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CRYOGENIC SYSTEM FOR THE SUPERCONDUCTING MAGNETS OF A FULL SCALE THERMONUCLEAR POWER PLANT

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ABSTRACT

A preliminary estimate has been made of the heat load on a cryogenic system for cooling the superconductivity coils of a 5000 Mw(t) thermonuclear power plant. The size, cost, and power requirements for this cryogenic system were then estimated using data for the large liquid helium refrigeration system employed for the 65 ft diameter by 125 ft tall space simulation chamber at the NASA Manned Space Flight Center at Houston.

INTRODUCTION

This memorandum was prepared to summarize the rough preliminary estimates made early in 1969 for the size, cost, and power requirements of the cryogenic system for the conceptual design for a 5000 Mw(t), full scale, thermonuclear power plant defined by Ref. 1. The heat load was estimated by summing the energy deposition in the superconducting coils and the heat that would be conducted into the coils through the thermal insulation, the lead-in conductors, and the support structure. The size, cost, and power requirements of a typical helium refrigeration system were obtained by using the data for the units serving the 65 ft diam by 125 ft high space chamber at NASA Manned Spaceflight Center at Houston, Texas, and scaling from these data to the conditions required for the cryogenic system of the study. The thickness of the layer of borated water and lead shielding designed to attenuate the energy input from the neutron and gamma flux incident on the cryogenic coils was increased to the point where rough estimates indicated that a further increment in its thickness would cause increases in the cost of the shielding plus the cryogenic coils plus the titanium retaining hoops that would approach the resulting reduction in the cost of the cryogenic system.

Heat Load

Energy Deposition in the Cryogenic Coils

The energy deposition in the cryogenic coils was obtained from multi-group calculations carried out by D. Steiner.[2] The heat generation rate in copper as a function of the thicknesses of the layers of lead and water shielding is shown in Fig. 1. These data indicated that a water shield thickness of 76 cm followed by a lead layer thickness of 17.2 cm would give about half of the emergent energy in gammas and half in neutrons and with an overall neutron attenuation factor of 1.35×10^{-5}. The multi-group calculations also indicated that the energy in neutrons and gammas leaking from the outer surface of the reflector would represent 0.545% of the total energy developed in the reactor. The energy deposition in the copper coils was estimated to be 1.15 kw. The effects of perturbations in the thicknesses of the borated water and lead layers were estimated by using an attenuation length of 10 cm of water or lead for neutrons, 25 cm of water for gammas, and 2 cm of lead for gammas. (Note that subsequent more refined calculations by Steiner[3] indicate that the thicknesses of the lead and water layers should be increased from the 17.2 cm and 76 cm used here to 24 cm and 93 cm respectively to give the same energy deposition in the cryogenic coils.)

Heat Conduction

It was assumed that the cryogenic coils would be cooled to 4°K with 2 cm of evacuated thermal insulation separating them from liquid nitrogen-cooled buffer coils at 70°K. The liquid nitrogen-cooled buffer coils were in turn separated on the inside from the water shield and on the outside from the atmosphere in the surrounding room by additional evacuated layers of thermal insulation each having a thickness of 2 cm. A cross-section through the arrangement contemplated is shown in Fig. 2, and the projected thicknesses of the various regions are shown in Table 1.

For a 5000 Mw(t) reactor with an energy flux through the vacuum wall of 10 Mw/m^2, the total internal and external surface areas of the cryogenic coils were taken as being 15,000 ft^2. The thermal insulation was taken as

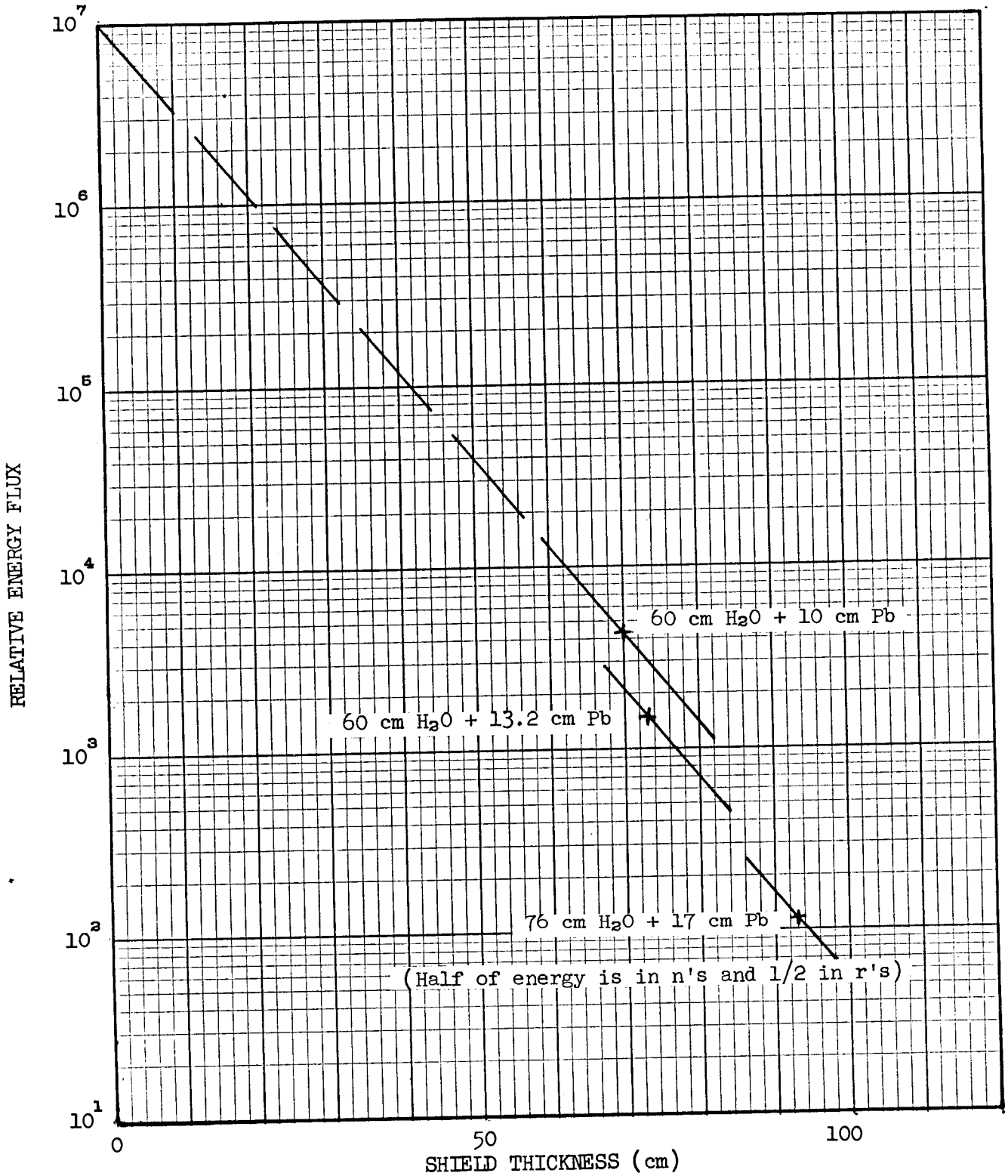

Fig. 1. Effects of Shield Thickness on the Attenuation of the Neutron and Gamma Radiation Leaking from the Reflector of the Reactor of Table 1. (The neutron energy leakage flux from the reflector is 0.8% of the total power.)

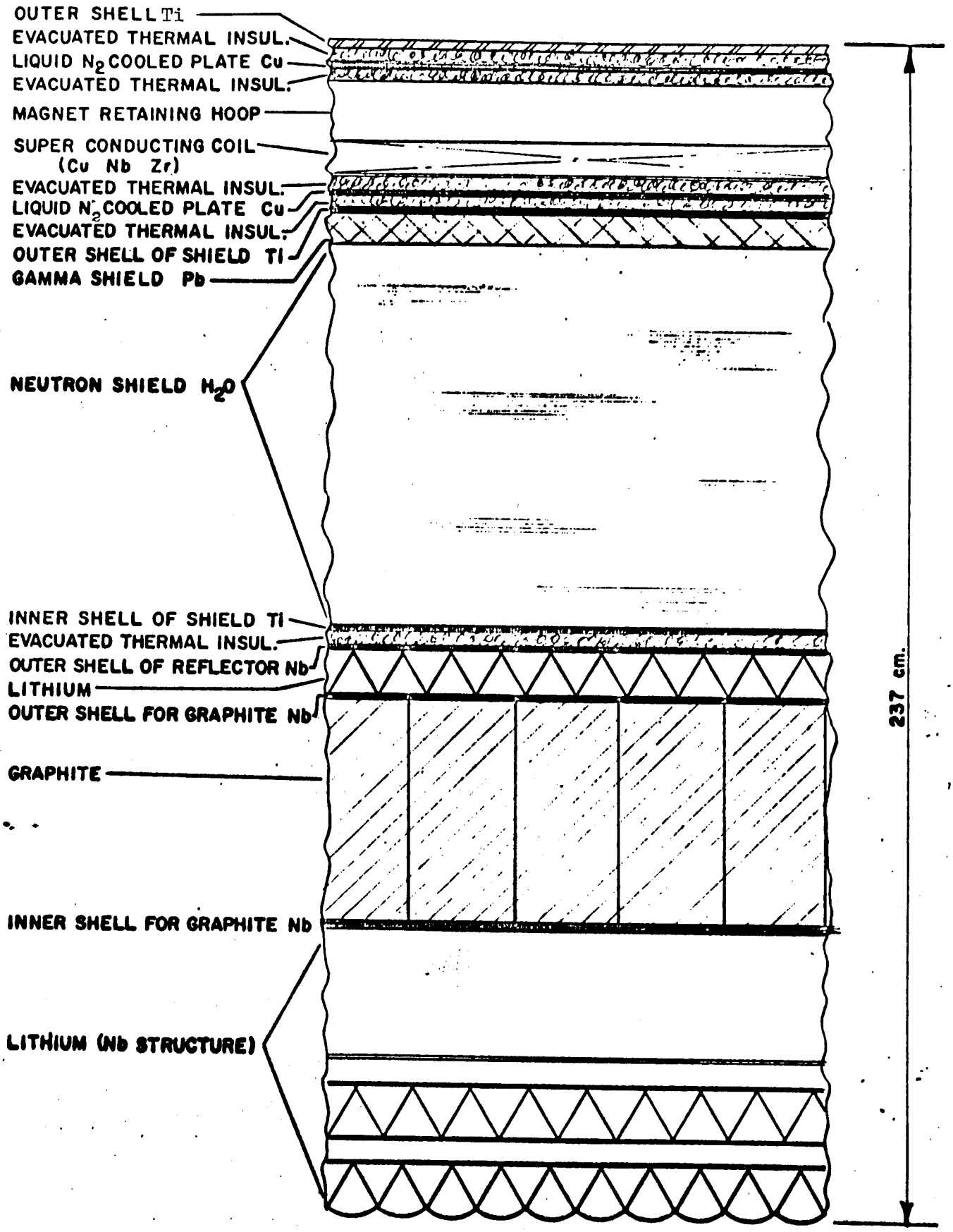

Fig. 2. Cross Section Through the Reflector-Shield-Superconducting Coil Region for the Conceptual Design of Ref. 1.

Table 1. Summary of Data on the Layers of Material in the Reflector, Shield, and Magnet Regions of a Reference Design Plant

Layer	Material	Inner Radius (cm)	Thickness (cm)
Vacuum wall	Nb	500	2
Lithium	Li	502	56
Inner shell for graphite	Nb	558	2
Graphite	C	560	44
Outer shell for graphite	Nb	604	1
Lithium	Li	605	4
Outer shell of reflector	Nb	609	1
Evacuated thermal insulation	Al_2O_3	610	3
Inner shell of shield	Ti	613	1
Neutron shield	H_2O	614	76
Gamma shield	Pb	690	17
Outer shell of shield	Ti	707	1
Evacuated thermal insulation		708	2
Liquid nitrogen-cooled plate	Cu	710	1
Evacuated thermal insulation		711	2
Super conducting coil	Cu+Nb-Zr	713	7
Magnet retaining hoop	Ti	720	12
Evacuated thermal insulation		732	2
Liquid nitrogen-cooled plate	Cu	734	1
Evacuated thermal insulation		735	2
Outer shell	Fe	737	1

having a thermal conductivity of 2×10^{-6} Btu/hr·ft·°F. Thus the heat leakage through the insulation becomes:

$$Q = \frac{KA\Delta T}{t} = \frac{2 \times 10^{-6} \times 15{,}000 \times 66}{.066} = 300 \text{ Btu/hr} = 88 \text{ w} \quad .$$

This is a remarkably low value and indicates how exceptionally effective the new types of evacuated thermal insulation can be.

The heat leakage through the thermal insulation into the liquid nitrogen-cooled layer would be the value obtained above for the helium-cooled region multiplied by the ratio of the temperature difference across the thermal insulation for the liquid nitrogen-cooled region to the temperature

difference between the liquid nitrogen and liquid helium regions. Since this factor is 3.6, the heat load on the liquid nitrogen-cooled region as a consequence of leakage through the layers of thermal insulation would be 1080 Btu/hr = 320 w.

One source of heat leakage into the liquid nitrogen and liquid helium-cooled regions would be along the electrical lead-in conductors. These conductors are estimated to have a heat flow path area of 10 in.^{2}, with a length of 120 in. extending into the cryogenically-cooled region, and would have a buffer region cooled with liquid nitrogen to minimize the heat load on the liquid helium system. The resulting heat load for the helium system thus was estimated to be:

$$Q = \frac{200 \times .0695 \times 66}{5.0} = 2640 \text{ Btu/hr} = 61 \text{ w} \quad .$$

The very large forces acting on the magnet coils, coupled with the greater effectiveness of the thermal insulation if maintained under a vacuum, favor placing the titanium structure to retain the magnets inside the helium-cooled region. This has the disadvantage that the thermal capacity of the helium-cooled region would be roughly doubled and this would increase the time and cost of cooling prior to startup, but it should yield both a structurally sounder system and a smaller heat leakage into the helium-cooled region. It has the additional disadvantage that the increased structure to support the titanium will increase the heat flow path area into the helium-cooled region. The magnitude of this loss was estimated by assuming that the total weight of the magnet coils and titanium hoops would be about 1.5×10^6 lb, and assuming that the structure supporting it would be titanium employed in tension or shear with a unit stress of 25,000 psi. This gives a cross-sectional area of 60 in.^{2}, or approximately 0.4 ft^2. Since the thermal conductivity of titanium is approximately 6 Btu/hr·ft^2·°F, the heat leakage into the helium-cooled region through a path 2 in. long from the nitrogen cooled region would be approximately 1700 Btu/hr, or 500 w. The heat load on the liquid nitrogen-cooled system would be increased by a factor of 3.5 over this value as indicated above, that is, it would run approximately 6000 Btu/hr.

The total heat load on the cryogenic systems obtained by adding up the heat inputs outlined above yields approximately 1.8 kw for the helium-cooled system and 2.4 kw for the liquid nitrogen-cooled system. Table 2 summarizes these data. Note that the heat leakage into the cryogenic coils both through the lead-in conductors and the structural supports could be greatly reduced by employing the regenerative system described by Efferson in Ref. 4

Table 2. Summary of Energy Inputs to the Cryogenically-Cooled Regions

	Liquid He Region	Liquid N_2 Region
Energy deposition, w	1150	50
Thermal insulation, w	88	320
Leads, w	62	250
Ti supports, w	500	1760
Total, w	1800	2380

Helium Liquefaction Equipment

The helium liquefaction equipment for the 65 ft diam by 120 ft high space simulation chamber at NASA Manned Space Flight Center in Houston, Texas, provided a point of departure for estimating the size, cost, and power requirements for the cryogenic system. The data for the Houston space chamber are presented in Table 3. In applying these data to the case at hand it was necessary to allow for the difference in design operating temperature of the cryogenically cooled coils, that is, 20°K for the Houston system and 4°K for the case at hand. This was done by applying a factor of 6.67 which was obtained from Fig. 3 (derived from data in Refs. 5, 6, and 7). Thus the heat removal capacity of each unit of the NASA helium cryogenic system would be reduced from 1.75 kw to 262 watts. Consequently, 10 of the NASA cryogenic units would have a heat rejection capacity of 2.62 kw, that is, about one-third more than the estimated

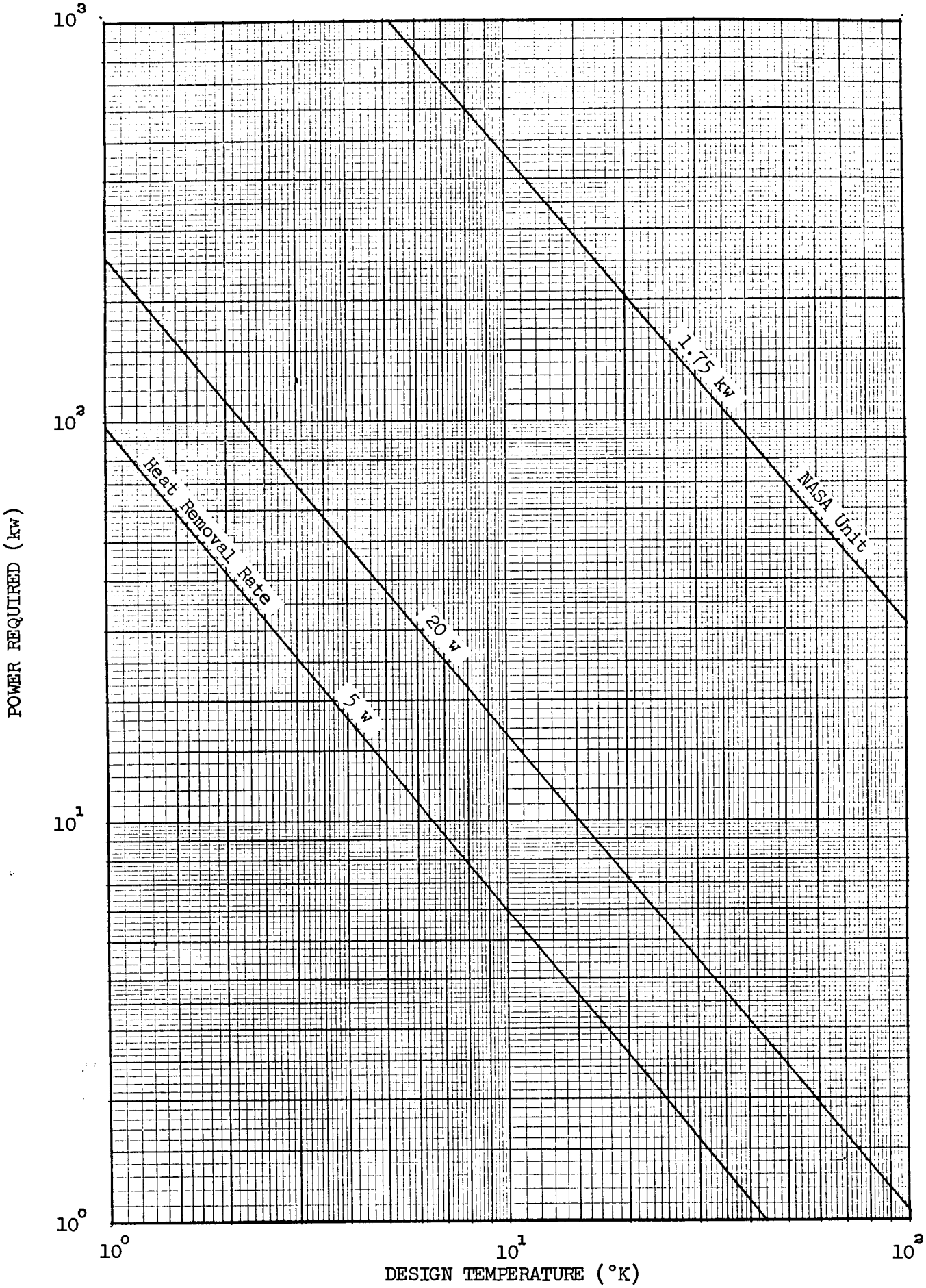

Fig. 3. Effects of Design Temperature on the Power Required to Remove Heat from a Low Temperature Region and Reject It at 80°F with a Helium Cryogenic System. (Data for 5 w and 20 w plotted from Ref. 5.)

Table 3. Cryogenic System for the 65 ft Diameter x 125 ft High Chamber at the NASA Manned Space Flight Center at Houston*

	Liquid N_2	Helium
Fluid flow rate, lb/hr	334,000	1704
Temperature to panels	-310°F	14°K
Temperature leaving panels	-280°F	20°K
Heat load, Btu/hr	135 w/ft^2 @ 250°K	7 kw @ 20°K
Circulating pump power, kw	120 hp	
Helium compressor power, hp		1000 hp
Liquid N_2 consumption rate, lb/hr	13,000	70
Capital cost of system, $		1,460,000
Floor space required for system, ft^2	10 x 30	40 x 80

Liquid N_2 tankage: 4 tanks of 28,000 gal each
2 tanks of 24,000 gal each
Amount of N_2 for initial cooling down: 60,000 gal

Heat input: (two banks of lamps in the chamber simulate the sun)

13' x 35' side "sun" 130 w/ft^2 (to be 20' x 65') – 60 kw
13' Ø top "sun" – 17 kw
Floor (electrically heated) – 215 kw

Note: The helium system is for cryogenic pumping to give a high vacuum. It is not intended to hold the chamber walls at 20°K when exposed to the simulated sun.

*These data were supplied by Frank Knox of the NASA Manned Space Flight Center at Houston, Texas.

Reduce to 6"
Reduce to 72% of original

Table 3

heat load on the helium system for the proposed CTR plant. The cost of these would be roughly $3,000,000.

The size of the cryogenic equipment for handling the liquid nitrogen system was estimated from Fig. 3 to be roughly 30% of that required for the liquid helium system. Three smaller nitrogen units operating in parallel were allocated the same floor space as three of the helium units. The cost of these would be about $1,150,000. Note that the NASA system of Table 3 does not include any nitrogen liquefaction equipment; the liquid nitrogen is purchased from a vendor and delivered in tank trucks.

Shielding

One advantage of the thick reflector, water shield, and cryogenic cooling coil layer is that this material also will serve to provide most of the shielding required. Inasmuch as these layers will attenuate the radiation to give approximately equal amounts of energy in the neutrons and gammas leaking from the outer surface, a good indication of the radiation dose level in the region immediately outside the cryogenic coils is given by working simply with the neutron leakage. Assuming a vacuum wall surface area of approximately 700 m^2, a reactor power output of 5000 Mw(t), and 3×10^{11} neutrons/watt, the neutron flux escaping from the surface of the plasma region will be given by:

$$\text{Neutron flux} = \frac{5000 \times 10^6 \times 3 \times 10^{11}}{700 \times 10^4} = 2.1 \times 10^{14} \text{ n/sec}\cdot\text{cm}^2 \quad .$$

For neutron energies ranging from about 1 to 10 Mev, a dose of 1 rem/hr is given by approximately 7×10^3 n/sec·cm^2. The neutron attenuation through the reflector region is approximately 100, that through the reflector plus the water and lead shield region would be approximately 0.74×10^5, and that through the copper coils and titanium hoops would be approximately 20. Thus the overall dose outside the reactor shield assembly would be:

$$\text{Dose rate} = \frac{2.1 \times 10^{14}}{7 \times 10^3 \times 0.74 \times 10^7 \times 20} = 200 \text{ rem/hr} \quad .$$

The above dose level of 100 rem/hr will require further shielding — about 4 ft of concrete. However, the dose level is not so severe but that it will be relatively easy to provide adequate shielding for shield penetrations for pipes and ducts by using trenches with approximately two right angle bends to stop line-of-sight radiation. Further, the bulk of the dose is from neutrons and capture gammas so that the dose rate will drop drastically when the reactor is shut down.

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