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STUDY OF SEAPLANE SYSTEMS EMPLOYING NUCLEAR POWER

Quarterly Progress Report for Period 1 April 1959 to 30 June 1959

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Contracts NOa(s)–56–891–c and NOa(s)–59–6210–c

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STUDY OF SEAPLANE SYSTEMS EMPLOYING NUCLEAR POWER

for Period 1 April 1959 to 30 June 1959

Quarterly Progress Report

MND–ANP 1988

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FOREWORD

This first quarterly progress report covers the period 1 April 1959 through 30 June 1959. Presented are the results of a study conducted by The Martin Company under United States Navy Bureau of Aeronautics Contracts NOa(s) 56-891-c (extended), and NOa(s) 59-6210-c.

Part I reports the technical progress for this quarter which includes the completion of the preliminary system designs for a Nuclear Powered Logistic Transport Seaplane. Included also are results of the first in a series of configuration studies for the Nuclear Powered ASW Seaplane.

Part II presents the completion of a study, previously initiated, on the design of an Engineered Unit Shield for the direct air cycle reactor system.

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Summary

Nuclear Powered Aircraft System Studies

System Design Philosophy

Study objectives--Nuclear powered aircraft studies underway at The Martin Company are directed primarily towards evolving the design of a Navy ASW seaplane system for first generation operational use employing the P&W Aircraft indirect cycle propulsion system.

Design approach--The development cycle currently envisioned for nuclear powered ASW systems includes a flight test aircraft for propulsion development, an operational prototype to evolve utilization procedures, and a first generation operational seaplane followed by subsequent operational aircraft of improved capability. This study program will focus on the operational prototype and first generation operational ASW seaplane system considered initially as the same basic design. Extensive studies have been completed which established the feasibility of the "SARO" Princess nuclear powered flight test aircraft.

Progress This Quarter

ASW system studies--The initial ASW configuration studied was an all-nuclear heat seaplane deliberately selected to furnish a reference system against which subsequent nuclear-chemical powered ASW systems can be compared. This configuration employs four T-57 turboprops, a single lithium-cooled unit shielded LMC reactor, and carries no chemical fuel except that necessary for auxiliary power unit operation. Gross weight is 392,000 lb with approximately 27,000 lb of weapons on board. Cruise speed at 10,000 ft is 250 kn. Addition of chemical emergency power to this basic configuration is necessary to bring this system within the first generation time frame.

Logistic transport system studies--Study of a turbofan nuclear powered logistics transport seaplane system was undertaken and completed during this quarter in order to determine the potential of the turbofan LMC propulsion system. The resulting configuration carries a 100,000 lb payload cruising above Mach 0.8 at a gross weight of 658,000 lb. Eight turbofan nuclear heat engines are required and chemical fuel is used in afterburners for takeoff.

Results of this preliminary design study show the feasibility of a high performance nuclear cruise logistics seaplane system with unlimited range capability independent of refueling bases. Evaluation of chemical fuel requirements for emergency cruise will be necessary if this system is considered for first generation operations.

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DAC unit shield design--The preliminary design and analysis of an engineered unit shield for a DAC nuclear powerplant was completed. The shield study, based on an advanced air cycle reactor, included the conceptual design of the shield system, selection of shielding and structural materials, and the analysis and preliminary optimization of of the shield materials array. The resulting RSA was incorporated into a realistic flight vehicle, a 600,000 lb gross weight logistic transport, to determine the influence of the aircraft on the shield design.

Dose rate.- The design dose rate for flight crew personnel was set at 20 mrem/hr; the computed dose rate was 16.25 mrem/hr, not including the small contributions from air capture gammas, structural sacttering, and gammas from inelastic fast neutron scattering in the air and shield. Dose rates were determined for a reactor power of 110 MW and a cruise altitude of 25,000 ft. The computed RSA weight was 201,310 lb, in good agreement with previous parametric studies.

Capture gammas.- Thermal neutron capture gammas proved to be an important contributor to crew dose rates; in particular, capture gammas from the forward lithium hydride neutron shield accounted for 50% of the direct dose rate at the crew position. At greater source angles interactions in the outer Inconel X pressure shell and in the beryllium side shield proved dominant. The importance of these thermal neutron interactions indicated that an investigation of additional secondary sources due to fast neutron interactions is warranted. Secondary sources in aircraft structure and internal shield structure, and radiation streaming through shield structural regions, were not evaluated, but are worthy of consideration in a more comprehensive shield analysis.

Conclusions.- The major conclusion drawn, from the structural installation of the RSA into the aircraft, was that close integration of the shield design with the vehicle design was necessary. For the selected configuration the thermal design criteria for the RSA and for the center wing box structure were significantly influenced, due to use of a crown-mounting concept for the nuclear power plant. The necessity of providing for RSA removal from the aircraft for maintenance, etc., purposes did not impose any strong restraints on vehicle design for this application as it might for an internally installed assembly; the design of the shield itself was affected, in that a portion of the neutron shield must remain in the aircraft during such operations.

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Future Study Plans

ASW systems--A series of preliminary ASW seaplane configurations having nuclear cruise capability with chemical assist will be evaluated in order to achieve an optimum minimum gross weight system. These preliminary ASW nuclear powered seaplane configurations will be compared to establish capabilities and define mission potential. The optimum system for a first generation operational seaplane is envisioned as one of minimum size and cost which will permit nuclear performance markedly superior to chemical aircraft. Substantial emergency chemical performance is required in case of reactor breakdown, but dual rotating machinery is not necessary. The selected reactor design will probably be sized for normal cruise performance with chemical assist for takeoff and maneuver capability.

For the prototype operational ASW aircraft, nuclear performance may be lowered in the interest of reduced system weight, and continuous chemical augmentation will also be considered in an effort to further minimize reactor requirements for prototype operation.

Effort has accordingly been initiated on a two T-57 ASW seaplane having chemical assist with the objective of significantly reducing aircraft gross weight as compared to the completed four T-57 all nuclear heat reference design. Indications are that the basic two T-57 configuration should receive major emphasis during the next quarter. A study will be completed in order to determine the most efficient selection of chemical power plants for this design. The preliminary evaluation of an ASW seaplane design powered by two T-57 turboprops and one gas generator J-57 unit driving two bleed turbine-propellor combinations looks promising enough to warrant more detailed study in the next quarter.

LMC unit shield design--The design of an engineered liquid metal cycle unit shield for the lithium cooled reactor will be undertaken beginning this quarter. The engineered unit shield design will be completed by the end of the contractual period and will include considerably more detailed analysis of the airframe-shield integration problem then previously undertaken.

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PART I

NUCLEAR POWERED SEAPLANE STUDY

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I. INTRODUCTION

The Martin Company is presently engaged in system studies primarily oriented towards evolving a minimum gross weight, first-generation nuclear powered ASW operational seaplane utilizing the Pratt and Whitney LMC propulsion system.

The four engine (T-57) ASW seaplane presented in this report represents the initial design in a series of configurations to be evaluated. This four engine ASW design will be used as a reference system to gauge the relative merit of the succeeding chemical-nuclear combination designs. An extension of our plans includes further refinement of the four T-57 all nuclear heat ASW seaplane which will be evaluated with addition of chemical power to bring the basic design into the first generation nuclear aircraft time frame. Work is currently underway on a two-engine (T-57) chemically assisted ASW seaplane system.

Evaluation of the turbofan indirect cycle system, to determine the characteristics of a high performance logistic transport seaplane system, has been completed.

The design of a unit shield for the direct air cycle airborne reactor, previously initiated, was completed during this quarter. Results of this design analysis are included in Part II of this report. No further work is planned for DAC shielding at this time.

Design of an engineered unit shield for the LMC lithium-cooled reactor was initiated and will continue throughout the remainder of the contractual period. This effort can be expected to result in a more detailed shield design and integrated airframe installation than was performed for the DAC unit shield.

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II. NUCLEAR POWERED ASW SYSTEM STUDIES

A. ASW SEAPLANE STUDY PROGRAM

1. General

A series of nuclear-powered ASW systems will be investigated to determine the best application of the low powered, long endurance, turboprop, unit shield, liquid metal propulsion system to the Navy ASW mission. Primary emphasis will be placed on system optimization making use of the above propulsion system components whose development is anticipated. Initially, a series of first generation operational ASW design will be carried through the preliminary configuration stage. The most promising system will then receive further refinement both in the airframe and ASW systems area. This ASW system will also be considered for use as a developmental prototype. Compromises to ASW capability and operational performance will be considered in the interest of achieving an early prototype ASW nuclear-powered aircraft. This prototype of minimal operational capability will retain growth potential which will permit development to first generation operational ASW seaplane.

Specific major design objectives for the proposed ASW system studies are:

(1) To achieve a significant reduction in the cost and weight of a first generation ASW aircraft.

(2) To evolve from this design a developmental prototype nuclear-powered aircraft which can be utilized by the Navy to demonstrate the low powered, long endurance, turboprop, liquid metal cycle, unit shield propulsion system.

The Pratt and Whitney Aircraft gas generator bleed-turbine propulsion system will also be considered when data is available. Limited effort will also be devoted to consideration of more advanced and less conventional designs for Navy ASW and combined missions.

Current requirements for an ASW airplane--possessing long endurance but only moderate speed--fit the proposed nuclear turboprop airplane study program admirably. In particular, some combinations of T-57 turboprops, with the Pratt and Whitney liquid metal cycle reactor, appear attractive.

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Martin studies of the SARO "Princess" flying boat, modified as a nuclear propulsion test configuration, have indicated that two T-57 engines will provide moderate flight performance in an aircraft of the 300,000-lb plus weight class. From the same studies it is apparent that additional propulsive thrust is required for takeoff, and possibly for acceptable high speed capability.

It appears that four is the minimum number of T-57's which will provide acceptable performance for a nuclear ASW seaplane of conventional arrangement, without installing auxiliary chemical engines for takeoff. It also is likely that takeoff is feasible with only four T-57's on nuclear power provided that the reactor system can supply a satisfactory turbine inlet temperature. Accordingly, it was decided to study initially an ASW seaplane employing four T-57 turboprops, a lithium-cooled reactor, and an NaK secondary heat transfer system. The results of this study will show the size and capabilities of the aircraft, and also provide a yardstick for comparison of the capabilities of other ASW aircraft to be studied.

Future study efforts in the ASW area will be centered first on evolving a smaller aircraft using two nuclear T-57 turboprops with auxiliary chemical power for takeoff. Subsequently, other powerplant combinations in less conventional configurations will be investigated. Results of expected Pratt and Whitney studies of bleed turbine nuclear powerplants will be utilized in this work.

2. ASW Seaplane Analysis

The design objectives selected for the study of the four engine (T-57) nuclear powered ASW seaplane were as follows:

Mission duration:	70 to 100 hr total
Cruise speed:	250 to 300 kn at 10,000 ft or higher for cruise to operations area
Maneuver capacity:	1,500-ft radius turn at 1,500 ft altitude
Integrated dose:	1 rem at 50 ft from the reactor for a 100 hr mission
Design gross weight target:	400,000 lb
Electronic equipment:	6,500 lb
Stores (weapons, etc.)	27,020 lb

It must be emphasized that the configuration presented herein is in the course of development, and does not yet represent a completed conceptual design. Some of the objectives outlined have not been fully attained and the work being reported is not all at the same stage of development.

Aerodynamic effort was first centered on attaining the desired cruise speed. A configuration capable of meeting this objective, and having satisfactory takeoff and landing characteristics, has been evolved. The maneuver performance at low altitude, however, does not meet the 1500-ft radius turn requirement. To meet this turn requirement a considerable increase in wing area will be necessary. This configuration change is discussed in this chapter.

The weights section reflects the first configuration effort, with the high wing loading designed for cruise performance. After the effects of the maneuver performance requirements on wing size, tail size, power plant, and shielding are more fully evaluated, these weights will be revised.

Figure I-8 shows the initial higher wing loading aircraft with a dunking sonar. In future studies the dunking sonar may be eliminated since the use of sonar requires frequent open ocean landings and the feasibility of these landings is not established. It should be noted, however, that where faborable sea states exist, the aircraft is capable of making open ocean landings. This capability may be used in the recovery of sonobuoys. The extremely long endurance provided by the nuclear ASW seaplane enhances the probability of favorable landing conditions.

B. ASW CONFIGURATION--FOUR T-57 ENGINES

1. Airplane Performance

Design objectives were set forth for a nuclear powered ASW seaplane capable of 100 hr operations.

These objectives are as follows:

(1) V_{max}/altitude	300 to 350 kn at 10,000 ft
(2) V_{cruise}/altitude	200 to 250 kn at 10,000 ft
(3) V_{loiter}/altitude	150 to 200 kn at 1500 ft

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(4)	Turn radius at 1500 ft at 1.3 V_s	1500 ft ($n_z \leq 2.0$ g)
(5)	Takeoff speed	60 to 80 kn
(6)	Sea state capability	3

Typical mission profiles for the chemical fuel counterpart of this type of aircraft are envisioned as shown in Fig. I-1.

The initial design derived in this study is based on an attempt to attain high speed and cruise speed objective at minimum aircraft weight. This basic objective has been fulfilled with an aircraft powered by four T-57 engines, wing loading of 88 psf and wing aspect ratio of 7.0. This airplane has a wing area of 4450 sq ft, a full-span double slotted flap typical of that used in the Martin 404 airplane and a mid-position horizontal tail. The hull design is of the type previously developed by The Martin Company as the high length to beam ratio (Model 270) and modified for use on the P6M seaplanes. The airplane thus configured does not meet the basic turn performance required of current ASW aircraft as specified in the initial design objective.

An alternative configuration was derived upon inspection of current turn performance requirements shown in Figs. I-2 and I-3. These turn performance requirements indicate that use of a partially deflected high L/D lifting system is required with a wing loading range of approximately 40 to 65 psf. This configuration compromises the aircraft maximum speed as shown in Figs. I-4 and I-5. Rates of climb are shown in Figs. I-6 and I-7. Without recourse to a completely detailed analysis of power effects on low speed performance and flying qualities, the configuration would appear to satisfy the general design objectives previously set forth with a wing loading of 64 psf. A comparison of the estimated performance of the two configurations is shown below.

	Configuration	
	Initial	Alternate
Takeoff gross weight (lb)	392,000	417,000
Wing area (sq ft)	4,450	6,500
Wing loading (psf)	88	64
Flaps	Full-Span Double Slotted 0.25c	
Engines (4)	T-57	T-57

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	Configuration	
	Initial	Alternate
V_{to} (kn)	81	
V_{s_L} (kn)	98	84
V_h at 10,000 ft	338 (kn)	325 (kn)
Turn radius at 1,500 ft (ft)	* 2,800	**1,500

* Power and lift limited with 25° δ f
** δ f = 25°

The results of this portion of the study show that a reduction in aircraft size and thrust level may provide an aircraft with more attractive performance characteristics, especially at low speed. It should be noted, however, that the turning performance requirements are directly a function of thrust/weight ratio as well as airplane L/D at the required maneuvering speed. Choice of future engine or engine combinations and flap system configuration should therefore be directed toward conserving maximum lift available by designing such that high balance tail loads and drag are minimized during the maneuver.

2. Propulsion System

Four modified T-57 engines, a lithium-cooled columbium reactor, radiators, heat exchangers, pumps and the associated ducting and piping systems comprise the power plant.

Reactor shield assembly.- The nuclear power plant heat source is a lithium-cooled, intermediate neutron spectrum, columbium alloy reactor using pin-type fuel elements. The lithium coolant enters the reactor at 1350° F and exits at 1800° F. Maximum reactor power is 154.4 MW. The approximate core volumetric composition is as follows (Ref. 1):

Beryllium oxide	0.343
Uranium dioxide	0.185
Lithium	0.253
Columbium	0.212
Helium	0.007

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The reactor core, approximately 18 in. in dia, and BeO reflector are contained in a pressure vessel together with drives for the control drums located in the reflector. Overall pressure vessel height is approximately 57 in., diameter 34 in.

Although the reactor and coolant system are sized for operation at a power level of 154 MW (adequate for all-nuclear takeoff), operation will be at approximately 102 MW during cruise.

The reactor shield has a shaped-unit configuration, with maximum neutron and gamma shield thicknesses in the forward direction along the reactor-crew axis. Shield thicknesses decrease with increasing angular displacement from this axis. Primary shield materials are assumed to be depleted uranium and lithium hydride, with 5000 lb of APU fuel also located in the shield. Total dry shield weight, not including core, controls, or primary coolant systems, is 117,500 lb. If APU fuel is not used as a shielding material, dry shield weight increases to 120,000 lb. Weight estimates are based on data presented in Refs. 1, 2, and 3.

Radiation environment.- The requirement for a large crew for ASW operations necessitates maintaining acceptable dose rates throughout a significant area of the vehicle. Consequently, the minimum weight shield for this application is attained through use of a shaped or quasi-unit shield; a further advantage results from reduced after-shutdown dose rates relative to those obtained with a divided shield.

The design dose rate for the inhabited portions of the aircraft was set at 0.01 rem/hr, for reactor operation at cruise power, 102 MW, and a cruise altitude of 15,000 ft. The crew dose rate during takeoff will be greater than this figure due to operation of the reactor at higher power. Operation of the reactor while the aircraft is on the water, such as during takeoff and landing and during the limited manuevering associated with waterborne search activities, imposes a constraint on shield shaping due to scattering of radiation by water. The weight penalty attendant to this constraint has not been included in shielding weight estimates; a complete definition of the vehicle operational procedures is required before adequate criteria can be established to evaluate this dose component.

An estimate was made of after-shutdown radiation levels around the reactor shield assembly. The point of maximum dose rate lies to the rear of the shield on the reactor-crew axis; at 50 ft to the rear of the shield, the gamma ray dose rate is estimated at 0.2 rem/hr 3 hr after reactor shutdown from long term operation at cruise power. Due to the use of a lithium isotope which does not become activated, the contribution to after-shutdown dose rates from radioactive decay of the coolant in the primary liquid metal loop is not important as it is for Na-NaK LMC power plants.

Engines.- Four T-57 engines provide the propulsive forces. They are mounted above the wing as shown in Fig. I-8. Installation in this manner avoids problems of carrying air from and to the outboard engines past the inboard engines and tailpipes. Ease of engine maintenance is obtained as well as adequate propeller-water clearance. Engines mounted in line with the wing which will maintain this same clearance, require a gull or pylon-mounted wing, and result in a heavier structural weight.

A description of the engine and some details of the required modifications can be found in Ref. 4. For the purposes of this investigation, no provisions are made in this design for chemical operation of the engine, it being assumed that the reactor is fully reliable and that sufficient backup measures are provided so that failure of any other single component will cause loss of but one engine. Safe flight can be maintained on three engines.

Liquid metal systems.- Lithium enters the heat exchangers at 1800° F and exits at 1350° F. Secondary system NaK will enter at 1150° F and leave at 1650° F. The heat exchangers (one for each engine) are of tube and shell design, lithium flowing in the zee shaped tubes. Four heat exchangers are used, two located forward of the reactor shield assembly to service the inboard engines, and two aft of the reactor shield assembly to service the outboard engines. The two lithium pumps located aft of the reactor shield assembly in the cold leg of the lithium loop are sized so that in the event of failure of one the other can supply partial power to all four engines. This partial power would be the equivalent of 3/4 normal rated power per engine. In normal operation, one pump would carry the load of two engines. Columbium alloy is used throughout the lithium loop.

A radiator and NaK pump are provided for each engine. Two each are placed forward of the reactor shield assembly and two each aft. Air is carried via ducting from and to the engines. To keep the wing structural box clean, and because of space limitations forward of the front spar, it was found necessary to run ducting for one engine forward of the structural box, and ducting for the other engine aft of the structural box, as shown in Fig. I-9. This in turn dictated the arrangement of heat exchangers, radiators, and pumps described above and shown schematically in Fig. I-10.

NaK enters the radiators at 1650° F and returns to the heat exchangers at 1150° F. A radiator by-pass line maintains the return temperature at or above 1150° F during operation. Stainless steel, type 316, is used throughout the NaK circuit. The pump is located in the cold leg of the loop.

Engine thrust determination. - Data presented in Ref. 1 was used. Specifically, the estimated performance of an advanced turboprop engine operating on chemical fuel served as the base from which nuclear performance was derived. For this study, it was desired that the airplane take off on nuclear heat only. Performance estimates for the advanced turboprop reflect a 15-1/2% total pressure loss between the compressor and turbine. This loss was retained even though the chemical burner has been eliminated from the system. In addition, the following assumed and calculated losses were accounted for in determination of thrust per engine: inlet recoveries of Fig. I-11, a tailpipe loss of 2%, 100 shp extracted for auxiliary drives and electrical power generation, and the bleeding of air required to drive the liquid metal pumps. Liquid metal pump horsepower required was calculated for friction pressure losses of a system in which the radiators would be wing mounted. It is felt the performance derived is slightly conservative because the liquid metal pumping requirements of this system are greater than would be realized with radiators located in the fuselage.

In determination of bleed air requirements to drive the liquid metal pumps, a turbine expansion ratio of 6:1 was assumed, with a turbine efficiency of 85% and a pump efficiency of 57%.

Each engine drives a four-bladed propeller 20 ft in diameter. Propeller efficiencies at cruise velocities were determined from Ref. 5. For takeoff, pounds of thrust/shaft horsepower were evaluated from Ref. 6.

A description of the propeller is as follows:

Diameter	20 ft
Number of blades	4
Activity factor	150
Integrated lift coefficient	0.400

Standard day engine thrust at normal rated power as a function of altitude and velocity is presented in Fig. I-12. Reactor power per engine as a function of altitude and velocity at normal rated power on a standard day is shown in Fig. I-13.

Auxiliary power plant.- An auxiliary power plant similar to the Air Research Manufacturing Company's GCTP 85-20 will provide air for engine start, emergency electrical service and prolonged aftercooling. A fuel supply of 5000 lb is provided. This includes fuel for 24 hr of aftercooling.

3. Weights

The (4)-T-57 ASW configuration has a gross weight of 392,000 lb. It is designed to carry weapons and crew provisions for a 70 to 100-hr flight. The airframe weight was estimated from statistical plots of past aircraft, and the power plant weight primarily from Pratt and Whitney estimates which were modified for this configuration. Electronics for search and localizing of enemy submarines, and communication and navigation have not been selected. For all this equipment, 6500 lb has been allocated; this is in excess of the amount carried on present and proposed ASW aircraft.

The weapons selected for a 70-hr mission total 27,020 lb and are broken down in the following table.

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TABLE 1

Type and Amount	Weight (lb)
MK44 Torpedoes (10)	4,250
MK101 Lulus (4)	4,800
AN/SSQ-23 Sonobuoys (375)	6,320
AN/SSQ-15 Sonobuoys (84)	6,048
MK5 Parachute Flares (10)	80
MK15 Practice Depth Charges (500)	2,250
(X) 13A Marine Markers (90)	2,160
MK7 Marine Markers (240)	960
BT Buoys (10)	90
Signal Pistol (2)	12
	27,020

This selection was used to determine a weight allowance for weapons corresponding to 70 to 100-hr mission. From this list it can be seen that the number of sonobuoys, practice depth charges, and marine markers normally used for searching, is very high.

In this configuration, the sole source of energy is the nuclear reactor. Should the reactor become inoperative and an emergency landing is necessary, 3600 lb of fuel is provided to operate the auxiliary power plant (APP) for 24 hr to remove reactor afterheat. For normal operation of the APP, 1400 lb of fuel is provided.

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TABLE 2

Group Weight Statement

	(lb)	(lb)
Wing		38,980
Vertical tail		3,270
Horizontal tail		5,260
Hull		53,760
Floats		4,750
Surface controls		3,700
Nacelles		5,760
Propulsion		208,030
Engines	26,400	
Propellers	14,000	
Controls	340	
Lubrication system	2,010	
Exhaust system	710	
Starting system	400	
Fuel system	200	
Reactor and primary loop	13,820	
NaK loop	6,480	
Reactor shield	117,500	
Purge gas system	500	
After-heat removal	600	
Shield cooling	500	
Reactor controls	1,500	
Radiators	9,320	
Air ducts	13,750	
Auxiliary power plant		600
Instruments		400
Power systems		8,000
Electronics		6,500
Armament		3,000
Furnishings and equipment		3,820
Air conditioning		400
Anti-icing		2,070
Auxiliary gear		1,800
Weight empty		350,100
Useful load		41,900
Crew (22)	4,400	
Oil	1,870	
Food	540	
Water	1,520	

TABLE 2 (continued)

Fuel	5,000	
Weapons	27,020	
Weapon carriers	1,050	
Miscellaneous	500	
Gross weight		392,000

4. Mission Capabilities

The mission considered for the four T-57 ASW seaplane was a simple extension of a conventional ASW aircraft mission with the addition of dunk sonar for use when sea conditions permit landing. Flight duration would be from 24 to 70 hr depending upon the rate at which sonobuoys had to be expended. The shortest duration would result from an intense Julie search. Longer flights would be possible in a Jezebel search or when acting as coordinator for shorter endurance ASW aircraft. In a smooth sea the dunk Sonar would be used to improve detection range, reducing the expenditure rate of droppable stores.

Crew.- Crew stations are adapted from current ASW aircraft with the personnel adjusted in number for long duration missions as follows:

Station	Number
Pilot	2
Copilot	2
Navigator	2
Radio operator	2
Flight engineer	2
Tactical coordinator	3
Sonobuoy--Jezebel	3
Julie--ACM	3
Radar--MAD	3
Dunk sonar	0
Total	22

Equipment.- The electronics equipment to be carried would be similar to that used in the P3V and P5M aircraft with the addition of dunk sonar. It should be noted that sufficient weight allowance has been made to add or duplicate equipment.

Stores.- Droppable stores were selected on the basis of those carried in P3V aircraft. Kill weapons were arbitrarily increased in number to improve fire power. Other droppable stores were increased to an approximate ratio of the difference in station-time between the P3V and the nuclear seaplane. Types and amounts of droppable stores are listed in Table 1.

Shield criteria.- The reactor shield assembly is designed to give a dose rate of 0.01 rem/hr at a point 50 ft forward of the reactor. On the upper deck this 50-ft point is at the aft end of the flight deck; on the lower deck it is in the aft bunk compartment. The dose rate is calculated for cruise power at 15,000 ft altitude. Before the integrated mission dose for the various crew members can be calculated, a study which defines the power and altitude requirements of a typical mission must be made. A number of takeoffs, or a considerable portion of the mission spent in high power maneuvers at low altitude, will tend to increase the dose rate. In addition, the rotation of duties among the crew, their time at flight deck stations and time spent in various parts of the living area must be investigated.

Emergency fuel.- At the present point in the design study no chemical fuel for emergency flight in the event of complete reactor breakdown has been provided for this aircraft. It is expected that a short study will be made to determine the trade-offs involved in providing such emergency range by reducing the payload, by substituting fuel for neutron shielding in the reactor shield assembly, or by overloading the airplane for missions where long emergency range is essential.

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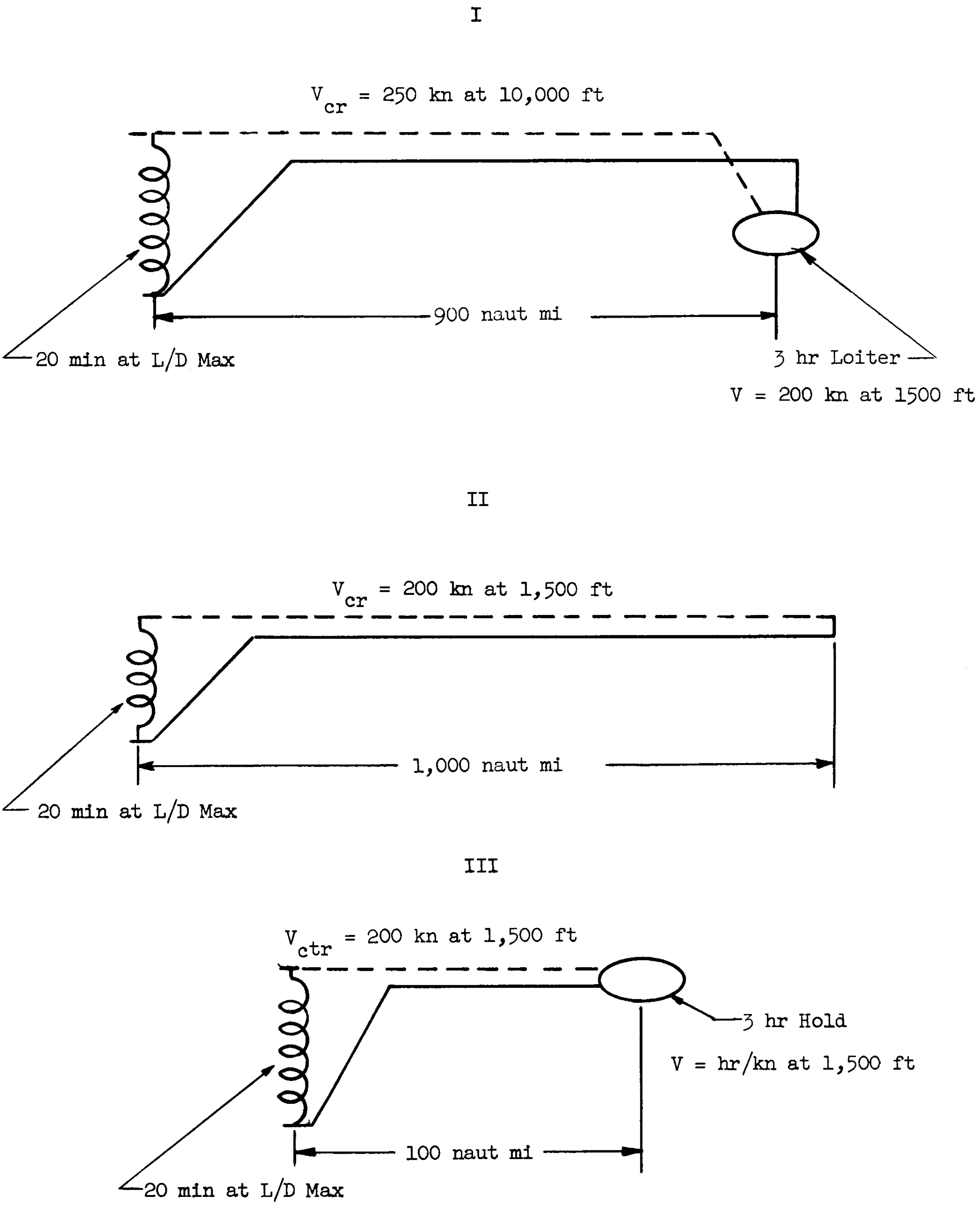

Fig. I-1. Typical Mission Profiles

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1500 ft

ϕ = 60°

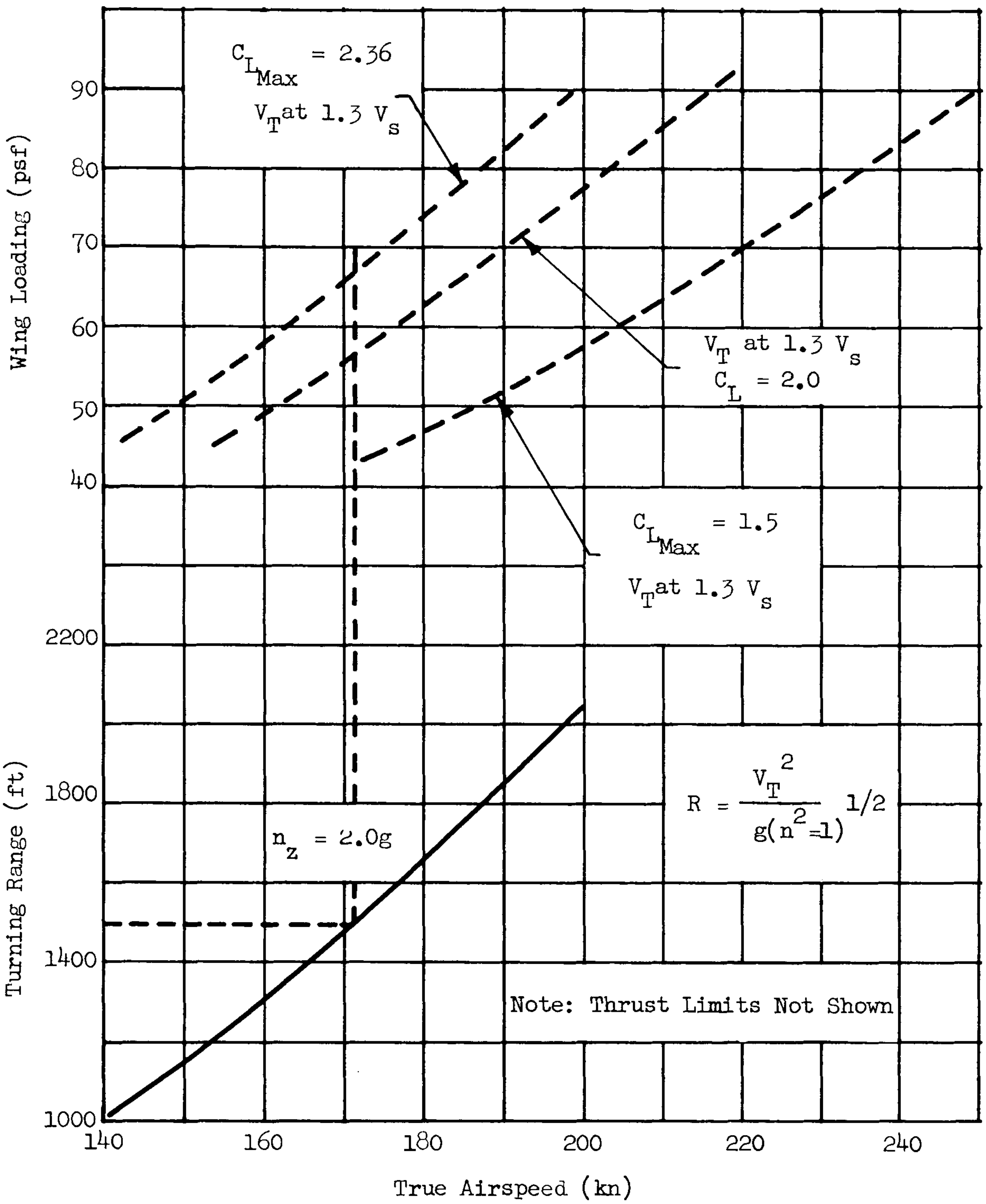

Fig. I-2. Turn Performance Requirements

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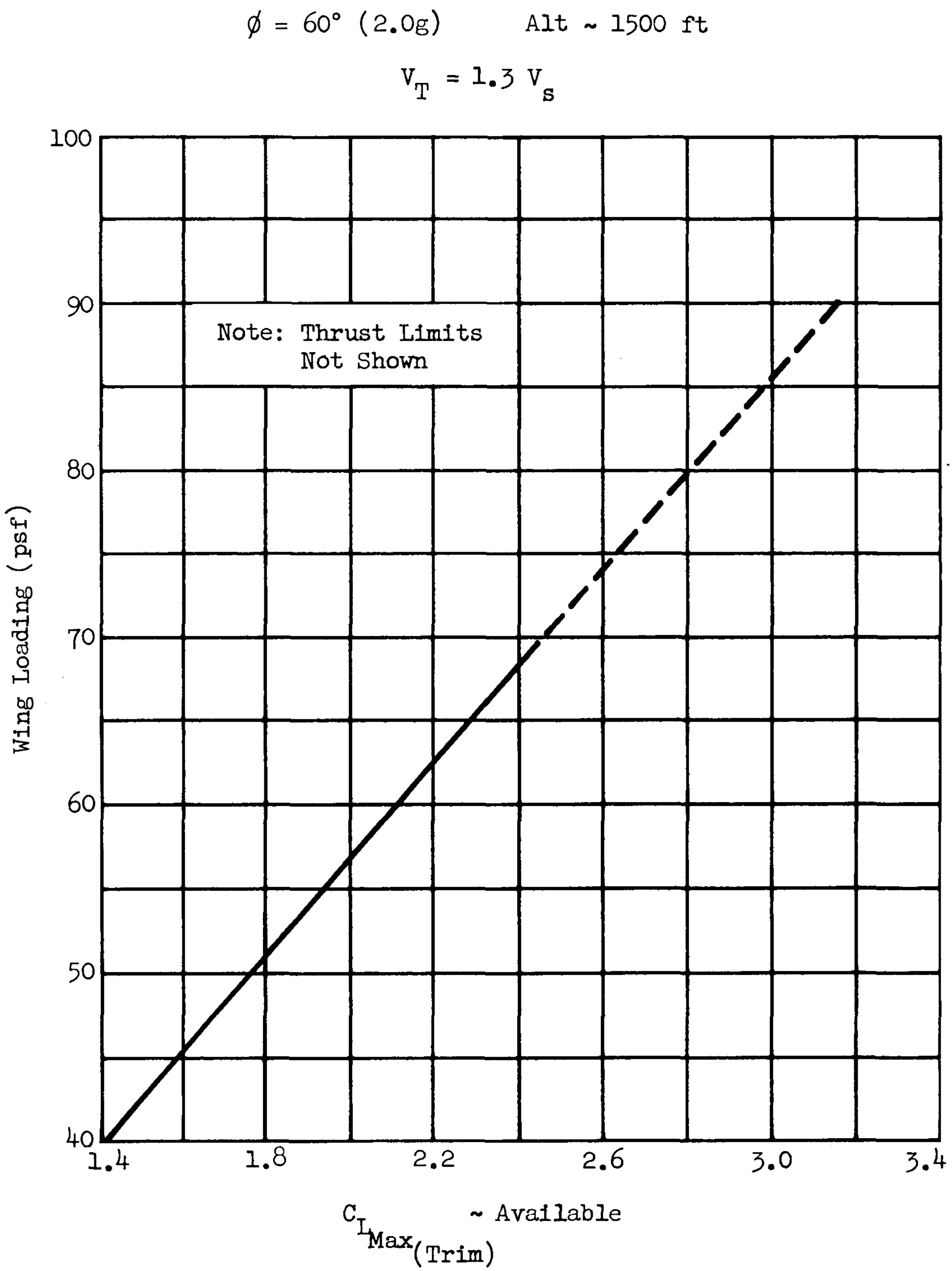

Fig. I-3. Turn Performance Requirements

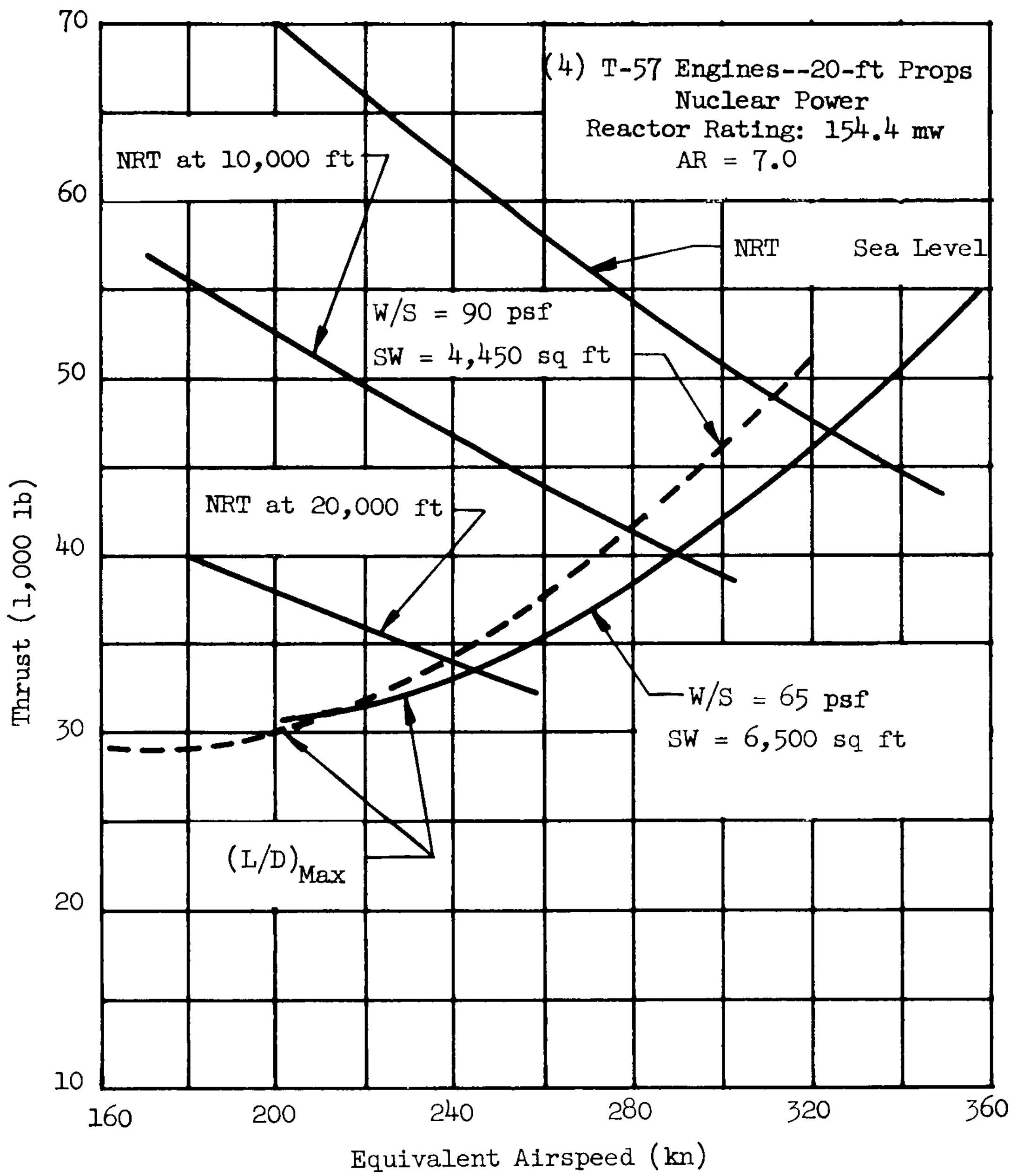

Fig. I-4. Estimated Maximum Level Speeds

[redacted]

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(4) T-57 Engines--20-ft Props
Nuclear Power
Reactor Rating: 154.4 mw
AR = 7.0

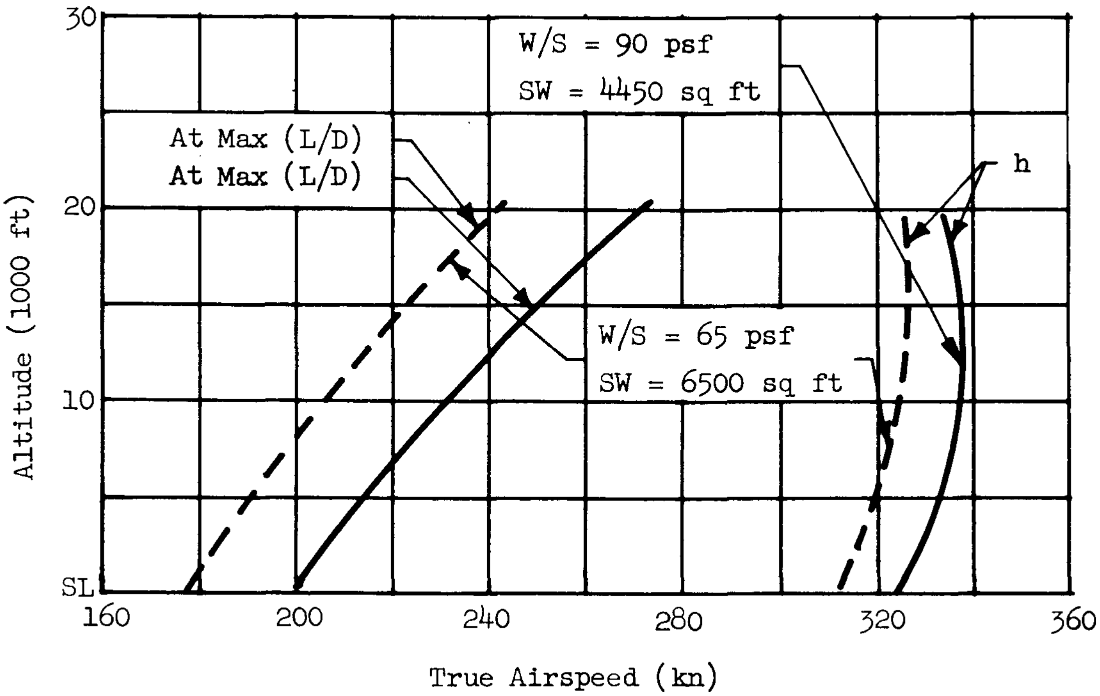

Fig. I-5. Estimated Maximum Level Speeds

(4) T-57 Engines--20-ft Props
Nuclear Power
Reactor Rating: 154.4 mw

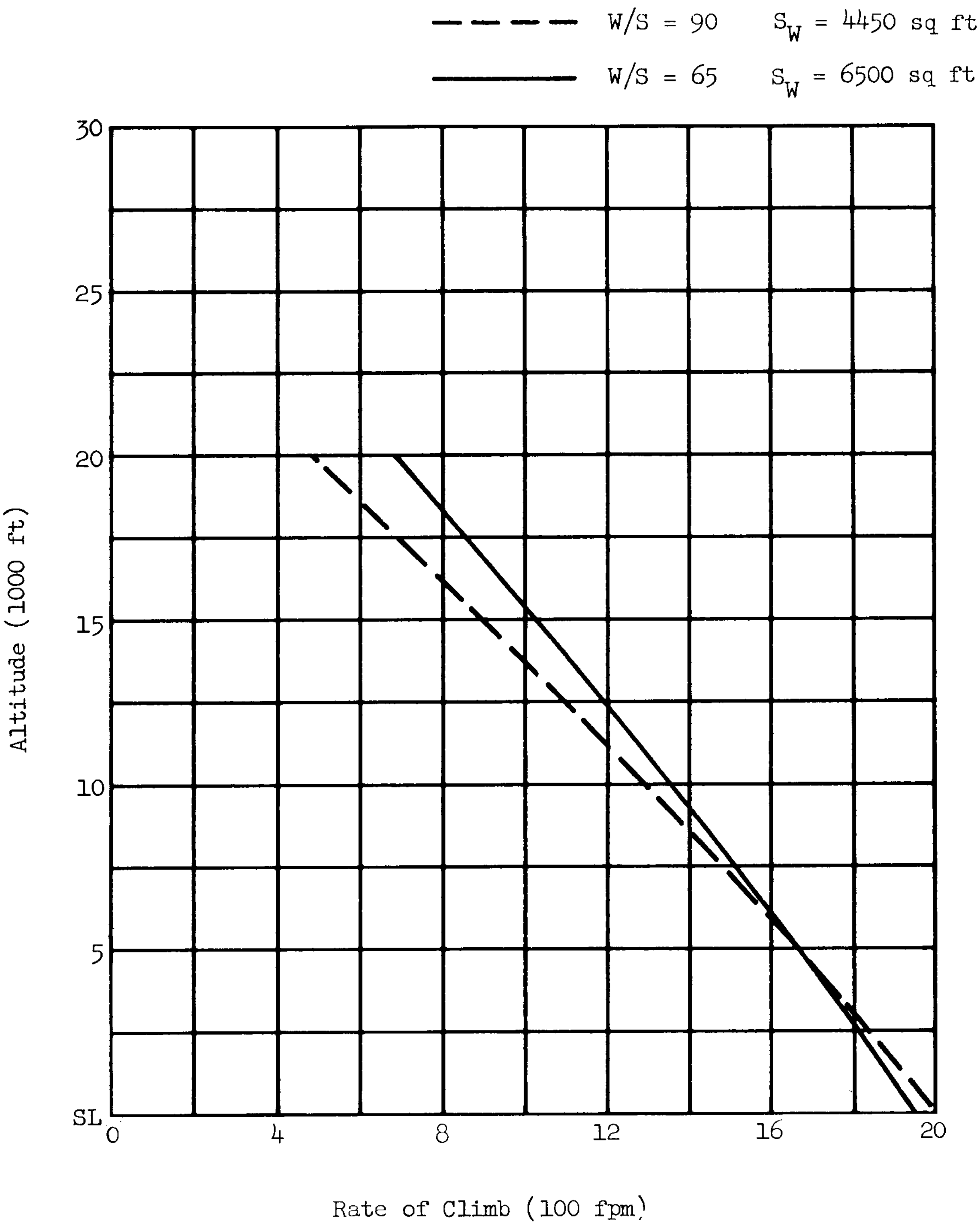

Fig. I-6. Estimated Maximum Steady State Rate of Climb

(4) T-57 Engines--20-ft Props
Nuclear Power
Reactor Rating: 154.4 mw

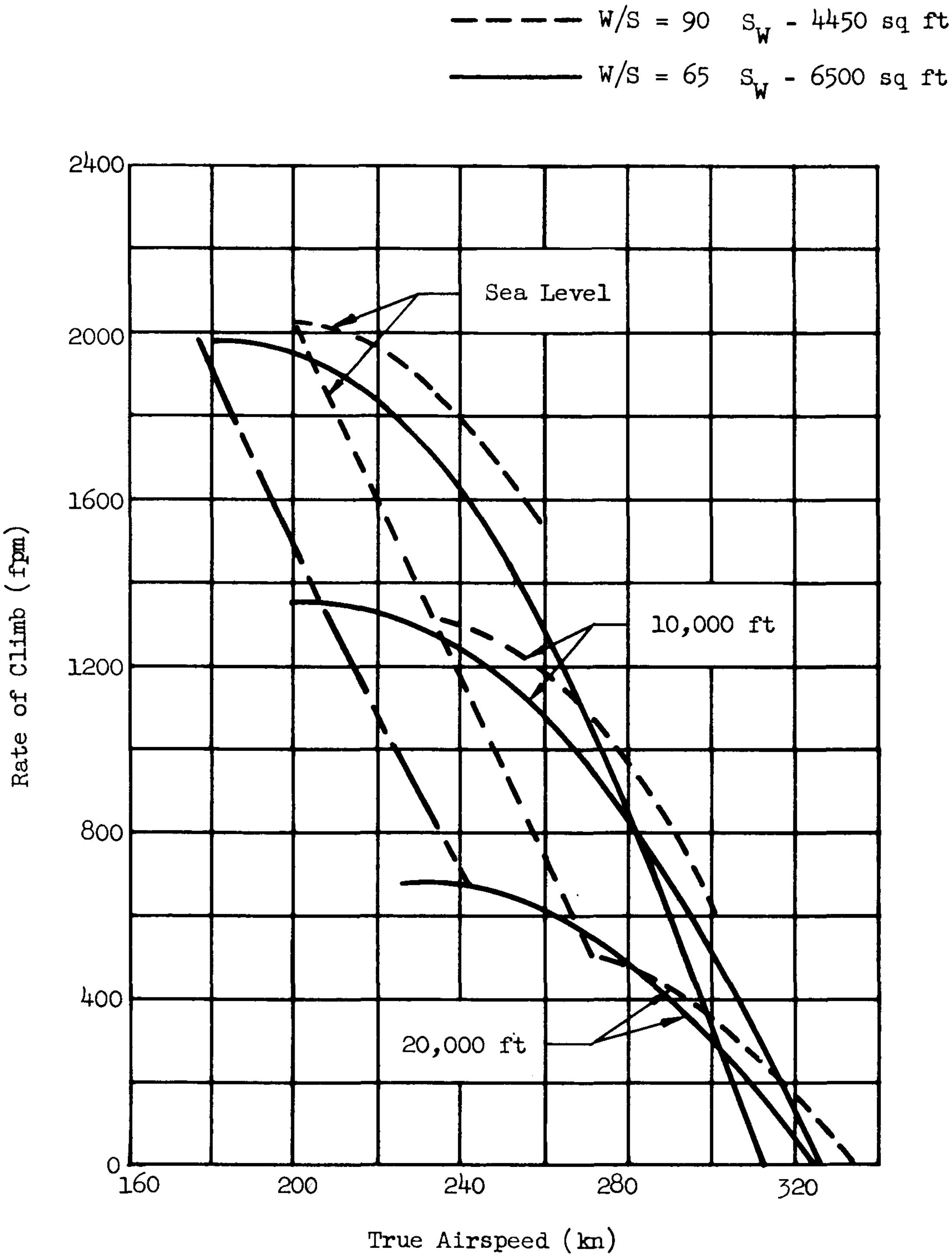

Fig. I-7. Estimated Maximum Climb Rates

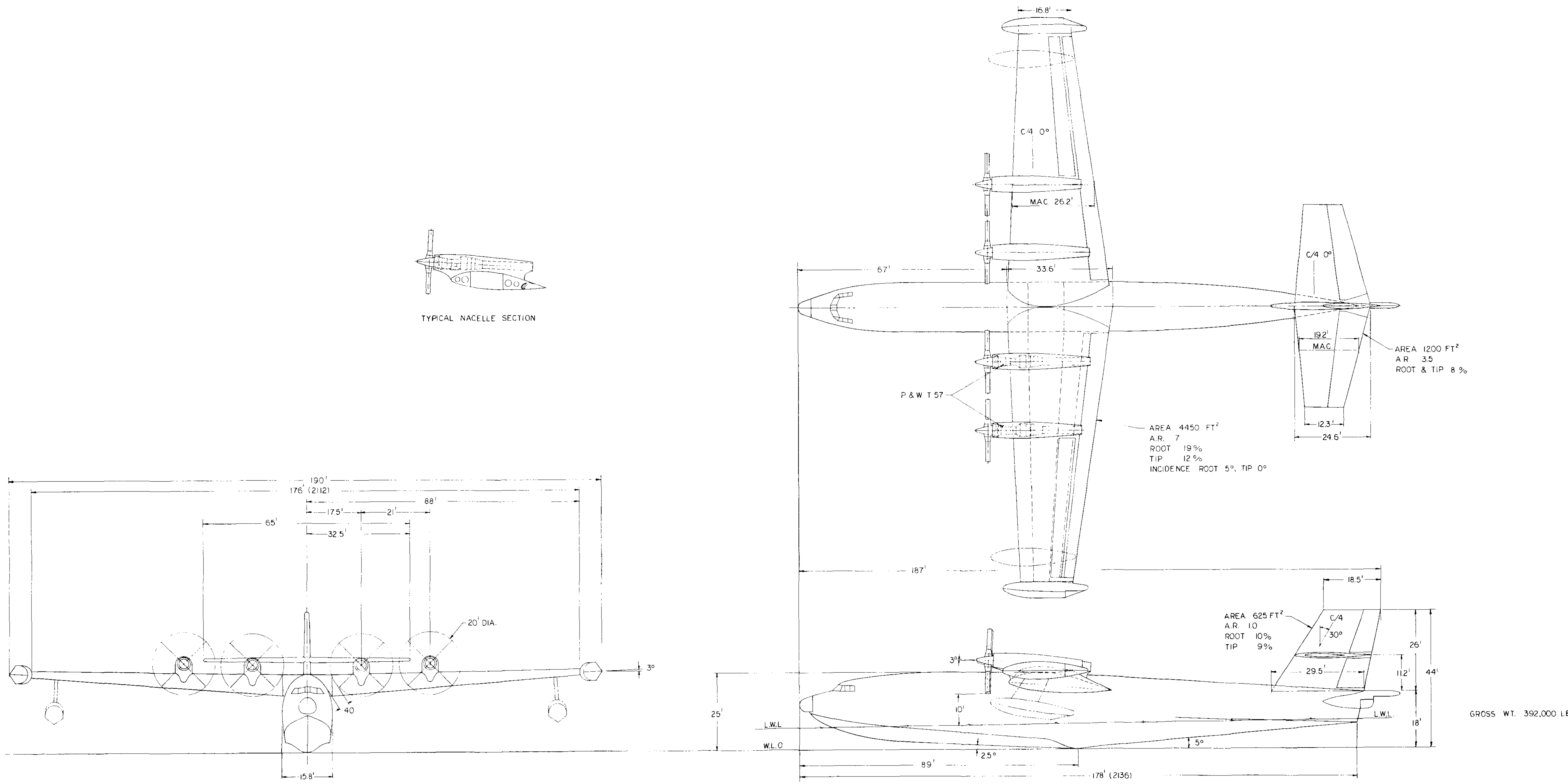

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Fig. I-8. ASW Configuration

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LEGEND

1 HEAT EXCHANGER
2 NaK PUMP
3 LITHIUM PUMP
4 RADIATOR
5 LITHIUM ACCUMULATOR
6 LAUNCHER FOR MK. 7 MARINE MARKERS
7 STOWAGE " " " "
8 " " AN/SSQ-15 SONOBUOYS
9 LAUNCHER " " "
10 STOWAGE FOR MK. 15 PRACTICE DEPTH CHARGES
11 SONAR SEA UNIT
12 STOWAGE FOR AN/SSQ-23 SONOBUOYS, MK. 5 FLARES & XI-3A MARKERS
13 LAUNCHER " " " " " " "
14 P & W T57 ENGINE
15 MK. 44 TORPEDO
16 MK. 101 LULU
17 AN/APS-80 SEARCH RADAR
18 ASQ-10 DETECTING HEAD

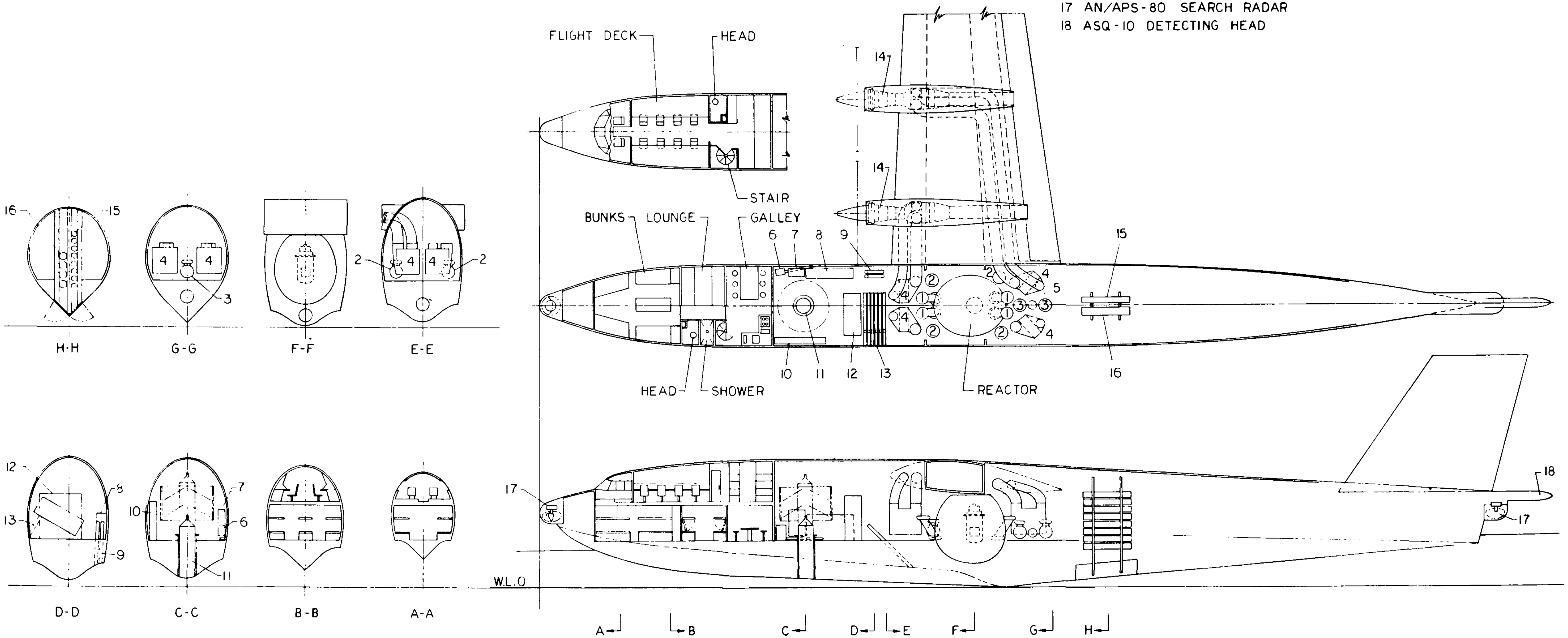

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Fig. I-9. Inboard Profile ASW

[redacted]

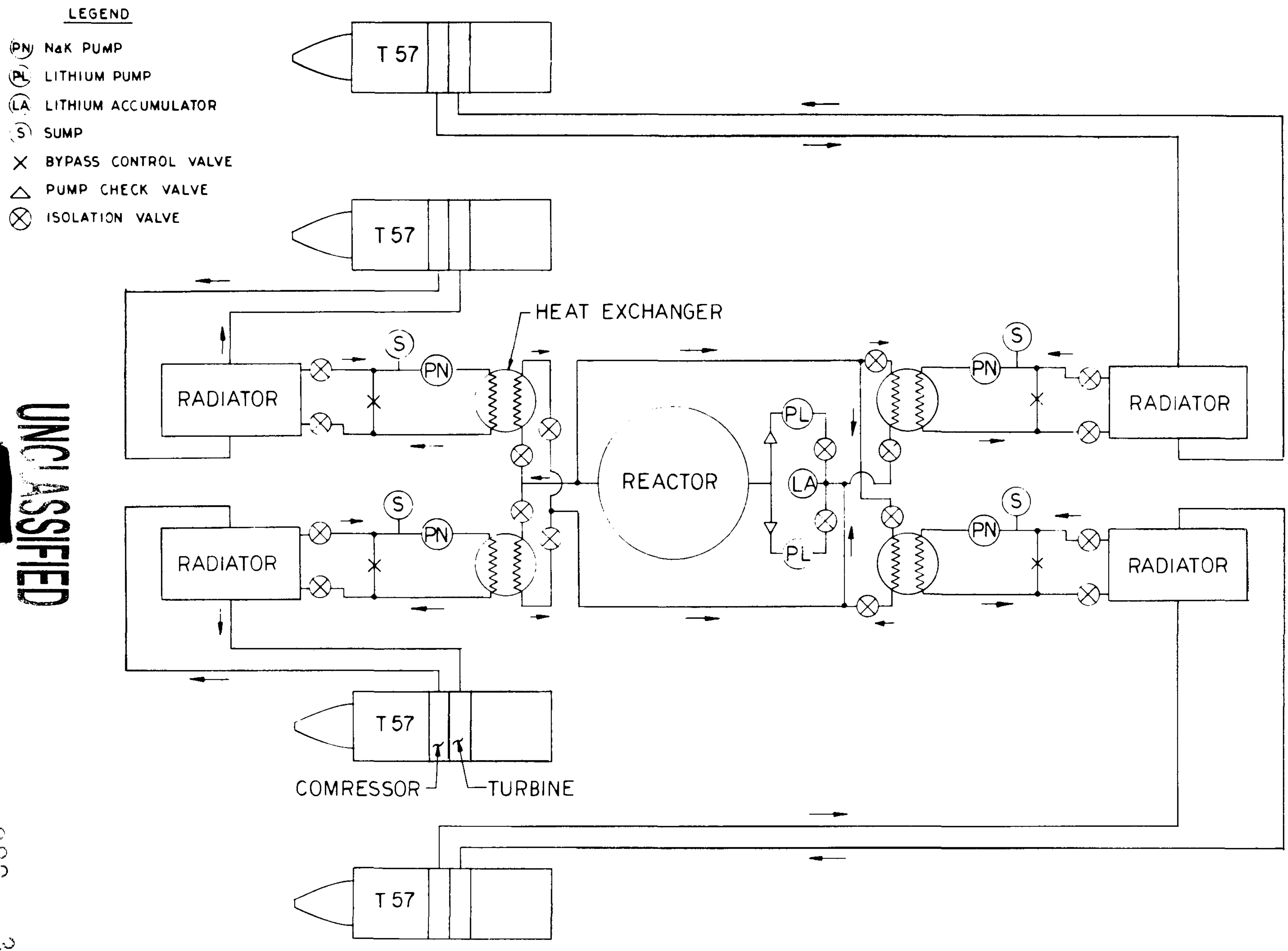

Fig. I-10. Liquid Metal Piping Schematic ASW

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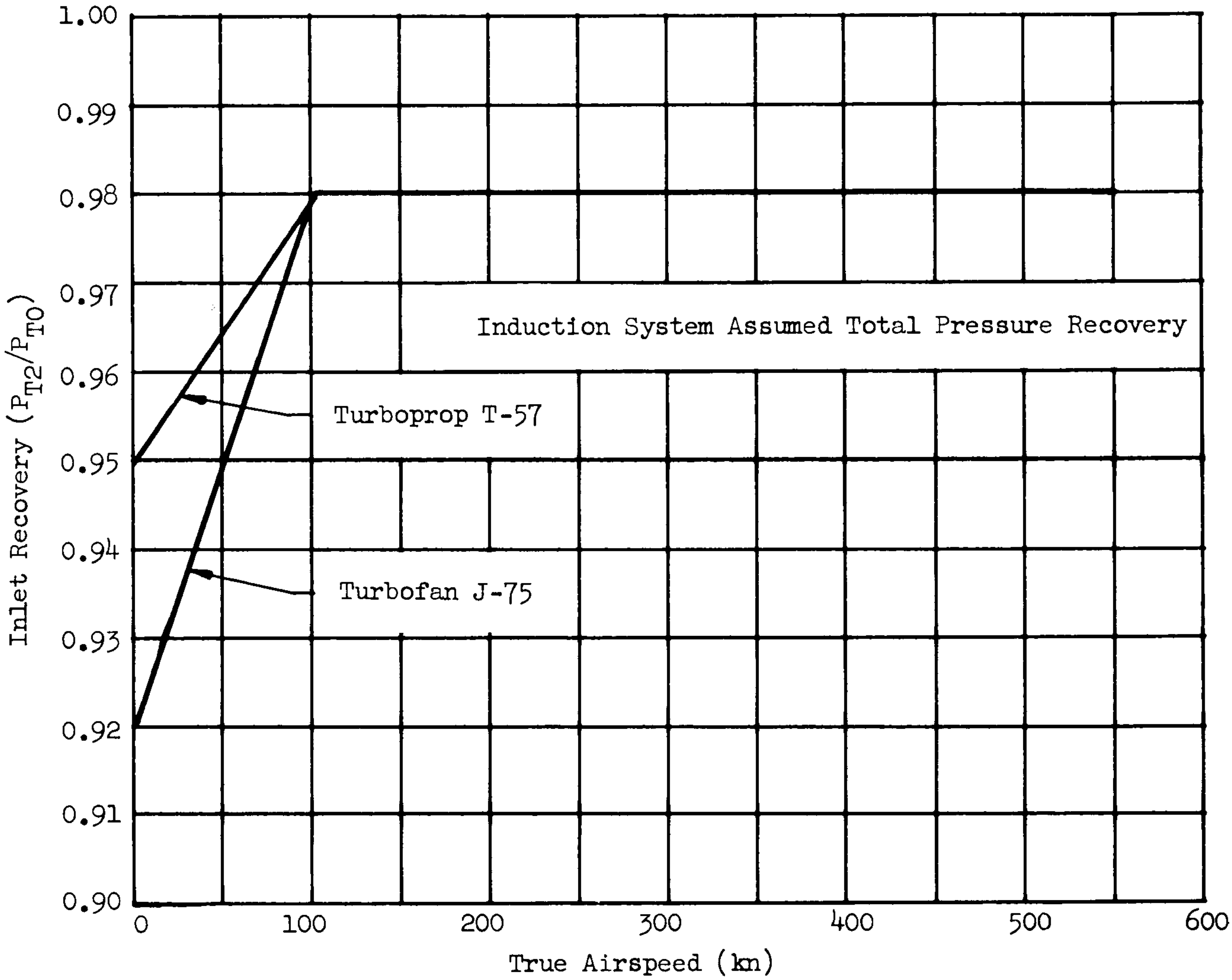

Fig. I-11. Inlet Recovery

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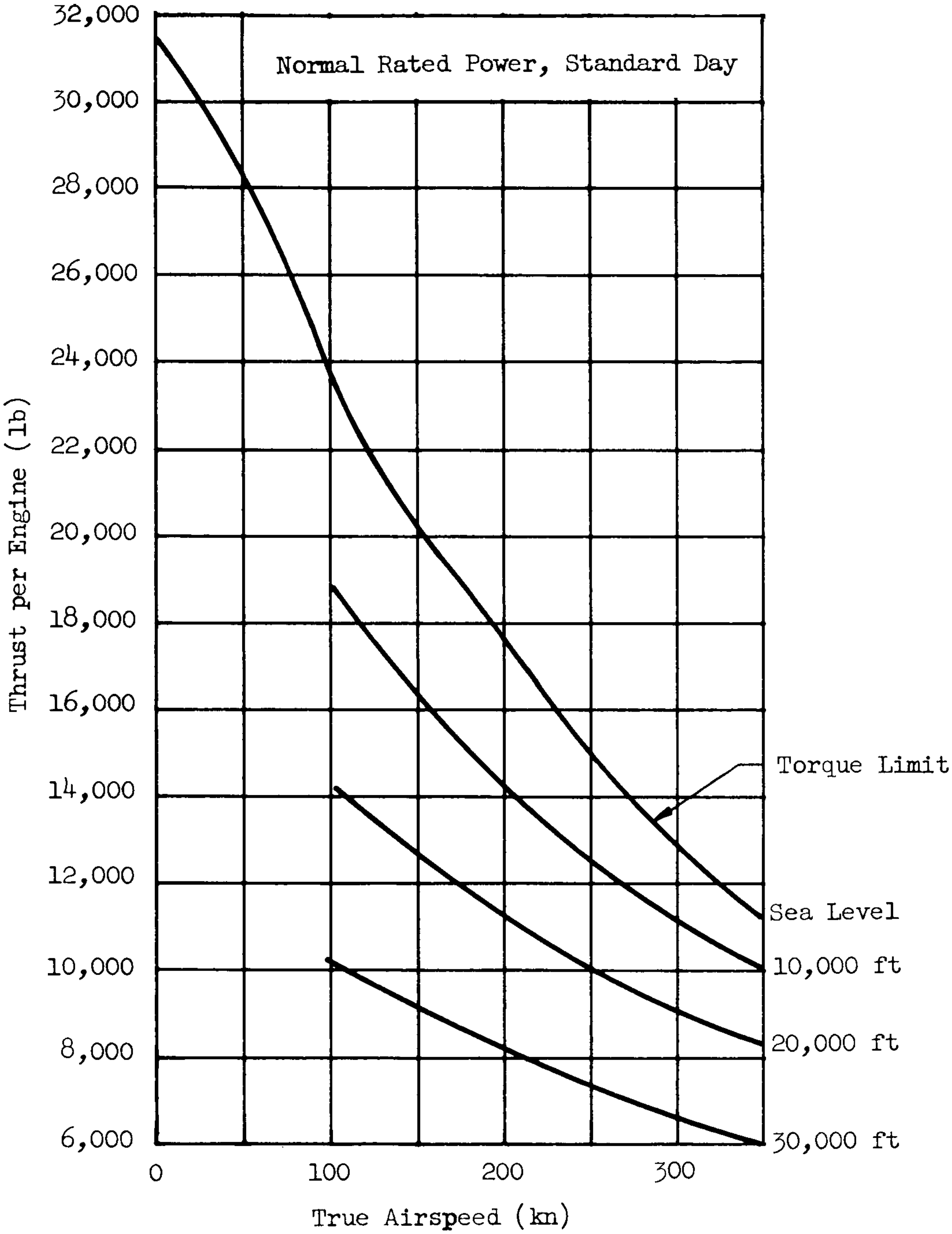

Fig. I-12. Advanced Turboprop T-57 Thrust

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Normal Rated Power, Standard Day

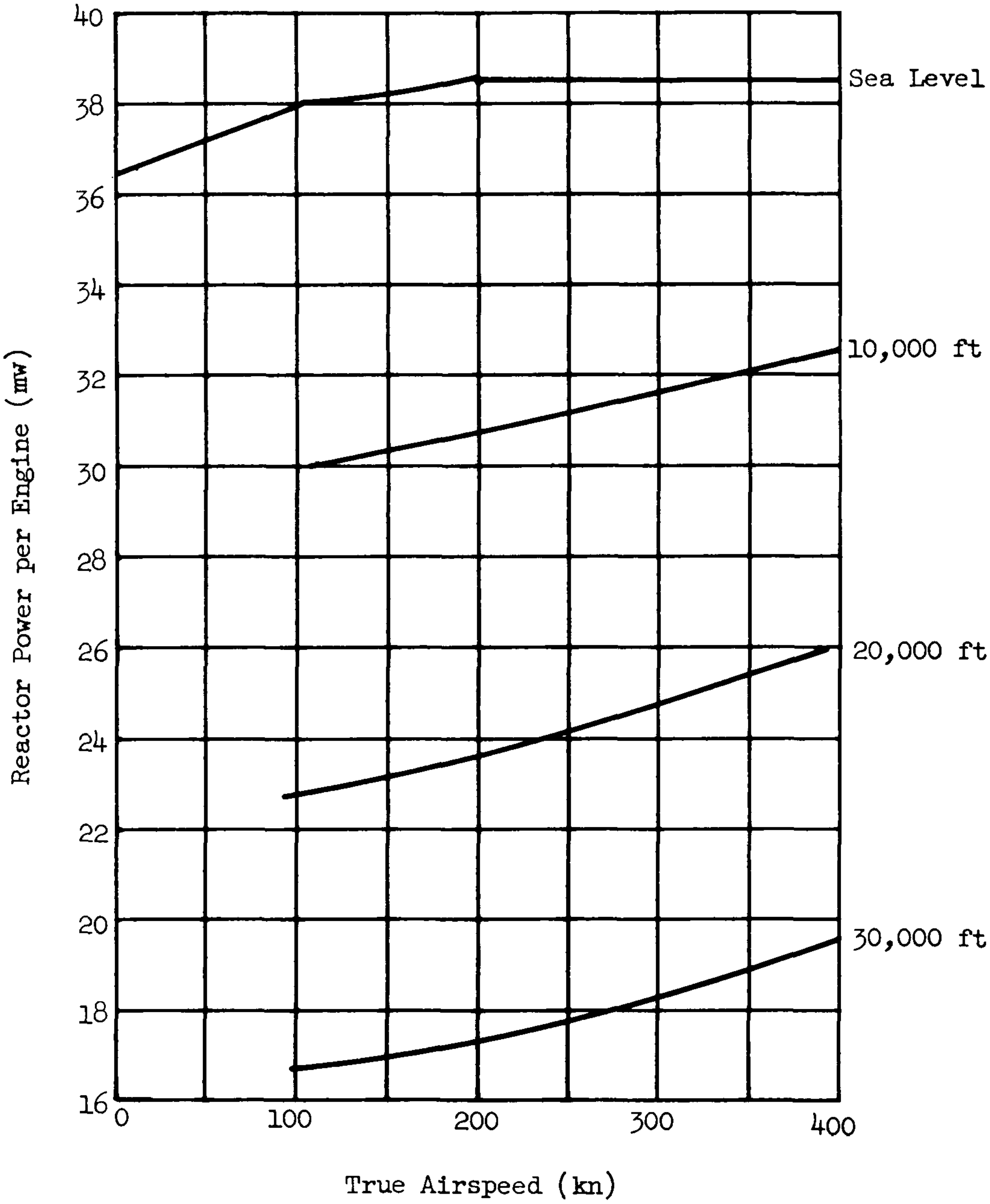

Fig. I-13. Reactor Power per T-57 Engine

III. NUCLEAR POWERED LOGISTIC TRANSPORT SEAPLANE

A. FLIGHT VEHICLE

1. Airframe

Logistic transport studies.- A study with the objective of achieving the conceptual design of a nuclear-powered transport seaplane comparable to an advanced chemical fueled design was undertaken in this quarter. The starting point for the design was a chemically powered Seamistress design (M307) in the 500,000-lb weight range, with a hull having takeoff potential of over 700,000 lb. Turbofan engines were selected for propulsion units in the nuclear propulsion system. The study resulted in a tentative configuration shown in Fig. I-14, and described in this report. This vehicle has a gross weight of 658,000 lb, and a cargo capacity of 100,000 lb.

The first powerplant installation considered for the nuclear transport combined four nuclear turbofan versions of the J-75 engine with four J-58 turbojet chemical engines for takeoff. A brief study showed that satisfactory takeoff could be achieved, but cruise speed and payload potential would be low. Reducing the auxiliary engines to two J-58's gave a better cruise potential, but undesirably long takeoff time. The number of nuclear engines was therefore increased to six J-75 turbofans. Cruise speed was still less than desired, and it was apparent that a further increase in nuclear power would give a better balance between takeoff and cruise ability. In addition, the jet engines, which were used during takeoff only, were excessively heavy for the service they rendered. The nuclear power plant for the configuration finally selected has eight J-75 turbofans, with heat supplied by a 300 MW, liquid metal cycle (LMC), lithium-cooled reactor. Heat is transferred to the engines by a secondary NaK circuit. Chemically fueled afterburners on the turbine exhausts of all engines provide augmented thrust for takeoff.

The NaK air radiators are located in the engines. NaK is pumped from the engine radiators to the reactor heat exchangers via a manifolded piping system. Locating the radiators in or near the engines has several advantages over piping engine air to radiators in the hull. The NaK lines are smaller than the air ducts, which makes the installation problem much easier. In addition, it seems desirable to keep the airflow through each engine independent of the other engines. The NaK lines can be manifolded without compromising this independence, whereas the air ducts cannot. From data available, the installation of the radiators in the engines offers a weight reduction compared to piping engine air to radiators in the hull.

The reactor shield assembly is placed above the cargo compartment, so as to maintain clearance for bow loading. The resulting protrusion on the top of the hull is undesirable from the drag standpoint, particularly when the area rule is considered. The drag penalty has been accepted rather than compromising the ability to load or unload cargo efficiently. The protrusion has been minimized by lowering the cargo deck locally. A twelve-foot clearance is maintained from deck to unaugmented reactor shield. If personnel are to be carried, the neutron shielding is augmented with JP-5 fuel, and this clearance is slightly reduced.

The engines are located in underwing nacelles, with the engine aft of the rear spar necessitating a long inlet. Fan air is discharged through vents in the nacelle lower surface, forward of the trailing edge. Other locations considered for the engines included a buried installation, with inlet or exhaust air ducted through the wing, and over-wing pylon mounted nacelles, with two engines in each of four nacelles. The buried engines have inherently low drag, but duct installation in the wing is difficult, since provision to transfer heat to the outboard engines must be maintained. A wing configuration which is locally thickened to accommodate the engine ducts would solve this problem, but at the expense of structural complexity. The underwing nacelles can be considered as representing such a wing, with higher drag. The pylon mounts must be well separated to reduce interference effects, thus imposing a requirement for long heat transfer lines. The resulting weight penalty was estimated to be 67,000 lb, and further study of this configuration was abandoned.

The nuclear transport and its counterpart--the chemical Seamistress--compares as follows:

	Nuclear Transport	Chemical Seamistress
Gross weight (lb)	658,000	500,000
Payload (lb)	100,000	100,000
Reactor and heat transfer (lb)	222,080	--
Fuel (lb)	14,700	177,100
Range (naut mi)	12,500*	3,000
Wing area (ft^2)	6,700	6,000
Aspect ratio	6.8	6.8

*Approximately 0.25 rem crew dose

Thus, it is seen that to provide equal payload the nuclear aircraft is substantially heavier. It offers the advantage that it can deliver cargo over long distances in one hop, and does not require refueling for return.

The payload of 100,000 lb for the nuclear transport is based on the assumption that no chemical fuel is carried for emergency propulsion. It is shown later that such emergency range can be achieved by reducing payload.

The study shows that the logistic transport of large size is a field of interest for aircraft nuclear propulsion.

<u>Airplane performance</u>.- Design parameters were set forth in order to derive a nuclear-powered logistic air transport based on a proposed water-based transport such as the Seamistress design (M-307). These design parameters include V_{cr} = 490 kn with a payload of at least 100,000 lb. Design objective for cruise altitude is 25,000 to 35,000 ft in order to provide terrain clearance and obviate problems associated with weather at lower altitudes. Standard day, calm water, zero-wind takeoff time objective is approximately 60 sec.

Variants of wing loading, aspect ratio, thickness and engine configuration were analyzed to obtain the minimum weight seaplane which would satisfy the above mentioned criteria.

Eight modified J-75 turbofan engines with afterburners for takeoff were selected to obtain the maximum amount of net thrust for a given reactor heat rating. These engines are configured in an underslung, inboard-wing mounted arrangement optimizing their location with respect to the reactor heat source at a penalty in nacelle drag, Divergent Mach number and maximum lift as compared to the basic Seamistress. An upper-wing pylon-mounted pod nacelle configuration (two engines in each pod) was investigated and proved to have less payload potential because of the higher weight and drag than the configuration selected. The increased weight was mainly due to the increased length of liquid metal lines to provide heat to the outboard engines.

Preliminary estimates of thrust available with nuclear heat at 25,000 ft (300 MW total) show that the required cruise speed and payload can be obtained with an airplane wing loading of approximately 98 psf (wing area of 6700 sq ft) and a wing aspect ratio of 6.5 to 7.0 (see Fig. I-15). The resultant gross weight at takeoff is 658,000 lb and the thrust to weight ratio for standard day takeoff with afterburning is 0.275 with an estimated time for takeoff of 65 sec, in calm water, zero wind, (see Fig. I-16).

The drag equation at $M \leq 0.80$ in. cruise configuration is:

$$C_D = 0.0206 + 0.064\, C_L^2$$

as previously noted, this drag equation is somewhat higher than that of the comparative Seamistress because of the nacelle configuration and reactor fairing drag. The reactor and fairing protrude from the hull to provide cargo space. Divergent Mach number is reduced to 0.91 M at $C_L = o$ (compared to 0.94M for M-307) to account for the adverse area-rule distribution of maximum area in the region of wing-body intersection.

The maximum lift coefficient in the landing configuration is estimated to be 1.5 with slotted flaps deflected 40°. The maximum lift is limited by nacelle location whereby flaps span the wing from approximately 0.35b/2 to 0.80b/2, whereas the Model 307 design with engines buried in the wing retains flap to the hull intersection. Stall speed, thereby, is approximately 139 kn with a wing loading of 98 psf. BLC flap system can be readily adapted to this airplane to provide significant improvements in takeoff performance and landing speed, should these improvements be desired.

A summary of the selected configuration is shown below:

Wing Area	6700 sq ft	
Aspect ratio	6.8	
Thickness	12% root 9% tip	64 A Series
Sweep at c/4	40°	
Incidence	5° root 0° tip	
Horizontal Tail		
Area	1000 sq ft	
Aspect ratio	3.5	
Sweep at c/4	40°	
Section	63A 008	
Elevator	P6M--type (slaved)	

Vertical Tail

Area	660 sq ft
Aspect ratio	1.0
Sweep at c/4	45°
Section	63A 010 root
	63A 009 tip
Rudder	P6M--type

Hull

M-270 type design--high length to beam ratio--forebody length to beam ratio = 6.7

Flap (single slotted)

Cf/c_w	0.25
Span	0.35b/2 to 0.80b/2
Travel	0 to 40°

Estimates of projected improvements in nuclear engine performance over the next ten years such as improved radiator design, mechanical or hydraulic liquid metal pump drives, by-pass ratio change, operating temperature increase and other refinements show that a 10 to 12% thrust increase is possible. This estimated increase in thrust would reflect an increase of 30 kn in V_{cr} at 25,000 ft for the selected configuration or an increase in operating altitude to 32,000 ft. Thrust-weight ratio at takeoff under these conditions would increase to 0.285 providing a standard day time for takeoff of 60 sec at a wing loading of 98 psf. These projected improvements in engine performance also indicate that a wing of aspect ratio 3.5 to 4.0 may satisfy the basic design criteria of V_{cr} = 490 kn at 25,000 ft necessitating a blown flap configuration for satisfactory takeoff and landing performance. This trend toward lower aspect ratio will require further detailed study through layouts of nacelle installation, wing and flap arrangement and refinements in overall area distribution of the configuration.

Drag Summary

Low Speed Cruise Configuration

	Index Area	C_{D_o}
Wing	6700	0.0055
Hull	420	0.00595
Nacelles	400	0.00595
Horizontal Tail	1000	0.0008
Vertical Tail	660	0.0006
Reactor Fairing	54	0.0012
Miscellaneous	--	0.0006
		0.0206

$$\mathcal{L} = \frac{\partial C_D}{\partial C_L^2} = \frac{1}{\pi AR e}$$

$e = 0.73$

$\mathcal{L} = 0.064$ for $AR = 6.8$

C_L	M_D ($dC_D/dM = 0.10$)
0	0.915
0.1	0.90
0.2	0.885
0.3	0.86
0.4	0.84

Maximum level speeds using current and projected nuclear thrust available with the eight turbofan J-75 engines as NRT are shown in Figs. I-17 through I-19.

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[redacted]

Fuel consumption data during chemical engine operation were examined to determine the optimum specific range as a function of speed, altitude and power setting. The data, as shown in Figs. I-20 and I-21, indicate the optimum cruise altitude to be 35,000 ft at V_{cr} = 460 kn, GW = 658,000 lb. The fuel flow data are increased by 5% as a normal service tolerance. This facet of flight operation was reviewed in order to determine the ramifications on airplane weight and configuration of providing chemical fuel to operate should the nuclear heat source become inoperative. Addition of this feature to the original design criteria would seriously affect the airplane weight and thrust requirements should an appreciable chemical range be required. For example, if 1500 naut mi range is required on chemical power, the weight of added fuel would require an increase in power plant thrust to two additional engines for takeoff and an increase in wing area to maintain low speed performance.

Structures.- In general, both the ASW and the transport configuration is a conventional design such that its structure falls within the existing state-of-art.

Utilizing the experience gained in the development of the P6M, the inboard engine was located approximately two exhaust nozzle diameters away from the hull sides and canted 5° outboard. The remaining engines were placed parallel to, and outboard of, the inboard engine. See Fig. I-14.

This compact engine configuration tends to minimize the spanwise effects on the wing lift distribution while providing reasonable acoustic and temperature effects on the hull afterbody.

The estimated exhaust velocities of the Pratt and Whitney J-75 turbofan are given below.

	Central Exhaust	Fan Exhaust
Takeoff--Non-afterburning*	1000 fps--37 in. dia	930 fps
Takeoff--With afterburning*	1580 fps--46 in. dia	930 fps
Cruise at 25,000 ft, Mach 0.80	1595 fps--34.6 in. dia	1075 fps

*Includes chemical interburner operation.

[redacted]

Taking the condition of takeoff with afterburners and only the central exhaust velocity, with an average takeoff velocity of 60 kn, the maximum sound pressure level on the hull afterbody was estimated to be 149 decibels. To prevent sonic fatigue at this sound pressure level, the hull afterbody will require structural reinforcement that can be acheived with a reasonable weight penalty.

No temperature distribution of the J-75 turbofan engine is available. However, judging from the past experience of the P6M, it is expected that the hull afterbody temperatures will not become a serious problem. If necessary the sound pressure levels and temperatures can be further reduced by moving the engines outboard along the wing span or by eliminating the afterburner on the inboard engine.

Weights.- The 50-ton logistics cargo carrier grosses 658,000 lb in flight. It has the capability of carrying a 100,000 lb cargo or troops and equipment totaling 90,500 lb. The difference of 9500 lb is required for additional neutron shield when personnel are carried in the cargo compartment.

The airframe and equipment weights were estimated primarily from statistical plots of past aircraft. The propulsion weights are primarily Pratt and Whitney estimates and modified to fit this particular configuration. The engines are modified Pratt and Whitney J-75 turbofan versions. NaK to air radiators are installed inline with the engine between the compressor and combustion sections, and an afterburner has been added. The derivation of the engine weight is:

	lb
Basic J-75 turbofan engine	6,200
Radiator	3,200
Afterburner	600
Allowance for increase shaft length	200
Total	10,200

Of the 14,700 lb of fuel carried, 8300 is for the second takeoff and the balance is for auxiliary power plant operation. This provides, under emergency condition, 24 hours of after shutdown cooling of the reactor and for normal operation of the APP for mooring, engine starting, taxiing and similar services. Fuel for emergency operation is utilized as neutron shield.

Although cargo mission is of primary importance, capabilities of carrying personnel have been provided at the expense of 27,600 lb of fixed weight which is broken into the following parts:

	lb
Additional gamma shield	14,600
Hull pressurization	4,000
Hull air conditioning	6,000
Furnishings	3,000
Total	27,600

In this configuration, at maximum payload, only one source of energy is available for flight. If the reactor becomes inoperative it will be necessary to land. An alternative is to carry chemical fuel, but this decreases the payload capability as shown in Fig. I-22 where payload is plotted versus range on chemical fuel. The fuel carried is traded off for lithium hydride such that dose rate remains constant. When all the lithium hydride has been replaced by fuel, payload is sacrificed for fuel. It is seen that while fuel is being traded for lithium hydride, i.e., up to 800 miles fuel range, a rather favorable ratio of range to payload reduction exists. When additional range is required the payload reduction is severe.

Balance of this configuration is such that center of gravity of the 50-ton payload can be positioned anywhere between station 1060 and 1250 and still stay within c.g. limits of 35 to 42% MAC.

TABLE 3

Group Weight Statement

Wing	89,100
Vertical Tail	6,000
Horizontal Tail	8,300
Bullet	640
Hull	71,700
Surface Controls	4,200
Nacelle	14,280
Propulsion	315,000

TABLE 3 (continued)

Engines	81,600	
Engine Controls	320	
Air Induction	3,890	
Lubrication System	700	
Exhaust System	400	
Starting System	340	
Fuel System	670	
Reactor and Primary Loop	23,500	
NaK Loop	48,580	
Reactor Shield	150,000	
After-Heat Removal	1,000	
Shield Cooling	1,000	
Reactor Controls	2,000	
Purge Gas System	1,000	
Auxiliary Power Plant		600
Instruments		500
Power Systems		12,000
Electronics		1,540
Furnishings and Equipment		4,700
Air Conditioning		6,380
Anti-Icing		2,510
Auxiliary Gear		2,600
Weight Empty		540,050
Useful Load		117,950
Crew	1,000	
Fuel	14,700	
Oil	900	
Cargo	100,000	
Miscellaneous	1,350	
Gross Weight		658,000

2. Propulsion System

Eight advanced Pratt and Whitney modified J-75 turbofan engines, a reactor, radiators, heat exchangers, pumps and associated piping systems and controls comprise the power plant for this airplane.

Reactor shield assembly.- The RSA for the logistic transport is similar to that for the ASW aircraft in so far as the configuration and composition of the reactor, control system, pressure vessel and primary coolant loop are concerned. Dissimilarities are primarily due to the greater design power of the system--300 MW.

The unit shield design for this power plant must meet dose rate criteria for two distinct missions--all-cargo and personnel transport. The criteria for the personnel transport mission are the more stringent, in that tolerable dose levels must be maintained throughout a large portion of the hull. The minimum weight shield concept for this mission,therefore, required shaping the shield to attain asymmetrical dose rate distributions about the reactor-cockpit axis. This disposition of shield material results in over-shielding during all-cargo missions, when the only critical area is the flight deck. During these missions it is then desirable to remove shield material and permit higher dose rates in the cargo compartments.

It does not appear practical to design the gamma shield in a manner such that a portion of it may be removed or drained, both because gamma shield materials are customarily in the inner region of the shield and because it is unlikely that acceptable gamma shield material will be available at all bases from which the aircraft will operate. However, the neutron shield may be so designed that supplementary shielding can be JP-5 fuel. Since the tank containing this fuel can be drained for all-cargo mission, only the incremental gamma shielding need be considered as a permanent weight penalty. This weight amounts to 14,600 lb. The weight of the supplementary neutron shield is a function of the total weight of fuel in the shield, due to the dependence of the shield envelope on this weight; for the shield in question this weight ranges between 9300 and 11,000 lb.

Total shield weight, not including reactor, controls, etc., or Li system weight, is presented in Fig. I-23 as a function of the weight of fuel-in-shield for both aircraft missions investigated. These data were used in the determination of payload vs emergency cruise range, presented elsewhere in this report. Data from Refs. 2 and 3, was used in estimating shield system weight.

Radiation environment.- The design dose rate for flight crew personnel was set at 0.01 rem/hr for all missions. The maximum dose rate in the hull during personnel-carrying missions is is 0.05 rem/hr provided that the distance of closest approach to the RSA is restricted to 20 ft, measured from the core centerline; the restricted area increases to 25 ft on the upper deck to the rear of the shield. The maximum dose rate in these areas during cargo missions is approximately 0.30 rem/hr, the chief contributor to dose rate being direct and air-scattered neutrons due to the absence of JP-5 fuel in the supplementary shield tank. All dose rates were established for assumed operation of the vehicle at a cruise altitude of 25,000 ft and reactor operating power of 300 MW.

Water-scattered radiation is not a significant contributor to integrated dose levels for this vehicle because of the asymmetrical distribution of shield materials about the reactor-crew axis. In addition, the vehicle is restricted to two takeoffs per mission by its dependence on chemical thrust augmentation, and consequently the duration of full power water-borne operation of the nuclear power plant is limited.

Due to the asymmetry of the shield, after shutdown dose rates within the vehicle will be relatively low. Maximum shutdown dose levels, 3 hr after reactor shutdown from long term full power operation, occur above and to the rear of the RSA, reaching an estimated 0.20 rem/hr at 50 ft.

Lithium loop.- The columbium alloy, moderated, 300 MW reactor is the main heat source for the engines. Lithium coolant is raised from 1350° F to 1800° F in the core. Two counterflow, shell and zee tube heat exchangers of 150 MW capacity each are mounted aft of the reactor shield assembly. Here, from lithium in the tubes, heat is transferred to NaK. NaK enters the heat exchanger shell side at 1150° F and exits at 1650° F. Each heat exchanger serves four engines.

The lithium flow rate is 640 lb per sec, half this amount being driven by each of the two pumps. The friction horsepower to be overcome by each pump is 350. For simplicity, light weight and reliability, bleed-air turbine drives are assumed for the pumps.

NaK loop.- NaK is the coolant used in the stainless steel secondary loop. Figure I-24 shows the piping system for which piping was sized and pressure drops calculated. This reflects an airplane design which incorporates paired engines in pylon mounts. The underwing nacelle engine installation selected for this airplane is shown in Fig. I-14. System components and general arrangement remain the same as for the pylon installation, pipe lengths only being changed. Calculated pressure drops are slightly pessimistic when referred to the underwing installation.

Radiators are of cruciform design (as suggested by Pratt and Whitney) mounted symetrically in quarter sections around the engine shaft between the compressor and the chemical fuel burner as shown in Fig. I-24. Quarter sections of the radiator have a heat transfer matrix approximately 36 in. long, 18 in. wide and 17.5 in. deep. The total radiator weight per engine is estimated to be 3200 lb. One NaK pump is provided to serve two engines. The piping system is valved in such a manner that a radiator failure in one engine will not affect operation of the engine paired with it. A NaK pump failure will secure nuclear heat operation of a pair of engines. Safe flight, at a Mach number below design, can be maintained on six engines operating on nuclear heat.

Several advantages accrue to placement of the NaK pumps close by the radiators. In the past, where designs incorporated wing mounted radiators, the pumps have been fuselage mounted. If the powerplant includes four or more engines the radiators on each side of the aircraft were placed in parallel circuits. The outboard radiator fixed the pressure drop of the system, the inboard engine being penalized unnecessarily. Moving the pump close by the radiator has permitted the inboard engine to realize the benefits of being closer to the heat source. Additionally, a longer portion of the cold leg of the NaK loop has been placed near the pump discharge. This being the region of highest internal pressure, system weight can be reduced. Weight is reduced for three reasons. First, the cooler pipe, of greater strength than the hot, will require less wall thickness to withstand a given internal pressure. Second, because of the greater density of NaK at the lower temperature, for a given flow velocity the pipe diameter is less, so that the additional wall thickness to accommodate high pressures is added at a lesser radius. And third, because the pipe stress is equal to the internal pressure multiplied by the radius, the lesser radius of the cold line reduces the stress to be contained, thus effectively reducing the wall thickness required. Wall thicknesses were determined for 1000 hr life using the Larson-Miller Master Rupture and Creep Curves of Fig. 43 in Ref. 7. Creep allowance of 0.2% was the critical design constraint.

Where possible further weight saving is obtained by manifolding NaK lines to and from engines into common carriers. Common lines also reduce system pressure drops, hence pumping requirements. An increase in pipe diameter reduces the relative roughness of the pipe and increases the Reynolds Number of the flow. Both changes act to lower the friction factor to which pressure drop and pumping power are proportional.

[redacted]

The NaK pump efficiency was assumed to be 57%, that of the drive system 90%. The NaK flow rate per pump at full reactor power is 548 lb/sec. The friction horsepower to be overcome by the inboard pump is 605, for the outboard pump 649. The pump drive system is undefined. Being close to the engine it may be hydraulic, mechanical, electric or a bleed-air driven turbine.

Engines.- The engine used is basically a turbofan J-75 engine. The total engine airflow (fan plus main engine) equals approximately the main engine air multiplied by 2.45. For nuclear use the concentric shafts connecting turbines and compressors must be extended 42 in. to accommodate the cruciform radiator. Basic engine weight is increased approximately 200 lb. The chemical burner is retained in line with the radiator. It will be used on takeoff and at such times when full engine rpm is desired but is not available on nuclear heat only. (In general, reactor power limitations will not permit operation of the engine on nuclear heat at full rpm at low altitudes and high speeds). The main engine exhaust is fitted with an afterburner and a two-position nozzle. This was dictated by takeoff thrust requirements and will be used only for takeoff thrust augmentation. A configuration with the eight engines installed below the wing was selected since it gave a lighter airplane with lower drag than pylon mounts. Installation of the engines in the wing, aft of the rear spar was rejected because of the structural complexity involved in carrying the inlet ducts through the wing. Of the installations attempted the best compromise of area rule, wing thickness ratio, lifting ability, wing and installation weights and power plant performance were obtained with the installation shown in Fig. I-14.

Inlets protrude forward of the wing, the distance fixed by the desire to increase lifting capability in the engine area, and alleviate water ingestion. Aerodynamically it would be better to place the inlet under the wing aft of the leading edge. This was undesirable hydrodynamically because ingestion of water was likely. In addition to alleviation of the hydro problem two further benefits derive from extension of the inlets. First, slope of the area rule curve is improved. Second, the inlet should operate better because intercept of incoming air is at smaller angles of attack. Flow at various positive angles of attack, even in level flight, is induced by the fuselage and swept wing. Fences are used between inlets. In an engine-out situation, these fences will prevent spillage of air into the inlets of operating engines. Distortion of flow in the inlets of operating engines will be prevented. Pressure drop calculations made for design point operation indicate that a total pressure recovery of 0.981 can be obtained. Because of the extreme length of the inlets, about 35 ft, internal boundary layer bleed of approximately 4% of the total airflow is used to assist in control of air velocity distribution at the

[redacted]

compressor face. Subsequently, but before dumping, this air can be used for cooling structure, the engine and the coupling between NaK pump and drive unit. It is believed that no problems will arise due to water ingestion. From outboard to inboard, the inlets are 8 to 11 ft above the load water line. Inlets are of sufficient length that fixes to any ingestion problem should be possible.

Engine thrust determination.- Data in Refs. 1 and 8 were used. The thrust per engine vs velocity, shown in Fig. I-25, assumes wing mounted Princess type radiators, a 15-1/2% air total pressure loss between compressors and turbines, 100 shaft horsepower extracted for electrical power generation and auxiliaries, lithium and NaK pumps driven by bleed-air turbines, a 2% exhaust system total pressure loss and inlet recoveries of Fig. I-11.

Because the airplane is of a design projected for the late 1960's, it was decided to project power plant development to that time period. It was assumed that the pressure drop between compressor and turbine could be reduced to 10% by using cruciform radiators, engine mounted. Additionally it was assumed that a turbine inlet temperature of 1550° F was attainable and that (coupled with refinements in engine design, turbine, compressor, adjustment of by-pass air ratio and optimization of fan and main engine nozzles) a further increase of 5% in installed thrust could be obtained. Locating the NaK pumps close to the engines will also result in a more efficient pump drive system. The resulting estimated performance is defined as that of an advanced turbofan J-75.

Design maximum reactor power per engine is 37.6 MW. Nuclear heat thrust per engine is shown in Fig. I-26. Thrust during straight chemical operation is shown in Fig. I-27, as well as thrust on chemical plus nuclear heat. Fuel flow during chemical operation only and during chemical plus nuclear heat operation is shown in Fig. I-28 through I-30 as a function of velocity, altitude and percent normal rated power. All thrust determinations assume atmospheric conditions of NACA Standard Day.

B. AIR LOGISTIC ANALYSIS

Although at the present time there is little indication that U. S. limited war capabilities will be increased, analysis of past and present behavior of the Soviet Union, and of the philosophy of its leaders, indicates that such a step is so important that it must eventually be made. Without detracting from the need to maintain and to improve our capabilities for all-out war, which we must have in any case, the U. S. and its allies should have the necessary assortment of weapons systems, both in number and in kind, to wage war at many levels short of total war.

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Because the Communist Bloc has far more conventional war power than we and our allies can reasonably expect to maintain, and because considerable time will elapse before an adequate level can be achieved, it will be necessary to emphasize quality both in weapons and in manpower. A not insignificant part of the required qualities will be long range mobility of a high order making it possible to rapidly apply substantial force whenever and wherever it is needed.

Effective long range mobility for a large force or forces, whichever the case may be, ready in a no-war condition to go immediately to any part of the world, requires an active transportation capability well in excess of that needed to fulfill normal peacetime requirements economically. In addition, when time might be a vital factor, a large segment of the available transport must be free of commitment at the time of need.

There are two basic methods for establishing transport capacity to meet emergency conditions:

(1) Augment existing transport systems, both air and surface.

(2) Establish systems whose sole function is to maintain a readiness for immediate deployment.

Of the two the latter is preferred because:

(1) Instantaneous readiness for deployment would be higher.

(2) Such systems would be designed for their mission and free to train with the forces they are intended to support.

(3) The impact of a sudden increased requirement for transport on other logistic committments would be less.

Our concern in this analysis is principally with airborne aspects to war logistics transport, and more specifically, the requirement for a water landing capability to give access to world areas where facilities for large landplane cargo carriers are not available. The geographic versatility of seaplanes would permit them to supplement landplane cargo carriers in most areas. In other areas the seaplane may be the only possible large air logistic carrier which could be used, although transfer to smaller short haul cargo aircraft may be required to reach the ultimate destination in some instances.

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1. Strategic Air Logistic System

A strategic air logistic system would consist of a fleet of seaplanes whose sole function would be to provide emergency airlift and to conduct operational training exercises with combat teams of the Marine Corps and the Army. It would provide a capability for immediate deployment of a substantial force to any area of the world. The size of the fleet would be determined by:

(1) The capability considered to be required during the first 30 days of any probable emergency. Thirty days is an approximate time for diverting vessels; moving troops, equipment, and materials to a port of embarkation; loading, completing 6000 naut mi of travel; and unloading.

(2) The limitations of other air carrier systems (military and civil) from the standpoints of divertible capacity, and the adequacy of world wide facilities for landplanes.

(3) For a nuclear logistic carrier, probable changes of the political climate in the landlord nations where chemical aircraft support bases are or would be located, would also be a consideration, since it would be independent of way-stop requirements.

The system would be expected to transport a balanced ratio of troops, equipment, materials (initial and resupply) to support a military operation, at the level for which it was designed, until such time as surface transportation can take over the bulk cargo supply line. Its function thereafter would consist of transporting troops and high priority cargo to the theater of operations and returning casualties to the U. S. It is obvious from Table 4 that, where bulk cargo only is involved and time is not a factor, the air carrier cannot complete with surface vessels. However, the table does show that for troop transport, a large subsonic seaplane is superior to the average surface transport. The fact that an air carrier also reduces the in-transit time for personnel, permitting maximum time for training, and contributing to the physical condition and morale of personnel at arrival, is an added benefit.

Analysis.- The analysis for this study was intended solely to evaluate, comparatively, some of the logistic factors involved in a strategic air logistic system. Table 4 is a compilation of these factors applied to a typical mission.

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TABLE 4

Logistic Capabilities of Various Vehicles--Unit Daily Rates

(Hypothetical Movement of Troops and Equipment from Ft. Lewis, Washington and Fort Campbell, Ky., to Tourane Indo-China)

		Payload	V_{avg} kn (1)	Origin	Via	Terminus	Total Naut Mi Round Trip	Trip Elapsed Time (2)	Delivered (3) Tons/da/ac		Delivered (3) Troops/da	Chem. a/c Fuel Req. Outside U.S. Fuel/PL	Tons/da
Chemical Seaplane	or	65 ton 420 troops	460	Seattle, (Ft. Lewis)	Hon. T.H. Kwaj., Guam Man. P.I.	Tourane I.C.	15,900	53 hr	18.8	or	120.5	5.2	98
NUCLEAR SEAPLANE	or	50 ton 400 troops	480	"	(Great Circle)	"	12,250	30.7 hr	19.5	or	153.5	0	0
Cargo Master (4)	or	35 ton 140 troops	250	"	Hon. T.H. Kwaj., Guam Man. P.I.	"	15,900	74.5 hr	5.5	or	21	4.25	23.4
Strato-Tanker Cargo (4)	or	25 ton 100 troops	480	"	Hon. T.H. Kwaj., Guam Man. P.I.		15,900	43.7 hr	7.58	or	30	7.58	50.8
Chemical Seaplane	or	70 ton 420 troops	460	Ky. Lake (Ft. Campbell)	S.F., Hon. T.H. Kwaj., Guam Man. P.I.	"	18,700	60.8 hr	17.2	or	103	4.6	79
NUCLEAR SEAPLANE	or	50 ton 400 troops	480	"	(Great Circle)	"	15,220	37 hr	15.7	or	126	0	0
Cargo Master (4)	or	38 ton 140 troops	250	"	S.F., Hon. T.H. Kwaj., Guam Man. P.I.	"	18,700	87.5 hr	5.06	or	18.5	3.87	19.6
Strato-Tanker Cargo (4)	or	25 ton 100 troops	480	"	"	"	18,700	51.5 hr	6.4	or	27	6.08	41.2
Cargo Ship	and	5000 ton 400 troops	15	Seattle	(Great Circle)	"	12,400	43.5 da	114	and	9.2	--	--
Transport Ship	and	2000 troops 3000 tons	15	"	"	"	12,400	41.5 da	69	and	46	--	--
Cargo Ship	and	5000 tons 400 troops	15	S.F.	(Great (Circle)	Tourane I.C.	13,020	46 da	108	and	8.8	--	--
Transport Ship	and	2000 troops 3000 tons	15	"	"	"	13,020	43.5 da	65.5	and	44	--	--
Tanker		11,200 tons	15	"	"	Hypothetical Point average of fueling points outside U.S.	8,880	29.6 da	377			--	--

(1) Considers climb and let down for all stops.

(2) Includes:

Loading Time
- 3 hr for seaplane
- 5 hr for landplane
- 3 da for cargo vessel

Refueling Stop Time
- 3 hr for seaplane
- 1.5 hr for landplane
- 3 da for cargo vessel
- 2 da for transport
- 2 da for tanker

Unloading Time
- 2 hr for seaplane
- 1 hr for landplane
- 2 da for cargo vessel
- 1 da for transport vessel
- 1 da for tanker

(3) Aircraft Flight Utilized - 10 hr/da
Cargo vessel underway - 19 hr/da
Transport and Tanker - 20 hr/da
Excludes loading, unloading, refueling and maintenance time for aircraft
No additional allowance is made for the fact that the nuclear seaplane saving of 40% in elapsed time in one case and 35% in the other over the chemical seaplane could have a substantial effect in actual operation.

(4) The Cargomaster and Strato-Tanker are used here only for comparison without regard to the availability of facilities at the Terminus.

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The factors used for comparison in compiling this table were adjusted to eliminate subfactors for which comparable data are not available. For example:

(1) The turn-around times for logistic surface vessels given in NWIP-11-21, which take into account delays and slowdowns in handling cargo, actually experienced in practice, are not used, since no comparable data are available for an air logistics system. Idealized figures are used instead of the assumption that these intangibles might be proportionate, and not influence the gross ratios appreciably.

(2) Aircraft utilization times were made equal for the same reason discussed above, although the nuclear seaplane would, with the same utilization, have 35-to 40% more time available at home base for maintenance.

(3) The capacity and speeds of the surface vessels used are similar to actual vessels, and are somewhat average.

(4) All payloads are in pounds or short tons (2000 lb).

Summary of conclusions.- A summary of conclusions inferred in the analysis from Table 4 are:

(1) The rate capacity of one nuclear seaplane between Seattle and Indo-China equals:

0.188 cargo vessels in capacity for cargo
3.33 personnel transport vessels in capacity for troops
0.282 personnel transport vessels in capacity for cargo and troops.

(2) An equivalent chemical seaplane would equal 0.150 cargo vessels between the same points, but require 0.380 tankers to support it.

(3) One hundred operating nuclear seaplanes could deliver 58,500 tons from Seattle to Indo-China in 30 days, or the equivalent of 11.7 cargo shiploads. This is approximately equal to a completely equipped Army division plus its support elements.

(4) Between the same two points, 100 operating chemical seaplanes could deliver 56,500 tons in 30 days, or the equivalent of 11.25 cargo shiploads, but would require the equivalent of 26.2 tanker loads of fuel distributed at Honolulu, Kwajelein, Guam and Manila.

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(5) For bulk argo, where time is not a factor, aircraft probably cannot compete with surface vessels economically, although for high cost items the value in the pipeline could indicate otherwise.

Comparison to other air carriers.- At the rates shown in the table, 158 operating nuclear seaplanes would have an annual capacity equal to the available passenger and ton miles flown by all civil U. S. scheduled airlines in 1958. Actual revenue passenger and ton miles could be equaled by 91 nuclear seaplanes.

On a similar basis, eight operating nuclear seaplanes could exceed in capacity the total ton miles flown by the military in a recent year.

General observations.-

(1) A strategic air logistic system consisting of nuclear seaplanes would provide rapid transportation of combat effective troops into areas not having adequate landplane facilities.

(2) The aircraft considered in this study could carry Marine Corps or Army equipment which cannot presently be considered for airlift because of size.

(3) With nuclear power the airlift capability would be constantly ready to deploy troops without requiring advanced bases, or world-wide fuel placement and fuel logistics back up.

(4) Because nuclear-powered aircraft do not require tanker support, it would be logical, logistically, to continue the airlift of bulk cargo. On the other hand, chemically powered aircraft would require more tankers to support it than it can carry in equivalent cargo vessel capacity.

(5) A water landing nuclear strategic air lift would provide a capacity which cannot be furnished by an existing system (civil or military) in these respects:

   (1) In available ton miles for a large scale deployment.

   (2) In capacity for all types of combat and support equipment.

   (3) In providing airlift accessibility to many areas of the world.

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Other factors.- Many of the logistic factors involved in operating a strategic airlift are not treated in the foregoing and economic factors are not treated at all. These factors are too complex or intangible for simple analysis and depend upon data which are not available and in some measure upon political-military considerations in which opinions are highly variable.

A more comprehensive analysis which is outside the scope of this study would evaluate the following:

(1) The availability of world-wide facilities for supporting a chemical aircraft system through the years ahead from a political and a physical standpoint.

(2) The cost of providing and supporting the additional facilities which would be required for a chemical aircraft system.

(3) The complete logistic requirements for combat equipped Marine Corps and Army units, in terms of men and equipment, to be transported initially and for resupply over a given time in order to determine the number of aircraft required and the number of ships required for either a chemical or a nuclear aircraft system. The number of ships required to be active to support any stipulated level of limited war capability would be substantially different for chemical versus nuclear aircraft and could have a significant effect on cost differences to maintain a capability.

(4) The cost, logistic load, military readiness obtained and the political implications of alternate methods for maintaining equal capability, such as, prepositioning men and materials in strategic locations throughout the world.

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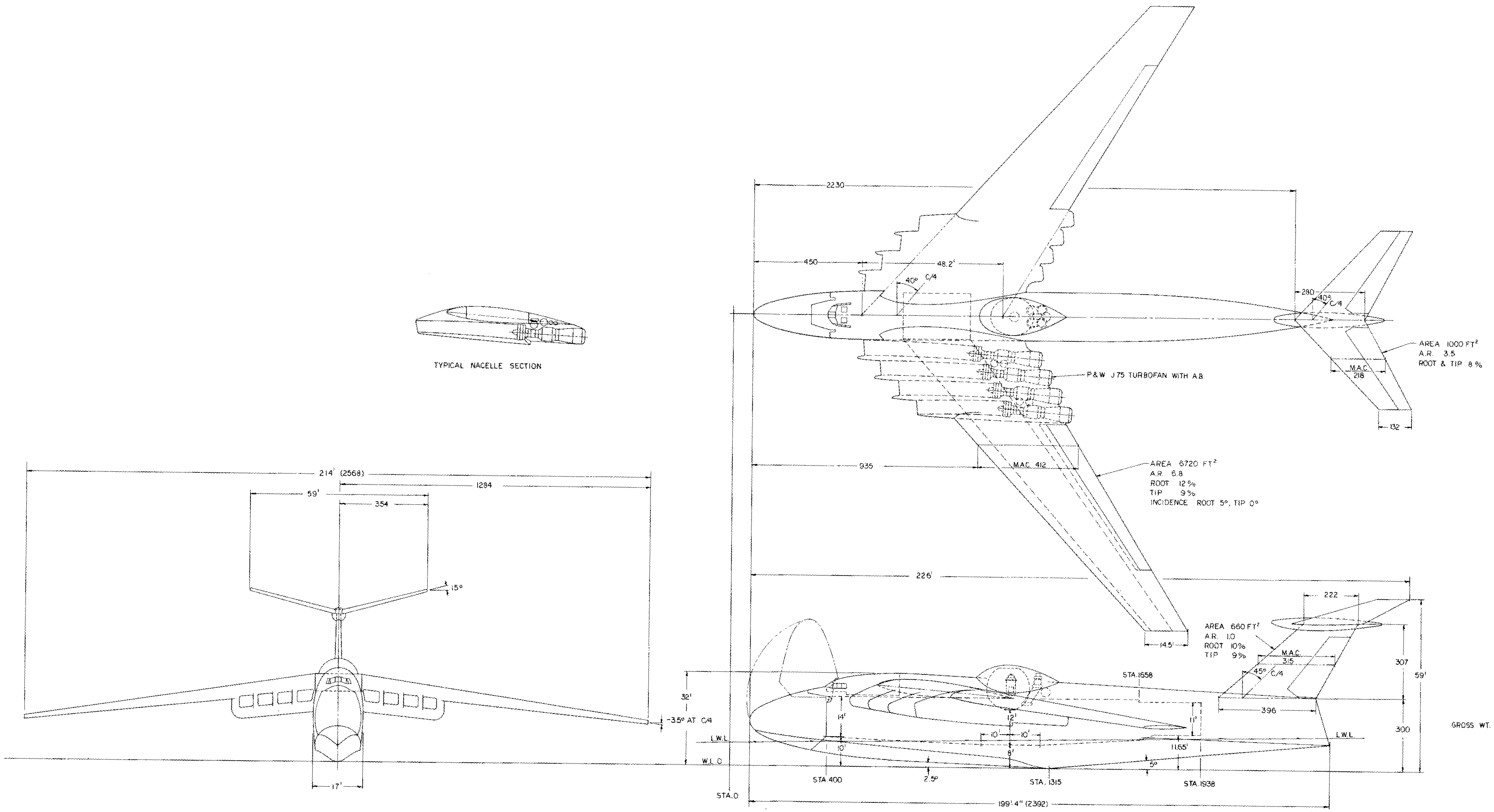

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Fig. I-14. General Arrangement, Logistic Transport

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(8) TF-75 A/B Engines

$\Lambda_{c/4} = 40°$ $t/C_{avg} \approx 0.105$

Payload = 100,000 lb

Hull = $L_f/b \approx 6.7$

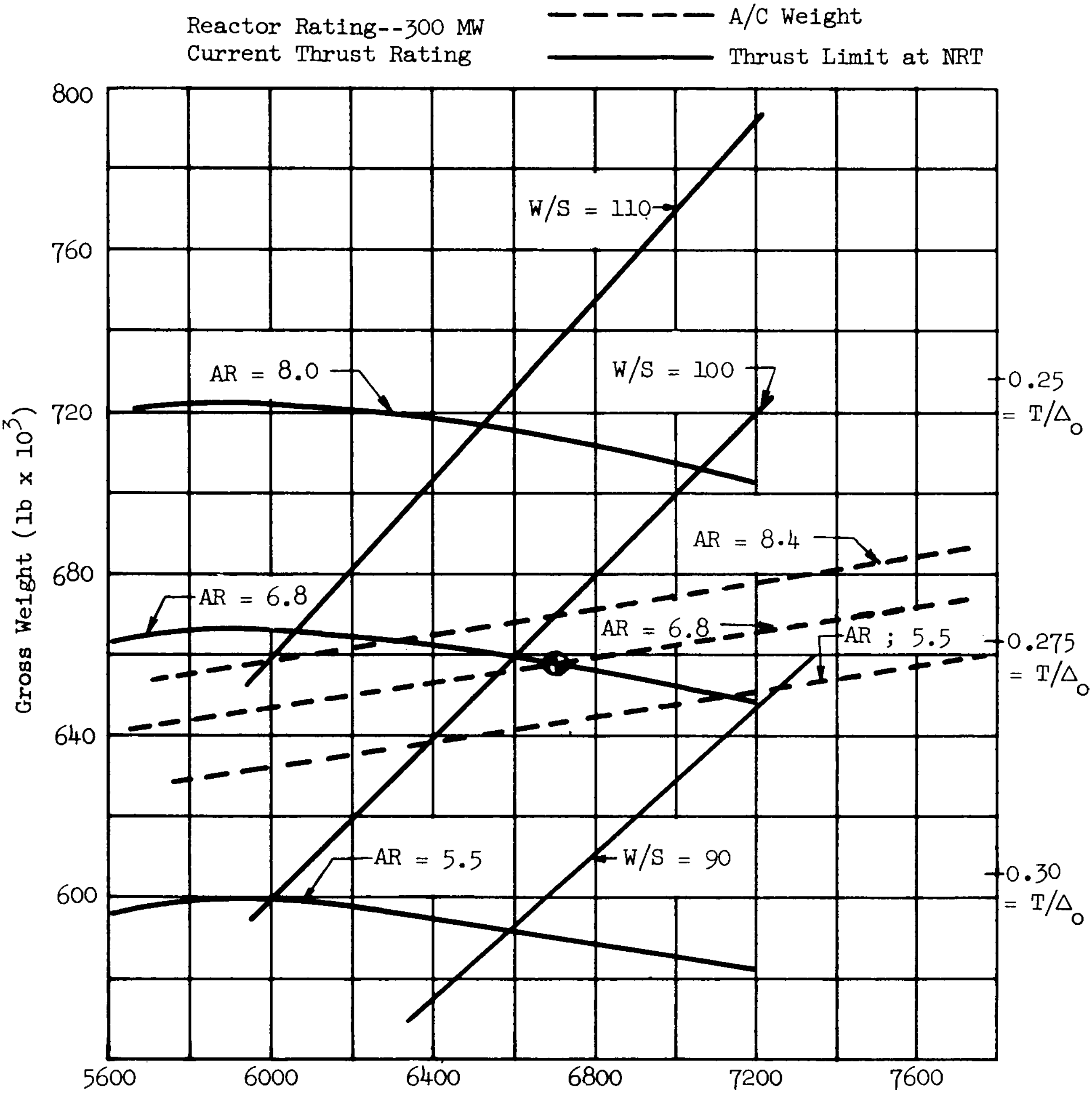

Fig. I-15. Wing Loading Variation

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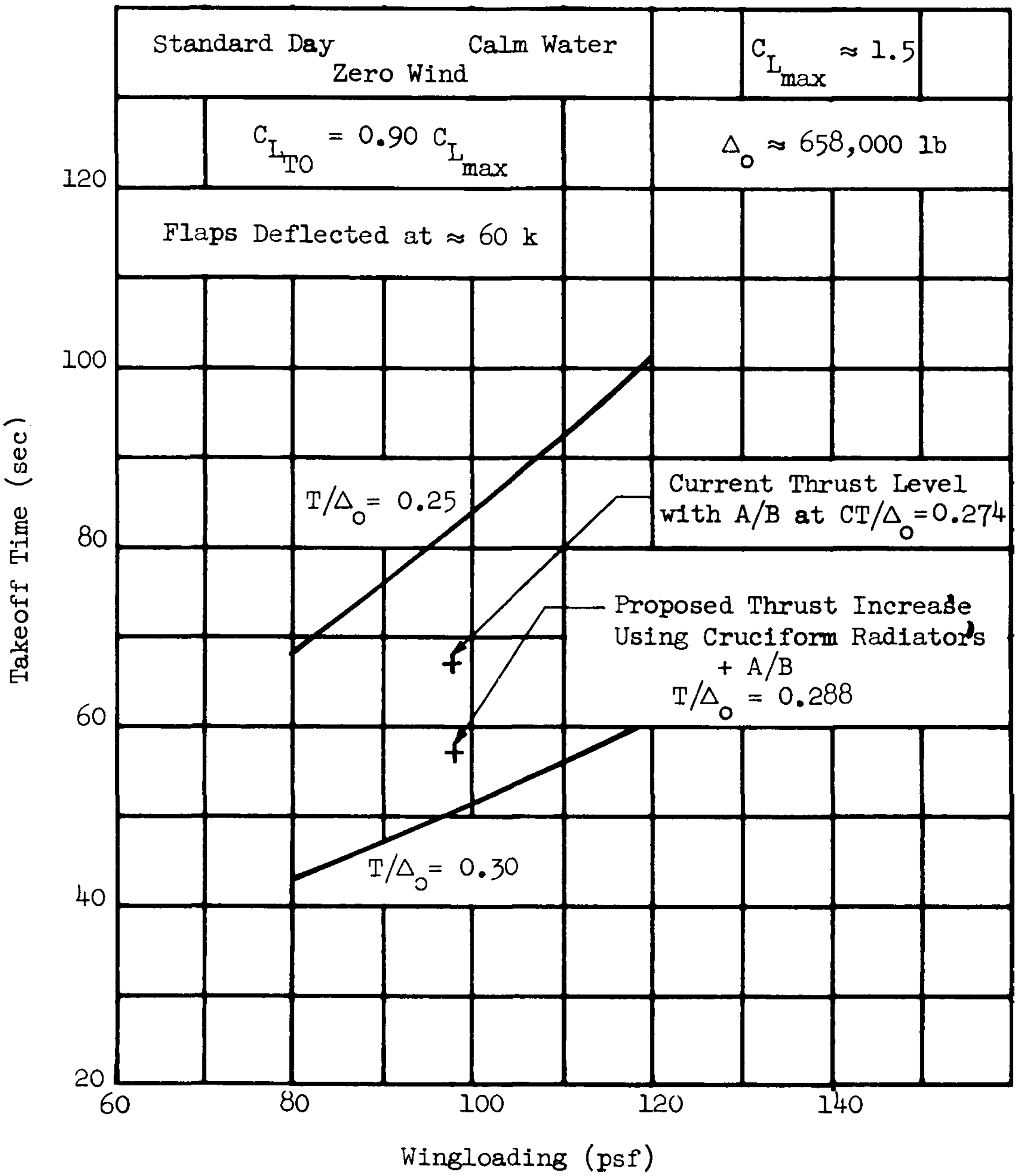

Fig. I-16. Estimated Takeoff Performance

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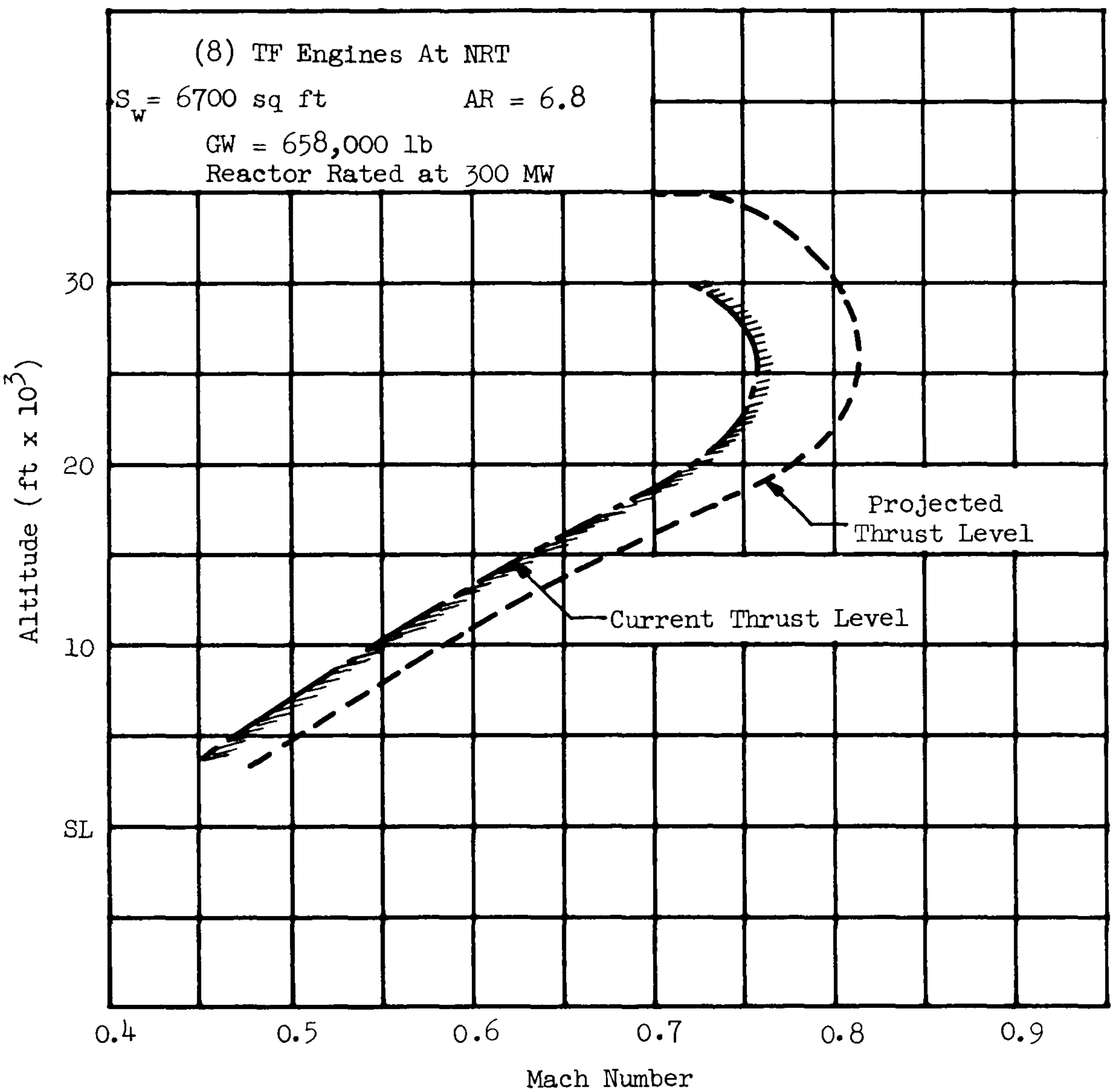

Fig. I-17. Maximum Level Speed at Altitude, Nuclear Power

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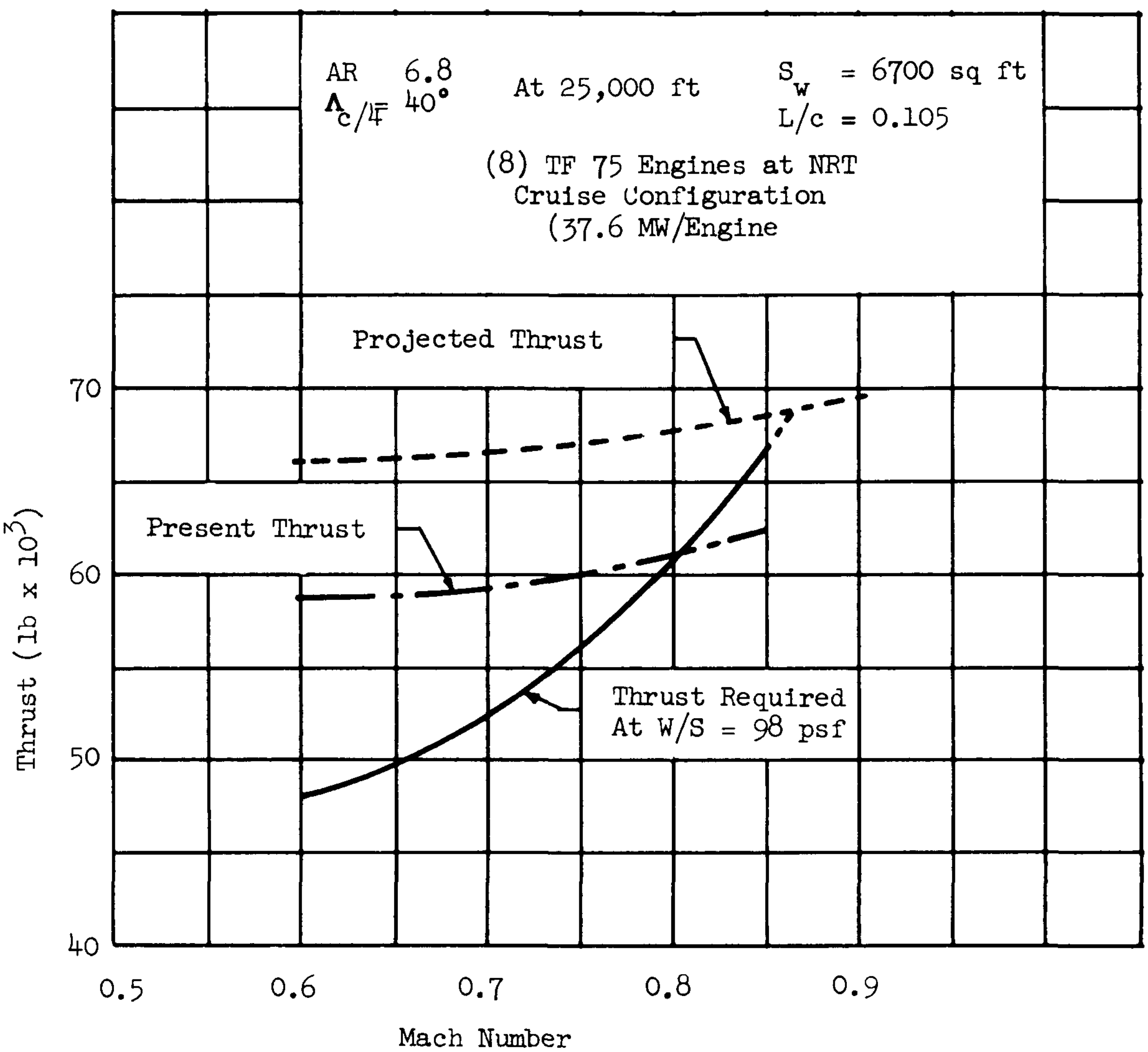

Fig. I-18. Estimated Thrust and Drag vs Mach Number, Nuclear Power

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AR = 6.8 At 15,000 ft S_w = 6700 sq ft

$\Lambda_{c/4}$ = 40° t/c = 0.105

(8) TF-75 Engines at NRT
Cruise Configuration
(37.6 MW Engine)

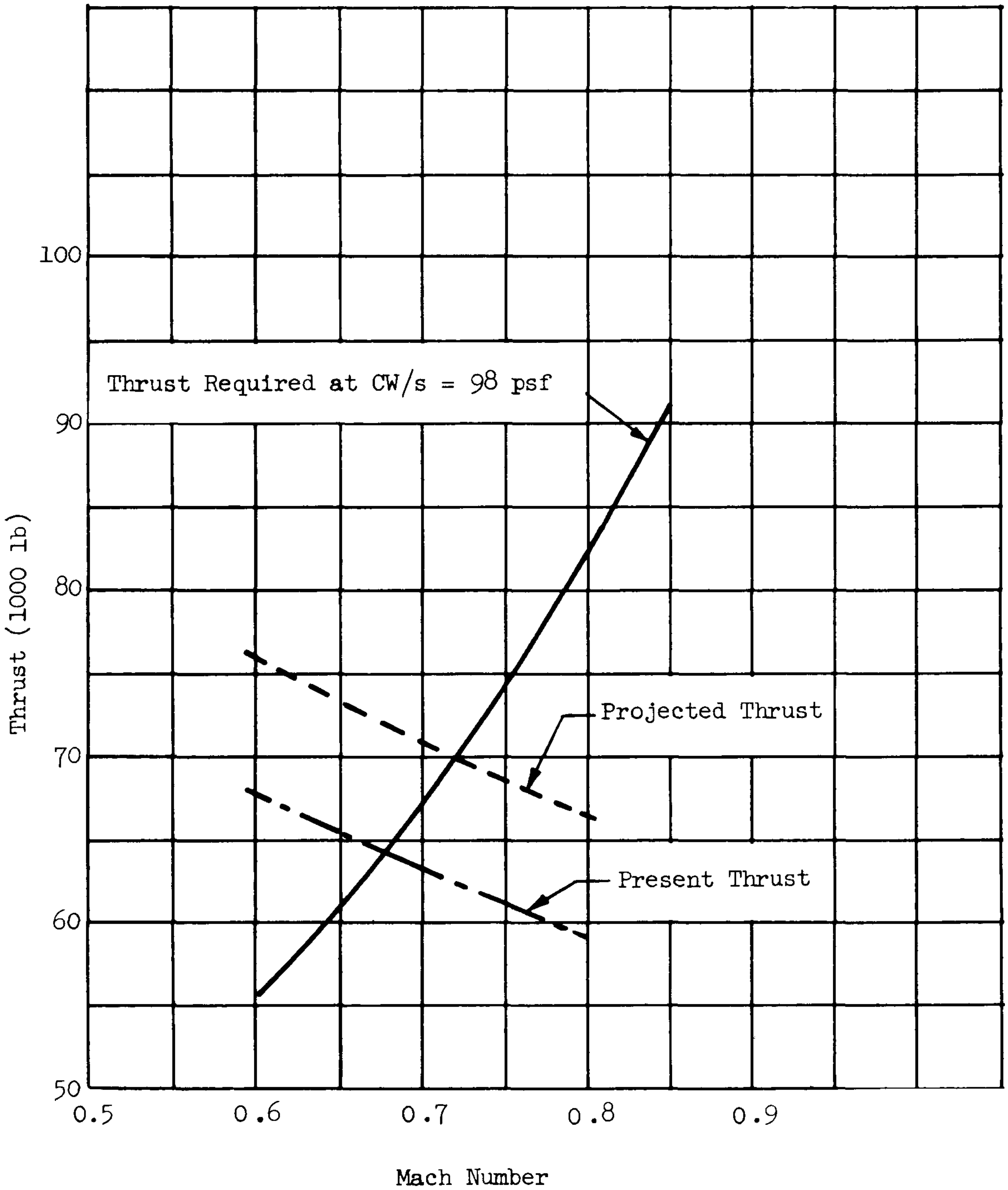

Fig. I-19. Estimated Thrust and Drag vs Mach Number, Nuclear Power

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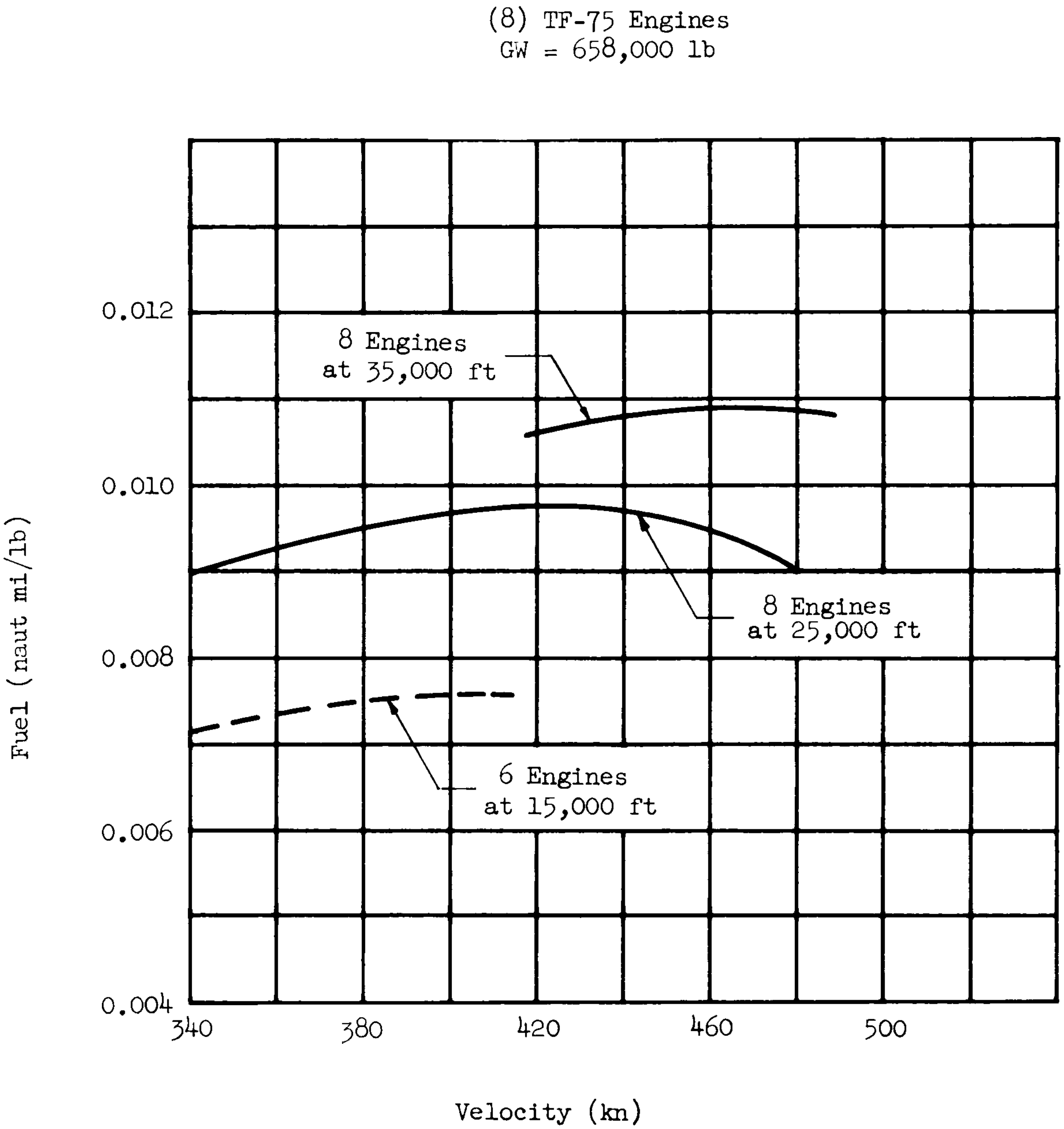

Fig. I-20. Estimated Specific Range vs Air Speed, Chemical Power

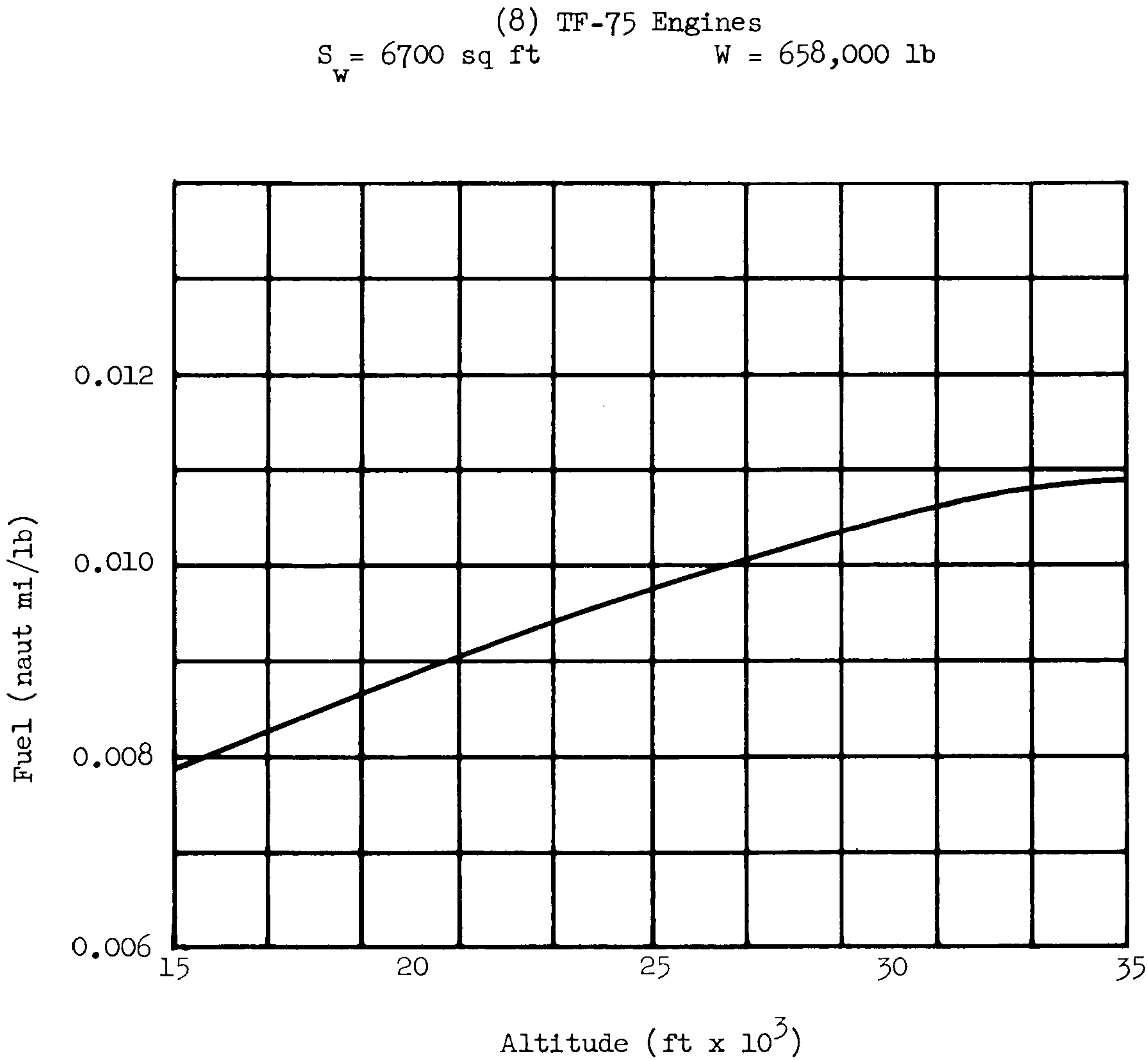

Fig. I-21. Estimated Specific Range at Altitude, Chemical Power

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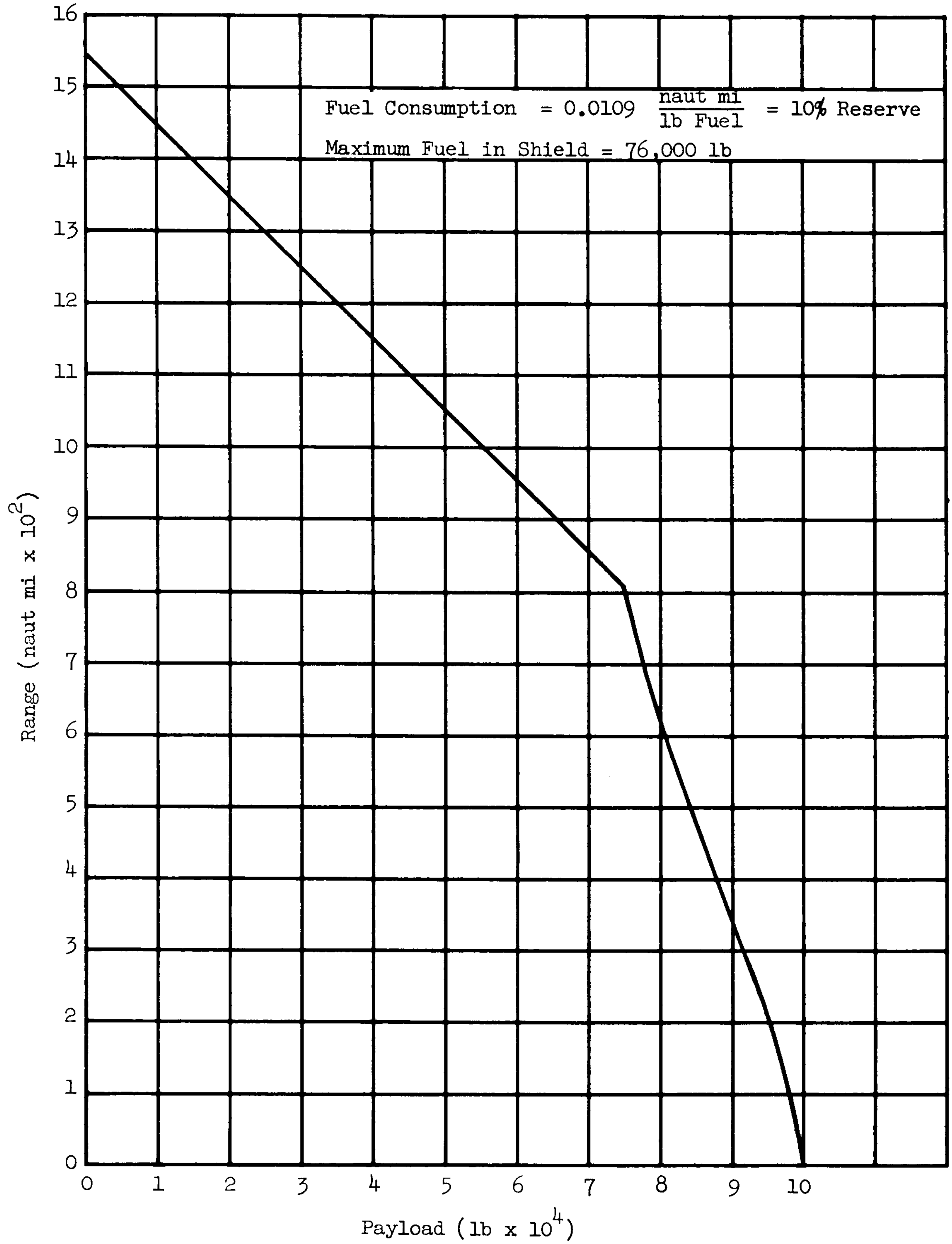

Fig. I-22. Payload vs Chemical Fuel Range

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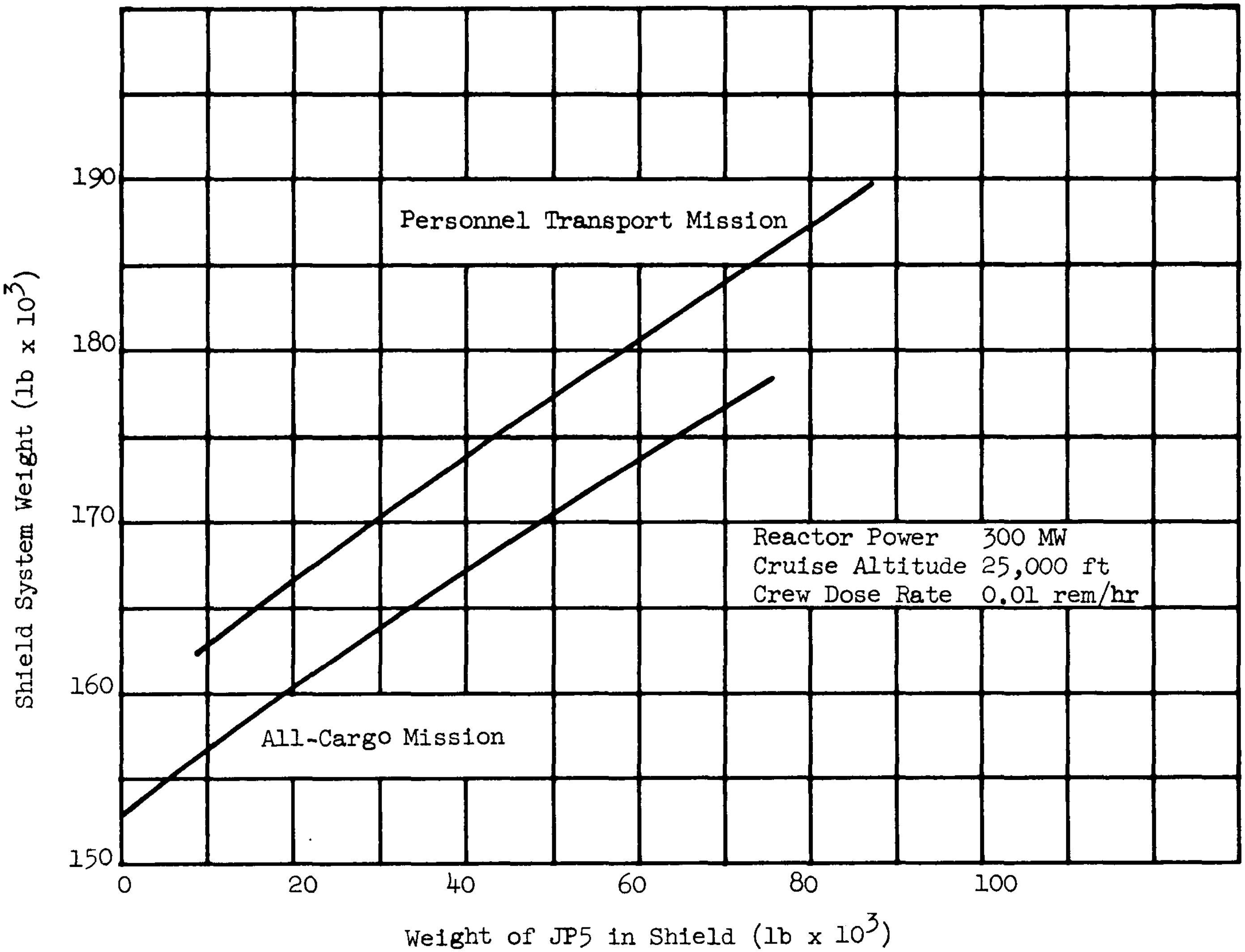

Fig. I-23. Shield Weight vs Weight of Fuel in Shield

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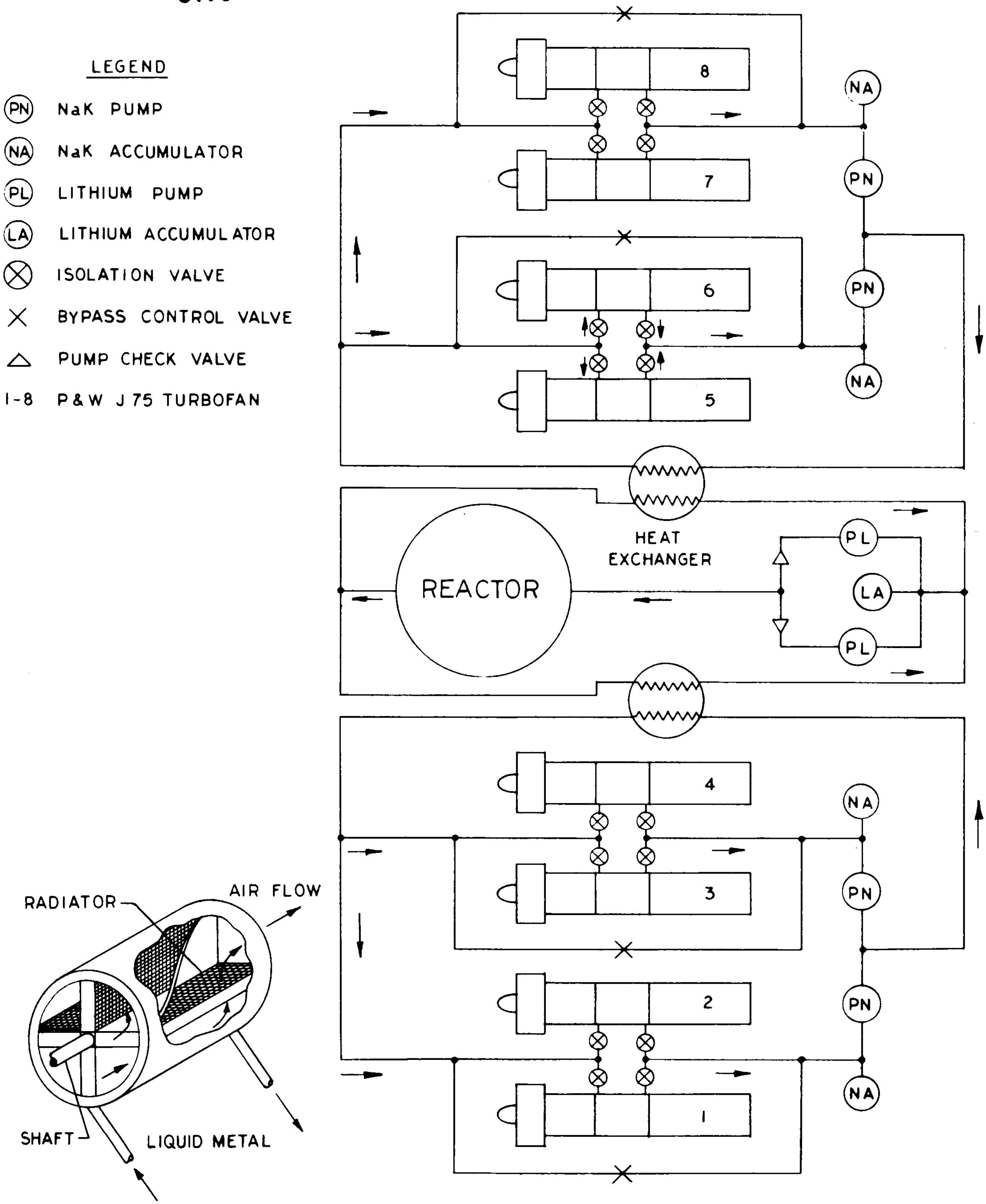

Fig. I-24. Liquid Metal Schematic

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Maximum Reactor Power/Engine--36.9 MW

- O Nuclear Heat Thrust Only
- □ Nuclear Heat and Chemical Interburning
- △ Nuclear Heat and Chemical Interburning and Afterburning

Princess Type Radiators, Wing Mounted Liquid Metal Pumps, Bleed Air Turbine Driven, Fuselage Mounted

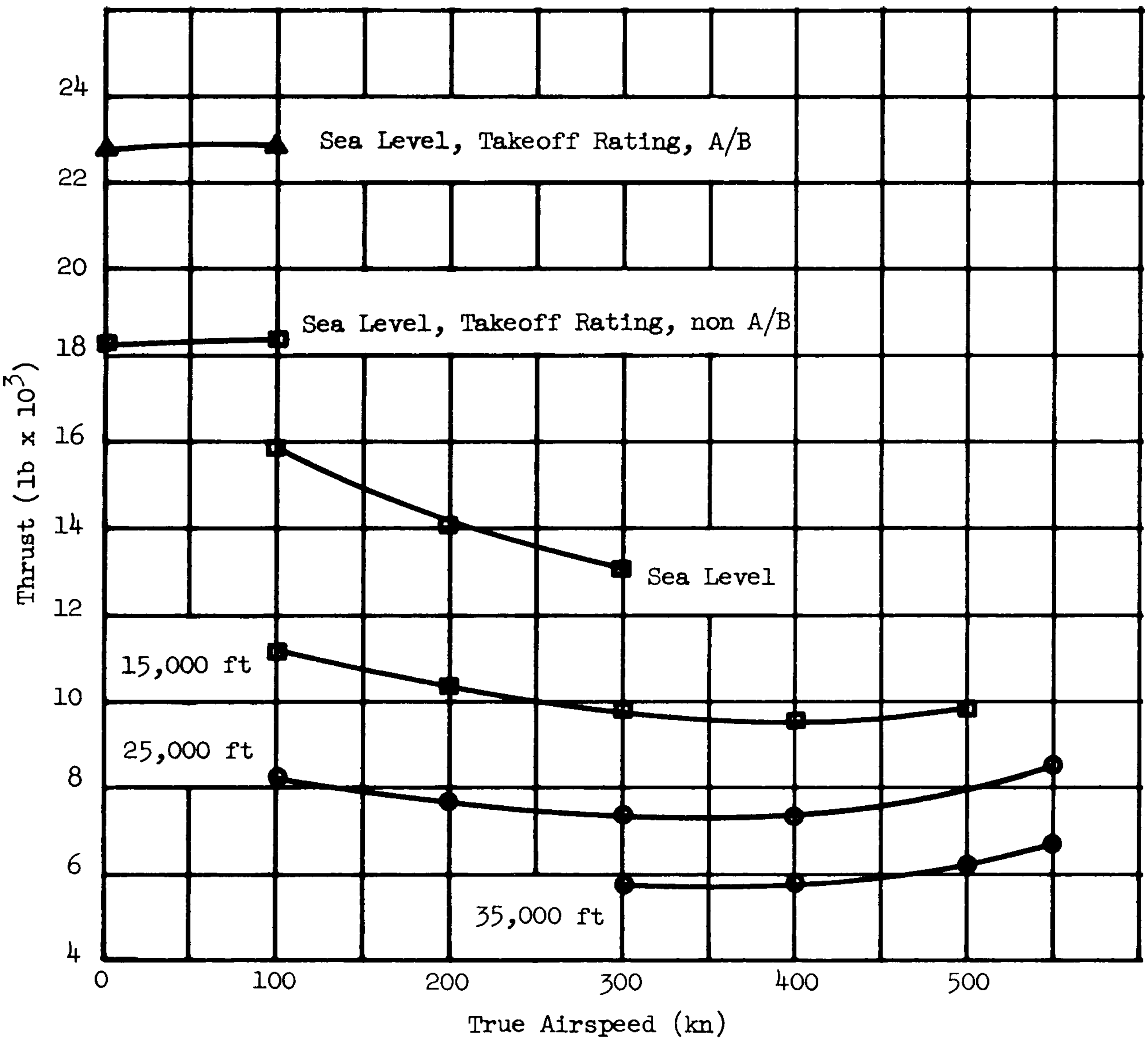

Fig. I-25. Normal Rated Thrust, Turbofan J-75

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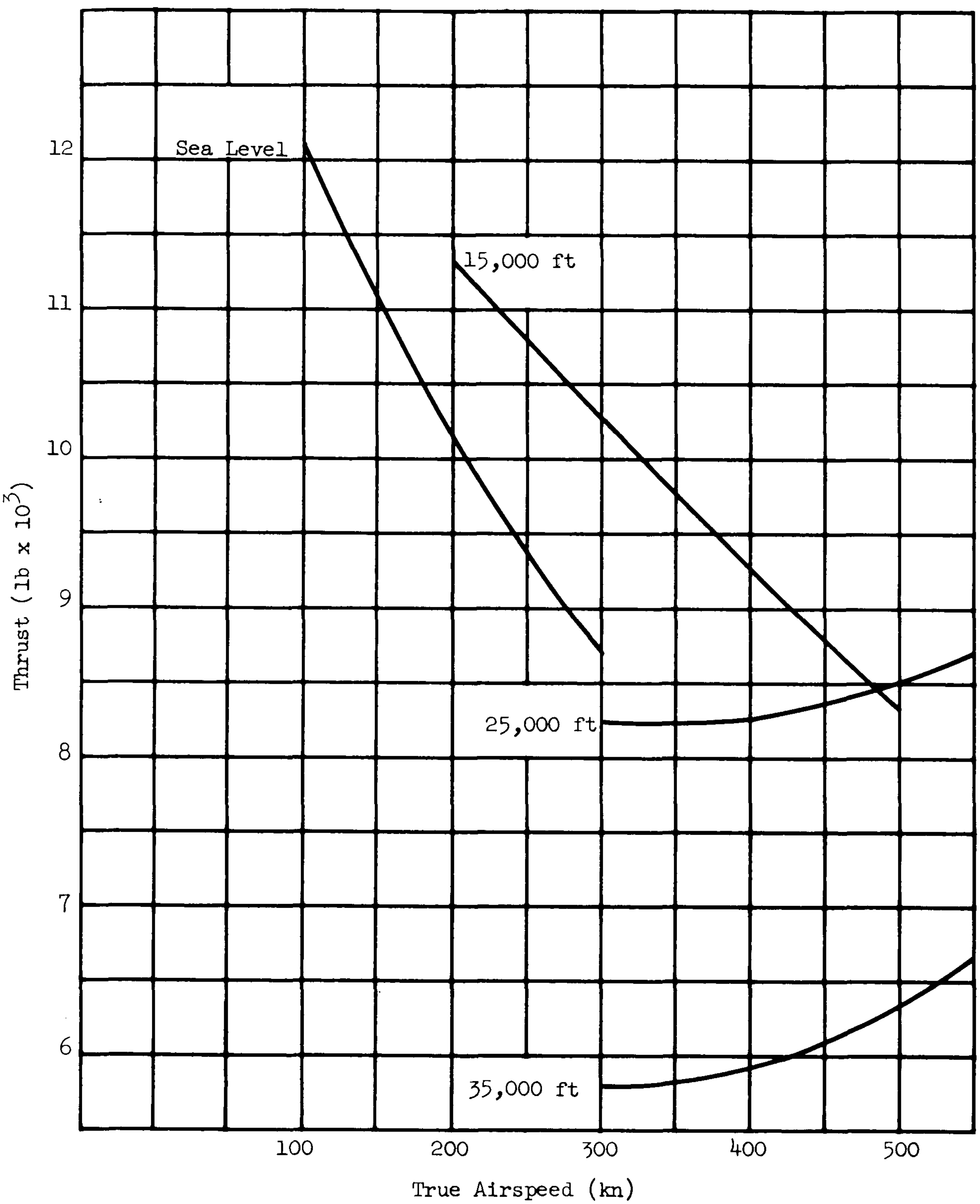

Fig. I-26. Nuclear Heat Thrust, Advanced Turbofan J-75

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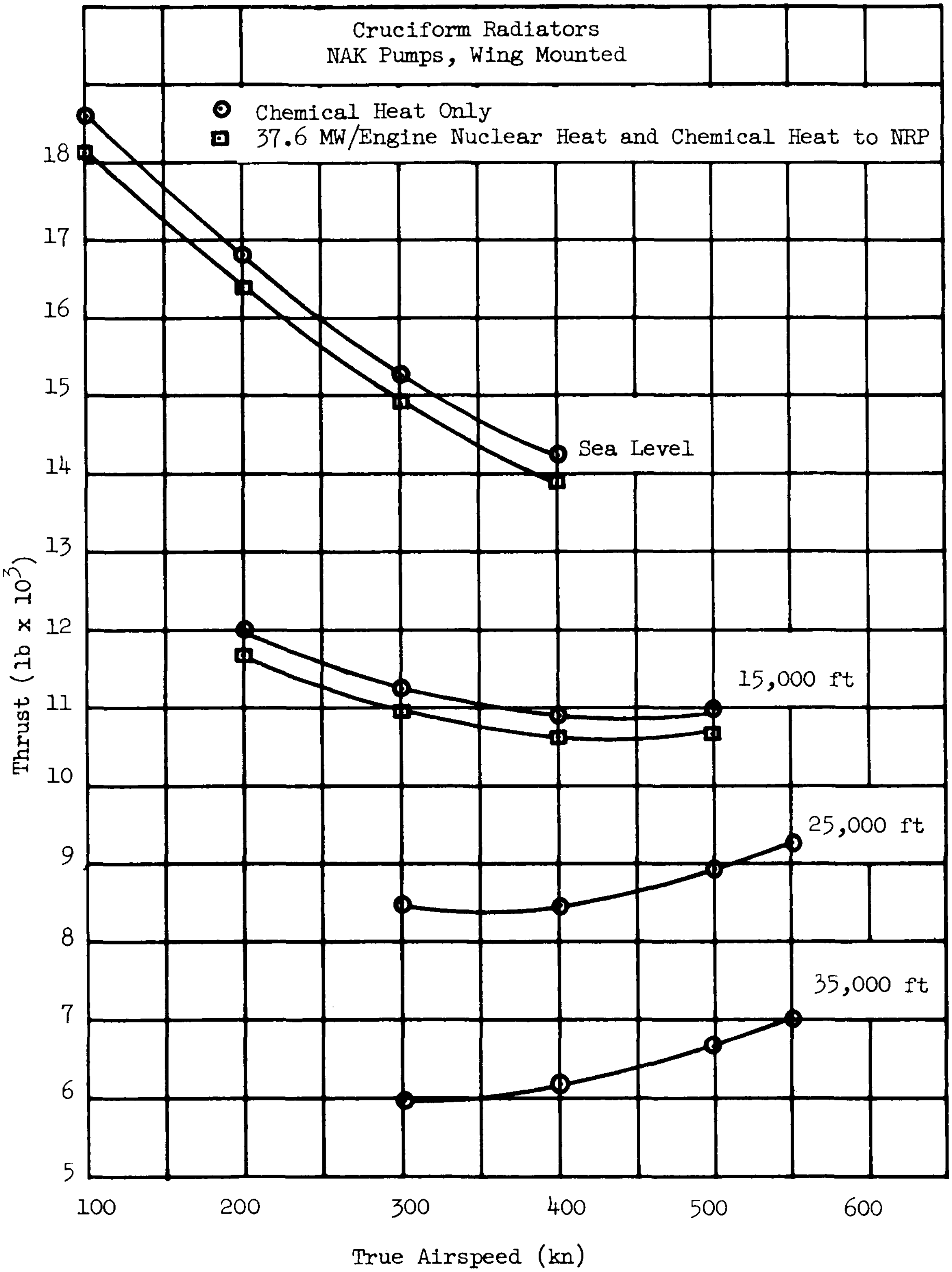

Fig. I-27. Normal Rated Thrust, Advanced Turbofan J-75

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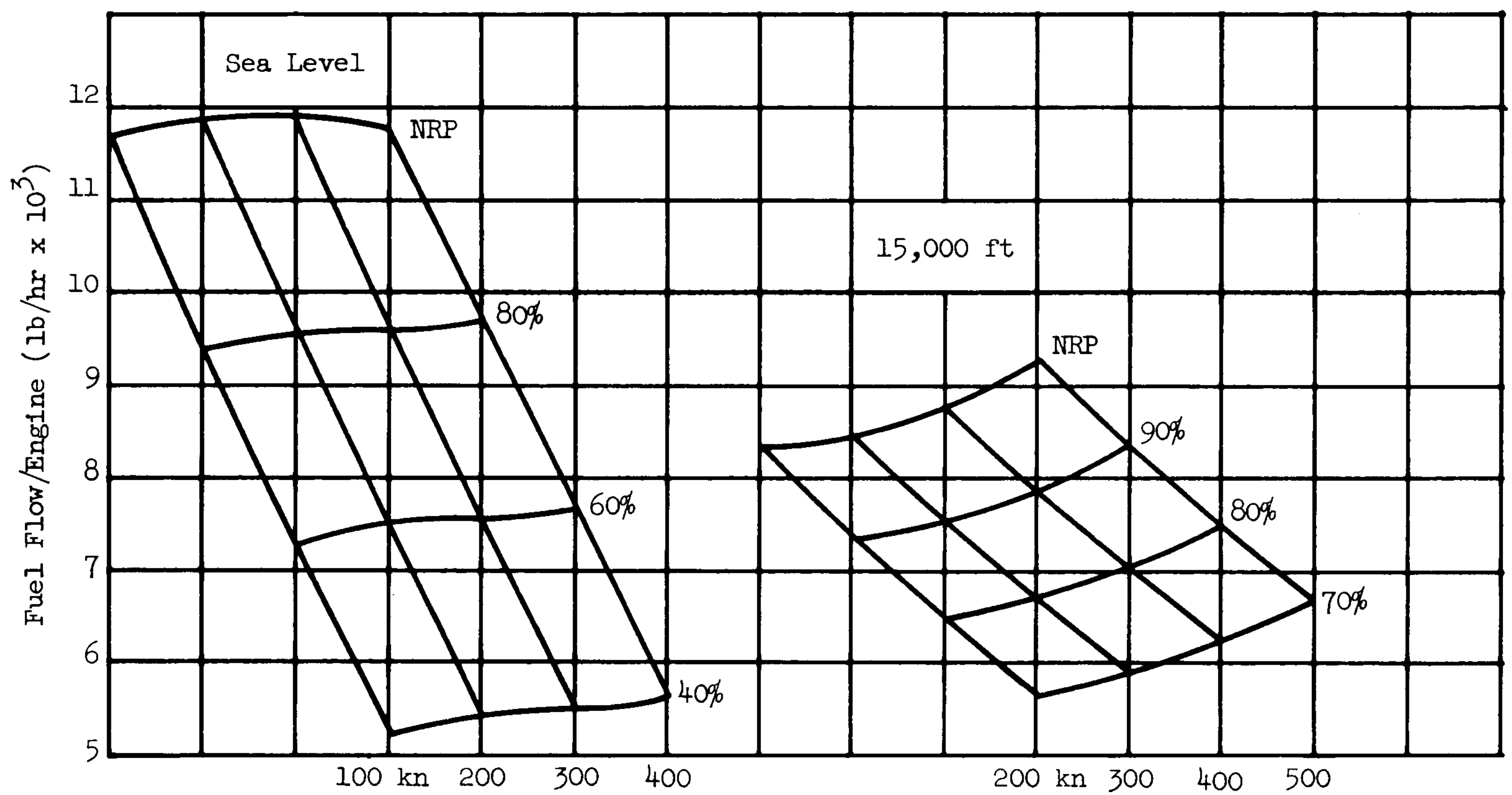

Fig. I-28. Fuel Flow Chemical Heat Only, Advanced Turbofan J-75

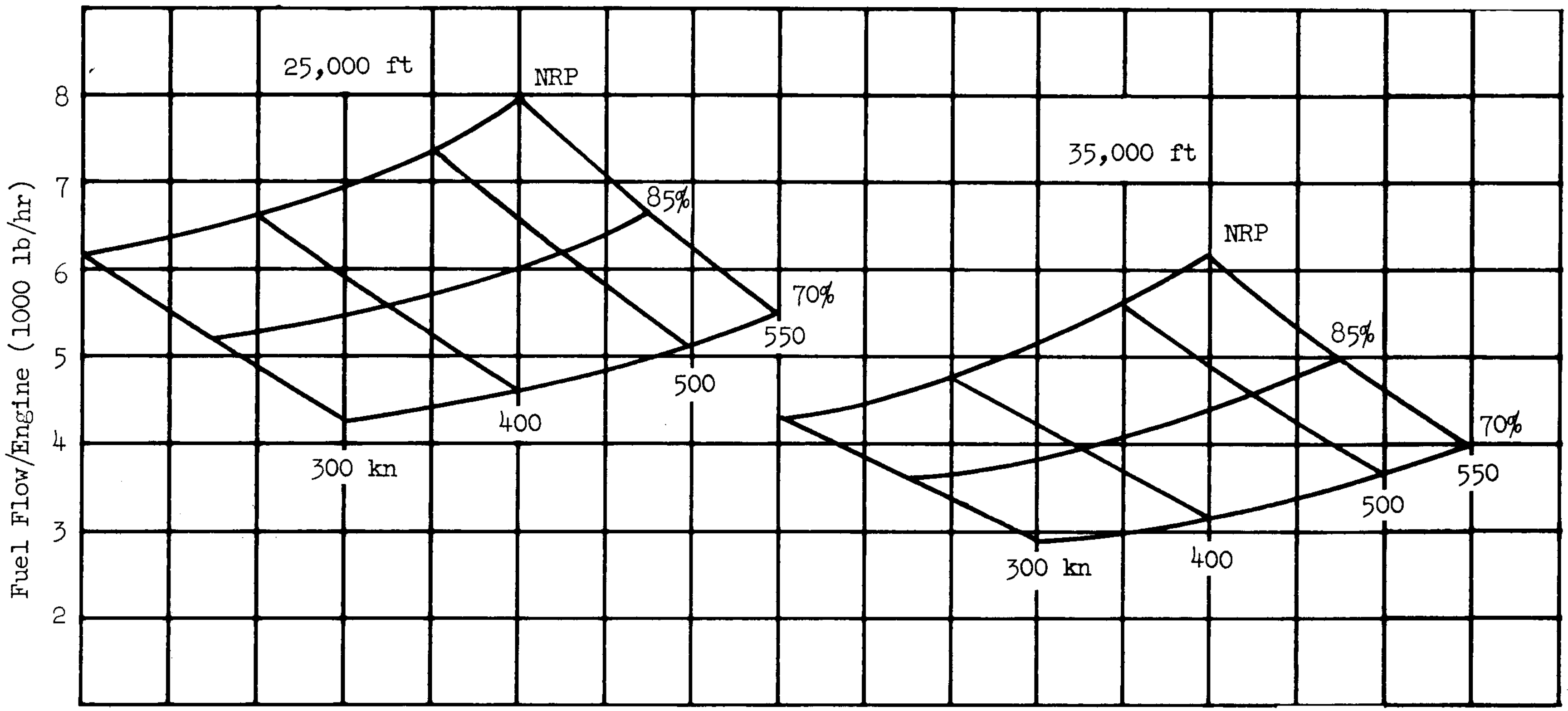

Fig. I-29. Fuel Flow Chemical Heat Only, Advanced Turbofan J-75

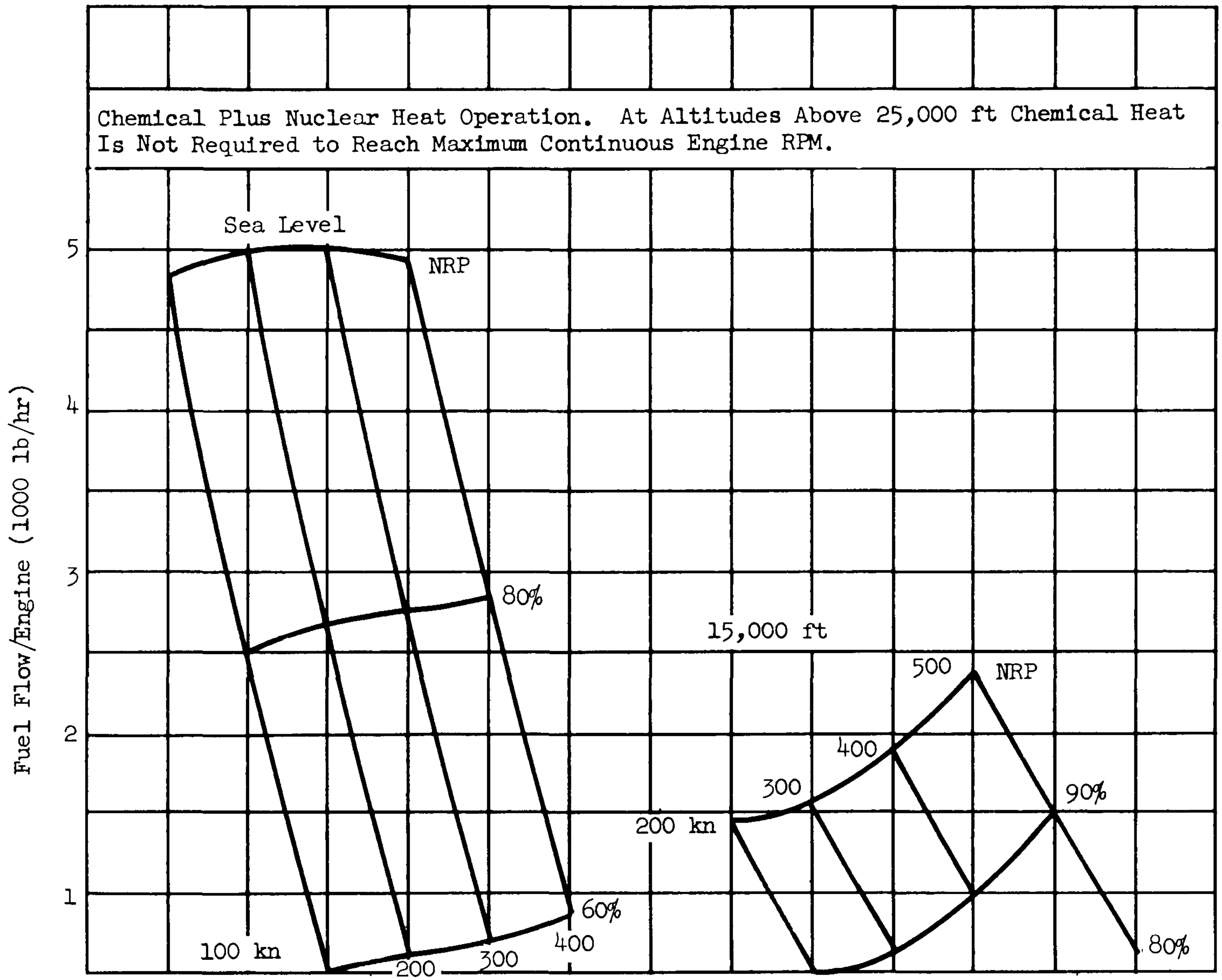

Fig. I-30. Fuel Flow, Chemical Heat Plus Nuclear Heat Operation
Advanced Turbofan J-75

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ENGINEERED UNIT SHIELD STUDY

PART II

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I. INTRODUCTION

During the last quarter the preliminary design and analysis of an engineered shaped unit reactor shield for a direct air cycle (DAC) airborne nuclear propulsion system was concluded. The objective of this task was to utilize existing shielding data and techniques, in so far as possible, in the preliminary design of a unit reactor shield for an airborne nuclear power plant. An important aspect of the study was the incorporation of the shield system into a realistic flight vehicle of the same time period as the reactor, in order to evaluate and include the effects of the aircraft on the shield conceptual design.

The nuclear analysis of the resultant shield includes the contributions to crew dose rate arising from radiation leaking from the core, and from secondary gammas generated within the shield, but does not include the capture and inelastically scattered gammas from the structural materials or leakage radiation along or through irregularities in the shielding materials arrangement. Radiation emerging from the air ducts penetrating the shield was evaluated using a Monte Carlo-albedo annular duct penetration code specifically developed for this purpose.

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II. ASSUMPTIONS

A. NUCLEAR POWER PLANT

The heat source for the nuclear propulsion system was assumed to be similar to the General Electric DAC reactor core designated model D103B. Where requisite data regarding the characteristics of this core were incomplete, they were extrapolated from available information on other DAC reactor systems. The D103B core is designed to fit the XMA-1 power plant core cavity and will have the capability of providing 1700° F exit air temperature. Core materials and operating temperatures are given in Ref. 1 APEX-28 as:

Component	Maximum Average Temperature (° F)	Composition Weight (%)
Hydrided moderator	1900	70Y-30Zr (Avg N_H = 5.0)
Moderator cladding	1900	75.5Fe-20Cr-4.5Al
Fuel core	2000	$40UO_2$+60 (Cr+1Ti)
Fuel cladding	2000	69Fe-30Cr-1Y
Reflector	1400	Be
Control rod	1600	$42Eu_2O_3$-43.5Ni-14.5Cr
Structure	1400	Inconel X
	1800	Hastelloy X

The following dimensional data were assumed in the geometric description of the core:

Reactor length (active)	27.5	in.
Reactor equivalent diameter (active)	56.61	in.
Reactor length (across tube sheets)	37.625	in.
Reflector outside diameter (Be)	61.953	in.
Forward reflector thickness (Be)	5.0	in.
Aft reflector thickness (ZrH_x)	0.5	in.

Number of cells	151	
Core loading (U^{235})	400	lb

Control rods and drive mechanisms were assumed to be arranged and operated in a manner similar to that utilized in the HTRE No. 3 design (Ref. 1 APEX-28) with rod drive linkages penetrating the forward shield materials, located along the reactor-crew axis.

The portion of the powerplant constituted by the rotating machinery was assumed to be represented by four modified T-57 turboprop engines operating at 350 kn and a cruise altitude of 25,000 ft. Operation of the reactor at a power level of 110 MW matches the core to the machinery for these operating conditions.

B. AIRCRAFT AND MISSION

The basic aircraft selected for incorporation of the nuclear power plant was a waterbased logistic transport, as shown in Fig. II-1. This vehicle is similar to one previously studied by The Martin Company (Ref. 2) and was selected as being representative of naval nuclear powered vehicles in the time period during which the selected reactor system would be available; i.e., 1965-70. The selected power plant is well matched to operation of this vehicle at a 600,000 lb gross weight at 350 kn and 25,000 ft.

The definition of the mission, logistical transport, effectively specifies certain characteristics of the aircraft, chief among which is the requirement for maintaining a clear cargo area. This consequence necessitates installation of the reactor shield assembly (RSA) in a fairing in the hull crown, above the center wing box.

Engine air is carried to and from the RSA by means of two sets of insulated ducts, one set serving the two engines in each wing. Chemical combustors, or interburners, are located in the wing, in order to have individual chemical power capability for each engine; increased aircraft reliability should result. The availability of adequate valving for the large diameter ducts to make this arrangement workable is assumed. Ducting sizes were established from pressure drop considerations.

The selected vehicle has an auxiliary chemical power plant of four buried J79 turbojet engines. These engines provide thrust augmentation for takeoff and also afford limited flight duration on chemical power in the event of failure of all or a portion of the nuclear power plant.

A group weight statement for the aircraft is given in Table 1 and indicates the payload capability of this vehicle. The figure given for payload includes all useful load items, fuel and any special equipment or provisions for a particular mission. No weight allowance has been included to provide the vehicle with a personnel transport capability.

TABLE 1

Group Weight Statement

	(lb)	(lb)
Wing		82,000
Tail		11,200
Hull		66,400
Floats		4,000
Surface controls		4,010
Nacelles		9,500
Propulsion		278,030
Engines (4) T-57	26,400	
Engines (4) J79	11,120	
Propellers	14,200	
Engine controls	280	
Air induction	780	
Lubrication system	2,200	
Exhaust system	1,400	
Starting system	640	
Fuel system	800	
Reactor shield assembly	201,310	
Interburner	3,000	
Ducts	14,400	
Afterheat removal	1,500	
Auxiliary power plant		600
Instrument		700
Power systems		11,000
Furnishings and equipment		3,500
Electronics		1,500
Air conditioning		600
Anti-icing		3,100
Auxiliary gear		2,100
		478,240
Useful load		121,760
Gross weight		(600,000)

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WING
- AREA — 7000 SQ.FT.
- ASPECT RATIO — 9.5
- AIRFOIL (CENTER WING) — NACA 23018
- AIRFOIL (TIP) — NACA 23010

HORIZ. TAIL
- AREA — 1050 SQ.FT.
- ASPECT RATIO — 3.5
- AIRFOIL — NACA 63A008

VERT. TAIL
- AREA — 1400 SQ.FT.
- ASPECT RATIO — 1.3
- AIRFOIL — NACA 63A010

POWER PLANT
- FOUR — TURBO PROP P&WT57
- FOUR — TURBO JET GE J 79
- ONE — AIR CYCLE REACTOR

WEIGHTS
- DESIGN GROSS WT. — 600,000 LBS.

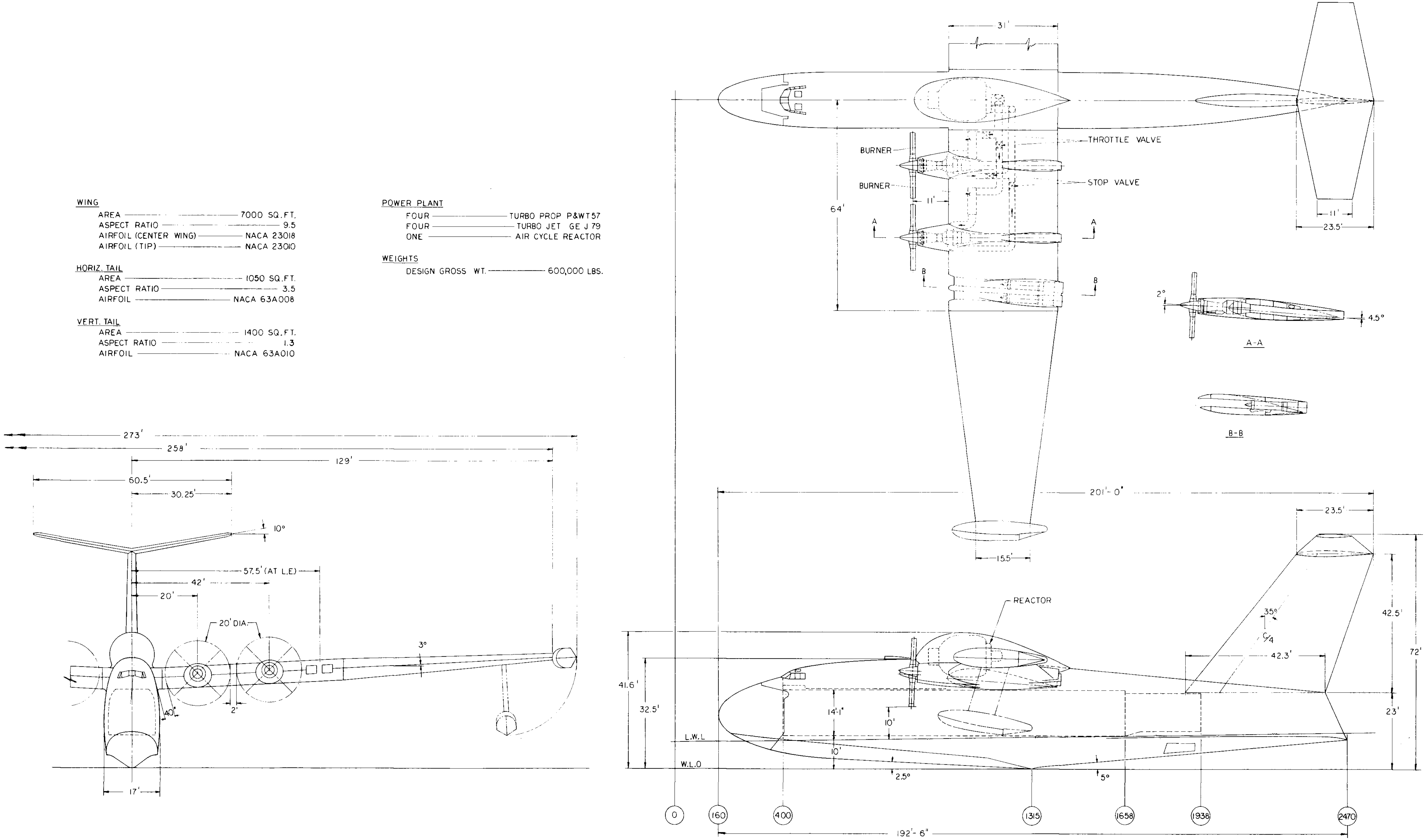

Fig. II-1. General Arrangement, Logistic Transport

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III. CONCEPTUAL SHIELD DESIGN

The shield design presented here represents an attempt to integrate the several influencing factors which are involved in the design of a radiation shield for a specific aircraft application. Emphasis was laid on the nuclear aspects of the design, with structural and thermal design criteria being established only for major components of the system.

The primary gamma shield material was selected as a tungsten compact of the Hevimet, Mallory 1000, etc., type. For analytical investigations, the nuclear and physical characteristics of Hevimet were used. The primary neutron shield materials are lithium hydride, beryllium oxide, and beryllium. Boron-loaded stainless steel is also used in the design. The structural material for the pressure vessels and regions internal to them was assumed to be Inconel X.

The use of chemical fuel as a shield material was not considered. Although utilization of fuel supplies in this manner can result in appreciably greater payloads or in reduced vehicle weights, it was felt that incorporation of this feature was beyond the scope of the design study.

A. NUCLEAR DESIGN CRITERIA

The ultimate design objective for the radiation shield for any airborne nuclear power plant is to provide radiation protection at minimum weight, in that the savings in shield weight are translatable directly into payload, for a given aircraft configuration; or into reduced aircraft gross weight, for a fixed payload. The means of obtaining such minimum weight must necessarily be consistent with the vehicle mission, ground support equipment, etc., in order not to prohibitively restrict the utility or maintainability of the vehicle. That is, the weight reduction must not come solely as a result of allowing increased operating and after-shutdown dose rates.

For this study, a dose rate of 0.02 rem/hr was selected as a design point; selection of this dose rate means that aircraft personnel will receive an integrated dose of approximately 0.5 rem on a 10,000 mi mission. Integrated doses will be significantly lower for many other missions. In relating integrated doses to the maximum dose levels recommended by the National Committee for Radiation Protection, 5 rem per year averaged over a ten year period, it should be noted that these recommendations are predicated on continuous occupational exposure to radiation for an average working lifetime. In view of the limited time

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period during which personnel responsible for the operation of this aircraft would be in the radiation field, it appears that a more significant dose rate design criterion would be the limit on absorbed dose, recommended by the committee as 50 rem by age 30 to 200 rem by age 60. Rotation of personnel to assignments not related to a nuclear environment may serve as a means of limiting absorbed dose to desired levels. With these provisions, the selected design dose rate of 0.02 rem/hr is justified as being of a reasonable magnitude. Further refinements in selection of a dose design point require both more complete information on human dose tolerance levels and rigorous specification of the schedule under which the vehicle will operate.

No criteria for maintaining acceptable dose rates in the cargo compartment for personnel transport missions have been employed. It was felt that alteration of the shield material distribution to meet such design criteria would require such extensive modification of the design as to render it unnecessarily cumbersome as a reference design.

A qualitative restriction on dose rates in the cargo area was used in a preliminary evaluation of dividing the shield between reactor and crew compartment. The desirability of maintaining relatively low dose rates throughout the vehicle to reduce radiation effects and activation of the vehicle and its cargo necessarily limits the extent of feasible shield division. Increased after-shutdown dose rates comprise a further consideration. Shield system weight savings, and consequent payload increase, due to use of a divided shield are small for limited division of shield weight between source and receiver points. For these reasons, incorporation of a full crew compartment shield, or shadow shield, was felt to be unwarranted.

Shaping of the shield comprises the major method of minimizing total shield system weight. The criterion used in optimizing shield material distribution about the reactor core involved obtaining equal contributions to the total crew dose rate from equal areas on the shield surface, i.e., "equal dose from equal areas." This permits a reduction in shield material thicknesses with increasing angular displacement from the reactor-crew axis, due to the decreasing probability of air-scattered radiation reaching the crew compartment. Application of the proper air-scattering probabilities, together with direct dose rate calculations, effectively defines the optimum angular dose rate distribution for both neutrons and gamma rays. The optimum neutron to gamma ray dose rate ratio at the crew area is determined by application of a graphical technique in which incremental neutron and gamma shield weights are compared for a particular configuration.

B. CONFIGURATION

The design evolved for the shield shown in Fig. II-2, consists of a double-walled pressure shell containing the reactor and gamma shield, and an external neutron shield. Supplementary gamma shielding is positioned in the neutron shield along the reactor crew axis. A reverse flow annular air ducting scheme is used in which compressor discharge air enters a semitoroidal plenum chamber at the rear of the RSA, flows between the pressure shells cooling side and front gamma shield layers, passes through the core and is discharged through an annular duct to an aft plenum chamber, from which it is carried back to the engines. All penetration of the shield by air ducts takes place at the shield sides and rear; the importance of radiation streaming through such voids as a contributor to crew dose rates is minimized by this technique.

A beryllium shield region is located within the pressure vessel assembly as shown in Fig. II-2. This provision allows a more uniform vessel shape than would otherwise be possible.

Attached to the pressure vessel head is a 0.5 in. thick region of boron-loaded steel, used to depress the thermal neutron flux and reduce secondary gamma source strengths in adjacent shield regions. Two boron steel shield layers are located midway in the forward neutron shield to reduce secondary radiation from neutron interactions in the lithium hydride.

The neutron shield has two major components--that portion of the shield attached to the pressure vessel and designed to be removed from the aircraft with the core, vessel, and gamma shield assembly, and a portion permanently installed in the vehicle. Some consideration was given to designing the neutron shield in several sections so as to reduce the weight of the removable assembly. The complications implied in the removal and handling procedures, as well as the extended time for such operations, did not justify this alternate concept.

Figure II-3 indicates the major shield components and subassemblies. This exploded view of the shield assembly shows that access to the core for inspection and fuel element changes is possible by removal of the rear shield plug. Access to the control rod linkages and forward core face requires disassembly of the forward shield regions. All such operations must be performed remotely in an adequately equipped hot shop subsequent to removal of the RSA from the vehicle. It is assumed that handling of the RSA in transit to and from the hot shop and during all disassembly and assembly operations will utilize a cradle to which the RSA may be rigidly attached by the same structural provisions which are made for its installation in the aircraft.

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C. SHIELD MATERIALS

The materials of the various shield regions are identified in the shield assembly drawing, Fig. II-2. Selection of these materials was based on comparative data available in the literature (Refs. 3 through 5), rather than on an intensive evaluation of shielding materials in the present configuration.

The materials most prominently considered for shielding against core gammas included depleted uranium and Hevimet. Data in Ref. 3 affords a comparison between these materials on the basis of experiments conducted at the ORNL Lid Tank. On a weight basis, uranium appears superior but the advantage is not marked, particularly when no boral is used to depress the thermal flux and secondary gamma source strengths become significant. In this shield configuration, the thermal environment does not permit the use of boral in the vicinity of the primary gamma shield material. Use of any other boron vehicles in this region indicates a net weight penalty. Furthermore, the advantages attendant to the use of compressor discharge air as a coolant for the gamma shield shells are compromised if uranium is employed. The appreciably greater thermal conductivity of Hevimet, relative to uranium, permits the use of thicker shells, due to a reduction in thermal stresses caused by radiation heating. In turn, this allows fewer coolant flow channels and reduces system pressure drop. For these reasons, Hevimet was selected as the primary gamma shield material.

The selection of lithium hydride as the bulk neutron shield material for this design was primarily based on weight considerations. Its thermal properties were an additional influencing factor; this material is capable of operation under appreciably higher temperatures than competitive hydrogenous shield materials and affords more latitude in providing for heat removal from the shield system.

The use of beryllium oxide in the rear plug is dictated by the thermal environment in which it must operate. Provision of a cooling system for this region presents more formidable problems, particularly in view of the necessity for periodic removal of the plug assembly for core inspection and fuel element changes. The only means contemplated for cooling this assembly uses reactor discharge air, restricting minimum operating temperature to exit air temperatures--approximately 1700° F. Of currently available materials, BeO should be the most satisfactory. No hydrogenous backing for this region is anticipated at present, although it may prove advantageous to employ a heavy metal hydride for this purpose.

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The beryllium region in the side shield within the outer pressure shell was included in order to maintain a uniform shell diameter. Use of beryllium permits designing this region to assist in distributing the inertial loads of the reactor and side shielding.

In the forward shield assembly, boron loaded 304 stainless steel is used to control the gamma ray dose rate due to thermal neutron capture in shield regions. Because the extent to which boron may feasibly be included in the steel is limited, it was assumed that Boron-10 rather than natural boron would be added.

D. THERMAL CONSIDERATIONS

No rigorous evaluation of the thermal aspects of the shield system design was undertaken. Approximate maximum temperatures in the several shield regions were estimated by manual methods in order to ensure compatibility of the materials with the environment. As previously discussed, a scheme for heat removal from critical regions within the pressure vessel assembly using compressor discharge or reactor exit air was assumed.

Provisions for maintaining an acceptable and uniform thermal environment in the vicinity of center wing box structure are made. A combination of insulation and a shield cooling system will be used to provide a means of thermal control in the portion of the neutron shield permanently installed in the aircraft.

No heat removal system for the bulk of the neutron shield material is contemplated. The magnitude of the heat generation in the front and side neutron shield was estimated to be sufficiently low that no cooling system was required. Verification of these estimates by a detailed thermal analysis is required to more accurately determine temperature distributions and thermal stresses, and to delineate requirements for insulation.

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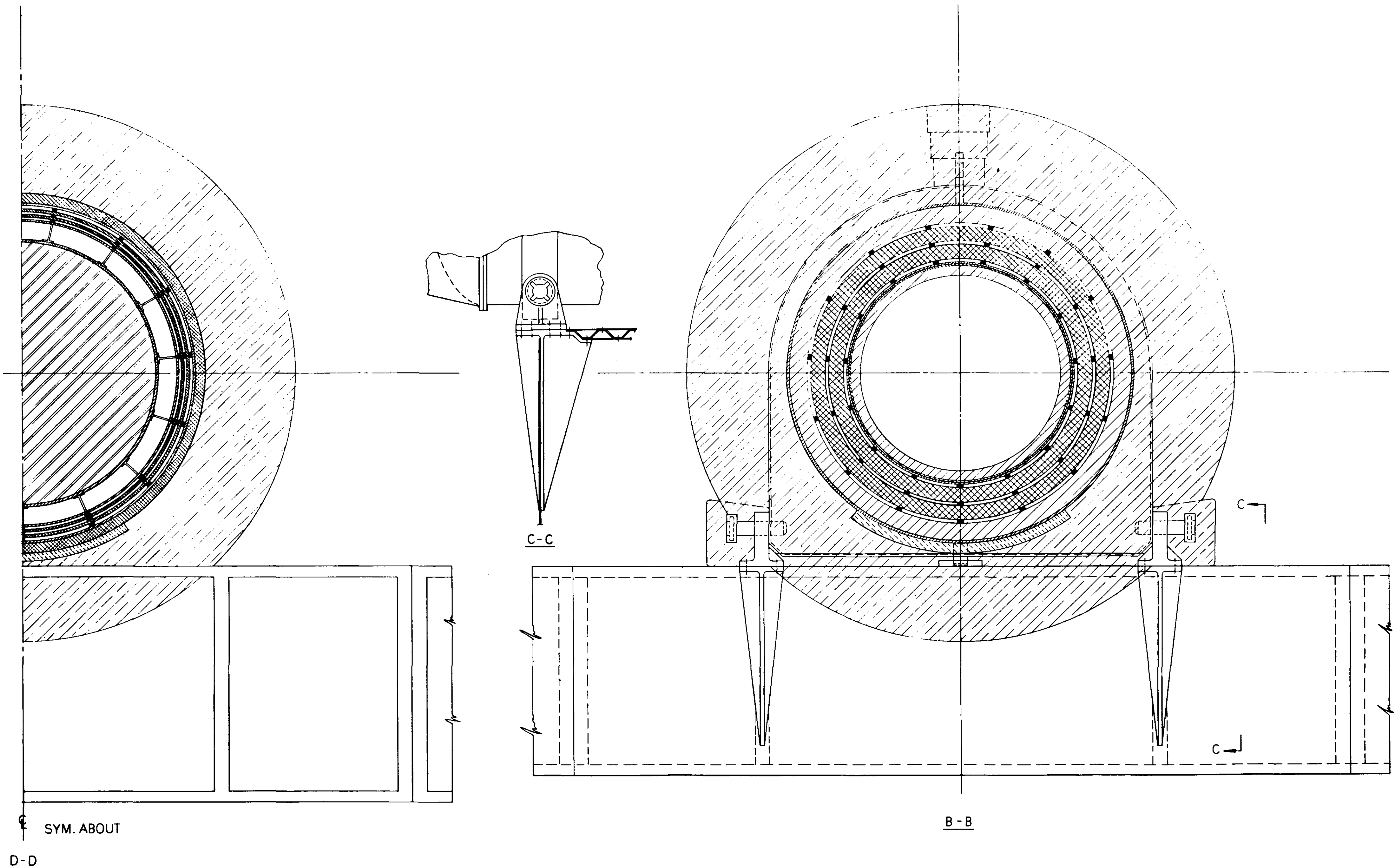

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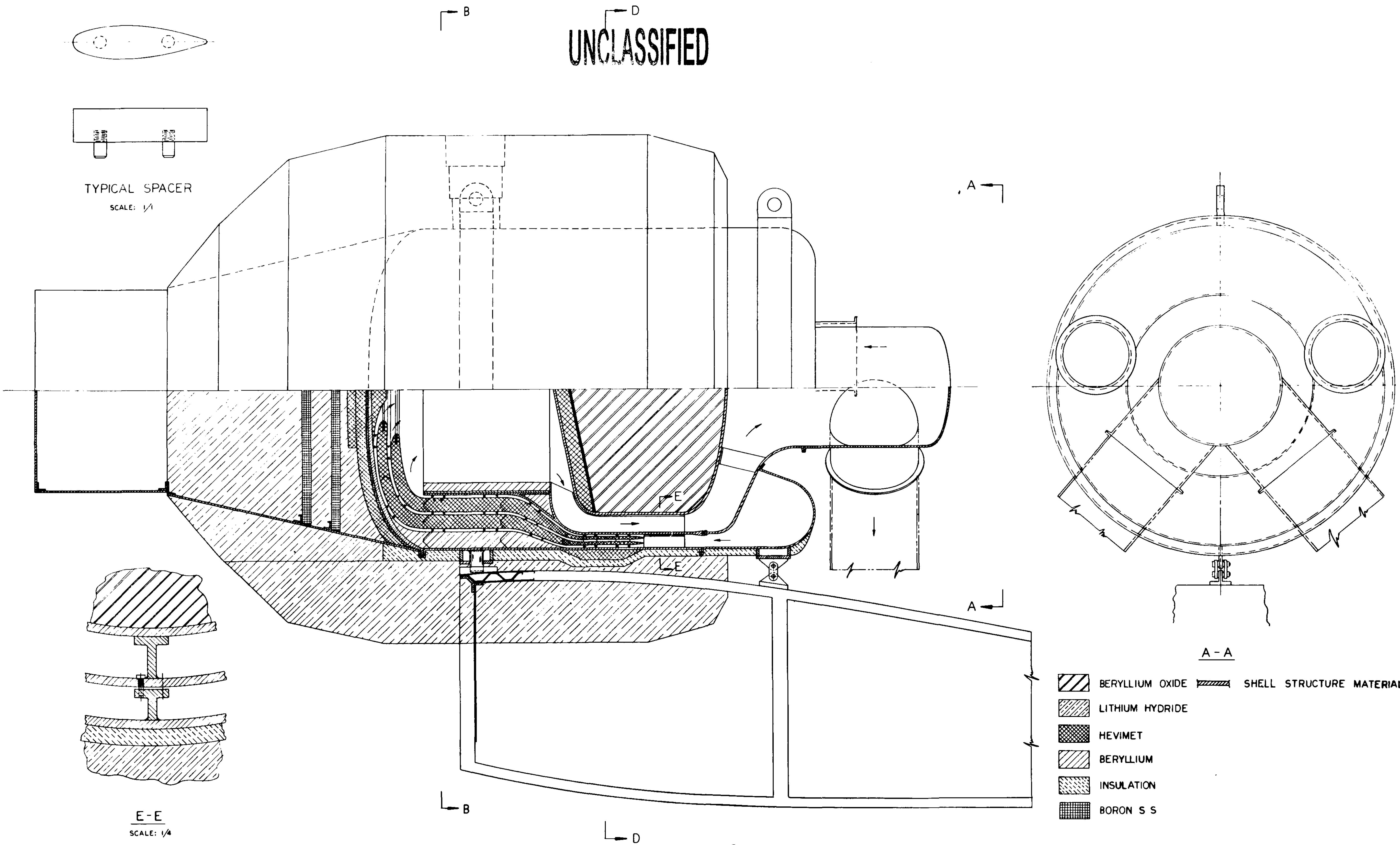

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Fig. II-2. Reactor Shield Assembly

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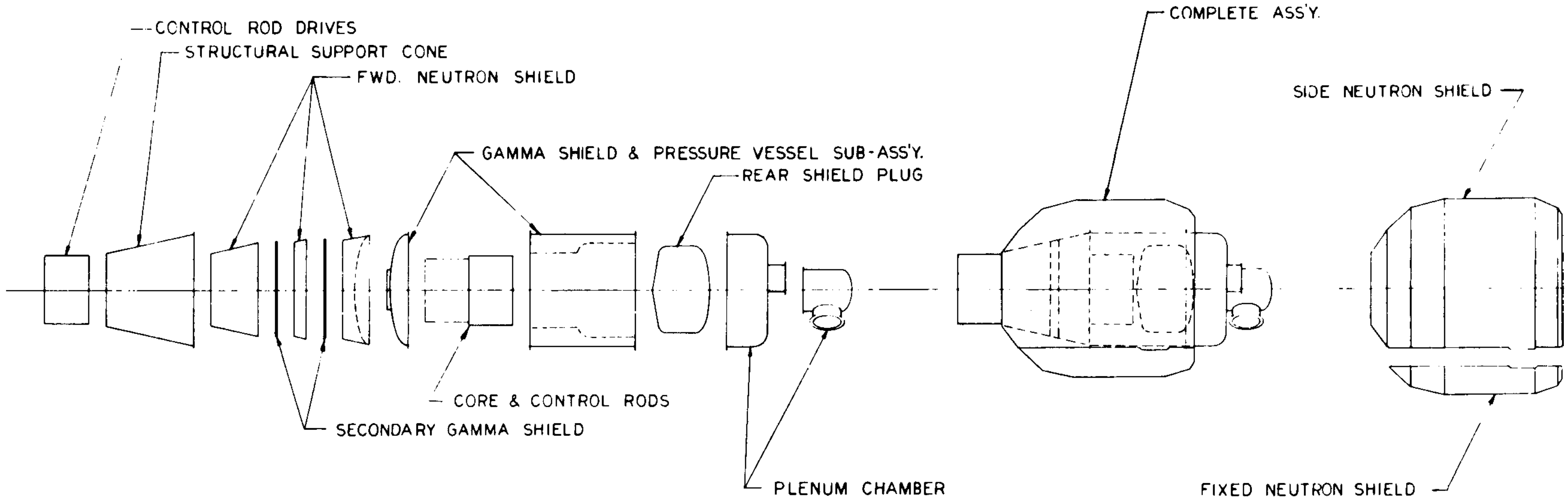

Fig. II-3. Reactor and Shield Subassembly

IV. NUCLEAR ANALYSIS

A. SHIELD ANALYSIS

1. Reactor Source Strength

The reactor core source term was simulated by fitting the radial and axial power distribution function from the XMA-1 design to cosine functions (Ref. 1 APEX-28). These functions appear as 64 volume-distributed source points in the General Electric 04-2 IBM 704 computer code (Ref. 6) which was used for part of the present analysis. The gamma radiation was represented by seven energy groups: 0.5, 1.5, 2.5, 3.5, 4.5, 5.5 and 6.5 mev. The neutron source was obtained from a modified Albert-Welton kernel as in Ref. 6.

2. Shield Penetration

The direct radiation from the outer unit shield surface was obtained at the crew position, which is 50 ft from the center of the core and as a function of source angle at 50 ft from the center of the core for air-scattering calculations.

The application of the 04-2 code to this shield design appears to be somewhat limited in the case of core gammas due to the fact that the shield thickness in number of mean free paths at certain source angles and energies is greater than the apparent capacity of the code in its present form. Some of the dose rates printed out correspond to the maximum number of mean free paths accommodated by the code and are, therefore, too high. In these cases the 04-2 code results were replaced by estimates based upon hand calculations.

In obtaining the direct dose rates as a function of source angle with the 04-2 code, occasional geometry stops were encountered. These were usually eliminated by slightly altering the geometry, and when this was not possible within the available time, the dose rates were interpolated from hand and machine calculations.

A summary of the direct core gamma and neutron dose rates as a function of source angle at 50 ft is given in Table 2.

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TABLE 2

Angular Direct Dose Rate Distributions

Source Angle (deg)	Neutrons (m rem/hr)	Core Gammas (m rem/hr)	Capture Gammas (m rem/hr)	Total Gammas (m rem/hr)
0	1	2	2.9	4.9
15	1.36	3.38	5.0	8.38
30	3.0	20.6	20.0	40.6
45	20	1×10^{3}	1.0×10^{3}	2×10^{3}
60	86	1.44×10^{4}	1.0×10^{4}	2.44×10^{4}
75	190	3.38×10^{4}	1.8×10^{4}	5.18×10^{4}
90	270	5.0×10^{4}	2.0×10^{4}	7.0×10^{4}
105	329	6.8×10^{4}	1.8×10^{4}	8.68×10^{4}
120	380	8.74×10^{4}	1.5×10^{4}	1.02×10^{5}
135	440	1×10^{5}	1.5×10^{4}	1.15×10^{5}
150	470	1.093×10^{5}	7.0×10^{3}	1.16×10^{5}
165	492	1.19×10^{5}	6.35×10^{3}	1.25×10^{5}
180	521	1.25×10^{5}	6.35×10^{3}	1.31×10^{5}

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3. Secondary Sources

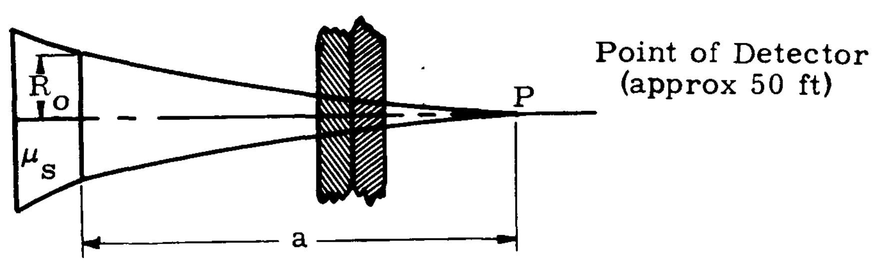
a. General

The most important secondary sources of radiation evaluated for this unit shield were the gamma sources produced in the shield and associated materials by the thermal neutron flux which resulted in (n, γ) reactions.

In order to analyze this contribution to the dose rate at 50 ft the thermal neutron flux as a function of position within the reactor shield was determined by the use of the C_2 F_2 code programmed for the IBM 704 Digital Computer. The results appear in Figs. II-4 and II-5. The capture gamma contributions to the total dose rate were determined by the following relationships:

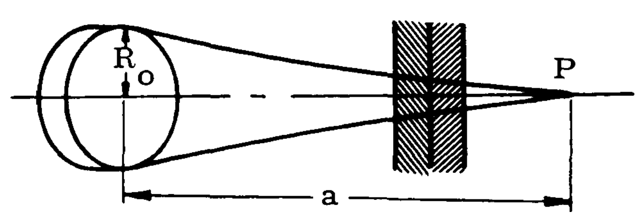
Axial

$$D(E) = \frac{B(E)\, S_V(E)\, R_o^2\, e^{-bi}}{\mu_s \quad 4a^2 c}$$



Radial

$$D(E) = \frac{B(E)\, S_V(E)\, R_o^2\, e^{-bi}}{8\,\mu_s \quad a^2 c} \quad \sqrt{\frac{R_o}{R_o + a}} \left(\text{D Conversion Factor} \right)$$



Assumed Shape of Side of Cylindrical Core

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$D(E)$ = dose in rem/hr from capture gammas of energy E

$B(E)$ = dose buildup factor as function of energy and shield material (Ref. 7)

$S_V(E)$ = volume source strength = $S_V(E) = E\ \Sigma_c\ \phi_{th}$

E = mev/radiative capture (Ref. 8)

Σ_c = microscopic capture cross section

ϕ_{th} = [redacted]al flux obtained from the C_2 and F_2 IBM 704 code results

c = conversion factor from flux to dose rate

μ_s = linear absorption coefficient of source

$\mu_{\dot{c}}$ = linear absorption coefficient of ith shield material

t_i = thickness of ith shield layer cm

b_i = $\sum_i^m \mu_{\dot{c}}\ t_i$

$\sqrt{\frac{R_o}{R_o + a}}$ = transformation from an infinite plane to a cylindrical source

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These asymptotic approximation relations were utilized, since at sufficiently large distances from any finite source, the spatial variation of the flux will closely approximate that from a point source (see Ref. 9).

In order to reduce the capture gamma radiation coming from the portion of LiH close to the pressure vessel, the thermal neutron flux was reduced by a layer of 304L steel with 1% boron-10, close to the forward edge of the pressure vessel. This depressed the thermal flux by a large amount as can be seen from Fig. II-4. The boron steel was placed in the forward end and the rear end of the unit shield where it was required to reduce both the capture gamma dose rate contribution and the activation dose rates from the reactor shield and structure after shutdown. The boron steel was not placed around the side of the cylindrical pressure vessel because the air-scattered gamma dose contribution at 50 ft forward was found to be acceptable.

The present unit shield design has the following capture gamma dose rate contributions to the total gamma dose at 50 ft from the shield.

0°	2.89 m rem/hr
90°	20.4 rem/hr
180°	6.35 rem/hr

As can be seen, the capture gamma dose rate in the forward direction is approximately 14% of the total specified dose rate of 0.02 rem/hr. The largest dose rate contribution due to capture gammas occurs to the side of the shield.

Axial contributions.- Table 3 gives a detailed summary of the capture gamma contributions from each shield component to the dose rate at the crew compartment.

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TABLE 3

Dose Rate Contribution at the Crew Compartment from Capture Gamma Sources Within the Shield

Region	Material	Dose Rate (m rem/hr)
I	LiH	6.09×10^{-3}
II	304L SS-B^{10}	2.04×10^{-3}
III	LiH	8.37×10^{-1}
IV	304L SS-B^{10}	9.16×10^{-3}
V	LiH	2.09
VI	Hevimet	4.36×10^{-3}
VII	304L SS-B^{10}	5.42×10^{-8}
VIII	Inconel X	3.22×10^{-8}
IX	Hevimet	4.65×10^{-9}
X	Inconel (grid)	6.88×10^{-8}
XI	Be (ref)	4.79×10^{-7}
Total		2.89

As can be seen from these values, Region V (see Fig. II-4), lithium hydride, located in a high thermal flux region (7×10^7 neutrons cm^2/sec), contributed the major capture gamma dose rate at the crew compartment. This dose rate is composed of 2.23 mev gammas from hydrogen capture and the gamma energy given off by material lithium. It was assumed that all the capture gamma given off by Li^7 were located in the 6.5 mev region along with gammas from Li^6 and that approximately 2.90 mev per capture was given off by Li^7. Li^7 has an actual binding energy for an extra neutron of approximately 2.03 mev. Region III, LiH, was next in line as a major contributor. The Inconel X pressure

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vessel, Region VIII, gave a relatively small contribution to the total dose rate from capture gammas because adjacent to it was placed the 304L steel with 1% boron-10 which depressed the thermal flux sufficiently to reduce the total number of captures and thereby the radiation source. The beryllium reflector gave a relatively small contribution. The material which, in general, contributed the lowest capture gamma dose rate from this shield configuration was Hevimet which was located in Regions II and IX where low thermal neutron fluxes were present. Two slabs of 304L steel with 1% boron-10 were also placed in the forward section of the LiH region.

The 304L boron-10 steel was placed behind the Hevimet in the BeO plug. This reduced the dose rate from the capture gammas in beryllium at the rear of the shield and also reduced the activation from the thermal flux after shutdown promoting ease of handling. From Table 4 it can be seen that the major contributor to the capture gamma dose rate was the lithium hydride surrounding the pressure vessel to the rear of the core. This was due to its large radiating area and to its capture gammas properties.

TABLE 4

Dose Rate Contribution at 50 ft (180°) from the Aft End of the Shield from Sources Created by (n, γ) Reactions

BeO plug (see Fig. II-4)	0.11 m rem/hr
LiH (annulus)	6.35 rem/hr

Total contribution at 50 ft from rear of shield, axially: 6.46 rem/hr.

Radial dose contributions.- Table 5 in conjunction with Fig. II-5 indicates the breakdown on capture gamma dose rate contributions for the various regions.

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TABLE 5

Dose Rate Contributions at 50 ft (90°) from Sources Created by (n, γ) Reactions

Region	Material	Dose Rate (m rem/hr)
I	Be	1.72×10^{-1}
II	Inconel X	54.8
III	Hevimet	3.19
IV	Hevimet	417
V	Be	4.39×10^{3}
VI	Inconel X	1.56×10^{4}
VII	LiH	9.26×10^{-1}
Total		2.04×10^{4}

As can be seen from this table, the major source of the capture gammas was the Inconel X pressure vessel which gave a dose rate of 15.6 rem/hr at 50 ft to the side of the RSA. The beryllium shell adjacent to the pressure vessel gave the next highest capture gamma dose contribution of 4.39 rem/hr. Beryllium was one of the major contributors since the thermal flux peaked in this shell and therefore established a large volume source of (n, γ) reactions.

4. Duct Penetration

The fast neutron and gamma streaming through the duct at the rear of the RSA was evaluated with the aid of a Monte Carlo code. A description of this code is to appear under separate cover as an engineering report by The Martin Company.

Very little has been published on the subject of radiation streaming through ducts. No presently known analytical procedure adequately solves the problem. In an attempt to improve this situation The Martin Company has developed a Monte Carlo code for the IBM 704. This code has been named the MC-DNG Code (Monte Carlo-Ducting of Neutrons and Gammas).

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Neutrons.- The neutron ducting code recognizes neutrons which emerge from the rear surface of the reactor core and selects polar and azimuthal angles of emission into the duct at random. The intersections of the resulting trajectories and the duct surfaces are computed. A surface normal at the point of intersection provides a reference from which new polar and azimuthal angles may be selected for the scattered leg of the neutron trajectory. The neutrons are weighted by a source spatial distribution, a source angular distribution and the albedo of the duct wall. The methods of expected values and splitting are employed as variance reduction techniques.

This program was designed so that the neutron albedo could be adjusted (calibrated) to an experimental measurement for a particular geometry, then by inserting known cross sections of ducts, different materials may be studied. The lack of experimental data prevented the calibration of the code. Substituting an educated guess for the calibration constant, the fast neutron dose rate at 50 ft aft was calculated to be 1600 rem/hr. This dose rate is for the configuration shown in Fig. II-2 and would drop by about 2 or 3 orders of magnitude when an additional 14,000 lb of LiH was placed at the rear of the RSA.

If the 1600 rem/hr quoted above is a correct order of magnitude for duct streaming of fast neutrons, approximately 0.5 rem/hr will be added to the crew dose rate 50 ft forward due to this effect (this 0.5 rem/hr does not appear in the summary of dose rate components).

Gammas.- For gammas, the albedo concept is replaced by the Klein Nishina and Compton equations relating energy and angle. A hand calculation to verify this part of the code remains to be performed.

5. Angular Dose Rate Distributions About RSA

The angular dose rate distributions are given in Table 2. The capture gamma contribution to the total direct gamma dose rate was determined radially and axially both fore and aft of the core at a distance of 50 ft. These values were interpolated for other source angles so as to yield values at every 15° interval of source angle about the reactor core. As previously indicated, the angular distribution of the direct core gammas was also determined at every 15° interval of source angle. The angular distribution of the direct neutron dose rate was obtained at the same angular intervals.

The angular dose rate distribution was adjusted separately for neutrons and core gammas in order to obtain equal differential dose rates from equal shield areas as explained previously.

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B. CREW DOSE RATE COMPONENTS

The total design dose rate for the present unit shield is 20 m rem/hr for an operating source of 110 MW and altitude of 25,000 ft. The calculated components totalled 16.25 m rem/hr which does not include the small contributions from air capture gammas, structure scattering and gammas from inelastic fast neutron scattering in the air and shield.

The scattered neutron dose rate of 10 m rem/hr at the crew position was obtained from the ORNL Tower Shield Facility data as given in Ref. 10.

The scattered gamma dose rate of 0.25 m rem/hr was obtained by application of the Monte Carlo calculated results presented in Ref. 11.

In each of the above mentioned scattered radiation calculations, the data in the references appeared as, or was put in the form of, the differential dose rate at the crew position per unit solid source angle and was then weighted by the angular distribution for the optimum shaped shield.

Summary of dose rate components at crew position for a reactor power of 110 MW and cruise altitude of 25,000 ft appears in Table 6.

TABLE 6

Radiation Component	Dose Rate (m rem/hr)
Direct neutrons	1
Air-scattered neutrons	10
Direct capture gammas	3
Direct core gammas	2
Air-scattered gammas	0.25
Total	16.25

[redacted]

C. EVALUATION

1. RSA Weight

The estimated weights of the reactor, shield and structural materials are as follows:

Item	Weight (lb)
Active core, reflector, tube sheets	10,710
Reactor controls system	4,900
Hevimet	70,460
Boron stainless steel	8,820
Lithium hydride (and containment)	65,020*
Beryllium	4,080
Beryllium oxide	16,140
Pressure vessels	12,290
Miscellaneous shield structure	2,920
RSA installation provisions	5,970
Total	(201,310)

*weight includes 14,000 lb of shield patch for annular ducts

2. Recommended Alterations and Improvements

Time did not permit a thorough analysis of all sources of radiation and their influence on crew dose rate. It is believed that those sources which have been neglected are not so significant in this shield design as to require any major changes in the configuration of the shield or in shield material thicknesses. The one exception is the neutron and gamma radiations which stream through the annular duct.

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The streaming of radiation received inadequate study for firm conclusions to be drawn. Since a preliminary study indicated that a dose rate on the order of 1600 rem/hr or more at 50 ft aft of the reactor was possible for the streaming of fast neutrons, it is apparent that further study of duct geometry is important.

The activation of surrounding structure will produce a handling problem after shutdown if the duct leakage is too high.

Additional sources which should be evaluated in a complete analysis include secondary gammas arising from neutron interactions in structural regions. Thermal neutron capture gamma source strengths in shield regions have been calculated. Capture gammas from the fast flux are not expected to be important. No estimate has been made of gammas from inelastically scattered neutrons, although the dose rates from these interactions are expected to be less important than the thermal neutron capture gammas.

Streaming of radiation along or through structural members should be estimated. Because no detailed structural analysis was performed, the placement and size of structural members within the shield are not defined and, therefore, no analysis was possible.

The inhomogeneity of the core has been neglected in this analysis. The importance of radiation streaming along void regions in the core requires evaluation in that the effective core self-absorption is reduced.

The activation of shield and structural materials during reactor operation has not been computed. Decay radiation from activated regions is chiefly important as a source of radiation after reactor shutdown, during maintenance and handling operations. Should activation be excessive, it is recommended that additional boron-10, in the form of borated steel, be introduced into the shield assembly to depress the thermal neutron flux in critical regions.

In some designs, using beryllium shield regions, photo neutrons are important. However, in this design all beryllium-containing shield regions are shielded from the core gammas by Hevimet, thereby minimizing this aspect of the shielding problem.

Gamma radiation from thermal neutron capture in air has not been evaluated for this unit shield since it was presumed to be a small contribution. A more complete analysis should include air capture gammas.

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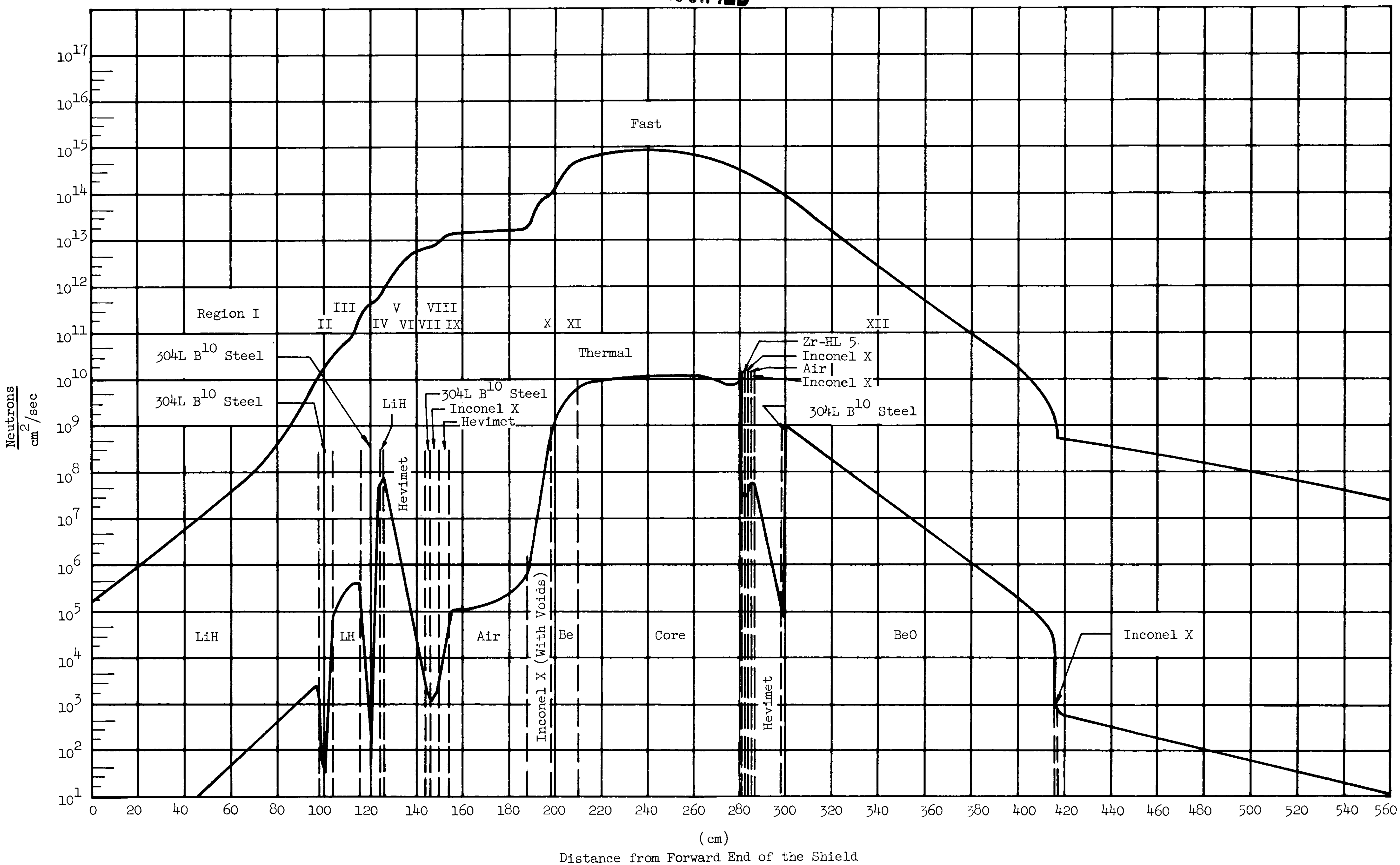

Fig. II-4. Axial Neutron Flux Distribution

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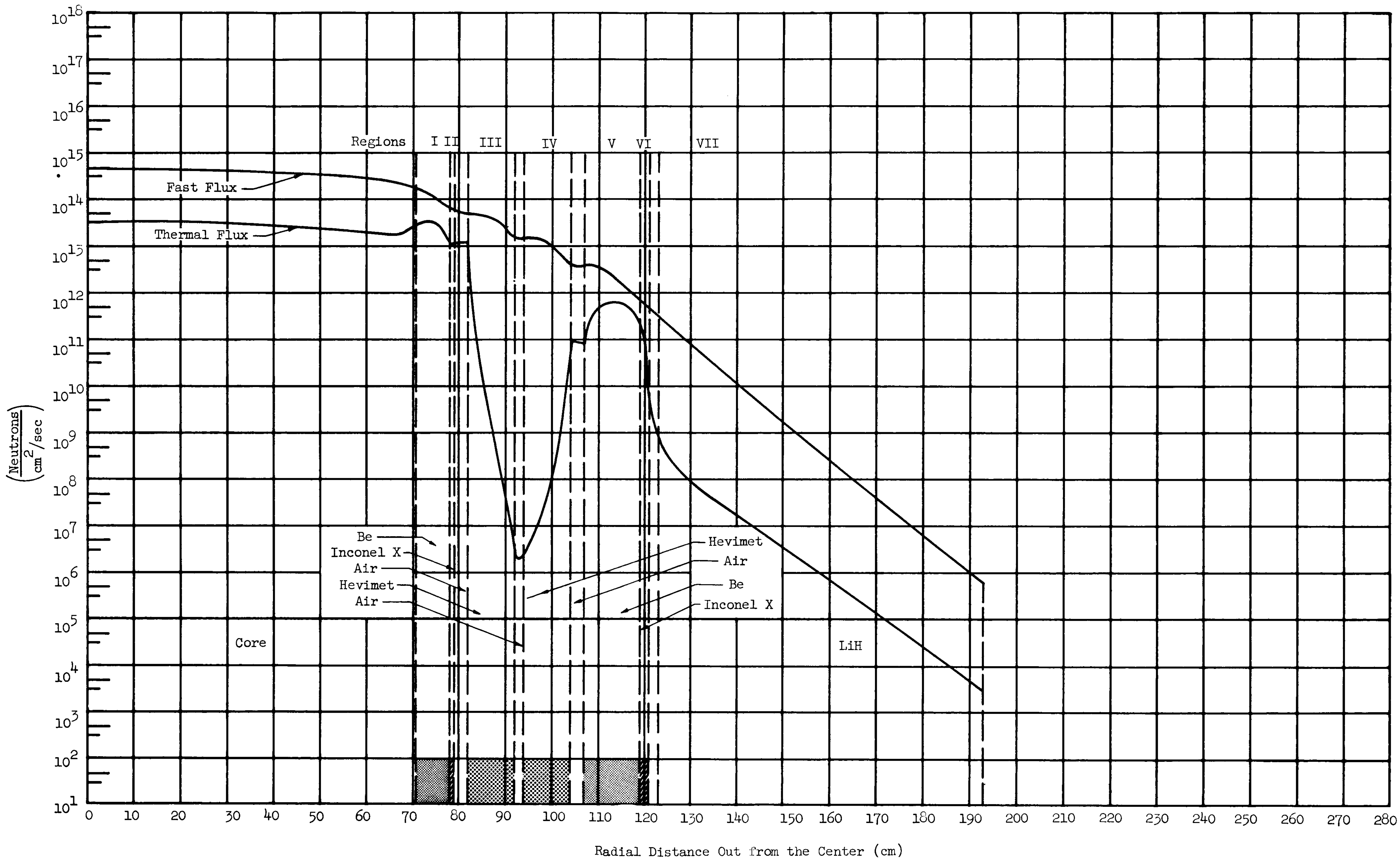

Fig. II-5. Radial Neutron Flux Distribution

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V. ENGINEERED SHIELD DESIGN

The major components of the nuclear power package consist of the reactor core and controls system, gamma shield and pressure vessel assembly, and a neutron shield. The neutron shield is composed of two major sections--an upper portion attached to the pressure vessel and removable with it, and a lower portion which is permanently integrated with the aircraft center wing structure. The lower portion of the neutron shielding is separated from the upper by the wing structure and several inches of a thermal insulation material (see Fig. II-2).

The removable portion of the RSA is designed to be separated from the aircraft as a unit by means of an overhead lifting device; this unit is directly attached to the center wing structure by means of three trunnion fittings. All flight and landing loads will be transmitted through the statically determinate trunnion mountings to the center wing spar and rib structure. The entire RSA is enclosed in a non-structural aerodynamic fairing designed for quick removal. For separation of the nuclear power package from the vehicle, the fairing is removed, pins at the trunnion fittings are disengaged, and the entire unit hoisted by means of lifting lugs provided on the outer pressure shell rings (see Fig. II-2).

A. DESIGN CRITERIA

1. Structural Design Criteria

The flight, landing and ditching accelerations at the center of gravity of the aircraft have been estimated for a gross weight of 600,000 lb, a landing speed of approximately 100 kn, a cruising speed of 350 kn at 25,000 ft, and 200 kn at sea level. The RSA is located very near the cg of the aircraft.

Results of this investigation indicate that the reactor shield assembly should be designed for the following ultimate accelerations:

(1) 9.0 g directed forward parallel to the longitudinal axis of the aircraft.

(2) 5.0 g directed downward parallel to and simultaneously with ± 2.0 g directed to either side of the longitudinal axis of the aircraft.

(3) ± 3.0 g directed to either side of the longitudinal axis of the aircraft.

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(4) 3.0 g directed aft parallel to the longitudinal axis of the aircraft.

(5) 2.0 g directed upward normal to the longitudinal axis of the aircraft.

Note that all cases are considered to be acting separately. In the detailed design, the trunnion loads must consider the RSA mass moment of inertia about its own cg.

2. Thermal Design Criteria

The following thermal design criteria have been established for the pressure vessels.

(1) To minimize any appreciable amount of undesired deformation, the structure shall be designed for limit pressures and compared to yield strength for a 0.2% creep-set for the time and temperature environment.

(2) To provide a margin of safety in respect to the ultimate strength, the limit pressure will be raised by a 1.25 factor and compared to the stress-rupture allowable for the estimated temperature and total life-time duration. However, should the allowable stress-rupture total strain interfere with the proper functioning or operation of the vessel, it will be then necessary to limit the stress-rupture allowable compatible to the desired or permissible total strain. The above criteria, in a sense, determine the volumetric set desired for the time-temperature environment at the working and ultimate pressures.

In a refined stress analysis of elevated temperature structures, the total strain of elastic and inelastic deformations can be computed. Therefore, the strains and stresses, compatible with the operating and failure conditions, can be established without the degree of conservatism implied by the above criteria. When the aircraft mission profile is established, combined load and thermal criteria can then be determined.

B. STRUCTURAL INSTALLATION

1. Wing--General

In a conventional chemically fueled aircraft, large amounts of fuel are located within the wing structure to provide wing inertia relief, thereby reducing the wing bending loads to accepted state-of-the-art values. With nuclear power plants, chemical fuel is at a minimum and is primarily used for shielding and for chemical engine thrust augmentation during takeoff and emergency cruise. As a result, with a minimum of wing inertia relief, the wing cover compression loadings for this nuclear aircraft are in the 50,000 to 60,000 lb/in. range.

Several types of wing construction have been examined for this aircraft, i.e., multiple spar and thick cover, and double skin and corrugations. At wing cover loadings of 50,000 to 60,000 lb/in., it was estimated that both types of construction resulted in approximately the same weight. However, the size of the chemical combustion chambers and ducting passing from the reactor through the wing structural box to the T-57 engines prohibited the use of an optimum multiple spar construction. Therefore, the double skin and corrugation sandwich wing construction was used for this preliminary study.

The wing construction consists of five spars, with single skin and corrugation for the outer wing and double skin and corrugation for the inner wing. The wing center section will consist of two spars and double skin corrugations. A load redistribution or closing rib is provided at the junction of the inner and outer wing.

Two special ribs are provided in the center section to redistribute loads from the forward trunnions. An additional transverse rib is located directly under the rear trunnion and between the special ribs to carry and transmit the rear suspension loads.

2. Center Wing

The center wing upper cover structure lies between the reactor pressure shells and the lower portion of the lithium hydride shielding which is contained within the center wing structure. During an aircraft cruise flight of 150 hr duration, the 670°F compressor discharge air passing between the inner and outer pressure shells will result in significant heating of the center wing structure unless some means of heat removal or insulation is provided. In order to permit usage of high strength aluminum alloys for the wing structure, the upper portion of the reactor shield assembly will be thermally isolated from the wing structure by a cooling system and insulation as shown in Fig. II-6.

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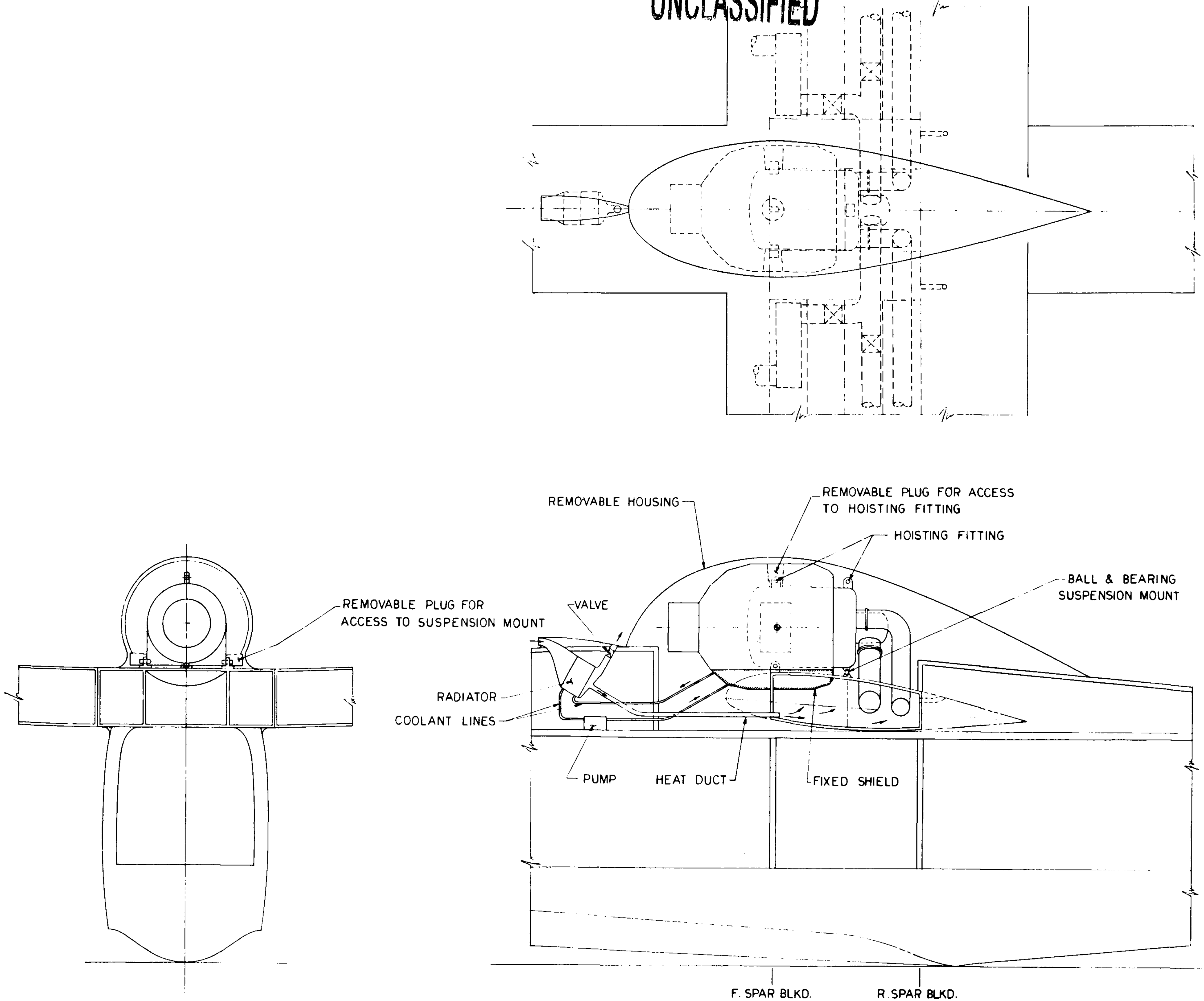

Fig. II-6. Reactor Shield Assembly Installation

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The thermal insulation is attached to the outer pressure shell to maintain its temperature, thereby minimizing the outer shell thermal stresses. The insulation thickness and cooling system will be such as to maintain a 300°F maximum temperature on the outer surface of the center wing upper cover.

The lithium hydride contained in the center wing structure will be cooled to 300°F by means of a closed cycle forced liquid cooling system. The remaining center wing structure will be heated to 300°F by discharge air from the radiator of the cooling system. The compressor and turbine air ducts in the center section area will be cooled by air flowing over the insulated double wall duct construction.

The combination of outer pressure shell thermal insulation and cooling, the cooling of the lithium hydride and the compressor and turbine air ducts, plus the heating of the remainder of the center wing structure will minimize or eliminate the thermal gradients in the center wing structure during reactor operation. The cooling system will be designed not to exceed a maximum center wing temperature of 300°F, thereby permitting the use of X2020 high temperature aluminum alloy.

Removable structural access panels will be provided in the inner and center wing structure for the purpose of inspection, maintenance and removal of the neutron shielding, chemical burners, air ducts, etc.

3. Fairing

The reactor fairing is primarily secondary structure which is designed for the airloads acting upon it. It will be quickly detachable by means of a series of indexing shear pins spaced about its periphery. The indexing pins will transmit the fore, aft and side loads to the hull crown structure. A minimum number of pins, carrying all vertical shear loads into the crown structure, will be provided. The fairing can be quickly detached by pulling out all pins, thereby permitting the hoisting of this structure by use of lifting lugs provided for this purpose.

4. Reactor Shield Assembly Suspension

The RSA is supported by a statically determinate three-point suspension system. The two forward trunnions are mounted at the intersection of the front spar and the special ribs, and carry vertical and fore and aft loads only. An additional shear pin is mounted on the intersection of the front spar and the aircraft plane of symmetry to carry side loads only. The rear suspension is a ball and socket type which carries vertical loads only and permits axial expansion of the reactor. The design loads on the suspension mounts will be as specified in the

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RSA design criteria. Note that the suspension mount loads must include the effect of the RSA mass moment of inertia about its own center of gravity.

In order to prevent excessive heat transfer to the wing structure by the RSA forward mounts, it will be necessary to insulate the structural attaching bolts and the mounts themselves from the wing structure.

5. Reactor Shield Assembly Removal

The basic RSA hoisting problem is to accurately determine the location of the center of gravity and the maximum inclination or rotation of the RSA in respect to a horizontal reference plane.

The removal system considered is as follows:

> To the outer pressure shell will be welded two box cross-section rings which completely encircle the outer shell. At the intersection of the forward ring and the aircraft plane of symmetry will be located a removable stepped cone shield plug. Removal of the cone plug will permit the lowering of steel cables which will hook into the lifting lugs attached to the outer pressure shell rings. The plug cone will permit the lifting cables to rotate relative to the RSA without damaging the lithium hydride containers of the external neutron shield. Withdrawal of the trunnion pins will then permit hoisting of the assembly.

Any other hoisting arrangement will require rigid structural members buried in the lithium hydride causing complicated container shapes but having the advantage of eliminating the stepped cone plug.

C. SHIELD STRUCTURAL DESIGN

1. Gamma Shield and Pressure Vessel Assembly

The principal load-carrying structure of the RSA is the outer pressure shell which basically consists of a cylindrical portion capped at one end by an elliptical head and by a semi-toroidal ring at the other. To each end of the cylindrical portion of the outer pressure shell is welded a box section ring which transfers all outer pressure shell loads to the center wing structure or to a hoisting cable arrangement. Within the outer pressure shell is an inner pressure shell, the reactor core and reflector assembly, the rear shielding plug and cylindrical gamma shield shells.

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A review of the mechanical properties of beryllia, beryllium and tungsten alloys, Refs. 12 through 14, indicates that these materials exhibit adequate elevated temperature properties to act as structural members. For this reason, a series of metallic streamlined-strut spacers have been inserted into the air flow to maintain the air gap and to transmit the inertia loads of the reactor masses to the shell structures. The location and number of these spacers will be determined so as not to exceed the allowable bearing and bending stresses of these shielding materials at elevated temperatures.

At the forward end some of the shielding mass is bolted directly to the ellipsoidal head. The curved Hevimet shielding is spacer-bolted at the inner ends to the head for fore and aft loads. Transverse rings embedded in the curved inner ends transmit the radial loads through the spacers to the ellipsoidal head.

The reactor core and its beryllium reflector transfer their vertical loads by bearing of the spacer-shielding material combination on the outer pressure shell. Fore and aft loads are picked up at the aft end of the reactor core by the inner pressure shell and are sheared out to the outer pressure shell by radial shear ties located between the inner and outer shells and just forward of the shells' aft assembly joint. The radial shear ties are welded to the inner surface of the outer shell and provide a gap between the shear tie and the inner shell. Pins tapped into the thickness of the inner shell engage matching holes in the shear tie to provide the shear connection with radial expansion of the shells through the gap. The rear shielding plug rests on rigid radial shear ties which are welded to the inner surface of the inner shell. These radial shear ties transmit the plug forward loads by shear into the inner shell and then by the floating shear ties located between shells into the outer shell. Both rigid and floating shear ties transmit the plug vertical loads to the outer shell by bearing and compression. A series of streamlined struts transfer the aft plug loads in compression to the inner ring of the semi-toroidal ring.

All other shielding masses transfer their loads directly by bearing and/or shear into the elliptical head and the inner pressure shell, then finally to the outer pressure shell.

To the elliptical head at its assembly joint is fastened a single skin and corrugation truncated cone which supports the reactor controls assembly and some of the forward neutron and gamma shielding. The borated steel gamma shielding bulkheads will be attached to the forward cone rings by high temperature fasteners in oversize holes in the cone rings. This type of attachment will permit free radial thermal expansion of this gamma shielding without inducing radial loads to the cone. Both ends of the cone will be attached by fasteners for ease of assembly.

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2. Neutron Shield

The outer portion of the reactor shield assembly is lithium hydride which is expected to reach a maximum temperature of approximately 670° F in the vicinity of the pressure shell. The containers for this material must be hermetically sealed to prevent the escape of hydrogen due to decomposition at this temperature, to resist the chemical corrosive attack, and to withstand the hydrogen generated pressures. At 670° F, the internal pressure of the container is approximately 3.0 psi. Any low carbon stainless steel material is suitable for the container design. The container size will be dictated by the center wing structural arrangement and the thermal gradients across the lithium hydride thickness. Results of Ref. 1 indicate that the addition of metallic honeycomb to the lithium hydride appears to greatly reduce or eliminate the cracking caused by thermal stresses and thermal cycling. The probable design for the containers will therefore consist of lithium hydride cast in layers of metallic honeycomb held in a stainless steel shell.

D. THERMAL ASPECTS

The strength design of the RSA involves the determination of the stresses in its component parts as produced by loads, temperatures and temperature gradients and evaluated in terms of their time-temperature histories. The stresses result from any one or a combination of the following:

(1) Thermal gradients associated with steady state heat flow.

(2) Thermal gradients resulting from reactor power changes due to start-up and shut-down, and due to reactor after-heat and its removal.

(3) Thermal stresses due to restraint or fixity of the component and different coefficients of thermal expansion.

(4) Thermal gradients due to internal heat generation by radiation.

(5) Gas pressures.

(6) Aircraft accelerations.

(7) Thermal cycling causing creep and fatigue.

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The classical method for the stress analysis of unheated structures is based upon the assumption of time independent linear deformations of the material where the basic stress does not exceed the proportional limit or yield stress.

The phenomena of creep in elevated temperature structures is now generally understood. It is recognized as a time-dependent irreversible function of deformation and is defined in terms of a stress producing a creep rate, a limiting creep or total deformation, and a stress causing creep rupture, all of which are related to the service life of the structure. The introduction of creep into thermal stress analysis results in a significant reduction of thermal stresses while only moderately effecting the load stresses. Since a small temperature gradient induces large thermal stresses, the importance of load stresses diminishes with creep becoming a more important factor at elevated temperatures.

A rational thermal stress analysis that includes the elastic and inelastic deformations, leads to a series of complex mathematical expressions where solutions require computations of considerable magnitude. To avoid these complications, most thermal stress analyses are based upon an elastic analysis where the thermal stresses and load stresses are additive. This generally results in a conservative solution and serves as the best available approximation to the real thermal stresses. Although an elastic analysis of the reactor structure is admissible for preliminary design, in view of the substantial weight and volume reduction offered, the relaxation stresses of creep must be considered for final design.

The Martin Company has several generalized structural heating automatic computation programs set up for their advance heating problems. These programs, with modifications, can provide analyses of time-dependent, elastic and inelastic elevated temperature problems similar to those encountered in reactor design.

E. STRUCTURAL MATERIALS

The problem of material selection for unheated structures has generally been standardized by comparing materials on the following bases:

(1) Strength to weight ratio

(a) Ultimate and yield tensile.

(b) Compression yield: plate buckling, columning, crippling, panel instability, etc.

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(c) Modulus of elasticity--stiffness.

(2) Fatigue: notch sensitivity, impact.

(3) Elongation: ductility.

(4) Fabrication: forming, welding.

In elevated temperature structures, the process is made more complex by the introduction of the creep phenomena, higher strength, heat treatment, thermal cycling, temperature gradients, time dependent functions, irradiation, nuclear requirements, etc.

For a specific application and by consideration of some of the environmental, structural and fabrication requirements, this formidable task is reduced to a selection of three or four materials. The resulting optimum material selection is principally based upon the creep rate, total deformation, stress rupture, structural efficiencies, and fabrication techniques.

A series of charts has been prepared to illustrate trends or typical effects of elevated temperatures on the mechanical properties of various materials commonly used in aircraft and missile construction.

These charts are indicative of the large amount of material development, testing and type of data required for elevated temperature material selection. For this reason, no attempt at material selection has been made, but a presentation of general understanding, familiarization and awareness of the problems involved.

Figure II-7 shows the typical variation of the ultimate tensile strength of aluminum alloys with temperature. Notice the general rapid decrease in strength of aluminum alloys beyond 300°F. It shows that X2020-T6 material has the best ultimate tensile strength in the 0 to 350°F temperature range and would be best suited for the entire wing structure.

Figure II-8 compares the short time and 100-hr soaking time tensile strengths of several common aluminum alloys. These alloys experience a sharp drop in strength beyond the 300°F temperature. Although no detailed investigation has been made, the estimate of limiting the wing structure to appoximately 300°F appears to be reasonable for preliminary design purposes.

Figure II-9 compares the effect of a 0.5% creep rate in 100 hr for aluminum alloys. At temperatures of 300°F all aluminum alloys show a loss in creep strength.

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Figure II-10 stresses the strength variation of X2219-T6 aluminum alloy for creep rates, with a soaking time of 100 hr at temperature.

Figures II-11 through 13 show the elevated temperature effects on the mechanical properties of magnesium alloys, and Fig. II-14, for titanium alloys. Figures II-15 though 18 deal with steels.

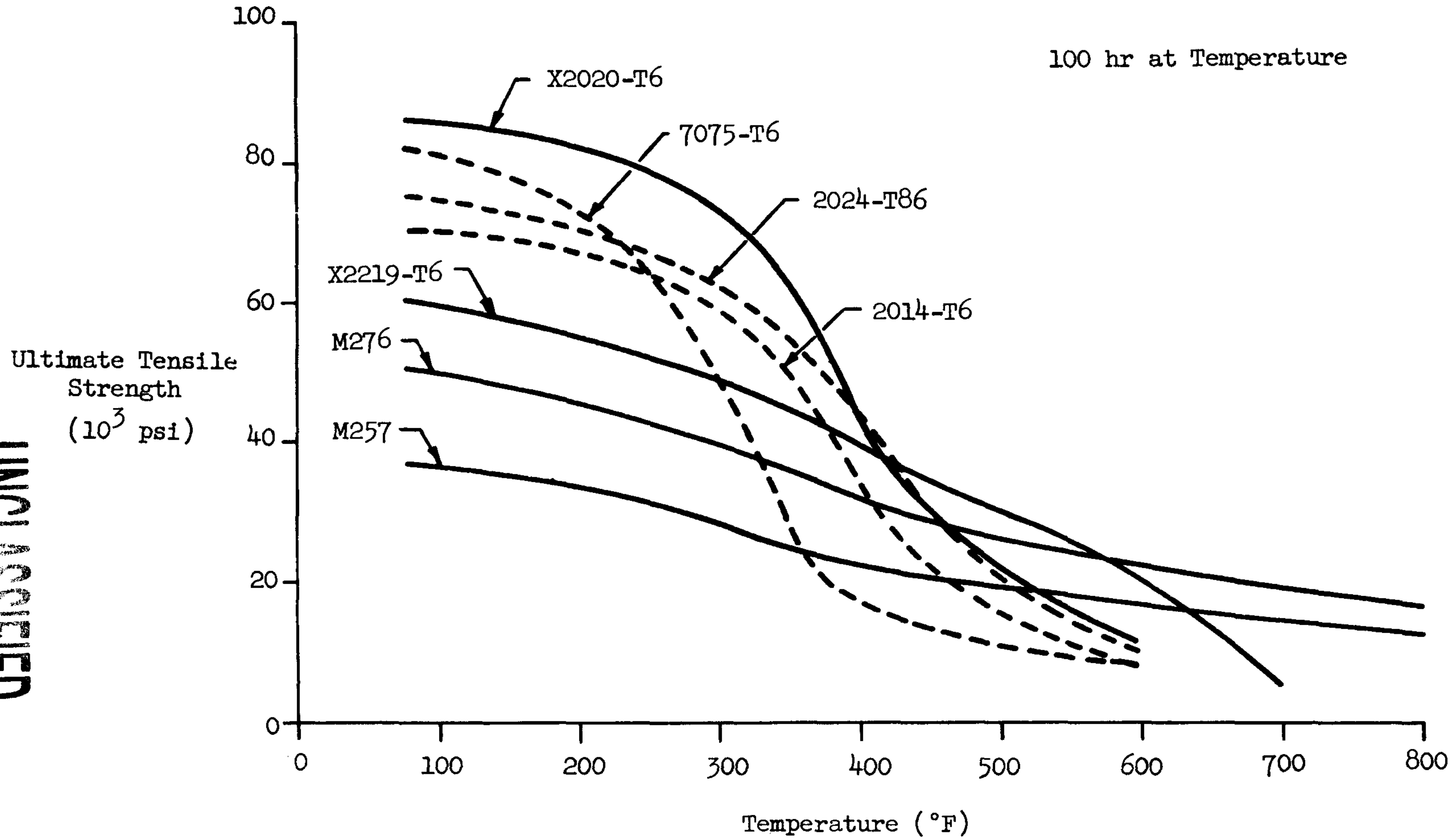

Fig. II-7. Mechanical Properties, Aluminum Alloys, 100 hr Soaking **Time**

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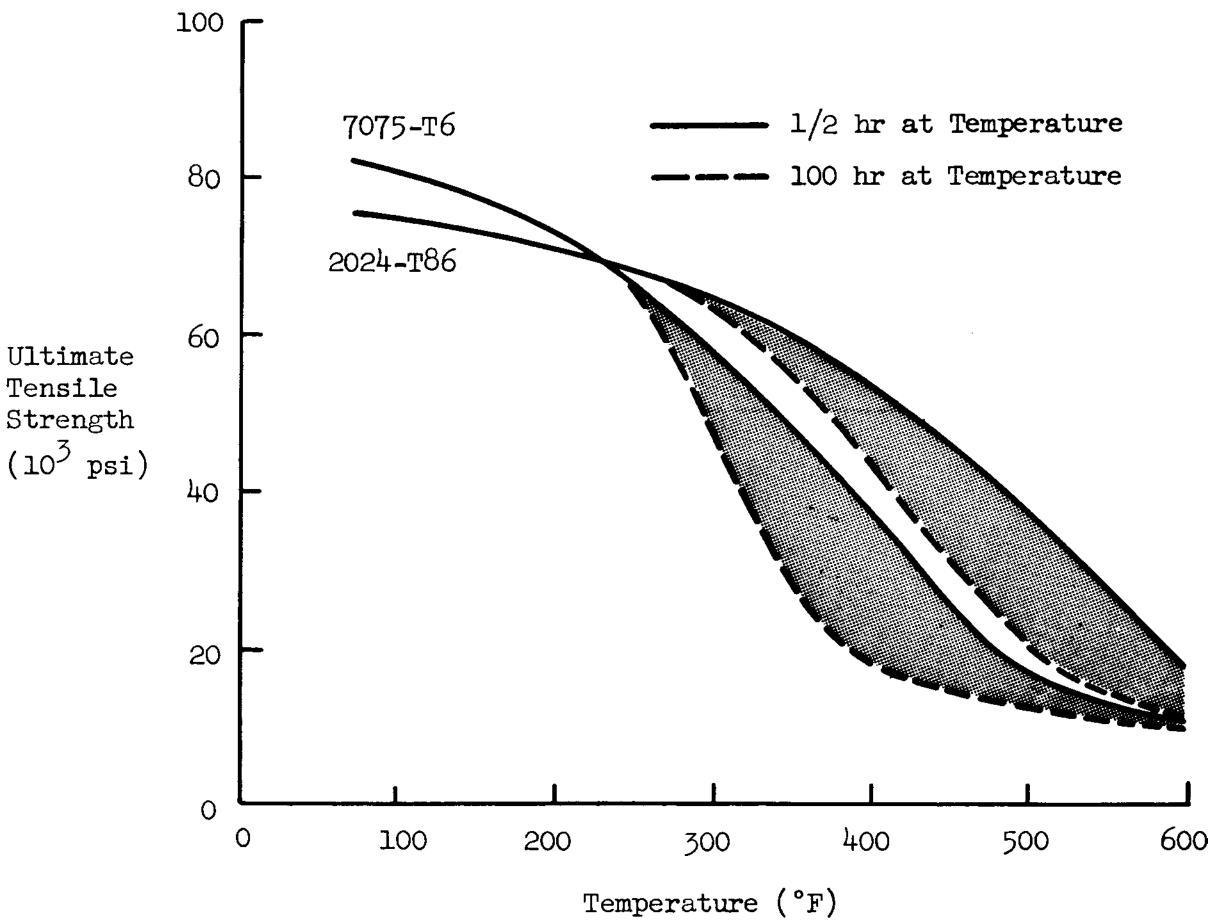

Fig. II-8. Mechanical Properties, Aluminum Alloys, 1/2 hr and 100 hr Soaking Time

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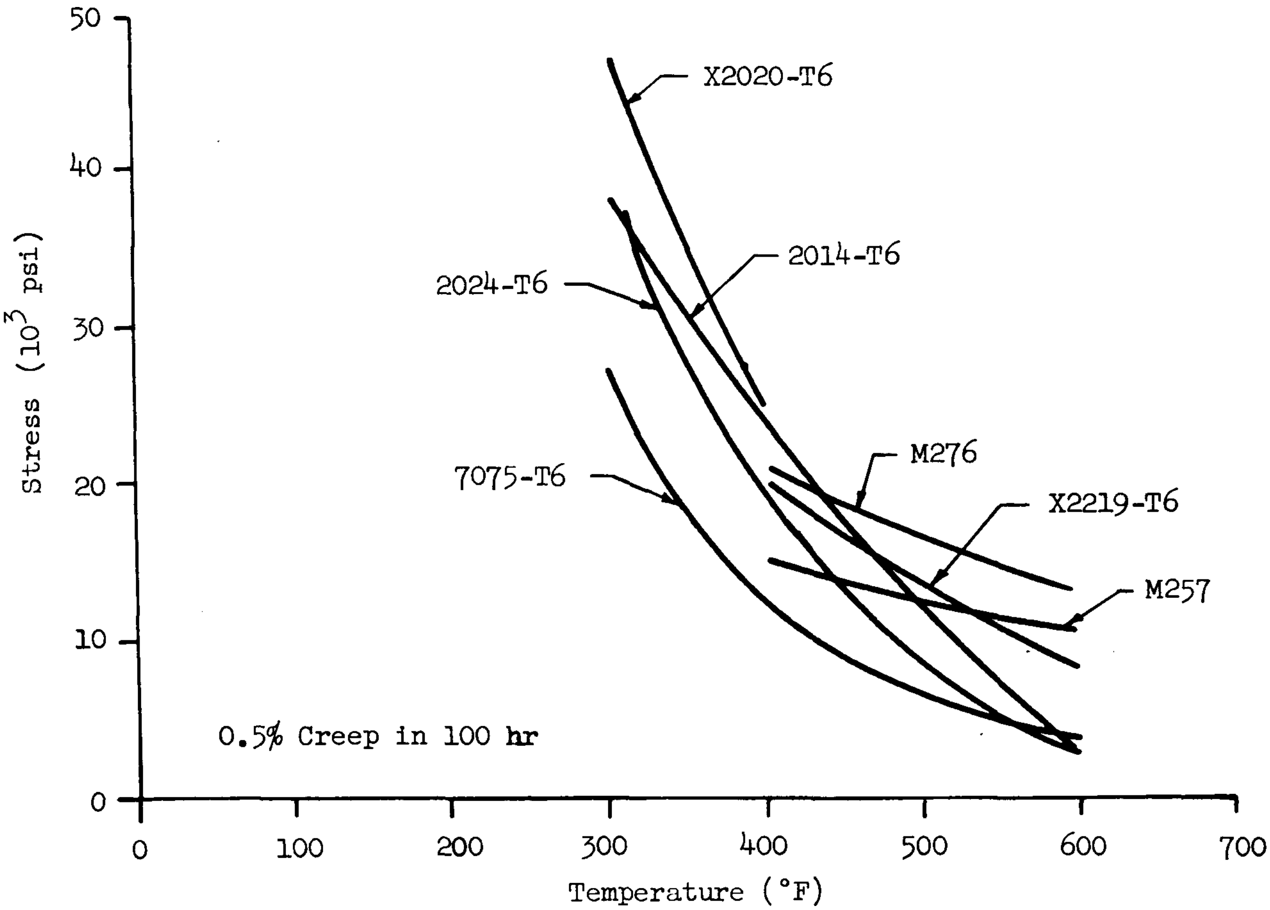

Fig. II-9. Mechanical Properties, Aluminum Alloys, Creep Strength

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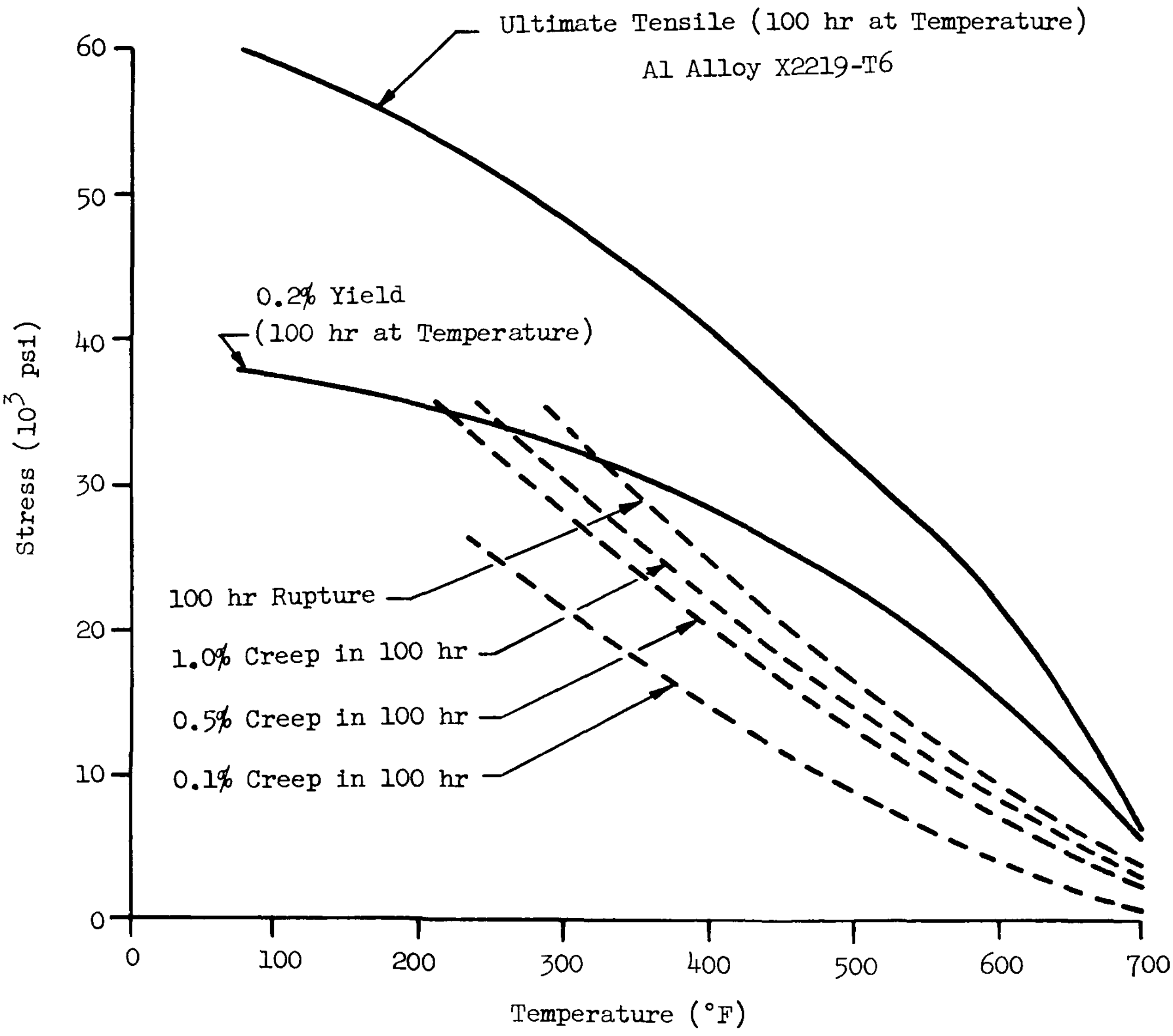

Fig. II-10. Mechanical Properties, Aluminum x 2219-T6, Effect of Creep Rate

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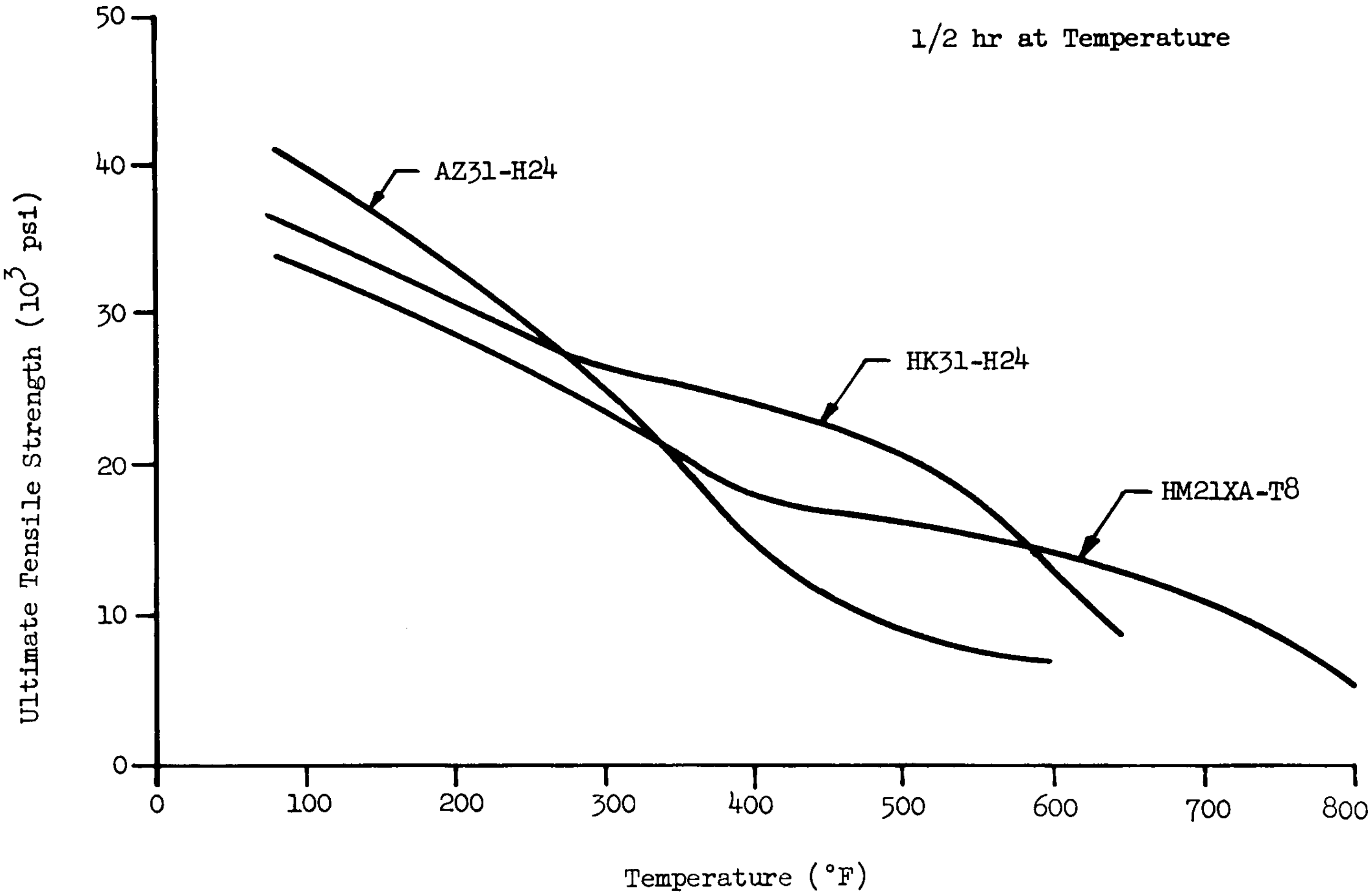

Fig. II-11. Mechanical Properties, Magnesium, 1/2 hr Soaking Time

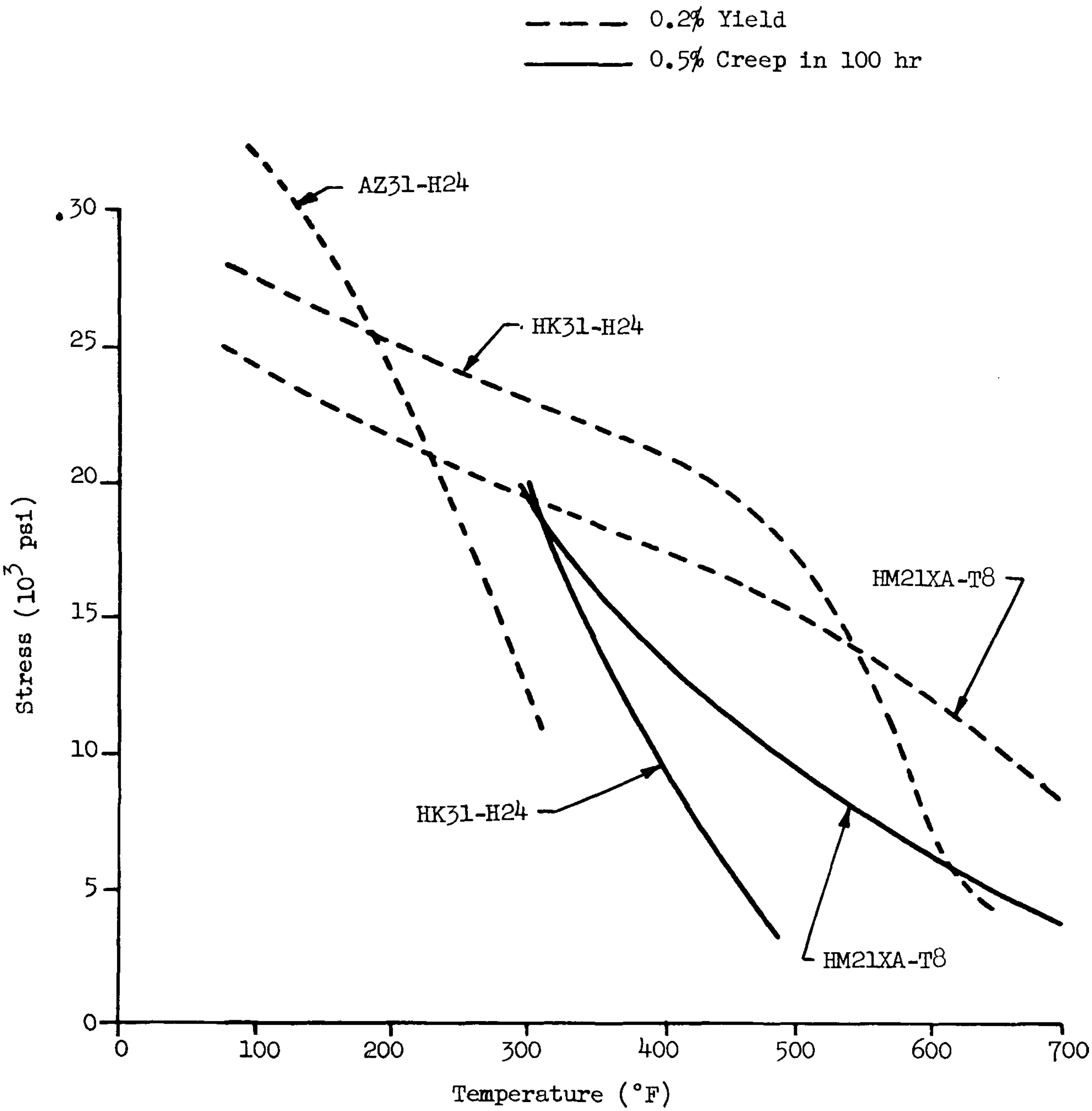

Fig. II-12. Mechanical Propêrties, Magnesium, Creep Strength

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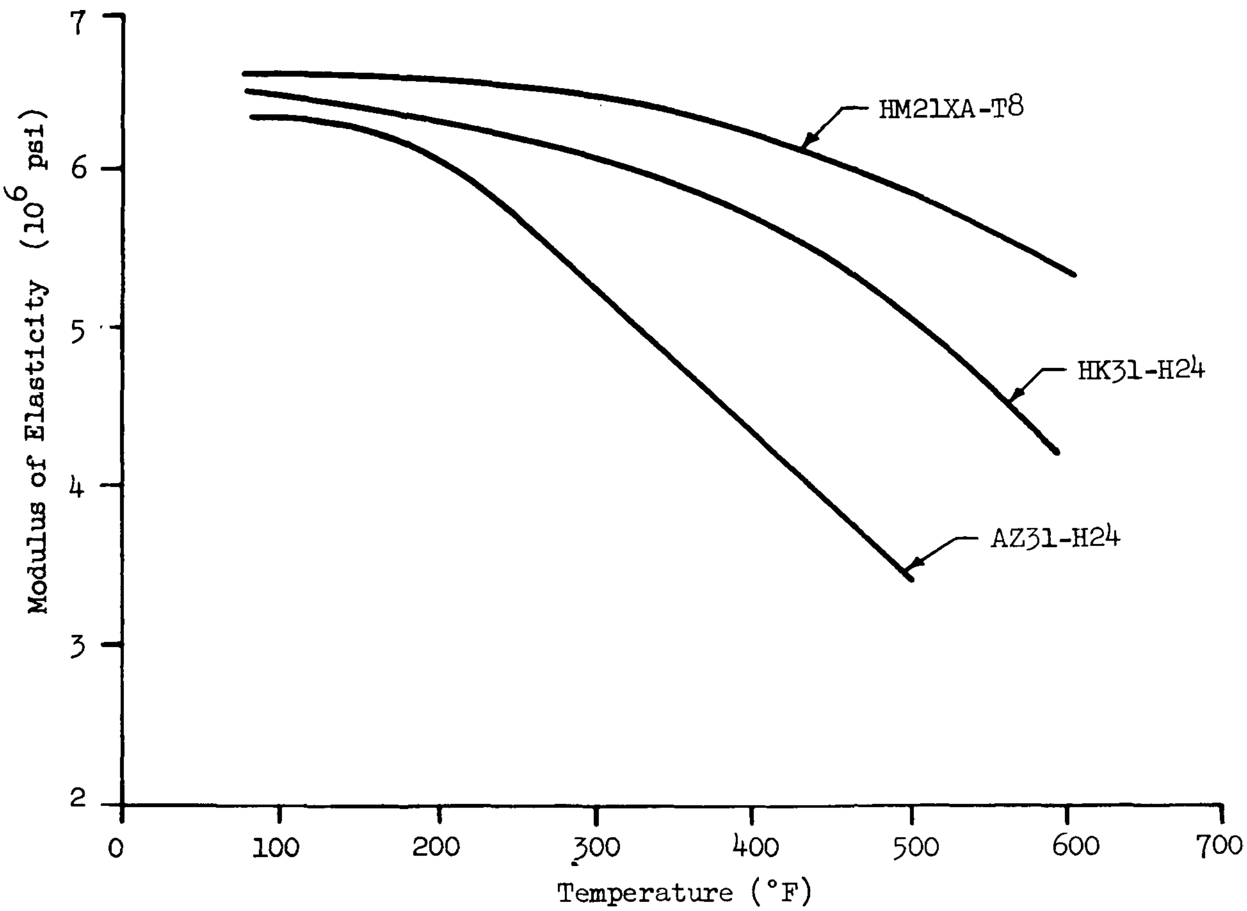

Fig. II-13. Mechanical Properties, Ductility

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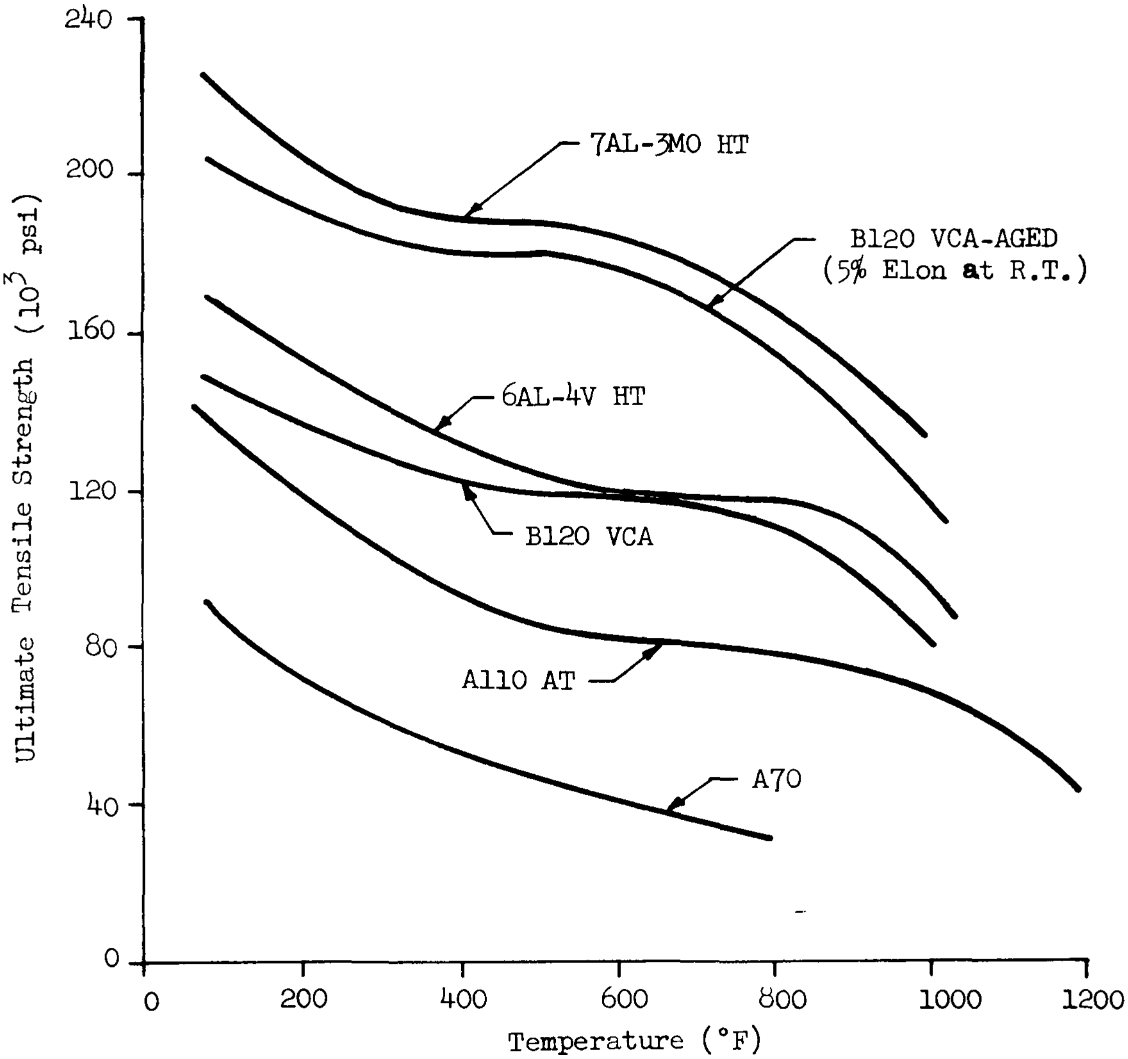

Fig. II-14. Mechanical Properties, Titanium Alloys

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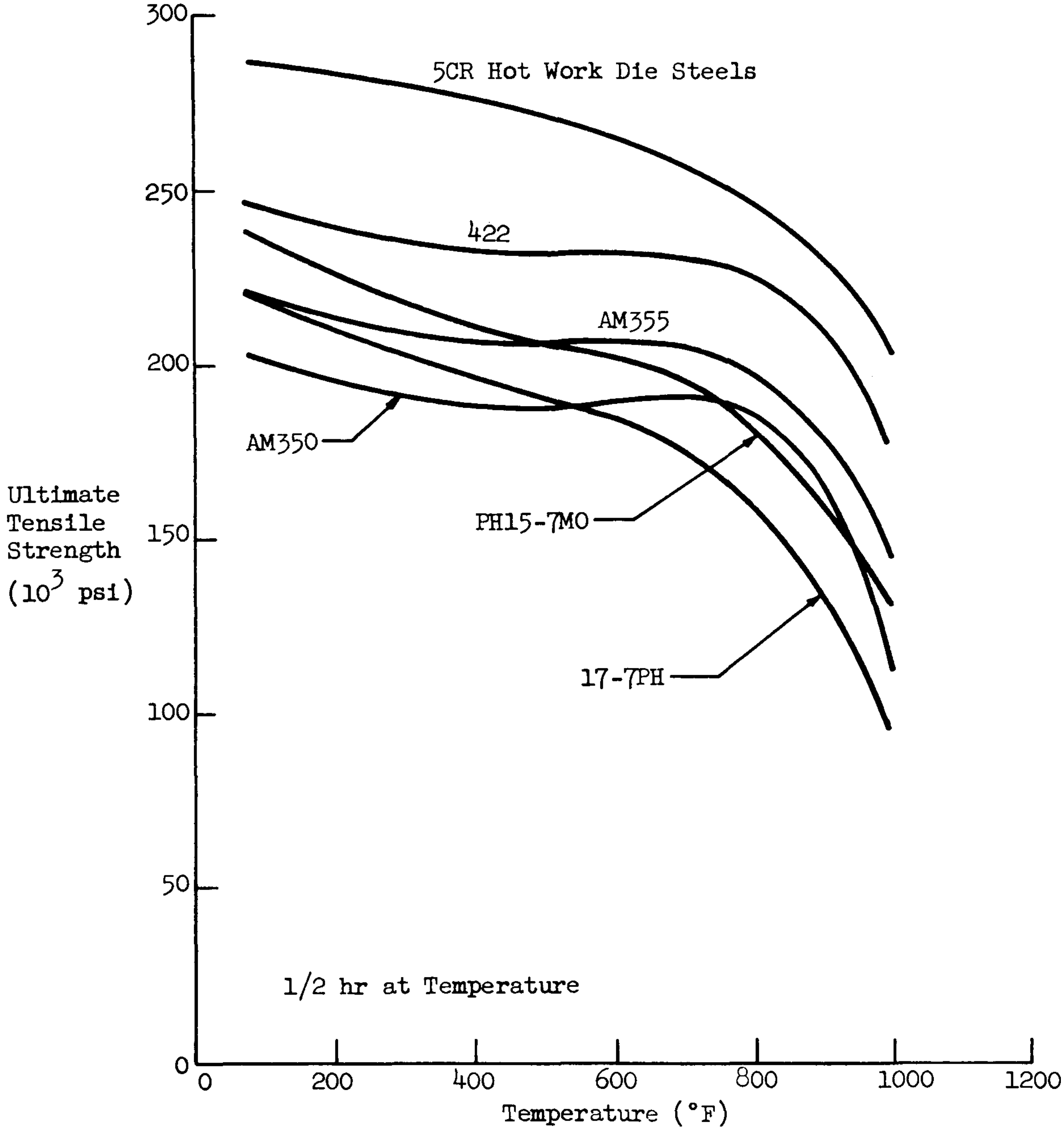

Fig. II-15. Mechanical Properties, Steel, 1/2 hr Soaking Time

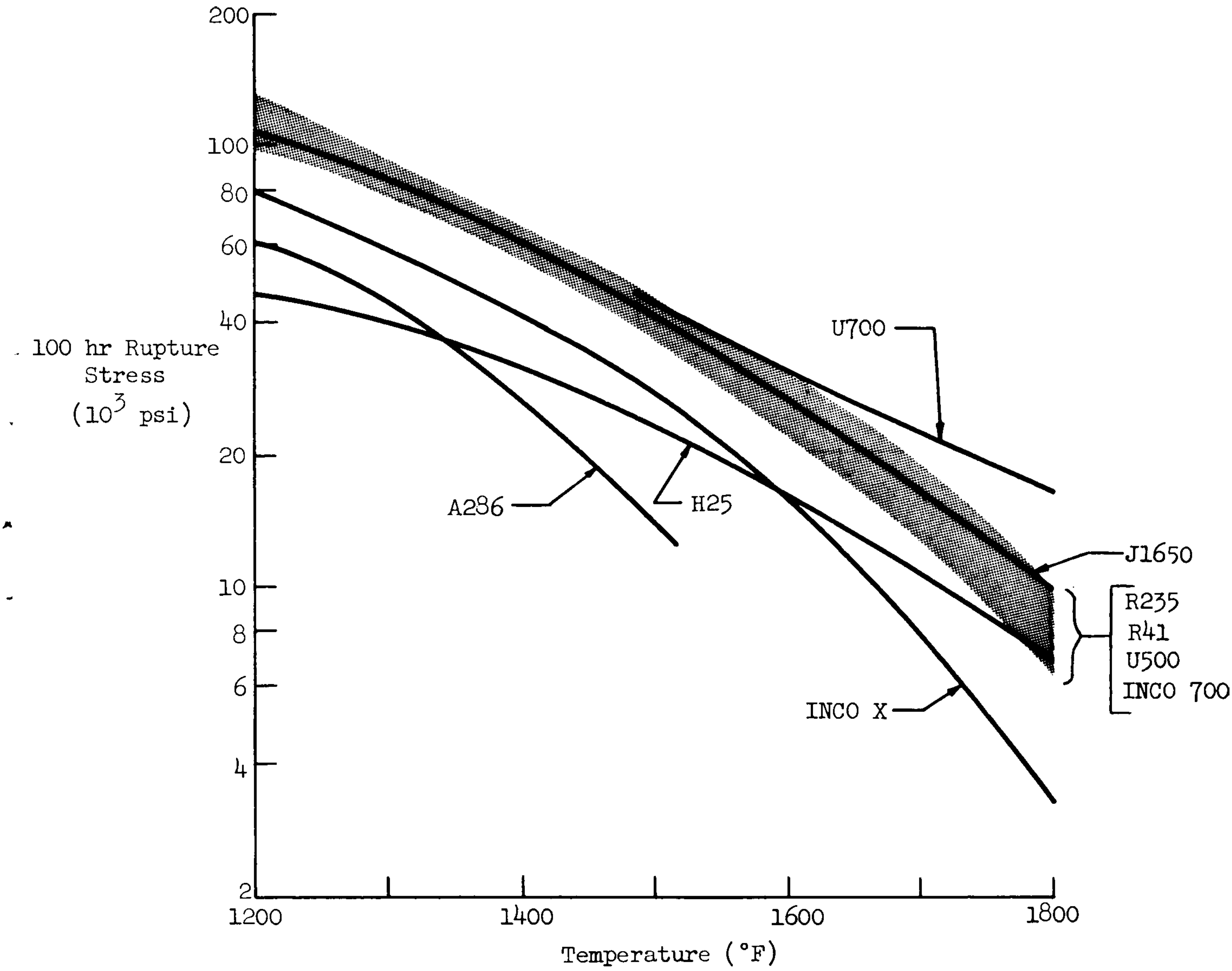

Fig. II-16. Mechanical Properties, Super Steel

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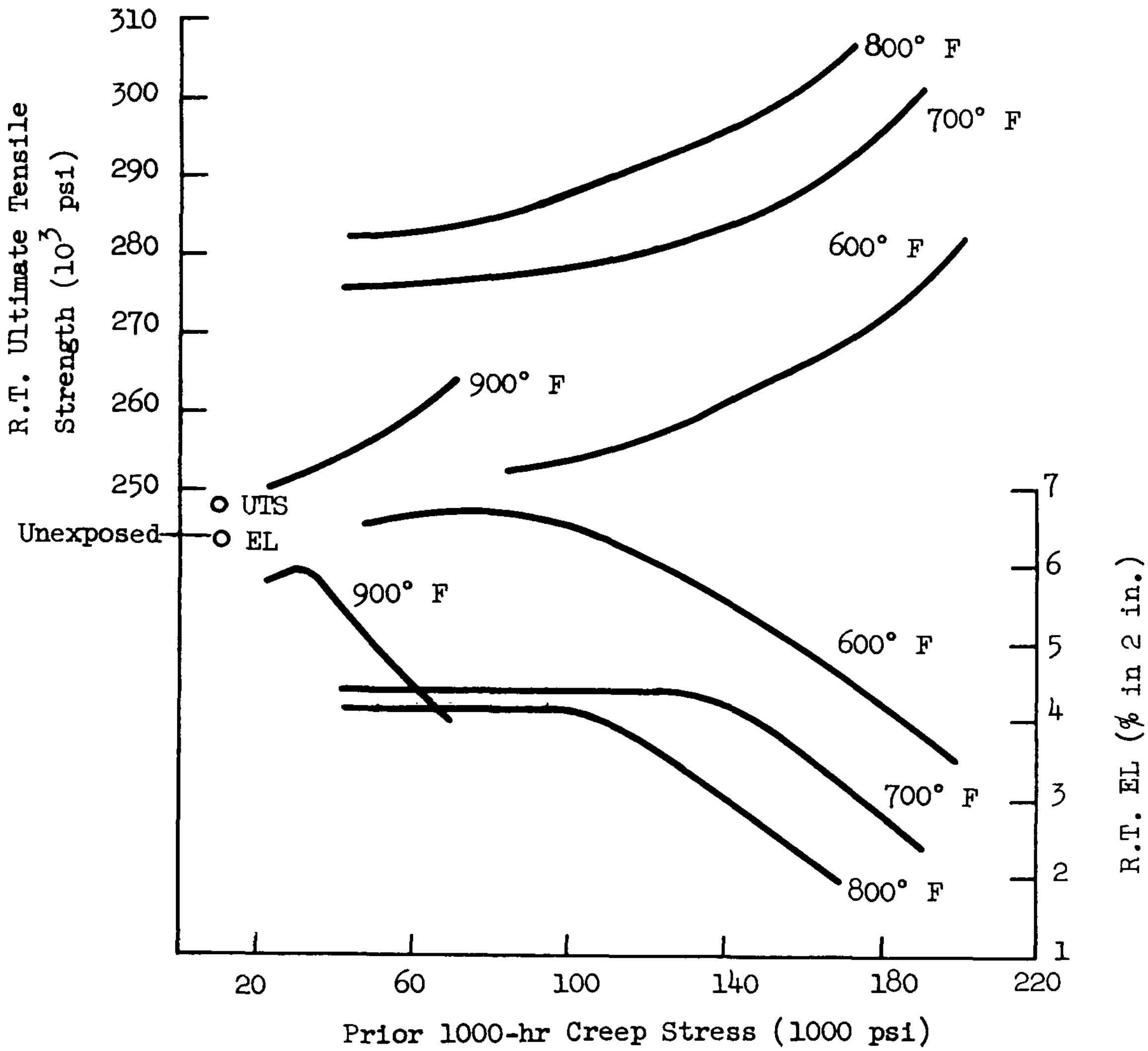

Fig. II-17. Mechanical Properties, Steel PH 15-7

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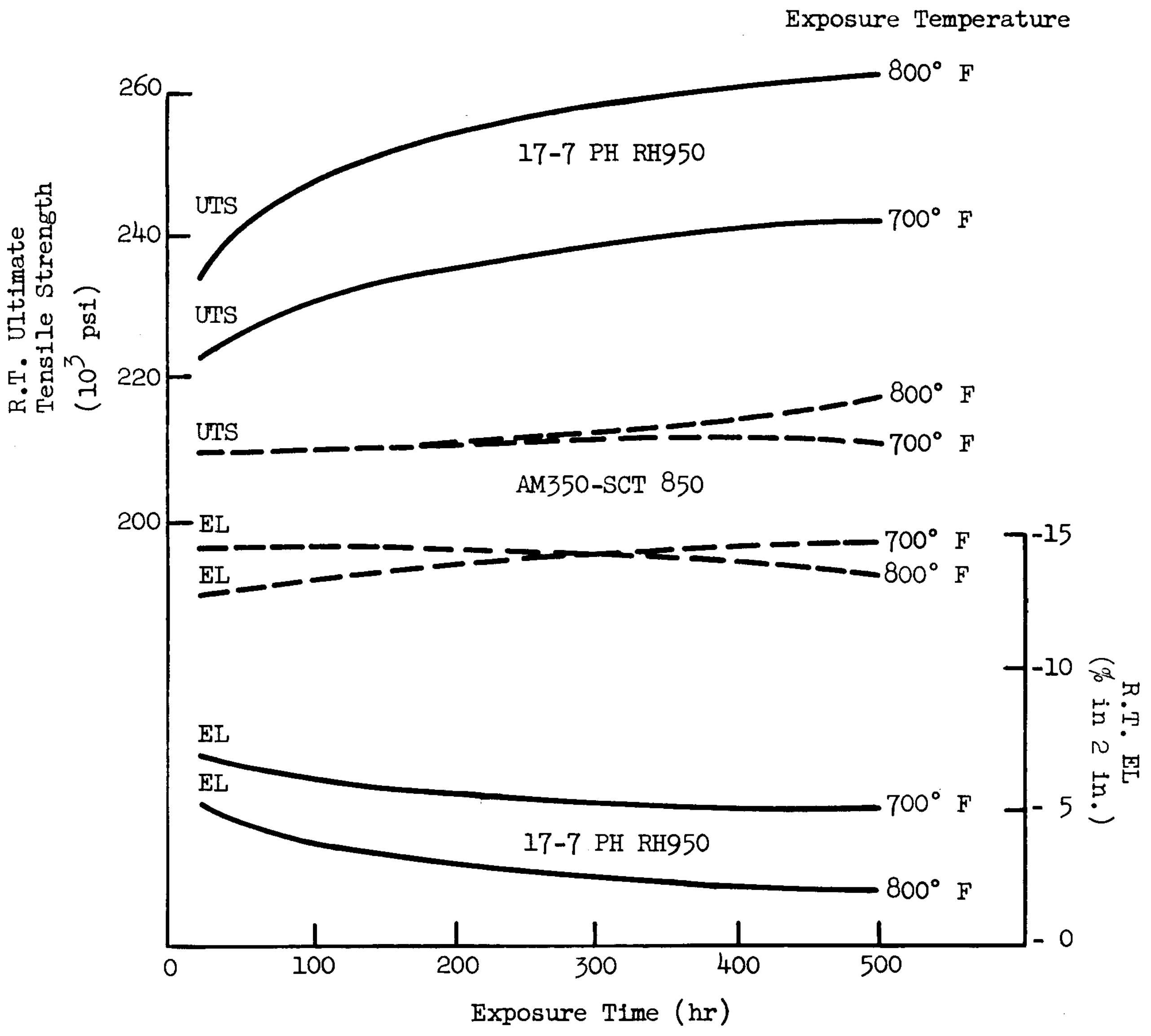

Fig. II-18. Mechanical Properties, Steels

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VI. RECOMMENDATIONS AND CONCLUSIONS

Some recommendations relating to the analysis of this shield design are contained in Chapter IV. These refer chiefly to the inclusion of additional radiation sources in determining crew dose rates in a more complete analysis. Further recommendations deal with the optimization technique employed in the shield design and with the structural design and analysis.

In future shield weight optimization calculations, secondary gamma sources resulting from neutron interactions within shield regions should be included in establishing angular dose rate distributions before applying a shield shaping procedure. Also, shield optimization criteria, whether applied manually or by machine, should be applied to the neutron and gamma ray angular dose rate distributions concurrently, in order to effect a more complete minimization of shield weight.

Further shield weight reduction may also result from a comprehensive iteration of both shield materials and their placement within the shield. This is particularly true with respect to regions intended to suppress the thermal neutron flux, thereby reducing capture gamma source strengths and activation. An extensive investigation in this area is warranted.

Further investigations are required on the effect of radiation streaming through the annular duct, specifically with respect to evaluating the influence of duct leakage on the magnitude and shape of the angular dose rate distributions. A rigorous comparison of methods for minimizing such streaming should be made for this application, i.e., a weight comparison between porous plugs, highly offset annular ducts, multiply bent annular ducts, etc.

An analysis of heat generation rates and temperature distributions within the materials of this shield system is desirable. Accurate definition of the thermal environment, in which shield and structural materials are located, will allow valid specification of these materials, and, in the case of major structure, will permit better estimates of dimensions and weights. The criteria for a shield cooling system may also be firmly established.

It is interesting to compare the RSA weight and dose rate determined for this design with previous results. Ref. 2 presents parametric data for the same design conditions assumed in this study and indicates good agreement, 1 to 2%, in RSA weight.

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A major result of the study is concerned with the importance of secondary gamma sources, in so far as they were determined. Since secondary radiation proved to be a significant contributor to operating dose rates, it is apparent that a comprehensive treatment of secondary source strengths and shield penetration by secondary radiation is required. A computational technique for this purpose was contemplated for this study, but time did not permit its application. In this procedure, secondary source strengths computed from neutron flux distributions within the shield are represented by a series of concentric cylindrical shell regions with exponentially varying source strengths. These source shells are then utilized in a shield penetration code such as 04-2 to determine dose rates external to the shield.

Some conclusions may be drawn from the conceptual structural design and installation of this nuclear powerplant. In this particular application, the nuclear powerplant has influenced the type of wing construction by requirements for location of ducting and burners in the wing. Close integration of the shield cooling system design with the design of the center wing structural box is necessitated. Structural installation of the RSA also affects the arrangement of major structure in this area. Finally, it is apparent that the aerodynamic drag penalty implied by the crown-mounted RSA may influence the aircraft configuration in order to minimize its effect; no explicit investigations of this aspect of the problem were performed for this vehicle.

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