Normal Conducting versus Superconducting

TF Coils in Next-generation Tokamaks,

a Competitive Study

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Abstract

Next-generation ignited, low-fluence tokamaks with normal conducting and superconducting coils were studied with a view to reducing direct capital costs with normal conducting coils. Costing basically relies on the JET cost breakdown and JET prices. Good agreement with INTOR cost estimates is obtained. Comparison of systems having equal performance objectives and plasma parameters shows a 50 % reduction of direct capital costs in the normal conducting case.

INTRODUCTION

In this study ignited next-generation tokamaks with normal conducting and superconducting coils are compared, with a view to reducing direct capital costs with normal conducting coils. This paper continues previous work on normal conducting TF systems /1, 2/.

In Ref. /1/ the basic feasibility of stationary, normal conducting TF systems was demonstrated for a wide variety of possible next-generation tokamaks. In particular, it was verified that stationary cooling poses no problems, and that the resistive powers are not prohibitive. The main concern was to reduce the risks and therefore tapewound D coils, for which a well-established manufacturing technique exists, were considered.

A first attempt to compare normal conducting and superconducting systems was made in Ref. /2/. The main result obtained there was a reduction of the stored energy by roughly 50 % in the normal conducting case relative to a superconducting system with equivalent performance, indicating the considerable cost-reducing potential of normal conducting coils.

To work out this point more quantitatively, a more elaborate cost model was added to the NORMCOIL /1/ and SUPER-COIL /3/ layout models for ignited tokamaks with normal

conducting and superconducting TF coils, respectively.

In its main parts this model is based on the cost breakdown of the extended version of JET and thus mostly relies
on actually paid costs /4, 5/.

In order to be specific, we confine ourselves in the following to low-fluence machines, with fluences in the range of $^{\sim}$ 0.2 MW y m⁻². Such a "physics machine" might prove to be necessary as an intermediate step between JET and an engineering test device. In such systems the cost of electricity due to the resistive losses of normal conducting coils is a negligible fraction of the total costs, and so the restriction to the direct capital costs is particularly justified. It is emphasized, however, that confinement to low-fluence systems is by no means intrinsic to the normal conducting concept /1/.

The following four systems are discussed in greater detail in this study:

This system is the reconstruction of the so-called INTOR alternative study point 5 (minimum capability) /6/ by the SUPERCOIL model. It has, in particular, the same performance objectives (fluence, burn duration, ignition margin) and plasma parameters (a, s, A, q(a), B_t^O) as the INTOR study point 5. This choice was made in order to allow comparison of our cost model with the INTOR cost estimates /6/.

- NC This system has the same performance objectives and plasma parameters as SC except that the coils are now normal conducting ones. Cost differences between systems SC and NC are then solely due to the different coil concepts.
- SC/O This system has the same performance objectives as

 SC, but the plasma parameters are now self-consistently determined by the requirement that the cost be
 minimized. (Note that the INTOR alternative study
 point 5 was required to have the same plasma parameters as the Phase I version of INTOR.) The SC/O
 system demonstrates the benefit of the more radical
 optimization.
- NC/O This system is defined by analogy with the SC/O system for the normal conducting case.

All systems under consideration thus have the same performance. The fluence, in particular, has the common value 0.2 MW y m^{-2} .

The remaining input data of the superconducting systems are identical to those of the example given in Ref. /3/.

As far as the non-coil-related input data are concerned, these figures were also chosen for the normal conducting systems. The coil-related input data are those of the

examples in Ref. /1/, except that the maximum allowable tensile stress in the TF coils is 100 MPa while the maximum OH current density is 2. \times 10⁷ A/m². All normal conducting coils permit steady-state operation.

The OH flux swing is sufficient to allow a burn time of 100 - 200 s.

The details of the cost model are outlined in Annexes 1 and 2. The following equivalences are used throughout: $1 \text{ MUC} = 2.35 \times 10^6 \text{ DM}$; $1 \text{ $\sharp} = 2.50 \text{ DM}$. All prices quoted are in DM at the 1982 level.

DISCUSSION OF RESULTS

In Table I the cost breakdown as given by the SUPERCOIL model for the SC system is compared with the cost estimate for the INTOR study point 5 as given in Ref. /6/.

(The 1981 costs in Ref. /6/ were multiplied by 1.1 to allow for inflation.) The INTOR breakdown was rearranged in order to have corresponding items in each row. The total costs are found to agree very well. Though there is some ambiguity in the procedure there is also sufficient agreement between the respective cost components. Major differences occur for the buildings and the neutral injection. It is suspected that the JET building costs are unduly high for local reasons. The JET neutral injection costs are enhanced by the special injector design, which leads, in particular, to enhanced pumping requirements.

Table II gives the cost breakdown for the SC and NC systems, as obtained with the SUPERCOIL and NORMCOIL codes, respectively. A cost reduction of nearly 50 %, corresponding to roughly 2.x 10⁹ DM, is found for the normal conducting case. Half of the reduction is contributed by the coils and their auxiliaries. This is mainly a consequence of the strong difference between the underlying specific costs of superconducting and normal-conducting coils (see Annex 2). The other half of the reduction is contributed by minor reductions of most of the other items. They are induced by a slight decrease in the size of the system. The shrinkage of the system is mainly a consequence of the reduced shielding thickness and the lack of thermal insulation in the normal conducting case.

In the normal conducting case the maximum allowable neutron dose behind the shield is 5. \times 10 9 rad. It is determined by the insulation lifetime.

In the superconducting case the corresponding limiting value chosen is 2. \times 10⁸ rad, which entails roughly 0.25 m of additional shielding. It is determined by the allowable enhancement of the stabilizer resistivity. Both figures essentially agree with, for instance, Ref. /9/.

Though the current density is slightly higher in the superconducting coils (see Table III), this beneficial effect is considerably overcompensated by the thermal

insulation (0.15 m thickness). The difference in size is reflected by, for instance, the reduction of the outer coil radius $\rm R_2$ in the normal conducting case. $\rm R_2$ is given in Table III along with other characteristic parameters of the systems under consideration. Though the SC and NC systems have equal plasma parameters and though $\rm R_2$ only decreases by 16 % in the normal conducting case, it is observed that the stored energy is severely reduced by 50 %.

Table III also lists data of the SC/O and NC/O systems. The overall optimization leads to a considerable further cost reduction of roughly 25 % relative to the SC and NC systems, respectively. The now self-consistently determined plasma parameters of the two systems do not differ much from those of the SC and NC systems.

The last two rows show the cost of the four systems when normalized to the SC and JET systems, respectively.

CONCLUSIONS

Next-generation ignited tokamaks with superconducting and normal conducting coils were studied, emphasis being placed on reducing direct capital costs by normal conducting coils. In order to be specific, attention was confined to low-fluence systems (physics experiments). Calculations

are based on the NORMCOIL and SUPERCOIL layout programs, which were extended to include a cost model. The cost model mainly relies on the JET (extended performance) cost breakdown and JET prices. The cost estimates for superconducting coils are based on the price of the EURATOM test coil for the Large Coil Task.

The INTOR alternative study point 5 (low-fluence INTOR) is chosen as reference point. For this reference system good agreement between the predictions of our model and the INTOR costing is obtained.

Direct comparison of the normal conducting and superconducting versions of this system (the two versions having equal plasma parameters and equal performance) shows a 50 % reduction of the direct capital cost with normal conducting coils, corresponding to roughly 2. x 10 DM in the case under consideration. Abandoning the requirement that the plasma parameters should coincide with the Phase I INTOR values but determining them self-consistently by the requirement of cost minimization, an even larger cost reduction is obtained. The self-consistently determined plasma parameters are found to deviate only slightly from the INTOR values. The capital cost of such a system is reduced to less than 40 % of the INTOR study point 5 value, this being roughly equivalent to twice the JET value.

As far as the capital costs are concerned, the statements on relative cost reduction remain valid for higher fluences. The cost of the electricity consumed amounts to less than 10 % of the direct capital costs for the low-fluence systems under consideration. Apart from the local tariff, it depends on specific design features (particularly on the design of the PF coil system) and is difficult to estimate in general. With typical figures, however, it can easily be verified that the "breakeven point", where the reduction of the investment costs is balanced by the enhanced costs of operation, is in the range of 2 MW y m⁻².

Cost estimations quite generally suffer from a great deal of ambiguity. This holds in our case particularly for the costing of the poloidal field system and the cryogenic system. Our main conclusions can, however, be well traced to the significant difference between current prices of normal conducting and superconducting coils and the size reduction in the normal conducting case, the latter being due to the reduced shielding requirements and the lack of thermal insulation in the case of normal conducting coils. They were therefore not substantially affected even by major modifications of the ambiguous parts of the cost model. A change of conclusion in favour of superconducting coils could, of course, happen if considerable progress were to be made in manufacturing superconducting coils.

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Annex 1: Cost-scaling relations

In this annex the cost-scaling laws are listed. Quantities C are specific costs to be determined in Annex 2.

If possible, the respective masses are taken as the relevant scaling parameter. This is adequate in most cases since both the materials costs and production costs are typically proportional to the masses. If no mass values are provided by the NORMCOIL and SUPERCOIL models, one sometimes uses volumes as scaling parameters, thus implicitly assuming a constant mass density. If none of these parameters is available, a scaling $E_{\rm m}^{0.7}$ is occasionally used, where $E_{\rm m}$ is the stored TF energy. In doing so the TF coil mass is effectively used as a representative scaling quantity. The cost of energy conversion or energy transfer systems, on the other hand, is assumed to scale as the powers or energies to be handled.

The cost of the toroidal field coils is estimated by

$$\emptyset_{\text{coil}}^{\text{T}} = C_{\text{coil}}^{\text{T}} M_{\text{coil}}$$
 (1)

where M coil is the mass of copper in the normal conducting case. In the superconducting case M coil is the sum of the mass of the conductor, stabilizer and reinforcing material.

The cost of the toroidal field power supply in the normal conducting case is estimated by

$$\emptyset_{\text{ohm}}^{\text{T}} = C_{\text{ohm}}^{\text{T}} P_{\text{ohm}}$$
 (2)

where $P_{\rm ohm}$ is the resistive losses. This scaling is relatively obvious if the coils are fed from the grid. If internal storage systems are used, the energy $E_{\rm s}$ that must be stored is a more adequate scaling parameter. In our case, however, where systems of equal pulse length are considered, it holds that $P_{\rm ohm} \sim E_{\rm s}$.

In the superconducting case we use instead of $\phi_{\mathrm{ohm}}^{\mathrm{T}}$

$$\phi_{\text{aux}}^{\text{T}} = c_{\text{aux}}^{\text{T}} M_{\text{coil}}, \qquad (3)$$

where \emptyset_{aux}^T is the cost for the power supply of the toroidal field coils and the cryogenic system.

We assume

$$\emptyset_{\text{coil}}^{P} = \emptyset_{\text{coil}}^{T}$$
, (4)

where $\emptyset_{\text{coil}}^P$, \emptyset_{ohm}^P and \emptyset_{aux}^P are the corresponding poloidal field system costs. The simple estimates according to eqs. (4) to (6) reflect the fact that the NORMCOIL and SUPERCOIL models do not involve the poloidal field system. For normal conducting systems the crude estimate according to eqs. (4) and (5) is in rough agreement with JET and TFTR data /4, 5, 10/. For superconducting coils eq. (4) was chosen in accordance with Refs. /6/ and /8/. Through eqs. (3), (4) and (6) the cost for the auxiliaries is ultimately assumed to be a fixed fraction of the total coil costs. This assumption was also made in accordance with Refs. /6/ and /8/.

The cost of the neutral injection system including the power supply is given by

$$\phi_{ni} = C_{ni} 2.2 P_{\alpha}/C, \qquad (7)$$

where P_{α} is the α -power, while C is the non-normalized ignition margin /1, 2/. The product 2.2 P_{α}/C is the estimated beam power required to reach ignition. The factor 2.2 is determined by the condition that the ratio

of the injection power to the α -power at marginal ignition (C \simeq 1.8) be equal to that in the Phase I version of INTOR /9/.

The cost of the buildings is estimated by

$$\emptyset_{\text{buil}} = C_{\text{buil}} 2 \pi R_2^2 (h + \Delta/2)$$
, (8)

where R_2 is the outer coil radius, 2h is the vertical bore of a TF coil, Δ is the radial coil thickness. The building costs are thus assumed to scale as the volume of the cylinder that envelops the TF system. The size of the reactor hall, if scaled in this way, permits linear movement of a TF coil in any direction by its full bore. The costs of the vacuum vessel and shielding is estimated by

$$\phi_{\text{vess}} = c_{\text{vess}} 4 \pi^2 R_0 (u/2+D) (a (1+s)/2 + 1) , (9)$$

where R_O is the plasma major radius, a is the minor radius, l is the scrape-off layer thickness, s is the plasma elongation, u is the vessel thickness, and D is the shielding thickness. Besides including the shielding, u+D contains the space for cooling ducts and the mechanical structure. The separation into shielding and vessel is formal and is only made in order to simplify the transition to systems with vanishing fluence.

In the absence of shielding the vessel thickness is typically determined by mechanical considerations, and its average mass density is likely to be lower than in the case where the shielding is incorporated into the vessel. This is crudely taken into account by taking u/2 in eq. (9).

The cost of the pumping system is given by

$$\emptyset_{\text{pump}} = C_{\text{pump}} 2 \pi^2 (a + 1) h R_0$$
 (10)

Here it is assumed that the vessel is the vacuum boundary, and that the cost for the pumping system is proportional to the evacuated volume. The vessel cross-section is assumed to be elliptic.

Constraints on the pumping capability arise from the necessity of He pumping and during the dwell phase when the initial pressure has to be restored. If the first constraint dominates, the fusion power is the relevant scaling parameter. If the latter constraint prevails, the total particle number at the end of the burn is the relevant scaling parameter. Since the operation densities vary only slightly in the systems under consideration, the particle number is approximately proportional to the evacuated volume. Underlying typical dwell times and current scrape-off divertor physics, the latter condition is indeed slightly more restrictive /9/.

The cost of the mechanical structure is estimated by

$$\emptyset_{\text{mech}} = C_{\text{mech}} E_{\text{m}}^{\text{O.7}}$$
 (11)

where \mathbf{E}_{m} is the stored TF energy. By taking the exponent 0.7 we essentially assume $\emptyset_{\mathrm{mech}}$ to scale as the TF coil mass.

The fixed costs are

$$\emptyset_{\text{fix}} = C_{\text{fix}}$$
 (12)

This item mainly comprises costs for control and data acquisition and diagnostics.

The cost of remote-handling equipment is estimated by

(see also \emptyset_{mech}).

The cost for tritium handling is given by

$$\emptyset_{\text{T-handl}} = C_{\text{T-handl}} 2 \pi^2 R_0 h (a + 1) . \qquad (14)$$

Here the same remarks as for ϕ_{pump} apply.

The cost of the cooling system is given by

$$\emptyset_{\text{cool}} = C_{\text{cool}} (P_{\text{ohm}} + P_{\text{f}}) , \qquad (15)$$

where $\mathbf{P}_{\hat{\mathbf{f}}}$ is the total fusion power. $\mathbf{P}_{\hat{\mathbf{O}}hm}$ is set equal to zero in the superconducting case.

$$\emptyset_{\text{others}} = (f - 1) \Sigma \text{ all other } \emptyset$$
 (16)

comprises some small contributions which are assumed to be a fixed fraction of the total direct capital cost. For more rigorous definitions of the geometrical parameters see Refs. /1/ and /3/.

Annex 2: Specific Costs

In this annex the specific costs C... are estimated. Apart from some modifications to be specified below, we rely on the actually paid and planned costs for the JET extended performance as given in Table IV. Table IV summarizes Annexes 4 and 7 of Refs. /4/ and /5/, respectively. The figures in Table IV are 1982 prices. The specific costs C... are obtained by putting the data of Table IV and the respective JET parameters into the equations of Annex 1. The following parameters were taken from Ref. /7/:

$$a = 1.25$$
, $R_{O} = 2.96 \text{ m}$, $R_{2} = 4.8 \text{ m}$, $h + \Delta/2 = 2.65 \text{ m}$, $1 = 0.15 \text{ m}$, $u = 0.12 \text{ m}$, $s = 1.68$, $E_{m} = 1.45 \text{ GJ}$, $P_{ohm} = 270 \text{ MW}$, $P_{ni} = 15 \text{ MW}$.

The value for 1 is estimated. By taking the basic performance value $P_{\rm ohm}$ = 270 MW instead of the extended performance value $P_{\rm ohm}$ = 380 MW we allow for any increase in the coil power supply costs due to the requirement of long-pulse operation.

The specific costs of the superconducting coils are based on the actually paid prices for the EURATOM test coil for the Large Coil Task and are taken as 5 times the value for normal conducting coils /11/. No attempt was made to estimate a possible cost rise for the more advanced coil technology required for next-generation devices or to estimate a conceivable cost reduction due to improved manufacturing techniques.

The assumptions contained in eqs. (4) and (5) are in sufficient agreement with the JET data according to Table IV. The coice $C_{\text{aux}}^T = 0.5 \ C_{\text{coil}}^T$ and eq. (6) were made in accordance with, for instance, Ref. /6/ and /8/. The resulting specific cost values are summarized in Table V.

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	<u>sc</u>		INTOR	R-STP-5
		x10 ⁶ DM		
mechanical structure	115		100	support structure
vacuum vessel + shielding	323		265	blanket/s hield
toroidal magnet	545		582	TF coils
poloidal magnet	545		498	PF coils
tor. magnet power supply	272		325	el. supply magnets +
pol. magnet power supply	272		325	cool./cryog.
buildings	854		455	reactor hall + facilities
neutral injection	604		460	neutral beam + El. supply
remote handling	129		98	close support
pumping system	108		187	vacuum system
tritium handling	62		98	tritium system
diagnostics + data acqu.	127		155	diagnostics + instrument.
cooling system	15			
others	103		157	others
	4074		3705	

Table I

Cost breakdown for systems SC (left-hand side) and INTOR alternative study point five (right-hand side)

(equal performance, equal plasma parameters) 115×10⁶ DM 68 mechanical structure 184 323 vacuum vessel + s hielding 545 105 toroidal magnet 105 545 poloidal magnet 1652 448 272 119 tor. magnet power supply 119 272 pol. magnet power supply 854 418 buildings 604 604 neutral injection 76 129 remote handling 72 108 pumping system 62 tritium handling 127 127 diagnostics + data aqu. 15 33 cooling system 54 103 others 2125 4074 total

Table II

Comparison of cost breakdowns for the systems NC and SC as resulting from the NORMCOIL and SUPERCOIL programs, respectively.

		NC	SC	NC/O	SC/0	INTOR- STP-5
a	(m)	1.2	1.2	1.0	1.0	1.2
R_{o}	(m)	4.9	4.9	3.8	4.2	4.95
B_{t}^{o}	(T)	5.3	5.3	5.4	5.8	5.38
I_p	(MA)	6.6	6.6	6.5	6.0	6.70
β_{T}	(%)	4.7	4.7	5.3	4.7	
P_{α}	(MW)	116	116	89	100	oq
R ₂	(m)	7.5	8.9	6.2	7.3	9.39
E _m	(GJ)	9.1	19.2	7.3	13.5	
j	(MAm ⁻²)	14.9	15.9	16.1	16.7	
D	(m)	0.27	0.52	0.27	0.52	
abs. cost	(DM)	2.1x10 ⁹	4.1x10 ⁹	1.6x10 ⁹	2.9x10 ⁹	3.7x10 ⁹
rel. cost, normal. to case SC		0.51	1	0.39	0.71	
rel. cost, normal. to JET		2.9	5.7	2.2	4.0	

Table III

Various characteristic data and cost estimates for the NC, SC, NC/O and SC/O systems. j is the average current density in a TF coil. (The thermal insulation is not included in the averaging.) D is the shielding thickness.

mechanical structure		18.8	x10 ⁶ DM
vaccum vessel + shielding		43.1	
toroidal magnet		25.2	
poloidal magnet		22.0	
tor. magnet power supply		55.7	
pol. magnet power supply		49.5	
buildings		132.4	
neutral injection		141.0	
remote handling		21.2	
pumping system		36.9	
tritium handling		21.2	
diagnostics + data aqu.		126.9	
cooling system		9.8	
others		18.6	
	total	722.6	

Table IV JET (extended version) cost breakdown

<u>Table V</u>

List of specific costs used in the cost model