SIZING OF THE THERMAL AND ELECTRICAL SYSTEMS FOR AN FED BUNDLE DIVERTOR DESIGN WITH MgO INSULATION

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December 1980

PFC/RR-80-28
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*Supported by U.S. D.O.E. Contract DE-AC02-78-ET510-13
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ABSTRACT

The high-order dependence of toroidal ripple from a bundle divertor on the magnet shield thickness increases the desirability of a magnet technology with minimal shielding requirements. A jacketed conductor with MgO powder insulation has been used successfully in highly irradiated environments. Its properties and limitations are described. A thermal and electrical sizing code has been developed for magnet design with this technology. Two design examples for ETF and FED missions show reduced recirculating power from previously reported designs.
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Because of the very high-order dependence of hot-ion ripple losses in a tokamak plasma, such as the Engineering Test Facility (ETF) or the Fusion Engineering Device (FED), on the magnetic moment of a bundle divertor coil system, it is interesting to investigate magnet technologies which require the least amount of shielding against neutrons and gamma rays. Previous studies [1,2] have indicated that, for both superconducting and normal conductor magnets with organic insulation, the most limiting factor is insulation life. Therefore, a good direction to look is at ceramic insulations, such as MgO powder. Ceramics have higher radiation resistance than organic insulations on general principles, because of their absence of easily broken chemical bonds. However, interest in ceramic insulations in general and MgO powder in particular is best justified by the superior operating performance of MgO powder insulated coils in high gamma irradiation and high-heat environments.

1) History

MgO powder insulation is used in commercial stove elements, thermocouples for nuclear reactors and as a magnet insulation for accelerator magnets in a high gamma flux environment. Approximately 40 such magnets have been built by A. Harvey's group at the Los Alamos Scientific Laboratory (LASL) and 20 for accelerators operated by SIN (Suisse Institut Nucléaire) in Switzerland. There have been no failures related to insulation degradation in the several dozen magnets using ceramic powder insulation in a high gamma irradiation environment. The world's record irradiation is not known, but is believed to be greater than $10^{10}$ rads in one of the SIN magnets. Some of the magnets at LASL have logged over 30,000 hours of failure-free dc operation.

The operational experience of organic insulations in radiation environments is difficult to obtain. Failure reports appear infrequently in the open literature [3]. Few magnets have failed because of radiation damage to the insulation. Most accelerators never achieve their original design specification radiation dosages. Insulations
are routinely inspected at laboratories such as Stanford and Brookhaven and are replaced when significant
discoloration or delamination of the insulation is observed. According to D. Hay [4], at the Stanford Linear
Accelerator (SLAC), magnets with Al₂O₃-filled epoxy glass insulation are routinely replaced after irradiations
of 10⁶ rads because of observed depolymerization. Therefore, magnets subjected to successful preventive
maintenance can not test the hypothesis that thin insulations will continue to function successfully at irradia-
tions well beyond the threshold to visible damage. The most spectacular unreported magnet failure, which
was unambiguously due to radiation damage, is the failure of the DESY ring magnets in West Germany at
radiation doses of about 10⁸ rads. These magnets used aliphatic amine cured epoxies with mica and glass
fillers. Dozens of magnets failed at radiation levels of 10⁶ rads. It is believed that the failure mechanism was
bubble rupture, bubbles being prevented from diffusing out of the insulation by the mica fillers. The most
encouraging example of nonfailure that I have identified that of the NINA bending magnets in Darsbury,
England (near Liverpool). R. Sheldon at Princeton [5] believes that these insulations have been irradiated to
greater than 10¹⁰ rads with no magnet failures. The insulations are S-glass filled imide epoxies, cured with
NMA. They are relatively thin, thus avoiding trapped gas formation.

While no spectacularly high magnet irradiations have been reported for MgO insulation, the insulation
of the neutron flux detectors in the Canadian Pickrell reactors is known to have been irradiated to 10¹⁴ rads
in the first three full power years [6]. No insulation failures occurred. When the detectors were removed
from service, the insulation resistance had changed from 10⁹ Ω to 10⁸ Ω at 100 V. This contrasts with the
order of magnitude reduction in the resistivity of G-10 after an irradiation of 10¹⁰ rads reported by Coltman
[7]. Brechna [8] reported a decrease in the unirradiated resistivity of wet-wound epoxy DER 332 of 5 orders
of magnitude at an irradiation of 10¹⁰ rads and of 10 orders of magnitude at an irradiation of 10¹³ rads.
Therefore, the electrical properties of MgO insulation appear to be far more stable under irradiation than
those of organic insulations.

The difference in the operating experience of inorganic vs. organic insulation magnets is one argument
in favor of using the MgO insulation in highly irradiated environments in ETF. The other, and probably
more powerful argument, is the lack of clearly identified integrated failure mechanisms for ceramic powder
insulation, as will be explained below. In order of applicability, relevant environments include (1) the bundle
divertor magnets, (2) toroidal ripple compensation coils, attached to a shield or vacuum vessel flange, (3) inter-
nal poloidal divertor coils or (4) the main TF coils if very high beta is established by the current experimental program.

(2) Design Code Description

The ceramic insulation technology has several limitations, which have been modeled in a thermal-electrical systems sizing code, entitled BUNDLE LCOIL. There are also several variations of this code in use at MIT which include models of L-shaped coils, such as have been recommended for use in bundle divertors, circular coils, internally-cooled conductors and externally-cooled conductors. Our worked example in section three will be a bundle divertor with L-shaped coils with internally-cooled conductors, since this appears to be the most attractive fusion application of the ceramic insulation technology. The limitations on how lightly shielded the magnet can be include (1) instantaneous nuclear heating, (2) copper transmutations, (3) copper lattice displacements, (4) neutron-induced leakage current in the MgO insulation, (5) electrolysis of the ceramic break in the external coolant line, (6) electrolysis of the MgO insulation by neutron-enhanced migration of ceramic impurities, (7) erosion of the copper by radiolyzed water derivatives, (8) swelling of the insulation and (9) embrittlement of the copper. These limitations will be discussed below.

Instantaneous neutron and gamma heating appears to be the single most limiting factor for coils built with the MgO insulation technology, even at very high duty factors and availabilities. Typical heating rates have been calculated by Engholm [9] and are modeled in BUNDLE LCOIL by the correlation

\[ Q'''' = 18.8 P_{\text{wall}} \exp(-\alpha \text{ Thick}_{\text{shield}}) \] (1)

where \( P_{\text{w}} \) is the wall-loading in \( (W/m^2) \) and \( \alpha \), the attenuation coefficient, is 13 m\(^{-1}\) for tungsten with titanium hydride and 11 m\(^{-1}\) for stainless steel and borated water. Notice that the Joule heating of a conductor with a current density in copper of 3 kA/cm\(^2\) is 15 W/cc. If the nuclear and gamma heating is to held to about one-tenth of that amount, then approximately 30 cm of stainless steel/borated H\(_2\)O shield, 24 cm of tungsten/titanium hydride shield or, possibly, 16 cm of tungsten/titanium hydride shield plus a 10 cm thick steel coil case would be required.

Copper is transmuted by neutrons to unstable isotopes of copper, which decay into nearly equal amounts of zinc and nickel. Each atom of zinc or nickel can be thought of as the equivalent of three or four lattice displacements in their effect on the copper resistivity. The code BUNDLE LCOIL uses the following uses the
The following relations:

\[ \text{Atom density}_{\text{Cu}} = 0.75 \times 10^{22} \text{ (cc}^{-1}) \] (1)

\[ \text{Transmutation density} = \frac{\text{Fluence}}{\text{efold distance}} \] (2)

where the e-folding distance of transmutations in copper is taken to equal 10 cm.

\[ \text{Appm} = \frac{10^6 \times \text{Transmutation density}}{\text{Atomic density}} \] (3)

where appm is the atomic parts per million of transmutations.

A single fusion 14 Mev fusion neutron can be expected to cause 1200 lattice displacements in copper. A typical fission spectrum would cause about 400 displacements per neutron. At room temperature, about 85% of those displacements would be almost immediately annealed out. There is also a saturation limit of about .1% defects that can be supported in copper at room temperature. Both the annealing and the saturation limits improve at elevated temperatures. However, I don't have design data over a range of temperatures and will use the conservative room temperature values. Therefore, each fusion neutron entering the magnet is assumed to cause \((400(1-.85)=60)\) sixty lattice displacements, until a level of .001 dpa is reached. Each transmutation is taken to be 3.5 times worse than each lattice displacement in its effect on additional resistivity.

\[ \Delta \rho_{\text{lattice}} = \frac{\text{dpa}}{0.001} \times 10^{-8} (\Omega - m) \] (3)

for dpa < .001 and

\[ \Delta \rho_{\text{lattice}} = 4 \times 10^{-8} (\Omega - m) \] (4)

for dpa > .001. The resistivity due to transmutations is

\[ \Delta \rho_{\text{transmut}} = 3.5 \times \text{appm} \times \frac{0.0148 \times 10^{-8}}{300} (\Omega - m) \] (5)

The temperature dependent resistivity of copper is taken to equal
The neutron induced leakage current in the MgO insulation is based on Clinard's irradiation experiments with Al₂O₃. Since there are, as yet, no data on neutron-induced free carriers in MgO, we have to assume that the behavior of alumina is typical of ceramics. As will be seen, this assumption has a significant effect on the magnet and electrical circuit design and requires more careful analysis and, hopefully, further experiment. Clinard found that the electrical conductivity of Al₂O₃ is almost linear with irradiation over a fairly broad range of irradiation intensities [10]. Clinard's data is fitted with the correlation

$$\sigma_{rad} = 5.6 \times 10^{-6} \left( \frac{\text{Grays}}{6.6} \right)^{.65}$$

where Grays is the instantaneous irradiation in Grays/second. Scaling from the LASL Reverse Theta Pinch Reactor (RTPR) ceramic first-wall design, the following conversion is used:

$$\text{Grays} = .05 P_w$$

where $P_w$ is the magnet wall-loading in W/m².

In order to predict the temperature rise in the MgO and, thus, the possibility of electrical breakdown due to thermal runaway, the following correlation was developed from the MgO thermal conductivity reported in Kingery, Bowen and Uhlmann [11].

$$T_{norm} = \frac{T_{\text{max,Cu}}}{100}$$

$$K_{MgO} = -0.7728 + 84.835 \frac{1}{T_{\text{norm}}} - 62.96 \frac{1}{T_{\text{norm}}^2} + 16.23 \frac{1}{T_{\text{norm}}^3}$$

Weeks [12] discovered that MgO crystals in a dc electrical field could suffer destruction through electrolysis at elevated fields. Dielectric breakdown was observed at fields as low as 10-100 V/mm after 5 to 150 hours of heating at 1200 K. Subsequent, unpublished tests on Al₂O₃ showed superior performance, with no evidence of electrolysis at temperatures in the range of 800-1000 C. While there is reason to believe that neutron and
gamma irradiation will enhance ion migration at the lower temperatures typical of magnets, I have assumed that electrolysis will not be a failure mechanism. However, this should be confirmed by experiment.

At high water velocities, very high purity water is required in order to prevent rapid erosion of a copper channel. A certain number of residual impurites, as well as gamma-hydrolyzed oxygen, may attack an internally cooled conductor, such as the jacketed conductors manufactured by Pyrotenax. The total absorption mass attenuation coefficient \( \mu / \rho \) of water is .03 cm\(^2\)/g over a broad range of photon energies. If all of the photon absorption energy went into chemical bond breaking, a worst-case 100 W/cm\(^2\) channel wall flux would cause an absorption rate of 3 W/cc or, at a weighted average of about 1 ev per molecular dissociation, \( 7.5 \times 10^{19} \) ions/cc per second. Recombination may not be negligible, but recombination products will include a significant fraction of corrosive free radicals and hydrogen peroxide; erosion is desired to be low. Therefore, if convection were the dominant ion removal mechanism, a 10 m/s water flow velocity through a 10 m hydraulic path would leave a residual ion population of \( 7.5 \times 10^{19} \) ions/cc, which is equal to the the number of hydrogen ions in an acid with a pH of 2.6. Although this calculation is extraordinarily crude, even if the population of corrosive radiolysis products due to gamma irradiation is 1,000 times lower, there is a strong prima facie case that there should be an erosion-resistant cladding between the water and the copper.

Radiolysis products also attack the ceramic break needed between the cooling channels of internally-cooled conductors and the grounded plumbing system. It is standard practice at the LAMPF facility [3] to provide a 6 mm sacrificial electrode in the ceramic tubing end. However, one insulator has failed after a few years at LAMPF because of electrolytic corrosion.

An interesting idea for a cladding-coolant combination might be to use stainless-steel or a hafnium alloy, which are good neutron absorbers in the epithermal range and borated H\(_2\)O, which is a good absorber of thermal neutrons and a good moderator over a wide range. It might be possible to reduce neutron absorption in the copper and insulation by a nontrivial factor (1.5-2) by this use of "internal shielding", while simultaneously solving lifetime limitations due to water erosion. (The relatively obscure hafnium alloys are very similar in their mechanical and thermal properties to the widely-used zirconium alloys. They are not used in nuclear reactors, largely because they are neutron absorbers.) A candidate reference conductor is shown in Figure 1.

According to F. Clinard [13], MgO swells about 1% at magnet temperatures, at relatively low doses
(10^{20} - 10^{21} \text{n/cm}^2), but then saturates. The dominant failure mechanism in bulk ceramics is cracking along grain boundaries, which don’t exist in the fine MgO powder. Of course, most of the stress “relief” comes from the fact that the powder may only have a 95-97 % packing factor. It should be noticed that the $10^{12}$ rad limitation on ceramic insulation, which one sees frequently quoted in fusion literature [2], must be referring to cracking in bulk ceramics due to swelling. This failure mechanism probably doesn’t exist for the ceramic powder technology. In fact, no lifetime limiting mechanism has been clearly identified for this insulation.

According to T.H. Blewitt [14], neutron embrittlement of the copper should not be a factor. Up to a fluence of $10^{20}$ n/cm$^2$, there should be no significant loss of ductility in copper or any other metal with face-centered-cubic crystals. Blewitt irradiated pure copper crystals to an irradiation of $10^{22}$ n/cm$^2$ on the HIFR reactor at room temperature and measured no significant change in the yield strength from the unirradiated case. Therefore, copper embrittlement has been ignored.

(3) ETF/FED Design Examples

A recent ETF bundle divertor magnetic design was developed by T.F. Yang [15]. Dimensions, except for currents, are shown in Figure 2. Each L-shaped coil near the main plasma required 6.72 MAT, while each coil far from the main plasma required 4.8 MAT. If a 10 cm thick coil case and 20 cm of tungsten-titanium hydride shielding are used, then a cross-section of at least 54 cm x 74 cm should be available for each conductor, or an overall current density in the near conductors of 1.89 kA/cm$^2$ and 1.2 kA/cm$^2$ in the far conductors.

Significant parameters of the electrical and thermal system were reported at the ETF Interim Design Review [15]. The reported power in the near coils of 48 MW per coil was undesirable, but there was very little design freedom to improve the situation, with current day conductor technology, which is limited at best to about 60 % overall packing factor in the conductor. However, A. Harvey’s group at LASL is currently collaborating with Pyrotenax to develop a conductor with an overall current density of 75 %. The new technology would involve larger conductors and preformed ceramic rings, instead of tamped in powder. They also hope to eliminate the failure mechanisms of copper erosion and ceramic break corrosion by using external steel or nickel-alloy conductors, without breaks. I have used the goal of 75 % packing factor as an input in a model of an internally-cooled conductor in order to find an ETF example with desirably low recirculating power.

One solution with a number of desirable features is shown in Tables I and II. The recirculating power in
each of the front coils is down to 28.2 MW. The maximum temperature in the copper is only 55 °C, keeping the copper resistivity low and considerably lower than allowable temperatures. Even with 30 paralleled leads to reduce the electric field in the insulation and the leakage current losses, the MgO loss/unit length is still 1,160 W/m, comparable to the 5,120 W/m lost in the copper. This necessitates a 134 kA bus for each of the front coils. The water velocity is 10 m/s and the head drop for each single turn hydraulic circuit is 12 atmospheres.

Currently, the ETF design center is considering a Fusion Energy Device (FED), which would have a reduced mission from that of the original ETF, such as a plasma $Q = 5$, and which would also, hopefully, have significant economies compared with the original ETF mission. A key feature of the FED is the reduction of the overall integrated duty factor to .02, from the ETF duty factor of .5. This allows both lower current and lower shielding in a bundle divertor coil. A possible FED bundle divertor design was generated by reducing the shielding by 10 cm, and keeping the original major machine and bundle divertor dimensions, while reducing all magnetic fields to reflect the reduced mission. This leads to a bundle divertor front coil requirement of 5.05 MA, with an overall conductor current density of 1.03 kA/cm$^2$, as shown in Figure 2. The candidate conductor for the front coils is shown in Figure 1.

The parameters of a candidate FED bundle divertor design are shown in Tables III and IV. All limitations have now been greatly relaxed. The power requirement of each front coil is only 10.9 MW, while the entire bundle divertor system requires slightly over 30 MW. The water velocity has been reduced to 5 m/s, significantly reducing any vibration problems that might arise at the higher water velocity. The number of terminal pairs has been held at 30, which reduces the loss/length due to leakage currents to 246 W/m, despite the decreased shielding, while the nuclear heating/unit length has risen to 1,287 W/m. The dc terminal voltage is now only 67 V, greatly reducing the possibility of insulation electrolysis or electrical breakdown, even in a highly irradiated environment.

If the insulation thickness is reduced and the heat flux from the insulation is held constant by placing more conductors in parallel, the electrical bus current must increase. In the reference design, with 7.6 kA conductors and 30 parallel turns per coil, two 105 kA busses are required for the near coils and two 60 kA busses for the far coils, if the conductors are connected $\pm$ to ground. If standard copper bus is designed for a total voltage drop of 10 V and costs $50/\text{kA-m}$ (9), then the bus losses would equal 4.5 MW and cost $4.5$ M for a 200 m run, forward and return. Large rectifiers have been purchased to drive the toroidal field coils of
ORMAK, Alcator C and TFTR at a specific cost of only $4/kW, including transformers and switchgear. If this is still possible, then the rectifiers and rectifier-transformers would cost $2.0 M. For the reference design, both the buswork and the rectifier costs will be functions of current only, so doubling the number of parallel turns will nearly double the cost of the electrical circuits. While not clearly desirable, there is some flexibility in this trade-off, if recirculating power is to be reduced further.

While an optimization code could certainly be written for the total electrical energy, the trade-offs are such that judgment on design limitations and inherent inaccuracies in modeling overwhelm the prospect of there being any reality to the computer-predicted gains in system performance. The two candidate systems were selected by the personal judgment of the author, after inspecting 36 possible designs for each system.

The technology of jacketed, MgO-insulated coils presents the safest way of doing magnet design at high irradiations. A disadvantage of the current technology is that it has a moderately low overall packing density. This could hopefully be remedied by a development program to work with larger billets for the same insulation filling gap or with lower filling gaps. In order to be attractive, more benefit can be imagined from coil topology optimization, relaxation of physics constraints or changes in overall reactor dimensions than from conductor size optimization.
References

1. J.H. Schultz, "Neutron Irradiation Limits on the ETF Toroidal Field Coils", ETF Design Center internal memorandum; October, 1979
4. D. Hay, private communication
5. R. Sheldon, private communication
6. Reuter-Stokes Canada, Ltd., Cambridge, Ont., Canada, private communication
13. F.W. Clinard, private communication
14. T.H. Blewitt, private communication
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joule heating</td>
<td>27.7 MW</td>
</tr>
<tr>
<td>Total electric power consumption</td>
<td>28.2 MW</td>
</tr>
<tr>
<td>Turns per coil</td>
<td>750 turns</td>
</tr>
<tr>
<td>Terminal pairs</td>
<td>30 pairs</td>
</tr>
<tr>
<td>Terminal voltage, dc</td>
<td>144 V</td>
</tr>
<tr>
<td>Conductor current</td>
<td>8,955 A</td>
</tr>
<tr>
<td>Copper resistivity</td>
<td>$2.32 \times 10^{-8}$ (Ohm-m)</td>
</tr>
<tr>
<td>Overall current density</td>
<td>$1.89$ kA/cm**2</td>
</tr>
<tr>
<td>Bus current</td>
<td>134 kA</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Conductor height</td>
<td>2.0 cm</td>
</tr>
<tr>
<td>Coolant channel height</td>
<td>6.0 mm</td>
</tr>
<tr>
<td>Water inlet temperature</td>
<td>20°C</td>
</tr>
<tr>
<td>Water outlet temperature</td>
<td>51°C</td>
</tr>
<tr>
<td>Inlet-outlet head loss</td>
<td>12 atmospheres</td>
</tr>
<tr>
<td>Water velocity</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Ideal pump power</td>
<td>0.3 MW</td>
</tr>
<tr>
<td>Heat flux</td>
<td>21.8 W/cm²</td>
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<tr>
<td>Maximum temperature in the copper</td>
<td>55°C</td>
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<tr>
<td>Joule loss/unit length</td>
<td>5120 W/m</td>
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<tr>
<td>MgO loss/unit length</td>
<td>1160 W/m</td>
</tr>
<tr>
<td>Nuclear heating/unit length</td>
<td>117 W/m</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Joule heating</td>
<td>10.86 MW</td>
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<tr>
<td>Total electric power consumption</td>
<td>10.94 MW</td>
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<td>Turns per coil</td>
<td>662 turns</td>
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<tr>
<td>Terminal pairs</td>
<td>30 pairs</td>
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<td>Terminal voltage, dc</td>
<td>67 V</td>
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<tr>
<td>Conductor current</td>
<td>7,625 A</td>
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<tr>
<td>Copper resistivity</td>
<td>$2.23 \times 10^{-8}$ (Ohm-m)</td>
</tr>
<tr>
<td>Radiation induced resistivity</td>
<td>$4.1 \times 10^{-9}$ (Ohm-m)</td>
</tr>
<tr>
<td>Overall current density</td>
<td>1.03 kA/cm**2</td>
</tr>
<tr>
<td>Bus current</td>
<td>114 kA</td>
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Table IV

THERMAL PARAMETERS OF FED BUNDLE DIVERTOR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor height</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>Coolant channel height</td>
<td>7.5 mm</td>
</tr>
<tr>
<td>Water inlet temperature</td>
<td>20 °C</td>
</tr>
<tr>
<td>Water outlet temperature</td>
<td>43.4 °C</td>
</tr>
<tr>
<td>Inlet-outlet head loss</td>
<td>2.7 atmospheres</td>
</tr>
<tr>
<td>Water velocity</td>
<td>5 m/s</td>
</tr>
<tr>
<td>Ideal pump power</td>
<td>0.05 MW</td>
</tr>
<tr>
<td>Heat flux</td>
<td>11.9 W/cm**2</td>
</tr>
<tr>
<td>Maximum temperature in the copper</td>
<td>45.9 °C</td>
</tr>
<tr>
<td>Joule loss/unit length</td>
<td>2,278 W/m</td>
</tr>
<tr>
<td>MgO loss/unit length</td>
<td>246 W/m</td>
</tr>
<tr>
<td>Nuclear heating/unit length</td>
<td>1,287 W/m</td>
</tr>
</tbody>
</table>
Appendix: Program Listing of BUNDLE LCOIL

c BUNDLE EXTKUL is an open-loop version of BUNDLE LCOIL, which analyzes
rather than sizing a magnet conductor for a highly-irradiated magnet,
using the technology developed by Pyrotenax of Canada, Ltd, for
accelerators. The conductor consists of an externally-cooled, squared-off
conductor, with MgO powder insulation, in a water-tight sheath. This
first program assumes that the development effort at the LAMPF facility
c at LASL will succeed in its goal of producing a conductor with 75 %
c overall packing factor.

implicit real(i-n,I-N)
integer n,ma,mh,mw thick,mv,NR,NW

2000 format(v)
NR=5
NW=6
kCu=350.
km on=21.8
Tin=20
Deltat=10

c kCu is the thermal conductivity of copper (W/m-K)
c km on is the thermal conductivity of monel (W/m-K)
c Tin is the inlet temperature of the cooling water (°C)
c Deltat is the wall drop (°C). The above input is just a first

guess
Tavg ess =100.
Tmax guess=150

c Tavg ess is the first guess at the copper average temperature (°C)
c Tmax guess is the first guess at the copper maximum temperature (°C)

Ampturns=6.72e6
Vleg=1.2
Hlegtor=1.2
Hle grad=1.2
Npairs=30.

c Ampturns is the total number of ampere-turns in one magnet (A-T)
c Vleg is the height of the vertical leg of an L-coil (m)
c Hlegtor is the length of a horizontal leg in toroidal direction (m)
c Hlegrad is the length of a horizontal leg in radial direction (m)
c Npairs is the number of pairs of leads paralleled at the bus ()
Pwall=2.4*10.**6
Jcond=1.89*10.**7

c Pwall is the neutron wall-loading of the reactor (W/m**2)
c Jcond is the current density over the entire conductor (A/m**2)
duty=.89
avail=5

years=5
c duty is the single-cycle duty factor ()
c avail is the integrated plant availability ()
c years is the desired lifetime of the magnet (yr)

S hthick=.3
Npar=4

c ShGreek is the shield thickness (m)
c Npar is the number of parallel conductors in one lead ()

RhoH2O=1000.
CpH2O=4178
CondH2O=.61

c RhoH2O is the density of water (kg/m**3)
c CpH2O is the specific heat of water (J/kg-°C)
c CondH2O is the thermal conductivity of water (W/m-°C)
do 3004 mh=1,3
h = 0.005 + mh * 0.005
do 3003 ma = 1, 3
    averh = 1 + 0.05 * ma
    do 3002 mwthick = 1, 2
        wthickoverh = 0.025 + 0.05 * (mwthick - 1.)
    do 3001 mv = 1, 2
    v = 5 * mv
a = h * averh
aw = averh
wthick = wthickoverh * h
Tmax = Tmaxguess
Tav = Tavguess
do 3000 n = 1, 4

 shield is the shield material. 0 means a tungsten and
titanium hydride shield. 1 is a stainless steel and borated
water shield

shield = 1
if (shield .eq. 0) Atten = 13
if (shield .eq. 1) Atten = 11
Fluence is the neutron fluence at the surface of the
coil (n/cm**2)
Fluence = 4.4e16 * Pwall * duty * avail * years * exp(-Atten * Shthick)
Atomdens is the atomic density of copper (atoms/cc)
Atomdens = 6.023e23 * 8 / 64
efoldcu is the e-folding distance of neutron capture in copper (cm)
efoldcu = 10.
Transmudens is the density of transmuted atoms in copper (atoms/cc)
Transmudens = Fluence / efoldcu
apm is the atomic parts per million of transmuted atoms ()
apm = Transmudens * 1.66 / Atomdens
Nuc Heat is the volumetric nuclear and gamma heating (W/m**3)
Nuc Heat = 18.8 * Pwall * (1 - Atten * Shthick)
Rhocu is the thermal resistivity of copper (m-K/W)
Rhocu = 1/kCu
Rhomon is the thermal resistivity of monel (m-K/W)
Rhomon = 1/kmon
Acu is the cross-section area of copper in the conductor (m**2)
Acu = h**2 * Npar
Tjack is the jacket thickness (m)
Tjack = h / (16 * 1.63)
Hjack is the flat-to-flat height of the jacket (m)
This is somewhat arbitrary, based on known goals of LASL program
to achieve overall packing factor of .75.
Hjack = h * 1.8 / 1.63
Tins is the insulation thickness (m)
Tins = (Hjack - h - Tjack) / 2.
Ajack is the area of the copper, in insulation and jacket (m**2)
Ajack = Hjack * Tjack * Npar
Acond is the total conductor area including cooling channels (m**2)
Acond = Npar * (h + 2 * Tins + 2 * Tjack) * (h + 2 * Tins + 2 * Tjack + 2 * wthick + a)
Qnuc is the dissipation per unit length due to nuclear heating (W/m)
Qnuc = Nuc Heat * Ajack
Pacfac is the overall packing factor (copper/conductor)
Pacfac = Acu / Acond
Jcu is the maximum current density in the copper itself (A/m**2)
Jcu = Jcond / Pacfac
Icond is the conductor current (A)
Icond = Jcond * Pacfac
Jjack is overall current density in conductor and jacket (A/m**2)
Jjack = Icond / Ajack
Lturn is the length of a single turn (m)
Lturn=2.*(Vleg+Hlegtor+Hlegrad)

Nturns is the number of turns required
Nturns=Ampturns/Icond

Minbend is the maximum permissible bending radius (m)
Minbend=12.*Hjack

dpn is the expected displacements per neutron after annealing
dpn=60

dpa is the expected lattice displacements per atom
dpa=dpn*appm*1.e-6

Rholattice is the electrical resistivity of the copper (Ohm-m)
due to lattice displacements.

if ( dpa .lt. .001 ) go to 17004
go to 17005

17004 continue
Rholattice=(dpn/.001)*.4*10.**(-8)
go to 17006

17005 continue
Rholattice=.4*10.**(-8)

17006 continue
Badtrans is the badness ratio of additional resistivity () due to a
single transmutation over that due to a single lattice displacement
Badtrans=3.5

Rhotransmu is the electrical resistivity of the copper due to
transmutations of the copper into zinc and nickel (Ohm-m)
Rhotransmu=Badtrans*appm*(.0148*10.**(-8))/300.

print."appm,Badtrans",appm,Badtrans
print."Rhotransmu",Rhotransmu

Rhotemp is the electrical resistivity of copper as a function of
temperature. (Ohm-m)
Rhotemp=(1.48 + .00754 * Tav)*1.e-8

print."Tav",Tav
print."Rhotemp",Rhotemp

Rhocu is the total electrical resistivity of the copper (Ohm-m)
Rhocu=Rhotemp + Rholattice + Rhotransmu

print."Rhocu",Rhocu

Qprime is the dissipation per unit length (W/m)
Qprime=Rhocu*Jcu**2*Acu

print."Qprime",Qprime

Jsquarerho is the power/volume dissipated in the conductor (W/m**3)
Jsquarerho=Rhocu*Jcu**2

tdiffcu is the difference between the copper hot-spot and cold-spot
temperatures (C)
tdiffcu=(Jsquarerho+Nucuat)/h/(2*Npar*kCu)

Turndiss is the power dissipated per single turn (W)
Turndiss=Lturn*Acu*Jsquarerho+Lturn*Acond*Nucuat

Turndisse is the electrical power dissipated per turn
Turndisse=Lturn*Acu*Jsquarerho

Qcu is the heat flux into the coolant tubes (W/m**2)
Qcu=Acu*Jsquarerho/(Npar*Hjack)

Coildiss is the power dissipated per coil (W)
Coildiss=Turndiss*Nturns

Coildisse is the electric power dissipated per coil (W)
Coildisse=Turndisse*Nturns

Acondtotal is the area required by all the turns of the coil (m)
Acondtotal=Nturns*Acond

Nchannel is the number of cooling channels in a conductor ()
Nchannel=Npar*Hjack/(a+2*wthick)

Qh is the heat flux into the water-cooling channel (W/m**2)
Qh=Turndiss/(Lturn*4*a*Nchannel)

Pw is the wetted perimeter (m)
\[ P_w = 4 \cdot a \cdot N_{\text{channel}} \]

\[ A_{\text{chan}} = a^2 \cdot N_{\text{channel}} \]

\[ D_h = \frac{4 \cdot A_{\text{chan}}}{P_w} \]

\[ \text{Visc} = \text{the viscosity of water as a function of temperature} \ (\text{kg/s-m}) \]

\[ \text{Visc} = (T_{\text{in}} + 20.)^{.9} \cdot \left( \frac{T_{\text{in}}}{400} + 1. \right) \]

\[ \text{Visc} = 95. / \text{Visc} \]

\[ \text{Visc} = \frac{\text{Visc}}{3600} \]

\[ G_m = \text{the mass flow rate/unit area} \]

\[ G_m = \rho_{\text{H}_2\text{O}} \cdot v \]

\[ \text{Re} = \text{the Reynolds number} \]

\[ \text{Pr} = \text{the Prandtl number} \]

\[ \text{Pr} = \frac{\text{Visc} \cdot \text{Cp}_{\text{H}_2\text{O}}}{\text{Cond}_{\text{H}_2\text{O}}} \]

\[ \text{Deltat} = \text{the wall drop} \ (\text{C}) \]

\[ \text{Deltat} = \frac{Q_{\text{h}}}{1 + \text{Deltat}} \]

3006

\[ \text{Deltiojoule} = \text{difference between outlet and inlet temperature} \ (\text{C}) \]

\[ \text{due to Joule heating} \]

\[ \text{Deltiojoule} = \frac{\text{Turnissi} \cdot \left(\frac{\rho_{\text{H}_2\text{O}} \cdot A_{\text{chan}}}{\text{Cp}_{\text{H}_2\text{O}}}\right)}{v} \]

\[ \text{Deltionuc} = \text{the difference between outlet and inlet temperature} \ (\text{C}) \]

\[ \text{due to nuclear heating} \]

\[ \text{Deltionuc} = \frac{\text{Turn} \cdot A_{\text{cond}} \cdot N_{\text{heat}}}{\left(\frac{\rho_{\text{H}_2\text{O}} \cdot A_{\text{chan}}}{\text{Cp}_{\text{H}_2\text{O}}}\right)} \]

\[ v_{\text{term}} = \text{the resistive terminal voltage at the coil} \]

\[ \text{Vterm} = \frac{\text{Vterm \cdot L}_{\text{cond}} \cdot N_{\text{pairs}}}{v \cdot \rho_{\text{H}_2\text{O}} \cdot A_{\text{chan}} \cdot \text{Cp}_{\text{H}_2\text{O}}} \]

\[ \text{Efield} = \text{the dc electric field across the insulation} \]

\[ \text{Efield} = \frac{\text{Vterm}}{T_{\text{ins}}} \]

\[ \text{K}_{\text{MgO}} = \text{the thermal conductivity of MgO} \ (\text{W/m-K}) \]

\[ \text{Thermophysical properties of MgO from Kingery, Bowen and Uhlmann} \]

\[ \text{Introduction to Ceramics, Wiley-Interscience, 1976} \]

\[ \text{Correlation by Schultz} \]

\[ T_{\text{norm}} = T_{\text{max}} / 100. \]

\[ \text{K}_{\text{MgO}} = -0.7728 + 84.835 / T_{\text{norm}} - 62.696 / T_{\text{norm}}^2 + 16.23 / T_{\text{norm}}^3 \]

\[ \rho_{\text{MgO}} = 1 / \text{K}_{\text{MgO}} \]

\[ \text{RTPRconv} = \text{the conversion factor} \ (\text{Gray/s/W/m}^2) \]

\[ \text{scaling from the RTPR design} \]

\[ \text{for a ceramic facing combine neutron and gamma radiation} \]

\[ \text{from W/m}^2 \text{to Gray/s} \]

\[ \text{RTPRconv} = .05 \]

\[ \text{Magrad} = \text{the maximum radiation absorption in the magnet insulation} \]

\[ \text{in Gray/s} \]

\[ \text{Magrad} = \text{RTPRconv} \cdot \text{Pwall} \]

\[ \text{Sigrad} = \text{the electrical conductivity of the insulator due to} \]

\[ \text{irradiation} \]

\[ \text{Data taken from Clinard's contribution to the} \]

\[ \text{LASL 1979 Special Purpose Materials Annual Progress Report} \]

\[ \text{Sigrad} = 5 \cdot 10^{-6} \cdot (\text{Magrad} / 6.6) \]

\[ \text{Emgo = the electric field in the MgO} \]

\[ \text{Emgo = Vterm / Tins} \]

\[ \text{Jmgo = the current density in the MgO} \]

\[ \text{Jmgo = Emgo \cdot Sigrad} \]

\[ \text{Powmgo = the power density in the MgO due to leakage currents} \]

\[ \text{Powmgo = Jmgo \cdot 2 / Sigrad} \]
Qmgo is the heat flux in the insulation

\[ Q_{mgo} = P_{mgo} \times T_{ins} \]

\[ \Delta t_{mgo} \] is the temperature rise in the MgO

\[ \Delta t_{mgo} = \left( P_{mgo} + N_{uheat} \right) \times T_{ins}^2 / \left( 2 \times K_{MgO} \right) \]

\( P_{mgo} \) is the power dissipation per unit length in the MgO (W/m)

\[ Q_{mon} \] is the heat flux generated in the monel (W/m²)

\[ Q_{inmon} = 2 \times Q_{mgo} + Q_{cu} \]

\( \Delta t_{mon} \) is the temperature drop in the monel coolant wall (C)

\[ \Delta t_{mon} = Q_{inmon} \times w_{thick} / k_{mon} + Q_{mon} \times w_{thick} / \left( 2 \times k_{mon} \right) \]

\( f \) is the friction factor.

\[ f = 0.04 / \left( R_{e}^{0.16} \right) \]

\( f_{Koo} \) is the friction factor. Good for \( R_{e} > 2000 \) in smooth tube

\[ f_{Koo} = 0.0014 + 0.125 / \left( R_{e}^{0.32} \right) \]

\( \Delta P_{pl} \) is the pressure drop per unit length

\[ \Delta P_{pl} = 2 \times f_{Koo} \times \rho_{H2O} \times \nu_{h}^{2} / D_{h} \]

\( P_{pl} \) is the ideal pump power per unit length

\[ P_{pl} = \nu_{h} \times A_{chan} \times \Delta P_{pl} \]

\( P_{delt} \) is the pressure drop per hydraulic channel

\[ P_{delt} = \Delta P_{pl} \times L_{t} \]

\( \mu \) is the Joule-Thomson coefficient -dP/dT at constant enthalpy.

\[ \mu = C_{pH2O} / \left( \rho_{H2O} \times \Delta P_{pl} \right) \]

\[ \Delta \mu_{mgo} = P_{delt} \times \mu \]

\( \Delta t_{io} \) is the difference between inlet and outlet water temperature (C)

\[ \Delta t_{io} = \Delta t_{tiojoule} + \Delta t_{ionuc} + \Delta t_{iomgo} \]

\( T_{out} \) is the outlet temperature of the water

\[ T_{out} = T_{in} + \Delta t_{iojoule} + \Delta t_{ionuc} + \Delta t_{iomgo} \]

\( T_{max} \) is the copper hot spot temperature (C) with the specified water temperature

\[ T_{max} = T_{out} + \Delta t_{diffcu} + \Delta t_{t} + \Delta t_{mgo} + \Delta t_{mon} \]

\( T_{av} \) is the average temperature in the copper (C)

\[ T_{av} = T_{max} - \Delta t_{diffcu} / 2 \]

\( \sigma_{pl20} \) is the stress in the jacket due to the water pressure (Pa)

\[ \sigma_{pl20} = P_{delt} \times a / (h-a) \]

\( E_{c} \) is the electrical power need for the pump motors

\[ E_{c} = 1.5 \times P_{pl} \]

\[ P_{total} = E_{c} + Coi \]

print."****************************************"
print."h,Tins,Tjack",h,Tins,Tjack
print."wthick,a",wthick,a
print."v",v
print."Tmax","Tmax"
print,"Tav",Tav
print,"Tout",Tout
print,"Deltio",Deltio
print,"Deltiojoule,Deltionuc,Deltionmgo",Deltiojoule,Deltionuc,Deltionmgo
print,"Deltimu",Deltimu
print,"Tdiffcu",Tdiffcu
print,"Deltatmgo",Deltatmgo
print,"Deltatmon",Deltatmon
3001 continue
3002 continue
3003 continue
3004 continue
end
Figure 1
Conceptual Conductor Design for an ETF Bundle Divertor Coil

- MgO Powder Insulation
- Copper Sheath
- Copper Conductor
- Steel Cladding
- Borated Water Coolant

Dimensions:
- 0.3 mm
- 0.75 cm
- 0.95 mm
- 1.3 mm
- 2.5 cm
Figure 2
ETF Bundle Divertor Example Design by T. F. Yang

R₁ = 7.70 m
R₂ = 11.40 m
dx₁ = 1.20 m
dy₁ = 1.20 m
dz₁ = 1.20 m
I₁ = 5.05 × 10⁶ MA-T
I₂ = 3.61 × 10⁶ MA-T