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Abstract

RadQuench is a computer code that calculates relevant protection characteristics of cable in conduit conductors (CICC), especially the maximum hot spot temperature in the event of a quench. The physical model employed by this code is based on a three phase quench process. The time scales of the three phases depend upon the dump time constant for the coil, the quench detection and response time of the system, and the time at which the conductor jacket's heat capacity is added to the heat balance. This last parameter is fitted to give the best result with experiment, and experimentally divergent cases with respect to time scales are used to check this fit. The experiments that were used as benchmarks are the well-documented Westinghouse LCP quench experiments. The Westinghouse LCP coil serves as a suitable benchmark, being a very large CICC coil designed to simulate larger fusion TF coils, which are the primary objects to be analyzed with this code. This three phase model has demonstrated the ability to predict the quench temperatures for the two typical cases of varying time scales to within 7%, and thus should be safe to use for a variety of coils (with varying protection time scales), including ITER. RadQuench is user-friendly, and runs on personal computers.

Introduction

The verification of the applicability and accuracy of RadQuench has been accomplished by benchmarking the code to one of the only large coil experiments that has been performed to date, the Large Coil Program [1]. Specifically, we have used the results of quench experiments for the CICC Westinghouse toroidal field coil to compare to RadQuench's predictions concerning maximum hot spot temperature. The conductor characteristics have been modeled, and Table 1 gives all of the relevant parameters. The conductor flowpaths can be demonstrated to satisfy the criteria which define 'long conductor' [2], with the total flowpath length being over 80 m for each of the parallel paths,

$$L^2 >> 4 V_q^2 \, t_m^2 \tag{1}$$

where L is the length of the flowpath, V_q is the quench velocity (which is reported in [1]), and t_m is the time at which the calculation is made. Basically this inequality shows that the quenching section does not 'feel' the end of the flowpath, given that the quench occurs near the center of the flowpath. Experimentally, the quenches occur close to the center of the flowpath for the Westinghouse coil, since they occur on the inner turn of the coil which is wound in double pancake fashion with each flowpath beginning on the outer turn. The quantity on the right hand side of equation (1), in the case of the Westinghouse coil, has a value of about 256 m^2 in the downstream direction (only 23 m^2 in the upstream direction), and L^2 is over 6400 m^2 (at least 25 times greater than the right hand side). Thus, the Westinghouse coil can be taken as typical of a TF coil in all respects.

Theory and Results

First Model

In order to determine the maximum hot spot temperature, the standard adiabatic approach has been taken. The quench is assumed to occur in two phases, one in which the current is held constant and the other in which the current is allowed to decay exponentially, as would happen when the quenching coil's current is dumped through an external resistor. The resistance of the

Table 1. Westinghouse - LCP Coil Parameters [1]

Operating Temperature (K)	4.2
Field at the Coil (T)	11.2
Field on Axis (T)	1.72
Copper RRR	258
Operating Current (kA)	17.625
Cable Space Current Density (A/mm^2)	59.24
Number of Turns	424
Total NI (MAt)	7.47
Wire Diameter (mm)	0.7
Void Fraction	0.32
Copper Fraction in Conductor	0.624
Cable Space Cross Sectional Area (mm^2)	297.5
Jacket Thickness (mm)	1.75
Number of Strands	486
Number of Pancakes	26
Winding Method	Four-in-Hand
Number of Turns per Flowpath	Over 8
Approximate Length of Turn	About 10 m

normal zone is considered negligible in the first phase (thus the constant current assumption). It is quite important to distinguish between the two phases of the quench, because it has been found that the jacket of the conductor does not contribute to the heat capacity during the first phase, while it does contribute during the second phase [1]. This, of course, is an oversimplification, but it does seem to be adequate for this study.

We begin by performing a heat balance over the cable space volume during the first phase,

$$I_{Cu,0}^2(t)\,R_{Cu}\cdot dt = c_{p,cs}(T)\,V_{cs}\cdot dT \qquad (2)$$

where $I_{Cu,0}$ is the initial current flowing through the copper (equivalent to the conductor operating current), R_{Cu} is the resistance of the copper in the quench region, $c_{p,cs}$ is the specific heat averaged over the cable space, V_{cs} is the cable space volume, t is time, and T is the temperature in the cable space (at the point of quench initiation, and assuming transverse thermal equilibrium). This equation cannot be readily solved analytically for the maximum temperature, since the properties of the component materials vary with temperature in a complicated way, but the equation can be solved very easily for the current density,

$$J_{op} = \left(\frac{1}{t_d} f_{Cu,cs} \sum_{i}^{cs} f_i I_i \right)^{1/2} \tag{3}$$

$$I_i = \int_{T_0}^{T_{\max}} \frac{c_{p,i}}{\rho_{Cu}} \cdot dT \tag{4}$$

where J_{op} is the allowed operating current cable space current density, t_d is the delay time (the time between the initiation of the quench and the dump of the current), $f_{Cu,cs}$ is the fraction of copper over the cable space, the summation is taken over all components within the cable space (copper, superconductor, and helium), f_i is the fraction of the i-th component over the cable space, T_0 is the operating temperature, T_{max} is the maximum hot spot temperature, $c_{p,i}$ is the heat capacity of the i-th component, and ρ_{Cu} is the copper resistivity.

Similarly, during the second phase of the quench we perform a heat balance over the entire turn volume (ideally, this would include the insulation as well as the jacket, but due to the short time scales involved we have neglected it),

$$I_{Cu}^2(t) R_{Cu} \cdot dt = c_{p,turn}(T) V_{turn} \cdot dT \tag{5}$$

$$I_{Cu}(t) = I_{Cu,0} \exp\left(-\frac{t}{\tau} \right) \tag{6}$$

where $c_{p,turn}$ is the specific heat averaged over the turn, V_{turn} is the turn volume, I_{Cu} is the current through the copper at any given time subsequent to the dump, and τ is the dump time constant. The current density in this phase decays exponentially with a time constant of τ, dependent upon the coil inductance and the resistance of the dump resistor. Again, this heat balance may be solved for the current density,

$$J_{op} = \left(\frac{2}{\tau} \exp\left(\frac{2 t_d}{\tau} \right) \frac{f_{Cu,cs}}{f_{cs}} \sum_{i}^{turn} f_i I_i \right)^{1/2}$$

where f_{cs} is the fraction of the cable space over the turn and the summation is taken over all components within the turn (copper, superconductor, helium, and steel). Note the extra exponential term as well as the cable space fraction term, both serving to reduce the allowed current density (when t_d is less than τ).

In both cases the current density has been derived by constraining it to match the actual operating current density while allowing the maximum hot spot temperature to vary. Thus, one is able to predict, using RadQuench, the maximum temperature. The results of these predictions are in good agreement with the experiment. The parameters of the quench case which was modeled were a dump time constant of 10 s and a delay time of 5.4 s. This time delay actually represents the delay between the time at which the quench begins to propagate and the time at which the current is dumped into the external dump resistor. Thus, at time zero in the energy balance, the temperature is not the original helium temperature but the critical temperature of the conductor. The effect of this slight modification is an addition of about 2 K to the temperature at the time of the dump and about 1 K to the maximum hot spot temperature.

The results of the predicted and measured temperature versus time are shown in Fig. 1. As can be seen the temperature versus time prediction for the case of the short delay time follows the experimental temperature versus time measurements quite well. For the case of the long delay time, the predicted temperature at the time of the dump is significantly higher than the measured temperature (22%). The most obvious and probable explanation of this discrepancy (which becomes a little smaller by the time the dump is finished) is that the heat capacity of the steel jacket is ignored during the entire first phase of the quench. This is probably not a good assumption, especially in cases of long delay times. This value of time delay with respect to the addition of the jacket heat capacity (not with respect to the current dump) should be sensitive to the speed of the temperature rise, but this speed does not vary much from design to design since the component fractions do not vary significantly enough from design to design. The value of time delay should also be sensitive to the current density of the conductor, as this affects the temperature rise speed. For such a simplistic model as the adiabatic model, there is no simple

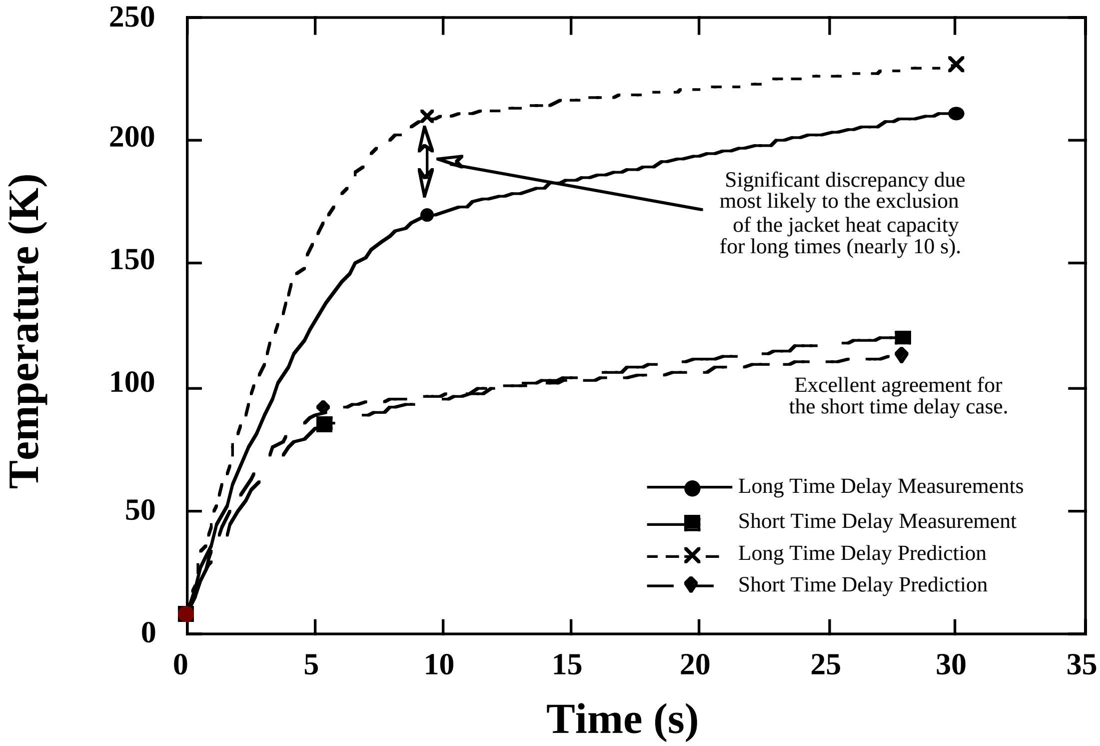

Fig. 1. The comparison between the hot spot temperatures as predicted by RadQuench using the two phase model and as measured by experiment for the Westinghouse Large Coil Program CICC TF coil.

expression determining the appropriate time delay after which the steel heat capacity should be added to the heat balance. For coils with a shorter dump delay time, however, such as ITER with a dump time delay of 1-2 s, this longer jacket heat capacity delay time must be taken into account.

Second Model

The difficulty encountered using the two-phase model has been addressed in both a qualitative and a quantitative way by the use of a slightly more sophisticated quench model. The model retains the simplicity of the adiabatic model, but employs a three phase description of the quench phenomenon rather than the two phase description given above. Let $t_{d,heat}$ be the time at which the jacket heat capacitance should be added to the heat balance and $t_{d,dump}$ be the time at which the current is dumped. If $t_{d,heat}$ is less than $t_{d,dump}$ the three phases are as follows: 1) the time period between the time of initial quench propagation and the time at which the jacket heat capacitance adds to the heat balance; 2) the time period between the time at which the jacket heat capacitance is added to the heat balance and the time at which the current is dumped; and, finally, 3) the time period subsequent to the current dump. If, on the other hand, $t_{d,heat}$ is greater than $t_{d,dump}$ the three phases are the following: 1) the time period between the time of initial quench propagation and the time at which the current is dumped; 2) the time period between the time at which the current is dumped and the time at which the jacket heat capacitance is added to the heat balance; and, finally, 3) the time period subsequent to the addition of the jacket heat capacitance to the heat balance.

The analytical development of this model parallels the development of the two phase model. Omitting details, the results of the heat balances (solved for J_{op}) in the case that the jacket heat capacitance adds to the heat balance before the current is dumped are as follows,

Phase 1:
$$J_{op} = \left(\frac{1}{t_{d,heat}} f_{Cu,cs} \sum_{i}^{cs} f_i I_i \right)^{1/2} \tag{8}$$

Phase 2:
$$J_{op} = \left(\left(\frac{2}{\tau} \right) \frac{1}{\exp\left(\frac{-2t_{d,heat}}{\tau} \right) - \exp\left(\frac{-2t_{d,dump}}{\tau} \right)} \frac{f_{Cu,cs}}{f_{cs}} \sum_{i}^{turn} f_i I_i \right)^{1/2} \tag{9}$$

Phase 3:
$$J_{op} = \left(\frac{2}{\tau} \exp\left(\frac{2t_{d,dump}}{\tau} \right) \frac{f_{Cu,cs}}{f_{cs}} \sum_{i}^{turn} f_i I_i \right)^{1/2} \tag{10}$$

where $t_{d,dump}$ is the delay time for the dump and $t_{d,heat}$ is the delay time for the addition of the jacket heat capacitance. For the case that the current is dumped before the jacket heat capacitance adds to the heat balance the results are similar,

Phase 1:
$$J_{op} = \left(\frac{1}{t_{d,dump}} f_{Cu,cs} \sum_{i}^{cs} f_i I_i \right)^{1/2} \tag{11}$$

Phase 2:

$$J_{op} = \left(\left(\frac{2}{\tau}\right) \frac{1}{\exp\left(\frac{-2t_{d,dump}}{\tau}\right) - \exp\left(\frac{-2t_{d,heat}}{\tau}\right)} f_{Cu,cs} \sum_{i}^{cs} f_i I_i \right)^{1/2} \quad (12)$$

Phase 3:

$$J_{op} = \left(\frac{2}{\tau} \exp\left(\frac{2t_{d,heat}}{\tau}\right) \frac{f_{Cu,cs}}{f_{cs}} \sum_{i}^{turn} f_i I_i \right)^{1/2} \quad (13)$$

In benchmarking the long time delay case, it was found that if the jacket heat capacitance began adding to the heat balance at about 8 seconds after initiation of quench propagation, the predictions obtained were in quite good agreement with the experiment. Then, since $t_{d,heat}$ should be independent of $t_{d,dump}$, the same value can be used in the short time delay case. The predictions for the short time delay case, using the $t_{d,heat}$ calibrated to the long time delay case, are in even better agreement with experiment than the predictions using the two phase model. As seen in Fig. 2, the predictions for the short time delay case are still slightly better than those for the long time delay case, but no temperature prediction is more than 7% off from the experimental value. Thus, the three phase model for quench is quite adequate for initial design studies. Moreover, both the case in which $t_{d,heat}$ is greater than $t_{d,dump}$ and the case in which $t_{d,dump}$ is greater than $t_{d,heat}$ agree with experiment.

Conclusion

The user-friendly computer code, RadQuench, has been developed and benchmarked for use in predicting the protection characteristics of large CICC coils, such as fusion TF coils. The physical model describing the quench phenomenon employs a three phase quench timescale distinction. The timescales represented in this model are the characteristic dump time of the coil, the quench detection and response time of the system, and the time at which the jacket heat capacitance is added to the heat balance. The inequality of the latter two timescales has profound impact upon both the temperature as a function of time and the maximum temperature, especially for the case in which the detection time delay is quite long (on the order of about 10 s). In the

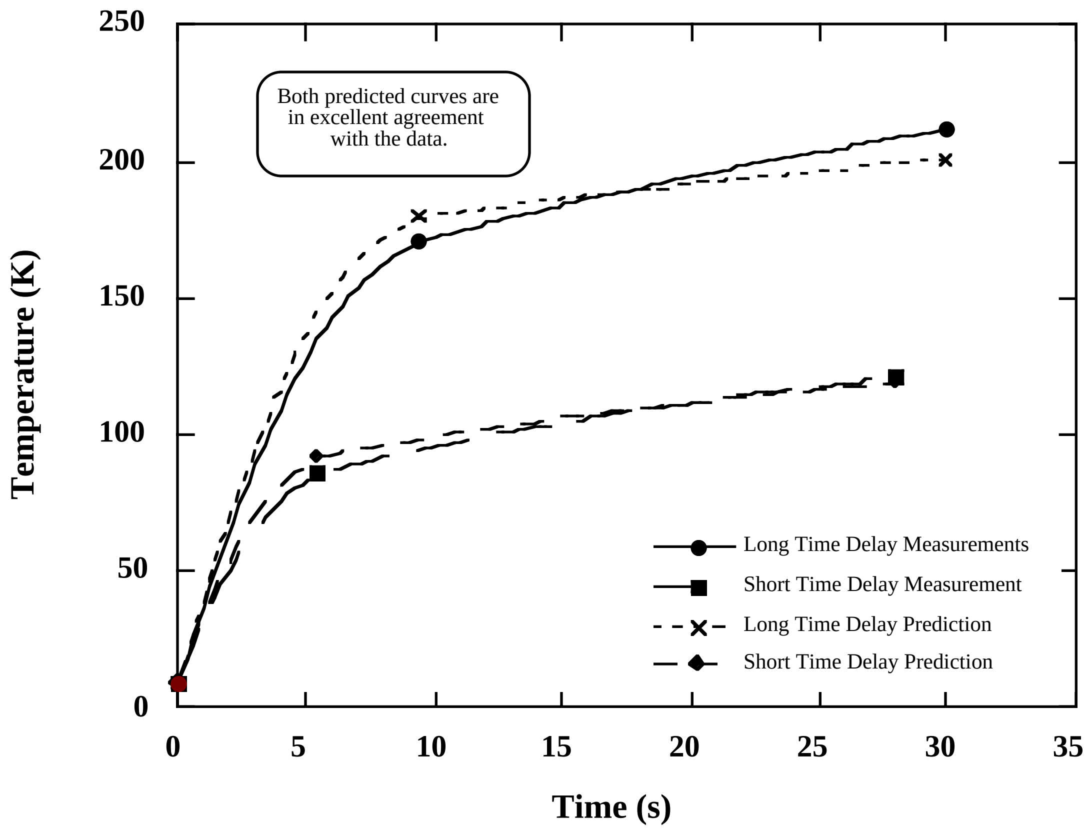

Fig. 2. The comparison between the hot spot temperature as predicted by RadQuench using the three phase model and as measured by experiment for the Westinghouse Large Coil Program CICC TF coil.

two typical cases studied, one in which the detection time delay was longer than the jacket heat capacitance time delay and the other being the converse of the first case, the three phase model predicts temperatures that do not deviate from the experimental temperatures by more than 7%. The value of time delay with respect to the addition of the jacket heat capacity (not with respect to the current dump) should be sensitive to the speed of the temperature rise, but this speed does not vary much from design to design since the component fractions do not vary significantly enough from design to design. The value of this time delay would also be somewhat sensitive to the current density of the conductor, as this would affect the temperature rise speed. For such a simplistic model as the adiabatic model, there is no simple expression determining the appropriate time delay after which the steel heat capacity should be added to the heat balance.

For coils with a shorter dump time delay, however, such as ITER with a dump time delay of 1-2 s, the three phase model does account for a longer jacket heat capacity time delay (about 8 seconds).

Acknowledgement

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