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THREE COMPUTER CODES FOR SAFETY AND STABILITY
OF LARGE SUPERCONDUCTING MAGNETS*

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THREE COMPUTER CODES FOR SAFETY AND STABILITY OF LARGE
SUPERCONDUCTING MAGNETS*

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ABSTRACT

For analyzing the safety and stability of large superconducting magnets, three computer codes TASS, SHORTURN, and SSICC have been developed, applicable to bath-cooled magnets, bath-cooled magnets with shorted turns, and magnets with internally cooled conductors respectively. The TASS code is described, and the use of the three codes is reviewed.

INTRODUCTION

A large superconducting magnet must be both stable and safe thermally. Stability analysis determines what happens when a section of conductor becomes normal conducting due to a mechanical perturbation or other heat input. To be cryostable, the magnet must have adequate cooling to return the conductor to the superconducting state. To be safe, on the other hand, the magnet must respond to any credible abnormal conditions in a way that will not endanger the public, the operators, other systems, or the magnet itself.

Three safety and stability computer codes which have been developed at Argonne National Laboratory (ANL) will be described here: TASS (Thermal Analysis for Safety and Stability), used to analyze the stability of a pool boiling cryostable magnet or its safety under different off-normal conditions; SHORTURN, used to analyze the safety of a cryostable magnet with shorted turn or turns; and SSICC (Safety and Stability of Internally Cooled Conductors), used to analyze magnets with internally cooled conductors (ICC). The codes had their origins in the need to analyze superconducting magnets being built for MHD research and have been developed as part of the program to ensure the safety of fusion reactors.

TASS

The program TASS originated as a stability code.¹ It proved useful in studying the stability of the MHD magnet built at Argonne National Lab-

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oratory for the Coal-Fired Flow Facility at the University of Tennessee Space Institute.² It was modified, primarily by changing from the forward difference method to the backward difference method, for studying the safety of that magnet.³ Finally it was generalized for use in studying the quench properties of fusion magnets, as part of the fusion safety program.⁴ It has been successfully used at the Fusion Engineering Design Center, Oak Ridge National Laboratory,⁵ and has been distributed elsewhere in the fusion magnet community.

Since its initial distribution, the code has been modified fairly extensively to broaden its applicability and to incorporate new data on physical properties, especially critical current density and transient heat transfer.

Applications of TASS

Stability. In stability analysis, a current and perturbing heat pulse are specified for a conductor otherwise operating under design conditions. Consideration of only a short time (a second or so) and a short length (a meter or so) will determine whether the normal region will collapse, grow without limit, or reach a steady state.

Uncovered conductor. An all too credible abnormal condition for a bath-cooled magnet is a low liquid level, resulting in a length of uncovered conductor. In TASS, such a length can be specified, either uncooled or vapor cooled by free convection. The heat transfer for convective vapor cooling is calculated from the Rayleigh number, using the temperature dependent properties of 1 atm helium vapor.

Helium depletion and replenishment in cooling channels. A nominally cryostable bath-cooled magnet may not be stable against large heat pulses. The pulse, and subsequent joule heating, may vaporize all the helium around the conductor. Replenishment of the liquid may then be too slow to return the conductor to its superconducting state.

The computer code TASS has now been modified so that during a time step Δt the fraction f of the channel volume of an element which is filled with liquid is changed by an amount Δf ,

$$\Delta f = r\Delta t - \Delta q/q_L \quad (1)$$

where: q_L is the heat needed to fill the channel with vapor, Δq is the heat which the element transfers to the helium in the cooling channel, and r is the reciprocal of the time needed to replenish the liquid in a vapor filled channel. The fraction f is constrained to lie between zero and one. The available experimental data⁶ on depletion and replenishment is inadequate to estimate the constant r or to test Eq. (1).

Changing current. Under off-normal conditions, the current may vary. The abnormal condition may consist of a specified varying current, or the magnet may be discharged in response to the abnormal conditions. Either of these can be treated in TASS.

For a discharging magnet, the power dissipated internally in normal regions of conductor and externally in the discharge resistor is calculated each step. The stored energy, initialized from the current and inductance, is decreased each step, and the new value of current calculated. The magnetic field value, used in calculating critical current each step, can be decreased proportionally with the current.

Space variation of magnetic field. A characteristic property of tokamak TF (toroidal field) coils, and some other cryostable magnets as well, is the variation of the magnetic field B around a turn of the coil. The field can vary by more than a factor of two over a distance of a few meters, as can field dependent parameters such as critical current, resistivity, and propagation velocity. This situation permits the possibility of a stable normal region of conductor, which never propagates into the low field region nor collapses in the high field region. TASS has demonstrated this effect.

Operation with HeII. Stability analysis of conductors cooled by superfluid helium has been incorporated into TASS, using the approach of Meuris, et al.⁷ As it has not been thoroughly tested, it will not be described here.

Operation of TASS

Heat balance. In the program, the conductor being modeled is discretized into elements along its length. A heat balance is applied to each element to compute the temperature of each element at each time step. From the temperature distribution, the program tracks the development of any normal region of conductor.

The heat flow into the element arises from nuclear radiation, frictional motion, or external heating. These are represented by an applied heat flux Q_{app} . If the element is in the normal or current sharing state, heat will also be produced by resistive joule heating Q_J .

Heat may flow out of the element through heat transfer to the helium coolant Q_{He} , and through conduction to neighboring conductor elements Q_{cond} and neighboring turns Q_{TT} . Symbolically, then, the heat balance may be written as:

$$Q_{app} + Q_J = Q_{He} + Q_{cond} + Q_{TT} + Q_{enth} ,$$

where Q_{enth} represents the increase in enthalpy of the element.

$$Q_{app} = P_{app} \Delta l \Delta t \quad (2)$$

where P_{app} is the externally applied heating per unit length of conductor, and Δl is the element length.

$$Q_J = \rho_e \Delta l (1 + 1/r) I_{eff}^2 \Delta t / A , \quad (3)$$

where ρ_e is the electrical resistivity of the copper, r is the volume ratio of copper to superconductor, $A = hw$ is the cross sectional area of the conductor, and

$$\begin{aligned} I_{eff}^2 &= I^2 && \text{if the element is fully normal} \\ &= I(I - I_g) && \text{if the element is above } I_g, \text{ the critical current} \\ &= 0 && \text{if the element is fully superconducting} \end{aligned}$$

$$Q_{He} = f p_w \Delta l q_h \Delta t = f p_w \Delta l (\alpha + \beta T_i) \Delta t , \quad (4)$$

where p_w is the wetted perimeter, and $q_h = \alpha + \beta T_i$ is the heat transfer coefficient (α and β may themselves be weak functions of T_i , the temperature of element i). The fraction of cooling available, f , is found by Eq. (1).

$$Q_{\text{cond}} = A \Delta t [k_{i,i+1}(T_i - T_{i+1}) + k_{i,i-1}(T_i - T_{i-1})] / \Delta x, \quad (5)$$

where $k_{i,i\pm 1} = 2(1/k_i + 1/k_{i\pm 1})^{-1}$ is the effective thermal conductivity between elements i and $i \pm 1$. Use of an averaged thermal conductivity such as this is needed so that the heat conducted from element i to $i + 1$ is the negative of that conducted from $i + 1$ to i , as required for overall heat balance.

$$Q_{\text{TT}} = g \Delta t \Delta t (2T_i - T_i^+ - T_i^-), \quad (6)$$

where T_i^+ and T_i^- are the temperatures of the i -th elements of the two neighboring turns, and g is the effective turn-to-turn conductivity.

$$Q_{\text{enth}} = V \rho_m C_p (T_i - T_i'), \quad (7)$$

where V is the element volume ($A \Delta x$), ρ_m is the mass density of the conductor, C_p is its specific heat, and T_i' is the temperature of element i at the previous time step.

These six equations are substituted into the heat balance equation for each element, which is then divided by $\rho C V$ to give it the units of temperature. The terms of the equation are rearranged to give

$$\begin{aligned} T_i [1 + (k_{i,i+1} + k_{i,i-1}) \Delta t / \rho_m C_p (\Delta x)^2 + f p_w \Delta t \beta / A \rho_m C_p + 2g \Delta t / w \rho_m C_p] \\ - T_{i+1} [k_{i,i+1} \Delta t / \rho_m C_p (\Delta x)^2] - T_{i-1} [k_{i,i-1} \Delta t / \rho_m C_p (\Delta x)^2] \\ = T_i' - f p_w \Delta t / A \rho_m C_p + \rho_e I_{\text{eff}}^2 \Delta t / A^2 \rho_m C_p \\ + P_{\text{app}} \Delta t / A \rho_m C_p + g (T_i^+ + T_i^-) \Delta t / w \rho_m C_p. \end{aligned} \quad (8)$$

The equations thus obtained for each element form a tri-diagonal system of simultaneous equations which can be solved for T_i . (Since Q_{TT} is typically very small compared to Q_{He} and Q_{cond} , the previously computed values for T_i and T_i are used on the right hand side in order to preserve the tri-diagonal form.) The backward difference method⁶ does not introduce numerical instability for any size time increment. The program thus determines the temperature of each element at each time step.

Details of Properties

Transient heat transfer. The transient heat transfer data of Steward⁹ and of Giarratano and Frederick¹⁰ can be represented in a simple form. The expression for nucleate boiling is used:

$$q_h = 0.8 \Delta T, \Delta T < \Delta T_{\text{max}} \quad (9)$$

where q_h is the heat transfer in W/cm^2 and ΔT is the temperature difference in kelvin between the conductor surface and the bulk helium. For steady state transfer this condition is taken to hold for $\Delta T_{\text{max}} = 1 \text{ K}$. For transient transfer, it is taken to hold up to

$$\Delta T_{\text{max}} = -0.7806 \ln(t - t_0) - 2.617 \quad (10)$$

where t is the time and t_0 the time at which ΔT for the element first exceeds 0.1 K , t and t_0 in seconds. For $\Delta T > \Delta T_{\text{max}}$, the expressions are used for film boiling or the transition region

$$q_h = 0.1271 + 0.0015 \Delta T, \Delta T > 2 \quad (11)$$

$$q_h = 1.45 - 0.65 \Delta T, \Delta T_{\max} < \Delta T < 2. \quad (12)$$

Critical current density of NbTi. Because of new data on the critical current density J_c of NbTi, particularly at low temperature T and high field B , we have refit the data over the range $1.8 \text{ K} < T < 8 \text{ K}$, $2 \text{ T} < B < 14 \text{ T}$. The new expression is

$$J_c = (T_c - T) (8.8 - 0.46 B + 0.32/T - 1.31/T^2) \times 10^5.$$

The critical temperature T_c is taken to be

$$T_c = 8.56 (1 - B/14.7)^{1/2},$$

and T is expressed in kelvin, B in tesla, and J_c in A/cm^2 .

Number of elements. For a single turn, thermally insulated from neighboring turns, up to 400 elements have been used to model half the conductor. When heat transfer to neighboring turns is included, up to ninety elements have been used in the specified conductor and in each of the six turns on either side.

Appropriate element length. Experimental studies of the cryostability of superconducting magnets have sometimes observed the occurrence of a stable normal region of conductor (SNR) which neither shrinks out of existence nor propagates to quench the magnet.¹¹ However, the TASS code may sometimes predict the occurrence of a SNR unrealistically because of too large a conductor element length Δl being used in the analysis. When the computation is repeated with the use of a smaller element, no SNR is predicted.

It is found that the code will predict a SNR when one element, at or near the temperature of maximum heat transfer to the coolant is just able to transfer to the helium all of the heat received from a neighboring element. As the heat transferred to the helium is proportional to Δl while the heat received through conduction is inversely proportional to Δl , it follows that a false SNR is possible for Δl greater than some critical value. To find the critical value, Q_{He} and Q_{cond} from Eq. (3) and (4) are equated, giving, after rearrangement:

$$\Delta l \leq \frac{A}{P_w} \frac{k(T_m) (T_c - T_m)}{q_h(T_m)},$$

where T_c is the superconductor critical temperature and T_m is the temperature of maximum heat transfer to the helium. For pool boiling helium I at 4.2 K, $T_m = 5.2 \text{ K}$.

Typical appropriate values for Δl are in the range of 0.5-1.0 cm. In any case where TASS predicts a SNR, it is advisable to repeat the analysis using a smaller Δl , perhaps half the original.

Provision is made to permit the size of each element to increase as the computation proceeds. When a specified element of conductor goes normal, three elements can be combined into one. The heat transfer to the helium by the new element is the sum of the heat transferred by the three old ones; the temperature of the new element is the temperature of the middle one; and the length and electrical resistance of the new element and three times those of the old ones.

If turn-to-turn heat conduction is included, then when an element of a specified turn (e.g., the seventh nearest neighbor to the initial turn) goes normal, three turns are thereafter treated as one. The heat transferred to the helium from the new turn is the sum of the heat from the three old ones; the temperature of the new turn is that of the middle one; the electrical resistance and turn-to-turn heat conductance are decreased by a factor of three; and the width and equivalent current are tripled.

In light of the possibility described above of predicting a false SNR, this option of increasing the element size must be used with great caution.

Use of TASS

US-SCMS magnet. TASS was first used¹ to predict the stability of the US-SCMS magnet for MHD research.¹² Consideration of turn to turn conduction raised the predicted recovery current from 640 A (classical $q_h = 0.34$ W/cm²) to 874 A (classical $q_h = 0.64$ W/cm²).

UTSI-CFFF magnet. TASS was used to evaluate the stability^{1,13} of several conductor concepts for the UTSI-CFFF magnet for MHD research.² The safety of the magnet with a 6 m half turn uncovered and cooled only by vapor was also studied.^{3,13}

HRS magnet. The former Twelve-Foot Bubble Chamber magnet at ANL has been reconfigured, with horizontal axis, as the High Resolution Spectrometer (HRS) magnet at SLAC. As the first of the large cryostable magnets, it had a very conservative design, with a copper to superconductor ratio of 80. It is end-cooled, and operates at 2000 A and 1.6 T.

The magnet was analyzed for the effects of low liquid level, with 3 m of conductor outside the liquid.¹⁴ The analysis showed that the HRS magnet to be safe even in the worst case (no cooling, free wheeling).

US INTOR solenoid. The US INTOR design chose a 50 kA cabled conductor developed at Los Alamos National Laboratory (LANL)¹⁵ as the reference conductor of the ohmic heating (OH) solenoid. Analysis with TASS^{5,14} predicted recovery at 50 kA from 2 cm of conductor initially at 50 K (150 J) or 16 cm of conductor initially at 50 K (1200 J).

Overcurrent in tokamak TF coil. If one toroidal field (TF) coil of a tokamak discharges rapidly while the others remain superconducting and are switched into a mode of free-wheeling individually, the currents can rise in the two neighboring coils and their high field regions can become resistive.

In a TASS simulation,⁴ over a wide range of currents, a stable normal region developed, neither growing to the low field (3T) leg nor collapsing to the high field (9T) leg.

SHORTURN: ANALYSIS OF SHORTED TURNS

An analysis code SHORTURN has been developed by modifying TASS. In an analysis with SHORTURN, the conductor first goes to the normal state in the neighborhood of the short; then the normal region propagates along the shorted turn. A study¹⁶ comparing a short analysis of a large MHD dipole via SHORTURN with two other methods which assumed a uniform temperature distribution around the shorted turn found a higher temperature with SHORTURN.

Analysis of two magnets^{17,18} which reportedly had shorted turns has been reported previously.^{19,20} Under reasonable assumptions of short resistance and discharge times, the General Dynamics and General Electric coils of the Large Coil Project¹⁷ were predicted to recover without reaching a high temperature. Simulation of the shorted superconducting coil of the 25T to 30T hybrid magnet system¹⁸ at MIT predicted the sort of periodic voltage spikes observed experimentally. More recently SHORTURN has been modified to treat a magnet with a shorted turn or turns neighboring a discharging magnet.

INTERNALLY COOLED CONDUCTORS: SSICC CODE

Conditions for the stability of internally cooled conductors are found to depend upon both steady-state and transient helium flow. In fact, ICC are found to be highly stable against short heat pulses even when the steady state helium flow is near zero.^{21,22} This effect is attributed to the improved heat transfer caused by the transient flow of helium following local heating and pressure rise.

Vincent Arp developed a computer code²³ for the stability of ICC. His code incorporates one-dimensional energy, mass, and momentum balance within the helium and predicts the high velocity, high pressure helium flows, which are not predicted by simpler models.

Arp's code has been modified and combined with TASS to form the code SSICC (Safety and Stability of Internally Cooled Conductor). The SSICC code successfully predicted²⁴ the multiple stability regions observed in the experiments of Lue, Miller, and Dresner.^{25,26} It was also applied²⁷ in a thermal safety and stability analysis of the TF coils of the FED (Fusion Energy Device) magnets²⁸ which employed ICC.

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