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DC CICC Retrofit Magnet Preliminary Design, Protection Analysis and Software Development

Quarterly Progress Report

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Simulations of Quench and Recovery in Proof-of-Concept DC Cable-in-Conduit Conductors

1. Introduction

In the past few years, several computer codes have been written for the purpose of analysing transient recovery and quench in internally-cooled cable-in-conduit superconductors

(ICCS)[1,2,3]. These codes all include a transient, compressible helium flow model. They differ in the 'dimensionality' of the models, ranging from one- to three-dimensional finite element modeling of thermal conduction. The code used in this study, Wong's CICC, is a 1 1/2 D code that models thermal conduction through the insulation of an individual conduit. Until recently, the calibration of CICC was restricted to measurements of helium expulsion in normal conductor. No actual quenches in ICCS coils had been simulated. In the past year, several experiments on ICCS conductors of differing topology have been performed and compared with CICC simulations, with varying success. This paper reports on the capability of CICC to predict and analyse

ICCS recovery and quench, and on the code's limitations and need for further improvements.

2. Results of Simulations

2.1. MHD Proof-of-Concept Conductor

In addition to its impproved structural characteristics, the MHD Proof-of-Concept Conductor (POCC) was designed to demonstrate the feasibility of a nearly-instantaneous quench in a large superconductor winding to be used in MHD power plants[4]. The concept uses a thick, conductive sheath that begins to develop I^2R heating uniformly though a winding, after a small section of the conductor is driven normal. This permits the winding to be dumped passively without having to rely on external circuits, because of the large reduction in temperature peaking during a dump. For this concept to work, it is necessary to have a conductive material as the sheath, such as copper or aluminum, as well as a thin insulating sleeve between the cable and the sheath.

The POCC experiment[4] used two different topologies of ICCS conductor: the first illustrated the concept and had a thin, perforated sleeve of insulation between the cable and a copper conduit; the second had an identical cable and conduit, but without the insulating sleeve. Both test samples were wound as single-layer, noninductive coils on G-10 mandrels. The length of ICCS conductor in each case was 9.2 m. A cross section of the conductor is shown in Figure 1, the mandrel and winding are shown in Figure 2, and a schematic of the instrumentation layout is shown in Figure 3. Dimensions of the conductor and winding are listed in Table I.

Table I

MHD POCC Conductors

$n_{strands}$	27	
D_{strand}	0.76	(mm)
Cu/Noncu	1.35	
$A_{cablespace}$	19.8	(mm^2)
$t_{conduit}$	0.855	(mm)
t_{sleeve}	0.305	(mm)

As shown in Figure 1, the conductor was heated by a 0.3 m long resistive heater, soldered onto the outer surface of the conduit. The conductor was sealed at both ends, beginning each experiment at 4.2 K and atmospheric pressure. By being sealed, the experiment was provided with well-defined boundary conditions (zero flow) and was thus, in principle, relatively easy to simulate compared with other CICC such as the US-DPC conductor developed as part of the US DOE program in magnetic confinement fusion.

3. Results

In order to simulate the POCC experiment, the CICC program was modified to include copper conduits, current-sharing between the superconductor and the conduit, and heating disturbances from outside the conductor. The code was not modified to include electrical insulation between the cable and conduit in time for this study. Shot 193 was selected for simulation, because it was the best documented of the conductor quenches with the uninsulated conductor. The critical parameters of Shot 193 are listed in Table II.

Table II

MHD POCC Experiment: Shot 193

B_{ext}	7.0	(T)
I_{cond}	2.96	(kA)
$I_{c,quench}$	4.25	(kA)
f_c	0.61	
T_{cs}	6.1	(K)
Cu/Noncu	1.35	
EM	550	(mJ/cm^3)

Numerical calculations of the energy margin bracketed the experimental result. The energy margins calculated by 1 1/2-D codes were essentially equal to the enthalpy in the helium between the bath and current-sharing temperatures, 304 mJ/cm^3. The measured energy margin was between 500 (no quench) and 600 mJ/cm^3 (quench). Using CICC, the energy margin was 300 mJ/cm^3 before current-sharing between the conductor and conduit was added to the model, and 1500 mJ/cm^3 afterwards. The reason is that since the conductor is being heated through the conduit wall, the energy margin will be almost equal to the enthalpy available in the helium, when axial heat conduction is small. However, when the conductor is driven normal, current transfers to the conduit, the fraction of critical current drops, the current-sharing temperature rises, and more enthalpy becomes available for stabilizing the conductor.

In the computer model, the current shared by the conduit transfers instantaneously and the beneficial effect to stability is exaggerated. The actual conduit may also have lower conductivity than that assumed in the model. Nevertheless, the 1/2 D and 1 1/2 D transient models had the expected qualitative behavior of predicting minimum and maximum limits for the measured energy margin.

Since rapid quench propagation is the purpose of the POCC conductor topology, quench velocity is an even more important simulation. The insulated conductor in shot 240 required only 250 ms for a 4.5 kA quench to travel from the heater between 0.5 and 0.8 m and the final voltage tap between 8.15 m and 8.7 m for an average quench propagation velocity of 31 m/s. By contrast, Shot 193 required 2.15 s, for an average quench propagation velocity of 3.5 m/s. The quench propagation velocity in Shot 193 was less nonlinear than that in the insulated case, but still highly nonlinear. However, the quench traveled from the voltage tap between 3.25 and 3.8 m in only 0.8 s, implying that the final quench propagation velocity, even without an insulating sleeve, must have been higher than 6.13 m/s. The simulation of Shot 193 with CICC suggests that the quench velocity accelerates nonlinearly, until it reaches the speed of sound in helium at the last time increment before total quench. The comparison between the quench propagation in the experiment and the simulation is shown in Figure 4.

In the case of 240, a large length of conductor (the superconducting portion) was heated uniformly by the Joule heating in the conduit. Most of the conductor was heated to the current-sharing temperature together, and the quench propagation accelerated rapidly. In the case of shot 193, the conductor was pressurized through the entire length. When the Joule-Thompson effect raised the helium to the current-sharing temperature thoughout the coil, it went normal. In both cases, the 'velocity' of the Joule heating and the helium pressurization were extremely fast in comparison with the initial quench velocity or with the averaged ratio of the conductor length to the quench time. Thus, the greater speed of the insulated run was not caused by limitations in helium heat convection, but because the Joule heating power was greater. The conduit contained 2.23 times as much copper as the conductor. At an initial current of 4.5 kA, the initial I^2R heating with the insulating sleeve was as much as 7.5 times as high as the initial heating without. Therefore, the POCC experiment does not demonstrate clearly the superiority of insulated conductors in speeding quench propagation, because there may have been little difference in the conductor peak temperatures. In this particular case, the length of the conductor divided by the speed of sound in helium was short, compared with the total quench time. In the commercial MHD magnet, the insulated topology suggested by Marston et al.[5] is still logically superior, but unproven by this particular experiment.

4. Discussion

Attempts to model the recovery of ICCS conductors, using transient compressible flow quench codes, have met with partial success. In all the cases reported, some parameters have been successfully predicted, others not. Energy margin has been one of the more successfully predicted parameters. The prediction of quench propagation velocity and helium outlet velocity have not, so far, received adequate calibration. In order to achieve adequate calibration, improvements in the numerical models may include the need to easily include external fluid and electrical circuits in a simulation, more flexibility in defining an actual complex conductor topology, such as insulating but perforated sleeves or dual channel flow, and the use of a broader range of thermodynamic properties. Additional experiments are necessary to complete measurement of thermophysical properties, permit better measurement of normal front propagation velocity by adding voltage taps directly on the conductor within the sheath, provide longer test lengths and improve the accuracy of test/modeling iteration.

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Figure 1: Proof Of Concept Conductor Cross Section

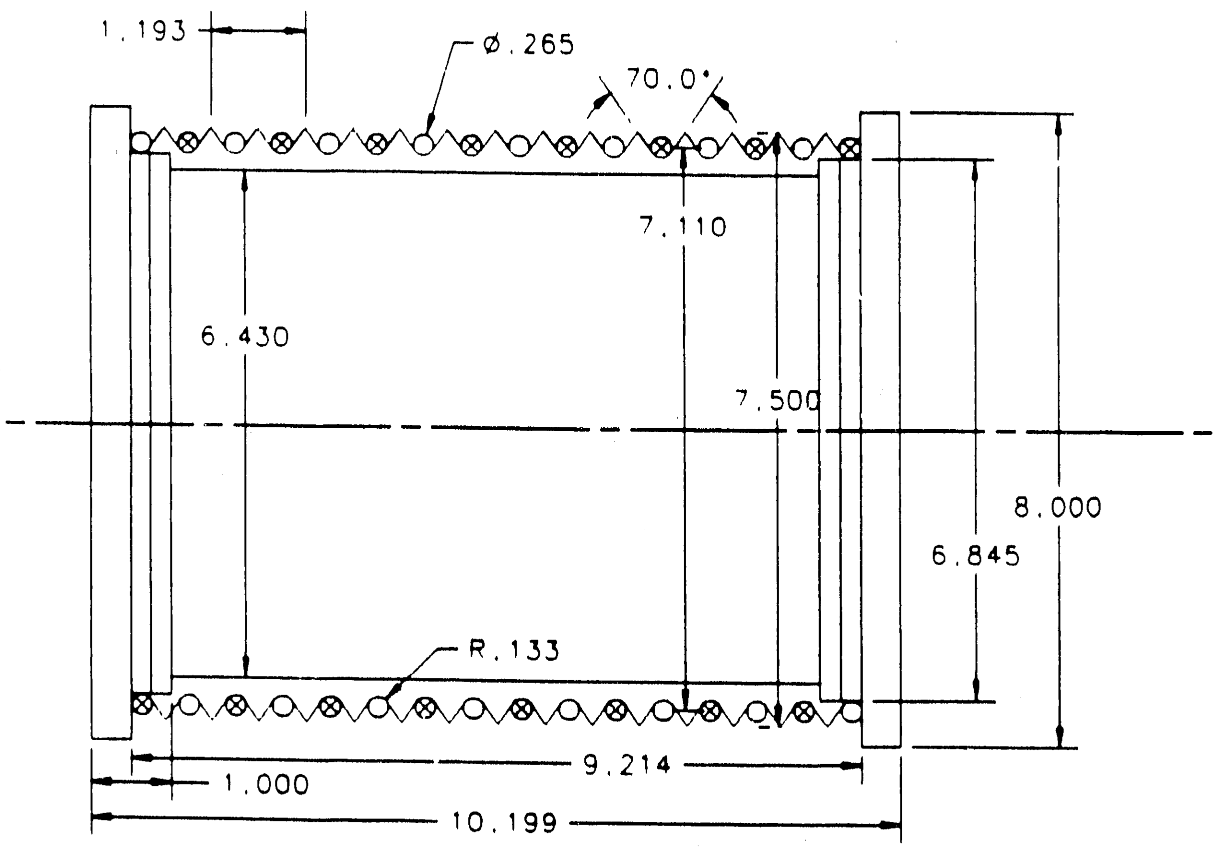

Figure 2: Proof of Concept Conductor Mandrel and Winding

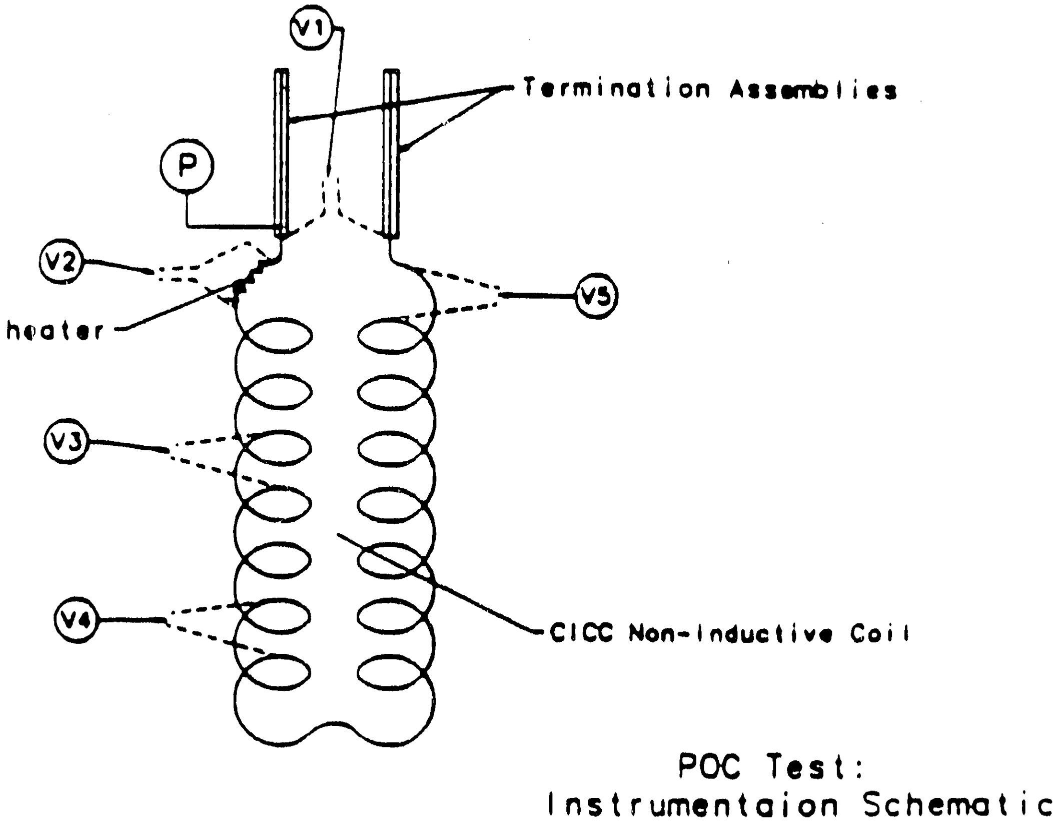

Figure 3: POCC Instrumentation and Winding Layout

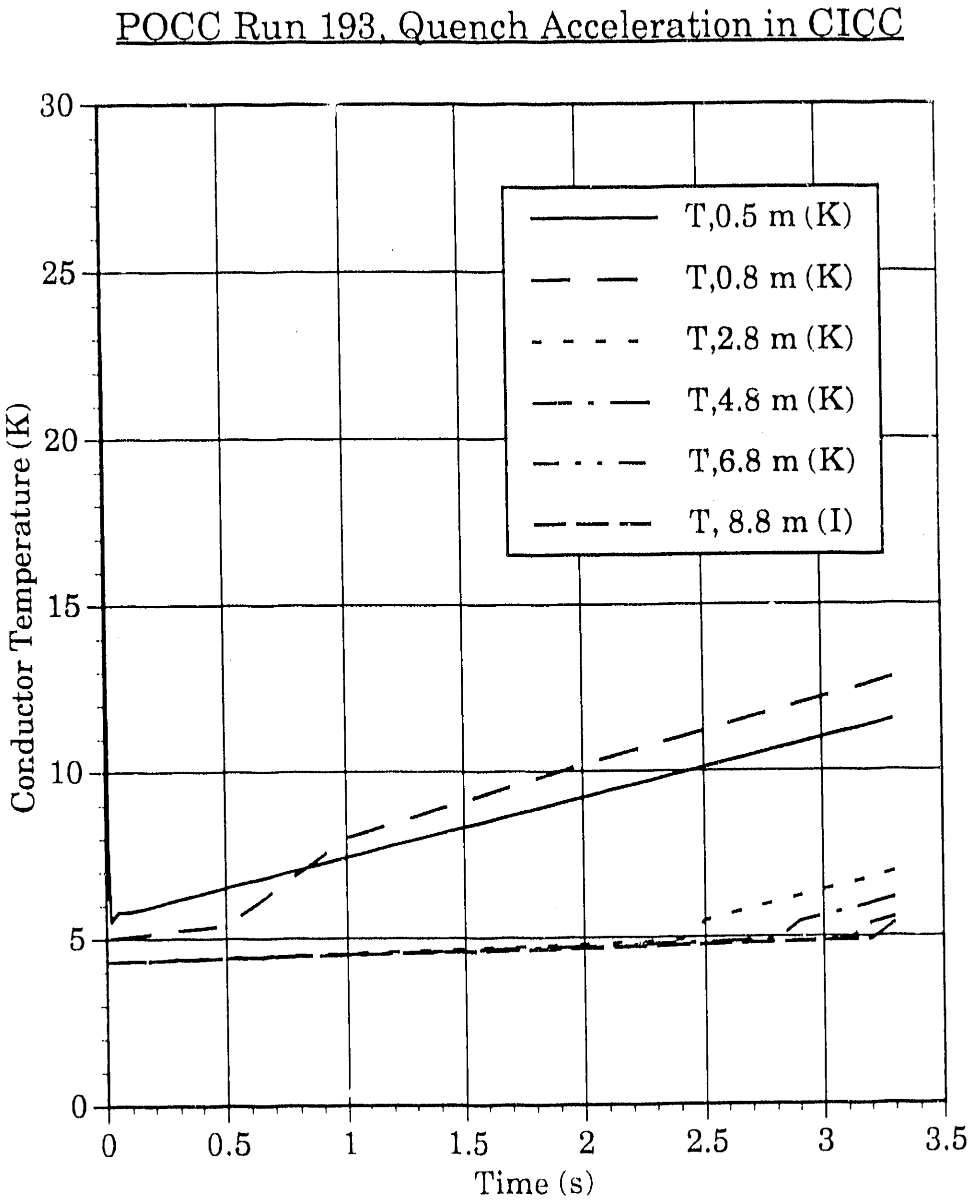

Figure 4: Quench Propagation in POCC Shot 193

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