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DESIGN AND ECONOMICS OF LARGE DC FUSION MAGNETS*

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Summary

Projections are made for superconductor costs for dc fusion magnets, assuming superconductor production levels appropriate to an economy some time after 2000 AD in which a large fraction of the new electrical power plants are fusion reactors. The detailed projections are made on the basis of present (1971) conductor characteristics and processing technology. It is found that the very great increase in production of superconductor material that would be associated with a fusion power reactor economy should greatly reduce superconductor cost, in some cases by more than an order of magnitude. No allowance is made for large-scale production for other purposes, which well may be the case, and which should lead to even lower costs. It is also found that material costs should strongly dominate total conductor cost. The projected conductor costs amount to only a few \$/kW(e) for the fusion reactor designs that have been proposed, and are almost an order of magnitude smaller than magnet structure costs.

1. Introduction

Magnet costs promise to be an important factor in the total cost of fusion power reactors. They can be divided into three components: the cost of the conductor (super and/or cryo), structure (reinforcing material, coil winding, assembly, and support), and cooling (cryostat and refrigeration). At present conductor prices, conductor cost dominates the total projected magnet cost of most fusion reactor designs. However, substantial reduction in conductor cost can be expected as superconductor production level increases. In this paper cost projections are made for candidate dc super- and cryo-conductors, assuming a production level appropriate to a mature fusion reactor economy some time after 2000 AD in which approximately 90 GVA of fusion reactor capacity is constructed each year. A number of conductors are considered: commercial superconductors that have been widely used (multifilament NbTi and GE diffusion-processed Nb₃Sn tape), new commercial superconductors (Linde plasma-sprayed Nb₃Sn, and diffusion-processed V₃Ga tape), a noncommercial superconductor for which reasonable cost projections can be made (Pb-Bi in glass fiber), and high-purity aluminum cryoconductor (25,000 resistance ratio). The cost projections are made as closely as possible on the basis of present conductor characteristics and present process parameters.

The total conductor cost includes both processing and materials costs. Processing costs are

estimated by laying out plant designs for each conductor and making detailed estimates of equipment cost, production labor, and building area for each plant. Uniform assumptions (Table I) are made for depreciation rates, labor costs, building costs, etc., and the cost of each superconductor production plant layout is computed. For a given conductor, the production capacity of each plant is close so as to supply approximately one-half of the fusion magnet conductor needed for a mature fusion economy.

TABLE I

Assumptions Used in Study

Fusion reactor construction rate	90,000 MW(e)/yr
Fusion reactor capacity	2,000 MW(e)
Output of superconductor fabrication plant/yr	50% of conductor for above construction rate
Capital and depreciation charges for production plant	25%/yr
Cost of capital investment	1.25 x capital equipment cost plus building cost
Building cost	\$100/ft ²
Cost basis	1971 dollars
Maintenance cost (not including scheduled replacement)	10%/yr of capital equipment cost
Labor cost (average)	\$25,000/yr per person
Type of production operation	4 shifts, round-the-clock
Overhead labor (administration and clerical)	40% of production labor
Fractional operating time of process equipment	≤80%
Power cost	10 mils/kWh
Profit allowance	None

Two sets of materials costs are used, present and projected (Table II). The first set is given by the lowest known current market price paid for the materials; the second set is estimated assuming a production level appropriate to the mature fusion economy of Table I. For materials like copper which are already in large-scale production, the projected price is taken equal to the current market price. For materials like niobium and gallium, the projected production level is much greater than the current level and the projected price,

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obtained by an analysis similar to that used to project conductor prices, is much lower than the current market price. There may be additional new markets for these materials, which would tend to further reduce cost, but this is not assumed in this study. These two sets of materials costs then lead to two different sets of projected conductor costs.

TABLE II

Costs of Raw Materials for Superconductor Fabrication

Item	Costs (\$/lb)	
	Current costs	Projected costs mature fusion economy
Copper	1.0	1.0
Tin	1.50	1.50
Lead	0.20	0.20
Bismuth	5.00	5.00
Fiberglass cloth (15 mil thick)	\$1/m ²	\$1/m ²
Niobium powder	15	4.50
Nb foil (1 mil)	100	18.90
Nb-Ti rod	35	6.25
Vanadium foil (2 mil)	100	20.96
Gallium	360	90
Aluminum (5000 resistivity ratio)	15	3.80
Aluminum (25,000 resistivity ratio)	--	8.04

The conductor costs estimated in this study are much lower than present prices, and it appears that in a fusion reactor economy the conductor will be only a small part of total magnet cost, which will be dominated by structure. Further, these projected costs should be an upper limit to the actual cost in a fusion reactor economy, since substantial improvement in conductor characteristics and processing technology seems likely.

2. Conceptual Conductor Characteristics

The optimum conductor design for fusion power magnets will depend on many technical and economic factors, and definitive designs are not now possible. However, illustrative conceptual conductor designs can show the effects of various design choices on cost. Two options are chosen for this study: the first is nonstabilized composite conductor (i.e., normal regions propagate) and consists of the superconductor plus the integrated substrate or matrix it is fabricated with; the second is fully stabilized conductor (i.e., normal

regions do not propagate and the superconductor recovers) and consists of the same composite conductor with sufficient low resistance stabilizer to prevent propagation at normal regions if they should be developed. In addition, for the first option it is assumed that the ratio of operating to critical conductor current is independent of field and is taken as $I/I_c \approx 2/3$. Since conductor current is constant in the magnet coil, this requires that the thickness of superconductor vary continuously along the conductor. This is, of course, impractical because it would require an extremely large member at joints, but it does establish the minimum amount of superconductor that is required for a given geometry, field, and current ratio. In the second option the ideal continuous variation of superconductor along the conductor is approximated by a series of constant thickness sections. Typically four or five sections are used to cover the range between zero and maximum field, with a conductor joint between each section. The field at which a joint is necessary is fixed by the amount of conductor and the condition that $I/I_c = 2/3$. Between joints $I/I_c < 2/3$, so more conductor is used than in the first option. The relative costs for the two options are then compared.

The conceptual conductor characteristics are summarized in Table III. A much more detailed description is given in BNL 16580.¹ The conductor width (10 cm) is chosen as a compromise between the goals of reducing conductor and magnet structural costs, which favor wide conductors, and stability, which favors narrow conductors. It should be noted that this width is a factor of two greater than the widest NbTi composite conductor used to date, and a factor of eight wider than the widest Nb₃Sn conductor used to date. High-purity aluminum (5,000 resistance ratio) is chosen as the stabilizer. Copper conductor widths > 5 cm would require unreasonably thick stabilizers. It should be noted that there is relatively little experience with aluminum stabilizer at the high stress levels considered in fusion magnet design. Because of the coil geometry in fusion magnets, large portions of the conductor winding cannot be effectively face-cooled by steady state natural convection, i.e., those portions with the conductor face normal to the gravity vector. A fully stabilized conductor then relies only on edge cooling. The conductor can be wound into a coil with reinforcing strip and electrical insulation, but without coolant passages between turns (though such passages might be desirable for transient stabilization against flux jumps associated with magnetization currents). The maximum I²R heating (full transport current in the stabilizer) is limited to 0.3 W/cm of edge, which is well below the nucleate boiling limit for the particular edge configuration chosen. This condition sets the stabilizer thickness, except that a minimum thickness of 10 mils is assumed for mechanical reasons. In some cases this results in a maximum I²R heating less than 0.3 W/cm of edge. The projected conductor costs appear to be dominated by materials

TABLE III

Characteristics of Conceptual Conductor

Characteristics	Superconductor type				
	Nb-Ti	Nb ₃ Sn		V ₃ Ga	Pb-Bi in glass fiber
		GE	Linde		
Conductor width (cm)	10	10	10	10	10
Thickness of superconductor in conductor subunit* (cm)	0.15, 0.20, 0.25, 0.30**	0.025, 0.050, ***	0.005 to 0.015, †	0.004	20 μ glass fiber, 0.038 cm ‡
Aluminum stabilizer thickness (cm)	0.2	0.025	0.025 to 0.063	0.025	0.05
I ² R heating, full transport current in stabilizer, W/cm of edge	≤ 0.3	≤ 0.3	≤ 0.3	≤ 0.075	≤ 0.15
J _c in superconductor (A/cm ²) B = 50 kG					
100	8.5 $\times 10^4$	7.2 $\times 10^5$	1.4 $\times 10^5$	2.0 $\times 10^5$	4.7 $\times 10^4$ §§
150	---	2.4 $\times 10^5$	0.75 $\times 10^5$	1.1 $\times 10^5$	---
150	---	0.72 $\times 10^5$	0.33 $\times 10^5$	0.69 $\times 10^5$	---
Conductor current in fusion magnet application, one or more subunits in parallel‡ (kA)	28	10	18	10	10

* A subunit has superconductor plus stabilizer, with one or more subunits in parallel to carry full current in a fusion magnet application.

** Thickness includes copper matrix (Cu/SC ratio = 3/1) in which Nb-Ti multifilaments are imbedded.

*** Thickness includes Nb₃Sn superconductor and unreacted Nb core. Either one or two 1-mil foils used in subunit.

† Nb₃Sn thickness varied by adjusting tape feed rate past plasma sprayer, or by adjusting powder flow rate to sprayer.

‡ Woven tape of 20 μ glass fibers imbedded in Pb-Bi matrix; high pressure injects Pb-Bi into fibers during fabrication.

§ Maximum number of subunits in parallel is six, used only at highest field range. I/I_c is always $\leq 2/3$.

§§ Overall current density of fiber including glass, but not matrix in which fiber is imbedded.

costs, with processing costs a relatively small part of the total. In this event, conductor cost should be relatively insensitive to conductor design. Consequently conductor prices would be relatively insensitive to width.

For the fully stabilized conductors of the second option, limitations on the thickness of the superconductor part of the various conductors are imposed by the need for stability and for mechanical integrity. Parallel conductor subunits

may be necessary, in order to carry full conductor current at higher fields. The following limitations on superconductor thickness are taken here:

- NbTi multifilaments in Cu matrix; 0.15 cm $\leq$ conductor thickness ≤ 0.35 cm soldered to aluminum stabilizer on one side.
- GE Nb₃Sn; either one or two tapes (each made from 1 mil Nb + 1% Zr foil) soldered together, plus a stainless steel backing on one face and aluminum stabilizer on the other.

- c. Linde Nb₃Sn; 2 mils $\leq$ plasma-sprayed Nb₃Sn layer $\leq$ 6 mils (100% equivalent density) on a 15-mil-thick copper substrate which in turn is soldered to an aluminum stabilizer. The lower limit on Nb₃Sn thickness is set by continuity requirements, while the upper limit is set by mechanical integrity.
- d. V₃Ga; either one or two tapes (each made from 2 mil V + 1% Zr foil) soldered together, plus an aluminum stabilizer on one face.
- e. PbBi in glass fiber; overall thickness of woven fiberglass tape impregnated with Pb-Bi is limited to 15 mils for stability and mechanical integrity; individual glass fiber diameter taken as 20 μ .

Choice of conductor current and the requirement that $I/I_c \leq 2/3$ then fixes the operating field range and number of conductor subunits required. For example, with 10 kA conductor current and GE Nb₃Sn conductor of the type chosen for this study, one has:

No. of parallel subunits	No. of tapes in subunits	Operating field range, kG
1	1	$0 \leq B \leq 60$
1	2	$60 \leq B \leq 90$
2	2	$90 \leq B \leq 120$
3	2	$120 \leq B \leq 140$
4	2	$140 \leq B \leq 150$
6	2	$150 \leq B \leq 160$

Critical current vs. field characteristics are taken from the manufacturers' data^{2,3,4,5,6} and from the literature.⁷ In some ranges, i.e., GE Nb₃Sn above 120 kG and Linde Nb₃Sn above 105 kG, critical currents have had to be obtained by extrapolation.

4. Layout of Production Plants and Cost Estimates

A detailed flowsheet is prepared for each conductor fabrication and materials preparation process, at the production level chosen; which is fixed by the condition that the plant supply conductor for 45 GW(e) fusion reactor capacity/year. The equipment, labor, and building area required are then estimated for each process step. For each process quantity, e.g., the throughput capacity of a rolling mill, estimates are obtained from different sources, principally fabricators and materials producers. These, together with a personal estimate based on visits to present plants, are used to synthesize a final estimate for the future large production plant. In some cases the various individual estimates agree closely. In other cases, e.g., the throughput capacity of a Z mill for 1 mil Nb + 1% Zr foil, they differ considerably. In this event, the final estimate chosen is on the pessimistic side.

Equipment costs are similarly estimated. However, building and labor costs are obtained using a simple average cost per person and per sq ft of building area.

The final result is then a set of detailed cost breakdowns for each plant which is given elsewhere.¹ (They are too lengthy to include here.) Because of this quantitative cost framework, specific adjustments and revisions can be made quite easily, if required.

The most important factor in total conductor cost is the cost of materials. Table IV illustrates this result; even with the much lower projected material costs, processing contributes only about 20% to total projected conductor cost. The principal material cost factors in each process differ as do the principal processing cost factors. With present material costs, the projected processing costs are an even smaller part of the total projected conductor cost, ~10%. Further significant (i.e., more than 10-20%) conductor cost reductions can only be accomplished by either further reducing material costs, or by improving the critical current capability.

5. Conductor Cost Results

The projected costs of the conceptual conductors described earlier are shown in Figures 1 through 5. The unit of cost is \$/kA·m at the particular field of interest, under the condition that $I/I_c \leq 2/3$. Where possible, representative present prices and costs projected by others are also shown. The projected costs are shown for both sets of material costs, present and projected. In Figure 6, the projected costs of the various conductors are compared, using only projected cost of high-purity aluminum (25,000 resistance ratio) cryoconductor. The latter cost includes the capital cost of the aluminum, the capital cost of the refrigerator (\$4/W for the cold box), the capital cost of the steam-drive He compressors (\$50/kW(e)), and the capitalized cost of the steam supply. These costs are included in the case of the aluminum cryoconductor because they are much greater than the corresponding costs with superconductors. Conditions of operation (i.e., T, and conductor cross section) are optimized to give the lowest total cost for Al cryoconductor. Since the magneto-resistance of aluminum saturates at a few kG, the cryoconductor cost is not affected by field in the operating range considered. Stress and/or thermal cycling effects are neglected.

Some interesting conclusions can be drawn from these results.

- a. The projected costs (using projected material costs) of the various conductors, with the exception of V₃Ga tape and aluminum cryoconductor, are quite low, typically \$0.50/kA·m at 50 kG. In the field range 0 to 80 kG, NbTi and PbBi in glass fiber conductors show essentially the same projected cost. The two Nb₃Sn conductors

TABLE IV
Conductor Cost Factors

Conductor	<u>Processing/total conductor cost</u>		<u>Principal costs involved in:</u>	
	<u>Projected materials cost</u>	<u>Present materials cost</u>	<u>Processing</u>	<u>Materials</u>
Nb-Ti	0.14	0.058	---	Nb-Ti, Cu, Al
Nb ₃ Sn-GE	0.32	0.090	Nb ₃ Sn reaction	Nb foil
Nb ₃ Sn-Linde	0.20	0.080	Plasma spray	Al, Cu
V ₃ Ga	0.22	0.084	Heat treat	V foil, Ga
Pb-Bi in glass	0.26	0.12	Jacketing	Al, Bi

TABLE V
Estimated Cost of Superconductors for Large
Fusion Power Reactors

	<u>Conductor cost, \$/kW(e)</u>					<u>Structure</u>
	<u>original</u>	<u>this study</u>				<u>cost, \$/kW(e)</u>
<u>Fusion reactor design</u>	<u>study</u>	<u>GE</u>	<u>Linde</u>	<u>Nb-Ti</u>	<u>Pb-Bi</u>	<u>original study</u>
<u>ORNL Tokamak</u> ⁽⁸⁾						
P = 2,000 MW(e)*						
P _{wall} = 3.45 MW(th)/m ²						
B _{max} /B _o = 2.1						
B _o = 37 kG	13.0	1.24	1.32	1.96	2.00	19.0
55.5	--	2.69	2.47	--	--	42.8**
74	--	5.94	4.64	--	--	76.0**
<u>LRL Mirror</u> ⁽⁹⁾						
P = 1,000 MW(e)						
B _{max} /B _{min} = 2.0						
B _{min} = 70 kG	66	5.4	4.6	--	--	54
<u>Culham Stellarator</u> ⁽¹⁰⁾						
P = 2,500 MW(e)						
P _{wall} = 10 MW(th)/m ²						
B _{max} = 200 kG						
B _o = 60 kG						
Helical winding ^{††}	--	16.0	13.2	--	--	25
Toroidal winding ^{††}	--	8.4	7.8	--	--	
Total	20†	24.4	21.0			

* 40% thermal efficiency assumed.

** Structure costs assumed to vary as B_o².

[†] Assumed to be 1/9th of present Nb-Ti costs.

^{††} V₃Ga used for portion of winding where B > 160 kG.

(GE and Linde) are very similar in projected cost up to 160 kG, and their cost seems definitely lower, than that for NbTi and PbBi. PbBi and NbTi are not usable in this range due to their lower critical fields. Above 160 kG only V₃Ga and aluminum cryoconductor seem usable, their projected costs at these fields are much greater than those for the other conductors below 160 kG.

NbTi shows the smallest reduction from present prices - about a factor of three--and the two Nb₃Sn conductors show the greatest reduction, about a factor of 40. This seems reasonable since the present production level of NbTi is considerably higher and the processing technology is simpler than that of Nb₃Sn. A factor of approximately 10 reduction is forecast for V₃Ga tape; this is limited by high projected material costs, assuming no other future demands for gallium. It is remarkable that the costs of NbTi, PbBi and the two Nb₃Sn conductors should project to such close agreement, considering the very different processing techniques, materials, and conductor characteristics.

b. The additional cost of full stabilization, even for the wide (10 cm) conceptual conductor, is a small part (typically 10 to 20%) of total conductor cost assuming that fully stabilized and non-stabilized conductors carry the same current per unit amount of super-conductor. If one has to operate non-stabilized super-conductors with substantially smaller currents than are possible with fully stabilized super-conductors, than the latter might be substantially cheaper.

c. The cost of discontinuously varying the amount of super-conductor in a magnet winding is small (10-20%) if several conductor joints are used to cover the operating field range. For example, with GE Nb₃Sn (Figure 3), curve A shows the projected cost assuming continuous variation (non-stabilized) of superconductor, while curve B shows the projected cost assuming discontinuous variation (fully stabilized).

6. Conductor Costs for Large Fusion dc Magnets

Table 5 illustrates the effect of the projected super-conductor costs on the cost of some proposed fusion reactors. For the tokamak and mirror machine designs, this study projects low conductor costs, on the order of a few \$/kW(e). These costs are small (~10%) compared to magnet-structure costs and a small fraction (~1%) of overall plant cost. For the stellarator design, the conductor costs projected by this study are considerably larger (~\$20/kW(e)) and are comparable to magnet structural costs. However, this higher cost is a result of the very high B_{max} (200 kG) chosen [such high fields may not be achievable in practice, however] in the stellarator design. This would require using large amounts of expensive V₃Ga conductor. If the design B_{max} is dropped to 160 kG so that only Nb₃Sn can be used, then conductor costs would be much smaller and more in line with these for the toka-

mak and mirror machine designs.

It appears that for the four conductors NbTi, GE Nb₃Sn, Linde Nb₃Sn, and PbBi, all project to similarly low costs, and that the choice of which conductor or conductors to use in fusion magnets will depend primarily on technical grounds, not economic ones. It would seem that economics would only be a factor if the various conductor choices were technically evenly matched, which does not seem likely.

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Figure 1 Projected cost of Nb-Ti superconductor for fusion magnets as a function of magnetic field, for fusion reactor construction at 90,000 MW(e)/year.

Figure 2 Projected cost of GE Nb₃Sn tape superconductor for fusion magnets as a function of magnetic field, for a fusion reactor construction at 90,000 MW(e)/year.

Figure 3 Projected cost of Linde plasma sprayed Nb₃Sn tape superconductor for fusion magnets as a function of magnetic field, for fusion reactor construction at 90,000 MW(e)/year.

Figure 4 Projected cost of V₃Ga tape superconductor for fusion magnets as a function of magnetic field, for fusion reactor construction at 90,000 MW(e)/year.

Figure 5 Projected cost of Pb-Bi in glass fiber superconductor for fusion magnets as a function of magnetic field, for fusion reactor construction at 90,000 MW(e)/year.

Figure 6 Comparison of projected costs for Nb-Ti, GE Nb₃Sn, Linde Nb₃Sn, V₃Ga, and Pb-Bi in glass fiber superconductors and aluminum cryoconductor, for fusion magnets as a function of magnetic field, for fusion reactor construction at 90,000 MW(e)/year.