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**COSTS OF MAGNETS FOR LARGE FUSION POWER REACTORS:
PHASE I, COST OF SUPERCONDUCTORS FOR DC MAGNETS**

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Abstract

Projections are made for DC magnet conductor costs for large fusion power reactors. A mature fusion economy is assumed sometime after 2000 A.D. in which ~90,000 MW(e) of fusion reactors are constructed/year. State of the art critical current vs. field characteristics for superconductors are used in these projections. Present processing techniques are used as a basis for the design of large plants sized to produce approximately one-half of the conductor needed for the fusion magnets. Multifilamentary Nb-Ti, Pb-Bi in glass fiber, GE Nb₃Sn tape, Linde plasma sprayed Nb₃Sn tape, and V₃Ga tape superconductors are investigated, together with high purity aluminum cryoconductor. Conductor costs include processing costs [capital (equipment plus buildings), labor, and operating] and materials costs. Conductor costs are compared for two sets of material costs: current (1971 A.D.) costs, and projected (after 2000 A.D.) costs. The latter are estimated on the basis of the same assumptions as those used in estimating superconductor cost. All costs, whether current or projected, are expressed in 1971 dollars. Conductor costs are also compared for non-stabilized and fully stabilized operation. Costs for fully stabilized operation are based on illustrative conceptual

conductors. With projected materials costs and full stabilization, conductor costs are ~\$0.50/KA·m at 50 KG for Nb-Ti and Pb-Bi in glass fiber, ~\$0.80/KA·m at 100 KG for GE and Linde Nb₃Sn, and ~\$5.00/KA·m at 150 KG for V₃Ga. Processing costs are a small fraction, typically 20%, of the total conductor cost. The principal cost is for materials. The cost of fully stabilized operation is typically 10-30% greater than non-stabilized operation at equal current densities. Conductor costs are calculated for several DC fusion magnet designs. The projected conductor cost for tokamaks and mirror machine designs is relatively small, \$5/KW(e) or less, and is on the order of 10% of the estimated magnet structure cost. The conductor cost for a stellarator magnet design is greater, ~\$20/KW(e), because of the helical winding. Modification of the stellarator design for somewhat lower fields could greatly reduce its conductor cost.

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1. Summary and Conclusions

1.1 The projected conductor costs are a relatively small part of total costs for DC fusion magnets. This especially holds for tokamaks and mirror machines; for the designs considered in this study, the projected conductor cost is ~10% of the estimated magnet structure cost excluding cryostat and refrigerator. The conductor cost/KW(e) depends on the magnetic field strength and the energy flux to the first wall. As an example, for magnets with a maximum field of ~160 KG and a wall flux of ~3.5 MW(th/m², the projected conductor cost is ~\$5/KW(e). It appears that insofar as magnet design is limited by cost, the limitation will be structural, not conductor, cost. The stellarator design considered in this study was somewhat of an exception, since the estimated structural and conductor costs were comparable. This resulted primarily from the high cost of the helical winding. However for stellarators with somewhat lower maximum fields (160 instead of 200 KG), the projected conductor costs will be much lower.

1.2 The projected costs for the different conductors are comparable except for V₃Ga tape. Using projected materials costs, the conductor costs are ~\$0.40 to 0.50/KA·m at 50 KG for Nb-Ti, Pb-Bi in glass fibers, GE Nb₃Sn and Linde

plasma sprayed Nb_3Sn , and $\sim \$0.80/\text{KA}\cdot\text{m}$ at 100 KG for GE and Linde Nb_3Sn , under the condition that operating current and with full stabilization. The limiting field for Nb_3Sn at 4.2°R is $\sim 160\text{KG}$. If V_3Ga is used for fields above this value, the conductor cost is $> \$5.00/\text{KA}\cdot\text{m}$, while high purity aluminum [resistance ratio of 25,000] cryoconductor would cost $\sim \$3.00/\text{KA}\cdot\text{m}$, including refrigeration and capitalized power costs.

It appears that for the field range 0-80 KG, all four conductors [Nb-Ti , Pb-Bi in glass fiber, GE Nb_3Sn and Linde plasma sprayed Nb_3Sn] are competitive and that choice of conductor would be primarily made on technical, not economic grounds. For the field range 0-160 KG, only GE and Linde Nb_3Sn are economic, and the choice between them would also primarily be made on technical grounds.

Above 160 KG only three options, all expensive survive: V_3Ga tape, aluminum cryoconductor and Nb_3Sn at very low temperatures ($\sim 1.8^\circ\text{K}$). It is not possible at this point to make a clear cut economic choice. If new high field superconductors like Nb_3Al or Nb_3Ge Al prove to have high critical current density, new and perhaps much cheaper options will be opened.

1.3 The major portion of conductor cost is for materials. This holds for all the conductors studies. With

projected materials costs, processing costs are typically one-quarter or less of finished conductor cost. With present materials costs, processing costs are a much smaller part of finished conductor cost. The largest cost savings are to be expected if the amount or cost of materials can be reduced.

1.4 The cost difference between non-stabilized and fully stabilized conductor is relatively small. For the fully stabilized conceptual conductors in this study, the conductor cost is ~10-30% greater than that of non-stabilized conductor, assuming the same current density in both. The conceptual conductors use 5000 resistivity ratio aluminum stabilizer. It may be somewhat cheaper to use lower resistivity ratio aluminum, e.g., 2000. Copper stabilizer appears to be substantially more expensive and limits conductor width.

1.5 The conductor cost is greater if the amount of superconductor is discontinuously rather than continuously varied along its length to accommodate changing magnetic field, but the difference is small for the conceptual conductors in this study. Typically four or five discontinuities were assumed. One advantage of Linde plasma sprayed conductor is the ability to vary conductor thickness along the conductor; it may even be possible to vary thickness rapidly enough to compensate for the rapidly changing fields in toroidal field windings.

1.6 There appear to be very ample reserves of niobium, vanadium, gallium, and bismuth to supply the superconductors needed for a very large fusion reactor economy.

1.7 The projected materials costs vary; in some cases there is no reduction from present costs, in other cases reductions by a factor of five are projected. No reductions are projected for bismuth since the additional amount required for superconductors will not substantially increase its total demand. A fourfold price decrease for gallium is forecast to \$90/lb, with an increase in total demand of over two orders of magnitude. A price decrease of a factor of two is forecast for Nb ingot, to \$4/lb, along with an increase in demand by over one order of magnitude. A threefold decrease in Nb powder cost is forecast, to \$4.50/lb, with an increase in total demand by several orders of magnitude. A fivefold price decrease is forecast for 1 mil Nb+1% Zr foil, to \$19/lb, along with an increase in total demand by several orders of magnitude. A fivefold decrease is also forecast for Nb-Ti alloy, to \$6.25/lb, along with an increase in demand by several orders of demand. Similar decreases are forecast for V ingot and V+1% Zr foil. A fourfold price decrease is forecast for 5000 resistivity ratio aluminum, to ~\$4/lb, along with an increase in total demand by three orders of magnitude.

2. Future Research Directions for Lower Conductor Costs

The conductor costs projected in this study are based on state of the art superconductor characteristics and processing techniques. Improvements in critical current, lower materials costs, faster processing, optimization of conductor design, etc. will lead to even lower cost projections. The following are some specific research directions that offer promise of substantially lower conductor costs:

1. Increase J_c for plasma sprayed Nb_3Sn .
2. Use of thicker, less expensive Nb-1% Zr foils for GE Nb_3Sn .
3. Increase J_c for V_3Ga tape, particularly for fields above 160 KG.
4. Increase J_c for Pb-Bi in glass fiber. This is being investigated by Watson through modification of the glass fiber structure.
5. Better utilization of superconductor in magnets where the field changes rapidly along the conductor (e.g., toroidal field coils). The amount of superconductor could be varied along the conductor, using only the amount needed for the local field. Plasma sprayed superconductor seems quite promising in this regard.
6. New and cheaper production processes for niobium and high purity aluminum. Two possibilities are the

duPont process for niobium and recrystallization
purification for aluminum.

In general, significant cost savings will only occur if the amount or price of materials used in making a given amount of KA-meter of conductor is reduced, since materials costs are the predominant part of conductor cost.

3. Conductor Costs - General Results

The conductor costs estimated in this study are summarized in Figures 3.1 through 3.6. Some general observations can be made:

First, the cost of the conceptual conductor (curves B and D) is, except for Nb-Ti, quite close to the base cost of the superconductor without stabilization (curves A and C).

With a more optimized design the cost of the Nb-Ti conceptual conductor would come much closer to the base cost of Nb-Ti superconductors, instead of being approximately 50% greater. This indicates that the cost of the superconductor will not be a sensitive function of conductor design, at least for edge cooled strip conductor, and will be close to the cost for the superconductor alone.

Second, the estimated cost of fusion magnet superconductors is considerably lower than those of other studies, except for the arbitrary cost assumptions in the study by Gibson, Hancox and Bickerton,⁽¹⁾ given in Table 3.1

The estimated costs of this study roughly correspond to their value of 1/9 of present Nb-Ti costs. The conductor costs in the study by Lubell, et al.⁽²⁾ and Moir and Taylor⁽³⁾ [Figures 3.7 and 3.8] are almost an order of magnitude greater

than those of this study. Since their estimated costs are comparable to present superconductor prices, they have not projected any reduction in price due to the very large volumes anticipated for the fusion economy. In some cases their costs are above current market costs. It should be noted that the costs in this study are not based on operating current equal to short sample critical current, but $2/3$ of it which increases the estimated cost.

Third, in this study, the conductors fall roughly into three relative groupings:

1. Low cost GE Nb_3Sn and Linde Nb_3Sn
2. Medium cost Nb-Ti and Pb-Bi
3. High cost V_3Ga

The low cost grouping is a result of the high current density and projected low cost of Nb_3Sn . The cost estimates for GE and Linde Nb_3Sn conductors agree fairly closely; this is coincidental. The projected cost of the Nb-1% Zr foil used for GE conductor is approximately four times greater than the projected price for Nb powder used in the Linde process, while the critical current density of the GE Nb_3Sn is also approximately four times greater. Since the principal cost is for materials, the two conductors tend to the same cost. However, if the critical current of the Linde Nb_3Sn conductor can be

raised substantially relative to GE Nb_3Sn critical current, then it will be considerably cheaper.

The medium cost grouping is a result of the considerably lower critical current density of Nb-Ti and Pb-Bi relative to Nb_3Sn . Considerably more superconductor has to be used to carry a given current, while the cost/lb is approximately the same. The conductor costs of Nb-Ti and Pb-Bi agree fairly closely since the critical currents and the projected cost/lb of the materials are comparable. The rationale for developing Pb-Bi in glass fiber as a replacement to Nb-Ti was that its cost/lb would be much cheaper, even though its critical current density was somewhat lower. However, the projected price of Nb-Ti while somewhat greater than that of Pb-Bi is close enough that its somewhat larger critical current density makes up the difference. Thus Pb-Bi can be regarded as a competitor for Nb-Ti, but not a replacement.

The high cost grouping (only V_3Ga) reflects the low critical current and high cost/lb of vanadium and gallium. The only chance for V_3Ga to compete effectively with Nb_3Sn in the high field range (>100 KG) would be to essentially triple its critical current density. This is not impossible, since relatively little development work has been done on V_3Ga . However, one cannot assume that Nb_3Sn development is finished, especially

with regard to the Linde Nb_3Sn conductor, so it is likely that Nb_3Sn will be a moving target for V_3Ga . Thus it appears that with further development V_3Ga might be a competitor for Nb_3Sn , particularly at the very high field range (≥ 130 KG) but it does not seem likely that it would ever be a clear-cut replacement.

Figure 3.1 shows the costs of Nb-Ti estimated for this study and compares them to some recent market costs. The NAL strip conductor cost⁽⁴⁾ - point G - (\$350,000 for 1.364×10^5 feet of 5000 A conductor) is substantially higher than the cost estimated even using present material prices. However, recent production indicates that prices have come down considerably. Point E represents the price charged for Nb-Ti rectangular multifilamentary conductor (57 x 117 mils) for AGS beam magnets at BNL.⁽⁵⁾ The total order involved was ~\$12,000. Point F is the quote price for a ~\$1,000,000 order for conductor for an AGS synchrotron.⁽⁵⁾ These costs are given on the basis of I/I_c equal to two-thirds, and it is evident that market prices are approaching the costs projected in this study.

Figure 3.2 shows the estimated costs for Pb-Bi in glass fiber superconductors. Curves A and B, and curves C and D touch at the steppoints because the stabilizer is an integral part of the conductor, not soldered on in a later process step as with the other conductors. There are no market prices for

Pb-Bi in glass fiber conductor since no commercial conductor has been developed.

Figure 3.3 shows the estimated costs for GE Nb_3Sn conductor. Table 3.2 gives recent projections by Rosner⁽⁶⁾ for GE Nb_3Sn conductor. Point F in Figure 3.1 represents 1/10 of the current market cost, while point E represents 1/10 of Rosner's projected cost for a production of 10^8 m/year (1/2 inch ribbon). The projections made in this study are an order of magnitude lower than Rosner's projections. This is probably due to a combination of reasons: lower projected Nb-1% Zr foil costs in this study, much wider ribbons (4 inches vs 1/2 inch) with consequent lower processing costs, and a larger production volume.

Figure 3.4 shows the estimated cost for Linde plasma sprayed Nb_3Sn conductor. Point E at 50 and 100 KG represents 1/10 the cost in \$/KA m at the current market price of \$2.15/foot of 1/2 inch wide ribbon. The current market volume is very small, more than five orders of magnitude below the volumes necessary for a mature fusion economy.

Figure 3.5 shows the estimated cost for V_3Ga tape conductor. Curve E represents the cost in \$/KA m at the current market price (\$2.00/foot of 1/2 inch wide ribbon). Again, the current market volume is many orders of magnitude smaller than that necessary for a mature fusion economy.

Figure 3.6 compares the estimated cost of the various conductors using projected materials costs, together with the projected cost of high purity aluminum cryoconductor (Appendix I). The capital cost of the refrigerator and capitalized power cost are included in the cryoconductor cost. If Nb_3Sn is technically practical in large fusion magnets, it will be definitely chosen. However, if it is not practical then aluminum cryoconductor seems a practical, economically valid alternative to Nb_3Sn for the high field winding. Nb-Ti would be used for the low field winding, of course. Aluminum cryoconductors would be preferable to V_3Ga in the very high field range at 170 KG and above, unless the cost of V_3Ga can be reduced.

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Table 3.1

Superconductor Costs Assumed by Gibson, Hancox,
and Bickerton⁽¹⁾ in an Economic Study of
Stellarator and Tokamak Fusion Reactors

	<u>Superconductor Cost, \$/KA m</u>		
	<u>B=50 KG</u>	<u>B=100 KG</u>	<u>B=150 KG</u>
Assumed equal to:			
Present Nb-Ti costs	3.60	7.20	10.80
1/3 Present Nb-Ti costs	1.20	2.40	3.60
1/9 Present Nb-Ti costs	0.40	0.80	1.20
GE Nb ₃ Sn *	0.30	0.94	1.84
Linde Nb ₃ Sn *	0.45	0.66	1.20
Nb-Ti *	0.60	-	-
Pb-Bi *	0.63	-	-

* This study, fully stabilized, with $I/I_c \leq 2/3$, and with small number of conductor points in fusion coil.

Table 3.2

Projected Price for Nb₃Sr Conductor
(GE Process)*

Cost/KA meter
Magnetic Field.KG

<u>Meters Produced/yr</u>	<u>50</u>	<u>100</u>	
2×10^3	\$9.5	\$28	Current sale range
10^4	5	15	
10^6	2.2	6.5	
10^8	1.3	4	

Conditions: 1/2" ribbon width, $I/I_c = 1$

* C. Rosner, private communication (1971).

Figure 3.1

Curve

- A. Projected cost of Nb-Ti superconductor without stabilizer; projected materials cost, $1/l_c = 2/3$.
- B. Projected cost of Nb-Ti superconductor with stabilizer, and designed to carry 28 kA in fusion magnet; projected materials cost, $1/l_c = 2/3$.
- C. Same as Curve A, but using present materials cost.
- D. Same as Curve B, but using present materials cost.
- E. Cost of AGS beam magnet conductor [$1/l_c = 2/3$].
- F. Projected price for AGS Synchrotron conductor [$1/l_c = 2/3$].
- G. Cost of NAL strip conductor [$1/l_c = 2/3$].

Figure 3.2

Curve

- A. Projected cost of Pb-Bi in glass fiber superconductor; projected materials cost; $I/I_c \approx 2/3$.
- B. Projected cost of Pb-Bi in glass fiber superconductor, and designed to carry 10 kA in fusion magnet; Projected materials cost, $I/I_c \approx 2/3$.
- C. Same as Curve A, but using present materials cost.
- D. Same as Curve B, but using present materials cost.

Figure 3.4

Figure 3.5

Figure 3.6

Projected costs of conceptual superconductors
for large fusion magnets

Figure 3.7

[after Lubell, et al. (2)]

The unit cost of NbTi compound conductor vs magnetic field for normal lengths ($10^4 - 10^5$ ft) and for very long lengths ($\geq 10^6$ ft).

Figure 3.8

[after Moir and Taylor (3)]

4. Conductor Costs for Typical Large Fusion Reactors

The conductor costs developed in this study are now applied to some typical large fusion reactor designs, and the resulting conductor costs for the reactor are compared to previously estimated costs. In all cases, the conductor costs taken from this study assume projected materials costs and include stabilization costs (i.e., conductor costs are given by curve B in Figures 3.1 through 3.5).

An ORNL study⁽¹⁾ has examined a large tokamak reactor of 5000 MW(th) total power. We assume here thermal efficiency of 40%, corresponding to a total electrical power output of 2000 MW(e). The superconductor costs for this reactor are summarized in Table 4.1 and compared to ORNL's estimate.

In the ORNL study only one value of central field, $B_0 = 37$ KG, was considered. The ORNL estimate of the Nb-Ti superconductor cost for the field was \$13.0/KW(e). For the same field, this study projects magnet superconductor costs of approximately an order of magnitude lower, i.e., \$1.24/KW(e) [GE Nb₃Sn], \$1.32/KW(e) [Linde Nb₃Sn], \$1.96/KW(e) [Nb-Ti] and \$2.00/KW(e) [Pb-Bi]. The ORNL estimate of magnet structure cost [excluding cryostat and refrigerator] is \$19.0/KW(e). It thus appears that the superconductor costs will be much smaller than the magnet structure costs. Further, the cost of the various superconductor options is low enough that the most technically desirable

conductor can be used without a large economic penalty.

The estimated superconductor costs for higher B_0 (but same output power, so stability is improved) are also shown in Table 6.1. The only conductors considered for these higher fields are GE and Linde Nb_3Sn ; V_3Ga is much more expensive while a compound winding (Nb-Ti for low field and Nb_3Sn for high field) is more expensive and does not offer any technical advantage over a straight Nb_3Sn winding. If B_0 doubles, the superconductor cost approximately quadruples. At higher B_0 , the Linde Nb_3Sn winding becomes cheaper than the GE Nb_3Sn winding. If the magnet structure cost varies as B_0^2 , a reasonable approximation, the conductor cost remains at less than 10% of the structure cost.

Similar low superconductor costs are found for the large D-T Tokamak fusion magnet proposed by File, Mills, and Sheffield⁽²⁾ at Princeton. Here the maximum conductor field is 160 KG, B_0 is 91 KG, and the amount of conductor (in KA·m) is approximately 30% of that required for the ORNL Tokamak with $B_{mak} = 158$ KG. Assuming that reactor power scales linearly with plasma radius [1.70 m for Princeton Tokamak vs 2.8 m for the ORNL Tokamak], then the superconductor cost for the Princeton Tokamak reactor is \$3.00/KW(e) for GE Nb_3Sn and \$2.30/KW(e) for Linde Nb_3Sn . However, the blanket and shield average

thickness in the Princeton reactor is on the order of one meter. This may be too small, and a larger, more costly, magnet may be required.

The Princeton design has been normalized to the ORNL Tokamak wall energy flux of 3.45 MW(th)/m^2 . However, a larger wall flux can presumably be generated by the plasma if B_0 is substantially greater than 37 KG. With a wall flux of 10 MW(th)/m^2 , the superconductor costs for the ORNL and Princeton Tokamaks would be reduced by almost a factor of 3. Conversely, if very low wall fluxes are desired to reduce radiation damage, the superconductor cost is low enough that it will not prohibit such operation. For example, the ORNL Tokamak with $B_0 = 37 \text{ KG}$ could operate at a wall flux of 1 MW(th)/m^2 , and the superconductor cost would still be only $\sim \$5/\text{KW(e)}$.

In these calculations, the conductor cost for a given turn of the coil generating the toroidal field is set by the amount of superconductor required by the maximum field experienced by the turn [i.e., the field at the minimum R (measured from the axis of the torus) of the turn]. Further, the field at this point decreases linearly with number of turns in the coil, being zero at the outer radius of the coil (r_1) and some maximum value, B_{max} , at the inner radius (r_0). Since the coil has a large number of turns and the radial thickness of the winding is small compared to its inner diameter ($2 r_0$), the

average conductor cost is closely approximated by

$$\bar{C} = \frac{\int_0^{B_{\max}} C(B) dB}{B_{\max}} \quad 6.1$$

where $C(B)$ is the cost/ $KA \cdot m$ at field B . The total superconductor cost for the toroidal magnet is then the product of the total $KA \cdot m$ required for the magnet and $\bar{C}$.

If it proves possible to vary the amount of superconductor along each turn of the coil in proportion to the local field, the total required amount of superconductor could be cut approximately in half, and the conductor costs could be substantially reduced. It would not be practical to do this by conductor joints during coil assembly-- 10^4 joints would be required in the reactor. It should be possible with certain conductor manufacturing processes, e.g., Linde plasma sprayed Nb_3Sn .

Mirror machines show similar low superconductor costs. Table 6.2 compares the superconductor costs estimated by Moir and Taylor⁽³⁾ for a Yin-Yang magnet for a 1000 MW(e) fusion reactor with those estimated by this study. The conductor length (8.5×10^6 $KA \cdot m$) and maximum field are given in Moir's and Taylor's paper, but not a breakdown of conductor length vs. field. However, the approximation of equation 6.1 above is adequate for this study, and the corresponding superconductor costs for GE and Linde Nb_3Sn are given in Table 6.2. As with the ORNL Tokamak, the superconductor costs are quite small,

~\$5/KW(e) and about an order of magnitude smaller than the structure cost.

Thus with tokamaks and mirror machines, the projected superconductor costs are quite small, even assuming no further improvement in critical current density or processing techniques. This holds provided the maximum conductor field is below 160 KG. If one wished to go to substantially higher fields, the magnet cost would jump by a very large factor since it would be necessary to go to V_3Ga conductor or aluminum cryoconductor for the portion of field winding above 160 KG, or to develop new superconductors. One interesting alternative would be to run the high field winding at a lower temperature, e.g., $1.8^{\circ}K$, which should extend the operating range of Nb_3Sn to over 200 KG. The extra refrigerator cost appears reasonable.

However, the structure costs increase so rapidly with B that a practical limit for tokamaks and mirror machines is probably on the order of 160 KG. It thus appears that the field capabilities of present superconductors are adequate for tokamaks and mirror machines, and that new higher field superconductors are not required.

The situation with stellarators is not so clear-cut, however. Table 4.3 summarizes the estimated superconductor costs for one stellarator design proposed by Gibson, Hancox and

Bickerton.⁽⁴⁾ As with the tokamaks, the cost of the toroidal field winding is relatively small; ~\$8/KW(e). However, in this case, ~75% of the toroidal field conductor cost comes from the V_3Ga tape, which is only used for the turns with maximum field between 160 and 200 KG. Moreover, the cost of the toroidal field winding for this stellarator would be much greater than that for the ORNL and Princeton Tokamaks except that the wall energy flux for the stellarator is much larger, $10 \text{ MW(th)}/m^2$ vs. $3.45 \text{ MW(th)}/m^2$ for the tokamaks. It is clear that a very large jump in conductor cost occurs when B_{max} exceeds 160 KG.

The most costly conductor, however, is the helical winding. Not only is the amount of conductor much greater for the helical winding, $2.7 \times 10^7 \text{ KA}\cdot\text{m}$ meter compared to $1 \times 10^7 \text{ KA}\cdot\text{m}$ for the toroidal winding, but the average field seen by the conductor is much greater. The peak field seen by each turn as it spirals around the torus is ~180 KG and the minimum is ~120 KG. A rough approximation is taken where 5/6 of the helical winding is at a field of 120 KG, 1/12 at 150 KG, and 1/12 at 180 KG. The corresponding cost for the helical winding is then \$16.0/KW(e) if GE $Nb_3Sn + V_3Ga$ is used.

The total conductor cost for the stellarator is then 24.4/KW(e) for GE $Nb_3Sn + V_3Ga$ and \$21.0/KW(e) for Linde

$\text{Nb}_3\text{Sn} + \text{V}_3\text{Ga}$, compared to \$20/KW(e) estimated by Gibson, Hancox and Bickerton, based on their 1/9 of present Nb-Ti cost.

The estimated structure cost is ~\$25/KW(e), a factor of three less than the ORNL Tokamak with about the same B_{max} . However, this stellarator design has almost a factor of three greater energy flux to the wall, which brings the two estimates of structure costs fairly close together when normalized to the same wall flux. However, one would expect the stellarator structure cost to be substantially greater than a tokamak because of the difficult helical winding, so there still remains a discrepancy between the estimates of structure cost.

It thus appears that such stellarators do have serious conductor cost problems, in contrast to the tokamaks and mirror machines, because of the helical winding and the high fields demanded. There are a number of possible approaches to this problem:

1. New cheap superconductors with high J_c at ~200 KG. None have been proven yet, though Nb_3Al and Nb Ge Al are candidates. Plasma sprayed conductor would seem to be very good for this purpose.
2. Much higher J_c for V_3Ga . One needs a factor of 2 to 3 over the present Sumitomo conductor.

3. Lower refrigeration temperature for Nb_3Sn helical winding. A 1.8°K operating temperature would permit Nb_3Sn to be used up to 200 KG.
4. Aluminum cryoconductor for the helical winding.
This does not appear to be economical unless the cost of 25,000 resistivity ratio aluminum is \$2/lb or less.
5. If one relaxes the maximum field requirement for the stellarator from 200 to 160 KG, the superconductor cost would drop by a very large factor. The 200 KG value selected by Gibson, Hancox, and Bickerton reflects their assumption that conductor cost per KA·m is linearly proportional to field. If in reality there is a very large cost jump at ~160 KG, then there is great incentive to design stellarators with maximum fields that do not exceed this value. This would result in a somewhat larger, lower wall flux stellarator, but it could be considerably cheaper in \$/KW(e).

It appears that further detailed examination and optimization of stellarators is warranted taking into account the cost of actual superconductor options rather than assuming that cost scales linearly with field.

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3. Gibson, A., Harrox, S., and Bickerton, R., "On the Economic Feasibility of Stellarator and Tokamak Fusion Reactors," Paper CN-28/K-4, Fourth Conference...ibid (June 1971)

Table 4.1

Estimated Cost of Superconductor for ORNL Tokamak Fusion Reactor⁽¹⁾

Reactor parameters: P = 5000 MW(th)
 P = 2000 MW(e) [assumed for this study]
 $P_{wall} = 3.45 \text{ MW(th)/m}^2$
 $NI = 2 \times 10^8 \text{ A-turns for } B_0 = 37 \text{ KG}$
 $\bar{R}_{av} = 5.85 \text{ meter winding radius}$

		Superconductor Cost, \$/KW(e)					
		<u>This Study †</u>					
<u>B₀</u>	<u>B_{max}</u>	<u>ORNL</u>	<u>GE Nb₃Sn</u>	<u>Linde</u>			<u>Structure Cost</u>
<u>(KG)</u>	<u>(KG)</u>	<u>Estimate</u>		<u>Nb₃Sn</u>	<u>Nb-Ti</u>	<u>Pb-Bi</u>	<u>\$/KW(e)</u>
37	79	13.0	1.24	1.32	1.96	2.00	19.0*
55.5	111	-	2.69	2.47	-	-	42.8**
74	158	-	5.94	4.64	-	-	76.0**

* ORNL estimate includes reinforcement, bobbin, winding, assembly, and outer reinforcement ring--does not include cryostat and refrigerator.

** Assumed to vary as B_0^2 .

† Curve B in Figures of estimated superconductor costs [Figures 5.1 through 5.5].

Table 4.2

Estimated Cost of Superconductor for
LRL Yin-Yang Fusion Reactor ⁽³⁾

Reactor parameters: $P = 1000 \text{ MW(e)}$
 $8.5 \times 10^6 \text{ KA-meter of conductor}$
 $B_{\text{max}} = 140 \text{ KG}$

	<u>Cost of</u> <u>Superconductors</u> <u>\$/KW(e)</u>	<u>Cost of Structure</u> <u>\$/KW(e)</u>
This study		
GE Nb_3Sn	5.4	-
Linde Nb_3Sn	4.6	-
LRL study	66	54

Table 4.3

Estimated Cost of Superconductor for Stellarator
of Gibson, Hancox, & Bickerton⁽⁴⁾

Reactor parameters: $P = 2500 \text{ MW(e)}$ $y = 2$
 $P_{\text{wall}} = 10 \text{ MW(th)}/\text{m}^2$ $t = 3$
 $R_{\text{major}} = 8.4 \text{ meters}$
 $R_{\text{helical}} = 4.0 \text{ m}$
 $R/a = 6$
 $B_0 = 60 \text{ KG}$
 $B_{\text{max}} = 200 \text{ KG}$

<u>Winding</u>	Amount of* Conductor (KA·m)	<u>Superconductor Cost, * \$/KW(e)</u>	
		<u>Nb₃Sn(GE) + V₃Ga</u>	<u>Nb₃Sn(Linde) + V₃Ga</u>
Helical†	2.7×10^7	16.0	13.2
Toroidal‡	1.0×10^7	<u>8.4</u> **	<u>7.8</u> **
		Total 24.4	21.0
Total \$20/KW(e)*** - conductor cost			
Estimated 25/KW(e) - structure			
by Gibson, Hancox, & Bickerton			

* Estimated by this study

** ~75% is for V₃Ga conductor

*** Conductor cost = 1/9 present Nb-Ti cost

† 5/6 at 120 KG, 1/12 at 150 KG, 1/12 at 180 KG

‡ Field assumed to vary linearly through radial thickness of winding

1. Introduction

The objectives of the phase 1 study are:

- a. To develop cost projections for candidate DC super and cryoconductors that will be applicable to a mature fusion economy (sometime after 2000 AD) in which several tens of thousands MW(e) fusion reactor capacity are constructed each year. Developed commercial superconductors are considered (multifilament Nb-Ti, Ge Nb₃Sn tape, Linde plasma sprayed Nb₃Sn tape, and V₃Ga tape), as well as non-commercial superconductors that reasonable cost projections can be made for Pb-Bi in glass fiber, multi-filamentary Nb₃Sn and V₃Ga). These projections are made as closely as possible on the basis of present superconductor characteristics, and present process parameters. Uniform assumptions are made as to depreciation rates, building costs, etc. These cost projections are made both on the basis of current raw material costs, and projected raw material costs. High purity aluminum cryoconductor cost projections are also made.
- b. Identify conductor materials which seem to offer the most practical design and the lowest costs for fusion magnets.

- c. Identify the predominant cost component for fusion magnets, i.e., whether it is conductor or structural cost.
- d. Develop options in the event that certain conductors are not technically feasible for large fusion magnets, e.g., what alternatives to Nb_3Sn are available for high field magnets.

The following assumptions have been used in this study:

- a. An installed U.S. generation capacity of $\sim 3 \times 10^6$ MW(e) [10 times present capacity] with growth and replacement at an annual rate of 6%. Of the new and replacement capacity of 180,000 MW(e)/year, half is in fusion reactors. One standardized type and power rating of fusion reactors is assumed. Most likely the type will be standardized, but the power rating may be somewhat variable. The magnet design is assumed to be standardized as is the conductor(s) used in it.
- b. The conductor fabrication plant is sized to produce approximately 50% of the conductor(s) needed for the magnets for an annual addition of 90,000 MW(e) of fusion reactors. The actual plant size would depend on many factors that are unknown at this time. It is clear that considerable economies of scale are possible

with fabrication plants, but competition may be desirable and indeed even required. The production cost will not greatly vary for plants supplying 20-100% of the market, so the 50% value was chosen as a reasonable size. For most superconductors at these production levels, it is quite possible that the superconductor fabrication will be part of an integrated facility where the raw materials are processed. For example, a niobium producer could start with the ore and end with Nb_3Sn diffusion tape since the predominant part of the cost will be the production of thin Nb foil. However, it has been assumed that the superconductor fabrication plants are not integrated with the raw material plants. Plant sizes for the various conductors are given in the appropriate appendices.

- c. The capital and depreciation charges are taken as 25%/year for all plants. The combined capital investment includes capital equipment and buildings. The capital equipment cost is taken as the sum of the estimated installed cost of all the component equipment in the plant, plus 25% for engineering and testing.

- d. General maintenance charges are taken as 10%/year of the capital equipment (minus engineering and testing) investment. Specific replacement costs, like the yearly replacement of RF power tubes in the high purity aluminum production plant, are added in separately.
- e. Building costs are taken as \$100/ft² (which includes utilities) for all plants except the very large plant producing 30,000 T/year of 25,000 resistivity ratio aluminum. The building costs in this case are taken as \$60/ft², which reflects the much larger plant size and simplicity of construction.
- f. All costs are expressed in 1971 dollars.
- g. Labor costs are lumped into one average cost of \$25,00/year/person covering salary and fringe benefits. This average covers all personnel, including operating, clerical, administrative, etc. Four shift, round the clock operation for the plant is assumed, with holidays and vacations covered by overtime. In actual practice, the plant would probably not operate continuously, but this should not significantly affect production costs.
- h. Process equipment is assumed to operate only ~80% of the time because of maintenance, scheduling problems, etc.

- i. Materials costs are summarized in Table 5.1. Projected costs for material with present large volume production (copper, tin, lead, bismuth and fiberglass) are taken as equal to current costs. Current costs for niobium, niobium-titanium, vanadium, gallium, and high purity aluminum are taken as the lowest known price paid by a customer. Projected costs of these materials are based on design and costing of plants sized to produce the very much larger amounts needed in the mature fusion economy discussed above.
- j. The costs estimated in this study are production costs and do not include profits for the manufacturer. The profit allowance is not well determined, but 10% of the production cost should be ample.
- k. Only DC conductors are considered in this study. Conductors for pulsed fusion reactors will be considered in a later report. Such conductors would be used in stellarators, mirror machines, and diffusion driven tokamaks and in pulsed tokamaks if shielded.

The fundamental aim of the phase 1 study is to establish an upper limit for the true cost of super- and cryo-conductors for large fusion magnets in a mature fusion reactor economy, and to find out how such costs compare with total fusion reactor and magnet costs. It is exceedingly likely that

there will be very great improvements in conductor performance in the next 30-40 years, and that much simpler production processes will be developed. Also, completely new and much superior superconductors will probably be developed. Thus the true costs may be much lower than this upper limit.

TABLE 5.1

Costs of Raw Materials for Superconductor(s) Fabrication

<u>Item</u>	<u>Costs (\$/lb)</u>	
	<u>Current Costs</u>	<u>Projected Costs Mature Fusion Economy</u>
Copper	1.0	1.0
Tin	1.50	1.50
Lead	0.20	0.20
Bismuth	5.00	5.00
Fiberglass	\$1/m ²	\$1/m ²
Nb powder	15	4.50
Nb foil (1 mil)	100	18.90
Nb-Ti rod	35	6.25
V foil (2 mil)	100	20.96
Ga	360	90
Aluminum (5000 resistivity ratio)	15	3.80

6. Conductor Design for Large Fusion Magnets

The optimum conductor design for fusion power reactors will depend on many technical and economic factors, and definitive designs cannot be made now. However, by means of illustrative conductor designs it is possible to see what effect various design choices will have on conductor costs. Two options are chosen for this study. In the first, costs are estimated for non-stabilized conductors (i.e., normal regions will propagate) consisting of only the superconductor plus the substrate or matrix it is fabricated with. This represents minimum conductor cost. In the second option, costs are estimated for fully stabilized conductors (i.e., normal regions do not propagate and the superconductor recovers) consisting of the same superconductor and substrate plus stabilizer. Costs of the two options are compared on the basis of equal current density in the superconductor. In addition, the second option also assumes a non-continuous variation of amount of superconductor with field, to see what effect the desire to minimize conductor joints in the magnet will have.

In the rest of this section, arguments for full stabilization of fusion magnet superconductors are summarized, and illustrative fully stabilized conductor designs are developed for each conductor.

The conductor design for large fusion reactor magnets is severely restricted by four factors:

1. Unfavorable geometry for cooling
2. Necessity of preventing quenches
3. Need for ultra-reliable operation
4. Desirability of lowest magnet system cost

In large fusion magnets, unlike large bubble chamber magnets, the axes of the coil windings are horizontal, not vertical. This greatly magnifies the cooling problems. Idealized fusion and bubble chamber magnet coil windings are shown in Figure 6.1.

In the bubble chamber winding, the face of the conductor strip is everywhere vertical (point A). This permits the designer to provide coolant passages between successive turns of the conductor strip by means of spacers. If the superconductor goes normal at a certain point in the strip, natural convective flow of helium through the coolant passages can maintain the temperature of the strip low enough that the normal region does not spread and the superconductor eventually recovers. This fully stabilized approach has been used in the FNL and NAL bubble chamber magnets. It was not used for the ANL bubble chamber magnet, since there the lineal current

density was low enough that fully stabilized edge cooling was adequate.

In the face cooled approach, a relatively large fraction of the face area must be in contact with the coolant, and the conductor strip width is limited by natural convection flow rate in the coolant passages. A number of coil pancakes are used, with separation between pancakes in order that some coolant mixing may occur.

The face cooled approach has worked satisfactorily for bubble chamber magnets, but cannot work for fusion magnets. An idealized coil for a tokamak is shown in Figure 6.1. At points A and C, the conductor strip face is horizontal, not vertical, and it is not possible to use natural convection cooling of the face. The conductor face is vertical at point B, but the coolant passage length is too long (more than 1 meter) to get adequate cooling.

Thus natural convection cooling of the conductor face is not possible for fusion magnets. One could visualize a conductor strip with its face everywhere in the plane of the coil winding, but this would be extremely difficult, if not impossible, to fabricate and wind into coils.

One possibility is forced convective cooling. However, because of the very large volumetric flow rates needed to

ensure adequate cooling, it would not be feasible to cool the conductor strip face by coolant cross flow (i.e., from one edge of the coil winding to the other). A hollow superconductor approach has been used by CERN for a large magnet, but very long coolant flow lengths, i.e., hundreds of meters, are necessary. For large fusion magnets, because of the very large stored energy and rapid temperature rise during a quench, it would be extremely difficult to get the helium coolant out before its rising pressure burst the conductor and possibly the winding. Periodic pressure relief valves along the conductor would be difficult to install, their reliability would be questionable, and because of speed of sound in liquid helium is low (100 meters/second), a very large number would be required.

It thus appears impractical to use forced convective cooling for large fusion magnets. The only choice seems to be natural convection edge cooled conductor strip. The consequent limitations on conductor current and width, together with normal metal stabilizer requirements, will be considered in more detail later.

The second factor is the necessity of preventing magnet quenches. If the magnetic field energy can be spread uniformly throughout the magnet structure, the average energy release is reasonable, $\sim 100 \text{ J/cm}^3$. Thus it appears that barring very non-uniform releases of field energy that no damage would be done

to a large fusion magnet, even if its entire field energy should be dissipated in the windings. However, it will take a long time, on the order of weeks, to re-refrigerate the coils and re-energize the magnet. Thus from the point of view of power plant reliability it would be most undesirable to have frequent magnet quenches. A quench frequency of more than one/year would probably be unacceptable. This low quench frequency argues strongly for a fully stabilized superconductor, as the best method of preventing quenches. A counter argument can be made for intrinsically stable multifilamentary superconductor as long as only Nb-Ti is used (though intrinsically stabilized conductor could very well be more expensive than fully stabilized conductor), but not if Nb_3Sn or V_3Ga tape conductors are used. There is substantial research on intrinsically stable multifilamentary Nb_3Sn and V_3Ga superconductors, but a practical, reasonable cost conductor is still far off. A weaker argument could be made for dynamically stabilized Nb-Ti conductor.

The third factor, the need for ultra-reliable operation, argues strongly for the use of fully stabilized conductor. Suppose that the superconductor becomes damaged at some point in the coil winding, e.g., cracking of the Nb_3Sn layer in a tape superconductor, or fracture of the filaments in Nb-Ti due

to local yielding, so that the transport current must flow outside the superconductor at that point. If the conductor is fully stabilized, i.e., able to carry the full transport current in a normal metal shunt without increasing the local temperature beyond the superconducting transition temperature, then the conductor can continue to operate indefinitely, although with some extra load on the refrigerator. If the conductor is not fully stabilized then the normal region will propagate because of I^2R heating, and the entire coil will go normal. Thus a non-fully stabilized coil would have to be replaced if any section became damaged. This would be a very expensive, difficult and time consuming operation, particularly if the fusion blanket was radioactive. Considering the very long operating lifetime of a fusion magnet (≥ 30 years), the very high stresses in the coil, and the very long conductor lengths, it would be difficult to guarantee that damaged sections would not occur. It thus appears very likely that fully stabilized conductors will be desirable for large fusion magnets.

The fourth factor, the desirability of lowest magnet system cost, also strongly effects conductor design. Since the conductor cost is small compared to the structural costs (winding of the coil, assembly into a magnet structure, reinforcement and support, etc.), conductor designs which minimize structural

costs will be favored, even if they cost more as conductors than other designs. It should be cheaper to wind, assemble, and support a few wide (e.g., 1 foot or more) pancake coils, than a much larger number of narrow (e.g., 2 inches or less) pancake coils. The overall magnet system cost could be substantially cheaper with wide pancakes even though the conductor might cost more.

Consider a conductor of the type shown in Figure 6.2. The superconductor is soldered to a stabilizing strip of low resistivity normal metal and is wound into a pancake type coil along with reinforcing strip (e.g., stainlesssteel). This type of pancake coil could provide the toroidal field for a tokamak or stellerator, or the field in a simple mirror machine. More complicated coil shapes would be necessary for the shear field winding in a stellerator, or the field of a baseball coil.

The pancake is edge cooled only. The edge of the low resistivity stabilizing strip is turned up to provide more heat transfer area to the helium bath. Successive turns of conductor and reinforcing strip are tightly wound with no coolant between. If desired, the reinforcing strip may be soldered to one side of the conductor, and successive turns may be bonded together with epoxy. Some type of electrical insulator, either plastic strip or an anodized surface, is used to insulate successive

turns. A very rigid structure is desirable, both to minimize conductor heating due to movement in the field, and to ease problems of magnet assembly and support.

We have assumed that there are no coolant passages between turns, since they do not aid the steady state cooling of the conductor. That is, if the superconductor goes permanently normal at one point, such coolant passages would not provide steady state cooling. However, such passages might be of use for transient enthalpy stabilization of temporary heating due to magnetization currents. This point is discussed in more detail later.

We define three restrictions that determine the minimum thickness of stabilizer necessary to fully stabilize the conductor, given the conductor current, conductor width, and the electrical and thermal conductivity of the stabilizer:

1. For full transport current in the stabilizer,

$$q_0(I^2R \text{ heating/cm of edge}) \leq q_{\max}$$

2. For full transport current in the stabilizer,

$$\Delta T_0 \text{ (difference in temperature between helium bath and center of conductor)} \leq (\Delta T_0)_{\max}$$

3. As the superconductor recovers and carries one-half the full transport current,

$$\Delta T_1 \text{ (difference in temperature between helium bath and hottest point in superconductor)} \leq (\Delta T_1)_{\max}$$

In most cases, the minimum stabilizer thickness will be set by the restriction on $q_{\max}$. The particular value chosen, 0.3 w/cm, is comparable to that for fully stabilized conductors for bubble chamber magnets. More specifically, we assume that each edge of the fusion stabilizer for the magnet conductor is turned up (Figure 6.2) so that the total height is 0.75 cm and that the edge is corrugated so that the effective/projected cooling area is 1.5/1. This gives a cooling area of $1.1 \text{ cm}^2/\text{cm}$ of edge corresponding to a maximum heat flux of 0.27 w/cm^2 . The corresponding maximum temperature difference between the helium bath and the stabilizer edge will then be $\sim 0.3^\circ\text{K}$. Spacers between pancake coils will reduce the effective cooling area and thus increase the temperature difference somewhat. For purposes of this study, however, the temperature difference is taken as 0.3°K for $q = 0.3 \text{ w/cm}$ of edge, and is assumed to be linearly proportional to q .

The restrictions on ΔT , and ΔT_2 are more than adequate for full recovery of the superconductors considered in this study at the maximum fields and current densities contemplated.

If we let

t = thickness of stabilizer, cm

w = width of conductor, cm

I = transport current/unit width of conductor, A/cm

α = fraction of transport current in stabilizer

K_{sc} = thermal conductivity of superconductor, $\text{w/cm}^\circ\text{K}$

$K_s(B,T)$ = thermal conductivity of stabilizer, $\text{w/cm}^\circ\text{K}$

at field B and temperature T

$\rho_s(B,T)$ = electrical resistivity of stabilizer, $\Omega \text{ cm}$,

at field B and temperature T

then

$$q_o = \frac{I^2 w \rho_s(B,T)}{2t} \quad 6.1$$

where the factor of 2 occurs because there are two edges to the strip. The temperature difference ΔT_o is given by (assuming constant heat transfer coefficient in the helium bath)

$$\Delta T_o = 0.3 \frac{q_o}{(q_o)_{\max}} + \frac{q_o w}{4tK_s(B,T)} \quad 6.2$$

and the temperature difference ΔT , by

$$\Delta T_1 = 0.3 \frac{q_1}{(q_o)_{\max}} + \frac{q_1}{K_s(B,T)} \frac{w}{4t} + \Delta T_{sc} \quad 6.3$$

where, since $\alpha \approx 0.5$

$$q_1 = 0.5 q_o = 2 q_s = 22q_{sc} \quad 6.4$$

First consider a conductor with a thin uniform layer of superconductor (e.g., Nb_3Sn) of thickness ζ on top of the stabilizer (stabilizer assumed on one side only). If we assume that the heating of the superconductor takes place uniformly throughout the layer, then the hottest point in the superconductor will be at the top of the layer, and

$$\Delta T_{SC-S} = \frac{q_{SC}}{w/2} \cdot \frac{\zeta}{2K_{SC}} = 0.25 \frac{q_o \zeta}{wK_{SC}} \quad 6.5$$

Taking maximum values of $q_o = 0.3 \text{ w/cm}$, $\zeta = 10^{-2} \text{ cm}$ and $K_{SC} = 0.5 \times 10^{-3} \text{ w/cm}^{\circ}\text{K}$, $w = 10 \text{ cm}$, ΔT_{SC-S} would be 0.15°K -- not negligible, but small.

If the stabilizer is on both sides of the superconductor, then

$$\Delta T_{SC-S} = 0.125 q_o \frac{\zeta}{wK_{SC}} \quad 6.6$$

where ζ is the half thickness of the superconducting layer.

In all cases considered in this study restriction #3 is more stringent than restriction #2, since restriction #3 is identical with #2 if ΔT_{SC-S} is negligible and $(\Delta T_1)_{\max} = 0.5(\Delta T_o)_{\max}$.

If the superconductor is not a thin layer of Nb_3Sn or V_3Ga , but multifilamentary Nb-Ti in Cu , the temperature drop from superconductor to stabilizer is [Purcell (1)]

$$\Delta T_{SC-S} = \frac{0.25 q_o}{N} \quad 8 \pi K_{SC} \quad 6.7$$

where N is the number of filaments in a half width of the conductor. For the designs considered here ΔT_{SC-S} with filaments is negligible.

A more sophisticated analysis including non-linear heat transfer to the helium bath would be made for a real magnet design; however, the above analysis is sufficient for the purposes of this study.

A full review of stabilization is given by Stekly⁽²⁾ and Stekly, Thome, and Strauss.⁽³⁾

Table 6.1 shows, given these restrictions, what stabilizer thickness is needed as a function of conductor width and current, and the corresponding values of q_0 , ΔT_0 , and ΔT_1 . Two stabilizers are considered; OFHC copper and high purity aluminum (5000 resistance ratio)--nominally 99.999% purity. A further restriction that the stabilizer layer not be thinner than 10 mils is made for mechanical reasons.

The zero field resistivity of aluminum at 4.2°K is taken as $\rho_{293}/5000$, where ρ_{293} is $2.64 \times 10^{-6} \Omega \text{ cm}$ and is taken independent of temperature until T approaches 15°K. The magnetoresistivity of aluminum saturates at low fields (>1 KG) and the $\rho(B)/\rho(B=0)$ is constant for all fields of interest in fusion magnets. The ratio $\rho(B)/\rho(B=0)$ is taken as 3.0 [Arp, (4), Danby et al (5)]. The value of $\rho(B,T)$ used in Table 4.1 is then $1.6 \times 10^{-9} \text{ cm}$, and is independent of B and T. No size effect correction has been made. According to Fickett,⁽⁶⁾ $(\rho l)_\infty = 6 \times 10^{-12} \text{ cm}^2$, and the resistance of 10 mil strip calculated by the Fuchs relation is only increased by ~5% over the bulk value. Thicker strip has an even smaller effect. Thermal conductivity is obtained from the Weiderman-Franz relationship

$$K(B,T) \rho(B,T) = 2.44 \times 10^{-8} \text{ T} \quad 6.8$$

which is valid for pure aluminum in the temperature range of interest [Arp (4)] $K(B,T)$ is then constant for all fields of interest and is 77 watt/cm²K at $T = 5^{\circ}\text{K}$.

The magnetoresistance of copper does not saturate with field. The value of $\rho(B,T)$ for Table 6.1 is taken as $4 \times 10^{-8} \Omega \text{ cm}$, which is characteristic of OFHC copper at 100 KG [Benz (7)] and is independent of temperature in the range of interest. Copper would have a somewhat lower resistivity at lower fields, but this nominal value is sufficient to illustrate its behavior as a stabilizer. The size effect correction is negligible. Thermal conductivity is calculated from the Weideman-Franz relationship to be 3 watts/cm²K. This compares with the measured values of 2.8 to 3.2 watts/cm²K for copper of comparable purity [Prodel (8)].

Strain induced resistivity changes occur with both aluminum and copper, but are more of a problem with the former, since its yield stress and resistance are much lower. Reed^(9,10) discusses this effect for aluminum. The yield stress is ~1500 psi for high purity aluminum. Because of this very low yield stress, the aluminum will plastically deform every time there is an appreciable elastic strain change in the field winding, and the plastic deformation will be almost as great as the elastic strain change. Further, if the elastic strain cycles, due for

example to the turning on and off of the magnetic field in the coil, the total plastic strain will be approximately the sum of the magnitudes of all elastic strain changes. An accumulated strain of 1% will cause an increase of 25% in the resistivity of 5000 ratio aluminum. This strain could be accumulated, for example, by cooling the magnet coil to 4.2°K, and turning the field on and off a couple of times. It is not anticipated that this will be a serious problem for large steady state fusion reactors, because the field will not be cycled. If because of some emergency the coil must be de-energized, for example, to repair the blanket, the accumulated strain in aluminum can be quickly annealed out at low temperature (~100°C) and the coil re-energized.

Below its yield stress, aluminum behaves elastically and does not accumulate strain. For example, cryogenic high purity aluminum synchrotron coils have been pulsed tens of thousands of times to stresses of ~1100 psi with no detectable increase in resistivity [Danby (11)].

For purposes of this study, no allowance is made for strain induced resistivity. Both aluminum and copper are now used commercially as stabilizers for superconductors.

The results in Table 6.1 indicate that quite wide strip, up to 10 inches wide, can be edge cooled if aluminum is used

as a stabilizer. However, if copper is used, the stabilizer thickness is approximately 30 times greater, and the conductor strip width is limited to 2 to 3 inches and current density to 1000 A/cm or less. It is difficult to set an upper limit on stabilizer thickness; 100 mils is certainly practical, while 1000 mils is not. An upper limit of ~200 mils seems reasonable; the problems of conductor fabrication appear to be too great for a greater stabilizer thickness. Also, the stabilizer starts to occupy too large a fraction of the radial thickness of the coil; e.g., 50 turns with 200 mil stabilizer takes 10 inches, or roughly half the total winding thickness.

In all cases with aluminum stabilizer the stabilizer thickness is set by the 0.3 w/cm limit on edge cooling, except for the 2 and 3 inch wide conductor with 1000 A/cm. The thickness in this case is taken as 10 mils for mechanical reasons. In general, the values of ΔT_0 and ΔT_1 are well below the limits of 1 and 0.5°K.

Similarly, in all cases with copper stabilizers, thickness is set by the 0.3 w/cm limit on edge cooling, except for the 2 and 3 inch wide conductor with 1000 A/cm. Here the limits on ΔT_1 will require a somewhat greater stabilizer thickness than shown in Table 6.1.

This analysis shows that the superconductor will recover

even if full transport current flows in the stabilizer. It also shows that a normal region will not propagate along the conductor; in fact, the temperature difference between the hottest point in the stabilizer and the helium bath will be considerably smaller than the values of Table 6.1 at the boundary between the normal and superconducting regions, since some heat will flow away through that portion of the stabilizer under the superconducting region where no I^2R heating is taking place.

Further, this analysis assumed the worst possible case in that the length of the normal region is taken as much greater than the conductor width. If the normal region length is comparable to or shorter than the conductor width, the additional heat conduction along the conductor will greatly reduce the temperature differences calculated here. For the most likely case, a single transverse break in a Nb_3Sn layer, the maximum conductor temperature will be within a few millidegrees of the helium bath.

The effect on stability of magnetization currents caused by the field component perpendicular to the conductor face must be considered. This is primarily a problem for Nb_3Sn and V_3Ga tape conductors since the twisted multifilamentary conductors ($Nb-Ti$, $Pb-Bi$ in glass fiber, Nb_3Sn , and V_3Ga) do not carry

appreciable magnetization currents if the magnet is charged slowly. Smith et al⁽¹²⁾ have pointed out that fully stabilized strip conductors can have large magnetization currents, and that if these currents transfer to the stabilizer, the I^2R heating can be much larger than predicted on the basis of transport current. Hancox⁽¹³⁾ has also considered the magnetization problem of strip conductors.

In order that the conductor be fully stable against heating caused by magnetization currents, two conditions must be met [the first condition is necessary, but not sufficient, for the second to hold] if the magnetization currents transfer to the stabilizer:

- 1) That the heat flux at the conductor edge not exceed the nucleate boiling limit.
- 2) That the magnetization currents not cause enough heating to make the normal region propagate along the conductor.

If the normal region does not propagate, then the magnetization currents will eventually die out, leaving only the transport current, and the superconductor will eventually recover.

Considering the first condition, the nucleate boiling limit in liquid He is ~ 0.8 watts/cm² for unobstructed surfaces.⁽¹⁴⁾ Since the 0.3 w/cm edge cooling limit corresponds to 0.27 w/cm² heat flux, we can assume a maximum I^2R heating of 1.2 w/cm per

edge of conductor during the time that the magnetization currents have transferred to the stabilizer. Under these conditions, and assuming the same current distribution as that taken by Smith,⁽¹²⁾ [where the field just achieves complete penetration of the strip] the critical lineal current density is

$$J_1 \approx 2J_T \quad 6.9$$

where J_T is the lineal transport current density, i.e., (1000, 2000, or 3000 A/cm). With this current, the maximum temperature difference between the hottest point in the stabilizer and the helium bath is then $\sim 4 \Delta T_0$, where ΔT_0 is given in Table 6.1. The temperature difference will be even smaller at the boundary between normal and superconducting regions since there is additional heat conduction along the stabilizer. It thus appears that the normal region will not propagate along the strip as long as $J_1 \leq 2 J_T$.

This does not provide much margin for magnetization currents. It is the most pessimistic case since it assumes that the magnetization currents all transfer to the substrate over a conductor length much longer than its width. However, this worst case design philosophy is probably necessary to assure ultra-reliable operation.

The magnetization currents are of particular concern for toroidal fusion reactors since the field seen by the conductor

varies by almost a factor of three in a single half turn of the toroidal field winding. Since J_T is set as some fraction (e.g., $2/3$) of J_C at the highest field point in the winding, J_T will be a much smaller fraction of J_C at the lowest field point in the winding. In addition, the problem is aggravated by the changing field with multiple turns, though this is alleviated to some extent by the fact that the winding will be compound (i.e., the amount of superconductor will be varied after a certain number of turns) to save on superconductor cost.

There are several approaches to overcome magnetization current heating in strip conductor:

1. More heat transfer area at the conductor edge.
2. Thicken stabilizer (a problem with copper).
3. Narrower conductor (increases structure and winding cost).
4. Coolant passages between turns for transient enthalpy stabilization (increases structure cost, and may increase the possibility of conductor motion).
5. Variation of amount of superconductor along each turn so as to keep J_T close to J_C (should be possible with Linde plasma sprayed Nb_3Sn , and maybe GE Nb_3Sn).

6. Periodic breaks in the continuity of the superconductor layer so that magnetization currents will be suppressed. A break every several meters will be sufficient. This increases refrigerator load, but not excessively.

The problems of heating due to conductor motion are not considered here. The heating due to elastic deformation of the coil as the field is energized will not cause any problems since adequate cooling is provided. Since the elastic displacements are appreciable, i.e., an inch or more, the refrigerator load will not be negligible, but the movement occurs so slowly that the heat is easily removed from the conductor. Rapid local motion due to local yielding may pose some heating problems.

Returning to the question of magnet reliability, the condition of 0.3 watt/cm of conductor edge means that a typical fusion magnet could lose ~10,000 cm of superconductor before doubling the refrigerator load. For example, the ORNL Tokamak reactor⁽¹⁵⁾ has a normal refrigerator load of 6700 watts (cold) at a cost of several million dollars. The 10,000 cm is equivalent to tens of thousands total breaks (or a much greater number of partial breaks) superconductor continuity. This should give an extremely reliable magnet that never needs

replacement. The cost of the extra refrigerator would be trivial compared to magnet replacement costs, particularly in view of the proximity of the radioactive blanket.

In this analysis of conductor design we have assumed that the coil windings are shielded against any rapidly changing field (e.g., the pulsed poloidal field in a tokamak) by a low resistivity cover. Without such shielding, it probably would be necessary to use multifilamentary conductor. Such shielding would not be necessary for diffusion driven tokamaks, mirror machines, and stellarators.

The characteristics of the conceptual conductors are given in detail in the appropriate appendices. A brief summary is given in Table 4.2, however. All were assumed to be 10 cm (4 inches wide). The magnetization current problem should be tractable with this width; much wider conductors might have serious problems. Much narrower conductors would result in substantially higher structure costs. However, the conductor costs per se should not be very sensitive to width either way, and it is felt that the results for the nominal 10 cm width are generally applicable to widths that are within a factor of two of the nominal value.

The choice of operating current for the various conductors was not optimized, but picked on the basis of giving a relatively reasonable number of joints, and is also consistent with the range of conductor currents considered for fusion reactors.

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Table 6.1

Stabilizer Thickness for Edge Cooled Tape Conductor
as a Function of Conductor Current and Width

		Aluminum Stabilizer				Copper Stabilizer			
		<u>t (mils)</u>	<u>q_o (w/cm)</u>	<u>ΔT_o ($^{\circ}$K)</u>	<u>ΔT_l ($^{\circ}$K)</u>	<u>t (mils)</u>	<u>q_o (w/cm)</u>	<u>ΔT_o ($^{\circ}$K)</u>	<u>ΔT_l ($^{\circ}$K)</u>
<u>Conductor width, cm</u>									
1.	W = 5 (2 inches)								
	I/W = 1000 A/cm	10	0.15	0.25	0.42	130	0.3	0.69	0.65
	2000	20	0.3	0.40	0.50	520	"	0.40	0.50
	3000	45	0.3	0.34	0.47	1170	"	0.34	0.47
2.	W = 7.5 (3 inches)								
	I/W = 1000 A/cm	10	0.22	0.43	0.35	215	"	0.69	0.55
	2000	30	0.3	0.40	0.40	780	"	0.40	0.40
	3000	68	"	0.34	0.37	1750	"	0.34	0.37
3.	W = 10 (4 inches)								
	I/W = 1000 A/cm	10	"	0.69	0.50	260	"	0.69	0.50
	2000	40	"	0.40	0.35	1040	"	0.40	0.35
	3000	90	"	0.34	0.32	2340	"	0.34	0.32
4.	W = 15 (6 inches)								
	I/W = 1000 A/cm	15	"	0.69	0.45	390	"	0.69	0.45
	2000	60	"	0.40	0.30	1560	"	0.40	0.30
	3000	125	"	0.34	0.27	3510	"	0.34	0.27
5.	W = 25 (10 inches)								
	I/W = 1000 A/cm	25	"	0.69	0.41	550	"	0.69	0.41
	2000	100	"	0.40	0.26	2600	"	0.40	0.26
	3000	225	"	0.34	0.23	5850	"	0.34	0.23

$$\xi = 10^{-2} \text{ cm (4 mils)}$$

$$K_{sc} = 0.5 \times 10^{-3} \text{ w/cm}^{\circ}\text{K}$$

$$t \geq 10 \text{ mils (lower limit for mechanical reasons)}$$

Table 6.2

Summary of Conceptual Conductors for Large Fusion Magnets

(width = 10 cm)

<u>Type of conductor</u>	<u>Total conductor current (KA)</u>	<u>No. of individual conductors or tapes in parallel</u>	<u>Field Range (KG)</u>	<u>I^2R heating for transport current in stabilizer (watts/cm of edge)</u>
Nb ₃ Sn	10	1	0 - 60	0.3
(GE)	"	2	60- 90	0.3
	"	4	90-120	0.15
	"	6	120-140	0.10
	"	8	140-150	0.075
	"	12	150-160	0.05
Nb ₃ Sn	16	1	0 - 42	0.3
(Linde)	"	2	42- 95	0.3
	"	3	95-125	0.26
	"	4	125-135	0.20
	"	6	135-160	0.13
V ₃ Ga	10	4	100-115	0.075
	"	5	115-140	0.06
	"	6	140-160	0.05
	"	7	160-170	0.045
Pb-Bi	10	1	0 - 35	0.15
	"	2	35- 65	0.075
	"	3	65- 78	0.05
	"	5	78- 87	0.03
Nb-Ti	28	Thickness of Nb-Ti layer, cm	0 - 38	0.3
	"		38- 50	"
	"		50- 62	"
	"		62- 73	"
	"		73- 80	"

Figure 6.1

Comparison of cooling geometries for large fusion magnets
and bubble chambers

Figure 6.2

Cross-sectional view of idealized edge-cooled
conductor for large fusion magnets

Appendix A

Projected Costs of Niobium and Niobium Alloys

Summary of Projected Niobium and Niobium Alloy Prices

The projected prices for Nb and Nb alloys are summarized in Table A-16, and compared to the known lowest prices for the same products. The greatest cost reductions are for the materials for which the increase in production levels are the largest. In each case, the projected price is probably somewhat higher than the true value would be if produced in the levels forecast.

Niobium Ore Reserves and Prices

There seems to be a virtually unlimited supply of niobium ores at a number of locations in the world, and at ore prices that contribute only ~20% to the price of purified Nb ingot. These reserves are principally in the form of pyrochlore, $\text{Na Ca Nb}_2 \text{O}_6 \text{F}$, containing relatively little tantalum (~2000 to 3000 ppm average value). There are 6.35 million tons of contained $\text{Nb}_2 \text{O}_5$ in the Araxa (D.E.M.A.) pyrochlore deposits⁽¹⁾ in Brazil with the ore averaging 3.0 to 5.0% $\text{Nb}_2 \text{O}_5$. The ore is on the surface and can be mined with bulldozers. This is by far the world's largest deposit. There are a number of pyrochlore deposits in Canada totalling ~1 million tons of contained $\text{Nb}_2 \text{O}_5$ at ore concentrations of ~0.2 to 0.6% $\text{Nb}_2 \text{O}_5$. This ore must be hard rock mined. There is at least 1.2 million tons of contained $\text{Nb}_2 \text{O}_5$

in pyrochlore deposits at various locations in Africa with average Nb_2O_5 concentrations of 0.2 to 0.8% in the ore. Since the niobium requirements for superconductors for a fusion reactor economy will be only on the order of 10,000 tons/year of Nb_2O_5 , it is evident that these rich deposits will suffice for hundreds of years of construction of fusion plants. One would run out of space for power plants before running out of niobium. Additional large uses of niobium may develop, such as structural material for fusion blankets or use in superconducting transmission lines, but ample reserves seem to exist for all these purposes.

Based on conversations with Wah Chang,⁽²⁾ it is estimated that Brazilian pyrochlore will cost on the order of 20¢/lb (of contained Nb metal), and that the price of the ore concentrate in the U.S. will cost on the order of 60¢/lb (of contained niobium oxide). If Brazilian ore is not available, Canadian ore will cost about 60¢/lb (of contained Nb oxide) to mine, and about \$1.00/lb for the ore concentrate.

Purification of Ore and Conversion to Niobium Oxide

The best method to open up the pyrochlore ore concentrate (65% to Nb_2O_5) is to dissolve it in HF. If the tantalum concentration in the ore is acceptable, then niobium hydroxide is precipitated and calcined to the oxide. On the basis of

conversations with Wah Chang, the cost of this step is ~\$0.50/lb of niobium oxide. The total cost of the niobium oxide from Brazilian ore in the pure state, ready for reduction to niobium metal, would then be ~\$1.10/lb, and of niobium oxide from Canadian ore, ~\$1.50/lb.

If the tantalum level is unacceptable then separation of tantalum will have to be done, probably through the Bureau of Mines liquid-liquid extraction process. The niobium and tantalum are extracted into MIBK (methyl iso-butyl ketone). The niobium is back extracted into the aqueous phase, leaving tantalum in the organic phase. This process may have to be repeated, depending on what initial concentration of tantalum is present and what final concentration is permissible. Based on conversations with Wah Chang, it is estimated that a tantalum separation and niobium oxide preparation process for pyrochlore ore will cost ~\$1.70/lb of niobium oxide compared to the \$0.50/lb to prepare oxide if tantalum is not separated. This would bring the cost of niobium oxide from Brazilian ore to ~\$2.30/lb of oxide and ~\$2.70/lb for oxide from Canadian ore.

In cost calculations in this appendix we assume that tantalum need not be separated, and that Brazilian ore is available. The cost of Nb_2O_5 before reduction is then \$1.10/lb.

Reduction of Nb₂O₅ to Metal

The principal reduction method now used commercially is the thermite reaction with aluminum powder. The reaction is

and is essentially stoichiometric, requiring ~0.5 lb of Al per lb of niobium metal product. The aluminum and niobium oxide powders are mixed together in a ball mill, poured into a ceramic lined steel pot, and touched off with a heated wire. The reaction is complete in a few seconds and the niobium metal quickly collects in molds at the bottom of the reaction vessel. After the metal and slag have solidified they are removed. A typical yield is 99⁺% of the niobium in the oxide, and a typical product weight is 1000 lbs per shot. The product weight is not inherently limited however, and could be considerably larger than 1000 lbs. The reaction does not occur spontaneously, and while precautions are taken (physical isolation during the mixing phase, and reaction sheds in separate buildings) there have been no accidents with this process at Wah Chang.

The cost of the process is predominantly the cost of the aluminum metal powder, or ~20 cents/lb of niobium metal product. The capital and labor charges are substantially smaller.

An alternate process for oxide reduction is the carbon reaction

under sufficiently good vacuum (few microns Hg). The cost of the low pressure reaction vessel plus the vacuum pumps would outweigh the small savings in aluminum costs.

Another alternate reduction process is to chlorinate niobium oxide and reduce with sodium. Here however the cost of the chlorine and sodium is comparable to the cost of aluminum, and it is a more difficult, expensive reaction to carry out.

There are a number of other reduction reactions, but they are clearly much more expensive.

An alternative to the alumino-thermic reduction of the oxide is really only of interest if the product metal does not have to be electron beam melted for purification. This is not the case with the alternate processes described above, so that the alumino-thermic reduction is clearly preferred. However, there is an additional process, the H_2 reduction of the chloride, that offers a chance of producing Nb metal that does not need EB purification, at least in some applications. There are three stages in this process, as developed by duPont: (3)

1. Chlorination of the pyrochlore concentrate (actually columbite was used in the pilot plant tests, but pyrochlore should perform at least as well) in a fluidized bed reactor.

2. Purification in a packed column of the chlorinated niobium to remove oxychloride.
3. Reduction of the purified NbCl_5 by H_2 in a fluidized bed reactor.

The quality of the pilot plant output (~600 lbs/day) is quite good, comparable to that from EB furnaces. The Brinell hardness is 48, N_2 is 4 ppm, O_2 50 ppm, H_2 45 ppm, Ta 250 ppm, iron 120 ppm, and chloride 400 ppm. A large part of the latter should be removed in a consumable arc melt.

The chemical reactions in the chlorinator are

The reaction is carried out in a fluidized reactor at ~500°C with a mixture of powder and carbon and ore concentrate. The powders separate into two zones in the reactor, carbon at the top and ore at the bottom. Some NbCl_5 returns to react with Nb_2O_5 in the bottom zone producing the oxychloride which then travels into the top zone, where it is almost completely converted to NbCl_5 . A small reactor (~12" I.D.) could produce 2000 lbs/day of NbCl_5 at 98% yield, containing as impurities 0.5% NbOCl_3 and 0.75% FeCl_3 (from ore).

The second stage, separation of the oxychloride by distillation, is relatively easy. In the pilot plant, two 12" diameter

columns were used, a 40 foot column for Ta separation and a 25 foot column for NbOCl_3 separation. An output of ~300 lbs metal/day was achieved, but this was limited by the difficult Ta separation. With low initial Ta concentration in pyrochlore, and no Ta separation, only one column would be needed, and the output should be considerably greater.

The third stage, reduction of NbCl_5 , was carried out in a 12" diameter fluidized bed, ~2 feet deep. This unit produced ~500 lbs/day of niobium.

The process seems ideal for large volume production of niobium. At what point it becomes cheaper than the aluminothermic reduction - EB purified process is not clear. However, a production rate of 10^7 lbs/year requires 8 EB furnaces costing \$2 million each and drawing ~10 MW of total power. This rate of production could probably be achieved in two or three H_2 reduction units of several feet in diameter. Similarly, the necessary chlorinator and oxygen purifier seem of quite reasonable size. It appears then that for production levels substantially in excess of 10^7 lbs/year H_2 reduction will be preferred. For example, at 5×10^7 lbs/year 40 EB furnaces would be necessary, as compared to ~10 H_2 reduction units. For very large scale production of Nb ($>10^8$ lbs/year) by H_2 reduction the price will probably be on the order of \$2.50/lb. It is not expected that there will be much reduction in the cost of the aluminothermic EB purified product above 10^7 lb/year.

Electron Beam Melt

The ingots from the thermite reduction process are welded together and purified by melting in an electron beam furnace. The impure ingot is fed from the top of the furnace into a zone where several intense electron beams (energy = 20 Kev) melt the end of the ingot. (The molten pool below the feed ingot is the point on which the electron beams converge.) The impurities in the niobium volatilize in the very high vacuum ($\sim 1 \mu$ Hg) and are removed by vacuum pumps. The molten pool of niobium is contained in a water cooled mold, and the purified ingot is withdrawn from the bottom at the same rate as the impure ingot feeds in at the top.

In order to meet the very stringent purity requirements (tens of ppm for O_2 and N_2) the ingot must be refined at least three, and occasionally four or five times. Generally the first two melts are extremely gassy while the third is much quieter.

The ingot feed rate must be slow to allow the impurities to volatilize out, on the order of 6 inches per hour. This restriction on throughput makes the EB melt the most expensive and time consuming part of the niobium production process.

The present EB furnaces at Wah Chang produce a purified ingot 12 inches in diameter and 20 feet long. At an ingot withdrawal rate of 6 inches/hour, this corresponds to a metal throughput rate of 62 tons/month (3 shift basis, 7 days a week). However,

since triple melts are necessary, the pure metal output is reduced to 21 tons/month; further, since ingots must be loaded and unloaded, electron guns changed, and furnaces serviced and maintained, the pure metal output is reduced by approximately a factor of two, giving 11-12 tons/month output.

Production can be speeded up by going to larger diameter ingots. Based on conversations with Wah Chang, an ingot size of 20 inches seems quite feasible and the pure metal output per furnace would increase to ~50 tons/month.

Some improvements in process technology can be foreseen. One of the principal problems in EB furnaces is degradation of electron guns and their need for replacement. This degradation is primarily due to shorting by the volatilized impurities. A partial solution to this problem has been to locate the electron guns behind shields and to magnetically guide the electron beams into the molten zone. However, the guns still need frequent replacement, particularly for the first two melts in which most of the impurities vaporize. One solution that seems very attractive is to use a low pressure plasma melt for the first two melts and an electron beam for the third. It is estimated that the output of a furnace could be approximately doubled if this were done. Wah Chang estimates that an EB furnace producing 12" diameter ingots costs \$750,000 and a furnace producing 20"

diameter ingots would cost \$2,000,000. A crew of three is sufficient to operate each of their present furnaces, including replacement of electron guns, loading and unloading, etc.

A rough estimate of purity is made between melts by measuring the ingot hardness, with a full analysis of all impurities after the final EB melt.

Preparation of Niobium-1% Zirconium Alloy

Nb-1% Zr alloy is used as a starting material for the GE superconducting tape. Much greater quantities have been produced for use in high temperature liquid metal systems. The present method of making the alloy is to add zirconium to an EB purified niobium ingot in a consumable electrode arc melting furnace. Here the feed ingot is introduced from the top and an arc is struck between it and the product ingot in a water-cooled mold. The end of the feed ingot melts due to the arc, and drips into the product ingot mold. The product ingot is withdrawn at the same rate as the feed ingot is introduced. Zirconium is added to the arc zone from the side, at the predetermined rate to give the correct composition. Since the feed ingot is pure, relatively little gas is evolved (in fact the arc pressure is relatively high, on the order of 100 μ Hg) and throughput rates are quite high. When operating a single arc melt furnace one can produce 2500 lbs/hour of 20 inch diameter ingot. The down time

is less than with an EB furnace.

To ensure homogeneity in the alloy, a double arc melt is usually used. The final product throughput on an arc melt furnace will then be on the order of 750 lbs/hour (double melt operation, round the clock operation, melting 60% of the time). Depending on throughput, it may be advantageous to use a smaller ingot diameter furnace.

If the Nb-1% Zr alloy is to be used as a starting material for GE superconductor, the Nb-1% Zr product ingot is then sent to a fabrication plant to be rolled into thin foil (nominal thickness of one mil). This part of the process is discussed later.

Hydride-Dehydride to Produce Nb Metal Powder

The niobium ingot from the EB furnace is rolled to a slab, then hydrided to an H/Nb ratio approaching 2, crushed to a powder (the dihydride is very brittle), and dehydrided to produce a Nb metal powder.

Massive pure niobium generally required a conditioning period before it will take up hydrogen. At BNL, this conditioning is done by heating the niobium metal to $\sim 400^{\circ}\text{C}$ for ~ 8 hours in H_2 ; after this period it will rapidly absorb H_2 . The integral heat of reaction is large, ~ 25 K cal/y mole of H_2 to NbH_2 , and the metal must be cooled to remove the heat. The monohydride

can be formed at elevated temperatures, but the dihydride must be formed close to room temperature. After crushing, the dihydride is heated under vacuum and the H_2 removed. As hydrogen evolves, the heat must be supplied to the powder. Both the hydride and dihydride have plateaus over which the hydrogen concentration can change greatly without altering the vapor pressure or temperature. Most of the hydrogen would thus be evolved under these conditions; however to fully dehydride the Nb the final end temperature must be $\sim 450^\circ C$ and the final end pressure a few microns.

Wah Chang estimates that this step could be carried out for \$0.50/lb of Nb metal in large quantities. It is felt that this is probably somewhat of an over estimate, but is the value adopted for this study.

Preparation of Nb-Ti Alloy and Fabrication into Rod

Nb-Ti is a difficult alloy to prepare because of the large differences in metallurgical properties between Nb and Ti, particularly with regard to uniformity of composition and freedom from defects. A method that gives very good results is that diagrammed in Figure 1; niobium and titanium powders are blended and compacted, and resulting sintered discs welded in a stack to form a consumable electrode. A double arc melt is used to assure homogeneity and good alloying. The resulting product ingot is then extruded to Nb-Ti rod. The ingot is analyzed at a number

of points for composition, and rods are generally sonically tested for defects.

The technology of the consumable arc furnace is the same as that described for the production of Nb-1% Zr alloy.

Wah Chang estimates that Nb-Ti alloy should cost less than \$10/lb if several million lbs/year is produced.

Rolling of Nb-1% Zr to Thin Foil

This is at present an expensive process step, with the final 1 mil thick foil costing on the order of \$100/lb. The two principal reasons for this high price are the very small amounts rolled, which makes setup costs high, and the demanding specs on gauge, edge quality, both of rolled and slit strip, and flatness, which result in a high reject rate. Since the Nb₃Sn superconductor in fusion magnets will be fully stabilized, a considerable easing of these specs can be expected. Also, the desired width of the Nb₃Sn strip for fusion magnets is several inches, instead of the 1/4 or 1/2 inch width now manufactured, so edge quality of the slit strip is less important. At present, defects in slit edges have been responsible for substantial rejection. Finally, it should be much easier to meet specs with a large volume plant which produces the same product ad infinitum since one does not have to retrace the learning curve for every batch of thin foil produced.

There is great reluctance on the part of manufacturers to discuss process details for rolling thin Nb-1% Zr foil. In large part this reflects commercial caution, but also because the processing parameters are ill defined. For example, everyone agrees that the bottleneck in the rolling step is the throughput capability of the Z (Zensimir) mill. However, there is wide disagreement as to the actual capability. In talking to four people experienced in rolling thin niobium foil, estimates of output of 10 lbs/hour, 40 lbs/hour, 100 lbs/hour, and $>>100$ lbs/hour of 1 mil foil were obtained for a Z mill starting with 30 mil foil and finishing with 1 mil foil. This is the average output of finished product, including setup time, maintenance time, etc., on a 12" wide mill. The ill-defined nature of the rolling process thus forces us in this study to be very conservative in design and costing. The ultimate true costs will probably be considerably cheaper than the costs estimated here.

The flowsheet for the rolling of thin foil is shown in Figure 2. The niobium ingot is first forged at $\sim 900^{\circ}\text{F}$ to a 2 inch slab. This elevated temperature aids the breakdown of the ingot, but does not cause any significant oxidation. The ingot could also be extruded or cold rolled, but the forging seems somewhat better. The slab is then annealed at $\sim 1100^{\circ}\text{C}$ for $\sim 1/2$ hour in vacuum, then cold rolled (all subsequent rolling is at room temperature) to ~ 100 mil strip without tension. The strip

may or may not be annealed at this point. It is then cold rolled under tension to ~30 mils, and annealed. The 30 mil strip is then rolled in a Z mill to 1 mil, probably with one intermediate anneal. As the strip becomes thinner, annealing becomes more difficult. There is general agreement that a final anneal at 1 mil is very difficult if not impossible because of the tendency of the foil to stick together. There is also general agreement that there is not too much of a sticking problem at 5 mils. The limiting thickness cannot be better defined than this, however.

It is generally agreed that the throughput capability of the forging mill and the first rolling mill (2" slab to 100 mil strip) should be greater than 400 lbs/hour.

Estimates of the average reduction pass in the first tension rolling mill (100 to 30 mil) and the Z-mill range from 10 to 20%, while exit strip speeds range from 15 feet/minute to 200 feet/minute. The curve of exit strip speed versus gauge should be fairly flat, with a small drop-off in exit speed only when the thickness approaches 1 mil.

Large Scale Plant for EB Purified Nb Ingot

The plant size is scaled at 5000 T/year (10^7 lbs/year) of niobium ingot. This is substantially larger than the requirements for either Nb-Ti rod (1250 T/year of Nb), Nb powder (3500 T/year), or Nb-1% Zr foil (1500 T/year of Nb). This partly reflects the multiple use of superconductors in fusion magnets (i.e., Nb-Ti

for the low field windings), but also reflects the assumption that there will be other large scale uses of niobium metal - e.g., for high temperature constructional material, both for fusion magnets and other high temperature uses. Since the principal cost is the EB purification, and the 5000 T/year plant uses 8 EB furnaces, the production cost in \$/lb will not be a very sensitive function of production level.

The process parameters are given in Table 1. The reduction pot charge is assumed to be 3000 lbs. The current value is ~1000 lbs; the larger value is easily achievable within the present state of the art. The Al/Nb ratio is assumed to be stoichiometric, although there probably would be a very slight excess of Al. The loading time for the pot will be short, at most 10-15 minutes, and the reaction and separation time will be even shorter, on the order of a minute. The principal delay comes in letting the reaction vessel cool, and the chipping out of slag to get the pot ready for the next shot. The pot is assumed to be capable of one reduction per day. Approximately 9 pots would then be required for 5000 T/year production. However, pots need to be relined after a number of charges, so a pot inventory of 20 is assumed. At 10 charges per lining, this would allow 10 days for relining pots. The pots are simply steel shells with the refractory lining. Since the composition and cost of the lining is proprietary, no allowance for replacement

linings has been included. However, this cost is said to be very small, on the order of a few pennies/lb of Nb.

The capital equipment, labor and building estimates are personal ones, based on seeing the present operation at Wah Chang. The estimated reduction cost of \$0.20/lb exclusive of aluminum and Nb_2O_5 costs (Table A-5) but including overhead, seems consistent with the present operation at Wah Chang.

The aluminum powder cost was assumed to be \$.40/lb of Al, which is probably somewhat high, and the purified oxide cost as \$1.10/lb Nb_2O_5 , as discussed earlier. This does not allow for Ta removal.

The purification cost is the predominant factor in Nb cost, amounting to ~\$2.00/lb of metal, including proportional overhead and power (Table A-5). This is to be expected, because of the cost and low throughput rates for EB furnaces. The cost of \$2,000,000 for a 50 T/month EB furnace is an estimate supplied by Wah Chang. The labor and building requirements are personal estimates, based on seeing the present operation at Wah Chang. These values are probably not significantly overestimated.

The estimated total cost of EB purified ingot is \$4.04/lb (Table A-5). This compares quite closely with the ~\$4.00/lb value based on conversations with Wah Chang, for a production level of 10^7 lbs/year. This production level is approximately an order of magnitude greater than present levels, and the

projected price is ~40% of the present ingot price. Because of the relatively small extrapolation, the projected price should be close to the true value. It most likely is slightly high because of the conservative write-off costs. In accord with present production practice, there is virtually no niobium scrap, and all reject metal is recycled through the EB furnaces. This tends to increase cost slightly, but only by a few percent.

The cost of preparing Nb powder is taken as \$0.50/lb, based on conversations with Wah Chang. This is probably somewhat high since the yearly plant cost for 10^7 lbs/year at this value is 5 million dollars. The principal cost would be for the hydriding-dehydriding reaction vessels, and these should cost considerably less than 5 million dollars/year. However, for this study, the cost of Nb metal powder is taken as \$4.50/lb.

The cost factors used in this study are summarized in Table A-15, and the results are summarized in Table A-16.

Large Scale Plant for Nb-1% Zr Ingot

Tables A-6 and A-7 summarize process parameters and costs for producing Nb-1% Zr ingot. The only process step is a double arc melt, with the Zr added at the side in the first melt. The 12 inch ingot diameter is chosen on the basis of rolling 14" wide foil; if wider strip is rolled, the product ingot diameter might be greater.

The arc furnace cost assumed in this study is slightly greater than estimates made by persons involved in the production of refractory metal. The arc furnace operates at less than 50% of its maximum capacity. In an integrated plant with other refractory products, the melting cost for Nb-1% Zr ingot could be reduced by using the arc furnace for other melting.

The miscellaneous equipment includes equipment to cut the Nb-1% Zr ingot into finished billets ready for forging into slabs.

The labor and building requirements are personal estimates, based on seeing similar operations at Wah Chang.

The cost of preparing the alloy is estimated at \$1.30/lb. With an Nb ingot price of \$4.04/lb, the total cost for Nb + 1% Zr ingot is estimated at \$5.34. This is probably slightly high, since equipment cost can be shared with other products in a multi-product plant.

Reject metal is recycled back to the arc metal furnace, or even to the EB furnace. The cost increase caused by such recycling is neglected because of the conservative nature of the cost analysis.

Large Scale Plant for Nb-Ti Rod

Tables A-8 and A-9 summarize process parameters and costs for producing Nb-Ti (48% Ti) rod. The three basic process steps

are: (1) mixing of Nb and Ti powders, compacting to round discs and welding to a raw ingot, (2) consumable arc melting (2 melts to final ingot), and (3) extrusion of the finished ingot to Nb-Ti rod. Quality control is particularly important for Nb-Ti rod, since the alloy is difficult to prepare. The homogeneity of the alloy must be checked, and the extruded Nb-Ti rods checked sonically to ensure that no voids or inclusions are present.

The estimate of capital cost for the consumable arc melting furnace is based on conversations with persons involved in the production of refractory metals, and is slightly greater than estimates given by these sources. The capital cost estimate of the extrusion press is based on conversations with representatives of manufacturers of extrusion presses.

The arc melting furnace operates at about 50% of maximum capacity, while the extrusion press operates at only ~5% of capacity. It is clear that substantial cost reductions can be effected by sharing both the arc melting furnace and extrusion press for production of other refractory metal products.

From the standpoint of capacity, there does not seem to be any incentive to go to larger ingot diameters than 12 inches.

The labor and building requirements for the various process steps are personal estimates, based on seeing similar processes at Wah Chang.

The choice of 3 inch diameter for the extruded Nb-Ti rod is not optimized; however, if the diameter is too much greater, rolling the rod to smaller diameters becomes difficult; if too much smaller, extrusion becomes difficult.

Nb-Ti scrap is assumed to be recycled without any significant cost increase.

The cost summary (Table A-9) shows the various contributions to the total cost of Nb-Ti rod, estimated at \$6.25/lb. The cost of Ti powder is taken as \$4.00/lb which is conservative. For this reason, and the underutilization of arc melting and extrusion equipment, the estimated cost of Nb-Ti rod seems high. In conversations with Wah Chang, a price of less than \$10/lb for Nb-Ti rod was forecast. The agreement between the forecast and the \$6.35/lb value estimated in this study is not as close as that for the price of EB purified ingot. Since the projected production level of Nb-Ti is two orders of magnitude greater than present production levels, it is not surprising that the values do not agree closely. The value estimated in this study does appear conservative, however, and is the one used for estimating Nb-Ti superconductor costs.

Large Scale Plant for Rolling Nb-1% Zr Foil

The flow sheet for the plant is shown in Figure 2, and the process parameters, etc. summarized in Tables A-10 through A-13.

The cost summary for the process is given in Table A-14.

Four steps are assumed in the process: forging to a 2" slab, followed by rolling to 100 mil strip, followed by tension rolling to 30 mil strip, followed by Z-mil rolling to 1 mil. The choice of steps represents an average consensus--probably no present producer would do it precisely this way.

The throughput is small enough ($\sim 3 \times 10^6$ lbs/year) that the first 3 steps (forging, slab rolling, and rough tension rolling) should require only one mill for each step. Quite possibly the slab and rough tension rolling mill could be the same unit. The price for each rolling mill is taken as \$1 million dollars. The Schloeman mill originally bought by duPont for rolling Ta and other refractory metals cost \$4 million and it is a much bigger (up to 36" wide) more versatile mill than any contemplated here. Based on conversations with a rolling mill manufacturer, the slab and rough tension rolling mills should cost on the order of \$200,000 to \$300,000 each. This has been increased to \$1 million to be conservative. The operating personnel is probably estimated slightly high--it should be possible to operate with 3 men instead of 4. The building area is also conservatively estimated.

The cost of the 14" wide Z-mill (\$1.0 million each) is taken slightly greater than the usual estimate of $\sim$ \$750,000 each. The throughput, of course, is not very well determined. For this

study, the throughput is taken as ~20 lbs/hour, which seems quite conservative by most estimates. The operating personnel/unit Z mill is probably correct, but the building area is probably somewhat overestimated.

Because of the edge control problems, the 1 mil strip is rolled to 14" width and then slit back to 12" width. Some of this material would probably be useful as feed material for other superconductor uses, but no credit has been taken for this. Instead, the scrap would be recycled to the consumable arc melter to be recast into Nb-1% Zr ingot; no charge is assigned for this step.

It is of interest that the cost of rolling 30 mil strip to 1 mil is ~\$9.00/lb (Table A-14) when the pro-rated overhead is included. This compares with \$4-5/lb estimated by a firm with considerable experience in rolling thin foils.

The costs of the vacuum annealing furnaces are based on conversations with a manufacturer, and were increased somewhat from their estimates. The annealing costs are thus probably somewhat overestimated by 10-20%. This tends to be confirmed by conversations with a producer of niobium.

The average power load for the plant is estimated as 15 MW and includes power for the mills, furnaces, lights, etc.

The estimated process cost from Nb-1% Zr ingot to 1 mil foil is thus \$13.58/lb. This includes the process cost due to reject material (overall yield 77% from ingot to 1 mil foil). The cost of the ingot supply is \$5.34/lb, and does not include cost due to reject, since the scrap Nb + 1% Zr is recycled to the arc melter. This is a very small additional cost to the final foil cost, on the order of \$0.20/lb. The total cost for the finished foil is then \$18.92/lb. This is probably somewhat high, and a more realistic cost would probably be in the neighborhood of \$15/lb. However, as we shall see, the higher price does not cause any serious penalty to the Nb₃Sn superconductor.

References

1. Barton, W. R., "Columbium and Tantalum, a Materials Survey," U. S. Bureau of Mines, IC 8210 (1962).
2. S. Yih, personal communication (1971).
3. Jacobson, H. W., et al., "Development, Design, and Operation of a Plant Scale Columbium Process," duPont Report.

TABLE A-1

Process Parameters for Large Scale Production of Nb Ingot
(5000 T/year)

Reduction

Al/Nb ratio	stoichiometric
Pounds of Nb metal reduced/charge	3000
Reductions/pot per day	1
Number of reaction sheds	2
Number of reductions/year	3300
Number of reductions/day	9.1

Purification

Number of melts in EB furnace	3
Production/ furnace (3 melts)	100,000 lbs/month
Ingot diameter	20 inches
Ingot processing speed	6 inches/hour

TABLE A-2

Capital Equipment Costs for Large Scale
Production of Nb Ingot
(5000 T/year)

Process Step	Unit Cost (\$ Millions)	Plant Cost * (\$ Millions)
1. <u>Reduction</u>		
Reduction pots (20)	0.03	0.6
Mixers (4)	0.10	0.4
2. <u>Purification</u>		
EB furnaces	2.0	16.0
Misc. equipment (EB welders, quality control, etc.)	-	4.0
	Total	21.0

* Does not include engineering and testing (25% additional)

TABLE A-3

Building Requirements for Large Scale
Production of Nb Ingot
(5000 T/year)

<u>Process Area</u>	<u>Plant Requirements (ft²)</u>
1. Reduction sheds (2)	0.4×10^5 *
2. EB furnaces (8)	1.2×10^5
3. Miscellaneous area (EB welding, quality control, offices, etc.)	0.5×10^5
	<hr/>
Total area	2.1×10^5

* Cost \$50/ft²

TABLE A-4

Labor Requirements for Large Scale
Production of Nb Ingot
(5000 T/year)

<u>Process Step</u>	<u>Labor Unit Requirements</u>	<u>Plant Requirements</u>
1. Reduction (mixer operators, remove product ingot and slag, etc.)	5/shift/shed	40
2. Purification		
EB operators (includes preparing ingots)	4/shift/furnace	128
Quality control		<u>20</u>
	Sub-total	188
3. Overhead (administra- tive, clerical, shipping & receiving)		75
	Total	<u>263</u>

Table A-5
Cost Summary for Large Scale Production of Nb Ingot
(5000 T/Year)

<u>Process Step</u>	<u>Plant Cost</u> <u>(\$millions/yr)</u>	<u>Product Cost</u> <u>(\$/lb metal)</u>
1. Materials		
aluminum powder	2.0	0.20
Nb ₂ O ₅	15.7	1.57
power	<u>1.8</u>	<u>0.18</u>
Subtotal	19.5	1.95
2. Reduction		
labor	1.0	0.10
capital equipment*	0.4	0.04
buildings	<u>0.5</u>	<u>0.05</u>
Subtotal	1.9	0.19
3. Purification		
labor	3.7	0.37
capital equipment*	8.4	0.84
buildings	<u>3.0</u>	<u>0.30</u>
Subtotal	15.1	1.51
4. Overhead		
labor	1.9	0.19
buildings	<u>2.0</u>	<u>0.20</u>
Subtotal	3.9	0.39
Overall Totals	<u>40.0</u>	<u>4.04</u>
Cost of Nb Ingot/lb		4.04
Cost of Nb powder/lb		4.50

*Includes engineering, testing, and maintenance.

Table A-6

Process Parameters Requirements for Large Scale Production of
Nb-1% Zr Ingot
(1500 T/year)

1. Consumable Arc Melting	
Number of melts/ingot	2
Ingot diameter	12 inches
Melting rate	2000 lb/hour
Labor (4 shifts)	20
Arc furnace equipment cost (1)	\$0.4 million*
Miscellaneous equipment cost	\$0.6 million*
Building	$2 \times 10^4 \text{ ft}^2$
2. Quality Control	
Labor	20
Equipment	\$1.0 million*
Building	$2 \times 10^4 \text{ ft}^2$
3. Overhead (Administrative, Maintenance, and Clerical)	
Labor	15
Building	$2 \times 10^4 \text{ ft}^2$

* Does not include engineering and testing (25% additional)

Table A-7

Cost Summary for Large Scale Production of
Nb + 1% Zr Ingot
(1500 T/year)

	<u>Plant Cost</u> <u>(\$ million/yr)</u>	<u>Product Cost</u> <u>(\$/lb of Nb+1% Zr)</u>
1. Materials		
Nb	12.12	4.04
Zirconium	negligible	negligible
Power (3 MW)	<u>0.26</u>	<u>0.08</u>
Subtotal	12.38	4.12
2. Consumable arc melting		
labor	0.50	0.16
capital equipment*	0.41	0.14
building	<u>0.50</u>	<u>0.16</u>
Subtotal	1.41	0.46
3. Quality control		
labor	0.50	0.16
capital equipment*	0.41	0.14
building	<u>0.50</u>	<u>0.16</u>
Subtotal	1.41	0.46
4. Overhead		
labor	0.40	0.14
building	<u>0.50</u>	<u>0.16</u>
Subtotal	<u>0.90</u>	<u>0.30</u>
Overall Totals	\$ 16.10	\$ 5.34

*Includes engineering, testing, and maintenance.

Table A-8

Process Parameters and Requirements for Large Scale Production of
Nb-Ti Rod
(2500 T/Year)

1. Powder compacting and ingot preparation		
labor (4 shifts)		40
equipment	\$2.0 million	
building	2×10^4 ft ²	
2. Consumable arc melting		
number of melts/ingot		2
ingot diameter	12 inches	
melting rate	2000 lb/hr	
labor (4 shifts)		20
arc furnace equipment cost (1)	\$0.4 million*	
miscellaneous equipment	\$0.6 million*	
building	2×10^4 ft ²	
3. Extrusion to Nb-Ti Rod		
billet diameter	12 inches	
billet length	24 inches	
billet weight	600 lbs	
number of billets/hr average		
on 1 shift basis		4
diameter of extruded rod	3 inches	
length of extruded rod after cutting	7.5 ft	
labor (1 shift)		5
cost of extrusion press	\$1.0 million*	
miscellaneous equipment cost	\$0.5 million*	
building	2×10^4 ft ²	
4. Quality control		
number of rods tested/hour (4 shift basis)		4
labor (4 shifts)		60
equipment	\$2.0 million	
building	2×10^4 ft ²	
5. Overhead (administrative, maintenance, clerical, shipping, and receiving)		
labor		48
building	3×10^4 ft ²	

* Does not include engineering and testing (25% additional)

Table A-9

Cost Summary for Large Scale Production
of Nb-Ti Rod (2500 T/year)

<u>Process Step</u>	<u>Plant Cost (\$ millions/year)</u>	<u>Cost (\$/lb of Nb-Ti)</u>
1. Material		
Nb & Ti	\$ 21.0	\$ 4.25
Power (5 MW)	<u>0.5</u>	<u>0.10</u>
sub-total	\$ 21.5	\$ 4.35
2. Powder compacting and ingot preparations		
Labor	1.0	0.20
Capital Equipment*	0.82	0.17
Building	<u>0.5</u>	<u>0.10</u>
sub-total	2.32	0.47
3. Consumable Arc Melting		
Labor	0.5	0.10
Capital Equipment*	0.4	0.08
Building	<u>0.50</u>	<u>0.10</u>
sub-total	1.40	0.27
4. Extrusion		
Labor	0.12	0.02
Capital Equipment*	0.6	0.12
Building	<u>0.5</u>	<u>0.10</u>
sub-total	1.22	0.24
5. Quality Control		
Labor	1.5	0.30
Capital Equipment*	0.82	0.17
Building	<u>0.5</u>	<u>0.10</u>
sub-total	2.82	0.57

Table A-9 (cont'd)

<u>Process Step</u>	<u>Plant Cost</u> <u>(\$ millions/year)</u>	<u>Cost</u> <u>\$/lb of Nb-Ti)</u>
6. Overhead		
Labor	1.2	0.24
Building	<u>0.75</u>	<u>0.15</u>
sub-total	1.95	0.39
Totals	33.3	6.25

* Includes engineering, testing, and maintenance

Table A-10

Process Parameters for Large Scale Production
of Nb + 1% Zr Foil (nominal 1 mil thickness)

5×10^6 /year

Process Parameters	Ingot forging	Process Step		
		Roll slab to 100 mil strip	Roll on rough tension mill	Roll on Z- mill
Input	750 lb ingot	2 in. slab	100 mil strip	30 mil strip
Output	2 in. slab	100 mil strip 14 in. wide 140 ft long	30 mil strip 14 in. wide 465 ft long	1 mil strip 14 in. wide 14,000 ft long
Plant throughput/hour	0.45 units	0.45 units	0.45 units	0.45 units
% reduction/pass	-	-	11%	10%
No. passes	-	-	10	32
Strip speed leaving mill	-	-	70ft/min	70ft/min
Rolled length/output length	-	-	6.6	9.1
Rolling time	-	-		
Actual	-	-	0.7 hours	30 hours
(reversing strip, changing coils and rolls, maintenance, etc.)	-	-	1.5 hours	8 hours
Total	<2 hours	<2 hours	2.2 hours	38 hours
Anneal	after forging	possible - not certain	after 30 mil strip is rolled	intermediate anneal
Yields:	90% from ingot to acceptable 14 in. wide strip, 1 mil thick			
	77% from ingot to acceptable 12 in. wide strip, 1 mil thick			
Output weight of foil/year - 2.26×10^6 lb				
Input weight of ingot/year - 2.94×10^6 lb				

Table A-11

Capital Equipment Costs for Large Scale Production of
Nb + 1% Zr Foil (nominal thickness of 1 mil) $5 \times 10^6 \text{ m}^2/\text{year}$

<u>Process Equipment</u>	<u>Capital Cost (\$) *</u>
1. Ingot forging mill	2×10^6
2. Rough mill for slab	1×10^6
3. Tension mill for 100 mil strip	1×10^6
4. Z mills (18)	18×10^6
5. Annealing furnaces (2)	1.0×10^6
6. Quality control equip- ment, test equipment, etc.	2×10^6
Total	25×10^6

NOTE: Mills include power supplies, etc.

* Does not include engineering and testing (25% additional)

Table A-12

Building Requirements for Large Scale Production of
Nb + 1% Zr Foil (nominal thickness of 1 mil) - 5×10^6 m²/year

<u>Process area</u>	<u>Building area (ft²)</u>
1. Ingot forging mill (1)	2×10^4
2. Rough rolling of slab (1)	2×10^4
3. Tension rolling of 100 mil strip (1)	2×10^4
4. Z mills (18)	2×10^5
5. Annealing furnaces (2)	1×10^4
6. Miscellaneous (quality control test, offices, shipping and receiving, etc.)	6×10^4
Total	3.3×10^5

Table A-13

Labor Requirements for Large Scale Production of
Nb + 1% Zr Foil (nominal thickness of 1 mil) - 5×10^6 m²/year

<u>Process step</u>	<u>Labor requirements per operating unit</u>	<u>Total require- ments for plant (4 shifts)</u>
1. Ingot forging - operators and helpers	4/shift	16
2. Rough rolling of slab - operators and helpers	4/shift	16
3. Tension rolling of 100 mil strip - operators and helpers	4/shift	16
4. Z-mill rolling - operators and helpers	3/shift	216*
5. Annealing furnaces	4/shift	32
6. Quality control	--	<u>20</u>
* 18 operating mills		316
7. Overhead (administrative, clerical, shipping and receiving, etc.)	--	<u>126</u>
		442

Table A-14

Cost Summary for Large Scale Production of
Nb + 1% Zr Foil (nominal 1 mil thickness) - $5 \times 10^6 \text{ m}^2/\text{year}$

<u>Process Step</u>	<u>Cost/year for Plant (millions of \$)</u>	<u>Cost, \$/lb of finished foil</u>
1. Ingot forging		
Labor	0.4	0.18
Capital Equipment*	0.8	0.35
Buildings	<u>0.5</u>	<u>0.22</u>
sub-total	1.7	0.75
2. Slab rolling		
Labor	0.4	0.18
Capital Equipment*	0.4	0.18
Buildings	<u>0.5</u>	<u>0.22</u>
sub-total	1.3	0.58
3. Rough tension rolling		
Labor	0.4	0.18
Capital Equipment*	0.4	0.18
Buildings	<u>0.5</u>	<u>0.22</u>
sub-total	1.3	0.58
4. Z-mill rolling		
Labor	5.4	2.39
Capital Equipment*	7.4	3.28
Buildings	<u>5.0</u>	<u>2.21</u>
sub-total	17.8	7.88
5. Annealing		
Labor	0.80	0.36
Capital Equipment*	0.40	0.18
Buildings	<u>0.25</u>	<u>0.11</u>
sub-total	1.45	0.65
6. Power	1.3	0.58

Table A-14 (cont'd)

<u>Process Step</u>	<u>Cost/year for Plant (millions of \$)</u>	<u>Cost, \$/lb of finished foil</u>
7. Overhead and quality control		
Labor	3.5	1.55
Capital Equipment*	0.8	0.35
Buildings	<u>1.5</u>	<u>0.66</u>
sub-total	5.8	2.56
Total	30.6	13.58 \$/lb
	Cost of Nb + 1% Zr ingot	
		<u>5.34 \$/lb</u>
	Total cost of foil	18.92 \$/lb

* Includes engineering, testing, and maintenance.

Table A-15

Cost Factors Used in Appendix A

Cost of aluminum powder	\$ 0.40/lb
Power cost	\$ 0.01/KWH
Labor cost	\$25,000/person/year
Building cost (except reduction sheds)	\$ 100/ft ²
Building cost (reduction sheds)	\$ 50/ft ²
Titanium powder	\$ 4.00/lb

Table A-16

Summary of Projected and Present
Prices for Nb and Nb alloys

<u>Product</u>	<u>Projected Cost</u> <u>(\$/lb)</u>	<u>Present Cost</u> <u>(\$/lb)</u>
EB purified Nb ingot	4.04	9.50
Nb powder	4.50	15.00
Nb-Ti rod	6.25	30.00
Nb-1% Zr foil (1 mil)	18.92	100.00

FIGURE A-1

Process flow sheet for large-scale production of
Nb and Nb alloys
(5,000 t/yr)

FIGURE A-2

Production cycle for 1 mil Nb + 1% Zr

Appendix B

Projected Costs of High Purity Aluminum

Introduction

At present, the primary market for high purity aluminum is the manufacture of electronic components. The principal producer, COMINCO, sells ~5000 lbs/year to this market. The purity of the aluminum is approximately equivalent to 4°K resistivity ratio of ~5000. Some aluminum is sold for use as a cryogenic conductor, both as a current carrier and as a stabilizer for superconductors, but the amount is tiny, only a small fraction of the electronics market.

A large scale fusion reactor economy could generate a much larger demand for high purity aluminum. If the aluminum is used as a stabilizer for superconductors, a nominal resistance ratio of 5000 is adequate. A production rate of 3000 T/year of this purity would provide enough aluminum to fully stabilize superconductor sufficient to build magnets for ~45,000 MW(e) of new fusion reactors each year, or half the amount projected in a mature fusion economy. This production rate of high purity aluminum is 3 orders of magnitude greater than the present production rate, and considerable reduction in Al price is to be expected.

If aluminum is used as the inner high field winding on a hybrid magnet (e.g., outer field winding is Nb-Ti), a production rate of 30,000 T/year of 25,000 resistivity ratio would be enough to supply ~45,000 MW(e)/year of fusion reactors with a 50 KG inner field winding. The present production rate of nominal 25,000 resistivity ratio aluminum is only a few hundred lbs/year.

At present, the only practical method to obtain aluminum of this purity is by zone refining. A resistivity ratio of ~5000 can be obtained by one zone refining (~50 zone passes). Approximately two-thirds of the ingot is usable, and the rest must be scrapped. For 25,000 resistivity ratio aluminum, three zone refinings are required (~50 zone passes/refining), and the ingot must be cropped and the center portion remelted before the next zone refining. The overall yield is only 30% of the starting material for this very high resistance ratio; the rest is scrap. Feed stock is selected to be low in certain impurities, like chrome and nickel, which have a very detrimental effect on resistivity ratio. Care in refining is necessary, including preconditioning the graphite boats that carry the ingot. Impurities in the graphite are leached out by melting ordinary aluminum in the boats with the aluminum then sent to scrap.

Different impurities have widely different effects on resistivity ratio, so it is not possible to closely correlate resistance ratio with purity. Generally, 5000 resistance ratio roughly corresponds to 99.999% purity, while 25,000 resistance ratio corresponds to 99.999% purity.

High purity aluminum can also be purified by electrolyzing⁽¹⁾ a solution of organo-aluminum fluorides [e.g., $\text{NaF} \cdot 2 \text{Al} (\text{C}_2\text{H}_5)_3$], in, for example, toluene. The anode and cathode are made from aluminum metal (preferably 99.99% purity). High purity aluminum is deposited on the cathode. Electrode gaps are on the order of 2-3 cm, and electrolyte temperatures are on the order of 100°C . The deposited material has a resistance ratio of ~5000 to 10,000. Subsequent zone refining raises the resistance ratio to 25,000 to 40,000. The production rate/unit electrode area is very low, typically about 100 kg/m^2 of electrode/year, and cannot be increased without degrading the product. A production rate of 30,000 T/year of high purity aluminum would require $\sim 2 \times 10^5 \text{ m}^2$ of electrode area. The organo-aluminum complex explodes spontaneously on contact with water, oxygen, hydrogen, and a large number of other substances. It is also very flammable. Considering its hazards, one would seek to avoid this process if at all possible. The total inventory of explosive organo-aluminum in the plant is on the order of 2×10^7 lbs,

or half of a Hiroshima bomb. The cells would have to be very widely dispersed to prevent the whole plant from going up if one cell exploded. This certainly would be a very hazardous, costly, large plant.

Fortunately, zone refining seems perfectly capable of supplying the desired resistance ratios. There seems to be ample selected feed stock to produce 3000 T/year of 5000 resistance ratio aluminum. It is not certain, however, that there is enough suitable feed stock to produce 30,000 T/year of 25,000 resistivity ratio aluminum. If not, organically purified aluminum might be used as a feed stock. However, the problems of operating this process on the sufficiently large scale are very great as noted above. It would be preferable to do some preliminary zone refining of substandard feed stock, or electrolytic 3 layer refining of commercial grade aluminum.

Zone refining and organo-aluminum electrolysis both increase the resistance ratio from the bulk metal by removing impurities from the bulk metal. Another method is to leave the impurities in the metal, but to precipitate them at localized regions, e.g., grain boundaries. For example, the resistivity ratio of copper can be increased from 2500 to 42,000 by an oxidization technique.⁽²⁾ Such a technique would be much cheaper than zone refining. Another possible technique would be segregate impurities at

seeded (probably boron nitride) particles.⁽³⁾

Another technique, which works very well with sodium and other alkali metals, but which has not been investigated with aluminum, is vacuum distillation. If feasible, this would be a very cheap way of getting very high resistance ratio aluminum since the most troublesome impurities have much lower vapor pressures than aluminum.

Another possible technique, which might produce very cheap high purity aluminum, is recrystallization⁽⁴⁾ of molten aluminum.

At present, though, we are restricted to zone refining for production of large amounts of high purity aluminum. We consider the two plants, producing 3000 T/year of 5000 resistance ratio aluminum, and 30,000 T/year of 25,000 resistance ratio. The flow sheets for the two processes are shown in Figures 1 and 1A, respectively. The primary difference between the two processes is that three zone refinings with intermediate croppings are required for the 25,000 resistivity ratio aluminum, while only one zone refining is required for 5000 resistivity ratio aluminum. The processes can be divided into the following basic steps: casting ingots into graphite boats, zone refining of the ingots, cropping ingots, casting the product into bullets, extrusion, and rolling. Tables 1 and 1A list the basic process parameters, Tables 2 and 2A the cost of capital equipment, Tables 3 and 3A the building areas, Tables 4 and 4A the labor requirements, and

Tables 5 and 5A summarize the costs breakdown for each plant.

Table 6 lists the basic cost elements used in cost calculations.

The process parameters of zone speed, ingot length, RF frequency, and number of zone passes are typical of those used in present zone refining. In fact, 50 zone passes is somewhat greater than is customary; 40 passes is more usual. The ingot size in the present process is 4" x 4"; we have increased it to 6" x 6". A 5" x 5" size is though to probably be feasible, and a 6" x 6" may be. If not, the process costs will not be significantly increased. The present zone spacing is 5 feet (the length of each ingot); we have decreased this to 2.5 feet, which should be feasible. The average input power per zone to the RF unit is ~30 KVA for a 4" x 4" ingot. Since the principal heat loss is by conduction along the aluminum ingot, the input power scales approximately as ingot area. The input power/zone is thus ~65 KW for a 6" x 6" ingot.

The ingots are presently processed by loading into a holder with one RF coil. The coil makes 40-50 passes along the ingot, and then the ingot is unloaded. The passes are unidirectional, with the coil quickly returning to the starting point at the end of each pass. Processing time/ingot is ~100 hours.

In the large production plants it is preferable to load and unload the ingots at as few points as possible. Therefore, the

refining process is made continuous: the ingot is loaded at one end of a refining line, travels down the line past 50 RF coils, and is unloaded at the end. With a 2.5 foot zone spacing, processing time is 50 hours. With this arrangement the number of loading and unloading points is cut by a factor of 50.

This arrangement has another very significant advantage. Successive zone refined ingots will be much more uniform since all will experience the same sequence of RF coils. Any variability in refining due to differences in RF coil current and/or coupling will be greatly reduced by this averaging process. Ingots refined by different refining lines will not experience the same sequence of RF coils; however, the averaging process will also work here to reduce variability in the product. The main source of variation in product resistance ratio will probably be due to variations in feed material purity. However, this can be kept to small levels by suitable blending of feed stocks. Since many ingots can be made from a given batch of feed stock, the production problems would be minimal.

Further homogenization of the product is achieved by melting several product ingots together (typically 12) after cropping, and then casting the melt to form billets (typically 4 bars in

a billet). These ingots can be from different refining lines. It should not be necessary to analyze each ingot, but it probably will be desirable to analyze each billet, both for impurities and resistance ratio. Because of the high degree of homogenization, the reject rate should be very small.

All operations with the aluminum at elevated temperatures, e.g., casting, zone refining, and extrusion have to be done under an inert gas blanket. Operations at room temperature, e.g., unloading ingots, cropping, and rolling, can be done in air.

Since the principal cost other than materials is the cost of RF equipment and power, it is worthwhile to consider this part of the process in more detail.

RF units are usually designed to have their own DC power supply, since for the small sizes customarily used, it is more convenient than building a separate DC supply system. For the very large RF powers considered here, however, there will be large cost savings by building a separate DC power supply for the plant, and plugging each RF unit into this DC supply. The plate supply voltage will be 8-10 KV, and the AC to DC conversion costs ~\$35/KW for the 3000 T/day plant and ~\$25/KW for the 30,000 T/day plant, based on current costs. Future advances in solid state switches will probably reduce these costs substantially.

Each zone is assumed to have its own tube, oscillator circuit and power controls. It would be considerably cheaper if a number of zones could be supplied from a single oscillator, but this may be impractical in terms of controls. In a multi-load design changing the power flow to one zone will affect all the other parallel loads, and would require a very sophisticated control system. With separate load circuits, control will be fairly simple and stable. The input power could either be controlled on the output RF current. Manual adjustment of either of these quantities should be sufficient to achieve the desired zone heating.

The DC-RF conversion efficiency generally is on the order of 50-60%. The lower value of 50% has been chosen for calculational purposes. Based on conversations with J. Manwaring,⁽⁵⁾ the estimated cost for RF units exclusive of power supply is \$250/KW of RF power output for a large number of units. This figure has been used for the 3000 T/year plant producing 5000 resistance ratio aluminum. The author has reduced the cost to \$200/KW of RF output for the 30,000 T/year plant for 25,000 resistivity ratio aluminum because of the much larger amount of units required (approximately 50 times as many). The tube cost is taken as \$1200/tube for the large plant and \$1000/tube for the small plant, with replacement once a year. This amounts

to about \$30/KW (output) for the tube, leaving approximately \$200/KW (output) for the oscillator circuit and controls. This seems high, and the cost may be substantially lower than the values taken for this study, particularly for the 30,000 T/year plant which requires some 30,000 RF units, all of the same type.

Process parameters for the plants are summarized in Tables B-1 and B-1a. capital equipment costs in Tables B-2 and B-2a, building requirements in Tables B-3 and B-3a, labor requirements in Tables B-4 and B-4a. and production costs are summarized in Tables B-5 and B-5a. Table B-6 summarizes the special cost factors employed in this analysis.

The total production cost for 5000 resistance ratio aluminum is \$3.77/lb, and for 25,000 resistance ratio, \$8.04/lb. Zone refining and material costs account for the great majority of production costs.

References

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2. Arp, V., "Properties and Preparation of High Purity Aluminum," p. 1095 in Proceedings of the 1968 Summer Study on Superconducting Devices and Accelerators, BNL 50155 (1968).
3. Kasen, M. B., private communication (1971).
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Table B-1

Process Parameters for Production of 5000 Resistivity

Ratio High Purity Aluminum (3000 T/year)

<u>Process</u>	<u>Unit Process Parameters</u>	<u>Material Handling Parameters</u> (Total Plant)
1. Zone Refining	<u>Ingots</u>	<u>Ingots</u>
	Cross section: 6"x6"	Ingots processed
	Length: 5 feet	per hour 4.7
	Weight: 218 lbs	Ingots processed
		per year 41,400
	<u>RF</u>	<u>Refining Lines</u>
	Zone passes: 50	No. of refining
	Zone speed: 0.5 inch/ min.	lines(installed) 12
	Zone width: ~3 inches	No. of refining
	Zone spacing: 2.5 feet	lines operating
	RF frequency: 5 MHz	(average) 9.5
	Input DC power: 6 [±] KW/ zone	Ingots processed/ hr/refining line 0.5
	DC to RF efficiency: 50%	Processing time per ingot 50 hrs
		<u>Power</u>
		DC input power
		(installed) 39 MW
		DC power used
		(average) 31 MW
2. Crop	Center 2/3 of ingot is saved; ends are scrap- ped. There is 145 lbs of product Al per ingot	4.7 ingots cropped/hr 1.18 billets processed/hr
3. Casting	<u>Billet</u>	
	Diameter: 12 inches	1.18 billets processed/hr
	Length: 4.23 feet	
	Weight: 580 lbs	
	# ingots cast into billet: 4	

Tabel B-1 (Cont'd)

4. Extrusion Bar stock produced, either as feed for rolling mill, or as product to be later co-extruded with finished superconductor (~3" diameter)
5. Rolling 2 inch to 10 inch width strip produced, 10 to 100 mils thick, to be later soldered to superconductor
6. Aluminum balance: Input: 4500 tons/year ingot feed
900 tons/year precondition
graphite boats
Output: 3000 tons/year output
2400 tons/year scrap

Table B-1a

Material Handling Parameters for Production of 25,000
Resistivity Ratio High Purity Aluminum (30,000 T/year)

Item	First Stage Zone Refining	Second Stage Zone Refining	Third Stage Zone Refining	Total
1. Aluminum input in ingots, T/year	103,000	68,000	45,000	103,000
2. Aluminum input to precondition graphite boats, T/year	21,000	14,000	9,300	44,300
3. Number of graphite boats consumed/yr	190,000	127,000	83,000	400,000
4. Number of ingots processed/hour	108	72	47	-
5. Number of ingots processed/year	950,000	630,000	414,000	-
6. Number of refining lines (installed)	270	180	120	570
7. Number of refining lines (average operating)	216	144	96	466
8. Input power to RF lines (installed), MW	880	580	390	1,850
9. DC input power (average operating), MW	700	465	310	1,475
10. Output product T/year (66 2/3% of ingot)	68,000 (to input of second stage)	45,000 (to input of third stage)	30,000 (product to billet casting)	30,000
11. Scrap from ends. T/year (33 1/3% of ingot)	35,000	23,000	15,000	73,000
12. Billets cast/hour (12" diameter, 4.2 ft long)	-	-		11.8
13. Rolls of strip/hr (580 lb rolls) [10 inch wide, 1/8 inch thick)	-	-		11.8

B-14

Table B-2

Capital Equipment for Production of 5000 Resistivity

Ratio High Purity Aluminum (3000 T/year)

<u>Process</u>	<u>\$ Unit Cost</u>	<u>Total Cost for Plant (millions of dollars)</u>
1. Casting ingots into graphite boats		
Melting and casting equipment	-	0.2
Miscellaneous equipment	-	0.05
2. Zone refining		
Roller lines to transport ingots	100/ft	0.06
Refining lines (includes instrumentation)	200,000/line	2.40
RF equipment (DC to 5 MHZ)	250/KW*	4.90
DC power supply	35/KW	1.37
3. Unloading equipment	-	0.05
4. Cropping	-	0.10
5. Casting billets		
Casting machine	-	0.20
Miscellaneous equipment	-	0.05
6. Extrusion		
Press	750,000	0.75
Miscellaneous equipment	-	0.25
7. Rolling		
Mill		0.30
Miscellaneous equipment		0.10
8. Analysis equipment (emission spectroscopy, cryogenics tests, etc.)		1.00
Total		11.78
Engineering, Installation & Testing		2.95

* Based on RF output power. With 50% efficiency, cost is 125/KW based on input DC power.

Table B-2aCapital Equipment for Production of 25,000 ResistivityRatio High Purity Aluminum (30,000 T/year)

<u>Process</u>	<u>Unit Cost</u>	<u>Total Cost for Plant (millions of dollars)</u>
1. First stage zone refining		
Casting equipment		1.5
Refining lines	\$150/000 line	40.1
RF equipment	200/KW*	83.6
DC power supply	25/KW	20.9
Unloading and cropping		<u>1.5</u>
		147.6
2. Second stage zone refining		
Casting equipment		1.0
Refining lines		26.8
RD equipment	same	55.8
DC power supply		13.9
Unloading and cropping		<u>1.0</u>
		98.5
3. Third stage zone refining		
Casting equipment		0.7
Refining lines		17.7
RF equipment	same	37.2
DC power supply		9.25
Unloading and cropping		<u>0.7</u>
		65.6
4. Casting billets (6 furnaces)		1.5
5. Extrusion (2 presses)	750,000/press	1.5
Miscellaneous equipment		<u>0.5</u>
		2.0
6. Rolling (2 mills)		0.80
7. Analysis		<u>10.0</u>
	Total	326.0
Engineering, Installation & Testing		81.5

* Based on RF output power. With 50% efficiency,
cost is \$100/KW based on input DC power.

Table B-3

Building Requirements for 5000 Resistivity Ratio
High Purity Aluminum Plant (3000 T/year)

<u>Building Area</u>	<u>Area, ft²</u>
Casting ingots into graduate boats (includes preconditioning)	8,000
Zone refining line (includes roller lines to deliver boats) per line	3,000
12 lines (200' x 300')	36,000
Unloading ingots from graphite boats	5,000
Cropping ingots	5,000
Casting product Al into billet	8,000
Extrusion	15,000
Rolling	10,000
Offices and Analysis Labs	15,000
Shipping and Receiving	<u>10,000</u>
Total	115,000

Table B-3a

Building Requirements for 25,000 Resistivity Ratio

High Purity Aluminum Plant (30,000 T/year)

<u>Building Area</u>	<u>Area, ft²</u>
First stage zone refining	
Casting ingots into graphite boats	50,000
(includes preconditioning)	
Zone refining lines (2000 ft ² /line)	540,000
Unloading and cropping ingots	<u>50,000</u>
	640,000
Second stage zone refining	
Casting ingots into graphite boats	33,000
(includes preconditioning)	
Zone refining lines	360,000
Unloading and cropping ingots	<u>33,000</u>
	426,000
Third stage zone refining	
Casting ingots into graphite boats	20,000
(includes preconditioning)	
Zone refining lines	240,000
Unloading and cropping ingots	<u>20,000</u>
	280,000
Casting product Al into billet	25,000
Extrusion	25,000
Rolling	25,000
Offices and Analysis Labs	100,000
Shipping and Receiving	<u>50,000</u>
Total	1,671,000

Table B-4

Labor Requirements for 5000 Resistivity Ratio
High Purity Aluminum Plant (3000 T/year)

<u>Process</u>	<u>Unit Labor</u>	<u>Total in Plant</u> (4 shifts)
1. Casting ingots into graphite boats	3/shift	12
2. Zone refining		
Loading and unloading ingots	4/shift	16
Process control	1/shift per operating line	40
Maintenance and repair	½/line	6
3. Unloading ingots from graphite boats	2/shift	8
4. Cropping	2/shift	8
5. Casting billet	3/shift	12
6. Extrusion	3/shift	12
7. Rolling mill	3/shift	12
8. Analysis	-	20
9. General Maintenance	-	<u>10</u>
	Sub-total	156
10. Administrative, clerical, shipping and receiving, etc. (40% of sub- total)	-	<u>62</u>
	Total	218

Table B-4a

Labor Requirements for 25,000 Resistivity Ratio
High Purity Aluminum Plant (30,000 T/year)

<u>Process</u>	<u>Unit Labor Requirements</u>	<u>Total in Plant (4 shifts)</u>
1. First stage zone refining		
Casting	22/shift	88
Refining lines (216 operating)	1.5/line	324
Unloading and cropping	22/shift	<u>88</u>
		500
2. Second stage zone refining		
Casting	15/shift	60
Refining lines (144 operating)	1.5/line	216
Unloading and cropping	15/shift	<u>60</u>
		336
3. Third stage zone refining		
Casting	10/shift	40
Refining lines (96 operating)	1.5/line	144
Unloading and cropping	10/shift	<u>40</u>
		224
4. Casting billets (40 operating furnaces)	4/shift/oper- ating furnace	64
5. Extrusion (1 operating press)	8/shift	32
6. Rolling (1 operating mill)	8/shift	32
7. Analysis		200
8. General maintenance		<u>100</u>
	Sub-total	1488
9. Overhead (administrative, clerical, shipping and receiving, etc.)		<u>595</u>
	Total	2083

Table B-5

Summary of Costs for Production of 5000 Resistivity

Ratio High Purity Aluminum (3000 T/year)

<u>Process</u>	<u>Total Cost/year for Plant (Millions of \$)</u>	<u>Cost Contribution to Product (\$/lb)</u>
1. Materials		
Aluminum for feed ingots	4.50	0.75
Aluminum to precondition boats	0.63	0.10
Graphite boats	1.06	0.18
Power to RF units	2.71	0.45
Replacement tubes	0.60	0.10
Plant power	0.39	0.06
Scrap aluminum	<u>-0.60</u>	<u>-0.10</u>
	9.29	1.54
2. Casting ingots		
Labor	0.30	0.05
E,I & M	0.10	0.02
Building	<u>0.20</u>	<u>0.03</u>
	0.60	0.10
3. Zone refining		
Labor	1.55	0.26
E,I & M	3.62	0.60
Building	<u>0.90</u>	<u>0.15</u>
	6.07	1.01
4. Casting billets (includes cropping)		
Labor	0.70	0.12
E,I & M	0.16	0.03
Building	<u>0.45</u>	<u>0.08</u>
	1.31	0.23
5. Extrusion		
Labor	0.30	0.05
E,I & M	0.41	0.07
Building	<u>0.37</u>	<u>0.06</u>
	1.08	0.18
6. Rolling		
Labor	0.30	0.05
E,I & M	0.16	0.03
Building	<u>0.25</u>	<u>0.04</u>
	0.71	0.12

* E,I and M include capital and depreciation charges on equipment and installation costs, and maintenance charges.

Table B-5 (Cont'd)

<u>Process</u>	Total Cost/year for Plant <u>(Millions of \$)</u>	Cost distribution to Product <u>(\$/lb)</u>
7. Analysis		
Labor	0.50	0.08
E.I & M	0.41	0.07
Building	<u>0.50</u>	<u>0.08</u>
	1.41	0.23
8. Overhead		
Labor	1.80	0.30
Building	<u>0.37</u>	<u>0.06</u>
	2.17	0.36
Overall Total	<u>22.64</u>	<u>3.77</u>

Table B-5a

Summary of Costs for Production of 25,000 Resistivity
Ratio High Purity Aluminum (30,000 T/year)

<u>Process</u>	<u>Total Cost/year for Plant (Millions of \$)</u>	<u>Cost Contribution to Product (\$/lb)</u>
1. Materials		
Aluminum to feed ingots	103.0	1.74
Aluminum to precondition boats	26.6	0.44
Graphite boats	48.0	0.80
Power to RF units	103.0	1.73
RF tubes	20.8	0.35
Plant power	6.1	0.10
Scrap aluminum	<u>-35.2</u>	<u>-.59</u>
	272.3	4.57
2. First stage zone refining		
Labor	12.5	0.21
E,I,&M*	60.5	1.01
Building	<u>9.6</u>	<u>0.16</u>
	82.6	1.38
3. Second stage zone refining		
Labor	8.4	0.14
E,I,&M	40.3	0.66
Building	<u>6.4</u>	<u>0.11</u>
	55.1	0.91
4. Third stage zone refining		
Labor	5.6	0.09
E,I,&M	26.8	0.44
Building	<u>4.2</u>	<u>0.07</u>
	36.6	0.60
5. Casting and extrusion		
Labor	2.40	0.04
E,I,&M	1.43	0.02
Building	<u>0.37</u>	<u>0.01</u>
	4.20	0.07

* E,I,&M include capital and depreciation charges on equipment and installation costs, and maintenance costs.

Table B-5a (Cont'd)

<u>Process</u>	<u>Total Cost/year for Plant (Millions of \$)</u>	<u>Cost Contribution to Product (\$/lb)</u>
6. Rolling		
Labor	0.80	0.01
E.I.&M	0.32	0.01
Building	<u>0.37</u>	<u>0.01</u>
	1.49	0.03
7. Analysis		
Labor	5.0	0.08
E.I.&M	4.1	0.07
Building	<u>1.10</u>	<u>0.02</u>
	10.2	0.17
8. Overhead		
Labor	17.4	0.29
Building	<u>1.10</u>	<u>0.02</u>
	18.5	0.31
Overall Total	<u><u>480.8</u></u>	<u><u>8.04</u></u>

Table B-6

Special Cost Factors Employed in Analysis

<u>Item</u>	<u>3000 T/year Plant</u>	<u>30,000 T/year Plant</u>
Feed aluminum for ingots	\$0.60/lb	\$0.50/lb
Aluminum to precondition boats	\$0.35/lb	\$0.30/lb
Scrap aluminum	-\$0.10/lb	-\$0.15/lb
Graphite boats	\$1.00/lb	\$1.00/lb
Power to RF units	10 mils/KWH	8 mils/KWH
Plant power	9 mils/KWH	7 mils/KWH
RF equipment	\$250/KW	\$200/KW
DC supply	\$35/KW	\$25/KW
Zone refining lines	\$200,000/line	\$150,000/line
Tube replacement (1/year/zone)	\$1200/tube	\$1000/tube
Building	100/ft ²	60/ft ²
Building area/refining zone line	3000 ft ²	2000 ft ²

FIGURE B-1

Production cycle for 5,000 resistivity ratio
high-purity aluminum

FIGURE B-1a

Production cycle for 25,000:1 purity ratio
high-purity aluminum

Appendix C

Costs of Vanadium and Gallium

Cost of Vanadium

Vanadium is primarily produced as a co-product with other metals. There are only a few small deposits that are economical to mine for vanadium alone. In the U.S., approximately 70% of the vanadium is produced as a co-product of uranium from the uranium-vanadium ores in Colorado (1). Most of the remainder is produced as a co-product of phosphorous from phosphate rocks in Idaho. A small amount is recovered from fly ash resulting from oil burning in power plants. In the rest of the world, most vanadium is produced as a co-product from titaniferous-meguelite and base-metal deposits.

The 1968 U.S. vanadium demand was 5770 tons and the rest of the world was 11,230 tons. Projected demands for 2000 AD is ~30,000 tons/year for the rest of the world. The projected 2000 AD price for commercial grade V_2O_5 is ~\$2.70/lb of contained vanadium (1). The estimate world reserves at this price are ~10,000,000 tons. Much larger reserves are available at somewhat higher prices.

The principal use of vanadium is an alloying component in ferrous and titanium alloys. This market accounts for ~95% of total demand.

The vanadium demand for fusion reactor superconductors will probably not exceed a few thousand tons/year. Barring any unforeseen vanadium demand, it is likely that there will be ample supplies of V_2O_5 in 2000 AD at a price of ~\$2.70/lb (in 1968 dollars) of contained vanadium.

Since the reduction, EB purification, and fabrication of vanadium into a form suitable for making superconductors is so similar to that outlined for niobium (Appendix A), similar processing costs are projected. These are summarized in Table C-1.

The reduction costs are close to these for niobium except that more aluminum powder is required per pound of reduced vanadium. This is principally due to the lower atomic weight of vanadium (51 vs 93), but also to a need for somewhat excess (above stoichiometric) amount of aluminum powder. Typical commercial practice is to use about 5% excess (above stoichiometric) aluminum powder for vanadium reduction, to ensure full reduction of the oxide. This excess aluminum appears in the crude vanadium ingot, and must be removed by the purification process.

Vanadium ingot is customarily purified by the same type of EB furnaces that are used for niobium purification (Appendix A). The factor that limits throughput rate is EB purification is the rate of release of impurities (it cannot be too fast, otherwise the electron guns will not function) from the molten pool at the end of the ingot. Thus, the volumetric throughput rate for vanadium ingots will be the same or even less than for niobium ingots since there are more impurities. Nitrogen and silicon impurities are not removed by EB melting, so care must be taken during the reduction to limit these impurities [an inert gas blanket is needed for the reduction pots, in contrast to the niobium reduction pots which can operate in air]. If the Si and N impurities prove objectionable, then the V_2O_5 feed to the reduction pots must be pre-purified.

For this study we assume that the EB purification costs per pound for vanadium are equal to the purification costs for niobium multiplied by the ratio of Nb metal density/vanadium metal density. On the basis of the above arguments, this probably somewhat underestimates the EB purification costs for vanadium.

The cost per pound of preparing vanadium powder are taken equal to the cost for niobium powder (\$0.50/lb), multiplied by the ratio of niobium atomic weight to vanadium atomic weight. This reflects the greater number of moles of H_2 to be reacted with vanadium metal than with an equal weight of niobium metal.

The cost per pound of preparing V + 1% ingot is assumed equal to the cost of preparing Nb + 1% Zr ingot (\$1.33/lb), multiplied by the ratio of niobium metal density to vanadium metal density. This again reflects the greater throughput volume of vanadium metal.

The cost per pound of rolling V + 1% Zr to thin foil is assumed equal to the cost of rolling Nb + 1% Zr to an equal thickness, multiplied by the ratio of niobium metal density to vanadium metal density. The cost of rolling to 2 mil niobium foil is estimated as \$8.90/lb (Appendix A - note that costs of rolling a 2 mil foil is substantially less than for 1 mil foil since the total rolled length for 2 mil product is cut by a factor of two compared to that for 1 mil product), so that the cost of rolling for 2 mil vanadium foil is estimated at \$12.46/lb.

The total estimated cost/lb of 2 mil vanadium foil then \$20.96/lb and is comparable to that for 1 mil niobium foil.

Costs of Gallium

The present price of gallium from ALCOA is ~\$1.0/gm for 99.9999% pure gallium. Less pure material, eg., 99.99%, which is probably suitable for V_3Ga superconductor is somewhat cheaper, on the order of \$0.80/gm. The present world production is on the order of 1 ton/year. Based on conversations with personnel from ALCOA the projected price for 200 T/year production would be ~\$0.20 to \$0.25/gm.

The ALCOA process for extraction of gallium shown in Figure C-1, is an adjunct to the Bayer process for recovery of alumina from bauxite. The gallium in bauxite (Al/Ga ratio of 3000/1 to 8000/1) concentrates the recycled sodium aluminate liquor until it reaches ~20 times the original concentration in bauxite. Continued additions of gallium to the circuit after this concentration is reached leave with the precipitated $Al(OH)_3$ product. Thus a ready made concentrate, with an Al/Ga ratio of between 150/1 to 400/1 exists in the recycled sodium aluminate liquor in the Bayer process, and can be periodically processed to recover the gallium. After processing, the gallium concentration is allowed to build up again. The Bayer process is almost universally used for recovery of alumina for electrolytic reduction to aluminum. The potential maximum production of gallium is

then on the order of 1000 tons/year if all the gallium in the yearly consumption of bauxite is recovered. This is certainly ample for any foreseen use of V_3Ga superconductor.

However, a gallium price of ~\$ 0.20/gm while acceptable, is still high. What are the chances of a large reduction in this estimated price?

A large volume of material must be processed to recover a small amount of gallium. In the ALCOA process shown in Figure C-1, approximately 1000 pounds of calcium aluminate is precipitated per pound of gallium metal recovered. This is an important cost factor. To recover the alumina, the calcium aluminate precipitate must be dissolved in a sodium carbonate solution, calcium carbonate filtered out, and the $Al(OH)_3$ precipitated by CO_2 addition. This is more expensive than the straight precipitation of the equivalent amount of $Al(OH)_3$ in the Bayer process if gallium were not extracted, and must be charged against the gallium product.

However, one encouraging fact is that the cost of materials (i.e., makeup $NaOH$ and $Ca(OH)_2$) is small, and the principal cost comes from extra equipment, labor, etc. On this basis a 20 fold increase in gallium production should lead to very large cost reductions, and the figure of ~ \$0.20/gm is probably too high.

For purposes of this study a price of \$0.20/gm (\$90/lb) is adopted as a reasonably conservative value, recognizing that it could go substantially lower if a very large and persistent market developed.

Stamper (2) projects a gallium price of \$1.20/gm (in 1968 dollars) in 2000 AD. However, his projected 2000 AD demand is very small, 2 tons/year, which is only twice the 1968 demand. The two orders of magnitude greater demand that would result if V_3Ga were significantly used in fusion power reactor magnets would be expected to result in a much lower gallium cost.

It would be nice if there were bauxite with a very rich gallium content, but unfortunately all bauxites have approximately the same content. There are other ones, but none seems to be sufficiently plentiful and/or as cheap to extract gallium from.

References

1. Griffith, R. F., "Vanadium," p. 417, Mineral Facts and Problems, Bureau of Mines Bulletin 650 (1970 Edition), U.S. Dept. of the Interior, Washington, D. C.
2. Stamper, J. W., "Gallium," p. 555, *ibid.*

Table C-1

Projected Costs for Large Scale Production of Vanadium

<u>Form of vanadium</u>	<u>Projected cost, \$/lb of contained vanadium</u>
Commercial grade V_2O_5	\$ 2.70
Vanadium metal, reduced by alumino-thermic process	3.45
EB purified vanadium ingot (3 melts)	6.98
Vanadium powder	7.68
V-1% Zr ingot (2 consumable arc melts)	8.50
2 mil V-1% Zr foil	20.96

FIGURE C-1

Gallium production process
(after Kirk and Othmer)

Appendix D

Projected Cost of Nb-Ti Superconductor

The operating conditions of steady state fusion reactors are very moderate in terms of Nb-Ti superconductor characteristics. The overall current density of the magnet windings is very low because of the large coil dimensions and extensive structural reinforcement, the conductor is fully stabilize , the magnetic field is essentially DC. and the magnet charging rate is very slow. Under these conditions, the Nb-Ti filament diameter can be relatively large, the twist rate small, and the Cu/Nb-Ti ratio high. One does not need the very fine multifilament and high twist rates characteristic of Nb-Ti superconductors for synchrotrons, but instead can use much cheaper ship conductors of the type developed for large bubble chambers.

The characteristics of a conceptual Nb-Ti superconductor for large fusion magnets is given in Table D-1 and Figure D-1. This conductor is extrapolated from the NAL bubble chamber conductor design.⁽¹⁾ The conceptual conductor is slightly thinner, 80 mils instead of 100, has a slightly smaller Nb-Ti filament diameter, a lower operating lineal current density (2800 A/cm vs 4000 A/cm), a slightly lower Cu/Nb-Ti ratio (3/1 vs 3.5/1), and is backed up with a much lower resistivity stabilizer (high purity aluminum [5000 resistance ratio] vs OFHC copper).

Except for the difference in Cu/SC ratio, these all represent a more conservative trend in conductor design. The major extrapolation is the use of a 10 cm wide conductor instead of the 1.25 cm wide conductor used in the NAL magnet.

In this conceptual design the width of Nb-Ti superconductor is the same as that of the stabilizer strip, i.e., 10 cm. In the NAL conductor design, the Nb-Ti strip is 1.25 cm wide, but is soldered to a 3.7 cm wide copper stabilizer strip. The yield stress of the aluminum stabilizer is very low, ~1500 psi. This restricts both the current/unit width and the mode of conductor construction. Stress concentration effects would be expected at the corners of the superconductor strip if it were soldered to a much wider aluminum strip. It was therefore decided to make the Nb-Ti conductor and aluminum strip of essentially the same width (though for edge cooling the aluminum strip projects slightly), and to limit the current/unit width. At 2800 A/cm the net compressive stress on the aluminum stabilizer is ~400 psi at the inmost turn of the Nb-Ti magnet winding (assuming $B_{\max}$ for Nb-Ti conductor in the fusion magnet to be 80 KG). A much larger current/unit width with its associated layer compressive stress would raise serious questions about the long term plastic flow of aluminum, which if it occurred would cause a large increase in resistivity of the stabilizer.

It would be extremely difficult to roll a single flat strip of Nb-Ti-Cu 10 cm wide and 0.2 cm thick. The Nb-Ti-Cu composite is twisted as a round rod just prior to rolling into a flat strip, and the twist rate imparted to the filaments limits the aspect ratio of the final flat rolled strip. The flat rolling can damage the filaments if the twist rate is too great. The NAL conductor strip has an aspect ratio (width/thickness) of 5/1 with a twist rate of $\sim 1/\text{foot}$. Since the fusion reactor magnet will be charged at a slower rate, less twist is necessary. A value of 1 twist/meter seems acceptable. A larger aspect ratio strip should thus be feasible; however, a strip 10 cm wide and 0.2 cm thick would have an aspect ratio of 50/1, which is probably unrealizable. A 5 cm wide strip, 0.2 cm thick (aspect ratio of 25/1) is thought to be probably feasible and is the design selected for this study. Two of these strips would be soldered to the 10 cm wide aluminum stabilizer. If it turns out that even this aspect ratio is too large, one can either use narrower strips (e.g., 4 strips, each 2.5 cm wide, with an aspect ratio of 12.5), or the same width strip with a lower twist rate.

The estimated critical current density in the Nb-Ti filaments is given as a function of B in Table D-2. These estimates are based on critical current densities for commercial Nb-Ti-Cu

composites, and are comparable to values for the NAL conductor. The corresponding critical currents for the conceptual conductor of 10 cm width and 0.2 cm thickness are also given in Table D-2. The estimated critical current at 50 KG is 42.5 KA. Taking the ratio of $I(\text{operating})/I(\text{critical})$ to be $2/3$, the operating current for the strip would be 28 KA.

In fusion magnet coils, the conductors current will be constant, so that the ratio of $I(\text{operating})/I(\text{critical})$ is also a function of field, if one uses a constant thickness superconductor. This option uses more superconductor than is needed in the low-field region since one sets the operating current on the basis of the maximum field.

It is much cheaper to vary the amount of superconductor as field varies. In Table D-2, the thickness of the Nb-Ti-Cu superconducting strip is given as a function of B for the conditions that: $I(\text{operating}) = 28 \text{ KA}$, $I(\text{operating})/I(\text{critical}) = 2/3$, and conductor width = 10 cm. Stabilizer thickness is constant with field since $I(\text{operating})$ is constant.

It may be possible to control the rolling process so that the Nb-Ti-Cu thickness could continuously vary along the strip. This would be the cheapest form of conductor, since materials cost far exceeds processing cost. As an example, a 400 meter length of strip could start out with a Nb-Ti-Cu thickness of

0.34 cm at one end and decrease to 0.15 cm at the other end. When wound into a fusion magnet coil of ~10 m diameter, this strip would provide the necessary current to increase the field from 40 to 80 KG, and the ratio of $I(\text{operating})/I(\text{critical})$ would remain as 2/3 independent of field. Another 400 meter length could start out at 0.15 cm and decrease to 0.1 cm at the other end (thicknesses less than 0.1 cm would probably be very difficult to roll) and this length could be used for the 0-40 KG winding.

If continuous variation of Nb-Ti-Cu thickness is not feasible, one would have to go to compound conductor windings, that is, the fusion magnet winding would be composed of a number of discrete conductors, each with its own constant Nb-Ti-Cu thickness. In the limit of a large number of discrete conductors one approaches a continuous variation of Nb-Ti-Cu thickness. However, there will be some compromise to keep the number of conductor joints at some practical number, e.g., 2 to 3. The costs of this type of winding will be somewhat greater than for a continuously varying conductor thickness but not unreasonably so.

Costs are shown in this appendix for various thicknesses of Nb-Ti-Cu superconductor. However, the primary cost calculation is made for a thickness of 0.2 cm, and other thicknesses obtained by assuming that the cost is linearly proportional to

the amount of Nb-Ti-Cu. Since the cost of flat strip rolling step is only ~1% of the total conductor cost, this assumption is quite accurate.

The process parameters for the large scale production plant are described in Table D-3. The diameters of the extruded Nb-Ti rod, the extruded Nb-Ti-Cu rod, and the Nb-Ti-Cu billet are comparable to those presently used in production processing.⁽²⁾ The overall yield from ingot to strip (90%) is comparable to present yields. The 18% reduction per pass in the Nb-Ti and Nb-Ti-Cu rod rolling mills are comparable to those now used. It is likely that somewhat greater reductions could be made, but the cost savings would be small.

Swaging is often used in the production of Nb-Ti-Cu superconductors since the production rate is much smaller and the product value much higher than in this study, that its higher cost is not significant. However, for the production rate envisaged in this plant (10^7 m/year of 28 KA conductor, enough for ~45,000 MW(c)/year of new fusion plants), the cost differential between rolling and swaging is very significant. Three rolling mills for Nb-Ti-Cu are sufficient for this plant, while something like 40 swaging units would be required. This results from the much lower throughput speed from a swaging machine.

The copper billets are assumed to be already drilled before reaching the plant and cost \$1/lb of copper in the billet.

Since 50,000 billets/year are required, it would be economical for the billet supplier to do the drilling on a automated ganged drill press, and to recover the scrap copper. In the superconductor plant therefore, the only billet assembly operation involves inserting 0.35 inch diameter Nb-Ti rods in the pre-drilled holes. This can be done automatically by a self-loaded machine. Another alternative would be to cast copper around the Nb-Ti rods. The cost differential is not significant, however, in terms of final conductor cost.

The billet throughput rate is 5.7/hour. The extrusion press can handle a maximum of ~40 billets/hour, so that if it were operated on a 4 shift round the clock basis, the press would only operate at 14% of maximum capacity. A 2 shift operation seems more reasonable, allowing 28% of maximum capacity. This allows more than enough time for crew-switching, maintenance, etc.

Rolling mill throughput speeds are based on conversations with a manufacturer of rolling mills, as are drawing throughput speeds. The Nb-Ti rods are rolled from 2 inches to 0.35 inch, though the smaller diameter range could probably be drawn instead. The Nb-Ti-Cu rods are rolled down to 1 inch and drawn to smaller sizes. Drawing is substantially faster than rolling, particularly as diameter decreases.

The twisted Nb-Ti-Cu drawn rod is rolled to flat strip in a 3 strand tandem mill. The 250 feet/minute average throughput speed is based on conversations with a manufacturer of such mills.

The soldering operation is based on manufacturer's experience soldering NAL conductor strip. The assumed throughput speed of 13 feet/minute on the soldering stand is the same as that used for the NAL strip, which appears to be more difficult to solder, since it involves 3 strips soldered to a base strip.

The capital equipment costs (Table D-4) are based on manufacturer's estimates and in most cases are taken considerably greater, i.e., twice, than the manufacturer's estimate. The total equipment costs are very small; the amortized costs only amount to ~3% of the product price.

The labor requirements (Table D-5) are generously overestimated on the basis of present practice. Even so, the labor costs are only about 6% of the total conductor cost. The building areas (Table D-6) are generous by present practice, and amount to ~3% of total conductor cost.

The total costs for the 0.2 cm thick, 10 cm wide Nb-Ti-Cu strip, soldered to 0.2 cm thick aluminum stabilizer, are given in Table D-7, both on the basis of projected and present materials costs. Even on the basis of projected costs, the materials costs

amount to ~85% of the total conductor cost, and on the basis of present material costs, amount to ~94% of the total. It is clear that the true cost is predominantly determined by material costs. Errors in manufacturing costs will not substantially affect conductor cost. Thus reducing processing costs, which in all probability have been somewhat overestimated, will not appreciably reduce conductor cost.

The validity of the Nb-Ti conductor cost estimate then really depends on the validity of the materials costs. It is felt that the projected material costs (see Appendices A and B) are valid, and if anything, are overestimates rather than underestimates.

Conductor cost estimates for other Nb-Ti thicknesses are shown in Table D-8. The stabilizer thickness is constant at 0.2 cm, but the Nb-Ti thickness varies from 0.1 to 0.35 cm. These estimates are then used to calculate Nb-Ti conductor costs in \$/KA m as a function of B (see main body of report).

Factors used for cost estimates are summarized in Table D-9.

Costs of heat treating have been neglected, since manufacturers are understandably reluctant to reveal details of these parts of the process. In general, however, these costs will be quite small since the heat treatment temperatures are low (typically 400°C), and inert gas atmospheres can be used. These

costs will undoubtedly be much smaller than the other costs. The scrap value of material salvaged from the various processing steps has not been included. Since the primary costs is for materials this will contribute towards lowering the predicted conductor cost by a few percent.

An alternate conductor using Nb-Ti filaments in an aluminum matrix was considered. Such a conductor is currently being manufactured,⁽³⁾ but with only three filaments that are not twisted. Because of the very large difference in strength between Nb-Ti and high purity aluminum, it would be very difficult to make a flat strip conductor with Nb-Ti twisted filaments. If it could be done, there would be a saving of about 25% due to the elimination of the copper matrix. However, it would seem more likely that such savings could be achieved more easily by reducing the Cu/ Nb-Ti ratio from 3/1 to 1.5/1 or less. The principal reason for the high Cu/ Nb-Ti ratio in this conceptual conductor is to permit one to make a conductor strip. If rolling techniques can be worked out where 1 to 2 inch wide strip of ~10 to 20 mils thickness proves practical, the extra copper would be eliminated.

References

1. Purcell, J., "Superconducting Magnet for the 15 Foot NAL Bubble Chamber," in preparation (1971).
2. Critchlow, P. R., Gregory, E., and Zeitlin, B., "Multi-filamentary Superconducting Composites," Cryogenics 11, 3 (1971).
3. Nomura, H., Obata, M., and Shimanoto, S., "Construction of a New Aluminum Stabilized Superconductor," Cryogenics, 11, 396 (1971).

Table D-1

Characteristics of Conceptual Nb-Ti
Superconductor for Large Fusion Magnets

Cu/Nb-Ti ratio	3/1
Nb-Ti composition	49% Ti
Conductor strip width	5 cm
Conductor strip thickness	0.2 cm (~80 mils)
Number of filaments in strip	300
Filament diameter	3.2×10^{-2} cm
Aspect ratio of strip	25/1
Number of strips in unit conductors	2
Overall width of unit conductor	10 cm (24 inches)
Stabilizer	High purity aluminum (5000 resistance ratio)
Stabilizer thickness	0.2 cm
Overall thickness of unit conductor plus stabilizer	0.4 cm
Estimated critical current of unit conductor at 50 KG	42.5 KA
Typical operating current	28 KA
I^2R heating if full transport current flows in the stabilizer	0.3 watts/cm of edge
Twist rate	1/meter

Table D-2

Critical Current vs Field Characteristics
of Conceptual Nb-Ti Superconductor

<u>B (KG)</u>	<u>Estimated J_C in Nb-Ti (A/cm²)</u>	<u>I_C for 10 cm wide strip 0.2 cm thick (KA)</u>	<u>Thickness for I/I_C = 0.66, with I = 28 KA (cm)</u>
20	1.8x10 ⁵	90.0	0.0945
30	1.4x10 ⁵	70.0	0.122
40	1.1x10 ⁵	55.0	0.155
50	8.5x10 ⁴	42.5	0.2
60	7x10 ⁴	35.0	0.242
70	6x10 ⁴	30.0	0.283
80	5x10 ⁴	25.0	0.34
90	3x10 ⁴	15.0	0.566
100	1.8x10 ⁴	9.0	0.945

Table D-3

Process Parameters for Large Scale Production
of Nb-Ti Superconductor (10^7 m/year of concep-
tual 10 cm wide conductor described in Table D-1)

Nb-Ti rod diameter after extrusion	2 inches
Nb-Ti " " " rolling	0.35 inches
Nb-Ti-Cu billet diameter	12 inches
" " " " length	24 inches
Number of Nb-Ti rods in billet	300
Billet weight - total	795
" " - copper	658
" " - Nb-Ti	137
Cu/Nb-Ti ratio	3/1
Extruded Nb-Ti-Cu rod diameter	2 inches
Nb-Ti-Cu rod diameter after rolling	1 inch
" " " " " drawing	~0.7 inch
Nb-Ti-Cu flat strip dimensions	5 cm x 0.2 cm
" " " " " length	400 meters
Overall yield - billet to strip	90%
Number of billets processed/year	50,000
Average number of billet processed/hour	5.7
Number of extrusion presses	1
% of maximum capacity for 4 shift operation	14%
Area reduction/pass in rolling mill (both Nb-Ti and Nb-Ti-Cu)	18%

Table D-3 (Cont'd)

Output of speed of rod from mill per pass	
Nb-Ti (2" to 1")	50 feet/min
Nb-Ti (1" to ½")	100 " "
Nb-Ti-Cu (2" to 1")	50 " "
Number of Nb-Ti-Cu rod mills	3
% of maximum capacity for 4 shift operation	76%
Number of Nb-Ti rod mills	3
% of maximum capacity for 4 shift operation	50%
Area reduction/pass for drawing Nb-Ti-Cu	18%
Number of drawing stands	3
Drawing speed	100 feet/min
% of maximum capacity for 4 shift operation	25%
Flat strip rolling - number of 3 stand tandem mills	1
Rolling speed per pass	500 feet/min
Number of passes through 3 stand tandem mill	2
Output speed of strip from soldering stand	13 feet/min
Number of soldering stands	6
% of maximum capacity for 4 shift operation	80%

Table D-4

Capital Equipment Costs for Large Scale Production
of Nb-Ti Superconductor (10^7 m/year)

<u>Process Step</u>	<u>Unit Capital Cost (\$ Millions)</u>	<u>Plant Capital Cost* (\$ Millions)</u>
1. Nb-Ti rod rolling mill	0.3	0.9
2. Billet assembly machines	0.1	0.2
3. Extrusion press	1.0	1.0
4. Nb-Ti-Cu rod rolling mill	0.3	0.9
5. Nb-Ti-Cu drawing stands	0.2	0.6
6. Nb-Ti-Cu flat strip rolling mill	0.6	0.6
7. Soldering stands	0.3	1.8
8. General materials handling equipment	-	3.0
9. Quality control equipment	-	<u>3.0</u>
	Total	12.0

* Does not include engineering and testing (25% additional).

Table D-5

Labor Requirements for Large Scale Production
of Nb-Ti Superconductor (10⁷ m/year)

<u>Process Step</u>	<u>Unit Labor Requirements</u>	<u>Plant Labor Requirements</u>
1. Rolling Nb-Ti rod	3/mill/shift	36 (4 shifts)
2. Assembly of Nb-Ti rods in billets	10/shift	40 (4 shifts)
3. Extrusion press	3/shift	6 (2 shifts)
4. Rolling Nb-Ti-Cu rods	3/mill/shift	36 (4 shifts)
5. Drawing Nb-Ti-Cu rods	1/stand/shift	24 (4 shifts)
6. Rolling Nb-Ti-Ci strip	3/shift	12 (4 shifts)
7. Soldering stabilizer to strip	2/stand/shift	48 (4 shifts)
8. General materials handling assistance		50
9. Quality control		<u>50</u>
	Sub-total	302
10. Overhead (clerical, administrative, shipping & receiving, etc.)		<u>120</u>
	Total	422

Table D-6

Building Requirements for Large Scale Production
of Nb-Ti Superconductor (10⁷ m/year)

<u>Process Step</u>	<u>Building area, ft²</u>
1. Rolling Nb-Ti rod	30,000
2. Assembly of Nb-Ti-Cu rods	10,000
3. Extrusion press	15,000
4. Rolling Nb-Ti-Cu rods	60,000
5. Drawing Nb-Ti-Cu rods	10,000
6. Rolling Nb-Ti-Cu strip	15,000
7. Soldering stabilizer to strip	30,000
8. Quality control labs	20,000
9. Offices, shipping & receiving, etc.	<u>40,000</u>
Total	230,000

Table D-7

Cost Summary for Large Scale Production of
Nb-Ti Superconductor (10^7 m/year)

<u>Process Step</u>	<u>Plant Cost</u> <u>(\$Millions/yr)</u>	<u>\$/m of 10 cm</u> <u>Width Conductor</u>
1. Materials (projected cost)		
Power (15 MW)	1.3	0.13
Nb-Ti	43.5	4.35
Copper	33.0	3.30
High purity aluminum	<u>47.0</u>	<u>4.70</u>
	124.8	12.48
2. Nb-Ti rod rolling		
Labor	0.90	0.090
Equipment*	0.36	0.026
Buildings	<u>0.75</u>	<u>0.075</u>
	2.01	0.20
3. Billet assembly		
Labor	1.00	0.100
Equipment*	0.08	0.008
Buildings	<u>0.25</u>	<u>0.025</u>
	1.33	0.13
4. Billet extrusion		
Labor	0.15	0.015
Equipment*	0.41	0.041
Buildings	<u>0.37</u>	<u>0.037</u>
	0.93	0.09
5. Nb-Ti-Cu rod rolling		
Labor	0.90	0.090
Equipment*	0.36	0.036
Buildings	<u>1.50</u>	<u>0.150</u>
	2.76	0.28

Table D-7 (Cont'd)

<u>Process Step</u>	<u>Plant Cost (\$Millions/yr)</u>	<u>\$/M of 10 cm Width Conductor</u>
6. Nb-Ti-Cu drawing		
Labor	0.60	0.060
Equipment*	0.24	0.024
Building	<u>0.25</u>	<u>0.025</u>
	1.09	0.11
7. Nb-Ti-Cu rolling to flat strip		
Labor	0.30	0.030
Equipment*	0.24	0.024
Building	<u>0.37</u>	<u>0.037</u>
	0.91	0.09
8. Soldering stabilizer		
Labor	1.20	0.120
Equipment*	0.73	0.073
Building	<u>0.75</u>	<u>0.075</u>
	2.68	0.27
9. Quality control		
Labor	1.25	0.125
Equipment*	1.23	0.123
Building	<u>0.50</u>	<u>0.050</u>
	2.98	0.30
10. Overhead & Materials Handling Assistance		
Labor	4.25	0.425
Equipment*	1.23	0.123
Building	<u>1.00</u>	<u>0.100</u>
	6.48	0.65
Totals (projected material costs)	145.0	14.50
Total (present material costs)	<u>345.0</u>	<u>34.5</u>

* Includes engineering, testing
and maintenance

Table D-8

Conductor Costs as a Function of Nb-Ti-Cu Thickness

Conditions: width = 10 cm
aluminum stabilizer
thickness = 0.2 cm

Nb-Ti-Cu Conductor thickness (cm)	Conductor Cost	
	Projected Material Costs (\$/M) *	Present Material Costs (\$/M) *
0.1	9.7	31.9
0.15	12.1	38.4
0.20	14.5	44.9
0.25	16.9	51.4
0.30	19.2	57.9
0.35	21.6	64.4

* Cost of soldering included with
aluminum cost.

Table D-9
Cost Factors for Large Scale Production
of Nb-Ti Superconductor

<u>Material</u>	<u>Unit Cost</u>
Drilled copper billet	\$1.00/lb
Nb-Ti rod (2" diameter)	\$6.25/lb Projected price
" " " "	\$30.00/lb Present price
High purity aluminum (5000 resistivity ratio)	\$3.80/lb Projected price
" " "	\$15.00/lb Present price
Building cost	\$100/ft ²
Labor cost	\$25,000/person per year
Power cost	\$0.01/KWH

Figure D-1

Cross sectional view of conceptual Nb-Ti superconductor
for large fusion magnets
(not to scale)

FIGURE D-2

Process flow sheet for large-scale production of
conceptual Nb-Ti superconductor for fusion magnets

Appendix E

Projected Cost of Nb₃Sn Superconductor (GE Process)

Precise answers to questions of processing techniques, current density in Nb₃Sn, etc. are understandably hard to obtain from manufacturers. However, from a variety of sources, both in the literature and private communications, it is possible to obtain a good picture of the manufacturing process and the characteristics of diffusion processed Nb₃Sn superconductor [hereafter referred to as the GE process for historical reasons].

Niobium foil with an admixture of zirconium (typically 1%) is dipped into a tin bath containing additives which promote both critical current capability and the reaction speed for Nb₃Sn formation. The Zr is primarily present as fine ZrO₂ particles generated by internal oxidation. When the tape is heated to a high temperature, ~1000°C, a Nb₃Sn diffusion layer forms. Without ZrO₂ doping, large columnar grains (1 to 2μ diameter) of Nb₃Sn form, while with the doping smaller equiaxed grains (0.5 to 1μ) form intermixed with the ZrO₂ precipitate [Benz (1)]. This doping accomplishes three important results:

1. The critical current density of the Nb₃Sn layer increases substantially.

2. The critical current density of the Nb_3Sn layer is constant with thickness (in the range investigated, 0-10 μ), instead of decreasing with increasing thickness as with the undoped niobium.
3. The critical current is virtually independent of the orientation of B to the tape as long as B is to I. That is, $I_{C\parallel} / I_{C\perp}$ is ~ 1 where $I_{C\parallel}$ has $B_{\parallel}$ to the wide face but to I, while $I_{C\perp}$ has $B_{\perp}$ to the wide face.

The latter result is also aided by the proper choice of reaction temperature. Reaction temperatures above 950°C tend to produce an anisotropy ratio $I_{C\parallel} / I_{C\perp}$ of ~ 1 [Jergel and Hlasnik (2)] while reaction temperatures between 900 and 950°C produce a ratio well above one.

Caslaw (3) has investigated the effect of additives to the tin bath and finds that copper is the only additive that both increases the rate of formation of Nb_3Sn and enhances critical current density. He finds that the critical current density is almost twice that given by Benz (1). The formation rate of the Nb_3Sn layer is quite rapid and 4.5 μ layers [thickness per side of tape] are formed in 3 minutes at 1000°C. Further the Nb_3Sn thickness is almost linearly proportional to reaction time [actually to (reaction time)^{0.9}], in contrast to the kinetic behavior without additives. Here the Nb_3Sn layer thickness is

found proportional to (reaction time)^{0.36} by Old et al. (4) and to (reaction time)^{0.5} by Smulkowski (5).

The reaction can be carried out in an inert atmosphere furnace [e.g., argon]. Generally, not all of the niobium foil is allowed to form Nb₃Sn. There is an unreacted Nb core which increases strength and handability of the Nb₃Sn tape.

After reaction, a stabilizing material, e.g., copper or high purity aluminum, can be bonded to the Nb₃Sn tape to reduce flux jumping. Both stabilizers are now offered commercially. The tape can also be soldered to stainless steel for additional structural strength. The properties of Nb₃Sn are reviewed by Echarri and Spadoni (6).

The conceptual conductor chosen for cost analysis is shown in Figure E-1 and its characteristics are given in Table E-1.

Two choices were made in the selection of this conceptual conductor:

1. The Nb₃Sn tapes are soldered to a 3 mil stainless steel backing strip to ensure adequate compressive stress on the Nb₃Sn during cooldown and magnet operation. The yield stress of high purity aluminum is so low (~1500 psi) that an aluminum only backing may be insufficient. This 3 mil strip is not the principal reinforcement for the magnet of course. Much thicker

stainless steel strip is wound in with the conductor when the magnet coil is wound. This 3 mil backing may not be essential since aluminum only backing with Nb_3Sn is being now used in small laboratory magnets. However, the additional stiffening does not greatly increase cost.

2. The conductor contains either 1 or 2 Nb_3Sn tapes (soldered together) with the tapes made from 1 mil $\text{Nb} + 1\% \text{ Zr}$ foil (thickness changes due to Nb_3Sn formation are neglected). It is possible to start with thicker foils and make thicker Nb_3Sn layers. However, there is much less experience with these thicker foils and the reaction times necessary for the thicker layers are not as well defined. If reaction layer thickness was linearly proportional to reaction time, and current density were independent of layer thickness (both probably somewhat optimistic assumptions) one would still require the same furnace volume. There would be small savings in not having to laminate Nb_3Sn ribbons together by soldering, and in reduced foil rolling costs. However, these savings must be balanced against the increased problems of mechanical integrity and the probably somewhat increased

furnace volume. It thus appears advantageous to select a foil thickness of ~ 1 mil. Smaller thicknesses are not as advantageous since foil rolling costs rapidly increase. For the conductor design shown in Figure E-1, 2 foils are laminated together, though the conductor may have just one foil. It is possible to laminate 3 or more foils together. Since the conductor is fully stabilized, 3 or more laminations should not present any stability problems. However, there is not enough experience to definitely prove the acceptability of 3 or more laminations. Two laminations seem quite satisfactory, however, and give results comparable to single ribbons. Thus either one or two Nb_3Sn ribbons will be used for the conductor depending on the range of magnetic field it is to be used in.

Various results for the critical current density of diffusion processed Nb_3Sn as a function of magnetic field are shown in Table E-2. The relative critical current densities are all normalized to 1 at 100 KG. For this study, the GE commercial (8) curve is adopted, together with a critical current of 750 A for 0.5 inch wide commercial ribbon of 1 mil overall thickness ($\text{Nb} + \text{Nb}_3\text{Sn}$) (8). This critical current corresponds to an

overall critical current density ($\text{Nb} + \text{Nb}_3\text{Sn}$) of $2.4 \times 10^5 \text{ A/cm}^2$. This current density, together with the normalized GE curve, is then used to calculate the critical current of a 10 cm wide, 1 mil thick $\text{Nb}_3\text{Sn} + \text{Nb}$ tape, as shown in the last column of Table E-2.

There is some difference between the normalized J_c vs B curves in Table E-2, but there is a much greater difference between Benz's (1) and Caslaw's (3) results for J_c at 100 KG, i.e., $2.4 \times 10^5 \text{ A/cm}^2$ vs 4.5 A/cm^2 . This results from Caslaw's use of copper additive in the tin bath. Benz (9) attributes the greater current density with copper additive to prevention of Nb_3Sn grain separation at the outer boundary of the Nb_3Sn layer. The critical current density of the Nb_3Sn grains has not been increased; rather, the grains are more effectively cemented together.

The Nb_3Sn critical current density in the 1 mil GE ribbon is not given, but judging from the amount of unreacted Nb and the overall critical current density, it is comparable to Caslaw's value.

The operating current of the 10 cm wide conductor for the fusion magnet is taken as 10 KA. This total current is carried by the one or more Nb_3Sn ribbons forming the conductor. With one ribbon, the 10 KA conductor can be used in fields up to

60 KG (Table E-1). At 60 KG the conductor critical current is 15 KA, so at this point, one would switch to a conductor with two laminated Nb_3Sn ribbons, which could be used up to 90 KG (Table E-1). Since a maximum of 2 laminated Nb_3Sn ribbons is allowed, fields above 90 KG require a number of parallel conductors. If 2 conductors, each with 2 laminated ribbons, are used in parallel, then 10 KA could be carried up to 120 KG (Table E-1), at which point the critical current of the 2 parallel ribbons is 15 KA. Similarly, 3 parallel conductors could be used up to 140 KG, 4 up to 150 KG, and 6 up to 160 KG. The rapid rise in number of conductors results from the rapid decrease in Nb_3Sn critical current densities. It does not seem practical to use Nb_3Sn for fields greater than 160 KG. Because of the condition that the aluminum stabilizer thickness be not less than 10 mils on each conductor, the I^2R heating/cm of edge if the Nb_3Sn goes normal drops below 0.3 watts/cm if multiple parallel conductors are used. If it proves practical to use thinner aluminum stabilizer or to use more than 2 Nb_3Sn lamina, some of the cost of the conductor for the very high field region can be saved.

The conductor design shown here is not optimized, but is representative. A constant Nb_3Sn thickness has been assumed along the conductor. This means that at the high field end of each conductor section that the operating current is 2/3 of the

critical current, but at the low field end, the operating current is more like 1/3 of the critical current. This provides a very large safety factor which not only may not be necessary, but may cause excessive diamagnetic currents. One might anticipate that considerable money could be saved if the Nb thickness could be varied along the conductor. This might be a difficult and costly rolling step however, and it is likely therefore, that no material savings could result from trying to reduce the Nb thickness. Thus one is pretty well restricted to a constant foil thickness. However, some savings could be effected by increasing the processing speed through the Nb₃Sn reaction furnace, so as to produce thinner Nb₃Sn layers on the tape for the low field ends. This would reduce the number and cost of furnaces needed. In addition to this type of cost saving one might anticipate similar savings in current capacity for conductors used in toroidal reactors where the field varies by a factor of 2 to 3 around a single turn of the coil. However, it is not certain that this variation is exploitable in a processing step.

The process parameters for the plant producing the conceptual GE Nb₃Sn superconductor for ~45,000 MW(e) fusion plants/year are given in Table E-3 and the process flow sheet in Fig. E-2. A length of 700 m per processed roll is chosen. Much longer lengths are not needed since several joints must be made in any

fusion coil to accomodate the conductor to the changing field. In the actual plant several different lengths would probably be processed. The 700 m length is representative, however, and corresponds to a difference of ~25 KG between ends if wound into a 10 m diameter fusion magnet coil.

The Nb_3Sn reaction time is 5 minutes, and it typical of present processes. According to Caslaw (3) results this will result in a total Nb_3Sn thickness of ~15 μ , leaving ~10 μ of unreacted Nb.

A vertical furnace is chosen, in accordance with commercial practice. The foil is wound onto a takeup reel at the top. It passes through a tin bath after leaving the bottom feed reel.

The processing speed through the reaction furnace is taken as 1.0 meter/minute, or about twice the present speed. This speed sets the height of the reaction zone at ~5 meters, or approximately double the present height. There does not seem to be any inherent reason why this greater height is not practical, as long as the foil is adequately guided through the reaction zone.

The furnace reaction zone is 8 inches in diameter with an argon atmosphere at slightly greater than 1 atm pressure. The Tape enters and leaves through cooler end zones with close fitting entrance and exit slits. The furnace heating power is on

the order of 50 KW. Because of the long vertical height several ceramic guides will probably be required. The reaction zone temperature is uniform to within a few degrees K and is $\sim 1000^{\circ}\text{C}$.

The width of the processed Nb_3Sn foil, 4 inches, is substantially greater than the maximum width of 1.25 inches made in commercial practice. However, people familiar with the manufacture of GE Nb_3Sn superconductors think that a 4 inch width is practical.

Each furnace processes two foils at the same time. At present, only one foil is processed per furnace. Multi-tape processing seems more efficient, and two tapes should be relatively easy. Three or more tapes might be more difficult, and would require some pilot plant experience. The two 4 inch wide tapes will fit comfortably inside the 8 inch ID furnace. They probably would use separate feed and takeup reels.

The processing time per 700 meter roll is thus ~ 12 hours, including time for loading and unloading rolls. As mentioned earlier, it may be desirable to process some rolls (or parts of rolls) through at a faster rate so as to limit the Nb_3Sn thickness and critical current capacity for the lower field ranges. The average output of the furnace would then be greater.

The overall yield for input foil to finished conductor is taken as 80%, with most of the loss occurring during the Nb_3Sn

reaction step. Current commercial rejection rates are 20-30%, and were much greater a few years ago. Improvements in process technology, plus the very important special condition that the fusion magnet conductor will be fully stabilized probably makes the rejection rate of 20% assumed for this study too pessimistic.

At present, the current capacity of the two ends of the processed tape are tested, and the lowest value is taken as the current capacity of the processed roll. This seems to be an adequate test for the fusion conductor, particularly since the conductor will be fully stabilized. Other methods of quality control, including photomicrographs would be employed.

The processing speed, throughput, and rejection rate, fix the number of operating furnaces as 47. Assuming 15% down at any one time for maintenance, etc., the number of installed furnaces is 56. This is a large number of furnaces, and could be reduced by faster processing speeds (with larger reaction zones) and/or operation with 3 or more tapes. However, there is some optimum operating point between a large number of simple low throughput furnaces, each relatively cheap, and a small number of complex high throughput furnaces, each relatively cheap, and a small number of complex high throughput furnaces, each relatively expensive. The nature of this optimum would have to

be determined by experience. The design considered here seems reasonable, however, and the costs are a small part of the total cost.

The reacted Nb_3Sn foils are then soldered together with aluminum stabilizer and stainless steel backing. The soldering speed is taken as 4 meters/minute, the same speed as for the NAL magnet conductor. It would seem that this flexible conductor could be soldered at a considerably faster rate. However, even with the low soldering rate, only 14 installed stands are required. Most of the conductor uses 2 Nb_3Sn lamina.

The estimated capital equipment costs for this plant are given in Table E-4. The most expensive part of the equipment are the 56 reaction furnaces at a total cost of 16.8 \$million. These furnaces are much less sophisticated than vacuum annealing furnaces operating at comparable temperatures. A much larger vacuum annealing furnace with rapid cycling provision (external cooling of inert gas flush) costs about 0.3 \$million. The Nb_3Sn reaction furnace on the other hand, is much smaller in volume and operates at constant temperature with an argon atmosphere at a constant pressure of slightly greater than one atm. The tin bath and feed and takeup reels do not seem like very difficult items. It thus appears that the estimated furnace cost should be conservative. The other costs also seem to be conservatively estimated.

The labor requirements for the plant are summarized in Table E-5. Round the clock operation is assumed for the reaction furnaces and soldering stands, while the quality control, administrative, etc., operations can be on a daily basis. The reaction furnaces will require approximately 16 man shifts/day for loading and unloading Nb and Nb₃Sn tapes, and about 8 man shifts/day for checking of operating variables. As at present, most of the time they run unattended. The total labor allotted for the reaction furnace is 141 man shifts/day. Some labor will be used in maintenance and repair operations, but it is doubtful that this could amount to more than 30 man shifts per day. This leaves almost 90 man shifts/day for other tasks. The labor estimates for the furnaces thus seem generously high and probably would be substantially less in an actual plant.

The estimates for soldering stands are also probably generous since the operation can be largely automated.

The estimate of 50 people for quality control is probably not an overestimate since ~200 processed rolls will have to be inspected and tested per day. It is likely that samples from a large number of rolls would be tested at the same time in a He dewar in order to reduce the amount of refrigeration necessary.

The estimated building area (Table E-6) corresponds to a 200 foot by 1000 foot building, which seems generous considering

the small amount of material processed/year--on the order of several million lbs/year. Each reaction furnace is allotted ~1000 ft², whereas its actual floor space will be on the order of 50 ft².

Table E-7 summarizes the various costs for the GE Nb₃Sn conductor. The total processing cost (reaction to Nb₃Sn, soldering to form conductor, quality control and overhead) amounts to ~20% of the finished conductor cost, assuming projected prices for Nb + 1% Zr foil and high purity aluminum, and ~10% at present prices for these materials. It thus appears that the final price of the finished conductor is primarily dependent on materials costs, not processing costs. Thus even though the processing costs may be overestimated, savings will not greatly reduce the cost of the finished conductor--more significant savings can be made by reducing the cost of materials.

Table E-8 gives the estimated cost of finished 10 KA conductor for various field ranges, for both present and projected materials costs. The conductor is quite cheap until 120 KG is reached. In the 150-160 KG range it is 3 times more expensive than at 120 KG.

Table E-9 lists the various cost factors used for cost analysis of GE Nb₃Sn superconductor.

What are the prospects of further cost reductions? Decrease in processing cost will not significantly lower the cost--rather one needs cheaper Nb + 1% Zr foil and aluminum, and higher critical current density. The prices projected for Nb + 1% foil and 5000 resistance ratio aluminum are probably somewhat high, but reduction by a factor of 2 or more do not seem likely. There has been a great deal of work on critical current capacity of diffusion processed Nb_3Sn , but it probably can still be further increased. It is not possible to estimate the likelihood of significant increases. With an increase of 2, however, the present conductor would carry 20 KA instead of 10 KA (it would require more stabilizer, however) and costs/KA-meter would almost be halved.

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Table E-1

Characteristics of Conceptual Nb₃Sn Superconductor
(GE Process) for Large Fusion Magnets

Width of conductor	10 cm
Number of Nb ₃ Sn tapes soldered together to form conductor	1 or 2
Number of Nb ₃ Sn layers in conductor	2 or 4
Number of unreacted Nb cores	1 or 2
Number of solder layers	2 or 3
Number of stainless reinforcing layers	1
Number of aluminum stabilizing layers	1
Thickness of stainless reinforcing layer	3 mil
Thickness of aluminum stabilizing layer	10 mil
Conductor operating current (includes all conductors in parallel)	10 KA
Conductor critical current	≥15 KA

<u>No. conductors in parallel for 10 KA current</u>	<u>No. of Nb₃Sn tapes in all conductors</u>	<u>Total watts/cm of edge if Nb₃Sn goes normal</u>	<u>Field at which I (operating)/I (critical) equals 2/3 (KG)</u>
1	1	0.3	60
1	2	0.3	90
2	4	0.15	120
3	6	0.1	140
4	8	0.075	150
6	12	0.05	160

Table E-2

Critical Current Density in Diffusion Processed Nb₃Sn TapesNormalization Factor for
Critical Current Density
in Nb₃Sn

B (KG)	Benz (1)	GE Commercial (7)	Caslaw (3)	Critical current for 10 cm wide foil 1 mil thick**
10	5.8	--	--	--
20	4.4	6.2	--	37.2
30	3.8	4.6	--	27.6
40	2.9	3.7	--	22.2
50	2.4	3.0	--	18.0
60	1.96	2.4	1.80	14.4
70	1.67	1.95	--	11.7
80	1.39	1.55	1.45	9.3
90	1.17	1.25	--	7.5
100	1.0(a)	1.0(b)	1.0(c)	6.0(d)
110	0.85	0.8	--	4.8
120	0.71	0.6	0.62	3.6
130	0.58	0.5*	--	3.0
140	0.48	0.4*	0.38	2.4
150	0.42	0.3*	--	1.8
160	0.34	0.2*	0.23	1.2

* Extrapolated

(a) J_c for Nb₃Sn = 2.4×10^5 A/cm² at 100 KG (1)(b) J_c for Nb₃Sn + Nb** = 2.4×10^5 A/cm² at 100 KG [based on ()](c) J_c for Nb₃Sn = 4.5×10^5 A/cm² at 100 KG (3)(d) Critical current for 0.5 inch wide Nb₃Sn + Nb ribbon (1 mil overall thickness)
is 750 A at 100 KG [Intermagetics tape] (8)** J_c includes unreacted Nb cross section - values based on GE commercial curve

Table E-3

Process Parameters for Large Scale Production
of GE Nb₃Sn Superconductor (4x10⁶ m²/year)

Feed Material

<u>Nb + 1% Zr foil</u>	<u>Basic Process Unit</u>
Width	3.94 in. (10 cm)
Thickness	1 mil (25.4 μ)
Length	700 meters
Area	70 m ²

Process Conditions

Reaction temperature	~1000°C
Reaction time	~5 minutes
Foil speed through reaction zone	1.0 meter/minute
Length of reaction zone	5 meters
Process time for 700m roll (including loading and unloading time)	12 hours
Overall yield, starting foil to finished product	80%
Number of rolls processed/ year	71,000
Number of finished rolls produced/year	57,000
Number of tapes processed per furnace	2
Number of operating furnaces	47
Number of installed furnaces (85% average operating capacity)	56
Soldering speed	4 meters/minute
Number of installed soldering stands	14
Number of operating stands	12

Table E-4

Capital Equipment Cost for Large Scale Production
of GE Nb₃Sn Superconductor (4x10⁶ m²/year)

Process Component	Unit Cost (\$ millions)	Plant Cost* (\$ millions)
1. 1000°C argon reaction furnaces (includes tin bath)	0.3	16.8
2. Soldering stands	0.4	5.6
3. Quality control equipment	-	5.0
4. Material handling equipment	-	<u>1.0</u>
		28.4

* Does not include engineering and testing (25% additional)

Table E-5

Labor Requirements for Large Scale Production
of GE Nb₃Sn Superconductor (4x10⁶ m²/year)

Process step	Unit labor requirements	Plant labor requirements (4 shifts)
1. Tinning and reacting to Nb ₃ Sn	1 shift per operating furnace	188
2. Soldering	2/shift/stand	96
3. Quality control	--	50
4. General materials handling	--	<u>20</u>
	Sub-total	354
5. Overhead (administrative, clerical, shipping and receiving)		<u>142</u>
	Total	496

Table E-6

Building Requirements for Large Scale Production
of GE Nb₃Sn Superconductor (4x10⁶ m²/year)

<u>Process Step</u>	<u>Building area, ft²</u>
1. Nb ₃ Sn reaction furnaces	60,000
2. Soldering stands	60,000
3. Quality control	35,000
4. Offices, shipping and receiving, etc.	45,000
Total	200,000

Table E-7

Cost Summary for Large Scale Production
of GE Nb₃Sn Superconductor (4x10⁶ m²/year)

<u>Process Step</u>	<u>Plant cost (\$ millions/year)</u>	<u>Unit cost (\$/m²)</u>
1. Formation of Nb ₃ Sn Layer		
Labor	4.7	1.18
Capital Equipment*	6.9	1.72
Buildings	<u>1.5</u>	<u>0.38</u>
	13.1	3.28
2. Soldering to form conductor		
Labor	2.4	0.60
Capital Equipment*	2.3	0.58
Buildings	<u>1.5</u>	<u>0.38</u>
	6.2	1.56
3. Quality control		
Labor	1.25	0.31
Capital Equipment*	2.10	0.52
Buildings	<u>0.88</u>	<u>0.22</u>
	4.23	1.05
4. Overhead and materials handling		
Labor	4.05	1.01
Capital Equipment*	0.41	0.10
Buildings	<u>1.12</u>	<u>0.28</u>
	5.58	1.39
Total processing cost	\$ 29.11 million/yr	\$ 7.28/m ²

	<u>Cost of Finished Conductor (\$/m)</u>			
	<u>1 Tape</u>		<u>2 Tape</u>	
	<u>Projected materials cost</u>	<u>Present materials cost</u>	<u>Projected materials cost</u>	<u>Present materials cost</u>
Power, solder, & tin	0.11	0.11	0.12	0.12
Nb + 1% Zr foil (1 mil)	1.15	6.00	2.30	12.00
Processing cost	1.00	1.00	1.46	1.46
Aluminum stabilizer	0.60	2.35	0.60	2.35
Stainless backing	<u>0.16</u>	<u>0.16</u>	<u>0.16</u>	<u>0.16</u>
Total	3.02	9.62	4.64	16.10

*Includes engineering, testing, and maintenance

Table E-8

Cost of Finished 10 Ka Conductor (GE Nb₃Sn)
vs Magnetic Field

<u>B (kG)</u>	<u>Cost of 10 KA Conductor*</u> <u>(\$/m)</u>	
	<u>Projected materials cost</u>	<u>Present materials cost</u>
0 - 60	3.02	9.62
60 - 90	4.64	16.10
90 - 120	9.28	32.20
120 - 140	13.92	48.30
140 - 150	18.56	64.40
150 - 160	27.84	96.60

*Ready to wind into coil - includes
 stabilizer and SS backing

Table E-9

Cost Factors Used in Analysis of GE Nb₃Sn Ribbon

Nb + 1% Zr foil (1 mil)	\$19.00/lb
Aluminum (5000 resistance ratio) 10 mil	\$3.80/lb
Stainless steel foil (3 mil)	\$1.30/lb
Buildings	100/ft ²
Labor	\$25,000/yr per person
Solder	\$1.00/lb
Tin	\$1.50/lb
Power	\$0.01/KW H

Figure E-1

Conceptual Nb_3Sn superconductor (GE Process) for large fusion magnets
(not to scale)

FIGURE E-2

Process flow sheet for large-scale production of
conceptual GE Nb_3Sn superconductor for large
fusion magnets

Appendix F

Projected Cost of Nb₃Sn Superconductor (Linde Process)

In the Linde process for Nb₃Sn superconductor, a mixture of Nb and Sn powder is sprayed onto a copper substrate at ambient temperature by a plasma torch (1). The Nb + Sn layer and substrate are then heat treated at ~800°C for ~1 hour to form Nb₃Sn. The copper substrate thickness is typically between 15 and 30 mils, while the Nb₃Sn thickness is typically between 3 and 8 mils (actual thickness). The Nb₃Sn layer is porous with a density about 75% of theoretical so that the equivalent thickness range on the basis of 100% density would be 2-6 mils. The greatest critical current densities are obtained with a Nb/Sn volume ratio of about 4/1, so that the deposited Nb₃Sn layer contains excess Nb. The Nb and Sn particle diameter is typically 30-40 μ. The argon plasma torch pressure is slightly greater than one atm, and deposits a fairly uniform Nb₃Sn layer on a 0.5 inch wide substrate.

The Nb-Sn powder is fluidized with argon, and the gas-solids mixture is fed to the torch. Torch power is typically 10 KW, and torch lifetime is typically on the order of one year. The copper anodes must be replaced much more often, however, i.e., on the order of every few hours. At present, about 50% of the powder

feed to the torch is lost because it misses the tape (0.5 inch wide). This powder is not recycled since it is partially oxidized (at present, the plasma spraying is done in air).

It is possible to plasma spray pre-reacted Nb_3Sn powder on the substrate, and at first glance this would appear very desirable. Unfortunately, the high torch temperature decomposes the Nb_3Sn powder, and the resulting deposit is essentially the same as if $\text{Nb} + \text{Sn}$ powder had been used. The 800°C heat treatment must then be used to get the proper β -tungsten structure for Nb_3Sn . The necessity of this heat treatment thus prevents plasma spraying onto an aluminum substrate, or any other low temperature substrate. Steel or other high temperature substrates can be used if desired, though adequate cryogenic stabilization must be ensured.

Substrates thinner than 15 mils can probably be used, but will require further development. Substrates thicker than 30 mils are not needed, are costly and the Nb_3Sn layer is more prone to fracture when coiled the wrong way (the layer is further from the neutral axis). Nb_3Sn layers thinner than 3 mils tend to be too non-uniform, while layers thicker than 8 mils tend to crack too easily. These limits can probably be extended with further development.

For purposes of this study the conceptual Nb_3Sn plasma sprayed superconductor shown in Figure F-1 and with characteristics outlined in Tables F-1 and F-2 is chosen. The conductor width is 10 cm wide, and the substrate is 15 mil copper. The Nb_3Sn layer is assumed to be of uniform thickness across the substrate. Actually, one of the advantages of the Linde process is that non-uniform layers can be deposited. For example, one could deposit several 1/2 to 3/4 inch wide strips of Nb_3Sn along a much wider substrate, with only normal metal between the strips. This would limit the likelihood of flux jumps at one location triggering adjacent regions of Nb_3Sn . In addition, the strips of Nb_3Sn could be interrupted every few meters without serious increase in refrigeration load. This would be equivalent to a twisted multifilament conductor in that persistent eddy currents would decay away in a reasonable time. However, questions of stress intensification at edges and their effect on the aluminum stabilizer must be investigated before this could be considered feasible. For purposes of cost estimation, the assumption of uniform Nb_3Sn thickness is reasonable.

There is only one set of experimental results for plasma sprayed Nb_3Sn superconductor (1). This set was taken on a 0.25 inch wide conductor [30 mil copper substrate, 3 mil (100% density) Nb_3Sn layer] for field values from 30 to 105 KG. The corresponding critical current densities in the Nb_3Sn layer are given in

Table F-2 [J_c is given in terms of Nb_3Sn of 100% density]. From these values of J_c , critical current are calculated for 10 cm wide conductor with varying thicknesses of Nb_3Sn . This assumes that critical current density is independent of conductor width and Nb_3Sn thickness. These assumptions seem reasonable, considering the highly disordered, random structure of the plasma sprayed Nb_3Sn layer. The critical current is also assumed isotropic with B [I_c independent of field angle, as long as B is $\perp$ to I]. This is true of diffusion processed Nb_3Sn with very small random grain structure (2), and would be expected to be true for the plasma sprayed Nb_3Sn .

Critical current densities outside the experimentally measured range are obtained by applying ratios found for diffusion processed Nb_3Sn . When the experimentally measured current density for plasma sprayed Nb_3Sn is divided by the experimentally measured current density for diffusion processed, ZrO_2 doped Nb_3Sn (2) [but without copper additive], a smoothly varying ratio is found, with a smallest value of 0.24 at 30 KG and increasing monotonically to 0.33 at 110 KG. The 0.24 ratio is assumed to apply for fields below 30 KG and the 0.33 ratio for fields above 110 KG; the critical current density for plasma sprayed Nb_3Sn outside the experimental range of 30 to 110 KG is then obtained from these ratios and the experimental values for diffusion processed ZrO_2

doped Nb_3Sn (2). This probably underestimates the critical current density above 110 KG.

It is interesting to note that the critical current density for plasma sprayed Nb_3Sn is a factor of 3 to 4 times lower than that for diffusion processed ZrO_2 doped Nb_3Sn , and approximately 6-8 times lower than that of diffusion processed ZrO_2 doped Nb_3Sn using copper additive in the tin bath. This suggests that it may be possible to substantially increase the critical current density of plasma sprayed Nb_3Sn by the use of additives and/or smaller powder sizes. Very little work has been done on methods of increasing critical current density in plasma sprayed Nb_3Sn while a great deal of work has been done on diffusion processed Nb_3Sn .

The Linde process gives one the capability of continuously varying the thickness of the deposited Nb_3Sn along the conductor in an easily controlled manner. For example, the feed rate of solids to the torches can be pre-programmed so as to start with a 2 mil layer of Nb_3Sn (100% density) at one end of the conductor and to finish with a 6 mil layer (100% density) at the other end, with a pre-determined thickness at all points in between. With this method one can conserve Nb_3Sn and reduce costs, by depositing on the tape only the amount of Nb_3Sn needed for the local value of magnetic field.

However, since there are physical limits on Nb_3Sn thickness (≤ 6 mils and ≥ 2 mils at 100% density), it would be uneconomical to use one tape for the full range of magnetic field from 0 to 160 KG. As with the GE tape one will probably use multiple parallel tapes, with the number of parallel tapes dependent on the field.

The conceptual plasma sprayed Nb_3Sn in Figure F-1 and F-3 and its characteristics are given in Table F-1. The width is 10 cm, the copper backing thickness is 15 mils, and the aluminum stabilizer and Nb_3Sn thickness are variable, depending on the field range that it is to be used in. The total conductor current is 16 KA. For fields ≤ 42 KG only one plasma sprayed Nb_3Sn tape is needed for the conductor with an aluminum stabilizer thickness of 26 mils. For fields from 42 to 95 KG two plasma sprayed tapes in parallel are needed, each carrying 8 KA. The aluminum stabilizer thickness is 13 mils for each tape. For fields from 95 to 125 KG, 3 parallel tapes are required, each carrying 5.33 KA. The aluminum stabilizer thickness is 10 mils on each tape. A thinner stabilizer could be used and still meet the criterion that the I^2R heating/edge be 0.3 W/cm (for full transport current in the stabilizer), but a lower limit of 10 mils on aluminum thickness has been imposed for mechanical reasons. Thus the total maximum I^2R heating/edge drops to 0.26 W/cm. Table F-3 gives the field range and number of parallel tapes for

fields up to 160 KG, along with the Nb_3Sn on each tape at 42 KG, 4 mils at 62 KG, and so on. Because the Nb_3Sn thickness varies with field, the operating/critical current ratio is always $2/3$ (critical current equals 24 KA) regardless of field. This is in contrast to the GE tape where the Nb_3Sn thickness is constant, and the operating/critical current ratio is $\leq 2/3$.

Because the Nb_3Sn is deposited on copper strip, it is not considered necessary to add a stainless steel reinforcing strip to the conductor (the steel would only be used to provide a compressive stress on the Nb_3Sn , not to contain hoop forces in the magnet coil). It may be possible to use thinner copper strip, but more development work on the plasma spray process would have to be done before this would be considered.

Critical current vs field characteristics for the conceptual plasma sprayed Nb_3Sn superconductor are summarized in Table F-2.

The process flow sheet for production of the conceptual conductor is given in Figure F-2, and the process parameters in Table F-4. A production rate of 2×10^7 m/year is assumed. This value refers to total length of single tape, not 16 KA conductor. Thus, for example, if an average of 2 tapes is used in parallel to make a 16 KA conductor, the total length of 16 KA conductor produced/year would be 10^7 m.

The tape speed rate is 3 meters/minute, the same rate as presently used for deposition of a 3 mil layer of Nb_3Sn

(100% density). A varying thickness of Nb_3Sn could be deposited either by changing the gas-solids flow rate to the torches, as previously discussed, or by keeping the gas-solids flow rate constant and varying the tape speed rate. Either can easily be done since the time rate of variation of the feed parameter is extremely small, i.e., $\sim 1\%$ /minute. If the tape feed rate is varied, then 3 meters/minute is the average tape speed.

At present Linde uses a single fixed plasma torch with a deposition zone of ~ 0.75 inch effective diameter. The 0.5 inch wide ribbon moves through this deposition zone at 3 meters/minute.

In the process envisaged here, there are four fixed torches, each with an effective deposition zone diameter of about one inch. The torch centers are spaced one inch apart along a line transverse to the moving tape (the centers of the two outside tapes are located 0.5 inch in from the edges of the tapes), and the torches are spaced ~ 1 foot apart along the moving tape. This latter spacing keeps tape temperature low. The Nb_3Sn thickness will vary slightly along a line transverse to the moving tape, but this does not present any problem. Unplanned variation of Nb_3Sn cross section along the tape should be minimized, so as to keep critical current capacity constant. Because of the 4 torch arrangement, it is likely that the variation along the tape due to torch fluctuations will be substantially less than that of

the present Linde tape with one torch (which variation is still perfectly acceptable).

Very uniform layers can be achieved by Linde by making many passes over a surface with a moving plasma torch. One could conceive of applying the same technique to the moving 4 inch tape, that is, either having a much larger number of fixed torches, each depositing a small fraction of the total thickness, or having moving torches swing back and forth across the tape. However, such refinements are complicated and do not seem necessary. With further development, high tape feed speeds should be achievable, though more torch power would be required.

The basic tape length/roll is taken as 1000 meters, or enough for ~30 turns on a typical fusion magnet coil. This is of the order of length between the joints that will be required because of the necessity of using more conductors as field increases. This tape length will require ~6 hours to process, including loading and unloading.

The tape roll will be ~3 feet in diameter and weigh ~1000 lbs. Each plasma spraying stand is designed to process two rolls at once. More could be processed if desired. The optimum number would have to be determined from experience, balancing equipment vs labor cost.

A 15% down time for the plasma spraying stand is assumed for maintenance, inspection, etc. The plasma torches and gas-solid feeders would be capable of quick disconnection so that their maintenance would be done separately without tying up the plasma spraying stand. The only equipment of concern would then be the feed and takeup rolls, together with the wire scraping brush that cleans the surface of the copper tape. These should require very little maintenance, and thus the plasma spraying stand probably can operate with less than 15% down time.

The heat treatment furnaces are fairly simple; the temperature is moderate, $\sim 800^{\circ}\text{C}$, the time short, ~ 1 hour, and an inert gas atmosphere is satisfactory. The heat treatment of the plasma sprayed Nb_3Sn is much easier than the vacuum annealing of cold rolled Nb strip (Appendix A).

The soldering speed is taken as 4 meters/minute, the same as that for the NAL strip. The conductor is approximately twice as wide but the soldering involves only three strips instead of four. Higher soldering speeds should be easily achieved. The average down time is taken as 15%, which is reasonable on the basis of experience.

Both the plasma spraying and soldering stand are operated on a round-the-clock basis.

Each plasma spraying region is in an inert (argon, p slightly greater than 1 atm) atmosphere enclosure, with the moving tape feeding into and out of the enclosure. Any Nb + Sn powder that is not deposited on the tape is periodically collected and recycled to the torch. At present the plasma torch sprays into an air atmosphere, and any Nb that is not deposited is oxidized too much to be recycled.

A rejection rate of 10% is assumed for the finished tape. This seems conservative, considering that the conductor is fully stabilized. The torches run smoothly and no significant operational variations are expected.

Estimated capital equipment costs and labor requirements are summarized in Tables F-5 and F-6. The estimates for furnace costs and labor are based on estimates made for vacuum annealing furnaces, while those for the soldering stands on observation of processing of the NAL conductor strip. Each plasma spraying stand is assumed to cost one \$million. This is probably much too high considering the inherent simplicity of the operation. The feed, takeup, and tape cleaning operations are quite simple and should be very cheap. At \$30,000 per torch the 8 torches on a plasma spray stand (plus 100% extra for replacements during maintenance) would cost \$480,000. The inside design of the Linde plasma spray torches is not given but judging from published information on plasma torches, a cost of \$30,000/torch

seems quite high. A yearly cost of \$30,000/operating torch for replacement parts (chiefly anodes) is also assumed. To put it another way, there is an inventory of 144 torches in the plant at an estimated initial cost of \$4.3 million and a yearly servicing cost of \$2.2 million for 72 operating torches.

Two operators per shift are assigned to each plasma spray stand; this is probably somewhat greater than needed, considering the automatic operation of the torches.

The estimated building areas for the plant are given in Table F-7. They seem quite ample.

The cost summary for the finished superconductor is given in Table F-8, and the individual cost factors that were used are given in Table F-10. The total cost of processing (not including Nb, Sn, Cu, Al, power, solder, and torch replacements) is slightly greater than \$1/meter of individual tape. This is ~25% of the total cost of the finished 16 KA conductor using projected materials costs and only ~10\$ using present materials costs. Thus the Linde plasma sprayed superconductor is similar to the other superconductors in this study in that the predominant part of the manufacturing cost is for materials.

The cost of the finished 16 KA conductor is given in Table F-9 as a function of magnetic field from 0-160 KG. There is an approximately 6 to 1 variation in conductor cost over this field

range. The cost at high fields can be reduced somewhat by using cheaper, lower resistance ratio aluminum stabilization, or by using, if feasible, less than 10 mils of the 5000 resistance ratio aluminum.

It is interesting to note that the total cost of the 16 KA conductor using present material costs is only about twice that using projected prices. This is a result of the smaller difference between the projected and present price for Nb powder than the difference between the projected and present price for Nb + 1% Zr foil.

Table F-11 summarizes some of the factors that may further reduce the price of Linde plasma sprayed Nb₃Sn superconductor. Process improvements and lower equipment and labor costs should lower costs; however, the processing cost even now is a small part of the total, so really significant reductions in total cost would not result even if processing costs were halved.

Lower materials costs would help, but a factor of two reduction below \$4.50/lb for Nb powder does not appear likely.

The principal cost reduction will come in the improvement of critical current density. If it is possible to double or triple critical current density, the finished conductor cost would be reduced by almost the same factor. Since very little research has been done on this conductor, this appears to offer the greatest hope of large cost reductions.

References

1. Fietz, W. A. and Reese, R. A., "Plasma Plated Superconducting Devices," XIII International Conference of Refrigeration, Washington, D.C. (August 1971).
2. Benz, M. G., "Superconducting Performance of Diffusion Processed Nb_3Sn Doped with ZrO_2 Particles," Trans - AIME, 242, 1067 (1968).

Table F-1

Characteristics of Conceptual Nb₃Sn Superconductor
(Linde Process) for Large Fusion Magnets

Conductor width	10 cm
Nb ₃ Sn thickness (actual)	2.7-8 mils
Nb ₃ Sn thickness (100% density)	2-6 mils
Copper strip thickness	15 mils
Nb/Sn powder volume ratio	4/1
Total conductor operating current	16 KA
Total conductor critical current	24 KA
Total aluminum stabilizer thickness	≤26 mils
Total I ² R heating for full transport current in stabilizer	≤0.3 w/cm of edge

Table F-2

Critical Current Characteristics of Linde Nb₃Sn Superconductor

B (KG)	Experimental* I _c (A _{mp})	Experimental J _c (A/cm ²)	I _c (calculated) for 10 cm strip (KA) Thickness of Nb ₃ Sn Layer** (mils)				
			2	3	4	5	6
10	-	3.4† x10 ⁵	17.3	26.0	34.7	43.3	51.9
20	-	2.5†	12.8	19.2	25.5	32.0	38.4
30	1030	2.13	10.8	16.2	21.6	27.0	38.4
40	800	1.66	8.5	12.6	16.9	21.0	25.2
50	680	1.41	7.2	10.7	14.3	17.8	21.4
60	590	1.22	6.2	9.3	12.4	15.5	18.6
70	520	1.08	5.5	8.2	11.0	13.7	16.4
80	460	0.95	4.8	7.25	9.7	12.1	14.5
90	405	0.83	4.2	6.4	8.5	10.6	12.8
100	365	0.75	3.8	5.75	7.65	9.6	11.5
110	325	0.67	3.4	5.1	6.8	8.5	10.2
120	-	0.56†	2.8	4.2	5.7	7.1	8.4
130	-	0.46†	2.3	3.4	4.7	5.9	6.9
140	-	0.38†	1.9	2.8	3.9	4.9	5.7
150	-	0.33†	1.7	2.6	3.4	4.2	5.1
160	-	0.27†	1.4	2.1	2.8	3.5	4.2

* Measurements made on 0.25 inch wide conductor (1) Nb₃Sn layer 4 mils thickness (equivalent to 3 mils at 100% density). Substrate is 30 mils of copper.

** Thickness of Nb₃Sn in terms of 100% density layer. Actual density is ~75%.

† Extrapolations based on measurements of diffusion processed Nb₃Sn (2).

Table F-3

Current and Field Characteristics of Conceptual
16 KA Linde Plasma Sprayed Nb₃Sn Superconductor
for Large Fusion Magnets

<u>Operating Field(KG)</u>	<u># of Tapes in Parallel</u>	<u>Nb₃Sn Thickness (100% den- sity) mils</u>	<u>Stabilizer Thickness Conductor (mils)</u>	<u>Walls/cm of edge (Total)</u>	<u>Individual Conductor Current(KA)</u>
8	1	2	26	0.3	16
12	1	3	"	"	"
22	1	4	"	"	"
35	1	5	"	"	"
42	1	6	"	"	"
-	2	2	13	0.3	8
42	2	3	"	"	"
62	2	4	"	"	"
80	2	5	"	"	"
95	2	6	"	"	"
-	3	2	10	0.26	5.33
-	3	3	"	"	"
95	3	4	"	"	"
113	3	5	"	"	"
125	3	6	"	"	"
-	4	2	10	0.20	4.0
-	4	3	"	"	"
-	4	4	"	"	"
125	4	5	"	"	"
135	4	6	"	"	"
-	6	2	10	0.13	2.33
-	6	3	"	"	"
135	6	4	"	"	"
150	6	5	"	"	"
160	6	6	"	"	"

Table F-4

Process Parameters for Large Scale Production
of Nb₃Sn Superconductor (Linde Process)
(2 x 10⁷ m/year)

Tape feed rate	3 meters/minute
Powder composition	80% Nb, 20% Sn (volume)
Torches	4 torches/tape 10 KW/torch 1 year torch lifetime
Number of tapes produced/stand	2
Length of conductor tape roll	1000 meters
Width of conductor tape	0.1 m
Plasma spray time/roll	5.5 hours
Load and unload time	0.5 hours
Weight of 1000 meter roll	1000 lbs
Number of tape rolls produced/year (pass quality control)	20,000
Rejection rate of finished tape	10%
Average down time/plasma spraying stand (maintenance, etc.)	15%
Number of installed plasma spraying stands	9
Heat treatment	800°C, 1 hour
Furnace atmosphere and pressure	argon, 1 atm
Soldering speed of tapes	4 meters/minute
# of tapes soldered/soldering stand	1
Soldering stand, average down time	15%
# of installed soldering stands	12
Torch power in plant	720 KW
Total plant power	10 MW

Table F-5

Capital Equipment for Large Scale Production

of Nb₃Sn Conductor (Linde Process)
 (2 x 10⁷ m/year)

<u>Process Step</u>	<u>Unit Cost</u> <u>(\$ millions)</u>	<u>Plant Cost</u> <u>(\$ millions)</u>
1. Plasma spraying stand (torches, instrumentation, powder feeders, inert atm., etc.)	1.0	9.0
2. Furnaces for heat treatment	0.3	0.6
3. Soldering stand	0.3	3.6
4. Material handling equipment	-	1.0
5. Quality control equipment	-	<u>2.0</u>
	Total	16.2

Table F-6

Labor Requirements for Large Scale Production

of Nb₃Sn Conductor (Linde Process)
(2 x 10⁷ m/year)

<u>Process Step</u>	<u>Unit Labor Requirements</u>	<u>Plant Labor Requirements</u>
1. Plasma spray	2/shift/stand	72
2. Heat treatment	-	15
3. Soldering	2/shift/stand	96
4. Quality control	-	30
5. General material handling	-	<u>20</u>
	Sub-total	233
6. Overhead (administrative, clerical, shipping and receiving, etc.)		<u>92</u>
	Total	325

Table F-7

Building Requirements for Large Scale Production
of Nb₃Sn Superconductor (Linde Process)
 (2 x 10⁷ m/year)

<u>Process Area</u>	<u>Plant Area, ft²</u>
Plasma spraying	40,000
Heat treatment	20,000
Soldering	60,000
Quality control	20,000
General (shipping & receiving, offices, etc.)	<u>40,000</u>
Total	180,000

Table F-8

Cost Summary for Large Scale Production
 of Nb_3Sn Superconductor (Linde Process)
 (2×10^7 m/year)

<u>Process step</u>	<u>Plant cost (\$ millions)</u>	<u>Unit cost (\$/m)</u>
1. Materials (except tin, niobium, and aluminum)		
Power (total plant)	0.88	0.044
Torch replacements	1.44	0.072
Copper (15 mils - including reject strip)	16.7	0.835
Solder (3 mils)	<u>3.0</u>	<u>0.150</u>
	22.0	1.10
2. Plasma spraying		
Labor	1.80	0.09
Capital Equipment*	3.70	0.18
Buildings	<u>1.00</u>	<u>0.05</u>
	6.50	0.32
3. Heat treatment		
Labor	0.38	0.019
Capital Equipment*	0.24	0.012
Building	<u>0.50</u>	<u>0.025</u>
	1.12	0.056
4. Soldering		
Labor	2.40	0.120
Capital Equipment*	1.50	0.075
Building	<u>1.50</u>	<u>0.075</u>
	5.40	0.270
5. Quality control		
Labor	0.75	0.037
Capital Equipment*	0.85	0.042
Building	<u>0.50</u>	<u>0.025</u>
	2.10	0.104

Table F-8 (cont'd)

<u>Process step</u>	<u>Plant cost (\$ millions)</u>	<u>Unit cost (\$/m)</u>
6. Overhead and General materials handling		
Labor	2.80	0.14
Capital Equipment*	0.40	0.02
Building	<u>1.00</u>	<u>0.05</u>
	4.20	0.21
Totals	41.32	2.06

	<u>(\$/m)</u>
Material cost of Nb ₃ Sn layer/mil projected prices**	\$ 0.210
Material cost of aluminum stabilizer/mil projected prices	0.060
Material cost of Nb ₃ Sn layer/mil present prices **	0.70
Material cost of Nb ₃ Sn layer/mil present prices	0.240

*Capital equipment includes depreciation and interest charges, engineering and testing, and maintenance.

**Includes cost of reject material.

Table F-9

Cost of Finished 16 KA Conceptual Nb₃Sn Superconductor
(Linde Process) as a Function of Field

Cost of finished 16 KA conductor
(\$/m)

<u>Magnetic field (KG)</u>	<u>No. of conductors in parallel</u>	<u>Nb₃Sn thickness (100% density) mils</u>	<u>Projected material costs</u>	<u>Present material costs</u>
8	1	2	\$ 4.10	\$ 9.70
12	1	3	4.30	10.40
22	1	4	4.50	11.10
35	1	5	4.70	11.80
42	1	6	4.90	12.50
42	2	3	7.00	14.50
62	2	4	7.40	16.00
80	2	5	7.80	17.40
95	2	6	8.20	18.80
95	3	4	10.50	21.80
113	3	5	11.10	23.90
125	3	6	11.80	26.00
125	4	5	14.80	31.80
135	4	6	15.70	34.60
135	6	4	26.00	43.60
150	6	5	22.20	47.80
160	6	6	23.50	52.00

Table F-10

Cost Factors Used for Cost Analysis
of Nb₃Sn Superconductor (Linde Process)

Nb powder	\$ 4.50/lb	(projected)
Nb powder	15.00/lb	(present)
Sn powder	1.50/lb	
Aluminum stabilizer (5000 resistance ratio)	3.80/lb	(projected)
Aluminum stabilizer	15.00/lb	(present)
Solder	1.00/lb	
Copper	1.00/lb	
Power	0.01/KWH	
Labor	\$25,000/yr per person	
Buildings	\$100/ft ²	
Torch replacements	\$30,000/yr per torch	

Table F-11

Factors That Should Lower the Costs
of Linde Nb₃Sn Superconductors

1. Increased lineal current density of Nb₃Sn layer
 - a) smaller Nb and Sn particle size
 - b) additives, e.g., copper, in Nb + Sn plasman spray
 - c) greater Nb₃Sn thickness
2. Lower materials costs
 - a) use of cheaper Nb - either less pure Nb [fewer EB melts] or Nb prepared by Dupont process [H₂ reduction of NbCl₅]
 - b) use of cheaper Al stabilizer [lower resistance ratio]
3. Process improvements
 - a) wider substrates
 - b) longer torch lifetime
 - c) faster rates of deposition and soldering
4. Cost improvements
 - a) longer write-off times
 - b) lower labor, equipment, and building costs

Figure F-1

Conceptual Nb_3Sn superconductor (Linde Process) for large
fusion magnets
(not to scale)

FIGURE F-2

Process flow sheet for large-scale production of conceptual Nb_3Sn superconductor (Linde Process) for fusion magnets

Appendix G

Cost of V_3Ga Tape Superconductor

V_3Ga tape superconductor has recently developed as a commercial superconductor in Japan by the Sumitomo Electric Company (1). No commercial V_3Ga tape is produced in the U.S. In comparison with the GE Nb_3Sn tape, there has been relatively little research on V_3Ga superconductor, both in processing technology and superconductor field and current characteristics. Significant improvement is likely for V_3Ga tape.

There are important differences in processing V_3Ga and Nb_3Sn diffusion tape. The niobium tape is dipped in molten Sn, and then reacted at very high temperatures for a short time (~ 5 minutes at $\sim 1000^\circ C$). In this short time, a $10\ \mu$ thick Nb_3Sn layer forms on both sides of the tape. The vanadium tape is dipped into molten Ga at $\sim 700^\circ C$ to form two layers ($\sim 4\ \mu$ thick) of V_3Ga_2 and VGa_2 (2),(3). The dipped tape is then coated with $\sim 5\ \mu$ of copper on both sides and heat treated at relatively low temperature ($\sim 700^\circ C$) for long times (~ 100 hours). The V+Ga layer changes to V_3Ga and increases to $\sim 10\ \mu$ in thickness. The excess Ga is extracted into the $5\ \mu$ copper layer, yielding as nominal concentration of ~ 15 atomic % Ga in copper.

The low heat treatment temperature, and consequent long reaction time, appear to be necessary to achieve adequate critical

current density. Heat treatment temperature of 800°C or higher yield very low critical densities, probably because of large V_3Ga grain size (2).

These processing restrictions do not seem to pose any difficulties in manufacturing large amounts of V_3Ga tape.

Critical current data is limited, and the three available sets of critical current density data are given in Table G-2. The Sumitomo values are for short samples of commercially produced V_3Ga tape (1) and Tachikawa's values are for laboratory experiments (2), (3). The particular values given here are for vanadium ribbon (no Zr addition) reacted with Ga at 675°C for 40 hours. They are close to the peak values obtained by Tachikawa. They are substantially higher than the critical current densities for Sumitomo tape, by more than a factor of two above 150 KG. Suenaga and Sampson's data (4) is also higher than that for the Sumitomo tape, though their data was taken from 3 mil V wires with 1-2 μ V_3Ga outer layer in a copper matrix.

It is very likely that substantial improvements will be made over the Sumitomo critical current density. There are indications that ZrO_2 to achieve small grain size will increase flux pinning, and the heat treatment conditions have probably not been fully optimized. For this study, however, the Sumitomo critical current densities have been adopted

and used to calculate the critical current of 10 cm wide V_3Ga tape (last column in Table G-2). As can be seen, the critical current for V_3Ga is substantially less than that of Nb_3Sn , for fields less than 150 KG.

The characteristics of a conceptual fusion magnet conductor (shown in Figure G-1) are given in Table G-1. As with the diffusion processed Nb_3Sn tape, a limit of two tapes is allowed per individual conductor. These two tapes are soldered together, with a 10 mil aluminum stabilizer (5000 resistance ratio) on one side. It would be desirable, if feasible, to solder more tapes together since the critical current density is so low in V_3Ga . The possibility would have to be experimentally investigated, however. It should be noted that the V_3Ga tapes are more than twice as thick as the Nb_3Sn tapes, since one starts out with 2 mil vanadium foils instead of 1 mil Nb foils, and then has an additional 10 μ of copper-gallium alloy per V_3Ga tape. Two V_3Ga tapes soldered together thus probably are more of a stability problem than two Nb_3Sn tapes because of greater thickness through the lower critical current of V_3Ga is a counterbalancing factor. No stainless steel stiffening strip is included. With the GE Nb_3Sn conductor (Appendix E), the amount of remaining Nb was not considered enough to provide adequate stiffening. With V_3Ga considerably more vanadium is left, and should be adequate.

A number of individual conductors, each with two V_3Ga tapes, are paralleled to carry the desired conductor current. In this study, 10 KA conductor current is assumed. With 4, 5, 6, or 7 parallel individual conductors, it is possible to carry 10 KA without exceeding the limit that operating current be less than or equal to two-thirds of the short sample critical current. The field ranges corresponding to the number of parallel conductors are given in Table G-1. A 10 KA conductor with four parallel individual conductors can be used for fields up to 115 KG, for example, while a 10 KA conductor with five parallel individual conductors can be used up to 140 KG [one would not use it below 115 KG since four parallel conductors would suffice there].

The other limit, that I^2R heating not exceed 0.3 w/cm of conductor edge if the full transport current flows in the stabilizer, is easily met. For the four parallel conductor case, the total I^2R heating for the 10 KA conductor is only 0.075 watts/cm of edge; and proportionately less as the number of parallel conductors increases. One could safely use thinner aluminum stabilizers if mechanical integrity permits, or lower resistance ratio aluminum. However, the aluminum cost is small compared to that of vanadium and gallium.

The process parameters for large scale production of the conceptual V_3Ga superconductor are given in Table G-3, and are modeled as closely as possible on present practice (even though that practice is probably not optimum). A 1% Zr concentration has been assumed in the vanadium foil, though no increase in critical current density has been assumed [as an aside, it is not known by the author whether the Sumitomo commercial tape contains Zr].

The weight of gallium required per m^2 of V_3Ga tape (20 μ of V_3Ga) is 0.12 lb. This includes the excess Ga in the Ga-Ga (15 atomic %) alloy on the surface, which amounts to about 25% of the total gallium requirement. The figure of 0.12 lb/ m^2 assumes that gallium from rejected tape is recovered and recycled to the molten gallium bath. The price of Ga is so high and the recovery process simple enough that this is feasible. On the other hand, vanadium from rejected tape is not recycled and is assumed to have zero scrap value, since its value as oxide is an order of magnitude lower than that as 2 mil metal foil.

The length of each processed roll is taken as 500 meters. This is nominal - the actual length will depend on the field range in which the tape is used.

The molten gallium bath is assumed at 700°C, as reported in the literature. The heat treatment temperature is assumed

as 650°C, and the heat treatment time as 160 hours. This is nominal and it is likely that the actual heat treatment temperature will be somewhat higher and the heat treatment time somewhat less.

A large number of rolls, i.e., forty, is heat treated at one time in each furnace. The total roll weight in the furnace is on the order of 12,000 lbs. The furnace atmosphere is an inert gas, e.g., argon, at somewhat greater than 1 atm.

The soldering stand throughput speed is 4 meters/minute, the same as that assumed for the other conductors in this report and equal to the soldering speed for the NAL conductor.

The plant equipment costs, labor requirement, and building areas are summarized in Tables G-4, G-5, and G-6. These estimates are similar to those made in previous appendices. The heat treatment furnaces are somewhat more expensive due to their large capacity. The soldering stand cost estimates are the same as those in previous appendices. The cost estimates for the gallium bath may be somewhat low considering the high temperatures involved. However, increasing the gallium bath cost even by a factor of three would not significantly affect the total cost of the finished superconductor. The labor and building estimates are probably somewhat overestimated. Costs of electroplating copper on the gallium dipped tape are neglected since this will be a much smaller item than other processing costs.

The cost summary for V_3Ga superconductor is given in Table G-7. As with the other superconductors studied, the processing costs are only ~20% of the total finished superconductor cost, even using projected material prices, and considerably less than 10% if present prices are used. The cost of a finished individual conductor using projected material prices is estimated as \$8.05/m [2 V_3Ga tapes, 10 cm wide, soldered to a 10 mil aluminum stabilizer backing]; with present material prices, but with the assumed large production volume, the cost of a finished individual conductor would be \$28.05/m. By way of comparison, the present Sumitomo price for an equivalent amount of V_3Ga without aluminum stabilizer is \$100/m [\$2.00/ft for 1/2 in. wide tape].

Costs of the conceptual 10 KA conductor are given in Table G-8 as a function of magnetic field. Up to 160 KG, Nb_3Sn conductor is much cheaper (Appendix E) even assuming \$0.20/gm price for Ga.

Cost factors used in this analysis are given in Table G-9.

The prospects for reducing the projected V_3Ga conductor cost would appear to be very good, principally by raising the critical current density. In some of Tachikawa's samples (3), the V_3Ga critical current density is on the order of three times that used in this analysis. Relatively little work has

done in V_3Ga and one would expect substantial improvements in J_c through reduced V_3Ga grain size.

Projected materials costs might be brought somewhat lower. Though it is doubtful that a factor of 2 reduction could be achieved. A thinner V foil would help to reduce costs but it would be necessary to make experiments on such a conductor. Since rolling costs would increase substantially per pound, the net effect on final conductor cost would not be too great, perhaps on the order of 30% reduction.

Plasma sprayed V_3Ga may be a possibility, and should lead to substantially lower costs since vanadium powder would be much cheaper than foil.

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Table G-1

Characteristics of Conceptual 10 KA V₃Ga Tape
Superconductor for Large Fusion Magnets

Conductor width	10 cm
Numbers of V ₃ Ga tapes per individual conductor	2 cm
V ₃ Ga total thickness per individual conductor	40 μ
Vanadium total thickness per individual conductor	60 μ
Cu-15 at.% Ga total thickness per individual conductor	20 μ
Aluminum stabilizer total thickness per individual conductor	10 mil
Overall thickness of individual conductor (including solder)	7 mil
Number of individual conductors in total conductor carrying 10 KA	4, 5, 6, or 7 depending on field

Operating field range (KG)	No. of individual conductors in total conductor carrying 10 KA	Ratio of operating current to critical current	Total I ² R watts per cm of 10 KA conductor*
B ≤ 115	4	≤ 2/3	0.075
115 ≤ B ≤ 140	5	≤ 2/3	0.06
140 ≤ B ≤ 160	6	≤ 2/3	0.05
160 ≤ B ≤ 170	7	≤ 2/3	0.045

*Full 10 KA in stabilizer

Table G-2

Critical Current Characteristics of V_3Ga Superconductor

B (KG)	<u>J_c, critical current density in V_3Ga layers (A/cm^2)</u>			<u>I_c, critical current for 10 cm wide V_3Ga tape (KA)³</u>
	<u>Sumitomo* (1)</u>	<u>Tachikawa** (2)</u>	<u>Suenaga and Sampson⁺ (4)</u>	
50	1.97×10^5	--	3×10^5	4.0
75	1.37	--	2	2.7
100	1.10	1.67×10^5	1.5	2.2
125	0.87	1.50	--	1.6
150	0.69	1.46	--	1.4
170	0.51	1.33	--	1.0
180	NA	1.25	--	--
190	NA	1.0	--	--
200	NA	0.66	--	--

* 1.27 cm wide ribbon, vanadium $\sim 30 \mu$ thick, with 2 V_3Ga layers each $\sim 10 \mu$ thick.
Heat treatment not specified.

** 0.3 cm wide ribbon, vanadium $\sim 30 \mu$ thick with 2 V_3Ga layers each $\sim 10 \mu$ thick.
Heat treated at $675^\circ C$ for 40 hours (no Zr in tape³).

+ 3 vanadium wires (each ~ 3 mil dia) in Cu-Ga matrix. V_3Ga layer on wire surface
 $\sim 1-2 \mu$ thick.

+ Calculated for 10 cm wide tape, vanadium $\sim 30 \mu$ fluid with 2 V_3Ga layers each
 10μ thick, using Sumitomo V_3Ga critical current density.

NA not available

Table G-3

Process Parameters for Large Scale Production
of V_3Ga Tape Superconductor
 $(2 \times 10^6 \text{ m}^2/\text{year}^*)$

Weight of Ga metal consumed/ m^2 of acceptable tape	0.12 lb [†]
Weight of V + 1% Zr 2 mil foil consumed/ m^2 of acceptable tape	0.75 lb [†]
Width of processed tape	10 cm
Length of processed tape per roll	500 m
No. of rolls processed/year	44,000
No. of finished rolls produced/year (10% rejection rate)	40,000
Temperature of Ga bath	700°C
Heat treatment	100 hr @ 650°C
Average number of rolls being heat treated at any given time	500
Average number of rolls heat treated/furnace	40
Fraction of time furnaces operate (4 shifts)	80%
No. of installed furnaces	15
Soldering speed (2 V_3Ga tapes + stabilizer)	4 meters/min
No. of installed soldering stands	6
Percentage of time soldering stands operate (4 shifts)	85%

* Makes 10^7 m/yr of finished superconductor [10 cm wide, with 2 V_3Ga tapes soldered to 10 mil aluminum stabilizer]

+ Ga recycled

† Vanadium not recycled - no scrap value

Table G-4

Capital Equipment Costs for Large Scale Productionof V_3Ga Tape Superconductor $(2 \times 10^6 \text{ m}^2/\text{year}^*)$

<u>Process Equipment Component</u>	<u>Unit cost</u> <u>(\$ millions)</u>	<u>Plant cost</u> <u>(\$ millions)</u>
1. 700°C gallium bath	0.4	2.4
2. Heat treatment furnace	0.6	9.0
3. Soldering stands	0.4	2.4
4. Material handling	--	1.0
5. Quality control	--	2.0
	Total	16.8

* Makes 10^7 m/yr of finished individual conductor [10 cm wide, with 2 V_3Ga tapes soldered to 10 mil stabilizer].

Table G-5

Labor Requirements for Large Scale Production
of V_3Ga Tape Superconductor
 $(2 \times 10^6 \text{ m}^2/\text{year}^*)$

<u>Process step</u>	<u>Unit Labor Requirements</u>	<u>Plant requirements (4 shifts)</u>
1. Gallium bath	2/shift per bath	48
2. Heat treatment	1/shift per furnace	60
3. Soldering stands	2/shift per stand	48
4. Quality control	--	30
5. Materials handling	--	10
	Sub total	196
6. Overhead (administrative, clerical, shipping and receiving, etc.)		<u>80</u>
	Total	276

* Makes 10^7 m/year of finished individual conductor [10 cm wide, with 2 V_3Ga tapes soldered to Al stabilizer].

Table G-6

Building Requirements for Large Scale Production
of V_3Ga Tape Superconductor
 $(2 \times 10^6 \text{ m}^2/\text{year}^*)$

<u>Process area</u>	<u>Plant area, ft²</u>
Gallium bath	40,000
Heat treatment	40,000
Soldering	30,000
Quality control	20,000
General shipping and receiving, offices, etc.	40,000
	<u>170,000</u>

* Makes 10^7 m/year of finished individual conductor [10 cm/year, with 2 V_3Ga tapes soldered to Al stabilizer].

Table G-7

Cost Summary for Large Scale Productionof V_3Ga Tape Superconductor(10⁷ m/year of conductor)

<u>Process step</u>	<u>Plant cost</u> (\$ millions/year)	<u>Unit cost</u> (\$/m of V_3Ga)**
1. Materials (Projected prices)		
Gallium	21.6	2.16
Vanadium foil	31.4	3.14
Solder	1.76	0.18
Power	0.88	0.09
Copper	0.78	0.08
Aluminum	<u>5.92</u>	<u>0.59</u>
	62.4	6.24
2. Molten Gallium Bath		
Labor	1.2	0.12
Capital Equipment*	1.0	0.10
Buildings	<u>1.0</u>	<u>0.10</u>
	3.2	0.32
3. Heat Treatment		
Labor	1.5	0.15
Capital Equipment*	3.7	0.37
Buildings	<u>1.0</u>	<u>0.10</u>
	6.2	0.62
4. Soldering		
Labor	1.2	0.12
Capital Equipment*	1.0	0.10
Buildings	<u>0.75</u>	<u>0.08</u>
	3.0	0.30
5. Overhead and Quality Control		
Labor	3.0	0.30
Capital Equipment*	1.2	0.12
Buildings	<u>1.5</u>	<u>0.15</u>
	5.7	0.57
Total	\$80.5 millions/yr	\$8.05 m of V_3Ga conductor

* Includes capital and depreciation charges (25%/yr on total capital investment), engineering and test charges, and maintenance charges (10%/yr)

** Two V_3Ga tapes, 10 cm wide, soldered to 10 mil aluminum stabilizer

Table G-8

Cost of 10 KA Conceptual V_3 Ga Tape Superconductors

<u>Field range (KG)</u>	<u>No. of individual conductors in parallel</u>	<u>\$ Cost/m of 10 KA conductors</u>		
		<u>Projected materials costs</u>	<u>Present materials costs</u>	<u>Present cost*</u>
$B \leq 115$	4	\$32.20	\$112.20	\$400
$115 \leq B \leq 140$	5	40.25	140.25	500
$140 \leq B \leq 160$	6	48.30	168.30	600
$160 \leq B \leq 170$	7	56.35	196.35	700

* Based on Sumitomo price of \$2.00/ft for 1/2 in. wide ribbon

Table G-9

Cost Factors Used in Analysis of V_3Ga Superconductor

Gallium

Projected price	\$ 90.00/lb
Present price	360.00/lb

Vanadium 2 mil foil

Projected price	20.96/lb
Present price	100.00/lb

Aluminum (5000 resistance rate)

Projected price	3.80/lb
Present price	15.00/lb

Copper - electroplated	2.00/lb
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Solder	1.00/lb
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Power	0.01/KWH
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Labor	\$25, 000/yr per person
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Building	\$100.00/ft ²
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Figure G-1

Conceptual V_3Ga tape superconductor for large fusion magnets
(not to scale)

FIGURE G-2

Process flow sheet for large-scale production
of V_3Ga tape

Appendix II

Projected Cost of Pb-Bi in Glass Fiber Superconductor

Since no commercial Pb-Bi-glass fiber superconductor exists, production costs are estimated for a conceptual conductor that is based on Watson's experiments. (1,2,3,4) This conceptual conductor is shown in Figure 1. The aluminum jacket provides both full cryogenic stabilization, mechanical support and protection for the Pb-Bi impregnated fibers. The thickness of the superconductor region (15 mils) is chosen to give ~ 1000 A/cm lineal current density at 50 KG. The width of superconductor (~ 4 inches) is somewhat arbitrary; it could be substantially wider or narrower and still be fully stabilized.

The loading of Pb-Bi is taken as $\sim 30\%$ by volume in the fibers, the alloy composition as Pb-40% (atom %), and the average pore size as ~ 35 Å, based on Watson's experiments. Since this superconductor is still in an early stage of development, more optimum parameters may be developed in the future.

The volume fraction of the superconducting region that is actually occupied by fibers is taken as 60%. This is slightly greater than the normal volume fraction in fiberglass tape, which is on the order of 50%. The 60% volume fraction seems readily achievable, however. The fiberglass tape is woven from 20 μ diameter fibers. The largest fiber diameter presently used

for fiberglass tape is $\sim 13 \mu$. Special weaving machines would probably be used; alternatively it may be desirable to use smaller fibers. Watson thinks fibers as small as 10μ may be practicable. [It should be noted that the critical current vs field curves used in this study were taken for 60μ fibers.]

It is also possible to impregnate thin glass tapes of several inches width, and it is conceivable that several layers of these tapes could be used instead of the tape woven from 20μ fibers. It would not be as flexible, but certainly would be sufficiently flexible to be used in large diameter fusion magnets. However, the woven tape permits one to both twist and transpose the fibers, effectively eliminating diamagnetic currents due to changing external and self fields. The cost of such weaving should be quite small. The woven tape thus seems ideal for this type of superconductor. Table H-1 summarizes the characteristics of this conceptual superconductor.

The production process for this conceptual superconductor must be specified. Figure 2 shows a proposed process, based on Watson's experiments, and Table H-2,3,4,5,6, and 7 summarize process parameters and costs for a large scale plant, producing enough superconductors per year for the low field windings of 45,000 MW(e) of fusion reactors.

The first process step is the acid leaching of the fibers to produce a porous structure in them. In experiments, this typically takes several minutes in a mild acid bath. For estimation purposes the time for this step has been assumed as 10 minutes. The practicality of this leaching step has been demonstrated for bundles of fibers, but not woven fiberglass tape. No problems are anticipated, however, provided the acid bath is kept moving relative to the tape. A speed of 2 meters/minute through the bath has been assumed; faster speeds with the same 10 minute leach time would require excessively large acid tanks, or an excessive number of passes through the tank. A stirrer in the tank should be adequate to keep the acid moving sufficiently fast relative to the tape.

The unit product length has been assumed as 1000 meters. This is sufficient to wind ~33 turns on a 10 M diameter magnet. Longer lengths are not needed, since a connection would have to be made at this point in any event, due to the change in critical current capability. That is, the outer ~33 turns would be wound using one tape and the next 33 turns, two tapes in parallel. The next connection would probably be to a high field superconductor, e.g., Nb_3Sn .

The 1000 meter product length takes ~8 hours to move through the acid leach bath. In order to minimize the number

of baths, 5 tapes are assumed to move through the bath at the same time. This figure is certainly conservative, and many more tapes could move through the bath.

The next process step is termed the combiner step. Here the acid leached woven tape is jacketed, together with the Pb-40 Bi alloy in high purity aluminum (5000 resistance ratio).

This procedure seems better suited to large scale production than the alternate procedure; that is, impregnating the porous fibers with Pb-Bi and then jacketing. In the latter method, one would have to unwind the coil of impregnated fibers (which is now much more brittle) at elevated temperatures (to prevent the Pb-Bi from freezing between the fibers), then jacket. There is a much greater risk of fracturing fibers with this procedure.

In the procedure suggested here, the 4 inch wide fiberglass tape is placed on one strip of aluminum, and molten Pb-Bi alloy is dribbled onto the tape, permeating between the fibers. It will not penetrate the fibers, however, because of the very small pore size. The top strip of aluminum is laid on and the edges cold welded to form a leak-tight jacket. Coils of jacketed tape are then sent to an impregnator.

The time averaged speed of tape through the combiner is taken as 2 meters/minute. This seems quite conservative.

The NAL magnet strip was soldered at a speed of 4 meters/minute, and the combiner step in this process appears process appears simpler. At this speed, a unit roll of tape would take ~8 hours to move through the combiner. Multiple tape movement through the combiner has not been assumed, though it is probably quite feasible. The cost of the combiner step, which is the largest part of the superconductor cost besides materials, is probably considerably overestimated.

The final step is the impregnation step. Coils of jacketed tape are placed in a large toroidal impregnator. The major diameter of the toroid is 3 meters and the minor diameter, ~0.6 meters. The toroid is split into upper and lower halves. The bottom half is fixed, while the top half can be lifted so that a 3 in diameter coil of jacketed tape can be inserted in the impregnator. The upper half of the impregnator is then lowered onto the bottom half, and the two halves are forced together by external jacks. The inner diameter of the impregnator is ~8 inches, and holds both the coil (4" x ~5" cross section) and the pressurizing fluid. The walls of the impregnator are very thick, ~6", because of the very high impregnation pressure (~70,000 psi). The pressurizing fluid could either be hot water or oil. The seals between the upper and lower halves of the impregnator do not have to be completely leak-tight, but the leakage rate must be small.

The impregnation time at pressure is very fast, on the order of a few milliseconds, since the barrier to impregnation is the pressure needed to overcome surface tension forces for 35 Å pores, not flow velocity through the pores. For this process, the nominal impregnation time is taken as 1 second. The time averaged load-unload time is taken as ~0.8 hour (including maintenance, etc.), necessitating 2 impregnators in the plant. It should be possible to operate with considerably faster load and unload times. However, this is not a significant part of the cost. The impregnator cost is taken as $\$2 \times 10^6$ apiece. This seems to be a considerable overestimate, since the equipment is really not that complicated--just massive. The impregnator would weigh on the order of 200,000 lbs, counting support stands, the two split halves, jacks, etc.

After impregnation the 1000 meter jacketed superconductor coil is removed, washed and dried, and shipped in the same 3 m. diameter coil to the fusion magnet assembly site.

The cost summary (TableH -6) shows that with the projected raw material costs, ~80% of the finished superconductor cost is for raw materials. Of these, only bismuth and aluminum are significant. The lead and fiberglass costs are small, and probably slightly overestimated at $\$0.20/\text{lb}^{(5)}$ for lead and $\$1/\text{m}^2^{(6)}$ for 15 mil fiberglass woven tape. The aluminum cost is the most significant raw material cost. The present price of $\$15/\text{lb}$

for 5000 resistivity ratio aluminum in very small amounts gives a finished superconductor cost of $\$66.58/\text{m}^2$; however, as shown in Appendix B, this cost will undoubtedly drop very greatly. The cost projected in Appendix B, $\$3.80/\text{lb}$, is probably still somewhat high. However, even at this price the cost of Pb-Bi superconductor drops to $\$3.14/\text{m}$ of conductor.

The 2000 AD projected price for bismuth is not very well determined. Until July 71 the price of bismuth stayed about $\$5/\text{lb}$,⁽⁷⁾ but currently has dropped to $\$3.50/\text{lb}$ (Jan. '72),⁽⁸⁾ probably because of the business downturn. However, bismuth is a by-product of zinc and lead refining, and its price depends on many factors besides demand. The 1968 free world production was about 8×10^6 lbs/year.⁽⁷⁾ The projected demand for bismuth in 2000 AD (exclusive of its use as a superconductor) is ~12 million lbs/year, and the projected price is $\$5/\text{lb}$.⁽⁵⁾ However, construction of 90,000 MW(e)/year of fusion reactors using Pb-Bi in glass fiber as a superconductor would add an additional 8 million lbs of bismuth demand. This might necessitate a price rise, in order to meet the additional demand by working less concentrated sources. However, for this study the projected price of bismuth is taken as $\$5/\text{lb}$. At this price the bismuth accounts for ~30% of the total superconductor cost.

The process costs estimated in this study are probably somewhat high; however, even if cut in half, they will change the superconductor piece only by 10%.

The superconductor short sample critical current densities for Pb-Bi in glass fiber are given in Table H-8 as a function of magnetic field. These are taken from Watson,⁽²⁾ and are the overall current densities for the fiber (including glass), but do not include the volume of Pb-Bi matrix between the fibers. (This region is normal above 20 KG and carried negligible current below 20 KG.) Also given in Table H-8 are the corresponding critical currents of the conceptual superconductor as a function of magnetic field. These current densities are based on experiments with 60 μ fibers in copper tubes. It should be noted that these are considerably larger than Watson's early results.⁽³⁾ Watson attributes the increase to elimination of organic impurities in the fiber caused by pressurizing fluid during the impregnator step. The copper tube jacketing prevents these organic impurities from degrading the fine porous structure in the glass as in the production process described in this appendix; the porous fibers are placed with Pb-Bi inside a metal jacket which is then sealed. The jacket is then pressurized and the Pb-Bi enters the porous fibers.

Also shown in Table H-8 are the cost/meter of a 10 KA conductor for fusion magnets (both projected and present materials costs), made by using 1, 2, 3, or 5 conceptual individual conductors described earlier, in parallel.

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Table II-1

Characteristics of Pb-40% Bi Superconductor Tape

Width (overall)	4.44 inches (11.4 cm)
Width of superconducting region	3.94 inches (10 cm)
Thickness (overall)	35 mils (0.692 cm)
Thickness of superconducting region	15 mils (0.038 cm)
% of superconduction region occupied by fibers	60%
% of glass fiber occupied by Pb-Bi	30%
Average pore size in fiber	35 Å
Length of conductor/m ² of superconductor	10 meters
Weight of Pb/m ² of tape	1.9 lbs
Weight of Bi/m ² of tape	3.3 lbs
Weight of Al/m ² of tape	3.15 lbs
Thickness change of tape when fibers take up Pb-Bi	2.7 mils

Table H-2

Process Parameters for Large Scale Production
of Pb-40% Bi in Glass Fiber Superconductor
($2 \times 10^6 \text{ m}^2/\text{year}$)

Unit Product Tape

Width of superconductor	0.10 meter
Length of tape	1000 meters
Area of tape (superconductor)	100 m ²
Weight of Bi in tape	190 lbs
Weight of Pb in tape	330 lbs
Weight of Al in tape	315 lbs
Weight of glass fiber in tape	126 lbs
Total weight of 1000 m tape	960 lbs

Acid leach time	10 minutes
Speed of tape through acid bath	~2 m/minute
Speed of tape through combiner	~2 m/minute
Diameter of coil in impregnator	3 meters
Impregnation pressure	70,000 psi
Impregnation time	1 second
Load & unload time on impregnator (includes maintenance, etc.)	0.87 hour
Number of unit tapes produced/year	20,000
Number of unit tapes processed/hour	2.3
Process time for acid leach (includes load and unload)	8.0 hours
Process time for combiner (includes load and unload)	8.0 hours
Number of parallel tapes in acid bath	5
Number of acid baths	4
Number of combiners	18
Number of impregnators	2

Table H-3

Capital Equipment Costs for Large Scale Production
of Pb-40% Bi in Glass Fiber Superconductor
($2 \times 10^6 \text{ m}^2/\text{year}$)

<u>Process Equipment</u>	<u>Unit Cost</u> <u>(\$millions)</u>	<u>Plant Cost *</u> <u>(\$millions)</u>
1. Acid baths	0.3	1.2
2. Combiners	0.3	5.4
3. Impregnators	2.0	4.0
4. Miscellaneous equipment (quality control, etc.)	-	2.0
	Total	<u>12.6</u>

* Does not include engineering and testing (25% additional)

Table II-4

Building Requirements for Large Scale Production
of Pb-40% Bi in Glass Fiber Superconductor
($2 \times 10^6 \text{ m}^2/\text{year}$)

<u>Process Area</u>	<u>Building Area (ft²)</u>
1. Acid baths	2×10^4
2. Combiners	5×10^4
3. Impregnators	2×10^4
4. Offices, Labs, etc.	$\frac{6 \times 10^4}{1.5 \times 10^5}$
Total	

Table H-5

Labor Requirements for Large Scale Production

of Pb-40% Bi in Glass Fiber Superconductor

(2×10^6 m²/year)

<u>Process</u>	<u>Unit Labor Requirements</u>	<u>Plant Requirements</u>
1. Acid leach	2/shift	32
2. Combiner	2/shift	144
3. Impregnate	4/shift	32
4. Quality control		<u>10</u>
	Sub-total	218
5. Overhead (administrative, clerical, shipping & receiving)		<u>87</u>
	Total	305

Table H-6

Cost Summary for Large Scale Production
of Pb-40% Bi in Glass Fiber Superconductor
 (2x10⁷ m/year)

	<u>Plant Cost</u> (\$ millions/year)		<u>Product Cost</u> (\$/m of Conductor)	
	<u>Present</u> <u>Prices</u>	<u>Projected</u> <u>Prices</u>	<u>Present</u> <u>Prices</u>	<u>Projected</u> <u>Prices</u>
1. Materials				
Lead	1.32	1.32	0.066	0.066
Bismuth	19.00	19.00	0.950	0.950
Aluminum	94.40	24.00	4.720	1.200
Fiberglass	<u>2.00</u>	<u>2.00</u>	<u>0.100</u>	<u>0.100</u>
Sub-total	116.72	46.32	5.84	2.32
2. Acid Leach				
Labor	0.80		0.040	
Capital Equipment*	0.50		0.025	
Buildings	<u>0.50</u>		<u>0.025</u>	
Sub-total	1.8		0.090	
3. Combiners				
Labor	3.60		0.04	
Capital Equipment*	2.20		0.08	
Buildings	<u>1.25</u>		<u>0.025</u>	
Sub-total	7.05		0.352	
4. Impregnators				
Labor	0.8		0.04	
Capital Equipment*	1.6		0.08	
Buildings	<u>0.5</u>		<u>0.025</u>	
Sub-total	2.9		0.145	
5. Overhead, quality control, etc.				
Labor	2.4		0.120	
Capital Equipment*	0.8		0.040	
Buildings	<u>1.5</u>		<u>0.075</u>	
Sub-total	4.7		0.235	
Total	<u>133.17</u>	<u>62.77</u>	<u>6.66</u>	<u>3.14</u>

* Includes engineering testing, and maintenance.

Table H-7

Cost Factors for Pb-40% Bi Plant

Bismuth	\$5/lb	
Lead	\$0.20/lb	
Aluminum (5000 resistivity ratio	\$3.80/lb	projected
Ditto	\$15/lb	present
Fiberglass tape	\$1/m ²	
Buildings	\$100/ft ²	
Labor	\$25,000	per person per year

Table H-8

Current Capability of Pb-Bi in Glass Fiber Superconductor

<u>Magnetic field, KG</u>	<u>Short sample critical current density, A/cm²</u>	<u>Short sample critical current for conceptual superconductor, KA</u>
0	1×10^5	22.9
10	1	22.9
20	0.9	20.6
30	0.73	16.7
40	0.6	13.8
50	0.47	10.8
60	0.37	8.5
70	0.28	6.4
80	0.20	4.6
90	0.11	2.5
100	0.06	1.4

Cost of Conceptual 10 KA Conductor for
Fusion Magnets with $I/I_c \leq 2/3$

<u># Conductors in Parallel</u>	<u>Watts cm of edge</u>	<u>Field Range (KG)</u>	<u>Cost, \$/meter</u>	
			<u>Projected Materials Costs</u>	<u>Present Materials Costs</u>
1	0.15	0-35	3.14	6.66
2	0.075	35-65	6.28	13.32
3	0.05	65-78	9.42	19.98
5	0.03	78-87	15.70	33.30

FIGURE H-1

Conceptual cross sectional view of conductor using
Pb-40% Bi in glass fiber

(NOT TO SCALE)

FIGURE H-2

Flow sheet for large-scale production of
Pb-40% Bi in glass fiber conceptual super-
conductor for large fusion magnets

Appendix I

Projected Cost of High Purity Aluminum Cryoconductors Including Refrigeration

A nominal zero field resistance ratio of 25,000 has been chosen for the aluminum cryoconductor. Determining an optimum value would require knowledge of how cost of the cryoconductor varied with resistance ratio. However, this nominal value will serve to indicate the potentialities of aluminum cryoconductor. The cost of this resistance ratio aluminum is estimated as \$8.00/lb (Appendix B).

An optimum operating temperature for the cryoconductor must also be determined. For purposes of this study, this is approximated by assuming that the lattice resistivity is 20% of the residual resistance due to impurities. Since lattice resistivity varies rapidly with temperature ($\sim T^3$ in this temperature range), a slightly higher temperature will result in a substantially higher aluminum resistance, but will not save very much on refrigerator power and costs. This condition corresponds to an aluminum temperature of 10°K , based on Fickett's (1) curve of lattice resistivity vs temperature. The zero field resistivity then becomes $1.25 \times 10^{-10} \Omega \text{ cm}$, and includes both lattice and impurity resistivity.

Taking the magnet resistance as 3 times the zero field resistance [Arp (2) and Danby (3)] the total resistance of the cryoconductor is then $3.75 \times 10^{-10} \Omega \text{ cm}$.

The refrigeration factor R, watts (input)/watt (ref) is given by

$$R = \frac{1}{\eta_{\text{ref}}} \left(\frac{T_s - T_{\text{ref}}}{T_{\text{ref}}} \right) \quad (\text{I-1})$$

with $\eta_{\text{ref}} \approx 0.3$, $T_s = 300^\circ\text{K}$, $T_{\text{ref}} = 10^\circ\text{K}$, $R = 96$. For very large refrigerators of the size necessary for this application, η_{ref} may be greater than 0.3, so that R may be less than 96.

Taking the unit length of aluminum cryoconductor as 1 meter, the current as 1 KA, and its cross sectional area as $A_o \text{ cm}^2$,

$$P_{\text{ref}} = \frac{(10^3)^2 \times 3.75 \times 10^{-10}}{A_o} \times 100 = \frac{3.75 \times 10^{-2}}{A_o} \quad (\text{I-2})$$

$\frac{\text{watt}}{\text{KA} \cdot \text{m}}$

$$P_{\text{input}} = \frac{96 \times 3.75 \times 10^{-2}}{A_o} = \frac{3.6}{A_o} \frac{\text{watt}}{\text{KA} \cdot \text{m}} \quad (\text{I-3})$$

The 10°K refrigerator has both an initial capital cost and a power consumption cost. Since the power for the refrigerator comes from the fusion reactor, and since the fusion fuel cost is essentially zero, the power consumption cost can be expressed in terms of the capital cost of the equipment needed to produce

the power. This includes the pro-rated cost of the fusion reactor and steam boiler. Also included here is the cost of the helium compressor for the refrigeration cycle. It should be considerably cheaper to use steam turbine drive for the helium compressors than to make electricity with a separate steam turbine-generator, and then use the electricity to drive the helium compressors. Large air separation plants often use steam turbine drive for their air compressors for this reason. A cost of \$80/KW power input is taken as the cost of the helium compressor with steam turbine drive for the refrigerator cycle, plus the cost of the steam supply (pro-rated from the fusion reactor plus steam boiler).

The cost of the cold box and plumbing is taken as \$4/watt of refrigerator input. The total cost of the refrigerator plus power is then

$$C_{\text{ref}} = \frac{3.75 \times 10^{-2} \times 4}{A_o} + \frac{3.6 \times 10^{-3} \times 80}{A_o} \quad \$/\text{KA}\cdot\text{m}$$

$$\frac{0.44}{A_o} \quad \$/\text{KA}\cdot\text{m} \quad (\text{I-4})$$

The material cost of aluminum is (at \$8.00/lb)

$$C_{\text{AL}} = \frac{8.00 \times A_o \times 2.8 \times 100}{454.4} = 4.94 A_o \quad \$/\text{KA}\cdot\text{m} \quad (\text{I-5})$$

with the total cost as

$$C_T = C_{\text{ref}} + C_{\text{AL}} = \frac{0.44}{A_O} + 4.94 A_O \quad \$/\text{KA}\cdot\text{m} \quad (\text{I-6})$$

the minimum cost occurs at

$$\frac{\partial C_T}{\partial A_O} = 0; \quad A_O^2 = \frac{0.44}{4.94}; \quad A_O = 0.30 \text{ cm}^2$$

and

$$(C_T)_{\text{min}} = \$2.94/\text{KA}\cdot\text{meter}, \text{ independent of } B$$

Aluminum cryoconductor thus appears economically feasible at \$8.00/lb. However, it would only be used in place of Nb_3Sn if the latter were not suitable for large fusion magnets. Above 160 KG. Nb_3Sn does not appear to be suitable because of its rapidly decreasing current density. Here aluminum appears to be substantially cheaper than V_3Ga .

Reductions in refrigeration and power beyond the values assumed above do not seem likely. If 25,000 resistivity ratio material can be obtained at a much cheaper price by a different purification process than zone refining (e.g., recrystallization) then cost could be significantly reduced. However, the total cryoconductor cost including refrigerator only scales as the square root of aluminum material cost. A reduction to \$2/lb would therefore drop the total cryoconductor cost to \$1.47/KA·meter. It would be most unlikely to expect any further reduction, so this value seem to be a lower limit for aluminum cryoconductor.

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