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DESIGN CONSIDERATIONS FOR THE TF COIL CENTER CONDUCTOR POST FOR THE IGNITION SPHERICAL TORUS (IST)

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FUSION ENGINEERING DESIGN CENTER

OAK RIDGE NATIONAL LABORATORY

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Fusion Energy Division

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CONTENTS

Abstract	v
1. Introduction	1
2. Description of Concept	1
3. Materials for TF Coils	3
4. Heating	4
5. Computational methods	6
5.1 Automatic adjustment of parameters	10
6. Costs	11
7. Results	13
8. Conclusions	20
Acknowledgments	32
References	33

Abstract

A trade-off study has been carried out to compare the differential costs of using high-strength alloy copper versus oxygen-free, high-conductivity (OFHC) copper for the center legs of the toroidal field (TF) coils of an Ignition Spherical Torus (IST). The electrical heating, temperatures, stresses, cooling requirements, material costs, pump costs, and power to drive the TF coils and pumps are all assessed for both materials for a range of compact tokamak reactors. The alloy copper material is found to result in a more compact reactor and to allow use of current densities of up to 170 MA/m^2 versus 40 MA/m^2 for the OFHC copper. The OFHC conductor system with high current density is \$24 million less expensive than more conventional copper systems with 30 MA/m^2 . The alloy copper system costs \$32 million less than conventional systems. Therefore, the alloy system offers a net savings of \$8 million compared to the 50% cold-worked OFHC copper system.

Although the savings are a significant fraction of the center conductor post cost, they are relatively insignificant in terms of the total device cost. It is concluded that the use of alloy copper contributes very little to the economic or technical viability of the compact IST. It is recommended that a similar systematic approach be applied to evaluating coil material and current density trade-offs for other compact copper-TF-coil tokamak designs.

1. Introduction

This investigation evaluates the relative merit of using pure copper versus high-strength copper alloy for the center leg of the toroidal field (TF) windings in a compact Ignition Spherical Torus (IST). The main items investigated in this study are the electrical heating and water cooling of the central legs of the TF coils. Temperature and stress limitations in the conductor material, as well as the electrical power requirements to drive the TF coils and the cooling pumps, are considered. Designs that keep these parameters in acceptable bounds are evaluated on the basis of their relative costs.

Section 2 describes the physical dimensions, magnetic fields, currents, etc., that define the tokamak being considered. The third section gives a brief specification of the mechanical and electrical properties of the copper and copper alloy being considered. A description of the calculation of the heating and cooling system operating conditions is presented in the fourth section. The computational methods are described in section 5. Cost assumptions and comparisons are presented in section 6. Results and conclusions are presented in sections 7 and 8.

2. Description of concept

The general configuration of the machine is conveyed by the designation Ignition Spherical Tokamak (IST). It is a compact, spherical tokamak designed to achieve ignition. The plasma major radius is in the range of 1.0 to 1.5 m. The aspect ratio is in the range of 1.3 to 1.6 with a field at the plasma center of 2 to 4 T. Four general parameter ranges are considered: machines with TF coils made of oxygen-free, high-conductivity (OFHC) copper and machines with TF coils made of high-strength, high-conductivity copper alloy. For both cases we consider machines with a constant aspect ratio of 1.57 and machines with a constant field at the plasma of 2 T. Within this domain machines of various sizes, and thus with various current densities, are considered. A discussion of the parameter ranges of interest to spherical tori is given by Peng [1,2]. This domain, extended for this study to somewhat smaller radii than those specified by Peng, is shown in tables 1 and 2.

Table 1
Range of cases considered

	Constant aspect ratio (= 1.57)		Constant plasma field (= 2 T)	
	OFHC copper	Alloy copper	OFHC copper	Alloy copper
Plasma radius, m	1.5-0.5	1.5-0.5	1.5-0.7	1.5-0.7
Aspect ratio	Fixed	Fixed	1.57-1.36	1.57-1.36
Field at plasma, T	2-4	3.5-2.3	Fixed	Fixed
TF coil current density, MA/cm ²	30-300	30-300	30-300	30-300
TF current, MA	15-10	14-9	14-7	14-7

Table 2
Key assumptions for IST center conductor post

Plasma Parameters:	
Plasma temperature	20 keV
Plasma elongation, κ	2
Major radius	$R_c + 1.1a + 0.05$ m
Ignition margin	1.5
Aspect ratio	1.57
Center Conductor Parameters:	
Coolant velocity	
For inlet-to-outlet temperature rise = 60°C	<25 m/s
For inlet-to-outlet temperature rise > 60 °C	25 m/s
Flow passage length	$2ak + 1.0$ m
Coolant volume fraction of coil	15%

Note that a is the plasma minor radius.

The reactor is expected to operate in a repetitively pulsed mode with each pulse lasting several tens of seconds. Each pulse will be flat for the duration of the pulse. The effects of the size of the plasma on the size of other components, such as the coil support structure and shielding, and the costs of these items are estimated using the Tokamak Systems Code [3]. In this way it is expected that the savings in size of the balance of the plant brought about by using the compact spherical design with high-current-density and/or high-strength copper alloy for the central leg of the TF coils can be balanced against the higher cost of equipment used to operate these high-performance TF coils.

3. Materials for TF coils

Two materials are considered here for use in the TF coil center legs: OFHC copper and the copper alloy C-17510 (Cu-1.8 Ni, 0.4 Be), which uses small amounts of alloy materials to increase the strength of the copper by factors of 4 to 5 while degrading the electrical and thermal conductivity only to about 60 to 80% of those of OFHC copper [4]. The advantage of such an alloy coil is that it may be able to withstand the increased forces that result from having the alloy conductor carry the same current as a copper conductor in a smaller area. This smaller size, especially in the center leg of the TF coil, can lead to a decrease in the overall size and thus cost of the balance of the tokamak equipment. In general, for a given weight of material the alloys will be more expensive to purchase and fabricate. The TF coils will also generate more resistive heating and require more power to drive. The additional resistance heating also leads to the need for more cooling, cooling pumps, and pumping power.

Therefore, the question is, To what extent will the decreased tokamak size obtained by using compact high-current-density TF coil center legs made of alloy copper counteract the increased conductor cost and increased cost of the balance of the plant?

It is important to model the properties that differ between OFHC copper and the alloy copper proposed here. These properties are the temperature-dependent properties, electrical and thermal conductivity, as well as the yield stress of both materials. The thermal and electrical conductivities of OFHC copper as a function of temperature are well

documented [5]. However, the conductivities of the new high-strength, high-conductivity alloys are less well known, especially at temperatures far from room temperature. The electrical and thermal conductivity properties of the alloy are taken to be a constant factor times the property for OFHC copper. The factor is assumed to be the conductivity of the alloy divided by that of OFHC copper at room temperature. The yield strength properties of OFHC copper and the alloy as a function of temperature are better known and are used for both materials. The conductivity data used can be seen in tables 3 and 4.

4. Heating

Heating in the TF coil will be most severe in the central leg due to the compact conditions and high current density that exist there and because the leg is completely surrounded by the plasma, which will impose a neutron heating load on the central leg.

The electrical heating is given by the product of the volume resistivity of the copper or alloy at the ambient conductor temperature times the square of the current density. Calculations of the distribution of current density as a function of time and position in the coil show that for pulses of 5 s or more there is very little spatial peaking of the current density during the pulse. Thus, the average current density may be used [6].

Neutron heating is generated by neutrons coming from the plasma and entering the outer surface of the inner TF leg. These neutrons are traveling at 14 MeV and are attenuated with a relaxation length of about 0.08 m as they move into the conductor and deposit their kinetic energy as heat. For exponential attenuation, the radial peak-to-average ratio of the neutron energy deposition is calculated using the Bessel function I_0 for the distribution function. The radial peaking factor is on the order of 3 and is calculated in detail for each case. In addition, the neutron flux striking the surface will vary as the inverse square of the distance from the plasma center, where neutrons are assumed to be released for the attenuation calculation, to any point on the central leg surface. Thus, the neutron heating will fall as one moves along the surface from the midplane to the top or bottom of the central conductor. The axial peaking factor is on the order of 3 also and is calculated

Table 3
Material properties of OFHC copper as a function of temperature

	Temperature, °C											
	-270	-240	-200	-150	0.0	15.0	30.0	100.0	200.0	300.0	400.0	500.0
Specific heat, J/(g·°C)					0.0	5.0	40.0	235.0	350.8	380.0		415.0
Resistivity, μΩ·cm	0.0		0.30						2.80	3.54	4.35	5.50
Thermal conductivity, J/(cm·s·°C)		2.9	1.2	0.94	0.92			0.90		0.82		0.79

Table 4
Allowable stresses in 50% cold-worked OFHC copper, annealed OFHC copper,
and C-17510 alloy copper as a function of temperature (from ref. 5)

	Temperature, °C								
	0	200	210	240	260	280	300	325	425
Stress in 50% cold-worked OFHC copper, MPa (ksi)	120 (17)	120 (17)		120 (17)	120 (17)	56 (9)	56 (9)		
Stress in annealed OFHC copper, MPa (ksi)	56 (9)	56 (9)		56 (9)	56 (9)	56 (9)	56 (9)		
Stress in C-17510 alloy copper, MPa (ksi)	310 (45)		280 (40)					245 (35)	190 (27)

in detail for each case. The use of inboard shielding will add further attenuation beyond the inverse square, but this variation is not considered here.

In general, the nonuniform neutron heating, even at the outer edge of the central conductor, is small compared to the electrical heating. Thus, cooling channels within the conductor will be uniformly spaced in the central leg of the TF coil. Although the cooling channels likely will be located in a hexagonal pattern in the conductor, it is assumed that the heat transfer calculations can be done for a cylinder of water surrounded by a cylinder of conductor that contains the same volume of conductor as the hexagon. This is assumed to be surrounded by a thin cylinder of electrical insulating material that allows no heat to pass. This is done to accommodate the electrical insulating material to be used in the construction of the TF coil windings and is consistent with the fact that no heat should cross a surface of symmetry between two cooling channels.

Calculations are made for the temperature rise of the water from inlet to outlet in the average channel as well as in the hottest (outer) channel. The temperature difference due to convection across the water/conductor film is calculated for the average coolant tube and for the hottest spot (the midplane) in the hottest tube (the outer tube). The temperature difference due to conduction radially from the water/conductor surface through the conductor to the insulating surface is calculated for the average conductor channel and for the worst point (the midplane) in the worst (outer) channel. Both average and peak quantities are presented.

5. Computational methods

Various models and equations are used to describe the geometry of the typical coolant channel, electrical heating, cooling of the conductor by the water, temperature drops in the conductor, conductor/water film, and water channel. Several unusual equations used in the calculations are shown below. The field at the surface of the conductor (in tesla) is:

$$B_c = \frac{\mu_0 J_c (1.04 \times 10^6)}{2\pi R_c} \quad (1)$$

The field at the plasma (in tesla) is:

$$B_p = \frac{\mu_0 I_c (1.04 \times 10^6)}{2\pi R_p} \quad (2)$$

The peak stress at the conductor outer surface caused by magnetic compression (in psi) is:

$$\sigma = \frac{B_c^2 (3 + 0.34)}{2(7 \times 10^6) \mu_0} \quad (3)$$

The angle a subtended by the length of the conductor L_c , viewed from the plasma center, is:

$$a = \arctan \frac{L_c}{R_p} \quad (4)$$

The angle b subtended by the radius of the conductor R_c , viewed from the plasma center, is:

$$b = \arctan \frac{R_c}{R_p} \quad (5)$$

The fraction of neutrons n_p striking the conductor post is:

$$n_p = (1 - \cos a) \frac{b}{\pi} \quad (6)$$

The relaxation length of neutron heat deposition in the copper/water/insulation media is on the order of 0.08 m. Assuming exponential attenuation of neutron radiation as it travels into the center post, we find that the neutron energy deposition will vary as the Bessel

function $I_0(r/0.08)$. Solving for the peak-to-average ratio of this function in the radial plane gives:

$$\text{radial peaking} = \left[1 - \left(\frac{R_c - 0.08}{R_c} \right)^2 \right]^{-1} \quad (7)$$

The axial neutron power peaking factor due to $1/r^2$ divergence is found by examining the function that gives this neutron intensity variation as one moves along the z direction on the surface of the conductor:

$$\text{neutron intensity} \sim \frac{1}{1 + [z^2/(R_p - R_c)^2]} \quad (8)$$

Integration gives the peak-to-average ratio of the neutron heating along the z direction:

$$\text{axial peak} = \frac{L_c/(R_p - R_c)}{\arctan[L_c/(R_p - R_c)]} \quad (9)$$

The coefficient of heat transfer [in $\text{W}/(\text{cm}^2 \cdot ^\circ\text{C})$], is given by [7]:

$$h_{\text{film}} = 2.27 \times \frac{[\text{water velocity}/(20 \text{ ft/s})]^{0.8}}{(0.25 \text{ in./water channel diameter})^{0.2}} \quad (10)$$

The hydraulic friction factor f is the solution to the Prandtl-von Karman equation [8]:

$$f = \frac{1}{f^{1/2}} + 2(0.4343) \ln \left(\frac{2.51}{R_e f^{1/2}} + \frac{2 \times \text{ratio}}{3.7} \right) \quad (11)$$

where

$$R_e = \frac{VD}{2} = \frac{\text{velocity (m/s)}}{30.45} \times \frac{2 \times \text{radius (m)}}{30.45} \times \frac{30.45}{1.9 \times 10^{-5}} \quad (12)$$

and the ratio of roughness to diameter is calculated using 0.00015 for the roughness of copper (in ft),

$$\text{ratio} = \frac{\text{roughness}}{\text{diameter}} = \frac{0.00015}{2 \times \text{radius (m)}/30.45} \quad (13)$$

The equation for f is solved using Newton's method.

The temperature rise in the the copper is obtained by integrating the Laplace heat conduction equation:

$$-k \times \nabla^2 T(r) = q''' \quad (14)$$

in cylindrical coordinates, from R_{water} to R_{Cu} , with the temperature at the water surface assumed known and the gradient of the temperature at R_{Cu} [that is, $k \cdot \text{grad } T(r)$, or q''] equal to zero:

$$T(R_{\text{Cu}}) - T(R_{\text{water}}) = \frac{(q_c)_{\text{max}}}{2k_{\text{Cu of } T(T_{\text{Cu est}})}} \times \left\{ R_{\text{water}}^2 [\ln(R_{\text{Cu}}/R_{\text{water}})] + \frac{R_{\text{Cu}}^2 - R_{\text{water}}^2}{2} \right\} \quad (15)$$

5.1 Automatic adjustment of parameters

Before the electrical heating in the conductor can be calculated, the temperature of the conductor must be estimated. In this way the resistivity can be estimated. Likewise, in order to calculate the water temperature rise, the water velocity must be known. Thus, the conductor temperature is initially estimated as 150°C and the water velocity as 10 m/s. From these estimates, all of the other quantities of interest, including the average conductor temperature and the water velocity, are calculated. Then the velocity is changed by 5% and the system of equations recalculated. Extrapolating the velocity to give the desired temperature rise is done using the inverse of the velocity because the pressure drop is proportional to the inverse of the velocity. The conductor temperature is simply adjusted to half the difference between the assumed and predicted values. This process is continued until the estimates and the predictions agree to within 1%.

The following restrictions are imposed on the acceptable range of calculated dependent parameters:

- The pressure drop along the cooling channel should be less than 1.4 MPa (200 psi) to prevent excessive piping and pumping costs.
- The velocity of coolant should be less than 30 m/s to prevent erosion of the conductor by the coolant.
- The conductor/alloy should be below 200 or 400°C to maintain reasonable strength in the conductor/alloy.
- The coolant should be below 300°C to maintain subcooling of the water at reasonable pressures.
- The size of the conductor cooling cells should be above a minimum size of one-tenth the radial thickness of the center conductor to keep manufacturing costs within reason.

If an automatic adjustment of the independent variables in the problem is to be included (as is done in the system code [3]), the restrictions on pressure, velocity, temperature, etc., should be included as a series of smooth, single-valued penalty functions of pressure, velocity, etc. Then the sum (or product) of the penalty functions should be minimized with respect to the independent variables. This will allow for smooth, continuous adjustment of the independent variables to produce a desirable combination of the dependent variables while staying away from the restricted area for the dependent variables.

6. Costs

An attempt is made to evaluate the cost differential of using OFHC copper versus high-strength alloy copper in the center leg of the TF coil. The alloy copper can work at higher temperatures and higher current densities than OFHC copper and thus can achieve the same magnetic field with smaller center leg dimensions, resulting in less radial build. This will lead to a smaller machine with cost savings due to the decrease in size. On the other hand, the alloy copper is more expensive to manufacture; it requires more electrical power to drive the TF coil and generates more heat. Removal of this heat requires more pumping capacity plus more power to operate the larger pumps.

Thus, the cost items to be compared for OFHC and alloy copper include the following:

- the cost of fabrication of the center leg,
- the cost of electrical equipment to drive the TF coil current through the center leg, and
- the cost of the pumps to drive the coolant through the center leg.

Then the expected additional cost of the compact alloy copper machine must be balanced against the cost savings of the overall smaller machine, estimated for example using the Tokamak Systems Code [3].

The cost of power supplies was assumed to be proportional to the current carried times the voltage drop in the power supply bus system. The voltage loss in the bus is empirically related to the length of the bus system. In addition, the cost of power supplies will be proportional to the power consumed in the center leg of the TF coils plus that needed to drive the coolant pumps [9]. The result is the following equation:

$$\text{Power supply cost (millions of dollars)} = \frac{0.046L_B I_c + (1.7 \times 10^5)[(W_c)_E + P_p]}{10^6} \quad (16)$$

where a bus length $L_B = 30$ m was used. The electrical power $(W_c)_E$ in the center conductor and the pumping power P_p are both calculated in the main part of the code.

The cost of fabricating OFHC copper is taken to be 99 \$/kg, versus 132 \$/kg for the alloy copper. If the conductor efficiency η_c is < 0.9 , then the unit cost is changed from 99 to 123 \$/kg. The mass of material in the conductor is calculated from the product of the cross-sectional area of conducting material times the length of the central leg times the density of copper,

$$[8.9 \times 10^3 (\text{kg/m}^3 \text{ of copper})] \pi R_c^2 L_c \times \frac{\text{volume of copper}}{100} \times (\text{material unit cost})/10^6 \quad (17)$$

The cost of the pumps is taken to be proportional to the volume flow rate and the head that they must work against. The empirical relation used is:

$$\begin{aligned} \text{Cost (millions of dollars)} = & 0.1 \pi R_c \times \frac{\text{volume of water}}{100} \times \text{water velocity (m/s)} \\ & \times \frac{\text{pressure drop (psi)}}{0.63 \times 200} \end{aligned} \quad (18)$$

The total of the costs that are expected to be directly affected by the change from OFHC copper to alloy copper is the sum

$$\text{Total cost} = \text{power supply cost} + \text{material cost} + \text{pump cost} \quad (19)$$

Estimates of the cost for the balance of the plant as the system is changed from OFHC to alloy copper are made using the Tokamak Systems Code [3].

7. Results

A series of calculations is presented using the information in section 6 to show the variation of plasma parameters as the current density is varied in the center leg of the TF coil. A plot of the field at the plasma, the current, and the major and minor radii of the plasma as a function of TF coil current density can be seen in fig. 1. Similarly, the center conductor length, radius, and current versus current density can be seen in fig. 2.

A series of design calculations for the center conductor post of the IST device is presented. The calculations attempt to estimate the electrical, thermal, and structural performance of the center leg of the TF coil as a function of current density. Cooling is provided by uniformly spaced, water-filled channels. The effects considered include (1) temperature rise and pressure drop along the cooling channel, (2) temperature difference across the water film at the water/conductor interface, (3) temperature difference from the water film into the body of the copper conductor, (4) magnetic field-induced stress in the conductor, (5) electric power requirements, and (6) the costs of fabricating conductor materials, pumps, and power to drive the pumps and the TF current.

Investigations are carried out for OFHC copper and for high-strength copper alloy with a conductivity that is 60% that of pure copper. In the first set of calculations, the size of the machine is reduced while the aspect ratio is held constant. In the second set of calculations, the size of the machine is reduced and the magnetic field at the plasma is held constant. Current densities in the TF coil central leg of 30 to 300 MA/m² are investigated.

Fig. 1. Variation of plasma parameters with center conductor post current density for aspect ratio = 1.57 and $\beta = 24\%$.

Fig. 2. Variation of center conductor post design parameters with current density for aspect ratio = 1.57.

Plasma radii from 1.5 down to 0.5 m are investigated. The magnetic field at the plasma is in the range of 2 to 4 T. These fields require total TF currents in the range of 8 to 15 MA. Coolant channel velocities of up to 30 m/s and pressure drops up to 5 MPa (700 psi) are investigated. For the cases presented here the neutron heating is set to zero.

Table 5 shows a brief summary of the limits on current density and current imposed by conductor center leg stress, conductor temperature, water velocity, and pressure drop. The same kind of information is shown in fig. 3 for OFHC in machines with a constant aspect ratio of 1.57. Figure 4 shows this information for machines with a constant magnetic field at the plasma of 2 T.

When the stress on the OFHC copper shown in figs. 3 and 4 is limited to the allowable value of 63 MPa (9 ksi) for annealed copper, current densities of up to 20 to 30 MA/cm² may be used. Imposing the limit of 90 MPa (17 ksi) for 50% cold-worked copper on the stress shown in figs. 3 and 4 shows that up to 50 to 60 MA/cm² may be used, as illustrated in fig. 5. For these values of current density and cold work, the copper stress and temperature, coolant velocities, and pressure drops will be in the acceptable range. These systems have a total cost differential for conductor, pumps, and electrical power supplies for the magnets and pumps of about \$24 million. Their most severe limitation is high stress in the copper, which can be carried best if the copper has been cold-worked to increase its strength.

Because the limiting factor in the use of OFHC copper is the compressive stress in the copper, it is useful to note that this stress is proportional to the square of the current density times the outer radius of the TF coil center leg or to the square of the current divided by the outer conductor radius. This relationship can be seen in fig. 6.

With the high-strength, lower-conductivity copper alloy the increased resistivity produces more electrical heating and higher copper temperatures, as shown in figs 7 and 8. The alloy is better suited to carrying higher stress at higher temperatures. When the limit of 210 MPa (30 ksi) is applied to the stress shown in fig. 5, current densities of 100 to 110 MA/m² can be used. The alloy system has a total cost differential for conductor, pumps, and electrical power supplies for the magnets and pumps of about \$32 million. The most severe limitations are high temperature in the alloy and the high coolant velocity.

Table 5
Limiting TF coil parameters

	Constant aspect ratio (= 1.57)		Constant plasma field (= 2 T)	
	OFHC copper	Alloy copper	OFHC copper	Alloy copper
Aspect ratio	Fixed	Fixed	1.57-1.36	1.57-1.36
Field at plasma, T	2-4	2-4	Fixed	Fixed
TF current density, kA/m ²	10	10	10	10
TF current, MA	11	11	9	9
Peak stress, MPa (ksi)	210 (30)	210 (30)	168 (24)	168 (24)
Water velocity, m/s	26	34	29	30
Water pressure drop, MPa (psi)	2.4 (336)	2.6 (381)	4.1 (586)	4.4 (623)
Maximum temperature of copper, °C	171	326	150	379
Differential cost, millions of dollars	19	40	18	36

Fig. 3. Variation of stress, water velocity, pressure drop, and peak copper temperature versus current density for various machines with constant aspect ratio, using OFHC copper.

Fig. 4. Variation of stress, water velocity, pressure drop, and peak copper temperature versus current density for various machines with constant magnetic field at the plasma, using OFHC copper.

Fig. 5. Maximum conductor temperature and resulting allowable stress as a function of current density for OFHC copper.

Fig. 6. Variation of stress versus the product of current density times the outer radius of the center leg of the TF coil.

Fig. 7. Variation of stress, water velocity, pressure drop, and peak copper temperature versus current density for various machines with constant aspect ratio, using high-strength copper alloy.

Fig. 8. Variation of stress, water velocity, pressure drop, and peak copper temperature versus current density for various machines with constant magnetic field at the plasma, using high-strength copper alloy.

These results can be presented in a more usable, but less obvious, form that includes the restriction that the rise of coolant temperature from inlet to outlet be kept at 60°C until the coolant velocity reaches 25 m/s, at which time the velocity is held constant and the temperature rise is allowed to increase. Figures 5 and 9 show the variation of the peak conductor temperature and the associated allowable stress in the OFHC and alloy copper. Figure 10 shows the limiting stress and current density for each of the three materials, OFHC annealed, OFHC 50% annealed, and alloy copper.

The variation of center leg, balance of plant, and net costs as a function of current density can be seen in figs. 11 and 12. The stress limits are also indicated. Figure 13 shows the net cost differential for both OFHC and alloy copper versus the current density and allows one to see the reason for the choice of 40 MA/m² as the limit for 50% cold-worked OFHC copper, giving a savings of \$32 million. It also shows the limit of 110 MA/m² for the alloy copper system and the savings of \$24 million. Detailed numerical results are presented in Tables 6-13.

8. Conclusions

A series of performance and cost trade-offs is presented for the central legs of TF coils with water cooling. For the case of OFHC copper, the limitation of compressive stress in the copper restricts the current density to 40 MA/m² if 50% cold-worked copper is used. If high-strength alloy copper is used, the limitations are on the water velocity, pressure drop, and temperature of the copper alloy. Use of the alloy will allow current densities of 110 MA/m² and thus the design of reactors that are more compact. The penalty is the higher costs associated with increased power to the TF coils and cooling pumps, as well as higher costs for the pumps and the TF coil material. The advantages are the reduced size and cost of the balance of the plant. This gives a savings of \$24 million when one goes from conventional to high current density in 50% cold-worked copper. The saving is \$32 million with the alloy copper system. Put another way, for high current density, there is an advantage of \$8 million in favor of the alloy system versus the 50% annealed copper system.

Fig. 9. Maximum conductor temperature and resulting allowable stress as a function of current density for alloy copper.

Fig. 10. Current density limits based on compressive stress in the center conductor post.

Fig. 11. Cost optimization with stress limits for OFHC copper center conductor.

Fig. 12. Cost optimization with stress limits for alloy copper center conductor.

Fig. 13. Cost comparison of OFHC, 50% cold-worked, and alloy copper center conductor materials as a function of current density.

Table 6
Computational results for the fixed-aspect-ratio machine using OFHC copper

	TF coil current density J_c , MA/m ²					
	30.00	70.00	100.0	140.00	200.00	300.00
R_c , m	0.39	0.24	0.19	0.16	0.13	0.10
R_p , m	1.50	0.98	0.82	0.71	0.61	0.52
L_c , m	4.80	3.50	3.10	2.80	2.60	2.30
I_c , MA	14.34	12.25	11.46	10.70	9.98	9.31
B_c , T	7.65	10.80	12.48	14.27	16.47	19.49
B_p , T	1.99	2.60	2.91	3.14	3.40	3.72
Stress, ksi	11.10	22.12	29.57	*38.67 ^a	51.48	72.09
$(W_c)_E$, MW	61.27	91.83	110.89	134.05	170.05	225.40
Water velocity, m/s	3.41	13.95	25.75	*46.64	91.21	193.06
Pump power, MW	0.01	0.21	1.03	4.79	28.85	207.03
R_{Cu} , cm	3.90	2.36	1.91	1.56	1.26	0.99
R_{water} , cm	1.51	0.91	0.74	0.60	0.49	0.38
Pressure drop, psi	3.67	84.39	336.06	*299.78	6131.76	
Channel ΔT , °C	60.03	60.02	59.92	59.96	59.94	59.99
Maximum film ΔT , °C	54.53	54.25	53.64	52.49	50.00	49.45
Maximum copper ΔT , °C	13.91	28.25	38.39	51.18	69.91	103.02
Maximum water temperature, °C	80.03	80.03	79.92	79.96	79.94	79.99
Maximum copper temperature, °C	148.37	162.52	171.95	183.63	*199.85	232.46
Costs, millions of dollars						
Power supplies	10.42	15.65	19.03	23.60	33.97	73.51
Material	1.72	0.46	0.27	0.16	0.10	0.05
Pumps	0.00	0.02	0.12	0.55	3.32	23.83
Total	12.14	16.13	19.41	24.32	37.39	97.39

^aThe * indicates a value in an unacceptable range.

Table 7
Computational results for the fixed-field machine using OFHC copper

	TF coil current density J_c , MA/m ²					
	30.00	70.00	100.0	140.00	200.00	300.00
R_c , m	0.39	0.22	0.17	0.14	0.11	0.08
R_p , m	1.50	1.09	0.98	0.88	0.80	0.73
L_c , m	4.80	4.00	3.70	3.50	3.30	3.10
I_c , MA	14.34	10.36	9.19	8.26	7.47	6.71
B_c , T	7.65	9.93	11.17	12.53	14.25	16.55
B_p , T	1.99	1.98	1.95	1.95	1.94	1.91
Stress, ksi	11.10	18.70	23.70	*29.82 ^a	38.53	51.97
$(W_c)_E$, MW	61.27	85.08	100.12	120.05	148.69	194.52
Water velocity, m/s	3.41	15.23	28.97	*54.11	105.97	231.14
Pump power, MW	0.01	0.30	1.62	8.58	52.18	430.80
R_{Cu} , cm	3.90	2.17	1.71	1.37	1.09	0.84
R_{water} , cm	1.51	0.84	0.66	0.53	0.42	0.33
Pressure drop, psi	3.67	129.22	586.96	*		
Channel ΔT , °C	60.03	60.01	60.01	60.01	59.95	59.98
Maximum film ΔT , °C	54.53	43.71	40.35	37.04	34.13	31.25
Maximum copper ΔT , °C	13.91	23.05	29.31	37.10	48.61	76.35
Maximum water temperature, °C	80.03	80.01	80.01	80.01	79.95	79.98
Maximum copper temperature, °C	148.37	146.78	149.67	154.15	162.69	*178.58
Costs, millions of dollars						
Power supplies	10.42	14.51	17.30	21.87	34.15	106.30
Material	1.72	0.44	0.25	0.15	0.09	0.05
Pumps	0.00	0.03	0.19	0.99	6.01	49.58
Total	12.14	14.99	17.74	23.01	40.25	155.94

^aThe * indicates a value in an unacceptable range.

Table 8
Computational results for the fixed aspect ratio machine using alloy copper

	TF coil current density J_c , MA/m ²					
	30.00	70.00	100.0	140.00	200.00	300.00
R_c , m	0.39	0.24	0.19	0.16	0.13	0.10
R_p , m	1.50	0.98	0.82	0.71	0.61	0.52
L_c , m	4.80	3.50	3.10	2.80	2.60	2.30
I_c , MA	14.34	12.25	11.46	10.70	9.98	9.31
B_z , T	7.65	10.80	12.48	14.27	16.47	19.49
B_p , T	1.99	2.60	2.91	3.14	3.40	3.72
Stress, ksi	11.10	22.12	29.57	*38.67	51.48	72.09
$(W_c)_c$, MW	102.80	157.31	192.83	237.36	310.98	429.50
Water velocity, m/s	5.72	23.91	*44.96	82.56	165.83	368.15
Pump power, MW	0.03	1.07	5.36	26.59	173.38	1435.53
R_{Cu} , cm	3.90	2.36	1.91	1.56	1.26	0.99
R_{water} , cm	1.51	0.91	0.74	0.60	0.49	0.38
Pressure drop, psi	10.16	247.95	*1011.94			
Channel ΔT , °C	60.03	59.98	60.05	59.98	59.97	59.94
Maximum film ΔT , °C	60.48	60.36	10.01	58.85	56.36	56.22
Maximum copper ΔT , °C	23.03	47.92	65.92	89.16	124.38	189.68
Maximum water temperature, °C	80.02	79.98	80.05	79.98	79.97	79.94
Maximum copper temperature, °C	163.53	188.29	205.98	227.99	260.73	*325.85
Costs, millions of dollars						
Power supplies	17.48	26.93	33.69	44.87	82.34	317.05
Material	2.29	0.61	0.35	0.21	0.13	0.07
Pumps	0.00	0.12	0.62	3.06	19.96	165.22
Total	19.77	27.66	34.66	48.15	102.43	482.35

*The * indicates a value in an unacceptable range.

Table 9
Computational results for the fixed-field machine using alloy copper:

	TF coil current density J_c , MA/m ²					
	30.00	70.00	100.0	140.00	200.00	300.00
R_c , m	0.39	0.22	0.17	0.14	0.11	0.08
R_p , m	1.50	1.09	0.98	0.88	0.80	0.73
L_c , m	4.80	4.00	3.70	3.50	3.30	3.10
I_c , MA	14.34	10.36	9.19	8.26	7.47	6.71
B_c , T	7.65	9.93	11.17	12.53	14.25	16.55
B_p , T	1.99	1.98	1.95	1.95	1.94	1.91
Stress, ksi	11.10	18.70	23.70	*29.82*	38.53	51.97
$(W_c)_E$, MW	102.80	144.35	171.39	207.85	251.91	352.55
Water velocity, m/s	5.72	25.97	*49.64	93.74	186.61	418.48
Pump power, MW	0.03	1.48	8.13	44.58	284.93	2556.59
R_{Cu} , cm	3.90	2.17	1.71	1.37	1.09	0.84
R_{water} , cm	1.51	0.84	0.66	0.53	0.42	0.33
Pressure drop, psi	10.16	373.13	*1723.46			
Channel ΔT , °C	60.02	59.92	59.95	59.97	59.97	60.04
Maximum film ΔT , °C	60.48	48.53	44.89	41.32	38.23	35.23
Maximum copper ΔT , °C	23.03	38.81	49.71	63.53	84.42	119.65
Maximum water temperature, °C	80.02	79.92	79.95	79.97	79.97	80.04
Maximum copper temperature, °C	163.53	167.26	174.55	184.83	202.61	*234.91
Costs, millions of dollars						
Power supplies	17.48	24.79	30.53	42.91	92.96	494.55
Material	2.29	0.59	0.34	0.21	0.12	0.07
Pumps	0.00	0.17	0.94	5.13	32.79	294.25
Total	19.77	25.55	31.79	48.25	125.88	788.87

*The * indicates a value in an unacceptable range.

Table 10
Computational results showing the effect of elevated channel ΔT on the fixed-aspect-ratio machine using OFHC copper

	TF coil current density J_c , MA/m ²	
	140.00	200.00
R_c , m	0.16	0.13
R_p , m	0.71	0.61
L_c , m	2.80	2.60
I_c , MA	10.70	9.98
B_c , T	14.27	16.47
B_p , T	3.14	3.40
Stress, ksi	*38.67 ^a	51.48
$(W_c)_E$, MW	163.10	275.12
Water velocity, m/s	*28.33	36.61
Pump power, MW	1.07	1.87
R_{Cu} , cm	1.56	1.26
R_{water} , cm	0.60	0.49
Pressure drop, psi	479.66	987.01
Elevated channel ΔT , °C	120.09	240.29
Maximum film ΔT , °C	95.15	100.49
Maximum copper ΔT , °C	59.98	100.49
Maximum water temperature, °C	140.09	260.29
Maximum copper temperature, °C	*295.22	527.79
Costs, millions of dollars		
Power supplies	27.91	47.09
Material	0.16	0.10
Pumps	0.12	0.21
Total	28.19	47.40

^aThe * indicates a value in an unacceptable range.

Table 11
Computational results showing the effect of elevated channel ΔT on the fixed-field machine using OFHC copper

	TF coil current density J_c , MA/m ²	
	140.00	200.00
R_c , m	0.14	0.11
R_p , m	0.88	0.80
L_c , m	3.50	3.30
I_c , MA	8.26	7.47
B_c , T	12.53	14.25
B_p , T	1.95	1.94
Stress, ksi	*29.82 ^a	38.53
$(W_c)_E$, MW	142.64	227.59
Water velocity, m/s	32.17	40.46
Pump power, MW	1.80	2.90
R_{Cu} , cm	1.37	1.09
R_{water} , cm	0.53	0.42
Pressure drop, psi	*918.22	1858.86
Elevated channel ΔT , °C	119.95	240.30
Maximum film ΔT , °C	66.73	112.85
Maximum copper ΔT , °C	42.80	68.16
Maximum water temperature, °C	139.95	260.36
Maximum copper temperature, °C	*249.47	441.40
Costs, millions of dollars		
Power supplies	24.56	39.18
Material	0.15	0.09
Pumps	0.21	0.33
Total	24.92	39.61

^aThe * indicates a value in an unacceptable range.

Table 12
Computational results showing the effect of elevated channel ΔT on the fixed-aspect-ratio machine using alloy copper

	TF coil current density J_c , MA/m ²	
	140.00	200.00
R_c , m	0.19	0.16
R_p , m	0.82	0.71
L_c , m	3.10	2.80
I_c , MA	11.46	10.70
B_c , T	12.48	14.27
B_p , T	2.91	3.14
Stress, ksi	29.57	*38.67 ^a
$(W_c)_E$, MW	236.85	390.52
Water velocity, m/s	27.42	*33.84
Pump power, MW	1.24	1.83
R_{Cu} , cm	1.91	1.56
R_{water} , cm	0.74	0.60
Pressure drop, psi	380.92	*684.39
Elevated channel ΔT , °C	120.21	240.39
Maximum film ΔT , °C	108.96	197.62
Maximum copper ΔT , °C	77.66	128.88
Maximum water temperature, °C	140.21	260.73
Maximum copper temperature, °C	326.83	*587.23
Costs, millions of dollar:		
Power supplies	40.47	66.70
Material	0.35	0.21
Pumps	0.14	0.21
Total	40.97	67.12

^aThe * indicates a value in an unacceptable range.

Table 13
Computational results showing the effect of elevated channel ΔT on the fixed-field machine using alloy copper

	TF coil current density J_c , MA/m ²	
	140.00	200.00
R_c , m	0.17	0.14
R_p , m	0.98	0.88
L_c , m	3.70	3.50
I_c , MA	9.19	8.26
B_c , T	11.17	12.53
B_p , T	1.95	1.95
Stress, ksi	29.57	*38.67 ^a
$(W_c)_E$, MW	236.85	390.52
Water velocity, m/s	27.92	*33.84
Pump power, MW	1.77	1.37
R_{Cu} , cm	1.71	1.83
R_{water} , cm	0.66	0.53
Pressure drop, psi	*623.52	
Elevated channel ΔT , °C	119.52	239.72
Maximum film ΔT , °C	81.05	136.91
Maximum copper ΔT , °C	57.78	89.97
Maximum water temperature, °C	139.82	259.72
Maximum copper temperature, °C	278.64	489.60
Costs, millions of dollars		
Power supplies	35.33	55.73
Material	0.34	0.21
Pumps	0.20	0.31
Total	35.87	56.24

^aThe * indicates a value in an unacceptable range.

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