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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
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**SIMULATION OF MULTIPLE STABILITY REGIONS IN AN INTERNALLY COOLED
SUPERCONDUCTING CONDUCTOR WITH THE COMPUTER CODE SSICC**

by

L. R. Turner and J. Shindler*

Fusion Power Program

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MASTER

*Participant, Summer 1984 Student Participation Program.
Present address: Physics Department, Carnegie-Mellon University,
Pittsburgh, PA

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ABSTRACT

The computer code SSICC (Safety and Stability of Internally Cooled Conductors) has successfully simulated the multiple stability regions observed experimentally by Lue, Miller, and Dresner of Oak Ridge National Laboratory. The simulation requires asymmetrical boundary conditions and a heating pulse duration short compared to the time for reflection of the transient pressure wave back into the heated region of the conductor.

1.0 INTRODUCTION

Unlike pool-boiling conductors, internally cooled conductors (ICC) cannot be cryostable because the amount of helium available for cooling during recovery is limited; although recovery occurs within tens of milliseconds, even with good flow the liquid remains in the coil for tens of seconds. Thus, ICC are metastable, since they can recover from lower heat pulses, while greater pulses cause a quench to occur. Yet, the regions of stability do depend not only upon steady state but also 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^(1,2) due to the improved heat transfer caused by the transient flow of helium following local heating and pressure rise.

Such transient helium flow effects have been found to produce "multiple stability margins". This multiple stability occurs within a range of operating conditions in which the conductor may be unstable against a moderate heat pulse, while recovering from an even greater pulse. Experiments performed by Lue, Miller, and Dresner at Oak Ridge National Laboratory⁽³⁾ found just such behavior for a specific ICC. Yet, while previous attempts have been made to model such multiple stability behavior by computer,⁽⁴⁾ until now no code has been able to reproduce this experimentally-observed phenomenon. This paper will describe the Oak Ridge experiment and our successful computer modelling of it.

2.0 THE EXPERIMENT

The experiment considered here featured a conductor consisting of a triplex of NbTi and Cu strands soldered around a heated wire, enclosed in a stainless-steel tube, and cooled by supercritical helium. The ends of the conductor were connected to helium reservoirs, and thus were essentially open and symmetrical. Table 1 lists the important physical parameters of the experimental setup.

The operating conditions which led to multivalued stability margins are listed in Table 2. In the experiment, the variables included the magnitude of the heat pulse, ΔH , the duration of the heat pulse, Δt_H , and the helium flow rate, v_H .

Table 1.
Physical Parameters of Test Conductor

Superconductor type	NbTi
Length	3.25 m
Cu/NbTi, ratio	4.5:1
Void fraction	44%
Conductor, cross section	$2.5545 \times 10^{-6} \text{ m}^2$
Critical current	400 A at 7 T, 4.2 K

Table 2.
Operating Conditions for Multiple Stability

	Experiment	SSICC Code Simulation
Current, A	400	410
Field, T	6	6
Helium temperature, K	4.2	4.2
Helium velocity, m/s	0	0.02
Helium pressure, atm	5.0	5.0
Heat pulse time, ms	6.25 7.14	1.0 5.0
Heated length, m	3.25	0.75

It was found that for $At_H = 7 \text{ ms}$ and $v_H = 0$, recovery occurred for $\Delta H \leq 35 \text{ MJ/cm}^3$, nonrecovery for $35 < \Delta H \leq 60 \text{ MJ/cm}^3$, recovery for $60 < \Delta H \leq 130 \text{ MJ/cm}^3$, and nonrecovery for $\Delta H > 130 \text{ MJ/cm}^3$.

3.0 MODELLING THE EXPERIMENT WITH SSICC

The SSICC (Safety and Stability of Internally Cooled Conductors) code^(5,6) incorporates one-dimensional energy, mass, and momentum balance within the helium and thus predicts the high velocity, high pressure transient helium flows necessary for the observance of multiple stability. This code

was formed by combining Vincent Arp's computer code⁽⁷⁾ for the stability analysis of ICC with ANL's TASS code.⁽⁸⁾ In a close modelling of the experiment, it reproduced the occurrence of the observed multivalued stability margins.

The SSICC code as applied to the experiment used the physical parameters shown in Table 1. However, some operating conditions necessarily differed. SSICC requires a nonzero helium velocity to avoid run-time errors, but the value chosen was small enough to give effectively equivalent results as for zero flow. The major differences between the simulation and the experiment included the heated length and the relative helium flow at the ends of the conductor. The heated length was markedly shorter in the simulation, in order to use much less computer time; this change still gave equivalent results when using a slightly higher operating current. The ends of the conductor were symmetrical and open in the experiment, but the simulation allowed only one end fully open, while the other was restrictive to helium flow. This asymmetry caused greater flow in the middle (heated) region of the conductor than did the symmetrical case, and hence improved the heat transfer due to transient helium flow. In fact, no occurrence of multiple stability regions had been observed when the code was run with symmetrical ends.

These and other experiments with ICC led Dresner⁽⁴⁾ to the proposal that the Nusselt number varies as the $4/15$ power of the Reynolds number. In SSICC,⁽⁵⁾ both $4/5$ power and $4/15$ power variation are permitted; the $4/15$ power variation was used in these computations.

4.0 RESULTS

For a 1.0 ms heat pulse time, the experiment was simulated with operating currents of 400 A, 410 A, and 420 A. Multiple stability was observed for $I = 410$ A: recovery took place for $\Delta H = 10 \text{ mJ/cm}^3$, nonrecovery for $\Delta H = 20 \text{ mJ/cm}^3$, recovery for $\Delta H = 50 \text{ mJ/cm}^3$, and nonrecovery for $\Delta H = 100 \text{ mJ/cm}^3$, as shown in Fig. 1. Note that the peak temperatures decreased slowly for $\Delta H = 100 \text{ J/cm}^2$ and 50 mJ/cm^2 , and rose for $\Delta H = 20 \text{ mJ/cm}^3$ between times 5 ms and 10 ms. Between times 10 ms and 20 ms, the reflection of the transient wave passed the heated region of the conductor. During that time there was a non-zero and generally high fluid velocity throughout that region, due to the

Figure 1. Time variation of peak conductor temperature for four values of the initiating heat pulse ΔH . Current = 410 A, helium flow velocity = 0.02 m/s, duration of heat pulse = 1 ms. The conductor recovers for $\Delta H = 10$ mJ/cm³ and 50 mJ/cm³, but not for $\Delta H = 20$ mJ/cm³ and 100 mJ/cm³.

asymmetrical boundary conditions at the two ends. This velocity enhanced the heat transfer and promoted recovery.

Effects of the higher heat transfer from higher transient flow velocities appeared not only at 410 A, where there were multiple stability regions, but also at 400 A, where recovery occurred for all four values of ΔH , and at 420 A, where recovery occurred only for $\Delta H = 10 \text{ mJ/cm}^3$. Table 3 shows that at 400 A, the conductor recovered sooner for $\Delta H = 50 \text{ mJ/cm}^3$ than for $\Delta H = 20 \text{ mJ/cm}^3$, and that at 420 A, the minimum peak temperature was higher for 20 mJ/cm^3 than for 50 or 100 mJ/cm^3 .

Table 3.
Response of a Conductor Carrying Current I to a Heat Pulse ΔH .
(Pulse duration, 1 ms; Imposed Flow Velocity, 0.02 m/s)

ΔH (mJ/cm ³)	I = 400 A	I = 410 A	I = 420 A
100	recovered in 18 ms	grew, $T_{\min} = 5.1 \text{ K}$	grew, $T_{\min} = 5.6 \text{ K}$
50	recovered in 16 ms	recovered in 19 ms	grew, $T_{\min} = 5.5 \text{ K}$
20	recovered in 17 ms	grew, $T_{\min} = 5.5 \text{ K}$	grew, $T_{\min} = 6.3 \text{ K}$
10	recovered in 3 ms	recovered in 4 ms	recovered in 5 ms

Other interesting results were also noted. Figure 2 shows the effects of increased steady state helium flow for $\Delta H = 20 \text{ mJ/cm}^3$. The conductor recovered for flow velocities of 0.1 m/s and 0.2 m/s but not for lower flow velocities of 0.02 m/s and 0.05 m/s. Note, however, that the flow velocity merely augmented the velocity from the reflected transient pulse. The peak temperature still rose until about 10 ms, and fell only after the reflected pulse arrived.

For symmetrical boundary conditions, the behavior was quite different. The superimposed steady helium flow shifted the zero velocity point, but flow velocities of 0.1 m/s and 0.2 m/s shifted that point to positions still within the heated region. Peak temperatures for those velocities continued to rise with time at about the rate of the upwardly sloping portion of Fig. 2. For a flow velocity of 0.5 m/s, the zero velocity point was shifted outside the

Figure 2. Time variation of peak conductor temperature for three values (1 ms, 5 ms, 10 ms) for the duration of the initiating heat pulse. Current = 410 A, helium flow velocity = 0.02 m/s, heat pulse $\Delta H = 50 \text{ mJ/cm}^3$.

heated region, the peak temperature began to fall at time 5 ms, and the conductor recovered at time 11 ms.

An increased heat pulse duration caused the multiple-stability region to shrink. Figure 3 shows that for a total $\Delta H = 50 \text{ mJ/cm}^3$, as the heat pulse duration increased from 1 ms to 5 ms, the recovery time increased, and for a duration of 10 ms, the conductor did not recover. For $\Delta H = 20 \text{ mJ/cm}^3$, the minimum peak temperature for a 5 ms pulse duration (5.47 K) was less than that for a 1 ms duration (5.51 K).

These trends suggest that multiple stability will disappear for long heating pulse durations. However for a heat pulse duration of 10 ms, the minimum peak temperature for $\Delta H = 20 \text{ mJ/cm}^3$ (5.90 K) was still above that for $\Delta H = 50 \text{ mJ/cm}^3$ (5.26 K).

5.0 DISCUSSION

These results suggest an explanation for the phenomenon of multiple stability regions. First, they show that for heat pulses of 20 mJ/cm^3 and above, joule heating is mostly independent of the initiating heat pulse size, since once a normal region is established, joule-heating losses do not vary much with temperature. Second, the velocity with which the reflected transient wave returns to the center does depend upon the size of the heat pulse.

Hence, for a given current, the heat that must be removed from the conductor during the time from 10 ms to 25 ms is largely independent of the magnitude of the initiating heat pulse, but the local helium velocity, and consequently the heat transfer coefficient, does increase with ΔH . It follows that larger values of ΔH are more likely to lead to recovery. Still larger heat pulses, and also longer heat pulses, can raise the liquid helium temperature above the current-sharing temperature of the conductor and make recovery impossible.

An immediate objection to these simulations and their results is that they required asymmetrical boundary conditions (three orders of magnitude difference in resistance to liquid helium flow at the inlet and outlet ends) to model a symmetrical experiment. We believe, however, that while a calculation can be exactly symmetrical, no experiment can be more than approximately symmetrical. In an experiment, for example, the initial transient pressure

Figure 3. Time variation of peak conductor temperature for four values (0.02 m/s, 0.05 m/s, 0.1 m/s, 0.2 m/s) for the helium flow velocity. Current = 410 A, heat pulse duration = 1 ms, heat pulse $\Delta H = 20 \text{ mJ/cm}^3$.

wave can be partially reflected from other discontinuities as well as from the ends. These could well lead to a zero-velocity position which lies outside the heated region or which moves with time, not staying anywhere long enough to impede the heat transfer and cooling.

6.0 CONCLUSIONS

The success of the computer modelling should be stressed here. The SSICC code was able to predict the occurrence of multiple stability within a range of operating conditions for an ICC, and also point to such important factors as the implementation of asymmetrical ends for aiding the heat transfer due to transient helium flow.

Certainly, multiple stability regions will play an important role in conductor design. In practice, conductors will not be designed to operate within such a region: It is hard enough to guarantee that no heat source larger than a specified value will occur and impossible to guarantee none between two smaller specified values. Still, this prediction of the SSICC code should aid in the understanding of multiple stability, and also permit greater confidence in other predictions of such codes.

7.0 Acknowledgements

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