ANALYSIS OF QUENCH-VENT PRESSURES FOR PRESENT DESIGN OF ITER TF COILS

Don S. Slack
Lawrence Livermore National Laboratory
Livermore, CA 94550

UCID--21642

DE89 009711

INTRODUCTION

An analysis of pressure and temperature rise versus time during a quench is done here for one of the present TF coil designs. Hand calculations using worksheets give a fair approximation of such parameters as pressure and temperature in the conductor, stored energy consumed by the quench, amount of vented helium, etc. The purpose is to provide design information for conductor design before a more accurate computer analysis is completed and to serve as a check against other analyses. An additional purpose is to provide insights into the quench vent process that may aid the designer of protective devices.

RESULTS

Figure 1 shows the various quench, flow-path parameters versus time. Here we assumed the full length of a twelve-turn pancake of the TF coil quenched at time zero. Large time increments were used to speed hand calculations, resulting in an estimated inaccuracy of about ±30%. However, major effects, such as increase of resistivity and heat capacity with temperature, were accounted for in the calculations. The analysis also assumes no active protection (dump resistors) are used. The analysis used heat capacities of both the conductor and conductor case, but not the insulation. The TF-coil-current decay assumes energy from a TF coil is deposited in a single, fully quenched flow path (one-half pancake). Only 10% of the coil stored energy is consumed after about 20 s of quench. Peak pressures of about 43 MPa result at about 16 s into the quench.

OBSERVATIONS AND SUGGESTIONS FOR ITER DESIGN

The worksheets of Tables 1 and 3 provide a number of insights helpful to ITER designers:

a. Quench pressures rise rapidly with time and reach large values. Conductor-sheath strength must support this.

b. Although heat capacity of the helium predominates below 20 K, the majority of heat is adsorbed by the conductor and sheath at higher temperatures. Consequently, the rate of helium venting has only a slight influence on rate of temperature rise.

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c. If only one pancake of a TF coil quenches, as assumed in this analysis, stored energy and current drops slowly. Only 9% of the coil-stored energy is used to raise the quenched pancake to 220 K. If, however, the entire coil of 18 pancakes quenched together or nearly together, the coil would be self protecting in that temperature rise would be less than 200 K. We are looking at ways to induce total coil quenching, possibly by back-pressure build-up in the header when a portion of the coil quenches.

d. The effect of mutual inductance between TF coils was not considered in the analysis.

ANALYTICAL APPROACH

To determine the effects of a fully quenching pancake, the process was considered in two steps. The first step was to calculate temperature and pressure rise in the conductor if it were not vented (i.e. the ends plugged). To do this, a worksheet (Table 1) was made. Using time increments of 0.5 to 2 seconds, the effects of electrical heating on conductor pressure and temperature were calculated. NBS 631 helium tables, curves for copper resistivity in a 10-T field as a function of temperature, and curves for copper or steel heat capacity as a function of temperature (Table 2) were used. Table 1 shows the results of this unvented, TF-coil pancake. Heat capacities of both the conductor strands and the case (conduit) were used, assuming negligible temperature gradient radially through the conductor and case. A hand calculation showed these radial-temperature gradients to be small.

The second step was to estimate the effect of venting from both ends of the pancake winding on temperature, pressure, and density in the coil. Average flow resistance of the conductor was estimated by using one-eighth the conductor length as a characteristic length, and multiplying the friction factor in the piping pressure-drop equation by 2.5 to correspond to empirical data for CICC conductors. Flow velocities were calculated based on this resistance and pressures developed by the quench. From this, the amount of helium vented and the decrease in average density were calculated. This new density in the conductor was then used to calculate the adjusted pressure for each time increment. Table 3 shows the worksheet for these adjustments. Here the following equation is used:

$$P_{\text{vented}} = P_{\text{no vent}} (1 - \%\ \text{vented})$$

Figure 1 shows the plotted results for the vented conductor. The temperature is not affected very much by the vent because heat capacity of the metals, not the helium, predominate during most of the quench process. In the early part of the quench, pressure is not affected strongly by the vent because a conductor path as long as the ITER TF coils limits vent rates. Flow velocities and percent of helium vented were calculated based on average density for the time increment. Expansion as the helium undergos pressure drop near the end of the conductor will decrease mass flow somewhat below that calculated. Consequently, reality will be between the vented and unvented curves of Figure 1, but closer to the vented curve. Figures 2 and 3 show the coil design used for these calculations.

ACKNOWLEDGMENTS

This work has been performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

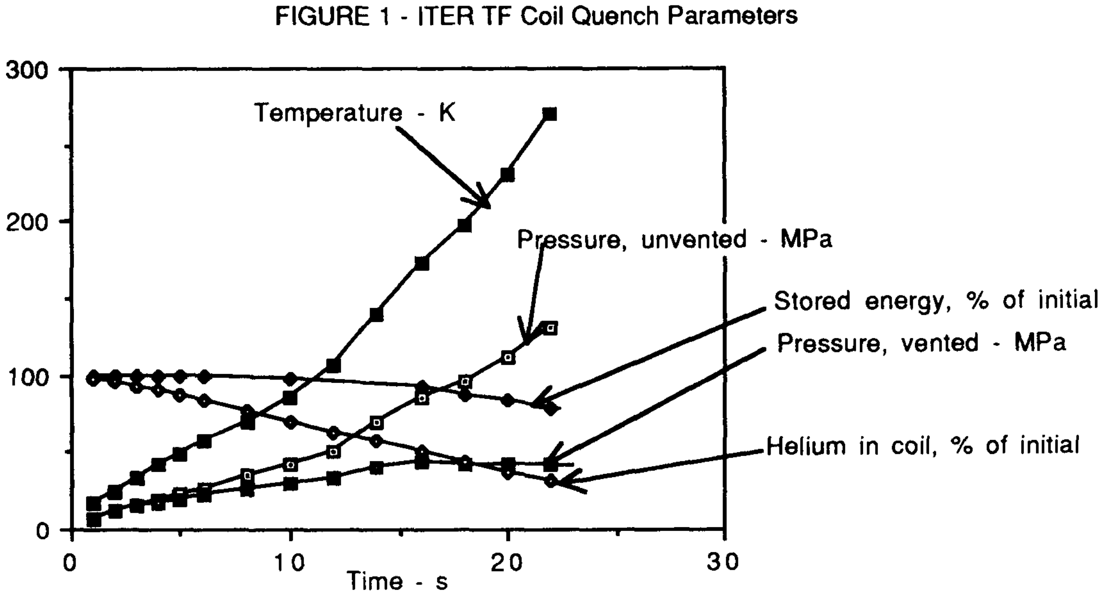

Figure 1.
ITER TF Coil Quench Parameters.

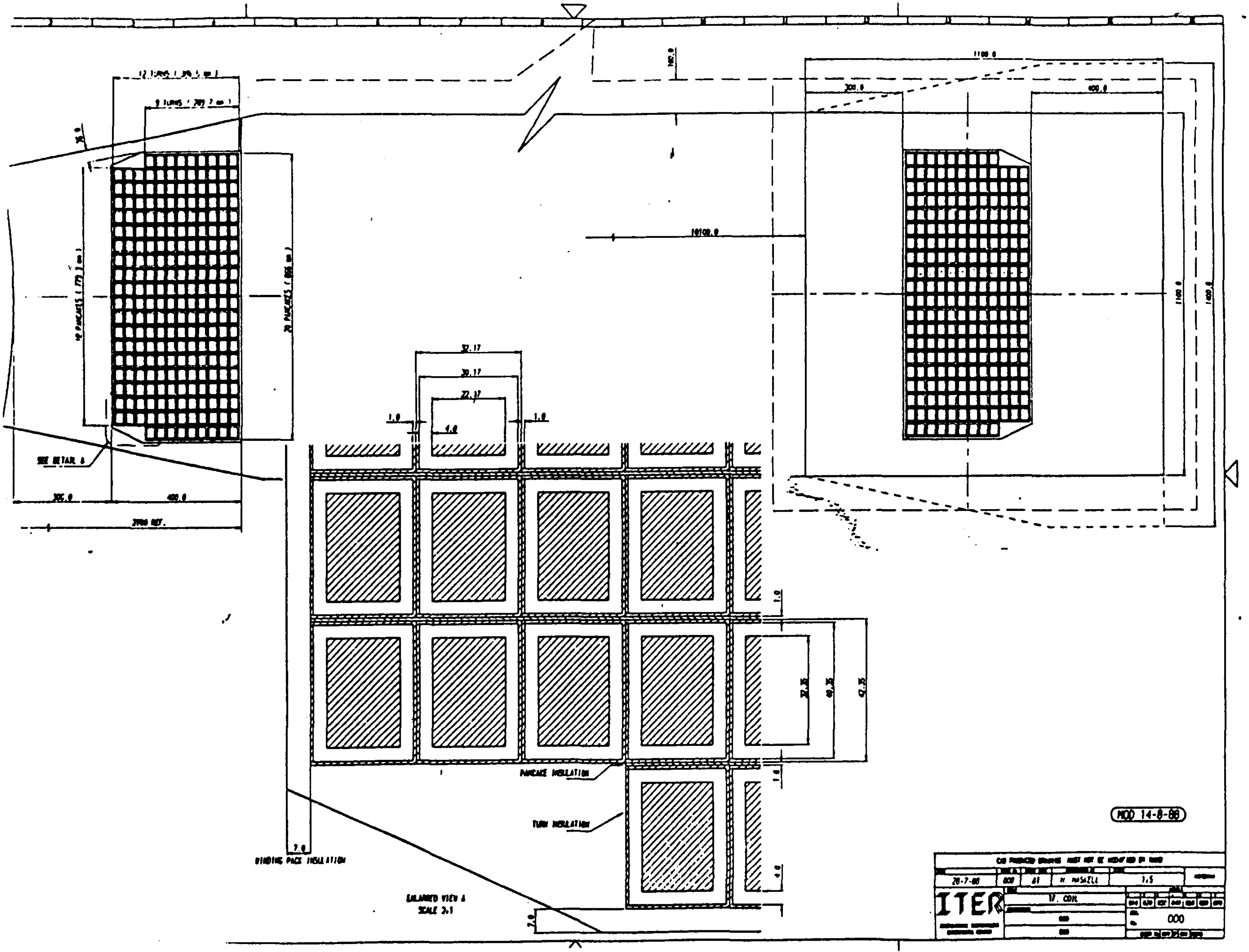

Figure 2
Coil Design Used in Analysis

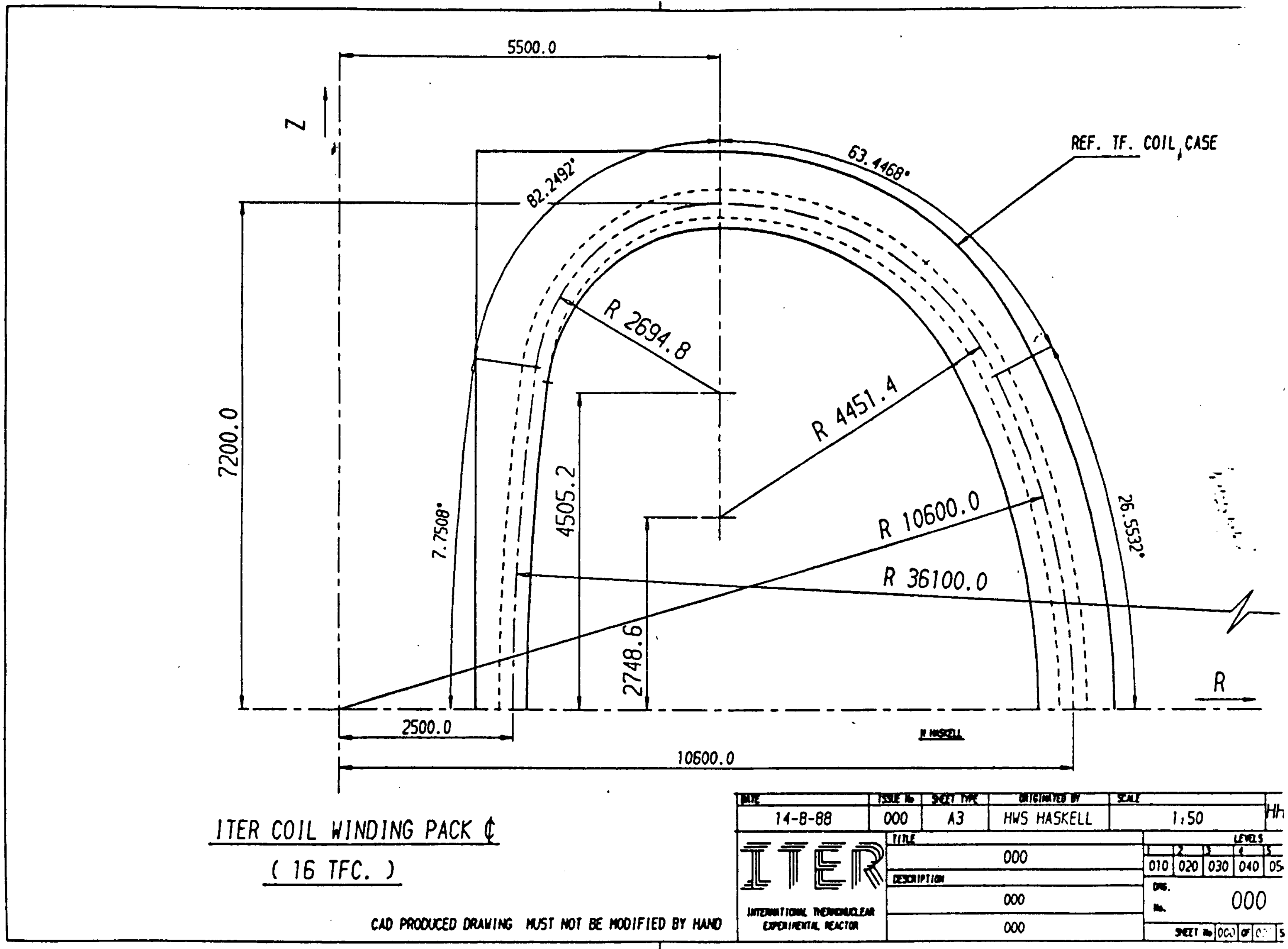

Figure 3
Coil Design Used in Analysis

TABLE 1. UNVENTED TF COIL PANCAKE

1 time s	2 time inc	3 current kA	4 I^2R j·103	5 % adsor by He	6 dU He	7 U He j/g	8 T K	9 P MPa	10 stor M
0		40				9	5	1.0	10^9
0.5	0.5	40	1.42	0.95	35	27	12	4.5	10^9
1.0	0.5	40	1.42	0.90	33	43	17	7.0	
1.5	0.5	40	1.42	0.82	30	58	22	10.0	0.998 x 10^9
2.0	0.5	40	1.42	0.76	28	72	25	11.8	
3.0	1.0	40	1.42	0.74	27	99	34	16.0	
4.0	1.0	40	1.42	0.55	20	119	41	19.0	
5.0	1.0	40	2.3	0.35	21	140	48	22.5	
6.0	1.0	40	4.0	0.24	25	165	57	26.5	0.995
8.0	2.0	40	5.7	0.17	25	215	70	35.0	
10.0	2.0	40	8.5	0.13	29	274	86	41.0	0.98
12.0	2.0	40	12.5	0.11	35	346	107	51.0	
14.0	2.0	40	22.8	0.085	50	446	140	70.0	
16.0	2.0	39	34.0	0.058	51	548	172	86.0	0.92
18.0	2.0	38	39.0	0.053	53	654	197	96.0	0.88
20.0	2.0	37	48.8	0.044	56	766	230	112.0	0.84
22.0	2.0	37	58.5	0.044	67	900	270	131.0	0.79

Columns

1. Time into quench—s
2. Time increment in calculation—s
3. Conductor current —kA
4. Electrical heating per unit length (m) of conductor, per unit time (s)—J
5. Percent of electrical heating adsorbed by helium in conductor (balance adsorbed by conductor strands and sheath)
6. Change in internal energy of helium per unit time—J/g – s
7. Internal energy of helium—J/g
8. Temperature—K
9. Pressure of helium in conductor—MPa
10. Stored energy of TF coil—J (initial energy less energy adsorbed by quench)

TABLE 2. PRESENT ITER TF COIL PARAMETERS USED HERE

Twelve turns per pancake
Twenty pancakes per coil
Length of turn—37.2 m
Helium path length (one pancake), 12 turns x 37.2 m—446 m
Initial current —40 kA
Conductor cross-section area—690 mm^2
Flow area of helium (40% of conductor 690 mm^2 cross section)—276 mm^2
Number of strands—588
Strand diameter—0.876 mm
Copper area of conductor—280 mm^2
Metal area of conductor (60% of 690)—415 mm^2
Metal area of case—915 mm^2
Percent area of helium—276/(915+276) = 0.23
Percent area of metal—0.77
Stored energy per coil—1.0 GJ

Copper resistivity—estimated from resistivity curves corrected for 10-T field:

30 K	2.5×10^{-10} ohm m
40 K	4×10^{-10}
50 K	7×10^{-10}
60 K	1×10^{-9}
100 K	3×10^{-9}
150 K	6×10^{-9}
200 K	1×10^{-8}
300 K	1.6×10^{-8}
400 K	2.6×10^{-8}
600 K	4×10^{-8}

Copper or steel heat capacity—estimated from curve:

10 K	10^{-3} J/gK
20 K	4×10^{-3}
30 K	9×10^{-3}
40 K	3×10^{-2}
60 K	9×10^{-2}
100 K	2×10^{-1}
200 & up	4×10^{-1}

TABLE 3. ADJUSTMENTS FOR CONDUCTOR VENTED AT BOTH ENDS

1 time s	2 press no vent	3 velocity m/s	4 density	5 %of initial He in cond	6 adj. press MPA
1	7.0	4.5	0.14 g/cm^3	0.98	6.9
2	11.7	4.7	0.137	0.96	11.4
3	16.0	5.8	0.135	0.93	14.9
4	19.0	6.6	0.13	0.90	17.1
5	22.5	7.2	0.126	0.87	19.6
6	26.5	7.8	0.122	0.84	22.2
8	35.0	8.5	0.118	0.77	27.0
10	41.0	9.5	0.109	0.70	28.8
12	51.0	10.2	0.100	0.63	32.4
14	70.0	11.3	.088	0.57	39.6
16	86.0	13.4	.080	0.50	43.0
18	96.0	14.6	.070	0.43	41.3
20	112.0	15.3	.060	0.37	41.6
22	131.0	16.6	.052	0.31	41.4

Columns

1. Time into quench—s
2. Pressure in conductor of not-vented (from Table 1)—MPa
3. Velocity of venting helium—m/s
4. Average density of helium left in conductor—g/cm^3
5. The percent of helium left in the conductor
6. Pressure in vented conductor—MPa

WORK SHEET CALCULATIONS

Table 1. Columns

1. Time into quench—s

2. Time increment used

3. Coil current— $I = I_0\ (E/E_0)^{0.5}$
   where $E = E_0 - \sum \Delta Q L_c \Delta t$ (i.e. initial energy less energy deposited in quench
   where $\Delta Q = I^2 r / A_{Cu}$ (r is from Table 2)
4. Energy deposited in conductor per unit length per unit time—(ΔQ)

5. Percent of quench energy adsorbed by helium during time increment
   $\%Q_{He} = C_{vHe}\rho_{H\varepsilon}\%A_{He}/(C_{Cu}\rho_{Cu}\%A_c + C_{vHe}\rho_{He}\%A_{He})$
   (where $\%A_c$ includes conductor plus case area)

6. Energy adsorbed by helium per unit time during time increment
   $\Delta U_{He} = \Delta Q\%Q_{He}/A_{He}\rho_{He}$ J/g)

7. Internal energy of helium – initial $U_{He} + \sum \Delta U_{He} \Delta t$

8. Temperature in conductor
   $T_{He} = f(\rho_{He} U_{He})$ from NBS 631

9. Pressure of helium in conductor
   $P_{He} = f(\rho_{He} U_{He})$ from NBS 631

10. Stored energy remaining in coil
    $E = E_0 - \sum \Delta Q \Delta t L_c$

Table 3. Columns

1. Time into quench—s

2. Quench pressure if not vented (from Table 1)

3. Velocity of venting helium
   $V = (2g\Delta P D_h/\rho 4 f L_v)^{0.5}$ (piping pressure drop equation)
   where L_v the average or effective conductor length for flow resistance is taken as $L_c/8$ (this is an educated guess based on pressure distribution in the conductor)
   D_h the hydraulic diameter is $4A_{He}$/periphery of strands = 0.68 mm

4f is taken as 2.5 times that given by the Moody diagram, based on empirical data on CICC conductor = 0.06.

[for the above conditions $V = .63\ (\Delta P/\rho)^{0.5}$ m/s where P is MPa and ρ is g/cm^3]

4. The density ρ used in the above equation is $\rho = \rho_0\,(1 - \%\text{He vented})$.

5. Percent helium vented from the conductor is the summation of helium vented per time increment.
   %He vented = $\Sigma(2V/L)\Delta t$ where the 2 accounts for venting from both ends

6. Pressure adjustment due to the vent is:
   $P_{\text{vented}} = P_{\text{no venting}}[1-(\%\ \text{He vented})]$

Notes:

1. In Table 3, velocity and density are calculated using values in the previous time increment.

NOMENCLATURE

P_{vented}—pressure in single flow path vented from both ends to one atmosphere. This is an average pressure which is close to maximum pressure under quench conditions.

$P_{non\text{-}vent}$—hypothetical pressure developed if flow path (conductor) was plugged at both ends

E—stored (magnetic) energy of one TF – J

E_o—initial stored energy at 40 kA

ΔQ—quench heating energy deposited in conductor per m of length per unit time (s) – J

L_c—length of single flow path (1/2 pancake) (12 turns) – m

A_{Cu}—area of copper in conductor

$\%Q_{He}$—percent of heat going to helium

C_v —heat capacity at constant volume for helium

$\%A_{He}$—percent area of helium cross section in conductor, excluding case

C_{Cu}—heat capacity of copper or steel

ρ_{He}—density of helium in conductor

ρ_{Cu}—density of copper or steel

$\%A_c$—percent area of metal, including strands and case

ΔU_{He}—energy adsorbed by helium per unit time – J/g

U_{He}—internal energy of helium

V—velocity of venting helium during quench

ΔP—pressure in conductor less one atmosphere at exit

D_h—hydraulic diameter of conductor = 4 x area/perimeter

4f—pipe-flow friction factor

L_v —a length used as an average or effective length for vent flow calculations