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Introduction

The encouraging results over the last few years in plasma research have generated renewed optimism that fusion feasibility will be demonstrated in the coming decade. Assuming that such is the case, the next logical step is the construction of a prototype power reactor. If this reactor employs plasma containment by intense magnetic fields, it is highly likely that superconducting magnets will be required for economic reasons. We have previously performed a study on the engineering design of a large superconducting magnet system in a toroidal geometry.[1] In this study (hereafter referred to as [I]), we considered a toroidal field B_0 = 37 kG, a maximum field at the windings B_{max} = 80 kG, a major radius of R = 10.5 m, and a minor coil radius r = 5.6 m, in a design using cryostatic stabilization of NbTi with copper. The design resulted in a magnet system with stored energy of 4×10^{10} J requiring 4.75×10^{8} ft of composite NbTi conductor. The total weight of the system including conductor, stainless steel interleaving, bobbin, bobbin reinforcement, and central compression ring was about 9,025 tons and the total cost was \$70,500,000. The cost breakdown of the major components is: compound conductor, 37%; structural reinforcements, 32%; winding, 13%; bobbins, 9%; and refrigeration, 4%. A schematic view of a 5000 MW(th) tokamak fusion power reactor incorporating such a magnet system is shown in Fig. 1.

In the present communication, our work is extended and general formulas are developed for arbitrary B_0, R, and r, for each of the cost items considered in [I], and the total costs determined for a variety of fields and sizes. Although not as accurate as a detailed study, the general formula developed will be useful for quickly estimating the cost of any similar toroidal system subject to the constraint $B_{max} \leq 85$ kG. The cost for any system is found to be proportional to the 4/5 power of the stored magnetic energy.

Cost Calculations

The ten items to be cost analyzed below are the composite conductor, structural reinforcement including the central compression ring and the bobbin reinforcement ring, stainless steel interleaving,

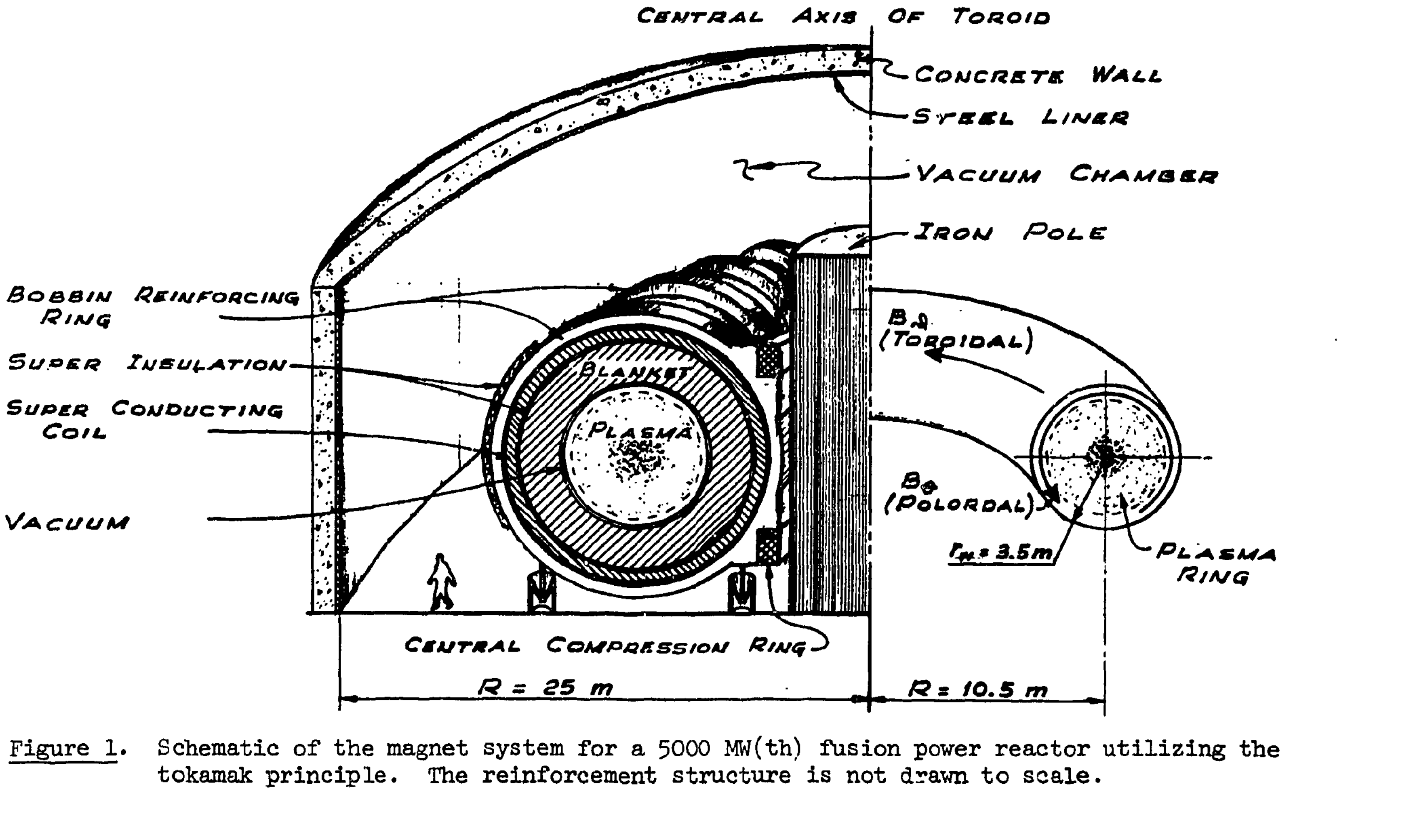

Figure 1. Schematic of the magnet system for a 5000 MW(th) fusion power reactor utilizing the tokamak principle. The reinforcement structure is not drawn to scale.

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electrical insulation, coil bobbins, winding, cryogenic insulation, refrigeration, power supplies, and auxiliary items. Storage dewars are also included in [I], but they have been omitted from the present work. A fixed cost for storage dewars can be added to the present results if desired since they are not field or size dependent to any extent. The following notation will be used in all final formulas presented: B_0, the toroidal magnetic field at the center of the minor cross section in kilogauss; R, the major radius in meters; r, the inner radius of the coil in meters; and C, the cost in dollars as of the end of 1971.

Composite Conductor

The future cost of superconducting material is difficult to assess properly, and there is no general agreement on the approach to be taken. The Culham group[2] calculate the cost of particular tokamak and stellarator reactor designs and then let the upper limit of acceptable total cost for the magnet system determine what the future cost of the superconducting material must decrease to for the system to be economically competitive with fission reactors of similar power output. The rationale for this method is that should calculations indicate, for instance, that the future cost of superconductors must be lower than the basic cost of the materials from which they are made, then clearly a fusion power reactor would not be economically viable. In fact, their studies[2] eliminate some designs and indicate that others are economically acceptable only if the current price of high field superconductors (Nb_3Sn or V_3Ga) drops to one-ninth the large quantity price of NbTi (i.e. if the present price of Nb_3Sn and V_3Ga drops by a factor of 20 and 40, respectively).

Another approach taken by Powell[3] is to assume a national power system sustained by fusion reactors and determine the price of superconductors fabricated in plants operating at full capacity specifically for the production of superconductors for use in the power systems. The projected costs of present commercial superconductors (NbTi, Nb_3Sn, and V_3Ga) and PbBi were determined and found to be reduced an order of magnitude when produced in such large quantities. Although it seems highly unlikely that known superconducting materials in their present form will be the optimum choice in the year 2010, Powell's approach shows a possible minimum cost of any new material or new form for known materials which might be developed. If such materials costs are achieved, then the structural costs will far exceed the conductor costs for fusion power reactors. Nevertheless, such long range future projections must not be used for predicting costs of prototype fusion plants which may be undertaken before 1990 since these plants must use the commercial superconductors available at the time of construction.

A third approach to conductor costs has been taken by Komarek,[4] Moir and Taylor,[5] Lee et al.,[6] and by ourselves.[1] The price trend in recent years has been analyzed, present manufacturers consulted, and a projected price developed which includes reduction for large orders. Although admittedly somewhat arbitrary, such an approach should produce realistic near term costs for the coming generation of fusion feasibility experiments and will yield conservative values for the long term when prototype reactors are ready for construction. However, in view of the wide variations in approaches taken, we will keep the cost expression for superconducting material separate from the other items so that substitution of any superconducting material cost can easily be made and hopefully our work will not be invalidated by changing prices.

For superconducting material, the cost is determined by the length and current carrying property which is field dependent. Thus the cost in dollars is given by $C_{sc} = 3.28 \times 10^{-6}\, L\, I\, u(B)$ where L is the length in cm, I is the current in A, and u(B) is the field dependent unit cost in mills/A-ft. The total length of conductor required to produce a particular central field is given by the total number of turns N multiplied by the average length of one turn which to a good approximation for large toroidal systems is given by $2\pi(1.05\ r)$. The current is given by the amp-turn relation $NI = 5RB_0$ where R is in cm and B_0 in G. The unit cost for long lengths of NbTi conductor as a function of field, u(B), is given in Fig. 2 of Ref. 1. Since the field of a toroidal magnet falls off as 1/R from the central axis of symmetry, it varies about the minor cross section in both the azimuthal and radial directions. It is thus advantageous to use concentric windings of material optimized for different fields. For simplicity, we have chosen two windings comprised of 42% high field (B_{max}) and 58% low field ($B_{max}/2$) material. Using the graph given in [I], the average unit cost becomes $\langle u(B) \rangle = 0.0154\ B_{max} - 0.108$. For a toroidal magnet the relation between the maximum field and central field is $B_{max} = B_0R/(R - r)$. Combining all these expressions and making the dimensional changes, we find

$$C_{sc} = 1173\,\frac{RrB_0}{(R - r)}\,(0.142\ B_0R + r - R). \qquad (1)$$

Structural Reinforcement

A major consideration in the engineering design of any large or high field magnet system is the electromagnetic forces and proper regard for the subsequent stresses they produce. For the windings the hoop stresses are taken care of by the selection of the type of winding employed and by the interleaving of a significant fraction of stainless steel; the axial compression forces are restrained by the large surface area in the axial direction of the epoxy fiberglass interpancake insulation. In addition there is a force on each bobbin directed to the major axis of the torus which arises because of the azimuthal as well as radial variation of magnetic field about the minor cross section. There is no force along the minor axis of the torus unless one or more coils quench, and then due to the large surface area, it can be contained by a small number of compression jacks separating each coil bobbin. On the other hand, the central force can be transmitted to fairly large central compression rings best positioned on top and bottom of the coil bobbin.

Another result of the steady central force is the large bending moment on each coil bobbin. These are restrained only by the addition of a massive reinforcing ring on each bobbin with lugs which nest against the central compression rings (see Fig. 1). The total radial force in tons is $F = 18.48\ B_0^2R^2[(R/\sqrt{R^2 - r^2}) - 1]$ and the length of the compression ring is $2\pi(R - 1.2\ r)$. The cross sectional area is determined by the assumed stress level which is taken at half the yield stress for Armco 21-6-9 stainless steel or 10^5 psi. The weight of the ring is determined and the total fabricated cost is assumed to be 3 x the material cost of $1/lb. The bobbin reinforcing ring cannot be readily generalized but is related to the central compression ring, and we have therefore used a factor of 10 x the central compression ring as a basis for the costing of the bobbin reinforcing ring. These assumptions yield a slightly higher value for the structural reinforcement components when applied to our study in [I]. In analytic form the total cost of both the central compression ring and the bobbin reinforcement ring is

$$C_{sr} = 66.8\ B_0^2r^2(R - 1.2\ r)\left[1 + \frac{3}{4}\left(\frac{r}{R}\right)^2 + \frac{5}{8}\left(\frac{r}{R}\right)^4\right]. \qquad (2)$$

Stainless Steel Interleaving

The choice of pancake windings was made for the mode of winding for two reasons. First, because of the selection of cryostatic stabilization (the most reliable method), cooling of the conductor by liquid helium is required and where large forces are present, edge cooling is more reliable and certain than face cooling. Secondly, pancake windings in general have better structural integrity than layer wound coils. For containment of the large hoop stresses and strengthening of coil windings, it is necessary to interleave stainless steel with the conductor. The cost is determined from the total length required (in [I], the cross sectional area of the stainless steel was 1.69 times the cross sectional area of the composite conductor) and the assumed price of $1/lb.

Electrical Insulation

Electrical insulation is needed between layers and properly grooved insulation between pancakes serves the triple role of electrical insulation, cooling channels, and structural members capable of withstanding the axial compressive forces. The interlayer insulation is calculated in a similar manner as the stainless steel interleaving. The interpancake insulation is calculated as a fixed percentage of the winding volume. Epoxy fiberglass priced by volume** at $400/ft^3 is the present choice for both insulations.

** Calculated from the sizes of commercially available sheets needed in the design of the magnet system.

Bobbins

The coil bobbins (48 in our original study) are priced by weight. The volume of the bobbin is calculated, the stainless steel material is assumed to cost $1/lb and 3 x material cost has been estimated to be sufficient for the fabrication cost.

Winding

There is no experience in winding coils of the size needed for fusion reactors. In our original study [I], we used two methods ($1/ft which is the highest estimate based on cost per unit length and $2/lb which is the average of the values given by Moir and Taylor[6] and Rose[7]) for the winding cost and averaged the result. In the present calculation, the winding cost is based on total weight of winding, but the factor of $1.35/lb is used to determine the total cost. This factor is determined by recalculating the winding cost of [I] on the basis of weight only but yielding the same cost (average) given in the paper. More consideration has to be given to this important item because the various approaches lead to widely different results. In determining the winding volume, it is necessary to assume a value for the average current density and in the present calculation 2000 A/cm^2 was chosen. Recent speculation[8,9] on this important design parameter indicates that this value is a reasonable upper limit for extremely large magnets. Furthermore, it is not difficult to show that for magnets with a large ratio of bore to winding thickness, a large change in average current density results in only a modest increase in conductor length.

Cryogenic Insulation

Since the whole magnet system is visualized as being enclosed in a vacuum chamber, it is not necessary nor desirable to have dewars about each coil in the system. Instead each coil is encased in a helium-tight bobbin and superinsulation is used on the inner and outer radii. Although it is only necessary to have the insulation just about the coils, an estimate is obtained by considering two toroidal shells, one inside the coils and a second enclosing the bobbin reinforcement structure. The area is determined and the cost calculated assuming a basic cost of $215/m^2 for 20 cm thick superinsulation.†

Refrigeration

The total refrigeration load including heat leak through structural supports, thermal radiation through the toroidal shells of superinsulation, heat input through the current leads, joule losses in contacts in the coils (assumed to scale linearly with R to yield correct value for R = 10.5 m and 1 m), and heating due to nuclear radiation (assumed to be attenuated 10^{-6} by the blanket and completely

† Cost estimate from bulk prices of aluminum foil and fiberglass paper with an added factor for insulation.

absorbed in the magnet system) is calculated in watts. A fixed average value for the plasma wall loading is taken to be 2 MW/m^2 (in [I] a value of 3.5 MW/m^2 and 0.7 MW/m^2 was used for the two systems discussed). The dissipation in the vapor cooled current leads and joule losses in magnet contacts depend on the number of coils in the system as well as the operating current chosen and cannot really be generalized in a completely satisfying manner. The total cost is obtained by using the factor $500/W of low temperature refrigeration power needed which applies to refrigerators in 1/2 to 1 kW size range. For the cost of a specific size machine, one should use the data (corrected for inflation) developed by Strobridge.[10]

Power Supplies and Auxiliary Items

These items were assumed to scale with the average size parameter $(Rr)^{1/2}$ and normalized to yield values consistent with the design in [I].

These last items, Refrigeration and Power Supplies and Auxiliary Items, are not a high percentage of the total cost so the crude approximations made are not significant.

Results

Since many of the above items have similar factors, an approximate convenient form can be obtained and the total cost of the magnet system is

$$C = 1.07 \{C_{sc} + C_{sr} + 0.638\, RrB_0^{2.3}\, (90 + r) + 17830\, (Rr)^{1/2}\, [(Rr)^{1/2} + 5.89] + 1530\, B_0^{1/2}\, [B_0R(1 + 0.116\, r) + 6.71\, r\, (1 + 1.75\, r)]\} \quad (3)$$

where C_{sc} and C_{sr}, the cost of the superconductor and structural reinforcement, are given in Eqs. (1) and (2), respectively. Owing to the approximation made in an effort to reduce the cost calculation to a three-parameter expression, the original application of Eq. (3) to our detailed study [I] shows that the results were 7% low. Hence, an adjustment factor of this amount has been added.

Using Eq. (3), the cost of various magnet systems has been calculated and normalized to the cost for the parameters in [I], namely B_0 = 37 kG, R = 10.5 m, and r = 5.6 m. In Fig. 2 the normalized cost vs B_0 is shown for R = 10 m (solid lines) at three different values of r. The dashed and chain lines yield the cost of small changes in R at similar values of r. In all the cases shown in Fig. 2, the lines are taken to the maximum cost value consistent with the constraint that $B_{max} \leq 85$ kG. By using a normalized plot, our assumptions concerning the cost of NbTi superconductors do not alter the conclusions, namely that the cost is most affected first by changes in B_0, second

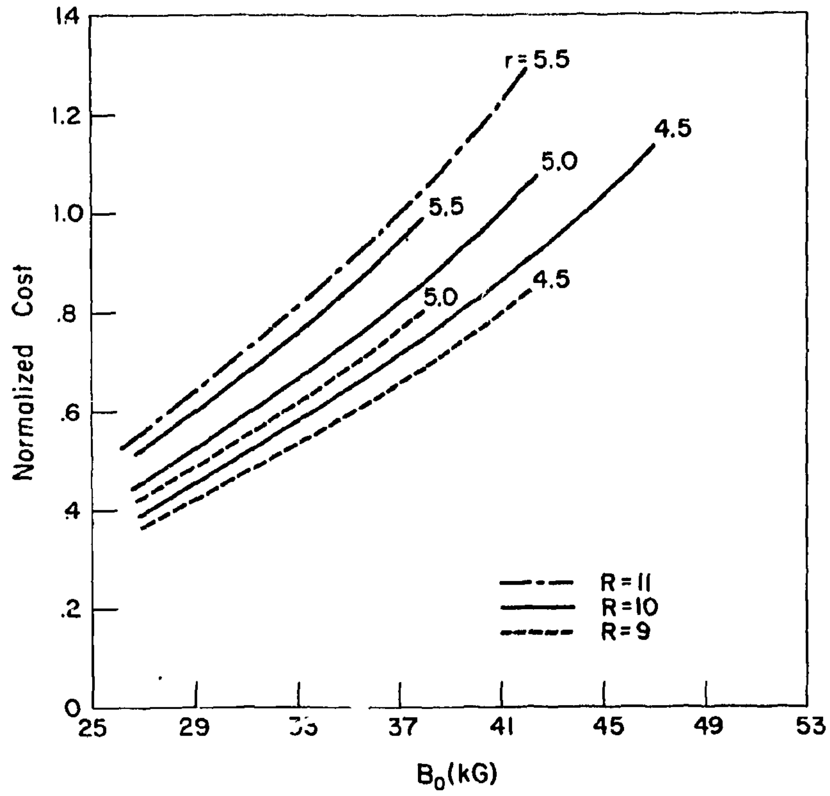

Figure 2. Cost of toroidal magnet system normalized to the cost given in Ref. 1 for a system with B_0 = 37 kG, R = 10.5 m, and r = 5.6 m versus central field, B_0. The lines terminate at B_{max} = 85 kG, the realistic limit of the applicability of NbTi.

by changes in r, and least of all by changes in R. If two of the parameters are held fixed and one varied, then we find for a 5% change in either B_0, r, or R, a cost change of 9.4%, 7%, and 3.4%, respectively.

Although the cost of superconducting material is likely to continually undergo changes, the dependence on the parameters in Eq. (1) will probably not change. One might have anticipated that the cost of a large magnet system would scale like the stored energy, $E_s = B_0^2$ x volume. However, the conductor cost scales more like E_s/r. The structural reinforcement, Eq. (2), does scale like E_s, but the remainder of the cost terms in Eq. (3) above do not. Figure 3 is a ℓn-ℓn graph of the cost vs stored energy for all possible cases of the variations of the three parameters consistent with the constraint $RB_0 = 80\,(R - r)$. The cases considered are a decrease of B_0, increase of R, and decrease of r with the other two held constant. Also considered are an increase in B_0 and R, increase in B_0 and decrease in r, increase in R and r, decrease in B_0 and increase in r, with the remaining one held constant; and also the three-parameter variation, decrease in B_0 and increase in R and r. The range is chosen so that the stored energy scans at least a decade from 10^4 MJ to 10^5 MJ and the cost covers the decade from 2×10^7 $ to 2×10^8 $. The stored energy in the bore in MJ is calculated from the following expression

$$E_s = 0.157\, B_0^2 R^3 \left[1 - \sqrt{1 - (1/A)^2}\,\right], \quad (4)$$

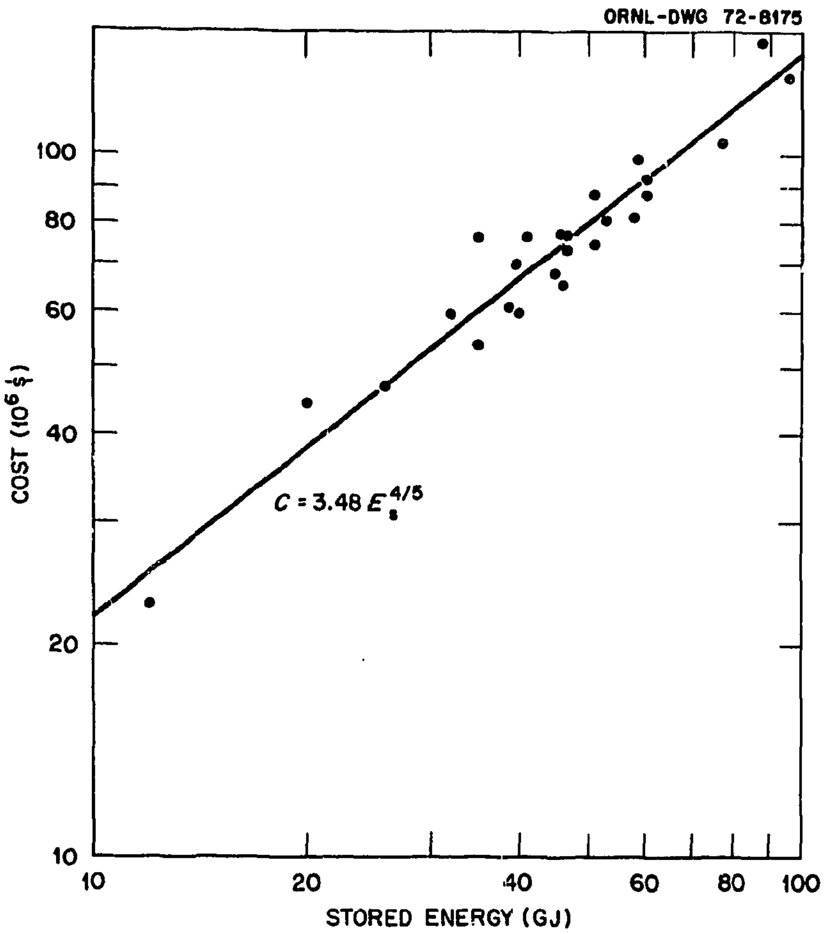

Figure 3. The cost of various toroidal magnet systems versus the stored magnetic energy of the system. The line is a least squares fit of the calculations.

where the aspect ratio, $A = R/r$. A correction of 5% was added to this value to cover the energy stored in the windings which was the amount calculated in [I]. A least squares fit of the points yields an 0.8 power dependence on stored energy.

$$C = 3.48 E_s^{4/5} . \qquad (5)$$

In this expression the cost is in 10^6 $ when E_s is in GJ.

In a listing of general equations for estimating purposes, Smith and Lewin [11] give the coil cost for toroidal magnets as being proportional to E_s/R. Although there are no applicable calculations to check our results against, it is worth noting that the above strong dependence on stored energy is not evident in the calculations on large toroidal systems given by Komarek.[4] He considers three systems scanning the range E_s = 17 GJ to 100 GJ, but the maximum fields considered B_{max} = 110 ± 2 kG put it well outside the range of applicability of our model. He finds no more than a 30% difference in cost between the three systems indicating less than a one-fifth power dependence on E_s (i.e. $C \sim E_s^{0.15}$). Oswald[12] has also given some detailed cost calculations of toroidal systems, but he considers sizes applicable for fusion feasibility experiments, and these are much smaller than the sizes calculated by us. Nevertheless, if we apply our calculation to the parameters chosen by Oswald and also correct for the difference in conductor cost, since he considers present superconducting material costs, we get surprisingly close agreement.

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