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CONSECUTIVE QUENCHES AND THE SAFETY LEADS

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The safety leads of the Energy Saver were designed to handle occasional quenches. In order to save capital investment in another system of plumbing they involve no gas cooling. In their design optimisation was sought on the ratio of load capability (for a single quench) to steady state heat leak into the liquid helium environment. Reference 1, describes the design considerations and tests on a prototype made out of constantan. The actual production models are made out of 304 Stainless Steel rods 13/16" diameter by 48.66" long² wrapped in Kapton film for electrical insulation.

Here the behaviour of production models relevant for consecutive quenches is analysed. The quenches are characterized by current pulses of the shape

$$I(t) = I_0 e^{-t/12}.$$

Since the time constant of 12. seconds is much smaller than the cooling time for recovery, the adiabatic approximation for the temperature increase in an element of length dx of the lead during a quench is accurately given by the energy balance equation:

$$\mu s c(T) dT = \rho(T) s^{-1} I(t)^2 dt$$

where:

$\mu = 7.86 \text{ g/cm}^3$ is the density of stainless steel³

$s = \frac{\pi}{4} (13/16)^2 \text{ in}^2 = 3.345 \text{ cm}^2$ is the cross section

$c(T)$ is the specific heat of stainless steel⁴ (J/g.K)

$\rho(T)$ is the electrical resistivity of stainless steel⁵ ($\Omega \cdot \text{cm}$)

T is the temperature of the element (K)

t is time (s)

rearranging and integrating:

$$\mu s^2 \int_{T_{\text{before}}}^{T_{\text{after}}} \frac{c(T)}{\rho(T)} dT = \int_0^{\infty} I_0^2 e^{-2t/12} dt = 6 \cdot I_0^2$$

The right hand side of the equations is usually referred to as the number of Miits ($10^6 \text{ A}^2 \cdot \text{s}$ or $\text{J}/\mu\Omega$) forced into the lead. Based on quench data, P. Martin⁶ has suggested a reduction of the value $6 I_0^2$ to $5.6 I_0^2$ in order to account for the initial deposition of energy in the magnet.

Figure 1 is a calculation of the integral

$$\mu s^2 \int_0^T c(T)/\rho(T) dT \quad \text{J}/\mu\Omega$$

and it allow us to find out the temperature excursion of an element of length given its initial temperature and the intensity of the quench either in $\text{J}/\mu\Omega$ (Miits) or the initial current using the scale on the right margin. This scale has not been corrected for the 5.6/6.0 factor in the number of Miits. The same Figure 1 allows us to evaluate the maximum current allowable if the temperature of the hottest spot in the lead is known and the maximum safe value (600. K for the integrity of the Kapton film) is stipulated. Since the electrical resistance of the lead can be estimated from quench data⁶, it is useful to have a calculated limit for the temperature of the hottest spot in the lead as a function of the electrical resistance. This is given in Figure 2. The calculation leading to this graph is explained further on.

The temperature profile of the lead is a very slow function of time between quenches as well as during warm up and cool down of the Energy Saver, since it is cooled only by conduction to its extremities. The superinsulation reduces infrared radiation to a negligible effect. We therefore neglect this effect.

In order to calculate the change of the temperature profile with time, we set up the following finite element difference equation for the energy flow:

$$Q(n,n-1) - Q(n+1,n) = h(n) \cdot (T_n(t+dt) - T_n(t)) / dt$$

where:

$Q(n,n-1)$ = heat conducted from element n to element n-1

$Q(n+1,n)$ = heat conducted from element n+1 into element n

$h(n) = \mu s dx c(T_n)$ = change in heat capacity of element n during dt

Let $\kappa(T_{n,n-1})$ be the thermal conductivity of stainless steel⁷ (w/cm.K) at the temperature $T_{n,n-1} = (T_n + T_{n-1})/2$ between elements n and n-1, then

$$Q(n,n-1) = s \cdot \kappa(T_{n,n-1}) \cdot (T_n - T_{n-1}) / dx$$

$$Q(n+1,n) = s \cdot \kappa(T_{n+1,n}) \cdot (T_{n+1} - T_n) / dx$$

For boundary conditions we impose $T_1 = 4.6 \text{ K}$ and $T_{62} = 298. \text{ K}$, the length of the lead being divided in 62 elements, each 2.0 cm long ($dx = 2. \text{ cm}$). The initial condition $T_n = 300. \text{ K}$ for $n = 2, 3, \dots, 61$ at $t = 0$ would be typical for the cooldown problem. The above expressions permit

the calculation of the temperature profile at time $t=dt$, and by repetition at any multiple of dt which was chosen to be $dt=6.0$ s. Figure 3 shows this condition as it evolves into the steady state profile. It is interesting to note that although thermal diffusivity is the relevant property in this heat propagation problem, its use leads to an erroneous linear temperature profile for the steady state condition. One has to handle separately, as we did above, the thermal conductivity and the specific heat for a proper simulation.

A public fortran program, QCHWAIT/UN=92532, in the Cyber was written to carry out the simulation. It uses approximately 1 minute of cpu time to simulate 10 hours of lead behaviour. This program is presented in Appendix 1. The output of this program for the quenches observed on April 9-10, 1984 is plotted in Figure 4. The development of the steady state temperature profile for a safety lead initially at room temperature presented in Figure 3 was also obtained with this program. The printing is done on intervals of approximately 15 minutes, it includes the time (decimal hours), the highest temperature (K) in the profile, the distance from the cold end (cm) at which it occurs and a series of temperatures (K) corresponding to positions separated by 10 cm. In the process of developing this program, we compiled in another program QCHWTST/UN=92532 the following properties of stainless steel: thermal diffusivity, specific heat, electrical resistivity, thermal conductivity, quench capability and inverse quench capability.

By using the electrical resistivity and the temperature profile at print out time, QCHWAIT or its later version calculates the total resistance

$$R = \sum_{n=1}^{62} \rho(T_n) s^{-1} dx$$

Plotting this total resistance as a function of the hottest point temperature for the three quenches of April 9, 1984 and several other quenches (2.0 kA, 3.0 kA, 3.5 kA and 7.7 kA) starting from steady state condition we obtain Figure 2. An envelope curve can be drawn in it. This curve is the temperature of the hottest spot possible for the given resistance. If the resistance of the safety lead can be measured in place, remotely, with a phase-locked-ac-milliohmeter for instance, or calculated from quench data this curve might be very useful as mentioned above in the first reference to Figure 2.

A plot of the temperature of the hottest spot as a function of time is presented in Figure 5. It includes the three quenches of Figure 4 starting with a delay of 4 hours and several other quenches starting from the steady state condition. It provides us with examples for estimating cooling or waiting times.

Due mostly to time limitation, this work is presented leaving a few rough edges. The following list is written while things that could be improved, expanded and polished are fresh in mind. It is a "to do" list in no particular order, if upgrading this work becomes a justifiable effort.

1. Figure 1 was calculated by hand not using the stainless steel

data functions that now are in the program, it might deviate a little from the values that these might generate for it.

2. Modify QCHWAIT for convenience and user friendliness to the accelerator operators, as well as, presenting the results in plots instead of tables.

3. Verify the performance of QCHWAIT with different values of dx and dt . The values chosen satisfy the thermodynamic principles condition

$$dx^2/2dt < \kappa/\mu c$$

at all temperatures. The calculations show good convergence and reasonable answers passing several tests. But, it is probably not the optimum compromise between simulation speed and detail.

4. Measure the electrical resistance of several safety leads and compare them with the calculated values shown in Figure 2.

5. Instrument a safety lead with thermometers and experimentally verify the results of this work.

6. Simulate the "bleeding gas fix" that was implemented in the few critical spool pieces for speedier cooling off.

REFERENCES

1. M.Kuchnir and T.H.Nicol - Safety Leads - Advances in Cryogenic Engineering 25 , 294-299, (1980).
2. Fermilab drawing No. 1620-MD-124599
3. Materials at Low Temperatures - Richard P. Reed and Alan F. Clark editors, American Society for Metals, Metals Park, Ohio 44073 (1983) p.377
4. Ibid p. 66
5. Ibid p. 164
6. Philip S. Martin, Private communication
7. Reference 3, p. 135

Figure 1. Load Capacity (Miits) for a Safety Lead

Figure 2. Hottest Spot Temperature vs. Lead Resistance

Figure 3. Temperature Profiles During Cooldown

Figure 4. Temperature Profiles for April 9, 1984 Quenches

Figure 5. Cooling of Hottest Spots for Several Quenches

Appendix 1

Simulation Program

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00001      PROGRAM QCHWAIT (INPUT,OUTPUT,HISTO,DET,TAPE1=HISTO,TAPE2=DET)
00002 C          THIS PROGRAM SIMULATES THE TIME DEPENDENCE OF
00003 C          THE TEMPERATURE PROFILE OF AN ENERGY-SAVER SAFETY LEAD.840413
00004 C
00005      DIMENSION T(62,150),TSS(62),QTIME(5),QCURR(5)
00006      DX=2.
00007      DT=6.
00008      S=3.345
00009      R=7.86
00010      DD=DT/(DX*DX*R)
00011 C      SAMPLE HISTORY:
00012      ACTIME=4.0
00013      DATA QTIME/ 4.38, 9.45, 13.1, 34.6, 110./
00014      DATA QCURR/ 2720.,3552.,3552.,2800.,-1./
00015      NQ=1
00016 C      QUENCH OF CONCERN:
00017      AIMAX=4000.
00018      QMAX=5.6E-6*AIMAX*AIMAX
00019      QM=FUNC1(300.)+QMAX
00020      TMAX=FUNC2(QM)
00021 C      STEADY STATE PROFILE:
00022      DATA TSS/ 4.6,33.,43.,52.,60.,67.,74.,80.,86.,91.,
00023      1 97.,102.,107.,112.,117.,122.,126.,131.,136.,140.,
00024      2145.,149.,153.,158.,162.,166.,170.,174.,179.,182.,
00025      3186.,190.,194.,198.,202.,206.,209.,213.,216.,220.,
00026      4224.,227.,231.,234.,238.,242.,245.,249.,252.,256.,
00027      5259.,263.,266.,270.,273.,277.,280.,284.,287.,291.,
00028      6294.,298./
00029      WRITE(1,51)
00030      PRINT 51
00031      51  FORMAT(" TIME HR      TMAX      LMAX      R MOHMS T 12      T 22      T 32
00032      1 T 42      T 52      T 62      T 72      T 82      T 92      T102 T112 T
00033      2122")
00034 C      SET INITIAL PROFILE TO STEADY STATE
00035      DO 1 I=1,62
00036      T(I,1)=TSS(I)
00037      1  CONTINUE
00038 C      HISTORY HANDLER
00039      71  IF(QTIME(NQ)-.25-ACTIME) 10,10,11
00040      11  N=150
00041      IFQ=0
00042      GOTO 2
00043      10  N=3600.*(QTIME(NQ)-ACTIME)/DT
00044      IFQ=1
00045      IF(N.GT.150) PRINT 12
00046      12  FORMAT( "N>150")
00047      IF(QCURR(NQ).LE.0) STOP
00048      GOTO 2
00049 C
00050 C      FINITE ELEMENT ITERATION

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00051      2 DO 3 J=2,N
00052          T(1,J)=4.6
00053          T(62,J)=298.
00054          DO 4 I=2,61
00055              T1=(T(I-1,J-1)+T(I,J-1))/2.
00056              DT1=T(I-1,J-1)-T(I,J-1)
00057              T2=(T(I+1,J-1)+T(I,J-1))/2.
00058              DT2=T(I+1,J-1)-T(I,J-1)
00059 C      WRITE(2,54) I,J,T1,DT1,T2,DT2
00060 C 54  FORMAT (2I4,4F10.1)
00061          C2=DD*COND(T2)/SPEC(T(I,J-1))
00062          C1=DD*COND(T1)/SPEC(T(I,J-1))
00063          T(I,J)=T(I,J-1) + C1 * DT1 + C2 * DT2
00064      4 CONTINUE
00065          TD=J-1
00066          L=J
00067      3 CONTINUE
00068          ACTIME=ACTIME+(TD*DT/3600.)
00069          TMAX=0
00070          R=0
00071          DO 5 I=1,62
00072              T(I,1)=T(I,L)
00073              R=R+DX*RESIS(T(I,L))/S
00074              H=I
00075              IF(TMAX.LE.T(I,L)) TMAX=T(I,L)
00076              IF(TMAX.LE.T(I,L)) HMAX=H*DX
00077      5 CONTINUE
00078          WRITE(1,50) ACTIME,TMAX,HMAX,R,T( 6,1),T(11,1),T(16,1),
00079 1T(21,1),T(26,1),T(31,1),T(36,1),T(41,1),T(46,1),T(51,1),
00080 2T(56,1),T(61,1)
00081 50  FORMAT(F8.2,2F8.0,F8.3,12F8.0)
00082          PRINT 52, ACTIME,TMAX,HMAX,R,T( 6,1),T(11,1),T(16,1)
00083          IF (IFQ.EQ.0) GOTO 71
00084 C
00085 C      EXECUTE QUENCH:
00086          QI=5.6E-6*QCURR(NQ)*QCURR(NQ)
00087          WRITE(1,53) QTIME(NQ),QCURR(NQ),QI
00088 53  FORMAT(F8.2," QUENCH WITH IO=",F6.0,"A ==>",F6.1," MIITS")
00089          TMAX=0
00090          R=0
00091          DO 7 K=1,62
00092              QE=FUNC1(T(K,1))+QI
00093              T(K,1)=FUNC2(QE)
00094              R=R+DX*RESIS(T(K,1))/S
00095              H=K
00096              IF(TMAX.LE.T(K,1)) TMAX=T(K,1)
00097              IF(TMAX.LE.T(K,1)) HMAX=H*DX
00098      7 CONTINUE
00099          WRITE(1,50) ACTIME,TMAX,HMAX,R,T( 6,1),T(11,1),T(16,1),
00100 1T(21,1),T(26,1),T(31,1),T(36,1),T(41,1),T(46,1),T(51,1),
00101 2T(56,1),T(61,1)
00102          PRINT 52, ACTIME,TMAX,HMAX,R,T( 6,1),T(11,1),T(16,1)
00103 52  FORMAT(F8.2,2F8.0,F8.3,3F8.0)
00104          NQ=NQ+1

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00105 C      EXAMINE MAXIMUM TEMPERATURE
00106      QE=FUNC1(TMAX)+QMAX
00107      TFUT=FUNC2(QE)
00108      IF(TFUT.GE.650) WRITE(1,8) AIMAX,TFUT,HMAX
00109      8  FORMAT(8X,"A ",F5.0,"A  QUENCH WILL GENERATE ",F4.0,"K AT ",
00110      1F5.0,"CM")
00111 C      EXAMINE MAXIMUM ALLOWABLE QUENCH
00112      QA=FUNC1(650.)-FUNC1(TMAX)
00113      IF(QA) 60,60,62
00114      60 WRITE(1,64)
00115      64 FORMAT(7X," EXCEEDED MAXIMUM ALLOWABLE QUENCH ")
00116      GOTO 71
00117      62 CUR2=QA/5.6E-6
00118      CUR=SQRT(CUR2)
00119      WRITE(1,66) CUR
00120      66 FORMAT(7X," MAXIMUM ALLOWABLE QUENCH CURRENT NOW:",F6.0,"A .")
00121      GOTO 71
00122      END
00123 C
00124 C
00125      FUNCTION FUNC1(T)
00126 C      QUENCH CAPACITY AS FUNCTION OF TEMPERATURE      MIITS
00127      IF(T.LE.400.) GOTO 31
00128      FUNC1=-22.5556+.475556*T
00129      GOTO 37
00130      31 IF(T.LE.275.) GOTO 32
00131      FUNC1=-42.2222+.522222*T
00132      GOTO 37
00133      32 IF(T.LE.200.) GOTO 33
00134      FUNC1=-52.5+.56*T
00135      GOTO 37
00136      33 IF(T.LE.96.) GOTO 34
00137      FUNC1=.736963E-3*T**2.13255
00138      GOTO 37
00139      34 IF(T.LE.4.6) GOTO 35
00140      FUNC1=1.16459E-6*T**3.54396
00141      GOTO 37
00142      35 PRINT 36
00143      36 FORMAT("T<4.6 FUNC1 TRAP")
00144      FUNC1=0.
00145      37 RETURN
00146      END
00147 C
00148      FUNCTION FUNC2(X)
00149 C      TEMPERATURE INCREMENT DUE TO QUENCH LOAD      K
00150      IF(X.LE.168.) GOTO 41
00151      FUNC2=(X+22.5556)/.475556
00152      GOTO 47
00153      41 IF(X.LE.102.) GOTO 42
00154      FUNC2=(X+42.2222)/.522222
00155      GOTO 47
00156      42 IF(X.LE.60.) GOTO 43
00157      FUNC2=(X+52.5)/.56
00158      GOTO 47

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00159 43 IF(X.LE.10.) GOTO 44
00160      FUNC2=(X/.736963E-3)**.468922
00161      GOTO 47
00162 44 IF(X.LE..00026) GOTO 45
00163      FUNC2=(X/1.16459E-6)**.282170
00164      GOTO 47
00165 45 PRINT 46
00166 46 FORMAT("X<.00026  -FUNC2 TRAP")
00167      FUNC2=0.
00168 47 RETURN
00169      END
00170 C
00171      FUNCTION SPEC(T)
00172 C          SPECIFIC HEAT OF STAINLESS STEEL  J/GK
00173      IF(T.LE.600.) GOTO 81
00174      SPEC = .49
00175      GOTO 89
00176 81 IF(T.LE.300.) GOTO 82
00177      SPEC = .22081519 * T ** .12285675
00178      GOTO 89
00179 82 IF(T.LE.200.) GOTO 83
00180      SPEC = .085829531 * T ** .29048871
00181      GOTO 89
00182 83 IF(T.LE.100.) GOTO 84
00183      SPEC = 4.1440952E-3 * T ** .86249648
00184      GOTO 89
00185 84 IF(T.LE.63.) GOTO 85
00186      SPEC = 85.005947E-6 * T ** 1.7064867
00187      GOTO 89
00188 85 IF(T.LE.35.) GOTO 86
00189      SPEC = 1.6692594E-6 * T ** 2.6551262
00190      GOTO 89
00191 86 IF(T.LE.4.2) GOTO 87
00192      SPEC = 478.40362E-6 * T ** 1.06370
00193      GOTO 89
00194 87 PRINT 88
00195 88 FORMAT (" T<4.2 ==> SPEC = 1.E-6")
00196      SPEC = 1.E-6
00197 89 RETURN
00198      END
00199 C
00200      FUNCTION COND(T)
00201 C          THERMAL CONDUCTIVITY OF STAINLESS STEEL  W/CM.K
00202      IF(T.LE.300.) GOTO 92
00203      COND = 44.707195E-3 * T ** .21222774
00204      GOTO 99
00205 92 IF(T.LE.200.) GOTO 93
00206      COND = .020037364 * T ** .3529301
00207      GOTO 99
00208 93 IF(T.LE.100.) GOTO 94
00209      COND = 11.822224E-3 * T ** .4525122
00210      GOTO 99
00211 94 IF(T.LE.60.) GOTO 95
00212      COND = 4.6622033E-3 * T ** .6545662

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00213      GOTO 99
00214      95  IF(T.LE.40.) GOTO 96
00215          COND = 1.6319045E-3 * T ** .9109541
00216          GOTO 99
00217      96  IF(T.LE.20.) GOTO 97
00218          COND = 435.29606E-6 * T ** 1.2691866
00219          GOTO 99
00220      97  IF(T.LE.4.2) GOTO 98
00221          COND = 394.94084E-6 * T ** 1.301663
00222          GOTO 99
00223      98  PRINT 100
00224      100 FORMAT (" T<4.2 --> COND=1.E-4")
00225          COND=1.E-4
00226      99  RETURN
00227          END
00228 C
00229      FUNCTION RESIS(T)
00230 C          RESISTIVITY OF STAINLESS STEEL          1.E-3*OHMS*CM
00231          IF(T.LE.148.) GOTO 75
00232          RESIS = .020581593 * T ** .21410886
00233          GOTO 79
00234      75  IF(T.LE.80.) GOTO 76
00235          RESIS = .020916588 * T ** .21087798
00236          GOTO 79
00237      76  IF(T.LE.40.) GOTO 77
00238          RESIS = .035922037 * T ** .087462841
00239          GOTO 79
00240      77  RESIS=.0496
00241          IF (T.LT.4.2) PRINT 78
00242      78  FORMAT ("T<4.2 IN RESIS")
00243      79  RETURN
00244          END
00244          END

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