71-000302-CLN-01

TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: STUDY OF OH COIL COOLING vs. REP RATE

References:

[1] 71-000222-CLN-01, "OH Rep Rate Minimization, Minutes Of Meeting"
[2] NSTX-CALC-13-3, "OH Thermal Simulation"

A study has been performed [2] to determine the OH $\int i^2(t)dt$ allowables at repetition periods of 300, 450, and 600 seconds.

A FORTRAN program was used to simulate the heating and cooling of the OH coil during a sequence of pulses. This program divides the coil conductor length into small sections from which heat is transferred into slugs of water which move from section to section as time progresses.

Parameters were set to those corresponding to one of the two-in-hand conductors in the outermost layer of the coil, which amongst the 8 cooling paths has the longest length. The water flow was set equal to the trip setting of the water flow switch. Simulation parameters are summarized in Table 1.

Table 1 – Simulation Parameters

Parameter	**Value**	**Units**
Path length	362.2	feet
Conductor cross sectional area	0.2192	in^2
Cooling hole diameter	0.1880	in
Water inlet temperature	10	ºC
Water flow rate	0.65	GPM

The temperature vs. time simulation at the end of the conductor (where the water exits the coil copper) was compared against an actual OH coil outlet water temperature strip chart recording taken during ISTP-001, and reasonably good agreement was obtained (Figure 1). It is noted that the temperature measurement was made using a thermocouple taped over a metal section of pipe which is in

the water stream after a section of plastic hose approximately 30 feet downstream of the actual outlet from the coil copper.

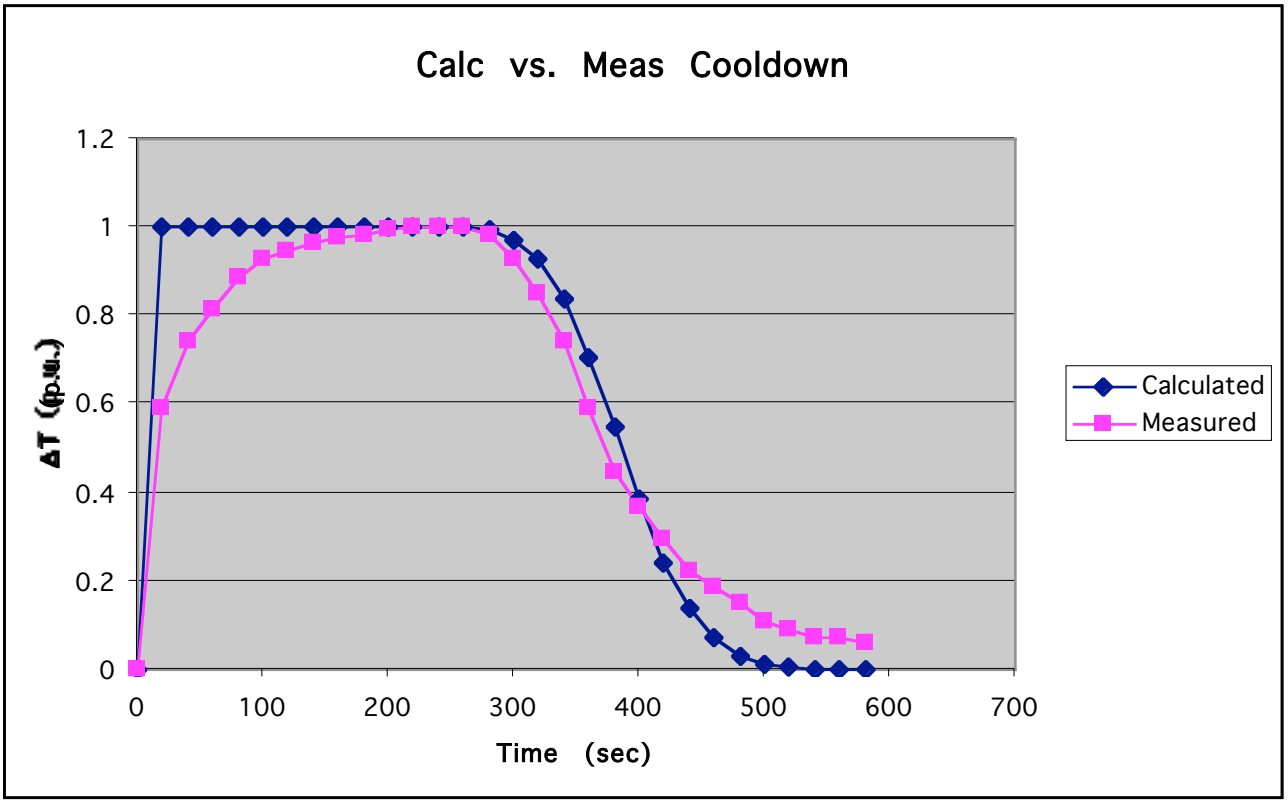

Figure 1: Calculated vs. Measured Cool Down

Simulation runs were made to determine the $\int i^2(t)dt$ allowables and ratched start of pulse (SOP) inlet water temperature at the three repetition periods with the constraint imposed that the maximum copper temperature at any time should not exceed 90 °C. This allows for the fact that, should a fault occur at I_{oh}=24kA and T_{oh} = 90 °C, the final temperature will not exceed 100 °C following an L/R decay of the current.

Table 2 summarizes the results obtained.

Table 2 – Simulation Results

Repetition Period	300 sec	450 sec	600 sec
Allowable $\int i^2(t)dt$	155.5 kA^2-sec	262.1 kA^2-sec	288.0 kA^2-sec
Allowable $\int i^2(t)dt$	54%	91%	100%
T_{sop}	43.4 °C	15.3 °C	10.0 °C

Figures 2 through 7 depict the copper temperature vs. time at the end (water outlet) of the winding for a series of 5 pulses, and the copper temperature vs.

time at the start (water inlet), middle, and end (water outlet) of the winding for the last of a series of 5 pulses (i.e. after ratcheting has taken place).

Note that, after the ratcheting stabilizes, the peak temperature at end of pulse is ≈ 90 °C, although this is not immediately evident on the curves (figures 2, 4, and 6) which depict the temperature evolution during the sequence of pulses because it occurs for a brief period only (until the entrained water and copper equilibrate a few seconds following the pulse) which is within the sampling interval of the graphics. Decay from the peak is visible, however, on figures 3, 5, and 7 which show the cooldown following the last pulse in the sequence, with 5 x smaller interval between plotted points.

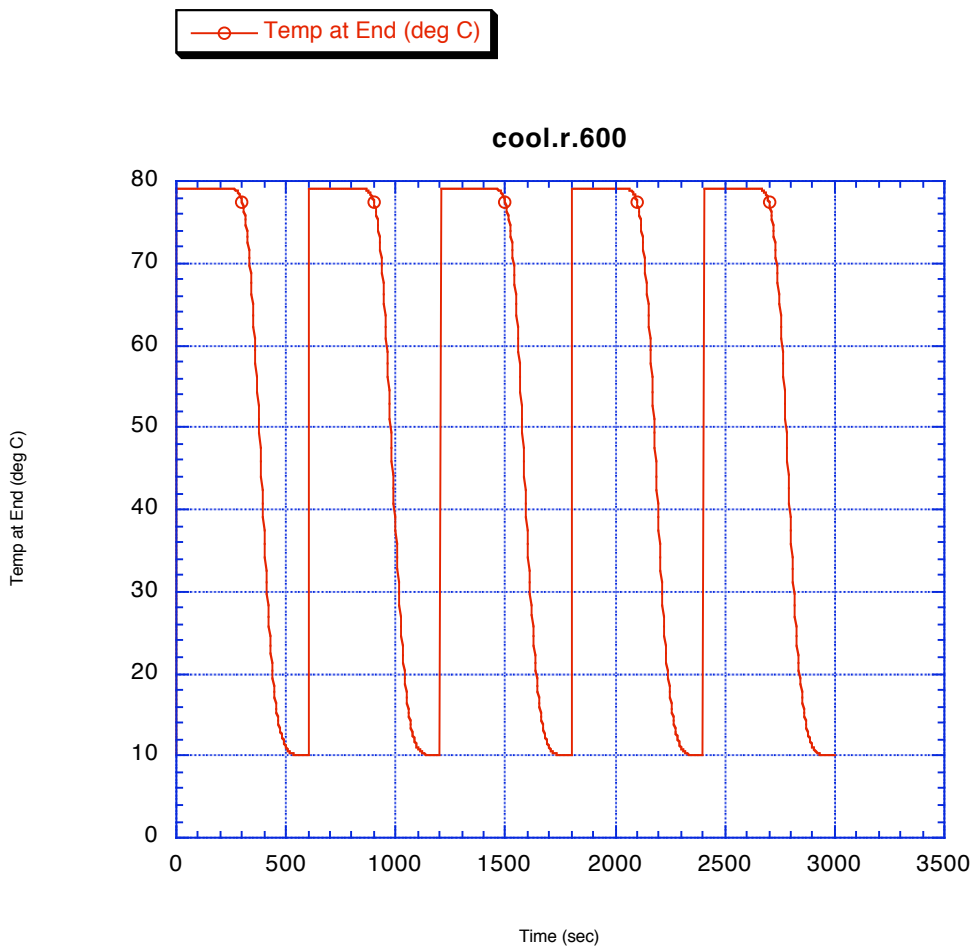

Figure 2: Temperature at End of Winding Due to Five Pulses in Sequence, 600 Second Repetition Period

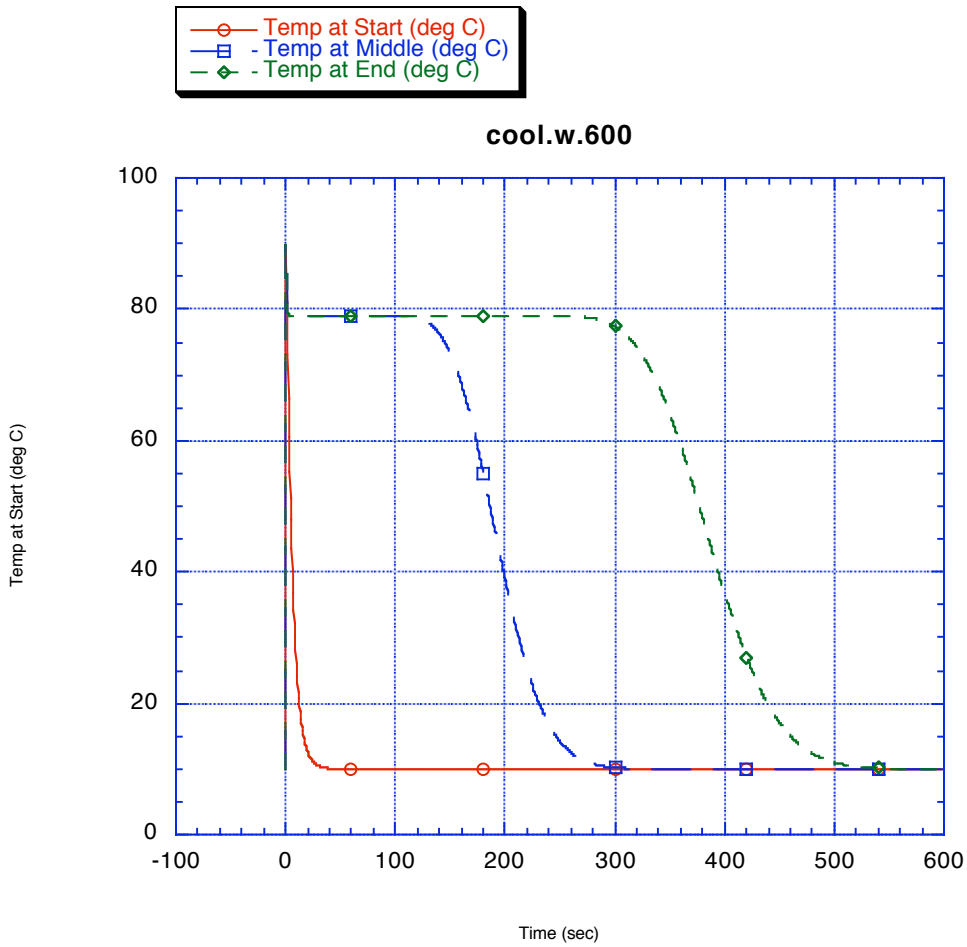

Figure 3: Temperature at Start, Middle, and End of Winding During and After Fifth Pulse, 600 Second Repetition Period

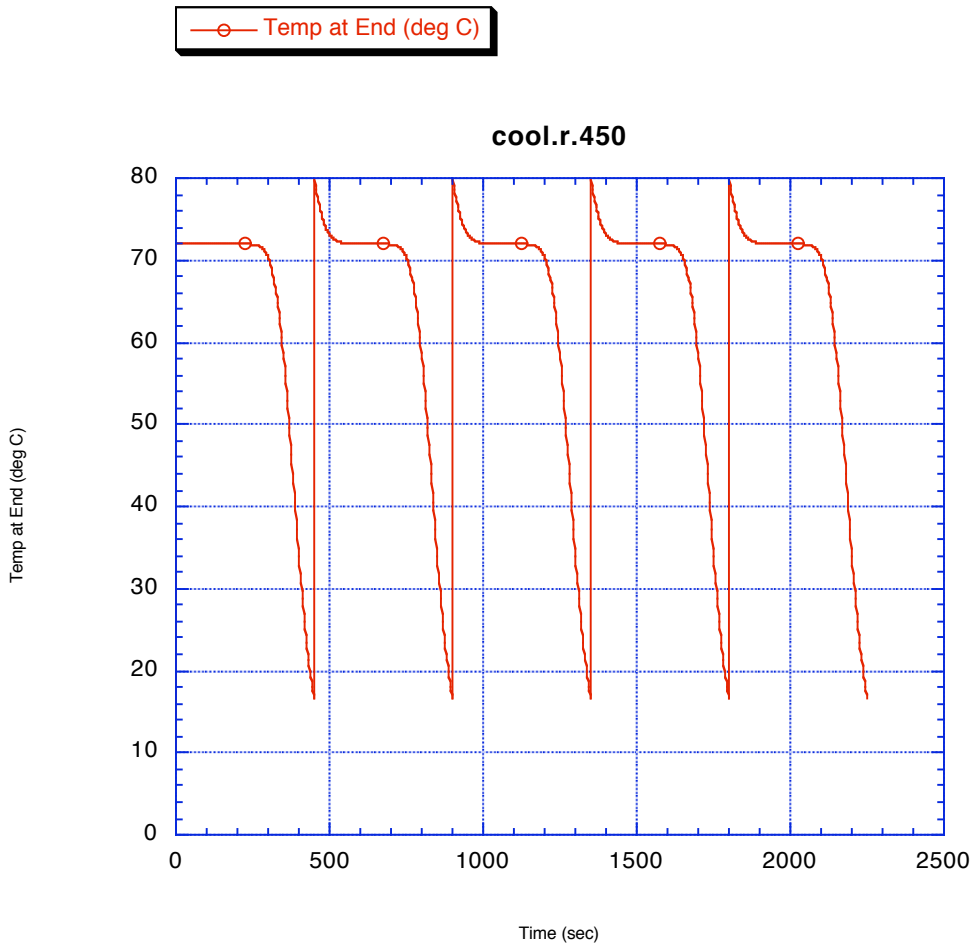

Figure 4: Temperature at End of Winding Due to Five Pulses in Sequence, 450 Second Repetition Period

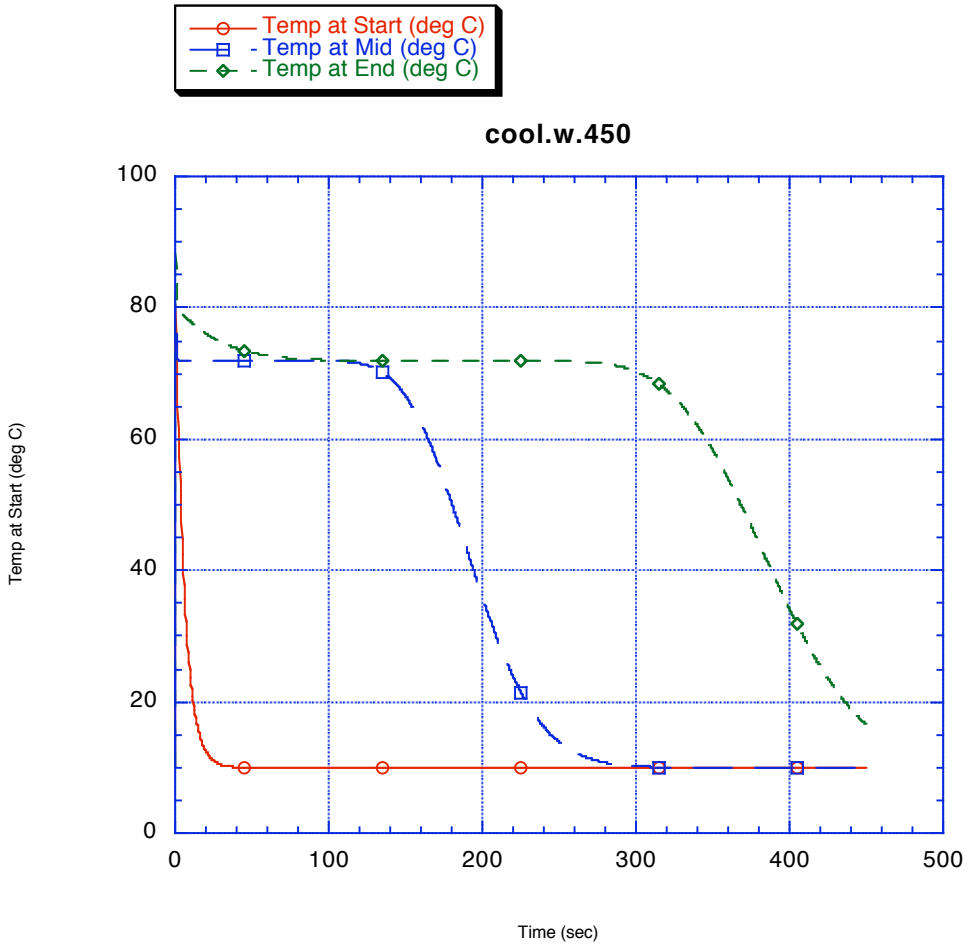

Figure 5: Temperature at Start, Middle, and End of Winding During and After Fifth Pulse, 450 Second Repetition Period

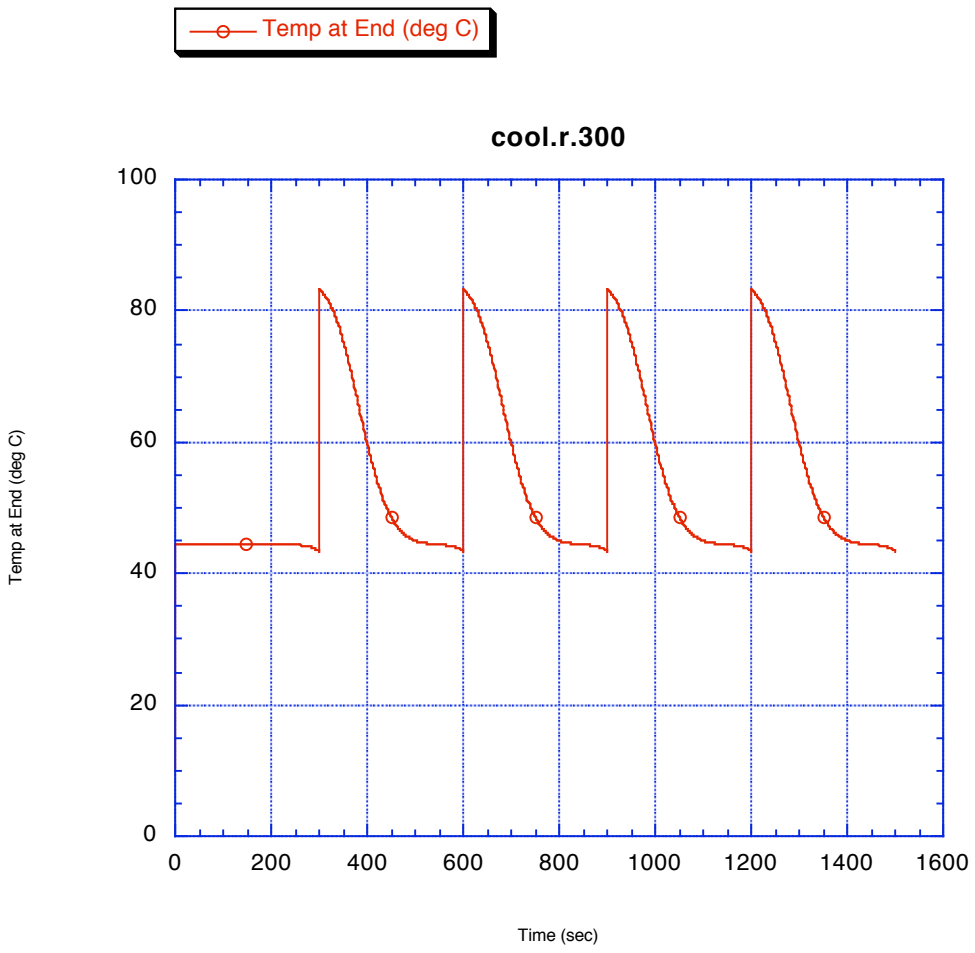

Figure 6: Temperature at End of Winding Due to Five Pulses in Sequence, 300 Second Repetition Period

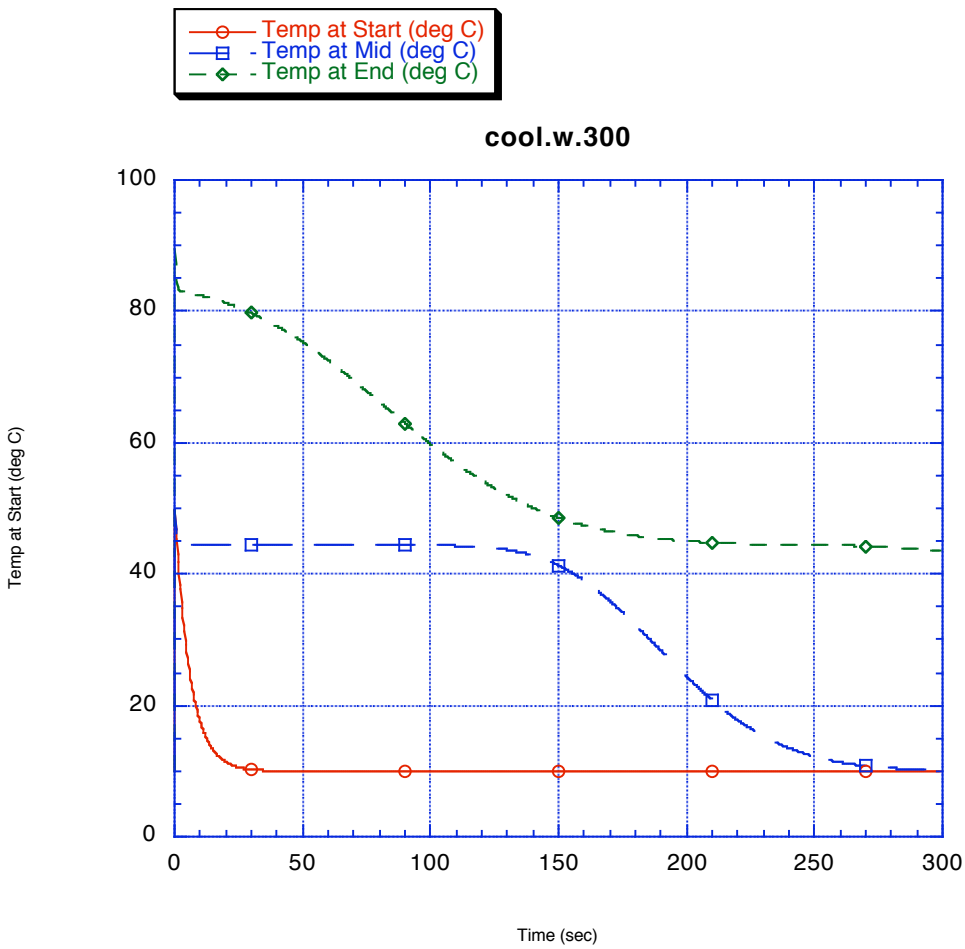

Figure 7: Temperature at Start, Middle, and End of Winding During and After Fifth Pulse, 300 Second Repetition Period

The Rochester Instrument Systems (RIS) protective device provides an $\int i^2(t)dt$ function along with a single time constant exponential decay. This simple model cannot effectively simulate the OH coil temperature vs. time because of the more complex behavior of the OH coil with its very long cooling paths and the attendant "cooling wave" effect. However, the RIS can still be used, in combination with the outlet water temperature interlock, to protect the coil. In this case the role of the RIS is to ensure that the $\int i^2(t)dt$ during a pulse is within the allowable, while the role of the water interlock is to ensure that sufficient

cooling has take place prior to the pulse (i.e. that the start of pulse temperature is sufficiently low).

In order to be used this way the RIS $\int i^2(t)dt$ accumulated during a pulse needs to decay more or less completely prior to the start of the next pulse. The RIS single time constant model was added to the simulation to allow comparison with the simulated coil temperature behavior. The simulation was set up with the RIS "action integral" normalized to the coil rated $\int i^2(t)dt$ corresponding to an 80 °C rise from 10 °C starting temperature, and the simulated coil temperature at the end of the coil normalized to 90 °C rise, i.e. 288 kA^2-sec. Considering that, to cover the 3 repetition rates, the RIS action must decay in as little as 300 seconds, a decay time constant of 60 seconds was selected. Simulation results for the three repetition periods are given in Figures 8, 9, and 10.

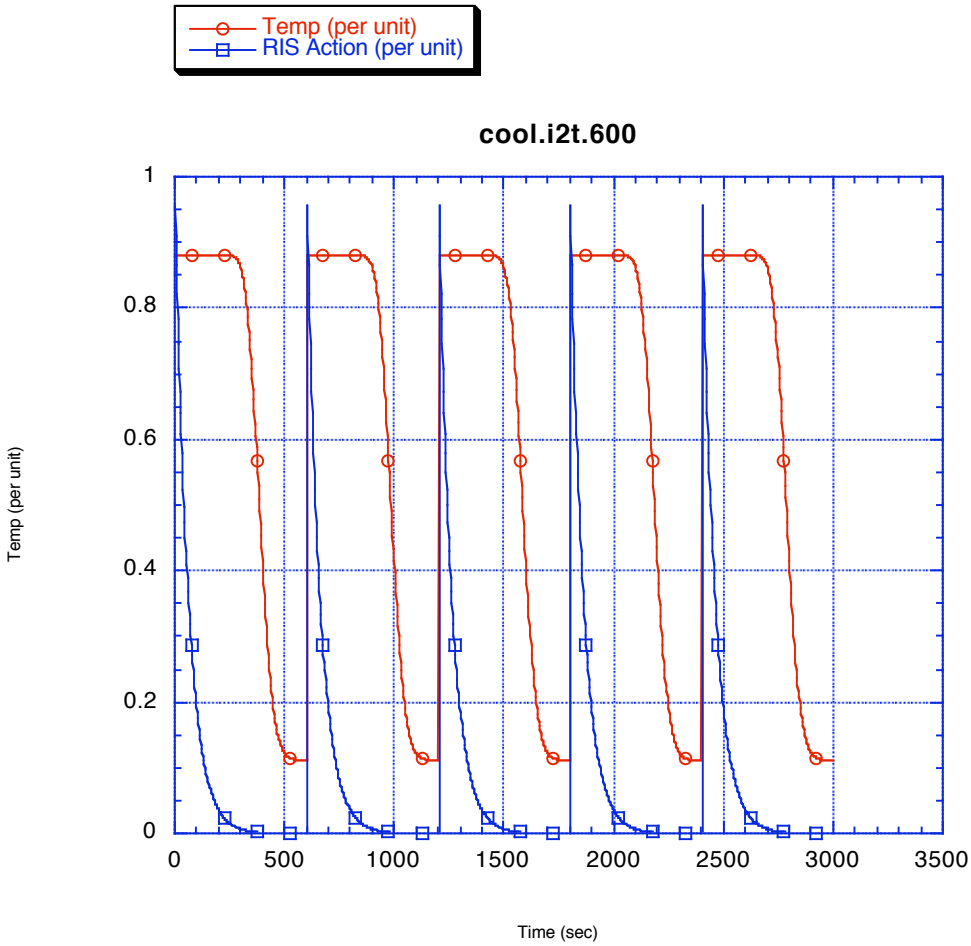

Figure 8: RIS and Temperature Simulation,
600 Sec Repetition Period

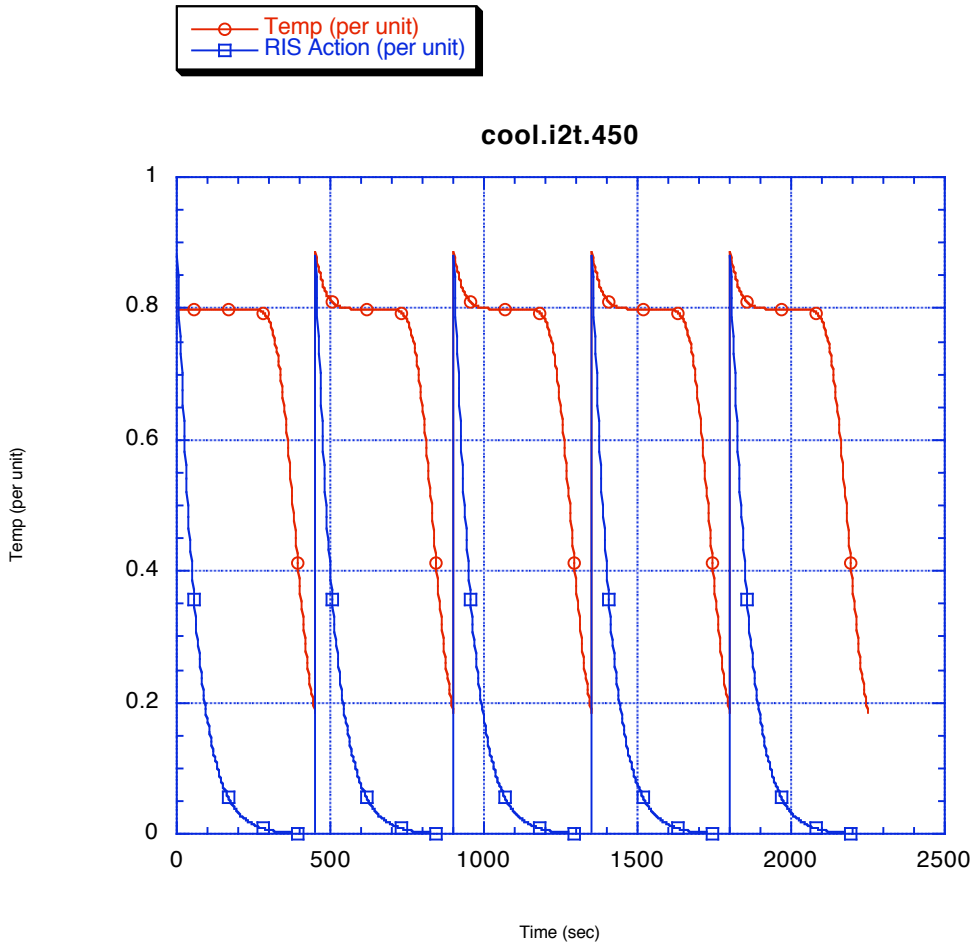

Figure 9: RIS and Temperature Simulation,
450 Sec Repetition Period

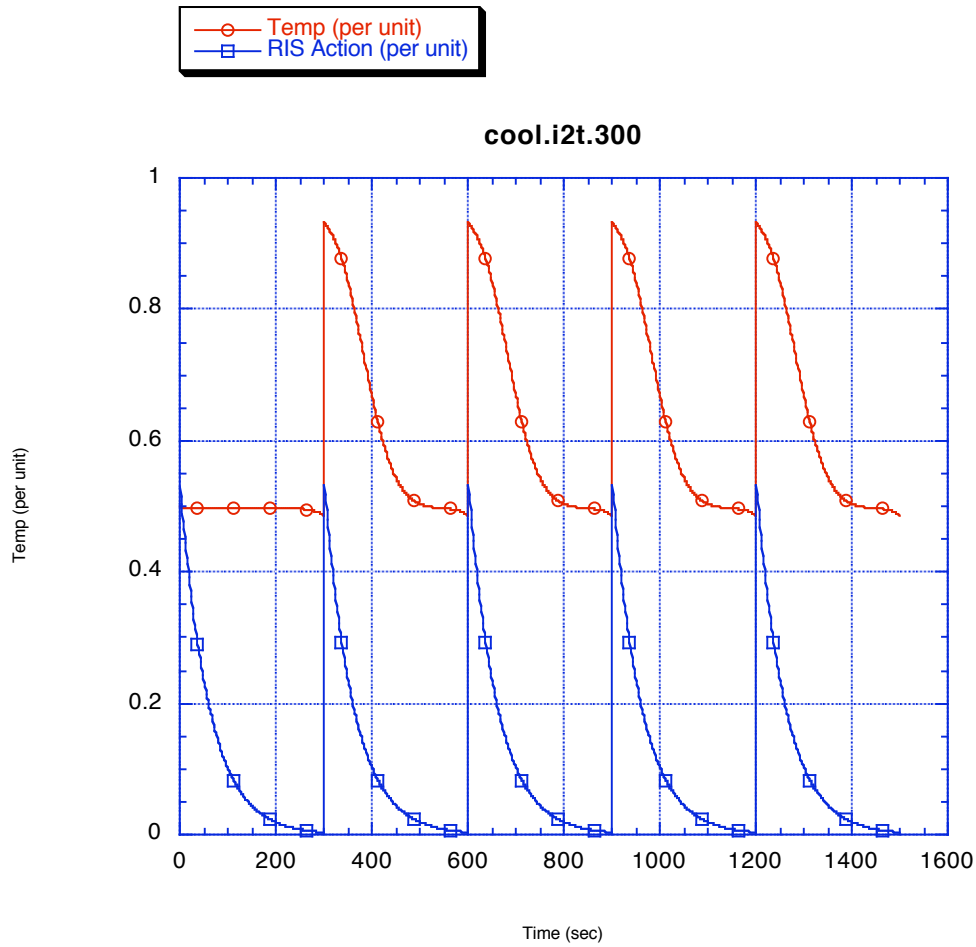

Figure 10: RIS and Temperature Simulation,
300 Sec Repetition Period

Thus if we set the RIS "rated action integral" to 288 kA^2-sec, and RIS "% trip" to the value from Table 2 which is appropriate for the desired repetition period (54% for 300 seconds, 91% for 450 seconds, 100% for 600 seconds), and "tau" to 60 seconds, then the RIS will limit the $\int i^2(t)dt$ appropriate for the repetition period. With the water interlock set to ensure proper starting temperature, the protection scheme is complete.

CONCLUSIONS

The following steps need to be taken:

1) Proper OH coil outlet water temperature monitoring needs to be implemented and interfaced with the Water Systems PLC and EPICS.

2) The water flow and flow switch calibration to the 8 OH cooling paths needs to be carefully measured/re-calibrated when the center stack is reinstalled prior to the next run period.

3) During the start up ISTP-001, the temperature measurements need to be recorded again (this time with better quality and correlation to actual pulse characteristics), and the simulation model described herein validated (using the measured flow rates instead of the set points as described herein) in terms of waveshape and amplitude.

4) Based on 3), the water temperature interlock settings need to be established in the Water System PLC for the 3 repetition periods.

5) Work needs to begin on a digital coil protection (DCP) system to replace the RIS. As soon as the algorithms are established they should be installed in the PSRTC control software which can provide redundancy to the DCP.

6) Until the DCP is implemented the RIS can be used in conjunction with the water temperature interlock to limit the $\int i^2(t)dt$ during a pulse.

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