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THE PRINCETON FUSION POWER PLANT SUPERCONDUCTING MAGNET SYSTEM AND COSTS

BY

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ABSTRACT

The Princeton University Reference Design of a proposed fusion power plant has been previously described. This paper describes details of the superconducting magnet system consisting of toroidal field, divertor, ohmic heating, equilibrium field and control field magnets, all of which are wound of Nb_3Sn conductor. The toroidal field coils are of the moment-free, "D" type, previously described. The toroidal field magnet is comprised of 48 discrete "D" coils, 12m x 19m bore. The magnet has a stored energy of 250×10^9 joules. The magnet which is operated at a maximum field of 16T is described in detail. Fault conditions are calculated and design conditions based on maximum fault forces are outlined. In addition, we describe the Dewar System, the refrigeration plant (requiring 280kW of refrigeration), the safety system, and the coil protection system for the magnets. Finally, an overview of the helium-steam generating plant and detailed cost data for the plant, the nuclear island and the magnet are presented.

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SUMMARY

This paper describes the superconducting magnet system and some of its details for the Princeton University Reference Design of a proposed fusion power plant. In addition we present an overview of the total helium-steam generating plant with expected costs of its components.

INTRODUCTION

The Princeton University Reference Design for a proposed fusion power plant[1] describes an electric plant which produces 2030 MW of electric power. The nuclear heat generated is 5305 MW with an overall net efficiency of 38%. Figure 1 shows a sketch of the power plant. The projected capital cost of this plant in 1974 dollars is $1,486,390,000 or about $732/kWe. The cost of energy at the busbar is 17.87 mills/kWh. The details of these costs are described below.

One of the principal systems of this power plant is the magnet system. The magnet system is composed of various sets of coils which have been named: toroidal field coils, vertical field coils, divertor coils and control coils. Figure 2 shows a cross-section of the machine on which the various coils are located, all of which are superconducting. The toroidal field coils generate the most intense magnetic field and the largest magnetic flux. They are formed in a special shape described below to eliminate large bending moments and thereby minimize the amount of material required to support the magnetic pressure. The superconducting material chosen is Nb_3Sn at a field level to match the current state of art of magnetic field design.

The vertical field coils are placed to give the proper shape and level of the magnetic field to maintain the stability and equilibrium of the toroidal plasma current of (14.6 MA) characteristic of this tokamak device.

The divertor coils are used to scrape off plasma impurities from the outside layers of the plasma column. These coils produce the sepatrix for the divertor field and steer the scrape off layer through the divertor channel into the plasma collection chamber.

The control windings provide a source of magnetic flux to generate the voltage that provide the ohmic losses of the plasma during the burn time of the plasma (100 minutes in this case).

Except for the toroidal field coils, which operate in a steady mode, the other coils are operated intermittently and will be referred to as the pulsed field coils in this paper.

The remainder of the magnet system is composed of the structure, the Dewars, and the refrigeration required to liquify helium and to maintain the magnet system at the operating temperature of 10K.

1. THE MAGNET SYSTEM

1.1. Toroidal Field Coils

1.1.1. Description The power density of a fusion reactor increases as B^4, and the cost of the magnet increases at a somewhat lower rate (somewhere between B and B^2). Because of these relationships, it is generally agreed that fusion reactor designers intend to take advantage of the highest fields available, consistent with other mechanical constraints such as first wall loading and stress limits of structural materials. As stated previously, commercially obtainable superconductors are already capable of producing magnets with fields in excess of 160,000 gauss[2] in relatively small bores. That field level taxes the known limits of structural design. In addition to high fields, fusion reactors will require larger working volumes (by several orders of magnitude) than any magnet previously designed. The combination of high field and large working volume requires the design of superconducting magnets well beyond present known technology.

A novel design of a toroidal magnet coil that partially accommodates the large forces generated by a high field, large volume magnet was previously described.[3,4,5] In a toroidal magnet, the field strength within the useful volume varies inversely with the radius from the axis of symmetry, and in almost all cases the conductors generating such fields will be subject to bending moments in addition to effective internal pressure. It was shown that a conductor tethered at either end and in a toroidal field will be stable if it is in pure tension and, therefore, not subject to bending moments. The net forces are then taken on a cylindrical structural element to which the conductor is tangent. Except where the conductor lies flat against the support, it lies in a curve such that its radius of curvature, ρ, is proportional to the radius from the axis of the torus, r; $\rho = kr$, k is a constant depending on the geometry of the system. (See Figure 3). A coil of this shape is now commonly known as the "D coil", or constant tension coil.

Rationale for the choice of superconducting material, supports, location etc. are given in detail in chapter 13 of Ref. 1. Suffice it to say here, that generally we proposed materials and technology either in existence or obtainable with a small extrapolation of the state of the art. These criteria lead us to propose cryogenically stable Nb_3Sn tape, capable of carrying 10kA with stainless steel reinforcement capable of withstanding strains of 0.003 (stress of 90,000) psi in the stainless steel) for the toroidal field coils. Figure 3 shows details of the coil proposed for this first generation fusion power plant. Figure 3 also shows the largest of the 15 types of superconducting tapes proposed for use, it is 4.5 cms wide by 1.5 cm thick, made of alternating layers of stainless steel, copper and superconductor.

Forty-eight coils, shown on Figure 4, evenly spaced and keyed to the supporting cylinder comprise the toroidal field magnet assembly. The cylinder is made of eight segments to match the assembly procedure for the reactor. Since each of the conductor strands is in tension and designed to be self-supporting, the segmented supporting cylinder is subjected only to the compressive magnetic pressure of 15,000 psi (the magnetic pressure at 160,000 gauss). The total centering force on the cylinder is about 5.52 x 10^9lb or about 1.12 x 10^8lb per coil.

The segmented cylinder is 14 m high, 2.25 m inside radius, 2.70 m outside radius and 0.45 m thick. It is made of work-hardened stainless steel with yield stress of 150,000 psi. The maximum stress in the cylinder, using a safety factor of 1.5, is 100,000 psi. Under maximum stress conditions, the cylinder deflects 0.75 cm. It weighs 2.2 x 10^6lb and is housed in a segmented Dewar as shown in Figure 1. This arrangement eliminates the need to transmit high forces through Dewar walls. The weight of the toroidal field magnet assembly is supported by low conductivity rods and pylons from the inside structure of the Dewar. Individual coils cannot be removed from the reactor unless the whole assembly is warmed up. Should one or more coils fail, the reactor continues to operate at reduced power. The affected coils are repaired during a long-term shutdown. It is assumed that the reactor could be kept on line until its power output decreases to one-half rated (i.e., 1000 MW). Inasmuch as power output varies as B^4, we see that 84%, or about 40 of the 48 coils, are needed to generate the required field to attain 1/2 power, provided that the coils taken out of service are approximately evenly spaced. Should they not be evenly spaced, fewer coil outages can be tolerated, and the number varies as the asymmetry of the out-of-service coils increases. Table 1 lists electrical and mechanical parameters for the proposed toroidal field coils.

1.1.2. Forces The toroidal field coils suggested above give rise to magnetic pressures which generate very high forces and moments. During operation the orthogonal toroidal and pulsed vertical fields cause a twisting moment of about 4.36 x 10^9 ft.-lbs. This moment is resisted by a torque frame, which is seen in Figure 1 and Figure 2. The torque frame is made of standard rolled or "built-up" shapes, made of stainless steel. The torque frame is also used to support the fault forces should one or more of the toroidal coils fail.

The fault forces, which could be as high as 10^8lb., are transmitted through the Dewar by low conductivity compression members that do not touch unless the magnetic field becomes asymmetric. Movement of 0.5 cm is required before contact with the compression member is made.

There are a large number of possibilities of coil failures. Only one of the possible modes is presented. This case considers the fault forces on all remaining coils if any one of the 48 coils fails and is no longer energized. Table 2 tabulates the forces on each of the remaining energized coils. We tabulate F_x, the radial force, F_z, the tangential axial force, F_t, the total force (the vectorial sum of F_x and F_z) M_{zx}, the overturning moment about the Y axis. Because of symmetry, the vertical force F_y, and the overturning moment about the x axis, M_{zy} are essentially zero, and therefore not shown. The total radial force is 5.52×10^9lb or 1.12×10^8lb per coil.

The case tabulated is one of the most probable modes of failure. On the other hand, it is clear that as the number of adjacent coils that fail is increased, the tangential forces increase. These are maximum when half of the torus becomes deenergized. Figure 5 is a plot of the maximum forces on any single coil and moments, F_x, F_z, F_t and M_{zx} as a function of the number of adjacent deenergized coils in the torus. The centering force, F_x, is maximum when all the coils are energized. The tangential force, F_z, and the torque about the Y axis, M_{xz} have maximum values when one half of the torus is deenergized. The total force F_t is a maximum when 20 coils are deenergized. Therefore the structure has been designed according to the following maximum conditions:

a) $F_x = 1.12 \times 10^8$lb. per coil

b) $F_z = 2.22 \times 10^8$ lb. per coil

c) $F_t = 2.30 \times 10^8$ lb. per coil

d) $M_{xz} = 2.05 \times 10^8$ ft-lb per coil.

We choose to design the reactor to withstand the worst possible fault conditions.

The compression pads, made of glass epoxy laminate, NEMA G-10, whose properties are given below, are designed for the worst fault conditions, both for strength and increased heat load. For strength, an allowable compressive stress of 10,000 psi is used. This results in each toroidal coil Dewar having 10 compression pads, each with a compression area of 2250 in^2.

When faults occur, causing some of the compression pads to touch, the heat leak through the Dewar increases. The outer pads are kept at liquid nitrogen temperature or lower, to minimize the heat load to the liquid helium. During the worst fault condition, the pads of 20 of the 48 coils make contact. This results in an increased heat load to the helium of 80 kW above the normal heat load of 280 kW.

1.1.3. Pulsed Field Coils The pulsed fields required to ignite, heat, stabilize, clean and control the plasma are pulsed over a period of 100 minutes, of which about 13 seconds is the rise portion of the pulse. There are three sets of pulsed field coils. They are:

a) The vertical field coils, placed inside the D coils, used to heat and ignite the plasma.

b) The divertor field coils, placed inside the D coils, used to produce the poloidal divertor field.

c) The control coils, placed outside of the D coils, used to induce a voltage to maintain the plasma current during the 97 minute burning period.

The vertical field and divertor coils are inside the toroidal field coils and when pulsed are energized to full current in about 13 seconds. For economic reasons, these coils will be made of Nb_3Sn with a peak current density of 2000 amperes/cm across the face of the coil. For compatibility with the D coil and refrigeration system, the material is Nb_3Sn similar to that shown in Figure 3, but the amount of stainless steel and copper is tailored to the pulsed field operating conditions, i.e., to achieve a 30,000 gauss peak in about 13 seconds. This moderate operating condition should not cause severe losses in the coil itself, and multifilament wire will probably not be necessary for these coils. However, each of the coils is easily adaptable to multifilament material, either of Nb_3Sn (if developed) or NbTi.

When the vertical field and divertor coils are pulsed, flux is produced during the rise. Some energy is dissipated as eddy current losses in the normal material of the toroidal field coils (copper and steel). This adds to the heat load on the refrigeration system. Alternatively the coils can be shielded by a high conductivity shield with high heat capacity in which the ohmic losses can be cooled during the pulse. A shield of this kind is massive and necessitates large amounts of copper that otherwise would not be needed. Therefore, the decision not to shield the coils is economic; the added refrigeration required is nominal and is less expensive than constructing the normal, external copper shield on the D coils. It was shown in Chapter 13 of Reference 1 that these losses are moderate (35kW out of a total of 280kW), and are easily calculated.

2. REACTOR COST ANALYSIS

This section gives the cost estimate of the Princeton Reference Design Fusion Reactor. Costs are given in 1974 dollars. We choose as a format the Atomic Energy Commission Guide for Economic Evaluation of Nuclear Reactor Plant Designs,[6] used by the power industry estimators to present cost analyses of nuclear power plants. Where necessary, adjustments are made to fit the particular needs of a fusion reactor.

2.1. Capital Costs

The capital cost of this 2030 MWe fusion power plant, excluding interest during construction is $1,004,320,000, resulting in a unit cost of $494.70/kW. Originally, (early 1974) it was estimated that the interest during construction would be applied at the rate of 7% per year over a 3 year construction period. This assumption added $210,910,000 to the capital cost resulting in a unit cost of $598.60/kW as reported in Reference 1. Since then the pressures of the world economy, the fossil fuel crises, in addition to pressures applied by the necessity of making extensive environmental studies, it is quite clear that the numbers used initially were inadequate. It is suggested that an interest rate of 8% during construction phase of 6 years is a more realistic assumption, thereby adding $482,070,000 to the capital cost resulting in a capital unit cost of $732.20/kW. Figure 6 is a plot of capital cost/kW (no escalation is imposed) of operating nuclear power plants as a function of the chronological time that the particular plant first started operation. The data are obtained from a Federal Power Commission report[8] and the 18th Steam Station Cost Survey given in Electrical World[9] Data from Reference 7 is plotted for the years 1972 through 1974 as a vertical bar giving low, high and average capital unit costs. The data represent both publicly and privately owned plants. Our fusion reactor was plotted in January 1974. Though the capital cost of our fusion reactor is somewhat higher than many of the earlier plants, which were built with less inflated dollars, it is seen that the fusion plant is highly competitive with capital costs of some of the more modern plants. Furthermore, the cost of operation of the plant is now quite competitive with both nuclear and fossil plants. Table 3 itemizes the cost estimate of the Princeton Reference Design.

Accounts 20 and 21, Land, Land Rights, Structures and Site Facilities are estimated from data obtained in References 8 and 9 on modern operating power plants, as well as from data obtained in a detailed analysis of Volume 1, A pressurized Water Reactor Plant of 1000 MWe.[10] We compare the needs of our reactor and make reasonable allowances for the larger size of the plant to arrive at estimates. Allowances for inflation are made at the rate of 6% per year from 1971 through early 1974.

Accounts 22 and 23, Reactor Plant and Turbine Plant Equipment, contain the nuclear island, the boilers, the cryogenic equipment, the turbine generators, etc. Most of the items in these two accounts have been estimated from actual costs of materials and equipment as well as from actual quotations from manufacturers. Other items were estimated with suitable adjustments from Reference 10. The cost estimate for the Nuclear Island, Account 221, the part of the fusion reactor that differs from other nuclear reactors, is described below.

Accounts 24 and 25, Electric and Miscellaneous Plant Equipment, are estimated either from actual requirements, by manufacturers or from Reference 10 with suitable adjustments.

Accounts 91 through 94 inclusive are known as the Indirect Cost Accounts. The first three are estimated using guides in References 8, 9 and 10 suitably adjusted for our reactor and for inflation since 1971. Account 94, Interest During Construction, reflects the interest that must be paid for the construction funds. This cost, therefore, varies with the time of construction and period required to construct the plant[7].

2.2. Superconductor Cost

In a study made for the Atomic Energy Commission, Powell[11] predicted the availability as well as the cost of superconductors when they will be required for reactors, some two or three decades from now. We have used this study to estimate the costs of our superconducting magnets.

2.3. The Nuclear Island

The total cost of the Nuclear Island is estimated to be $403,050,000, resulting in a unit cost of $198,55/kW. The Nuclear Island was designed using present known technology, materials and manufacturing processes. Experience gained in construction of previous plasma physics research devices at Princeton University, as well as experience by others in the fast breeder reactor technology, was relied upon heavily for engineering decisions made in this study.

3. THE COST OF POWER

The estimated cost of energy at the busbar for the Princeton Fusion Reactor is 17.9 mills/kWh. The components of the total, which are itemized in Table 4, are the following:

a) The cost of return of investment (based on 15% return and 85% availability) is 14.75 mills/kWh.

b) The cost of operation including wages of all personnel, maintenance, replacement and repairs are taken from the averages of the privately owned nuclear plants reported in References 9 and 10. In addition, we have included the maintenance, repair and replacement costs of features unique to a fusion reactor such as the first wall, the cryogenic system, etc. The cost of operation is estimated to be 3.1 mills/kWh.

c) The cost for the tritium handling equipment, initial tritium inventory and the initial lithium inventory is shown in Table 3. Tritium used in the D-T reactor is essentially free, inasmuch as the tritium breeding ratio is greater than 1. The only fuel cost, therefore, is that of the deuterium being consumed in the D-T reaction. That cost is only $300,000 per year or less than 0.02 mill/kWh.

We note that the fuel cost for a fusion reactor is vanishingly small when compared to all other fuels. On the other hand, because of the intricacy of the nuclear island, the capital cost is higher than for other kinds of plants. The cost of labor, repair, replacement and maintenance is comparable to the other plants. Accordingly, it can be shown that for a fusion reactor the cost of energy at the busbar is favorably comparable to present day plants. Further, as the cost of fossil and nuclear fuels (see Figure 7 for recent data on costs of fossil fuels) spiral upwards at rates higher than the average inflation rate, the cost of energy at the busbar will become even more attractive for fusion reactors.

ACKNOWLEDGMENTS

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Table 1

Parameters for Proposed Fusion Reactor Toroidal Field Coils

Superconductor	Nb_3Sn
Width of Conductor	4.5 cm
Thickness of Conductor	0.48 - 1.52 cm
No. of Pancakes/Coil	7
Maximum Field at Conductor	160,000 gauss
Nominal Plasma Radius	1050 cm
Field at Nominal Plasma Radius	60,000 gauss
Ampere Turns/Coil	6.57×10^6
Minimum Current Density (Conductor Area)	2170 amp/cm^2
Current/Conductor	10,000 amperes
Energy Stored in Field	250×10^9 joules
Inductance of Torus	5×10^3 henries
Weight of Cylinder	10^6 kg
Weight of Toroidal Coils	6.2×10^6 kg

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Table 2 Force and Torque Matrix; One Coil Fails (48 Coil Torus)

Coil Number	Radial Force Fx (lbs)	Tangential Force Fz (lbs)	Total Force Ft (lbs)	Torque About Y-Axis Mzx (ft-lbs)
1	This Coil Fails			
2	-1.057D 08	-8.880D 07	1.381D 08	-8.388D 08
3	-1.060D 08	-4.161D 07	1.139D 08	-3.963D 08
4	-1.065D 08	-2.540D 07	1.095D 08	-2.426D 08
5	-1.069D 08	-1.714D 07	1.083D 08	-1.631D 08
6	-1.074D 08	-1.217D 07	1.081D 08	-1.145D 08
7	-1.078D 08	-8.897D 06	1.082D 08	-8.218D 07
8	-1.083D 08	-6.634D 06	1.085D 08	-5.968D 07
9	-1.086D 08	-5.015D 06	1.087D 08	-4.358D 07
10	-1.090D 08	-3.830D 06	1.090D 08	-3.187D 07
11	-1.093D 08	-2.949D 06	1.093D 08	-2.328D 07
12	-1.095D 08	-2.286D 06	1.095D 08	-1.695D 07
13	-1.097D 08	-1.782D 06	1.099D 08	-1.226D 07
14	-1.099D 08	-1.395D 06	1.099D 08	-8.791D 06
15	-1.101D 08	-1.095D 06	1.101D 08	-6.231D 06
16	-1.102D 08	-8.615D 05	1.102D 08	-4.352D 06
17	-1.103D 08	-6.773D 05	1.104D 08	-2.982D 06
18	-1.104D 08	-5.307D 05	1.104D 08	-1.995D 06
19	-1.105D 08	-4.128D 05	1.105D 08	-1.295D 06
20	-1.106D 08	-3.164D 05	1.106D 08	-8.106D 05
21	-1.106D 08	-2.361D 05	1.106D 08	-4.843D 05
22	-1.107D 08	-1.677D 05	1.107D 08	-2.728D 05
23	-1.107D 08	-1.075D 05	1.107D 08	-1.406D 05
24	-1.107D 08	-5.247D 04	1.107D 08	-5.834D 04
25	-1.107D 08	-2.290D-08	1.107D 08	-3.249D-07
26	-1.107D 08	5.246D 04	1.107D 08	5.828D 04
27	-1.107D 08	1.075D 05	1.107D 08	1.406D 05
28	-1.107D 08	1.677D 05	1.107D 08	2.728D 05
29	-1.106D 08	2.361D 05	1.106D 08	4.843D 05
30	-1.106D 08	3.164D 05	1.106D 08	8.105D 05
31	-1.105D 08	4.128D 05	1.105D 08	1.295D 06
32	-1.104D 08	5.307D 05	1.104D 08	1.995D 06
33	-1.103D 08	6.773D 05	1.104D 08	2.982D 06
34	-1.102D 08	8.615D 05	1.102D 08	4.352D 06
35	-1.101D 08	1.095D 06	1.101D 08	6.231D 06
36	-1.099D 08	1.395D 06	1.099D 08	8.790D 06
37	-1.097D 08	1.782D 06	1.098D 08	1.226D 07
38	-1.095D 08	2.286D 06	1.095D 08	1.695D 07
39	-1.093D 08	2.949D 06	1.093D 08	2.328D 07
40	-1.090D 08	3.830D 06	1.090D 08	3.187D 07
41	-1.086D 08	5.015D 06	1.087D 08	4.358D 07
42	-1.083D 08	6.634D 06	1.085D 08	5.968D 07
43	-1.078D 08	8.897D 06	1.082D 08	8.218D 07
44	-1.074D 08	1.217D 07	1.081D 08	1.145D 08
45	-1.069D 08	1.714D 07	1.083D 08	1.631D 08
46	-1.065D 08	2.540D 07	1.095D 08	2.426D 08
47	-1.060D 08	4.161D 07	1.139D 08	3.963D 08
48	-1.057D 08	8.880D 07	1.381D 08	8.388D 08

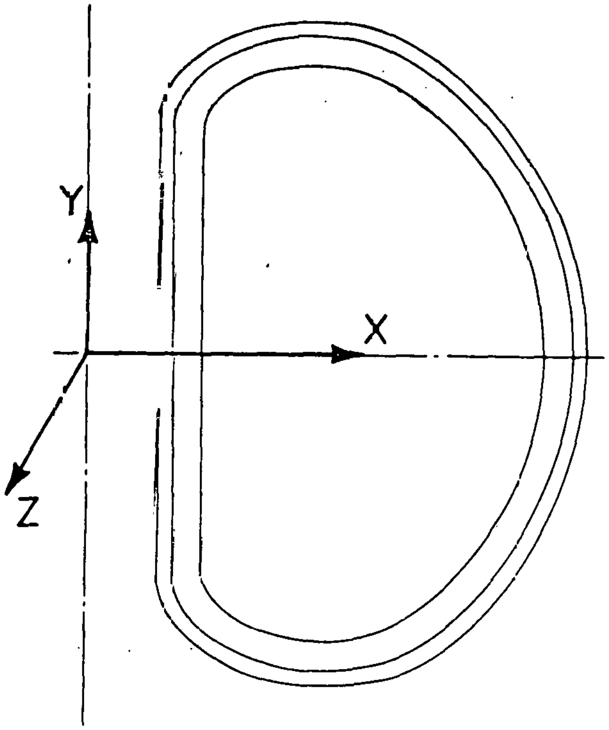


Table 3

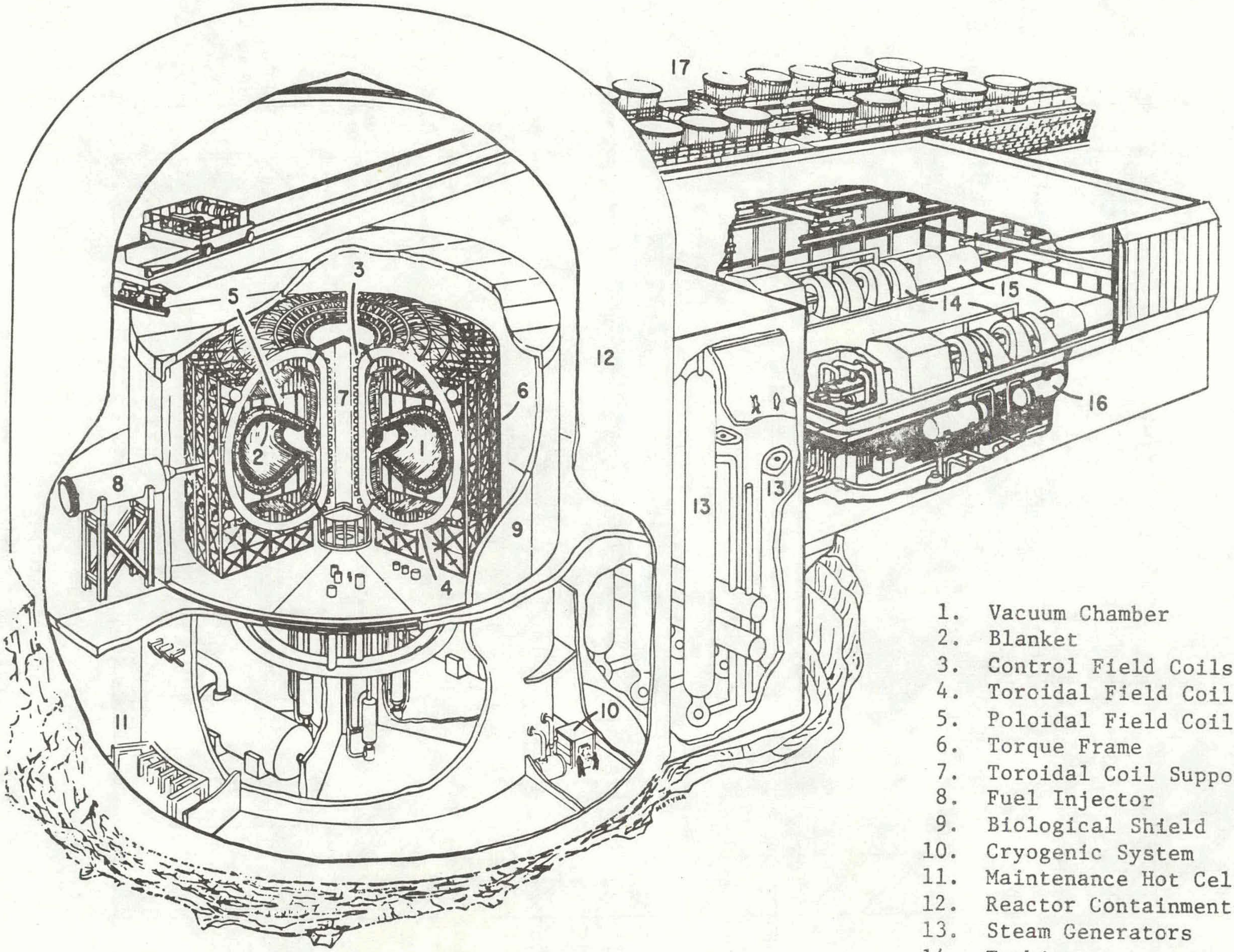
Cost Estimate for the Princeton Reference Design

Account No.		Amount (Thousands of Dollars)
20	Land and Land Rights	$ 1,000
21	Structures and Site Facilities	100,260
22	Reactor Plant Equipment	605,840
23	Turbine Plant Equipment	124,790
24	Electric Plant Equipment	31,890
25	Miscellaneous Plant Equipment	16,200
91	Construction Facilities, Equipment and Services	61,300
92	Engineering Services	33,000
93	Other Costs	30,040
94	Interest during Construction	482,070
	TOTAL CAPITAL COST	$1,486,390

Table 4

Cost of Energy at the Busbar

		Cost Mills/kWh
Cost of Return on Investment (15% Return and 85% duty factor)		14.75
Cost of Operation and Maintenance		
Steam & Electric Operation Expenses	0.50	
Maintenance of Steam, Boiler, Electric & Nuclear Island Plants	1.00	
First Wall Replacement (5 yr. interval)	1.03	
Engineering and Supervision of Operations and Maintenance	.57	
Total Cost of Operation & Maintenance		3.10
Cost of Fuel	.02	.02
Total Cost of Energy at the busbar		17.87



1. Vacuum Chamber
2. Blanket
3. Control Field Coils
4. Toroidal Field Coils
5. Poloidal Field Coils
6. Torque Frame
7. Toroidal Coil Support Cylinder
8. Fuel Injector
9. Biological Shield
10. Cryogenic System
11. Maintenance Hot Cell
12. Reactor Containment
13. Steam Generators
14. Turbines
15. 3600 RPM Generators
16. Feedwater Heaters
17. Cooling Towers

Figure 1 754154

Princeton Fusion Power Plant

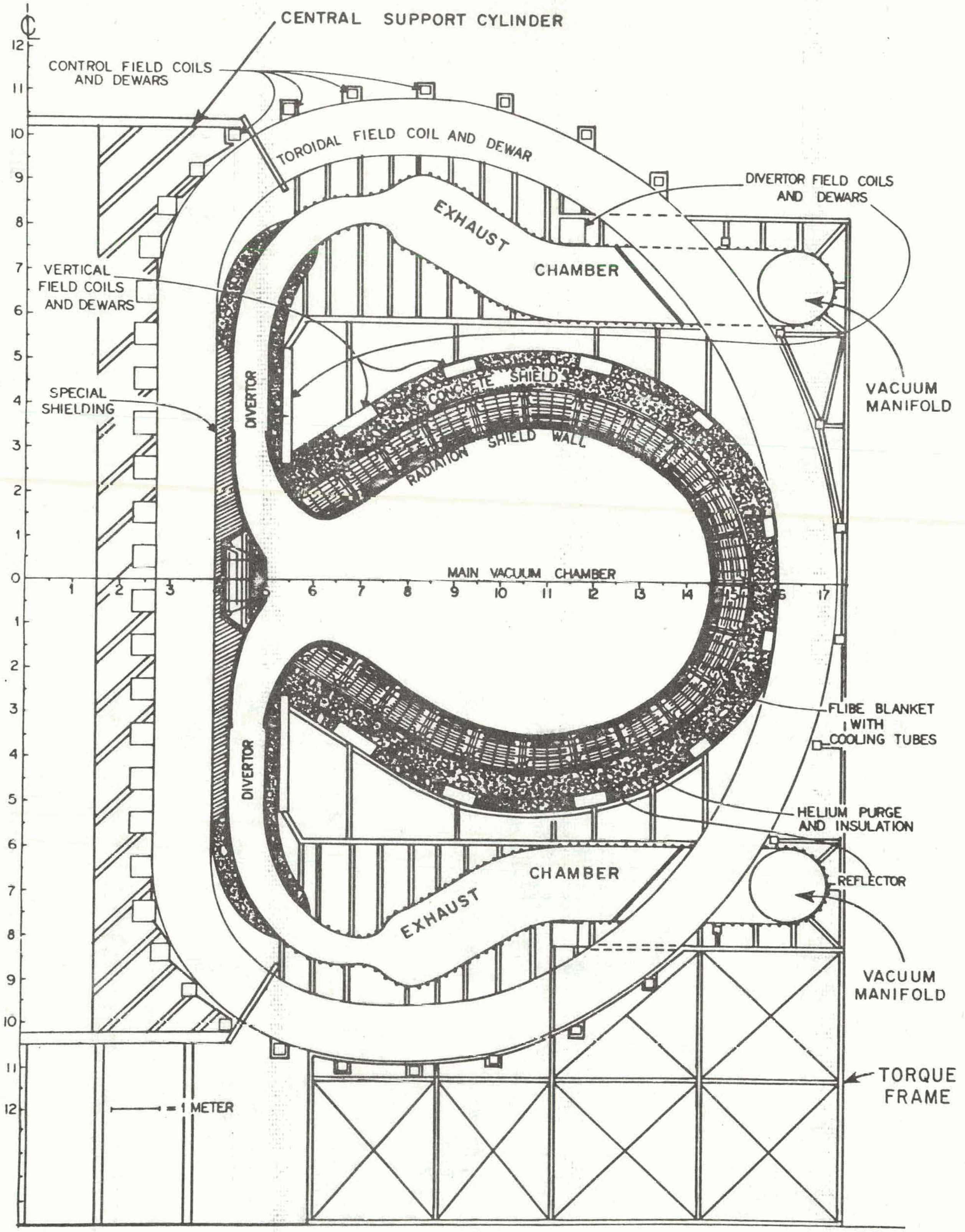


Figure 2

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Cross-section of the reactor

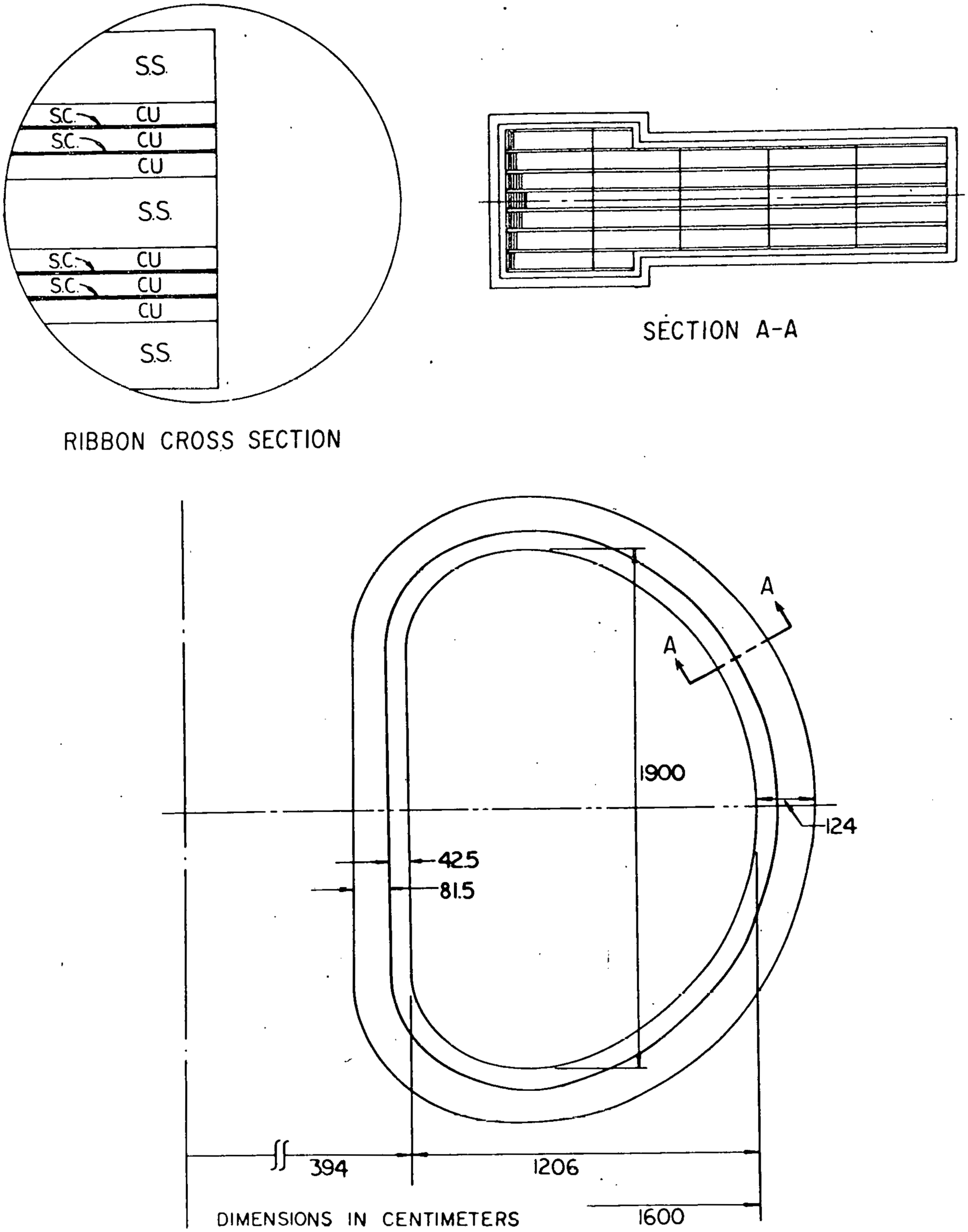


Figure 3 754155

Size and shape of constant tension coil designed for the Princeton Fusion Reactor-also shown is the cross-sectional view and the detail of the superconducting ribbon.

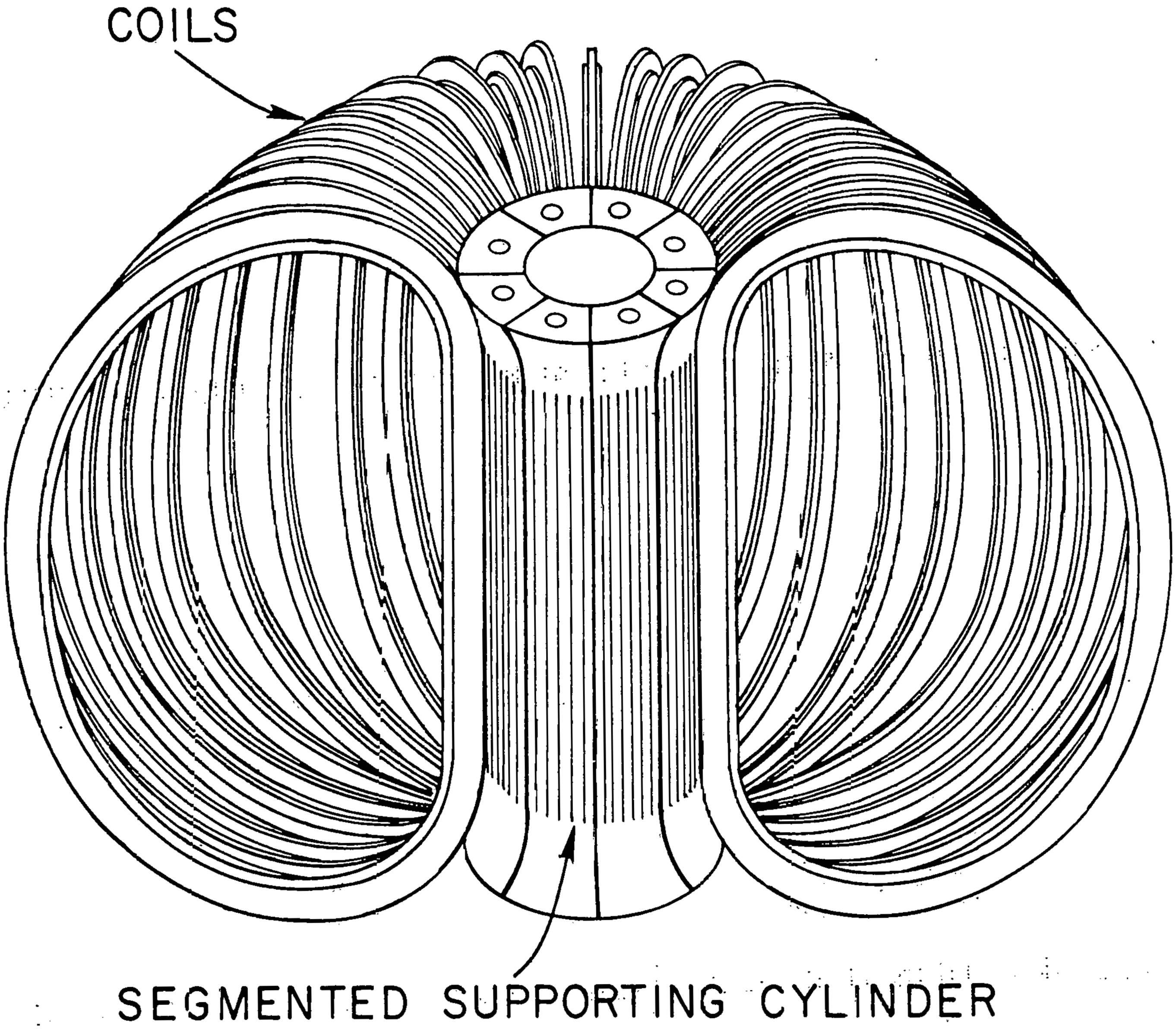


Figure 4

744497

Isometric drawing of the coil arrangement, showing segmented support cylinder.

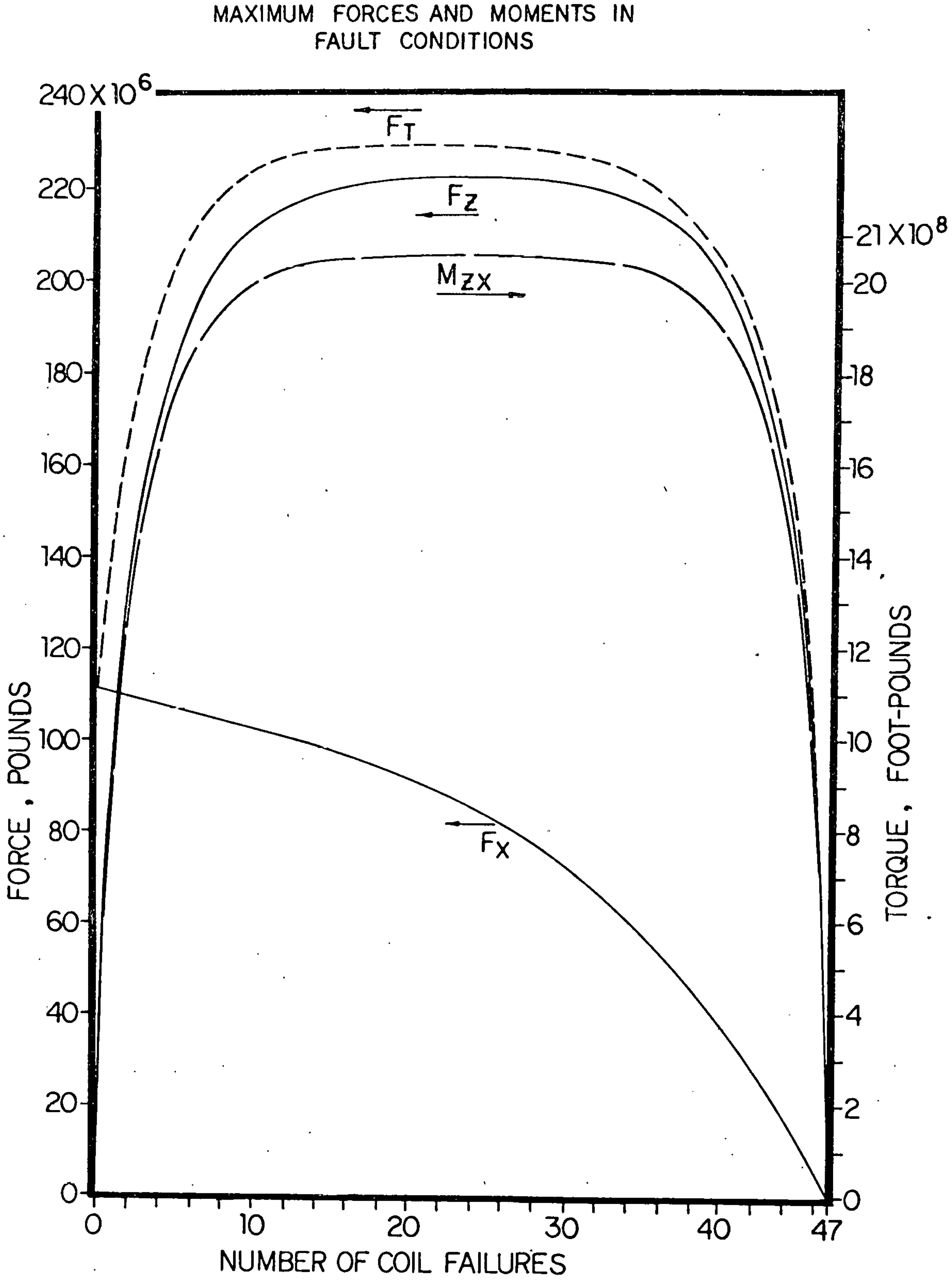
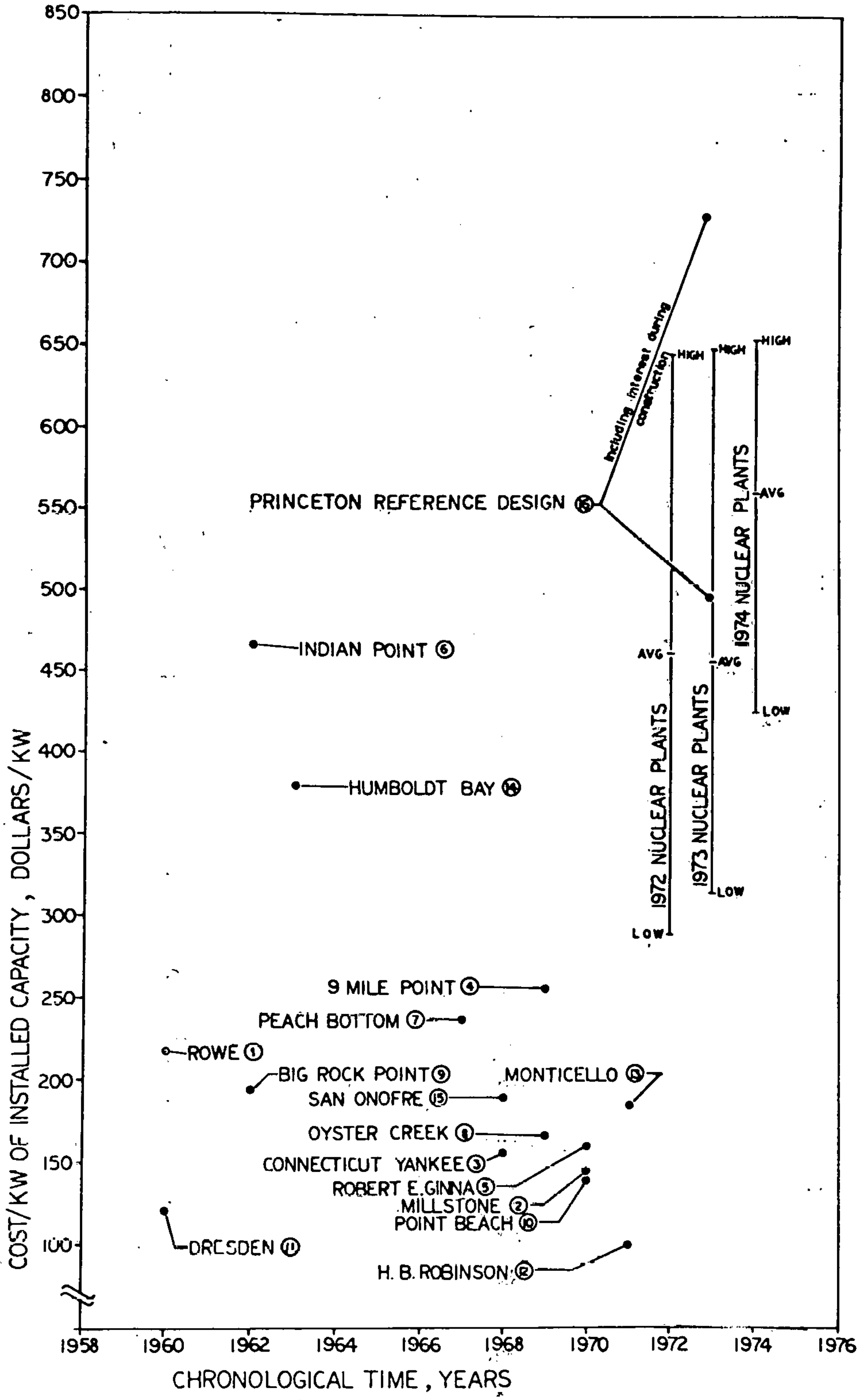


Figure 5

744462

Plot of maximum fault forces and moments on any single coil as a function of the number of adjacent coil failures



DATA OBTAINED FROM REFERENCE 7,8 and 9

Figure 6 754160

Cost per kilowatt of installed capacity for all commercial nuclear plants operating in the United States prior to 1975

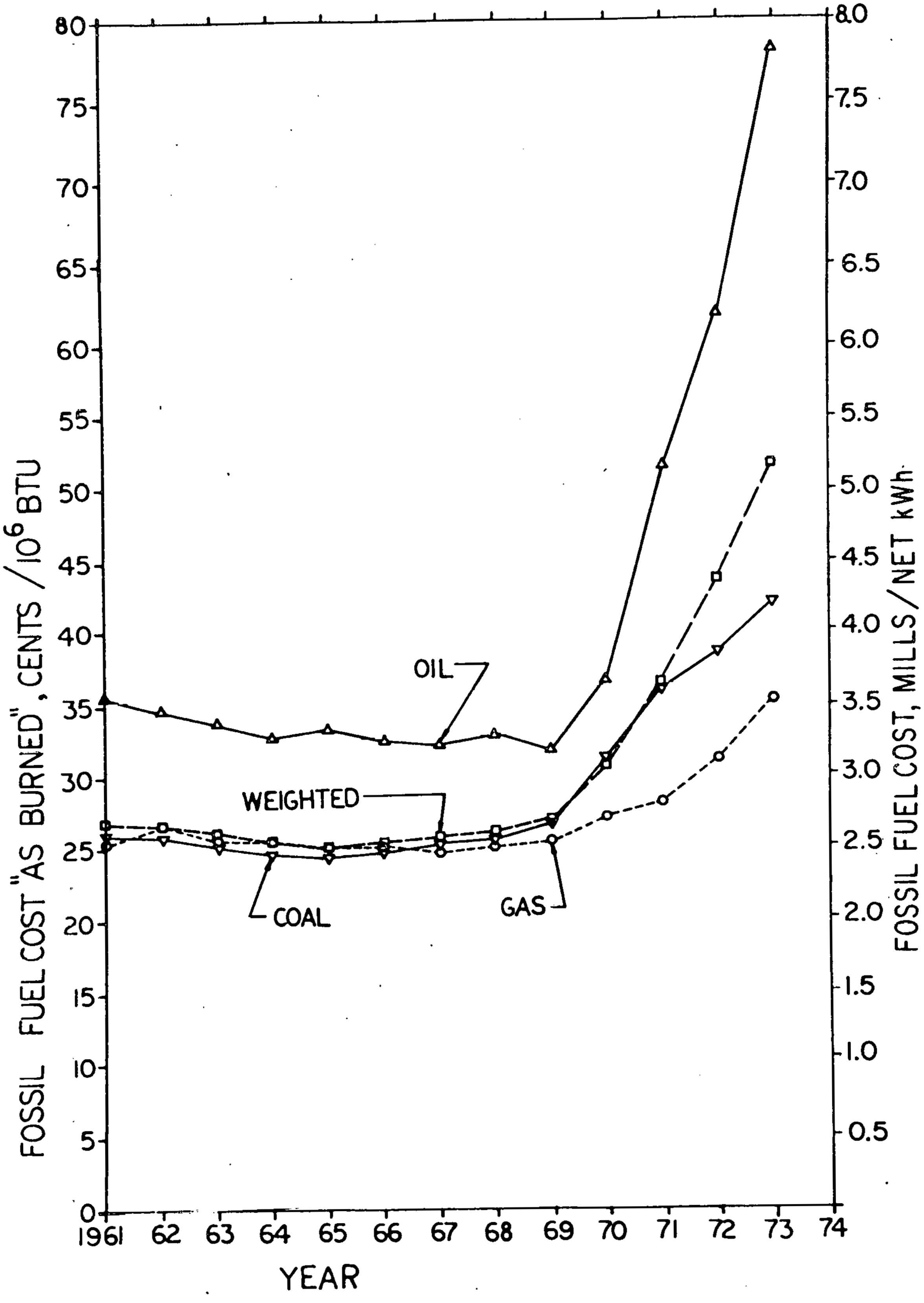


Figure 7

754157

The cost of the fossil fuel as a function of time cost were rising dramatically from 1970 to 1973 and are not available beyond that time. Thermal efficiency of 34% is assumed.

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