in one or a combination of the following were considered: (1) physical overspeed, (2) compressor stall, and (3) over-temperature of either reactor core, combustor or turbine. Consideration was given to one or more failures in each of the following systems: (1) main fuel, (2) nozzle area, (3) reactor, (4) safety, (5) compressor stator, (6) exit guide vanes, (7) electrical, (8) stator and nozzle hydraulic, (9) power plant hydraulic, (10) lubrication, (11) main ignition, (12) pneumatic, and (13) starter. A detailed discussion of this study may be found in reference 47.

An operating procedure was developed to evaluate the concept of utilizing a single operator console for basic control of the power plant. An operating mockup of this console was built and tied into the power plant simulator. Studies were made utilizing this setup to determine the adequacy of both the console and the procedure. The detailed operating procedure may be found in reference 48.

6.5 DATA INSTRUMENTATION

The first test model of the XMA-1 was to have been very heavily instrumented for its initial operation. This was especially true for the reactor-shield assembly since this would be its first test. Much of the reactor and shield instrumentation had to be built into the components during the manufacturing process. The turbomachinery was in the process of being developed separately utilizing a chemical burner system in place of the reactor-shield assembly and thus, required only those items of instrumentation necessary to assure that it was operating normally during the XMA-1 test.

The major problems encountered in instrumenting the reactor shield assembly were (1) routing the leads to the outside of the assembly, (2) pressure sealing the thermocouple leads, (3) attachment of the leads, (4) assembly, (5) accuracy requirements, and (6) reliability.

It was necessary to route instrumentation leads from the front- and rear-shield plug and the reactor core through the main bolted flanges at the fore and aft ends of the reactor-shield assembly. Each component design had to be modified to enable the attachment and routing of each lead. Since the quantity of leads was so great, they had a significant effect on the cooling airflow area and the heat transfer in the cooling passages.

The Fiberglas insulated thermocouple leads, which were routed from the inside to the outside of the pressure shell, presented a significant leakage problem. Work was being performed on developing a seal for these leads when the program was terminated.

Attachment of the instrumentation to age hardened Inconel X was difficult due to the notch sensitivity of the material. All forms of welding produced microcracks in the grain structure which in turn caused early failure of the structure. For instrumentation installation purposes, it was not practical to attach instrumentation to annealed Inconel X and subject it to the subsequent heat-treating and handling operations. Three methods of attachment were investigated. One method utilized Inconel pods, fusion welded to the Inconel X prior to heat-treat. Another method used a flame sprayed metalized coating to cement the leads to the structure. The third method used flame spraying to build up a pod. Final selection of a method had not been made at the program termination.

The major problem anticipated during assembly was damage to the leads. Extreme care would be required to prevent damaging the relatively delicate leads while assembling heavy structural parts.

Accuracy requirements were so stringent that pressure transducers had to be located in accurately controlled environments on the power plant.

Since most of the instrumentation was assembled directly into the components, any failure occurring after a significant amount of operation could not be repaired or replaced. Therefore, a high degree of reliability had to be designed and built into the instrumentation.

Further details on the various aspects of the instrumentation may be found in references 49 through 55.

6.6 STATUS SUMMARY AT PROGRAM TERMINATION

6.6.1 REACTOR CONTROLS

6.6.1.1 Systems

The second stage of development of both the reactor startup and power-range control systems was nearly completed at the end of the program. Breadboard and development models of both systems had been built and evaluated.

The first model of the startup control utilized a discontinuous period servosystem. Two complete channels, either of which could be used for control, were used. The final system utilized a continuous period servosystem. Again, two channels of control were used with one for control and period safety and one for period safety only. Power leveling was also added in the development model to provide the capability of holding power constant in the startup range. Evaluation of the startup system was carried out using the output signal of a uniform pulse rate generator. Operation of the period computer and logarithmic count rate equipment was observed with inputs from a nuclear source.

The development model power-range system was tested (except for safety trips) with all the magnetic components and with one shim loop and one dynamic loop. Reactor kinetics, reactor heat transfer, the ion chamber, and the thermocouples were simulated on the analog computer. It was planned that final adjustments would be made when operating with the simulated engines. The control performed satisfactorily in controlling both flux and exit temperature. Final changes required were incorporated in the service test model design.

6.6.1.2 Electrical and Electronic Components

Breadboard and development models of the electrical and electronic components of both startup and power-range systems had been built and evaluated.

First models of the pulse preamplifier, which was the only power-plant mounted electronic component, had been built and undergone considerable non-nuclear testing. Service test models were in the final design and manufacturing stage prior to evaluation in a nuclear environment. All of the parts had been tested in a nuclear environment. Some magnetic components of service test model design had been built. The manufacturing drawings of service test model hardware, which was designed both for ground and flight test, for both startup and power range control were about 80 percent complete. Plans were being made for manufacturing three complete systems plus spare modules. One system was for use in Idaho, one for use in the systems laboratory in Evendale, and one was to be used in evaluating components under environmental conditions. Some of the spare modules were also to be used for environmental evaluation.

6.6.1.3 Rod Actuators

Experimental models of both the shim-scram and dynamic rod actuators were built and evaluated. In addition, extensive testing of components such as servovalves, clutches, air motors, extension rods, grates, and ball screws was carried out. At the end of the program, the manufacturing drawings for the development models were complete. In addition, parts manufacturing and procurement were almost complete. The first development units were scheduled to be assembled within a month. Test equipment to be used in evaluating 12 shim-scram and 8 dynamic actuators was being built.

6.6.1.4 Nuclear Sensors

Drawings for development model nuclear-sensor packages were complete. Manufacture of two complete assemblies for development testing was nearly complete. Plans were being made to test the sensors in a reactor facility.

6.6.1.5 Temperature Sensors

First models of the temperature-sensor probe had been received from the vendor, and evaluation tests were being carried out. A test rig, which simulated the air inlet configuration was built for checking time response. Tests carried out in the rig indicated that the time response was far in excess of specification. At the end of the program, the vendor was in the process of modifying the design to improve the time response. The remote handleable mounting and electrical connector were in the final design stage.

6.6.2 POWER PLANT SYSTEMS

6.6.2.1 Valve Actuation System

A detailed actuation specification system for six combustor inlet valves and the two halves of the reactor inlet valve had been written. Procurement action had reached the stage of completing proposal evaluation and selection of a vendor. Systems were being procured for use on the power plant at Idaho, for testing on an engine in Evendale, and for off power plant evaluation in a nuclear radiation environment.

Work on a hydraulic power supply was in the block diagram stage. A heat transfer study had been completed which provided information required for sizing the cooling system.

A study had been made to compare methods of mechanization for the 16th-stage stator actuation system.

6.6.2.2 Control Console

A control console for use with both ground test and a flying test bed airplane was in final design. It was sized and arranged to permit a single operator to completely control a power plant. An operating mockup of the console was built for use with the power plant simulator. A secondary console containing monitoring instrumentation was being designed for use during ground test and flight test of the single power plant airplane. The twin power plant airplane would require two primary consoles and would not have room for the monitoring consoles. It was planned that telemetering data to an operator on the ground, who was in radio contact with the flight operator, would serve the monitoring function.

6.6.2.3 Electrical Power Supply

A slightly modified 20 kilovolt-ampere, 400 cycle, single phase, 110/208 volt electrical power supply consisting of a hydraulic constant speed drive and alternator had been evaluated. This evaluation was performed under dynamic conditions in a nuclear radiation environment equivalent to 1000 hours of power plant operation. The drive was modified, prior to test, to remove the materials most susceptible to nuclear radiation damage. The results of the test indicated no noticeable effects of radiation on performance during the test. Post-irradiation inspection of components also indicated no noticeable effects.

6.6.2.4 Starter

A 500 horsepower airturbine starter with associated inlet control valve was being developed. Some component testing had been completed and most of the parts needed for assembling the first unit were on hand. The control valve was the major exception. The first valve was found to be unstable and a redesign program was underway. No other major problems were encountered.

6.6.2.5 Power-Plant Control Systems

A nonlinear analog computer simulation was used as the basic tool for analyzing the power plant with its control. The capability of operating on either chemical power, nuclear power, or transferring between the two was demonstrated. The simulation was utilized in developing the control console layout as well as the proposed operating procedure. Detailed analysis of some types of failures such as jet nozzle failure had been completed.

6.6.3 ENGINE CONTROLS AND ACCESSORIES

6.6.3.1 Systems

Systems under development at the end of the program included (1) automatic jet nozzle speed control, (2) manual jet nozzle area control, (3) automatic stator control (flight type), (4) automatic stator control (slave), and (5) manual fuel control. The primary emphasis was being placed on developing systems for ground test and flying test bed operation.

Development of both the automatic speed control and manual jet nozzle control had progressed to the point where they were satisfactory for engine use.

The automatic stator vane control was in the process of being designed. System steady-state and transient accuracy studies had been conducted to determine the individual component requirements. An analog study was being conducted to improve the loop's stability, response, and accuracy, and to investigate effects of feedback backlash, oil bulk modulus, etc. The automatic slave stator control system was in use on engine test.

6.6.3.2 Accessories

The fuel pump was suitable for engine use. Accumulated test time was 1900 hours, including 280 hours of engine time. Maximum time on any one pump was 500 hours. The main fuel filter was considered satisfactory for engine use. The stopcock was in the process of being redesigned to be fail safe in the closed direction.

Both the nozzle servo-hydraulic pumps and the variable-stator hydraulic pumps had accumulated over 2500 hours of testing. The nozzle actuators had accumulated several hundred hours of testing. Some further development of the actuator cooling flow device was required.

All ignition system components had demonstrated satisfactory performance.

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7. TEST SUPPORT EQUIPMENT

The XMA-1A power plant was planned to be ground-tested in the Flight Engine Test facility (FET) at the Idaho Test Station (ITS). The planned test equipment consisted of the power plant support structure, transport vehicle, and necessary auxiliary systems.

A common trackage system interconnecting the Initial Engine Test facility, the Flight Engine Test facility, and the hot shop - cold shop complex would be utilized. The XMA-1A power plant would be transported (and possibly tested) on a vehicle that would negotiate a four-rail track system identical to that at ITS.

The design of the previously-operated power plants (HTRE No. 1, No. 2, and No. 3), allowed for transportation of the turbomachinery, reactor, and supporting equipment to the hot shop on a dolly. The power plant elements were removed from the dolly using the hot shop manipulators and other remote handling tools. A similar procedure would be impossible for the XMA-1A, however, since no manipulators existed or were planned in the FET and the exact capabilities of the Beetle[1] (a mobile shielded cab with remote manipulators) had not yet been determined. APEX-911 includes a detailed description of the Beetle.

To simulate the airframe manufacturer's design of power plant installation, a structure representing the airframe was designed for semipermanent installation in the FET. A vehicle was designed which would run on the four-rail track system, and could install the power plant into the structure at the FET. The vehicle would carry aftercooling equipment, carbon dioxide fire protection for the aftercooling diesels, nitrogen for inerting the fuel supply for the diesels, and a helium system for use in the side shield. This vehicle was also designed to carry the combined structure and power plant back to the hot shop for separation there, or for remote maintenance of support equipment.

In HTRE No. 1, No. 2, and No. 3, required turbojet auxiliaries were mounted directly on the integrated dolly and superstructure. This procedure eliminated the complexities and dangers of special disconnects, by eliminating the flow of combustible fluids through the coupling station. The procedure was continued in the design of the XMA-1A with the auxiliaries designed to be mounted on the support structure.

7.1 STRUCTURE

7.1.1 SUPPORT STRUCTURE

The support structure was designed to contain the XMA-1A power plant during tests in the FET. It would also support the FET facility coupling plug, auxiliary packages such as the hydraulic and lubrication systems, and other equipment necessary for power plant operation. The power plant was to be installed and removed from the support structure by remotely controlled equipment.

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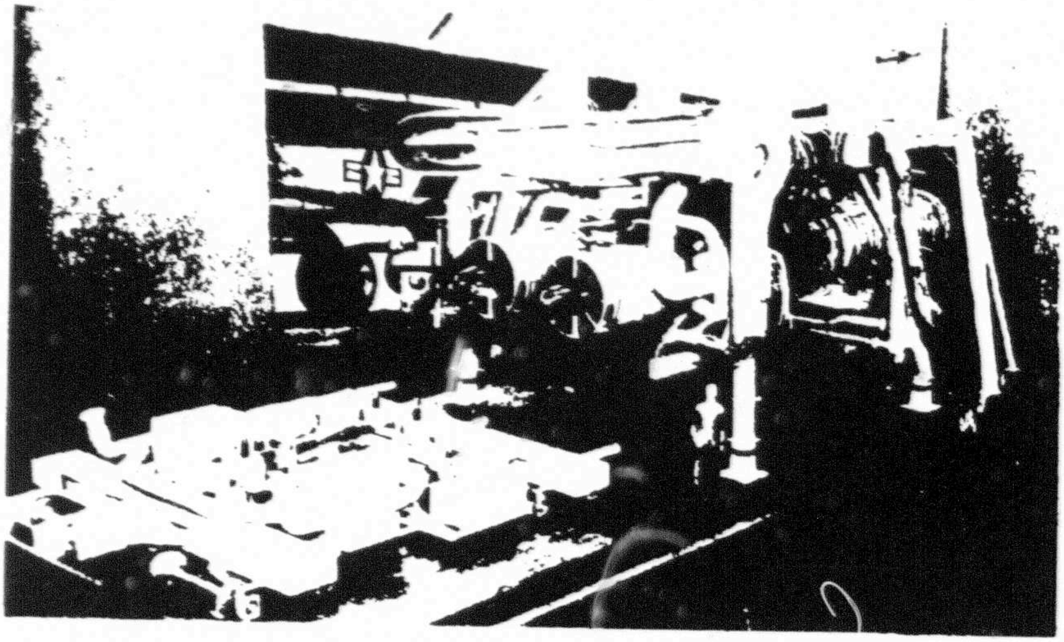

Fig. 7.1 – XMA-1A support structure and transport vehicle (Neg. C22653)

The support structure, shown in Figure 7.1, was designed with four main legs, each canted at a compound angle with the vertical angle. In the design, a vertical auxiliary leg would extend from each main leg. The base of the main leg would mate with the support structure pedestal in the FET. The auxiliary leg would contain the leg-jack assembly which would mate with the transport vehicle when removal of the structure itself was desired.

7.1.2 POWER PLANT SUPPORT LATCHES

The XMA-1 power plant was designed to be secured in the support structure by latches bolted to the structure. Proposed power plant installation methods using the latches simulated aircraft installation. The power plant would be raised vertically and then moved forward to its installed position. The latches were also designed for flight load capability. Should a malfunction prevent the normal removal of the power plant from the latches, suitable emergency release provisions would be available.

The latches would be opened, closed, or locked in the closed position by linear electromechanical actuators. Limit switches integral with these actuators would provide control panel signals to indicate the position of the latch.

7.1.2.1 Aft Side Latch

Sloped guide surfaces mounted on the aft end of the latch were designed to accomplish rough centering of the aft trunnion ring during power plant elevation to waterline 120 (0.5 inch above installed position). Forward motion of the power plant would place the side trunnions into the latch. During power plant lowering to waterline 119.50 (installed position), roll of the power plant in relation to the latch supporting surfaces would be removed. The locking linkage would be closed and held on or slightly over center by the linear actuator.

7.1.2.2 Front Latch

In the front latch design, the supporting member on the latch was pivoted and the end of it shaped to align itself automatically with the power plant support fitting as the power plant moved forward at waterline 120. Lead-in on the end of the supporting member would also remove yaw of the power plant in relation to the latches as the forward motion occurred. During lowering of the power plant to waterline 119.50, the supporting member would pivot to the horizontal, picking up the power plant load. A locking block, inserted between the supporting member and the latch housing by the linear actuator would lock, preventing the supporting member from pivoting.

7.1.2.3 Thrust Pin Assembly

Prior to the upward motion of the power plant during the power plant removal process, the thrust pin assembly would be pivoted rearward and the two diagonal links folded. The pin itself would be retracted into the housing. As the power plant was raised, the forward projection from the latch main housing would enter a void between the shield and the trunnion ring. When the power plant was moved forward, the thrust fitting pushing against this housing projection would return the thrust pin assembly to the vertical.

Emergency release provisions were to be included in each latch. In the front and aft side latches, remote removal of a "pip" pin which held the linear actuator in place would provide emergency release. This removal was to be accomplished by the Beetle. Thus, the lock could be disengaged by moving the entire linear actuator.

Emergency release for the thrust pin assembly was intended to be accomplished through the thrust pin emergency release. The linear actuator of the latch would be first disconnected from its normal anchor by energizing two explosive latch pins. Explosive latch pins would be used instead of manually released pip pins because extremely close clearances and surrounding equipment prevented access to the pip pins by the Beetle. Once the latch pins were retracted, the Beetle would pivot the linear actuator forward where a pull on the end of the emergency release cable would retract the thrust pin from the power plant fitting and break the diagonal links over center so that normal power plant removal could be accomplished.

7.1.3 SUPPORT STRUCTURE LEG-JACK ASSEMBLY

The leg-jack assembly was to be used to mate the support structure to the transport vehicle for remote removal and reinstallation into the FET.

The final design of the leg-jack assembly is shown in Figure 7.2. The jack would be driven through a flexible coupling by a 3-horsepower gear motor. A station switch would be mounted on the assembly, permitting manual control of the jack and motor by the Beetle should the drive motor fail.

7.1.4 SNUBBER LATCHES

7.1.4.1 Requirements

Vibration snubbers, which would be attached to the compressor front frame and turbine rear frame of the X211 turbomachinery, were to be used. To permit installation of the power plant, the snubbers would be anchored to the support structure. Further conditions of snubber installation would include:

1. Snubbers would be remotely latched to the support structure.
2. The support structure would be expected to supply adequate stiffness to absorb load transmitted to snubbers.

[redacted]

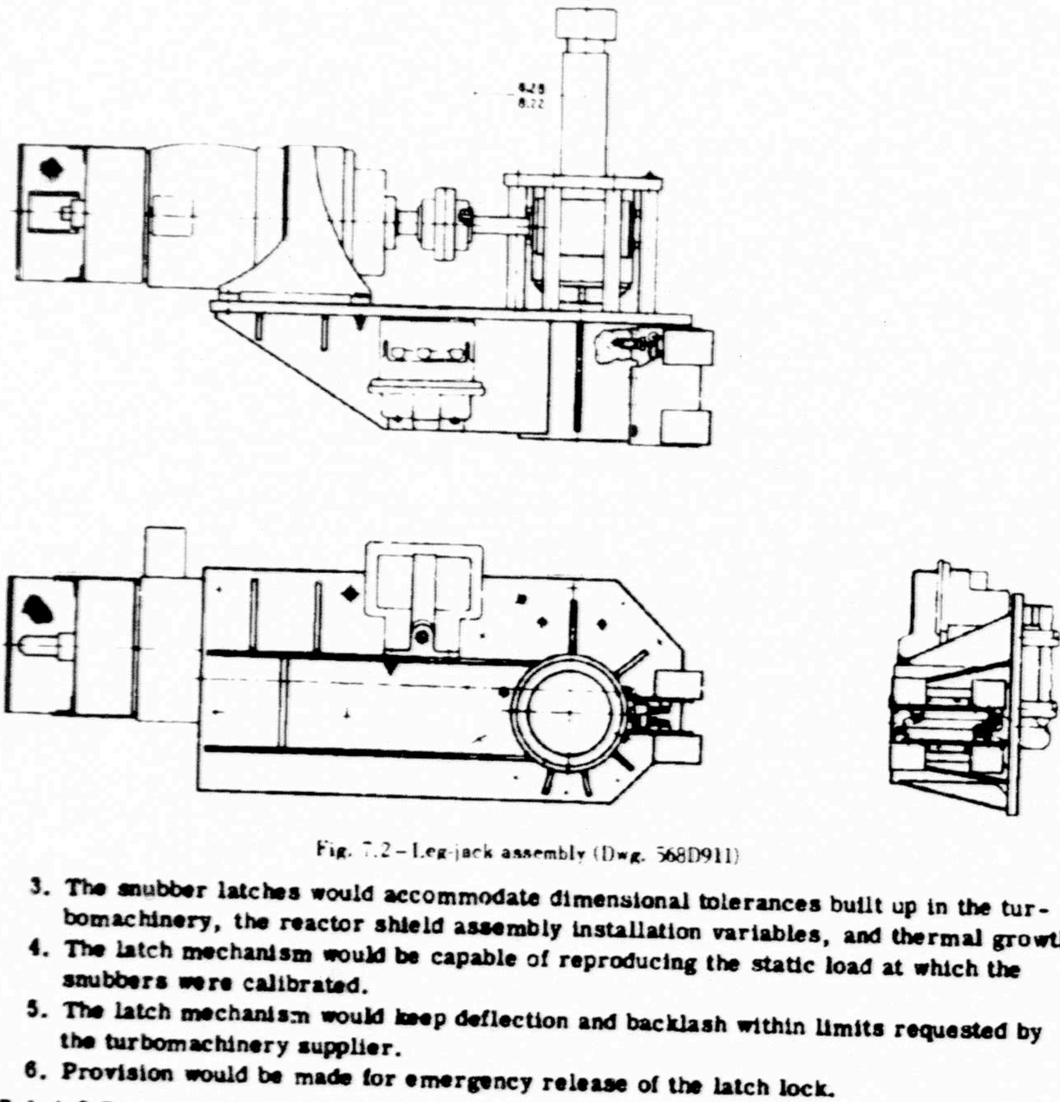

Fig. 7.2 – Leg-jack assembly (Dwg. 568D911)

3. The snubber latches would accommodate dimensional tolerances built up in the turbomachinery, the reactor shield assembly installation variables, and thermal growth.
4. The latch mechanism would be capable of reproducing the static load at which the snubbers were calibrated.
5. The latch mechanism would keep deflection and backlash within limits requested by the turbomachinery supplier.
6. Provision would be made for emergency release of the latch lock.

7.1.4.2 Design Data and General Information

Tests were conducted to determine the effectiveness of the snubbers. The following information provided by the tests was incorporated into the design of the latches.

1. The engine moved in all directions in the X and Y planes. After a run, the snubber parts would probably stabilize at a position different from the original. The snubbers would remain in a nonneutral position and would have to be manually reset before reinstallation of the power plant.

[redacted]

2. Snubbers would be calibrated to slip at 9000 pounds for the turbine units and 7000 pounds for the compressor units. They would be loaded to these calibrations on test by individual adjustment.
3. The test cell thrust frame was considered adequately stiff for test runs.
4. Total deflection and clearances in the latch and attachments were to be less than 0.005 inch.

7.1.5 DISCONNECT PANELS

Three disconnect panels would be required; one between the structure and the left front pedestal, one between the structure and the facility, and one between the structure and the transport vehicle. The panels would contain fluid and electrical disconnects to supply various services to the power plant and the auxiliary systems. A typical panel is shown in Figure 7.3.

The panels were designed to be gimbal mounted to compensate for large misalignment. To compensate for slight misalignment, the individual couplings would be mounted with 0.063-inch radial clearance between the coupling halves. To couple the panels, a pneumatic actuator would move one-half of the panel to the other half. Forward movement of the structure or the transport vehicle would accomplish uncoupling. Self-locking individual disconnects would lock the panels; horizontally mounted antifriction bearings would permit relative motion between the structure and the panel assembly.

7.1.6 WIRE TRAYS

An arrangement of wire trays, to be located on the top, rear, and front legs, and laterally in the rear of the support structure, would carry cables from the disconnect panels on the power plant, and from the auxiliaries on the structure to the facility plug.

7.1.7 FACILITY PLUG

The XMA-1 facility plug was designed to connect the power plant, when it was in the support structure, to the test facility. Provisions would be made on the face of the plug for interconnecting facility-based instrumentation, power wiring and piping, with various points on the support structure and power plant.

In designing a facility plug disconnect panel which would facilitate both cable loading at the cold shop and electrical connector maintenance at the FET, various configurations were investigated. To assist in this investigation, a partial full-scale mockup of a typical disconnect panel was built.

In the final design, the weight extending rearward from the support structure was minimized by specifying that the plug portion would be aluminum. To minimize the deflections caused by development of considerable moment, reinforced steel pipe would be used to support the facility plug.

7.1.8 TRANSPORT VEHICLE

A vehicle capable of transporting the XMA-1 power plant between the hot shop and the FET was designed. The vehicle contained a suitable lifting mechanism for installing the power plant into the support structure and removing it from the structure. If, due to some failure, the power plant would become jammed in the support structure, the vehicle could have removed the support structure with the power plant installed.

The design of the transport vehicle is shown in Figure 7.4. The power plant would rest on the lifting mechanism at the center of the vehicle and the support structure would rest on the ends of the transverse beam. The aftercooling system and other accessory equipment would be carried on frames on the front, back, and either side of the vehicle.

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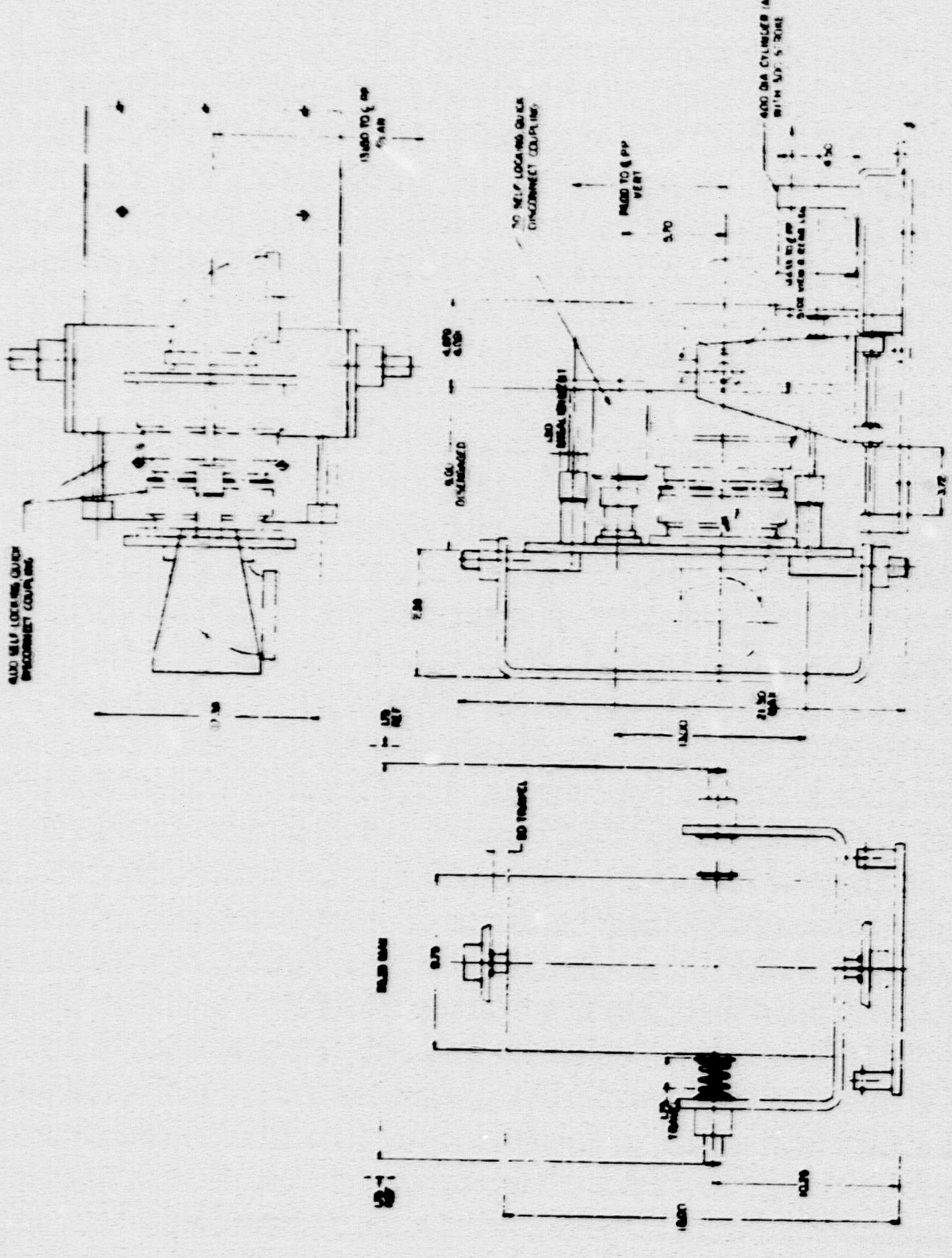

Fig. 7.3 – Disconnect panel (Dwg. 629E219)

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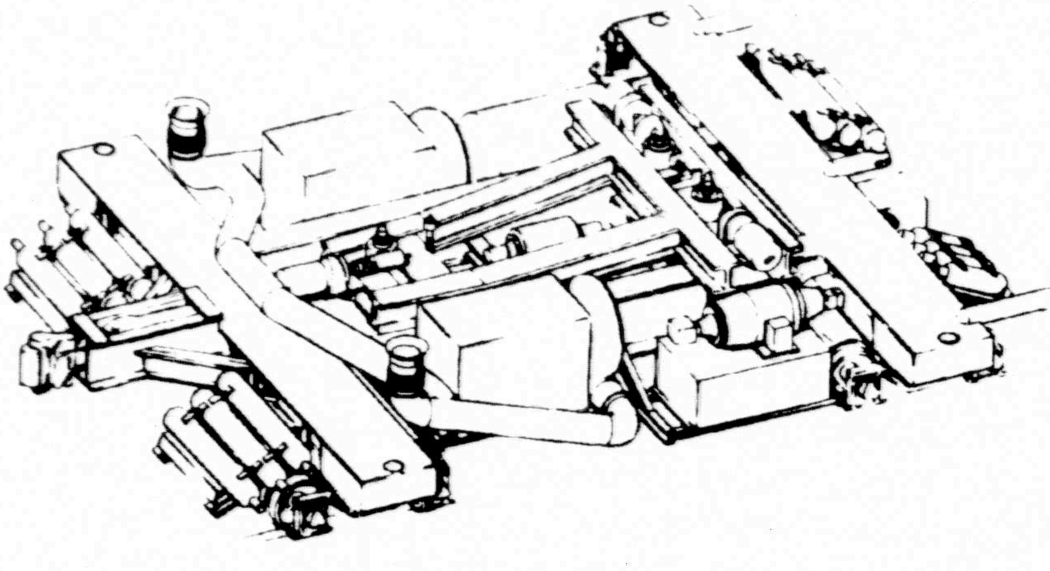

Fig. 7.4 – Transport vehicle (Dwg. G-1447)

7.1.9 POWER PLANT LIFTING MECHANISM

The lifting mechanism on the XMA-1 transport vehicle could both carry and position the power plant. Capable of withstanding 2-G dynamic loads while in motion, the mechanism would lift the power plant by means of three jacks on the jack frame, and position it in the latches by floating the jack frames on hydrostatic bearings. The opposite procedure would be used to remove the power plant.

The lifting mechanism, shown installed on the transport vehicle in Figure 7.4, consisted of:

1. Three hydrostatic bearings which were bolted rigidly to the transport vehicle.
2. A triangularly-shaped jack frame which rested on the bearings, providing a floating base for the power plant lifting jacks.
3. Three power plant jacks, of 50-ton capacity each.
4. Three synchronous gearmotors to drive the jacks.
5. Three motor couplings to connect the motors and jacks.
6. Two lateral positioners installed between the forward end of the jack frame and the vehicle to keep the jack frame centered during initial phase of the power plant installation procedure.

7.1.10 COUPLER SUPPORT STAND

The coupler support stand was designed to transmit the thrust loads to the FET floor through railroad couplers mounted on the stand and on the support structure, and to serve as a mounting for the thrust measuring system and other power plant auxiliaries. The coupler stand is shown in Figure 7.1.

By installing the rear leg pins at assembly, sufficient alignment and adjustment would be available to align the structure within the prescribed tolerances. The structure was also designed to be disassembled without disrupting the structural integrity of the assembly, and to be easily reassembled.

7.1.11 THRUST MEASUREMENT SYSTEM

To assure that the power plant tests would include accurate thrust measurements, the thrust measurement system was extensively investigated.

Accuracy requirements were established which permitted an uncorrectable over-all error of 1 percent of reading, or 100 pounds, whichever was larger. This error would include instrumentation, friction, and umbilical forces. In addition, the system was to be capable of reuse with any current or planned power plant.

Original thrust measurement system investigations were conducted using a truck-trailer arrangement of the power plant support structure dolly with the smaller dolly holding the auxiliary equipment. This procedure complicated the measurement problem, however, when railway truck friction or a suspension system was considered. After the single vehicle arrangement was introduced, numerous solutions were considered and evaluated.

All systems under consideration included three basic conditions: (1) isolation of the power plant to minimize random and tare errors, (2) sensing of thrust forces by strain gage type load cells in series with anchorage of the power plant to the facility, and (3) readout and calibration equipment.

Beside suspension (friction) errors, other conditions would be considered:

1. Instrument error, to be no greater than 0.1 percent of reading above 20 percent of scale and 25 pounds maximum below this point, would occur. This value was determined based on regular servicing of equipment and operation.
2. Umbilical loads from electrical and fluid connections to the facility would exist. These could be large and difficult to measure. Magnitude could be reduced only by the careful design of all such connections.
3. Reading error would occur. This error would be reduced essentially to zero by selection of readout equipment.

7.1.12 THRUST TETHERS AND CALIBRATION PROBES

The thrust tethers, were designed to anchor the support structure to the facility and to measure the maximum thrust developed in the XMA-1 power plant through a load cell analogy.

In addition, a hydraulically actuated probe was designed for each thrust tether assembly to calibrate the thrust-measuring load cells.

To minimize errors in thrust measurement, where restraining linkage was involved, spherical seats were designed to be placed at mating surfaces of the eye bars and pins. By locating these surfaces perpendicular to one another, a point contact would be achieved. This procedure would prevent side forces from being induced in the load cells as the structure shifted laterally on the pedestals.

A standard three-quarter size railroad coupler would be employed to secure the power plant to the facility. One-half of the coupler would remain with the support structure. A pneumatically actuated locking device would be provided to remotely disconnect the support structure from the facility.

To check the thrust cell, a calibration cell of equal capacity was designed. The equivalent thrust force required would be developed hydraulically and applied directly to the support structure. Lead plates surrounding each load cell would reduce the effects of nuclear radiation.

As an integral part of the load cell construction, a heating blanket would be used to keep the load cell at a constant temperature.

7.1.13 THRUST MEASUREMENT HYDRAULIC SYSTEM

A hydraulic system would be required in the FET facility to:

1. Supply 1500-psig oil at a minimum flow rate of 11 gpm to each of four pedestal hydrostatic bearings.
2. Supply oil to two calibration probe cylinders mounted on the coupler support stand. The oil pressure would be adjustable from 75 psig to 1200 psig.
3. Supply oil at a minimum pressure of 200 psig to two hydraulic cylinders mounted on the support structure rear pedestals.

The hydraulic system, shown in Figure 7.5, was planned to consist of two independent subsystems utilizing a common oil reservoir. A 3-gpm, 1200-psi pump would supply oil to the hydraulic cylinders. Pressure regulation in the calibration cylinders would be obtained through a diaphragm-type pressure control valve in the cylinders' supply line. A 44-gpm, 2000-psi pump would supply oil to the four hydrostatic bearings. Scavenge pumps on the discharge side of the bearings would return the oil to the reservoir. A water-to-oil heat exchanger in the reservoir return line would remove excess heat from the oil.

7.1.14 PEDESTALS

The power plant support structure was designed to rest on four facility-mounted pedestals. The pedestals, would provide a low friction base for thrust measurement and enable the support structure to be transferred to the transport vehicle.

Each rear pedestal was designed with a support structure leg restrainer. The restrainers would be composed of a shoe to contact the leg, a flexure plate to support the shoe, and a hydraulic cylinder to retract the plate for movement of the structure. Designed to prevent side slippage of the structure on energized hydrostatic bearings with low, or no thrust, the restrainers would also prevent resonant oscillation.

7.1.15 HYDROSTATIC BEARINGS

Installed on the transport vehicle, the hydrostatic bearings were designed to provide the jack frame with a frictionless support for positioning the power plant in the support structure. Installed in the pedestals, they were to provide a frictionless base for the support structure when thrust measurements were being taken.

These hydrostatic bearings, shown in Figure 7.6 were to consist of two horizontal plates separated by a high pressure fluid several mils thick. The lower plate would remain stationary whereas the upper plate would move on the lower. Because there would be no metal-to-metal contact between the two plates, practically no friction would exist.

7.2 AUXILIARY SYSTEMS

7.2.1 LUBRICATION SYSTEM

The lubrication system was designed to supply each set of turbomachinery with 0 to 43 gpm of oil for lubrication and removal of generated heat. The oil supplied to each of the main lube pumps was to be within a temperature range of 0^{o} to $200^{o}F$ and a pressure range of -20 inches Hg to 30 psig. The oil was to contain no more than 10 percent air by volume nor any dirt or impurities larger than a 40-micron particle size. The heat removal rate of the system was to be 530,000 Btu/hr. Two independent and identical loops, one for each set of turbomachinery, would be used to perform this function.

Figure 7.7 shows the arrangement of the system.

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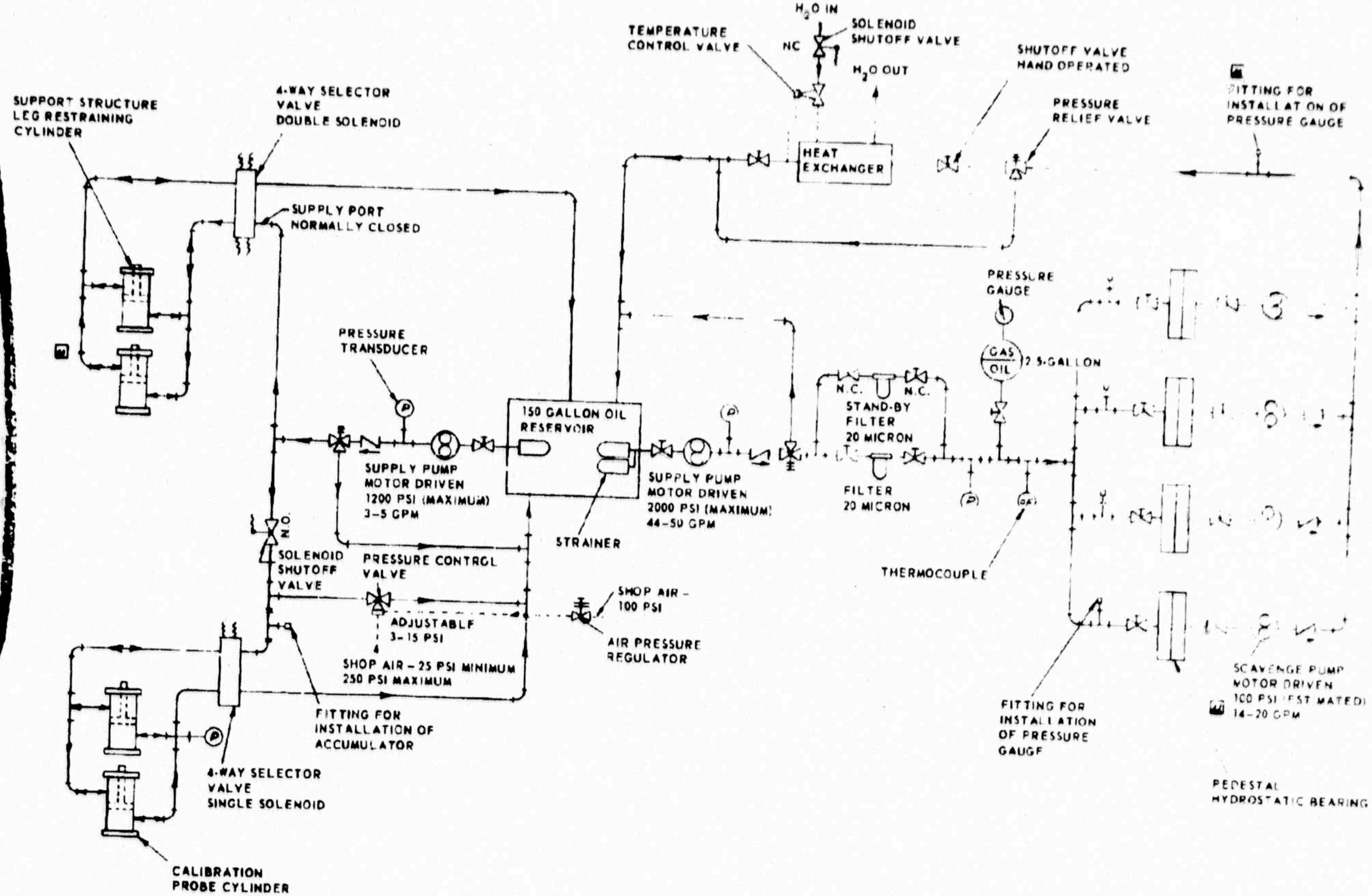

Fig. 7.5 – Thrust measurement hydraulic system (Dwg. 568L879)

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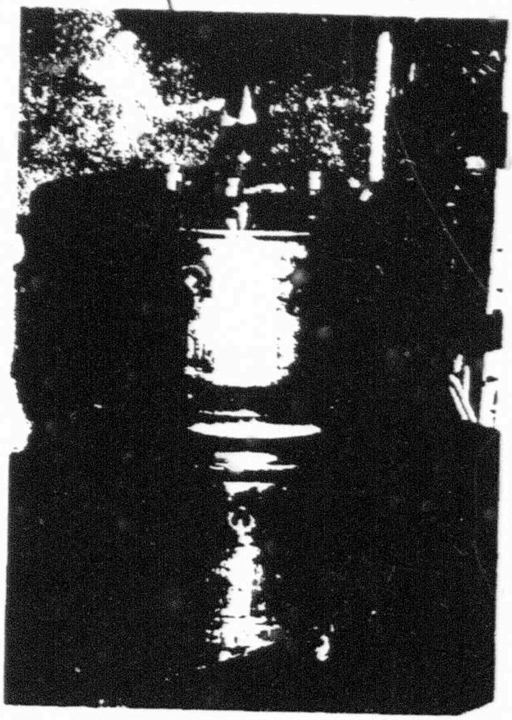

Fig. 7.6 – Hydrostatic bearings (Neg. U37397-F)

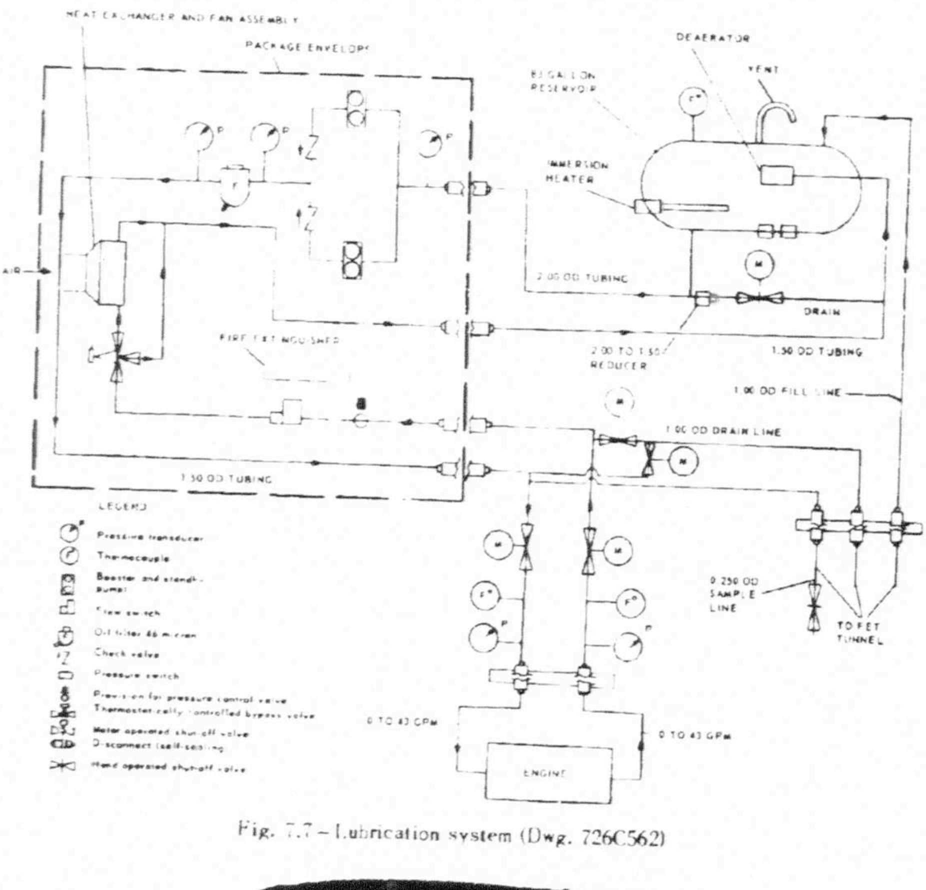

Fig. 7.7 – Lubrication system (Dwg. 726C562)

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7.2.2 SECONDARY COOLANT SYSTEM

The secondary coolant system was designed to remove heat generated by the engine-mounted hydraulic systems, nuclear propulsion hydraulic systems, starter cooling systems, and the constant speed drives. To remove this heat, oil would be circulated through the engine-mounted oil-to-air heat exchanger.

Except for the system reservoir and piping to the liquid-to-liquid heat exchanger, the components of the system were to be housed in a remotely removable package atop the forward end of the support structure.

Figure 7.8 indicates the planned arrangement of the system, oil flow rates, oil temperatures, and heat rejections of the heat exchanger.

7.2.3 AUXILIARY FUEL SYSTEM

An auxiliary fuel system would be required on the power plant support structure to transfer fuel from the facility fuel system to the power plant during the chemical operation.

The maximum fuel flow rate to each set of turbomachinery would be 120,000 pounds per hour with 42,000 pounds per hour being distributed to the main fuel system and 78,000 pounds per hour to the afterburner fuel system. The fuel supplied to the power plant was to be free of particles larger than 40 microns in size.

Fuel flowmeters were designed to measure fuel flow rates to each main and afterburner fuel system. The inaccuracy of the flow measuring systems was not to exceed ±1 percent of actual flow throughout the entire flow range.

The auxiliary system supply lines would handle the combined flow of the main and afterburner fuel systems. The fuel packages would enclose only the main system auxiliary components; afterburner system components were to be installed at a later date in a redesigned package.

A 4-inch quick-disconnect mounted on the aft right leg of the power plant support structure would connect the facility fuel system to the auxiliary fuel system. From this point, the fuel would be delivered through the 4-inch tubing to the forward end of the support structure where it would be directed to two fuel packages.

The fuel would be directed from the package through a 2-inch quick-disconnect to a disconnect panel mounted on the front leg of the support structure. The disconnect panel would mate the auxiliary fuel system to the engine fuel system. Figure 7.9 shows the auxiliary fuel system.

7.2.4 STARTER AIR SYSTEM

The starter air system was designed to direct the flow of engine starter air from the termination of the facility-installed supply system to the inlet connection of the starters. The system was to be mounted on the power plant support structure and coupler support stand, and was designed to be remotely attached to, and separated from the facility system and the starters.

7.2.5 INTRANSIT COOLING SYSTEM

A vehicle-mounted cooling system was designed to be used while transporting a hot nuclear power plant between the FET and the assembly area. Reactor cooling by the intransit cooling system would begin immediately after shutdown of the initial aftercooling system and would continue until the disassembly cooling system began operation. There would be no interruption of cooling airflow during a changeover from one system to another. The system would contain its own starting aids, emergency signals, and power source for the cooling air blower. The blower power source, consisting of a pneumatic

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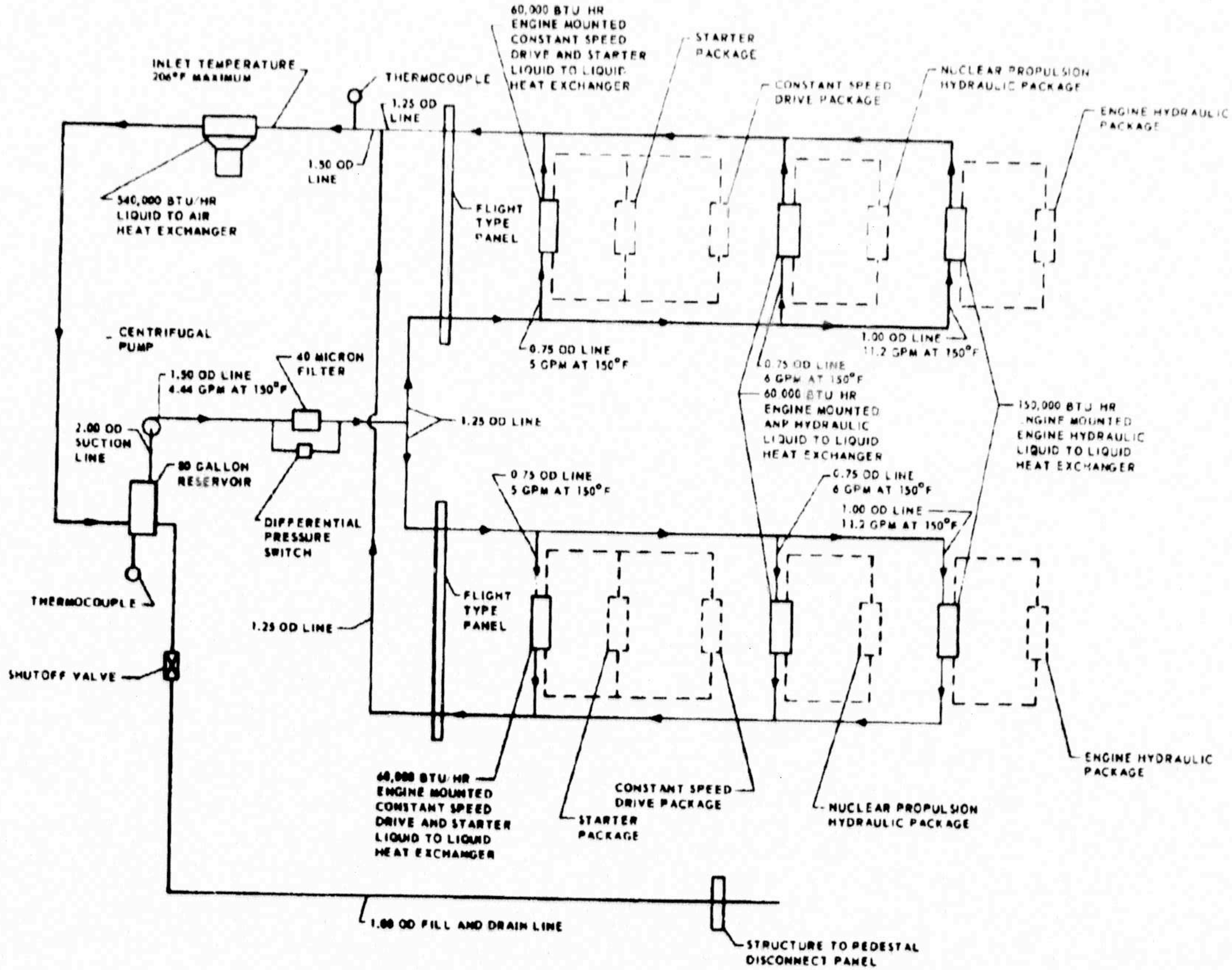

Fig. 7.8 – Secondary coolant system (Dwg. 568D930)

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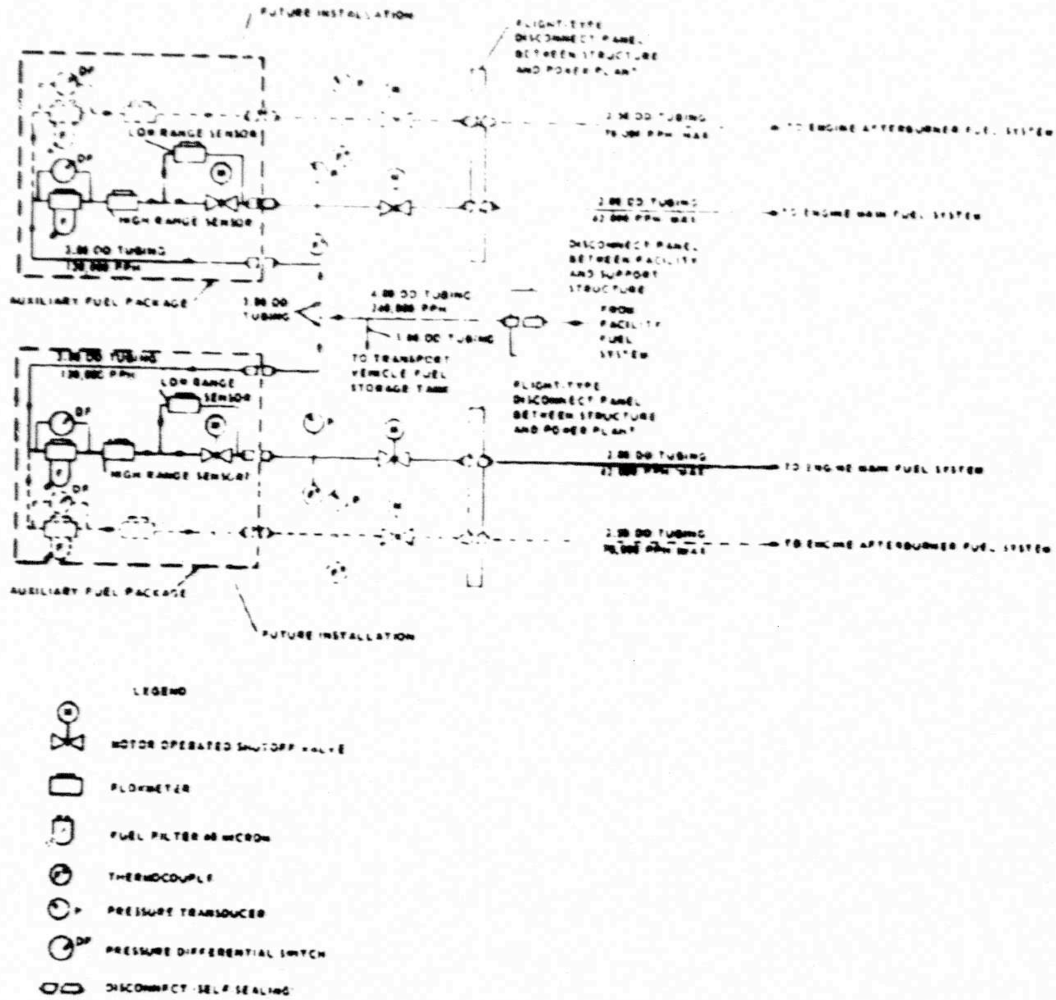

Fig. 7.9 – Auxiliary fuel system

blower powered by an enclosed diesel engine, was a packaged unit to be mounted on the transport vehicle.

The duct system for delivering air to the engine is shown in the schematic in Figure 7.10.

7.2.6 POWER PLANT FIRE CONTROL SYSTEM

The power plant fire control system was designed to detect and extinguish any fires (other than salt fires) occurring on the exterior of the XMA-1A power plant.

As a part of the fire protection system, a portable, three-sided wind screen was designed to envelope the power plant, reducing the local wind velocities. This screen would also help contain the extinguishing agent in high wind velocities.

The system, using carbon dioxide as an extinguishing agent, would have a 31-ton capacity which could be either remotely or manually discharged.

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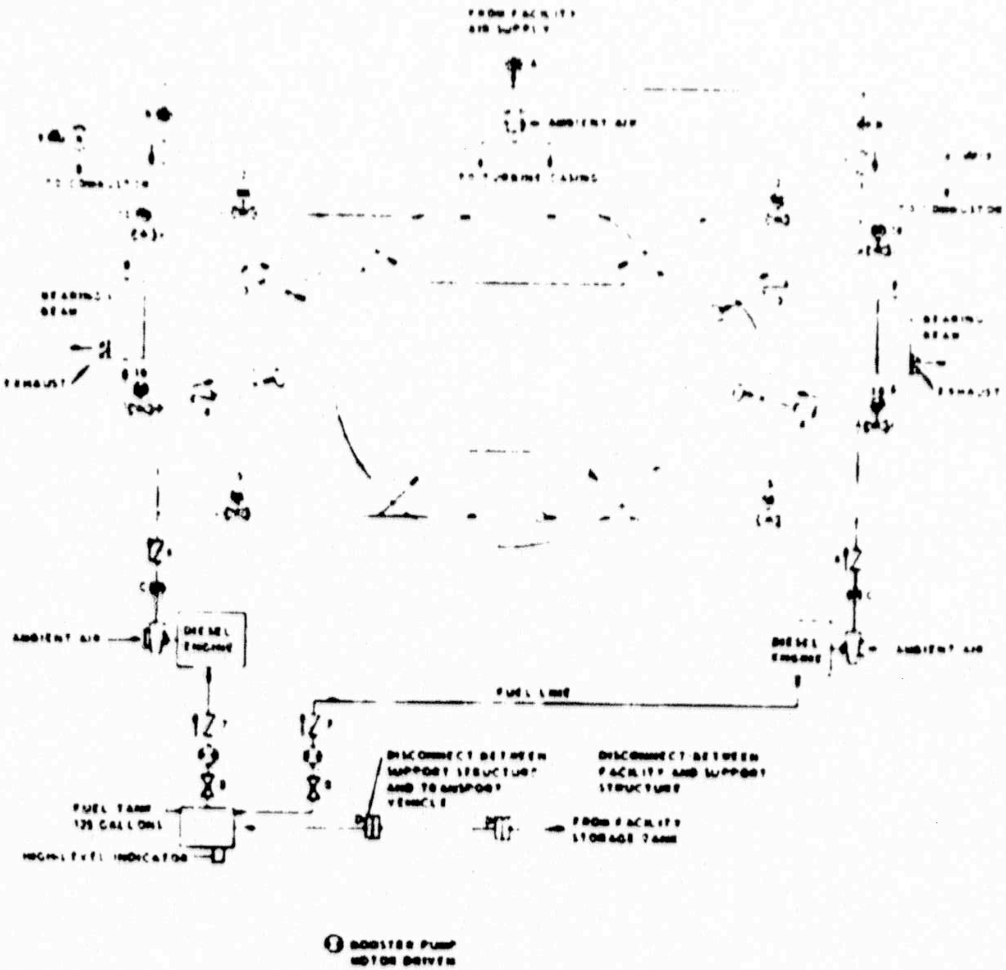

OPERATING CONDITION		POWER PLANT OPERATION	INITIAL AFTERCOOLING	INTRANSIT AFTERCOOLING
VALVES	1	OPEN	OPEN	CLOSED
	2	OPEN	OPEN	OPEN
	3	CLOSED	OPEN	OPEN
	4	CLOSED	OPEN	OPEN
	5	OPEN	OPEN	OPEN
	6	CLOSED	CLOSED	OPEN
	7	CLOSED	CLOSED	OPEN
	8	CLOSED	CLOSED	OPEN
	9	OPEN	CLOSED	CLOSED
	10	OPEN	OPEN	OPEN
COUPLINGS				
	A	CONNECTED	CONNECTED	
	B	CONNECTED	CONNECTED	DISCONNECTED
	C	DISCONNECTED	DISCONNECTED	CONNECTED
	D	DISCONNECTED	DISCONNECTED	CONNECTED

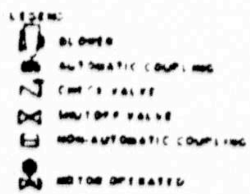

Fig. 7.10 – Intransit cooling system (Dwg. 568D858)

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7.2.7 PNEUMATIC SYSTEM

The pneumatic system was designed to supply and regulate the flow of compressed air to actuate air cylinders required in the installation and removal of the power plant, the power plant support structure, and associated equipment. During power plant operation, the system would supply air to cool the equipment and to operate the pneumatically operated power plant systems. The system is shown in Figure 7.11.

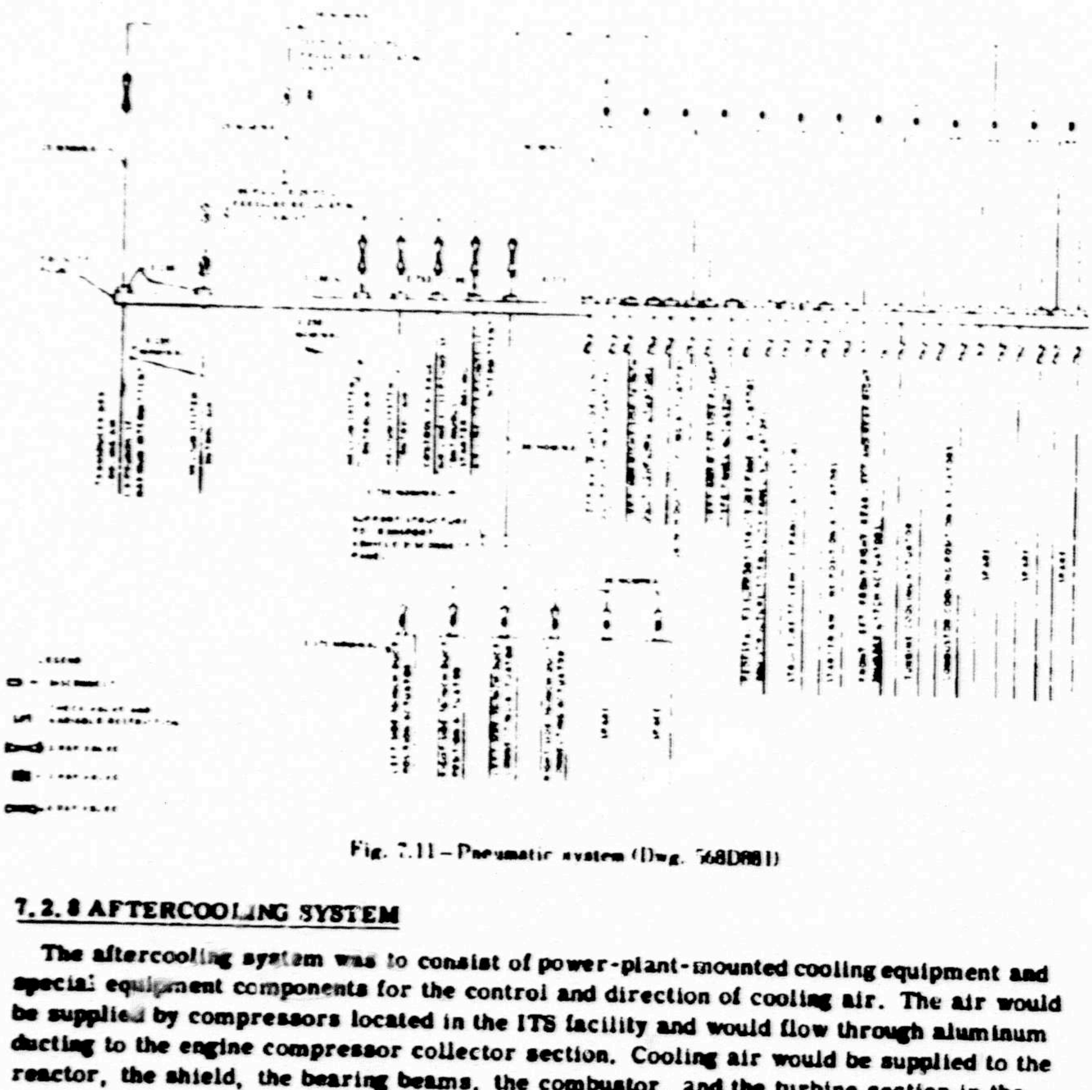

Fig. 7.11 – Pneumatic system (Dwg. 568D881)

7.2.8 AFTERCOOLING SYSTEM

The aftercooling system was to consist of power-plant-mounted cooling equipment and special equipment components for the control and direction of cooling air. The air would be supplied by compressors located in the ITS facility and would flow through aluminum ducting to the engine compressor collector section. Cooling air would be supplied to the reactor, the shield, the bearing beams, the combustor, and the turbine section in the quantities required during each phase of power plant operation. All components of the power-plant-mounted duct system were designed to be handled by remote handling equipment. Arrangement of the system is shown in Figure 7.12.

7.2.9 DISCONNECT PANEL

This disconnect panel was designed to contain sufficient fluid and electrical disconnects to carry those fluid and electrical services normally required between the aircraft and the

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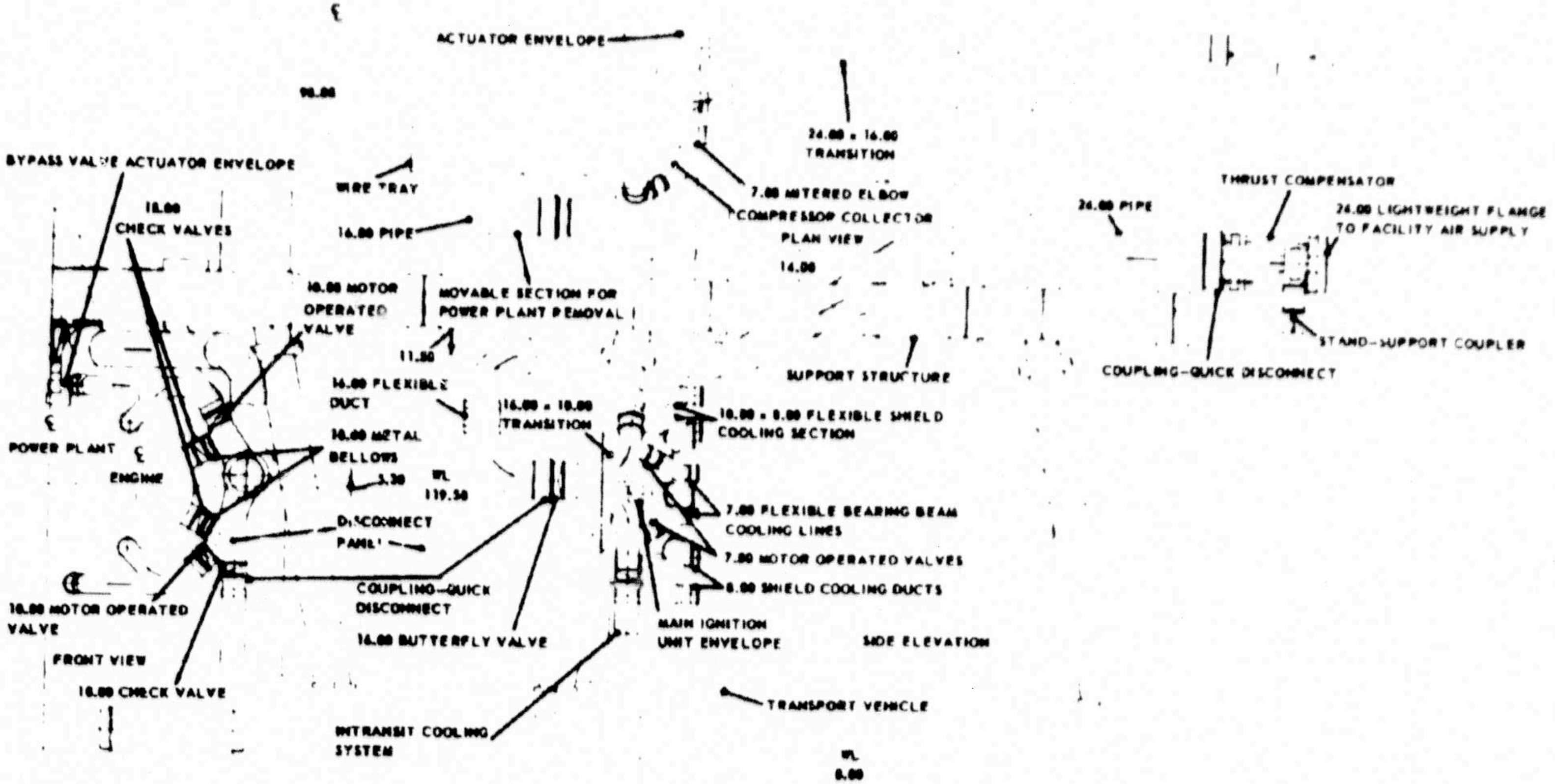

Fig. 7.12 – Aftercooling system – general arrangement

[redacted]

power plant. The panel halves were engineered to couple and uncouple automatically. Figure 7.13 shows the design layout of the panel. This design simulated the panel that would be used when the power plant was installed in an aircraft.

7.2.10 TRANSPORT VEHICLE HYDROSTATIC BEARING HYDRAULIC SYSTEM

A self-contained hydraulic system would be required on the transport vehicle to supply high pressure oil to the hydrostatic bearings during power plant installation and removal. The system would be capable of supplying 1000-psig oil at a minimum flow rate of 11 gpm to each of three hydrostatic bearings. The oil delivered to the bearings would be free of foreign particles larger than 25 microns in size.

The system would consist of a 100-gallon oil reservoir, a 37-gpm, 1500-psi motor-driven supply pump, two 20-micron oil filters, a 1-gallon oil accumulator, three motor-driven scavenge pumps, an air-to-oil heat exchanger, plus valves and instrumentation. A 40-horsepower double-end motor would be used to drive the supply pump and one scavenge pump, and a 5-horsepower double-end motor would be used to drive two scavenge pumps. The hydraulic system is shown in Figure 7.14.

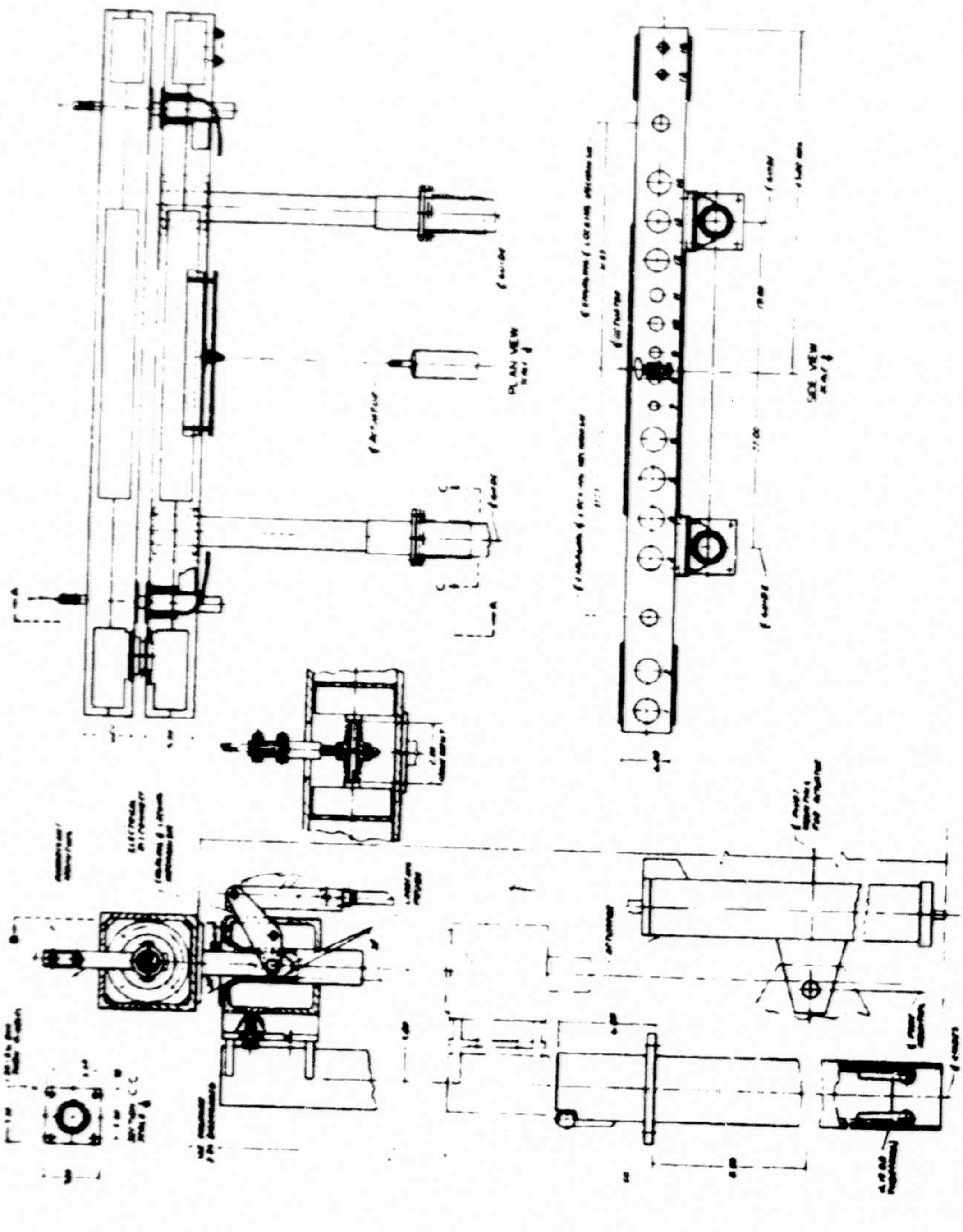

Fig. 7.13 – Disconnect panel structure to power plant (Dwg. 629E235)

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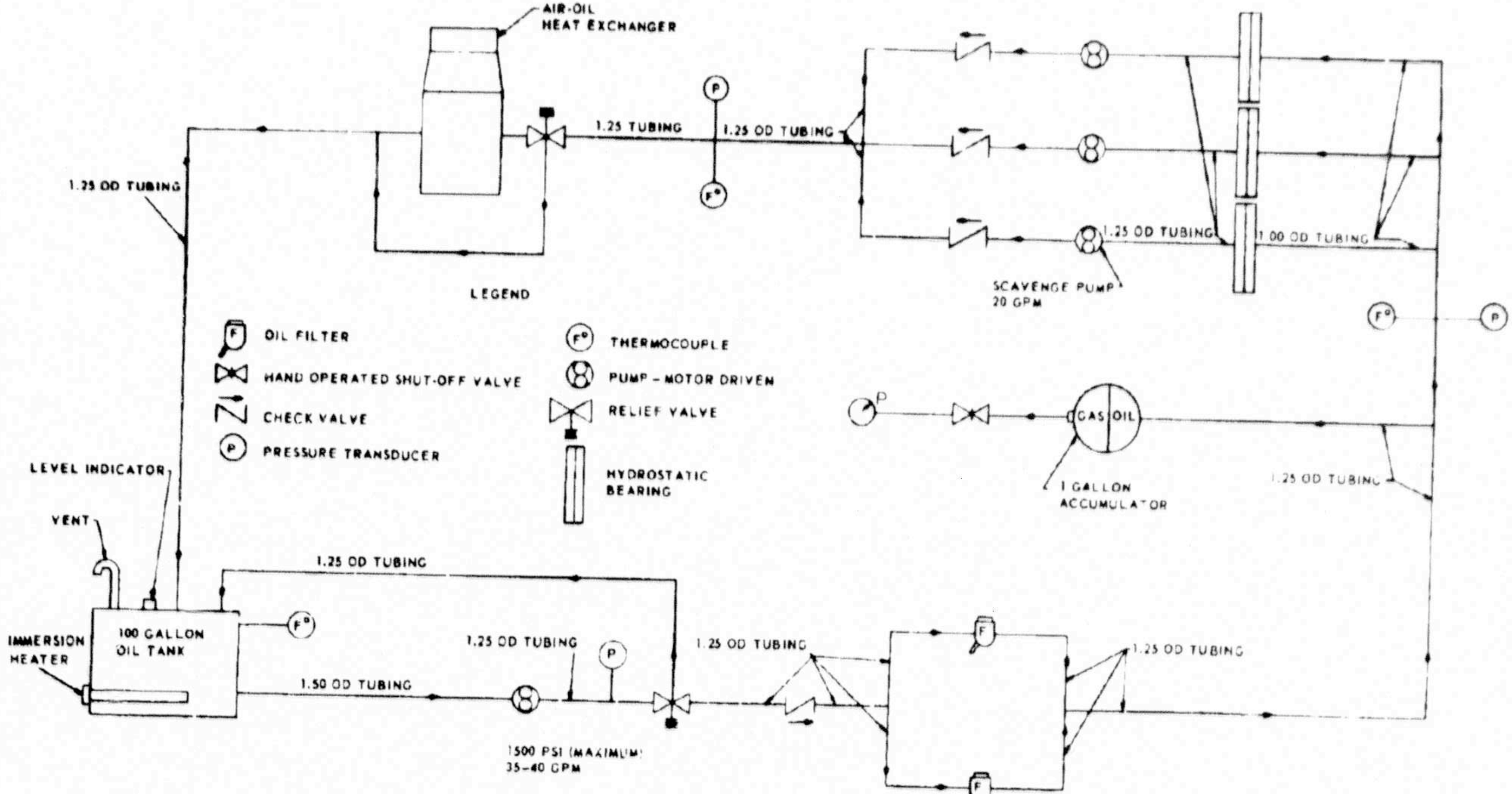

Fig. 7.14 – Transport vehicle hydrostatic bearing hydraulic system (Dwg. 568D859)

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8. REMOTE HANDLING EQUIPMENT

Plans for maintenance of the XMA-1A prototype power plant paralleled the philosophy used in the design of the power plant; i. e., the XMA-1 remote handling equipment would serve as prototypes for the flight power plant remote handling equipment. The over-all disassembly and assembly procedure evolved for the flight power plant was used in prototype planning.

The Reactor Assembly Machine (RAM) was the principal handling device planned for the XMA-1A. The RAM design incorporated methods for mounting the power plant utilizing conventional mounting points; for alinging the handling equipment relative to the power plant, and for disassembling or assembling the power plant.

Test cell operation would necessitate on-the-spot minor maintenance to eliminate the need of moving the power plant to a handling area. Specifications were issued for a shielded personnel vehicle with manipulators, called the "Beetle" to perform these operations.

This section of the report includes a description of the objectives and requirements of power plant maintenance, a discussion of the considerations leading to the RAM device, a description of RAM, the proposed disassembly and assembly procedures, and test cell maintenance requirements.

8.1 OBJECTIVES AND REQUIREMENTS

Analysis of the XMA-1A requirements indicated that the radiation level emanating from the power plant after a few hours of operation would necessitate remote maintenance of the assembled power plant. If, however, the reactor-shield assembly were removed from the power plant, limited manual maintenance could be performed on the remaining components.

All of the power plant components requiring cell maintenance were designed for handling by standard general purpose type manipulators. Other components were designed to be removable from the power plant for manual maintenance in a separate area. A shielded vehicle which could enter the operating test cell a short time after operation to perform repairs would eliminate the necessity of returning the power plant to the hot shop for minor maintenance. Specifications were written for a mobile shielded cab with manipulators. This vehicle is discussed in detail in APEX-911. Figures 8.1 and 8.2 show a model of the shielded cab, called the "Beetle," performing maintenance operations on a model of the power plant.

The assembly, handling, and maintenance objectives and requirements as stated in reference 2 are summarized here for the convenience of the reader:

"The power plant will be designed so that major assemblies of the power plant can be remotely carried from component buildup stations to the power plant assembly stations, remotely positioned and remotely assembled into a complete power plant assembly and conversely can be disassembled remotely.

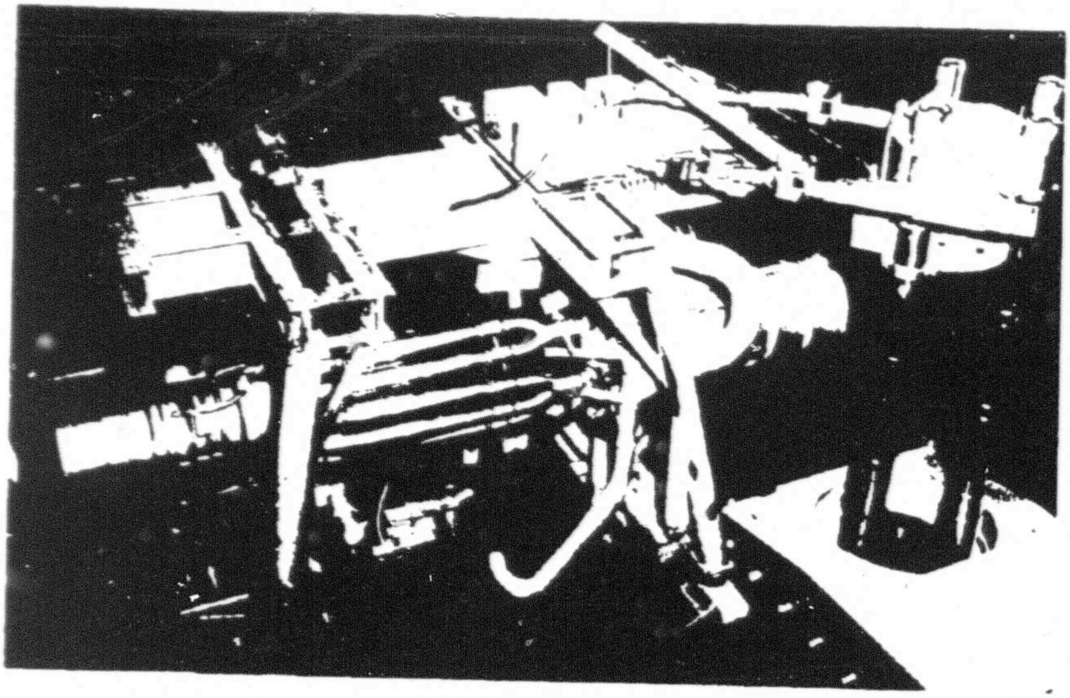

Fig. 8.1 – Beetle handling auxiliary equipment (C22077)

Fig. 8.2 – Beetle handling combustion system components (C22074)

"The reactor-shield plug assembly components will be capable of remote assembly and disassembly and will be designed to admit aftercooling air to the reactor core. Provision will be made to insert poison rods when the control rods are removed.

"The reactor side shield and rear shield plug assembly, all piping, wiring, external power plant appurtenances, instrumentations, and controls will be capable of remote installation and removal from the power plant. Major assemblies, other than the reactor shield assembly, will be handled with conventional manual maintenance and service procedures as established by the Air Force, component manufactures and ANPD after induced activity has decayed to a level consistent with established standards."

8.2 HANDLING PROCEDURE

8.2.1 DISASSEMBLY PROCEDURE

Listed below is the outline for the disassembly procedure for the XMA-1A power plant. For a more detailed description see reference 1.

1. Preparation for and the transfer of the power plant from the FET to the hot shop.
2. Place the power plant in the roll-over machine, (RAM).
3. Removal of Bellmouths.
4. Removal of the starter from the left hand turbojet.
5. Removal of the combustors or parallel burners.
6. Remove side shield fluid lines.
7. Remove electrical lines.
8. Remove bleed air lines.
9. Close roll-over rings.
10. Remove shaft coupling bolts - compressor end.
11. Remove shaft tunnel bolts.
12. Support coupling shaft.
13. Remove air cylinder operators from front plug valve.
14. Remove accessory tray and gearboxes.
15. Remove "X" brace from compressors.
16. Remove control rod actuators.
17. Remove lines across compressor collector flange.
18. Remove compressor.
19. Remove forward collector, front plug valve, core instrumentation flange and any portion of the control rods or actuators still attached.
20. Erect forward assembly.
21. Separate the collector and control rod actuators from the control grate rods, control rod grates, control rods, front plug valve, front plug and core.
22. Remove control rods and grate.
23. Remove forward shutoff valve.
24. Remove heat sensors.
25. Remove turbines and tail pipes.
26. Remove rear collector and rear plug.
27. Erect rear assembly collector and plug.
28. Place the power plant rear section on the hot shop turntable and separate the rear plug from the aft collector.
29. Remove nuclear sensors.
30. Remove bearing beam and coupling shaft.

8.2.2 ASSEMBLY PROCEDURE

Listed below is the assembly outline of the XMA-1A power plant. For a more detailed description see reference 2.

1. Install side shield.
2. Install bearing beam and coupling shaft.
3. Install nuclear sensors.
4. Assemble rear plug and aft collector.
5. Install rear plug and aft collector.
6. Install turbines and tailpipes.
7. Install heat sensors.
8. Assemble core, front plug, front plug valve, control rods, grates, actuators, and collector.
9. Install forward assembly.
10. Install compressors.
11. Install compressor "X" brace.
12. Install accessory trays and gearboxes.
13. Install coupling shaft bolts.
14. Install electrical lines and bleed air lines.
15. Install side shield fluid lines.
16. Install parallel burners.
17. Install starters.
18. Install bellmouths.

8.2.3 FET MAINTENANCE REQUIREMENTS

Provisions were made for performing necessary manual repairs at the Flight Engine Test facility (FET). The following list describes the type of service envisioned for the FET facility.

Component	Location	Service Provision Required
1. Bellmouth	Compressor front frame	Remove and replace (1) bellmouth (2) bellmouth screen (3) instrumentation.
2. Starter	Inlet gearbox	Connect and disconnect all service lines to starter.
3. Dynamic actuators	Actuator support frame	Connect and disconnect all service instrumentation lines to actuators. Remove and replace actuators.
4. Shim actuators	Actuator support frame	Connect and disconnect all service and instrumentation lines to actuators, remove, and replace actuators.
5. T_2 Sensors	Compressor front frame	Remove and replace (1) sensors (2) pneumatic lines to sensors.
6. Compressor tie bars	Compressor front frame	Remove and replace.
7. Function generator	Compressor front frame	Connect and disconnect pneumatic and sensing lines to the function generator. Remove and replace function generator.
8. Service lines to gear cases and accessory tray	Compressor section	Connect and disconnect those service lines connecting the gear case mounted controls and accessories with the rest of the power plant.

Component	Location	Service Provision Required
9. Accessory tray and gear cases	Compressor section	Remove and replace.
10. Main fuel filter	Accessory tray	Remove and replace filter.
11. Hydraulic oil filter	Accessory tray	Remove and replace filter element.
12. Air filter	Compressor collector	Remove and replace filter.
13. Main ignition unit	Compressor collector	Remove and replace (1) ignition unit (2) electrical harnesses and (3) spark plugs.
14. Temperature sensor package	Turbine collector	Remove and replace sensor packages, connect and disconnect electrical connectors, remove and replace sensor package electrical harness.
15. Nuclear sensor package	Side shield	Remove and replace sensor package, connect and disconnect electrical connectors, remove and replace snesor harness.
16. Control and instrumentation junction boxes	Side shield	Remove and replace junction boxes, connect and disconnect electrical connectors.
17. Reactor inlet valve actuators	Compressor collector	Remove and replace actuators, connect and disconnect service lines.
18. Exit guide vane actuator	Compressor rear frame	Remove and replace actuator, connect and disconnect service lines.
19. Variable stator actuator	Compressor stator casing	Remove and replace actuators, connect and disconnect service lines.
20. Nozzle actuators	Nozzle	Remove and replace actuators, connect and disconnect service lines.
21. A9 Computer feed back and error detector	Turbine rear frame	Remove and replace error detector, connect and disconnect service lines.
22. $T_{5.1}$ Sensor	Turbine rear frame	Remove and replace sensors, connect and disconnect service lines.
23. Instrumentation harness	Aft of the side shield	Connect and disconnect electrical connectors, remove and replace instrumentation harness.
24. Combustion intake air valve	Chemical combustion system	Remove and replace actuators, disconnect and connect service lines.
25. Combustion air intake manifold	Chemical combustion system	Remove and replace.
26. Expansion duct	Chemical combustion system	Remove and replace
27. Combustion casing	Chemical combustion system	Remove and replace combustion casing, connect and disconnect fuel manifolds
28. Turbine tie bars	Turbine rear frame	Remove and replace.
29. Combustion duct dampers	Chemical combustion system	Remove and replace.
30. Hydraulic constant speed drive	Aft gear case	Remove and replace.

[redacted]

Component	Location	Service Provision Required
31. Speed sensing switch	Aft gear case	Remove and replace.
32. Tachometer generator	Aft gear case	Remove and replace.
33. Motor operated shut-off valves	Support structure	Operate manual over-ride lever on valve.
34. Hydraulic package	Support structure	Remove and replace package, connect and disconnect service lines to package.
35. Lube package	Support structure	Remove and replace package, connect and disconnect service lines to packages.
36. Fuel supply line shutoff valve	Support structure	Remove, replace, and adjust valve.
37. Fuel return line shut-off valve	Support structure	Remove, replace, and adjust valve.
38. Lube system drain	Support structure	Remove and replace valves.
39. Front trunnion latch	Support structure	Operate latch emergency release, inspect to see if latch actuation has occurred.
40. Center pin latch	Support structure	Operate latch emergency release, inspect to see if latch actuation has occurred.
41. Vibration snubber latches	Support structure	Operate latch emergency release, inspect to see if latch actuation has occurred.
42. Aftercooling couplings	Aftercooling systems	Nature of service other than observation not determined.
43. Control system adjustment	Control system	Exact nature of control system adjustments are undefined.
44. Instrumentation items	Dummy bearing beam	Remove and install nuclear instrumentation hardware in dummy bearing beam as required.

8.3 MAJOR POWER PLANT MAINTENANCE

In planning for remote handling equipment, two possible power plant disassembly and assembly methods were considered. One method would perform the operations with the power plant in a vertical position, and the other method would perform the operations with the power plant in a horizontal position.

Although the vertical method offered the advantages of minimizing flange engagement problems, and positioning the power plant with available equipment, this method was not practical within the limitations of the existing hot shop. The total stacked power plant height in the handling fixture was to be beyond the height at which the cranes could operate. With the horizontal method, equipment could be provided for all operations.

8.3.1 RAM

Selection of the vertical maintenance method indicated the need for a handling fixture to provide precise alignment of components during major assembly or disassembly operations. A subcontract was negotiated with the Willamette Iron and Steel Co. for further design of the Remote Assembly Machine (RAM). Design details of the RAM are presented in reference 3.

[redacted]

The proposed remote assembly machine is shown in Figure 8.3. This design utilized a remote assembly car with precision ways on one end only. On the opposing end was a turntable on which were mounted the roll-over device which surrounded the entire power plant. The power plant was placed in the RAM and locked into place; the top half of the roll-over device was then placed on the RAM. The power plant was then rolled over or rotated on the turntable in position for inspection or maintenance. The desired gimballed assembly horseshoe fixture with handling frame was placed on the assembly carriage mounted on the precision ways, to maintain the compressor or turbine end of the power plant.

The basic RAM could be accurately leveled in the hot shop by use of a telescope and collimator mounted in the frame of the RAM. The operator would energize the required jacks to properly line up the targets on the frame.

8.3.2 POWER PLANT MOCKUPS

Two full scale mockups of the XMA-1A were designed for use in the remote handling planning. One was known as a "quadrant" mockup and represented half of the power plant from triple flange to triple flange and included the combustion system. The other was a full scale mockup, 83 percent weight simulated, which was designed and built to test and check out the RAM. The quadrant mockup had been used several times at Idaho Test Station

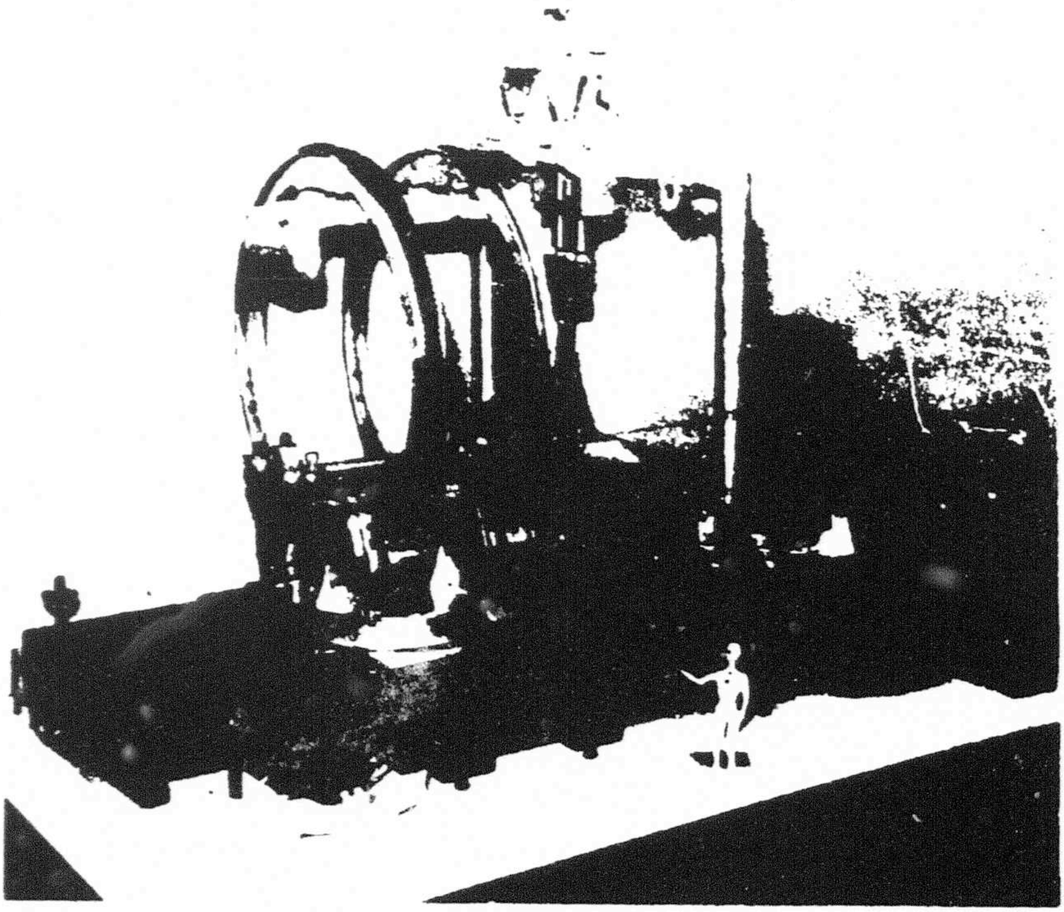

Fig. 8.3 – Remote assembly and maintenance machine (RAM) (Neg. U37404B)

to work out problems involved in handling the combustion system. A report of this work is presented in reference 4.

Only the turbojet parts of weight-simulated mockup were completed. Remote handling simulation was not built into the main drive shaft nor into splined connections through which auxiliary equipment is driven. A number of other features were lacking, such as piping and wiring, captive nuts and bolts, accessory tray and additional stage compressor kit.

8.4 FET REMOTE HANDLING SUPPORT EQUIPMENT

During the initial XMA-1A power plant operations planned for the FET, power plant operation would have been at a low power level and most of the maintenance requirements could have been performed manually. At about the point of 100 megawatt hours operation, however, the possibility of manual maintenance would have been questionable. Certainly in the high power, long term test phase, almost all maintenance would have been by remote handling methods. The Beetle was designed for this purpose. This shielded cab vehicle is fully described in APEX-911.

8.5 REFERENCES

1. "Disassembly Procedure for XMA-1A Power Plant," GE-ANPD, DC 61-8-8, August 1961.
2. "Assembly Procedure for XMA-1A," GE-ANPD, DC 61-8-7, August 1961.
3. "Remote Assembly Machine," Willamette Iron and Steel Co., WISCO No. 0111, July 1959.
4. Wheeler, G. L., "Remote Handling Checkout XMA-1 Collector Heat-Exchanger Mock-up," GE-ANPD, XDCL 59-10-741, October 1959.