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ESTIMATES OF PRESSURES AND TEMPERATURES GENERATED DURING QUENCHES OF SSC MAGNETS

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Summary

Helium pressures and temperatures occurring during a magnet quench are estimated by means of a procedure which is much simplified, employing only ordinary differential equations rather than sets of partial differential equations. A purpose of this calculation was to obtain early indications as to whether, during a quench, design pressures for the helium containment vessel and for the beam tube may be exceeded with the long, high field SSC magnets. It is found that, without providing a fair amount of venting (or other means) in order to reduce maximum pressures, design pressures could indeed easily be exceeded by as much as a factor of 3. Additional problems are presented by the large pressure drops occurring along the long beam tube, exposing the latter to perhaps unsustainable external pressures. These results have justified a more extensive effort to perform much more detailed calculations which, besides vents, take into account the possibility of, all along the magnet, venting the helium passage around the beam tube into the helium bypass tubes. Initial results look promising. Derivations and results will be discussed in later Notes. In this Note we present some basic thermodynamic facts, also pointing out the large ($\sim 10atm$) pressure difference (at low temperatures only) between unmixed and mixed states of helium masses at originally different temperatures. We show that results for pressures and temperatures depend essentially on 10 different parameters, such as the amount of helium present in cavities between the superconducting wires forming a cable (pressure $\approx 370atm$ during quench if no escape for helium possible!), the quenched fraction of the magnet length, quench duration, vent operating times, etc.

Many thanks are due Kurt Jellett who, including much advice, provided and operated the computer program needed to obtain the results presented in this Note.

1. Introduction.

When a superconducting magnet ceases to be superconducting — when it quenches — at some location in the magnet coil, heat is generated. While the quench propagates longitudinally, azimuthally, and radially in the coil, more heat is generated. Since this heat is due to the energy stored in the magnet, the current decreases until the stored energy has been dissipated. By that time the generated heat will be distributed over some region of the coil, whose size depends on parameters which determine the spatial quench propagation velocity. The temperature distribution will have a maximum at the quench origin and decrease to magnet operating temperature at the limits of the quenched region or to some other temperature at the coil boundaries.

Superconducting magnets are generally cooled with helium in its liquid ($\leq 2.24atm$ pressure) or supercritical ($> 2.24atm$) phase. The SSC magnets are to be operated at an average pressure of $4.3atm$ and average temperature of $4.24°K$. Forced-flow cooling is to be used. During normal operation a small amount of helium ($\sim 1g/sec$ mass flow) is to flow through a passage between coil and trim coil–beam tube assembly, and a much larger amount ($100g/sec$) is bypassed through holes in the iron yoke laminations. The average helium flow velocity in the coil passage is then only about 6 cm/sec.

The coil windings consist of cabled strands. Between the strands remain spaces (cavities) whose size depends on the amount of compression of the strands due to the cable-shaping process and on the coil prestress which acts on the cable insulation. These cavities are filled with helium which remains mostly stagnant during normal operation because the cables are wound with two layers of Kapton tape and then bonded with epoxy-filled fiberglass tape. If the pressure in the cable should rise, the helium would most probably not remain completely trapped but leak out more or less rapidly, depending on the available pressure difference and the "porosity" of the coil assembly.

For the SSC magnets the duration of most of the dissipation of the stored energy is expected to be as short as 0.3 sec. Since the magnet coils are well-insulated on the outside and surrounded by stainless steel collars - and thus are imbedded in low heat conductivity materials - these components, as well as the yoke, will receive little heat during the mentioned short quench duration.

Therefore most of the energy has to be dissipated by the coil material and by the helium in the cable voids and coil passage.

Since the helium in the cable voids (mass m_2) is distributed over a multitude of small spaces, the surface area for heat exchange is very large. In addition, this helium is not insulated from the coil material. In contrast, the helium in the coil passage (m_1) is insulated from the coil and also, since here the surface area is only that at the inside of the coil, heat exchange can be expected to be much smaller. Thus, if enough helium can leak out of the cable voids during the quench time, its temperature will mainly influence the pressure developed in the magnet, besides, of course, various other influences such as number of magnets quenched, vent lines provided, and the amount of helium (m_3) contained in the magnet interconnection (magnet end) volumes.

The mass (m_c) of the coil is large enough that, in spite of the small heat capacity of the coil material at low temperature, one must expect that a substantial fraction of the energy stored in the magnet will be absorbed by the cable. Since, as mentioned above, helium mass m_2 is thermally very closely coupled to the coil, its temperature should rise about as that of the coil. At low temperature the heat capacity of the coil material rises approximately exponentially with temperature, starting at very small values. Therefore the temperature of m_2 will rise rapidly, and therefore also its pressure. Of course, one must take into account that the heat capacity of helium (per gram) is very large compared to that of the magnet.

A fraction of the helium warmed up in the coil passage (m_1) and cable voids (m_2) will flow into the cold magnet end volume. Although the exit flow velocity is high (20 to 60 m/sec), mixing of m_1, m_2, m_3 may require considerably more time than the quench time. Therefore the unmixed case should be assumed first, and after that only mixing of the three fluid masses. We shall show that, for helium at low temperatures, pressure differences between mixed and unmixed states can indeed be expected.

2. Unmixed and Mixed States.

Assume that n helium masses m_n have respective temperatures T_n and common pressure p. The m_n are confined in a common volume V. Thus

$$\sum m_n/\rho_n = \sum m_n v_n = V \tag{1}$$

where the ρ_n are densities, or the v_n their reciprocals. When mixing the m_n, without adding or subtracting energy:

$$\sum m_n (dU_n + p dv_n) = 0 \tag{2}$$

according to the "first law of thermodynamics" (energy conservation). The U_n are internal energies (per gram) defined by

$$U_n = \int_o^{T_n} c_V (p, T_n) \, dT_n \tag{2a}$$

where $c_V (p, T_n)$ is the heat capacity per gram at constant volume. According to eq. 1:

$$\sum m_n dv_n = 0$$

Therefore, from eq. 2

$$\sum m_n dU_n = 0$$

and, summing,

$$\sum m_n U_n = U_m \sum m_n$$

or

$$U_m \equiv U(p_m, T_m) = \left(\sum m_n U_n\right) / \sum m_n \tag{3}$$

U_m, p_m, T_m are internal energy, pressure, and temperature, respectively, of the mixed state whose density is

$$\rho_m \equiv \rho(p_m, T_m) = \left(\sum m_n\right) / V. \tag{4}$$

Generally, eqs. 3 and 4 can be solved for p_m and T_m, at least numerically if $U(p, T)$ and $\rho(p, T)$ are given by tables or functions, and there is no reason to expect the pressures p for unmixed and p_m for mixed states to be equal. Let us now assume that $c_V (p, T)$ is constant. Then according to eqs. 2a and 3, simply;

$$T_m = \left(\sum m_n T_n\right) / \sum m_n \tag{5}$$

The assumption that $c_V = const$ applies to gases whose tempertures are well above those of their liquid phases. Such states would be described by the "ideal gas law"

$$pv_n = p/\rho_n = RT_n/M$$

and (6)

$$p_m v_m = p_m/\rho_m = RT_m/M$$

where R is the "gas constant" and M the molecular weight. In addition to eq. 1 we can also write

$$\left(\sum m_n\right)/\rho_m = V = \sum (m_n/\rho_n) \tag{1a}$$

Making use of eqs. 1a, 5, 6, we obtain

$$p_m = p \tag{7}$$

for pressures of unmixed states of "ideal gases" that become mixed. Thus there is no pressure difference between unmixed and mixed states for this case. For helium at cryogenic temperatures c_V is not constant and the ideal gas law is far from applicable. For these reasons we shall find substantial pressure differences between unmixed and mixed states. At low temperatures and elevated pressures, unmixed states can persist for considerable times (many seconds to minutes) because of the relatively large density differences at different initial temperatures before mixing.

3. Diffusion Times and Illustration of Dynamic Calculation.

As mentioned in the introduction, we shall here restrict ourselves to the coil region since during the short quench duration very little heat will leak into collars or, especially, the iron yoke. According to J. G. Cottingham, overall stored energy dissipation times of 0.3 sec were predicted and indeed observed in recent measurements. In Magnet Division Note 134-20, page 5, a diffusion time of $\tau = 16$ sec was estimated for heat passing from coil into iron, simply using the well-known expression

$$\tau = \frac{s^2 D_s c_s}{4k_s}$$

where

$$s = \textit{distance from heat source}$$
$$D_s = \textit{density of material}$$
$$c_s = \textit{heat capacity}$$
$$k_s = \textit{heat conductivity}$$

The cited value for $\tau = 16$ sec was calculated for temperatures not far from 4.5°K. At higher temperatures c_s usually increases faster than k_s. Therefore τ increases further. The contribution to τ by the stainless steel collars alone was 6 sec which is $\gg 0.3$ sec. If aluminum collars were used heat would more readily pass into the yoke. If only a thick-walled plastic sleeve were used, as in the CBA magnets, τ would increase. In any case, here we will let all of the stored energy be dissipated by coil and helium, especially since there is a multitude of other parameters to be considered. If or when necessary, the present calculations can easily be extended to include other components.

The diffusion time for heat through the insulation between inner coil and helium passage is only 0.02 sec ($\ll 0.3$ sec). Therefore the helium in this passage, whose flow is turbulent, can indeed absorb heat during the quench time of 0.3 sec.

Below we shall estimate the size of the cavities, containing helium, in the cable. There the diffusion time is again only 0.02 sec so that the helium can readily absorb heat.

During a magnet quench we are obviously dealing with a dynamic process which can be described by partial differential equations for helium flow and heat diffusion through solids. Helium flow through a passage can be described by a set of three simultaneous equations in location x and time t. Three equations are required because the x- and t- dependent variables are, for instance, pressure, temperature, and velocity. If several passages are involved, such as coil and yoke bypass passages, as well as heat diffusion through coil and yoke, etc., a computer time-consuming system of equations results. Nevertheless, the needed equations were derived and an existing program ("PDECOL") was applied approximately in 1978 for ISA magnets and later for CBA magnets. For illustration, only of the process, we show Figures 1 to 3, obtained from

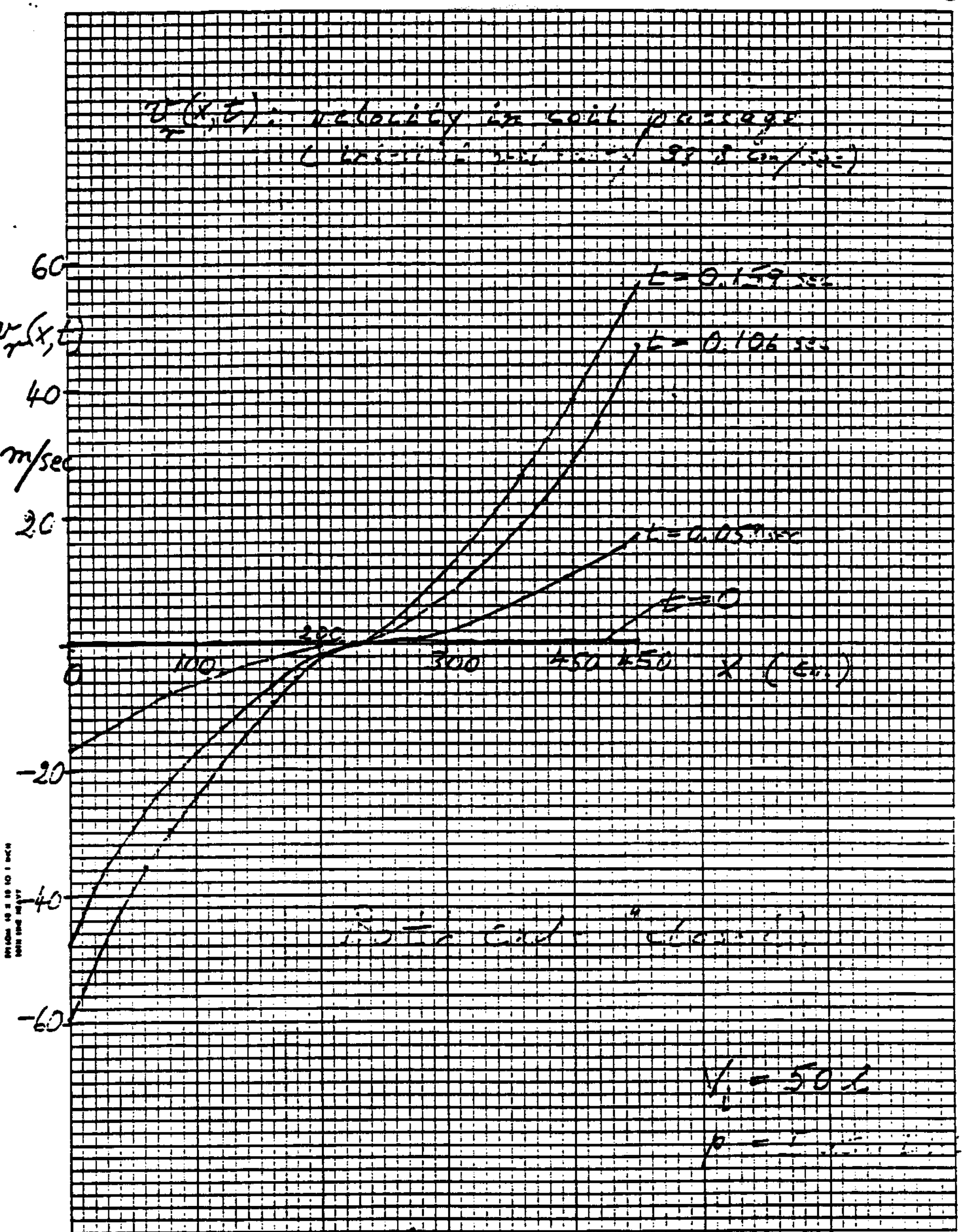

v_r(x,t): velocity in soil passage
60
40
20
-20
-40
-60
v_r(x,t)
m/sec
t = 0.159 sec
t = 0.106 sec
t = 0.053 sec
t = 0
0
100
200
300
450
450
x
V_1 = 50 ℓ

Fig. 1

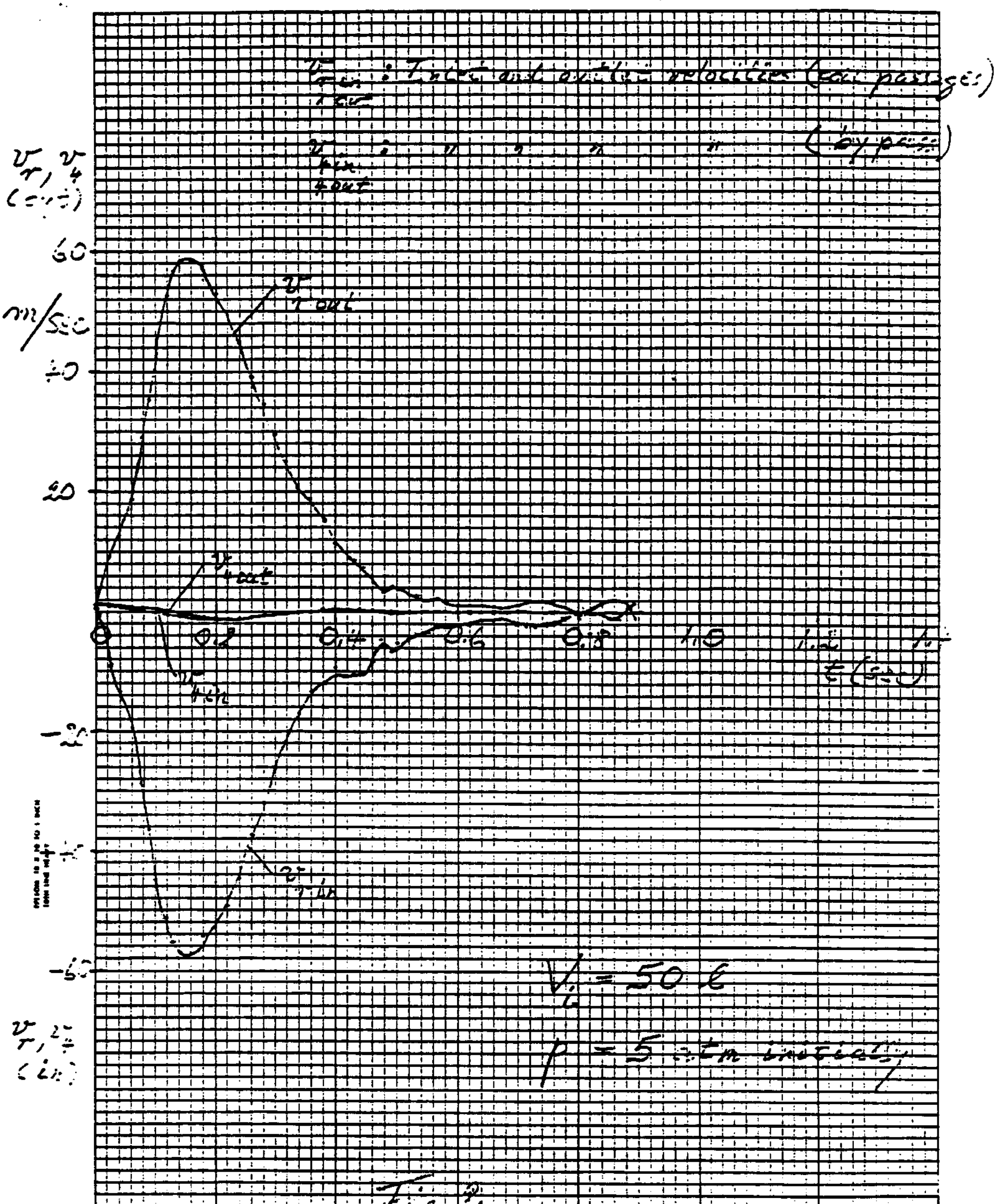

Inlet and outlet velocities
(bypass)
m/sec
60
40
20
0
0.2
0.4
0.6
0.8
1.0
-20
-40
-60
V = 50 l
p = 5 atm initially

Fig 2

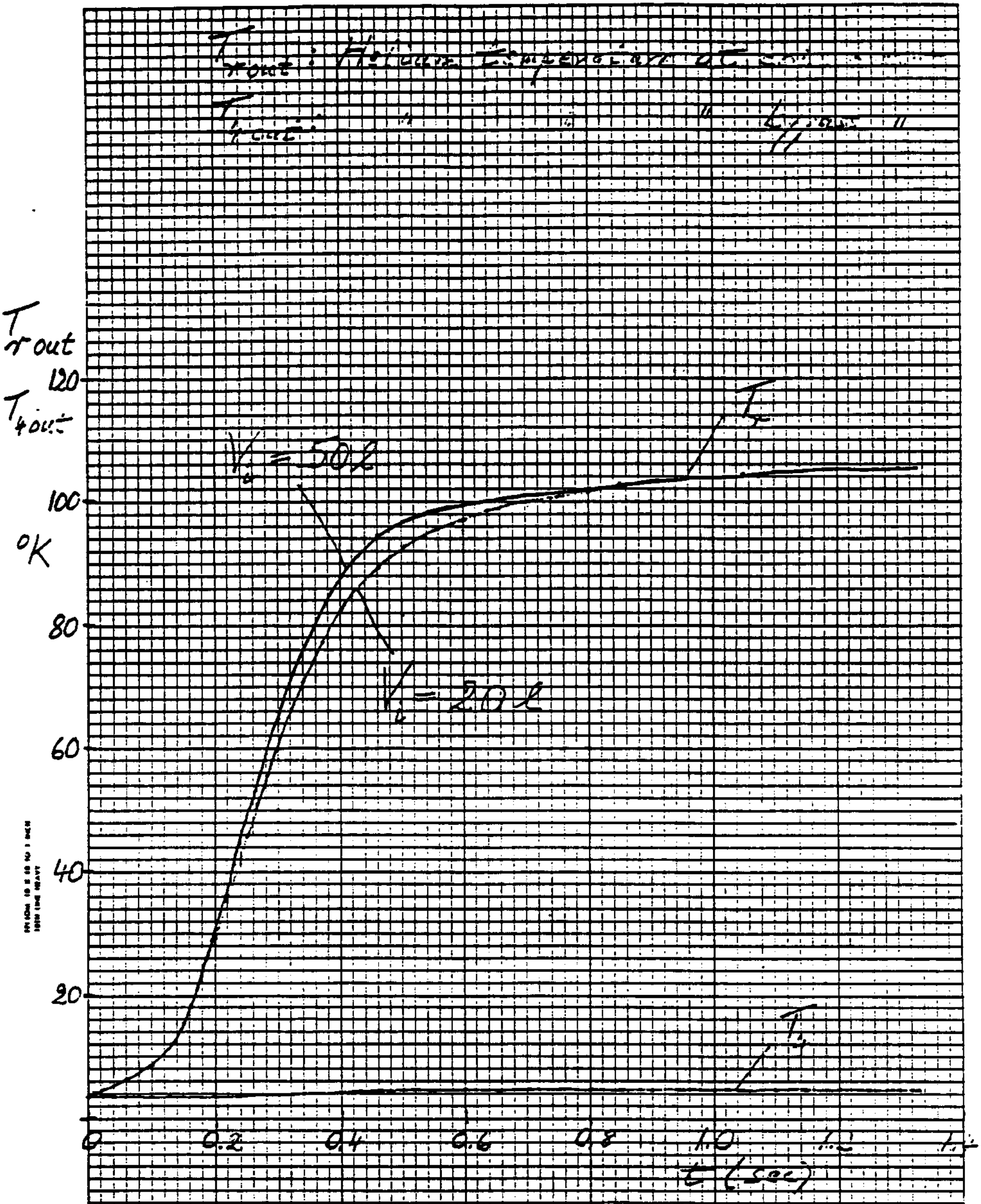

$T_{r\,out}$
$T_{4\,out}$
°K
120
100
80
60
40
20
0
0.2
0.4
0.6
0.8
1.0
$V_c = 50\ell$
$V_c = 20\ell$
t (sec)

Fig 3

these early calculations. Figure 1 shows the coil passage velocity as it builds up toward the magnet ends. In these calculations it was assumed that the stored energy is dissipated uniformly over the magnet. $V_i = 50$ liters was the volume in each of the ends of the helium vessel for these magnets. These volumes were closed (not vented) for the illustrations. Figure 2 shows the velocity build-up as a function of elapsed time at the ends of both the coil passage and the bypass in the yoke. The maximum velocity of almost 60 m/sec is substantial ($\sim$ 200 kilometers/hour). Sound velocities in helium in the temperature (and pressure) region of interest vary between 100 and about 500 m/sec. Figure 3 gives helium temperatures at ends of coil passage and bypass.

The above-mentioned dynamic calculations for the SSC magnets are now being attempted, especially since, because of their great length, large pressure differences may be encountered between magnet center and ends. However, in this Note we shall restrict ourselves to the simpler calculation in order to try better to understand the effects of the many parameters affecting helium pressures and temperatures during quenches. Special attention will be focused on the effect of the helium located in the cable cavities.

4. Heat Exchange in Cable Cavities

Since the cable strands are not insulated from each other, the helium in the cavities is thermally very closely coupled to the strands and therefore will turn out to be the most important contribution to the pressure in the magnet vessel after a quench. Unfortunately, there is a fair amount of uncertainty about how much of the helium can actually leave the cavities, by what route, and in what time. If the helium remained trapped, a very large pressure would have to be expected which is unlikely to be sustainable by the insulation around the cables. The Kapton insulation is overlap-wrapped around the cables which then are single-wrapped with B-stage-impregnated fiberglass-epoxy tape and cured to form the wound coils. The insulation faces the helium passage only at the inside of the inner coil. Here it passes around the inner cable edge with a "radius" of only 0.026". The total Kapton tape thickness is 0.002" (and the fiberglass-epoxy tape $\sim$ 0.003"). Assuming that most of the pressure is supported only by the Kapton, one would find a tensile stress of 19,000 psi per 100 atm pressure difference across the tape. The fiberglass epoxy-tape might, at least partially, act to seal the Kapton tape overlap. The ultimate tensile strength of Kapton tape is about 35,000 psi at cryogenic temperatures where the yield point is not far below the ultimate strength. Therefore the helium pressure that might be sustained could be still higher than 100 atm. Breakage of the insulation at the inner coil edges, that could have been due to large pressure differences, has apparently not been observed. One can conclude then that much of the helium from the cable cavities exits through the tape overlaps and through gaps and pores through the fiberglass-epoxy tape. Exiting of helium from the outer coil, however, is more inhibited because this coil is surrounded by multiple layers of Kapton and Teflon. Both inner and outer coils are rather well encapsulated at the ends by various supports.

The helium in the cavities can very probably flow quite freely along the cable strands although the strands run from cable edge to edge, and the inner edge has been highly compressed and deformed. The strands at the outer (thicker) edge, however, are rather loosely packed. If the helium could not flow along the cables, a locally occurring quench, resulting in very large ($\leq 800°K$) local temperatures could still result in very high local pressure even if most of the helium could escape through the insulation layer. Note that with increasing temperatures the Kapton loses its strength rapidly.

If a certain amount of pressure is sustained by the insulation during the stored energy dissipation time (quench time), this pressure would then be relieved by helium continuing to leak from the cables. Thus, without venting, the pressure rise in the helium vessel could continue after the quench time has passed.

The shape of the cross section of the cable cavities is very irregular. We can determine their average size from the initial (circular) strand size, the number of strands, and the final cable dimensions. Calling η the ratio of total cavity to total of strand cross sections in cable, we find for the total cavity cross section a_2 in the SSC two-layer coil

$$a_2 = 18\eta \tag{8}$$

For approximately circular cavity cross sections, the hydraulic radius ($\equiv 1/2$ actual radius) would be

$$r_h = 0.0195\eta^{1/2} \tag{9}$$

The total mass of helium in the coil cavities is

$$m = 2.45\eta\ell \tag{10}$$

if ℓ is the length of the magnet. The heat exchange area along the cavity walls is

$$A = 935\eta^{1/2}\ell \tag{11}$$

a relatively very large number because of the large number of small cavities. The actual value of η for our cables may be between 0.05 and 0.1.

For the heat exchange function we can, with good approximation, use the well-known expression

$$h = 0.023\frac{k}{4r_h}R^{0.8}P^{0.4} \tag{12}$$

where k = helium heat conductivity, R = Reynolds number

$$R = \frac{4r_h\rho v}{\mu} \tag{13}$$

with ρ = helium density, v = velocity, μ = viscosity. P is the Prandtl number ($= \frac{c_p\mu}{k}$, with c_p = helium heat capacity at constant pressure). An average for the velocity can be obtained by dividing the mass of helium actually leaving the cavities by a_2, ρ, and quench time Δt.

The heat transfer from coil to coil cooling passage is impeded by the cable insulation. A simple derivation here leads to the heat exchange function

$$h' = 1/\left(\frac{d}{k_p} + \frac{1}{h}\right) \tag{14}$$

where d = thickness of the insulation and k_p its temperature-dependent heat conductivity. We merely use k_p as a function of $\left(\frac{T_a+T_b}{2}\right)$ for an average, with T_a and T_b being the temperatures at the two sides of the insulation.

5. Quench Pressure Calculation for Unmixed State.

Call m_c the mass of the coil, T_c its temperature, and $c_c(T_c)$ its, at low temperatures, strongly temperature-dependent heat capacity. Call q the rate at which heat is generated in the coil, q_{he1} and q_{he2}, respectively, the rates at which heat is transferred to the helium in the coil cooling passage and to the helium flowing out of the cable cavities. Finally, K is the product of heat capacity times the mass of helium left in the cable cavities. Then, due to energy conservation:

$$(m_c c_c + K)\, dT_c + (q_{he1} + q_{he2})\, dt = q dt \tag{15}$$

where dt is a time element. Next, referring to eq. 2

$$m_1 (cv_1 dT_1 + \gamma p dv_1) = q_{he1} \tag{16}$$

$$g m_2 (cv_2 dT_2 + \gamma p dv_2) = q_{he2} \tag{17}$$

$$cv_3 dT_3 + \gamma p dv_3 = 0 \tag{18}$$

m_1, m_2, m_3 are the helium masses in coil passage, cable cavities and helium vessel end volumes, respectively, $T_{1,2,3}$ their temperatures, $v_{1,2,3}$ the density reciprocals, $cv_{1,2,3}$ the temperature-dependent heat capacities at constant volume, p the common pressure, and γ a dimension-converting constant. g is a fraction of m_2 determining the amount of helium leaving the cable cavities. Corresponding to eq. 1,

$$m_1 v_1 + g m_2 v_2 + m_3 v_3 = V = const. \tag{19}$$

V again referring to the helium vessel end volume (adding the substantial volume of the bypass holes through the iron). Thus

$$m_1 dv_1 + g m_2 dv_2 + m_3 dv_3 = 0 \tag{20}$$

We wish to determine T_c, T_1, T_2, T_3, and p. In order to eliminate v_1, v_2, v_3, we must know the equation of state for the helium. For this purpose we write

$$dv_{1,2,3} = \alpha_{1,2,3} dp + \beta_{1,2,3} dT_{1,2,3} \tag{21}$$

where

$$\alpha_{1,2,3} = -\frac{1}{\rho_{1,2,3}^2} \left(\frac{\partial \rho}{\partial p}\right)_{T_{1,2,3}} \tag{22}$$

$$\beta_{1,2,3} = -\frac{1}{\rho_{1,2,3}^2} \left(\frac{\partial \rho}{\partial T_{1,2,3}}\right)_p \tag{23}$$

The $\rho_{1,2,3} \equiv \frac{1}{v_{1,2,3}}$, again, are the helium densities. The $\alpha_{1,2,3}$ and $\beta_{1,2,3}$ are obtainable through the National Bureau of Standards program on Thermophysical

Properties of Helium, and thus eq. 21 will serve as the required equation of state. Applying eqs. 21, 22, 23 to eqs. 15 to 18, and 20, results in the five differential equations

$$\frac{dT_c}{dt} = \frac{q - q_{he1} - q_{he2}}{m_c c_c + K} \tag{24}$$

$$\frac{dT_1}{dt} = \left(q_{he1} - \theta_1 \frac{dp}{dt}\right) \frac{1}{\lambda_1} \tag{25}$$

$$\frac{dT_2}{dt} = \left(q_{he2} - \theta_2 \frac{dp}{dt}\right) \frac{1}{\lambda_2} \tag{26}$$

$$\frac{dT_3}{dt} = \left(-\theta_3 \frac{dp}{dt}\right) \frac{1}{\lambda_3} \tag{27}$$

$$\frac{dp}{dt} = \left(\frac{m_1 \beta_1 q_{he1}}{\lambda_1} + \frac{g m_2 \beta_2 q_{he2}}{\lambda_2}\right) \frac{1}{\xi} \tag{28}$$

where

$$\lambda_1 = m_1 (cv_1 + \gamma p \beta_1)$$
$$\lambda_2 = m_2 (cv_2 + g\gamma p \beta_2)$$
$$\lambda_3 = cv_3 + \gamma p \beta_3$$
$$\theta_1 = \alpha_1 m_1 \gamma p$$
$$\theta_2 = g \alpha_2 m_2 \gamma p$$
$$\theta_3 = \alpha_3 \gamma p$$

$$\xi = m_1 \beta_1 \frac{\theta_1}{\lambda_1} + g m_2 \beta_2 \frac{\theta_2}{\lambda_2} + m_3 \beta_3 \frac{\theta_3}{\lambda_3} - (m_1 \alpha_1 + g m_2 \alpha_2 + m_3 \alpha_3)$$

We summarize all definitions and input data:

$q = \frac{6511\ell}{\Delta t} f$ $Watt$ = average rate of heat generation in coil during "quench".

ℓ = coil length (can be varied).

Δt = quench time (can be varied).

f = parameter to vary stored energy ($0 \leq f \leq 1$) and, correspondingly, the amount of conductor: a magnet for lower or higher field. For f = 1, $\ell =$

1660 cm, $\Delta t = 0.3 sec$, q becomes $= 3.6 \times 10^6$ Watt. Corresponding stored energy is then 1.08×10^6 Joule as calculated by G. H. Morgan for the Design D magnets.

$q_{hc1} = h_1' A_1 (T_c - T_1)$ = rate of heat transfer from coil through insulation to helium in inner coil passage.

$h_1' = 1/\left(\frac{d}{k_p} + \frac{1}{h_1}\right)$

d = 0.02 cm = equivalent insulation thickness at inside of inner coil, taking into account some local build-up of epoxy during curing of the coil.

$k_p \approx 4.54 \times 10^{-5} (T_{av} + 11.4) (Watt/cm°K)$ for $T_{av} \leq 15°K$

$\approx 1.44 \times 10^{-5} (T_{av} + 68.5)$ for $T_{av} > 15°K$. Heat conductivity through insulation.

$T_{av} = (T_c + T_1)/2.$

T_c = coil temperature.

T_1 = helium temperature in coil passage.

$h_1 = 0.023 \frac{k_1}{4r_{h1}} R_1^{0.8} P_1^{0.4} (Watt/cm^2 °K)$, heat exchange function from insulation to (turbulent) helium flow in coil passage.

$k_1 = k(p, T_1)$ = heat conductivity of helium

p = helium pressure in magnet vessel.

$P_1 = P(p, T_1)$ = Prandtl number $\left(= \frac{c_{p1}\mu_1}{k_1}\right)$.

$r_{h1} = 0.064 cm$ = hydraulic radius of coil cooling passage (= one-half of gap width).

$R_1 = \frac{4r_{h1}m'}{\mu_1 e_1 \Delta t}$ = Reynolds number.

$m' = 0.45 m_1 \alpha\beta$ = effective helium mass leaving coil passage at one end: factor of 0.45 takes into account that helium can exit at both ends of coil and assumes that, as an average, only 90% of m_1 will leave coil passage.

$m_1 = 0.179\ell$ (gram) = helium mass initially in coil passage (at p = 4.5 atm and $T_1 = 4.4°K$).

α = fraction of 90% of m_1 and m_2 flowing through quenched region of coil passage during quench. $(0 \leq \alpha \leq 1)$.

β = fraction of magnet length actually quenched and therefore dissipating stored energy. $(0 < \beta \leq 1)$.

$a_1 = 1.31 cm^2$ = average cross section of coil passage.

$\mu_1 = \mu(p, T_1)$ = helium viscosity.

$A_1 = 10.7\ell\beta\,(cm^2)$ = heat exchange area of coil passage.

$q_{he2} = g h_2' A_2 (T_c - T_2)$ = rate of heat transfer from coil to helium in cable cavities.

$g\,(0 \leq g \leq 1)$ = fraction of helium in cavities actually passing through insulation assembly.

$h_2' = 0.023 \frac{k_2}{4r_{h2}} R_2^{0.8} p_2^{0.4}\,(Watt/cm^{2\circ}K)$ heat exchange function from coil to (turbulent) helium flow in cable cavities.

$k_2 = k(p, T_2)$.

$P_2 = P(p, T_2)$.

$r_{h2} = 0.0195\eta^{1/2}\,(cm)$ = average hydraulic radius of cable cavities (see above).

$R_2 = \frac{4r_{h2}m''}{\mu_2 a_2 \Delta t}$

η = fraction of insulated, assembled cable cross section consisting of cavities. Usually $\eta \leq 0.1$. $(0 < \eta < 1)$.

$m'' = 0.45 m_2 \alpha\beta$.

$m_2 = 2.45\eta\ell f\,(gram)$ = helium mass initially in cable cavities ($p = 4.5atm$, $T_2 = 4.4^\circ K$)

$a_2 = 18\eta f\,(cm^2)$

$\mu_2 = \mu(p, T_2)$

$A_2 = 935\ell\eta^{1/2} f\beta\,(cm^2)$ = total heat exchange area in all cable cavities.

$m_3 = 76\ell_3 + 3.63\ell$ = helium mass in bypasses through yoke ($3.63\ell = 6200gm$ for $\ell = 1660cm$) added to mass in end volume ($76\ell_3$).

ℓ_3 = length of end volume (to be varied), (ℓ_3 is to be two times one-half the length of the interconnection volume at each end of every magnet if one assumes that several magnets in a string quench essentially simultaneously, which is likely for active quench protection of, for instance, a complete half-cell. If only one magnet should quench, one can use two full interconnection lengths for ℓ_3).

$m_c = 123\ell f\beta$ = coil mass involved in quench
$(= 2.04 \times 10^5 gm$ for $\ell = 1660, f = \beta = 1)$

$c_c(T_c) \approx 9.27 \times 10^{-3} e^{(0.0407T_c)} - 1.001 \times 10^{-2}$ (Joule/gm° K) for $T_c \leq 80°K$.
$\approx 2.93 \times 10^{-4}(T_c - 80) + 0.2305$ for $T_c > 80$.
= heat capacity of cable material.

T_c = coil temperature

$K = (1 - g)\, m_2 cv_2$ = correction for helium remaining in cable cavities, to be added to $m_c c_c$.

$cv_{1,2,3} = cv\,(p, T_{1,2,3})$ = helium heat capacities at constant volume.

$\gamma = 0.1013$ joule/atm cm^3 = conversion factor.

$\alpha_{1,2,3}$, $\beta_{1,2,3}$: see eqs. 22, 23.

Of the parameters that have been defined above, we shall be able to vary

α for helium actually flowing through quenched region of coil cooling passage and cable cavities.

g for helium leaving cable cavities ($g = 0$: no helium leaves).

η for fraction of cable metal cross section consisting of cavities.

ℓ for length of magnet coil.

ℓ_3 for length of magnet end volume of helium containment vessel.

β for fraction of magnet length actually quenched.

f for changing magnet quench field, including modification of conductor quantity (lower or higher field magnet than SSC Design D).

Δt for quench duration.

Finally, we shall be interested in the total thermal energy carried off by the helium which exits from the coil:

$$Q_{he} = \int_0^{\Delta t} (q_{he1} + q_{he2})\, dt$$

Initial conditions for solving eqs. 24 to 28 for $T_{1,2,3,c}$ and p are here to be:

$$t = 0 : T_{1,2,3,c} = T_o = 4.4^\circ K$$
$$p = p_o = 4.5 atm$$

For g = 0 (all of helium in cable cavities remains trapped) one easily calculates the resulting pressure p_2. In this case the helium density must remain constant, namely equal to $\rho_o = \rho(T_o, p_o) = 1/v(T_o, p_o)$. Therefore eq. 21 becomes

$$\alpha_2 dp_2 + \beta_2 dT_2 = 0$$

or

$$p_2 = -\int_{T_o}^{T_c} \left(\frac{\beta_2}{\alpha_2}\right) dT_2 + p_o$$

Due to the very close thermal coupling confirmed by the results we shall set $T_2 = T_c$ for the present purposes. One can write

$$dp = \left(\frac{\partial p}{\partial T}\right)_\rho dT + \left(\frac{\partial p}{\partial \rho}\right)_T d\rho$$

For constant pressure it follows that

$$\left(\frac{\partial \rho}{\partial T}\right)_p = -\left(\frac{\partial p}{\partial T}\right)_\rho / \left(\frac{\partial p}{\partial \rho}\right)_T$$

Therefore

$$\frac{\beta_2}{\alpha_2} = \left(\frac{\partial \rho}{\partial T}\right)_p / \left(\frac{\partial \rho}{\partial p}\right)_T = -\left(\frac{\partial p}{\partial T}\right)_\rho$$

and

$$p_2 = \int_{T_o}^{T_c} \left(\frac{\partial p}{\partial T}\right)_{\rho=\rho_o} dT + p_o \tag{29}$$

Since $\left(\frac{\partial p}{\partial T}\right)_\rho$ is contained in the above-mentioned NBS program, the integral for p_2 can be calculated. For $g \neq 0$, a more complicated expression could be determined, but we have merely solved the equation

$$\rho(p, T_{cmax}) = \rho(p_o, T_o)$$

for p by using the NBS Tables on Thermophysical Properties of Helium.

6. Adding Vent Lines at Magnet Ends.

It will be shown below that, depending on how much of m_2, the helium in the cable cavities, actually flows into the coil passage, pressure could become unacceptably high. Therefore one must consider addition of vent valves which open when a magnet quench is sensed. These valves may have to be installed at the ends of every dipole or perhaps less frequently, depending on the dynamics of the helium flow through the magnet passages. One will have to take into account that the opening time for a vent valve cannot be zero.

Assume that from the two magnet end volumes ($2 \times \frac{1}{2}$ interconnection), added to the total bypass line volume, a mass flow M_V exits through valves into a (large) vent volume. Then we can write

$$M_V = -\frac{dm_3}{dt} \tag{30}$$

so that the remaining helium mass $m_3(t)$ is

$$m_3(t) = m_3(0) - \int_0^t M_V(t)\, dt \tag{31}$$

Equation 19 is still valid, but instead of eq. 20 we have

$$m_1 dv_1 + g m_2 dv_2 + d(m_3 v_3) = 0 \tag{32}$$

Therefore now

$$\sum_{\nu=1}^{3} g_\nu m_\nu (\alpha_\nu dp + \beta_\nu dT_\nu) = \frac{M_V}{\rho_3} dt \tag{33}$$

instead of zero. $g_\nu = 1$ for $\nu = 1$ and 3 and varied ($\equiv g$) for $\nu = 2$. M_V is determined by the vent valve aperture $2r_V$ and the available pressure difference for which we can write

$$p - p_V = 10^{-6}\left[\left(0.0014 + \frac{0.125}{R_V^{0.32}}\right)\frac{M_V^2 \ell_V}{r_V \rho_{aV} a_V^2} + n\frac{M_V^2}{2\rho_3 a_V^2}\right] \tag{34}$$

where p_V = vent volume pressure, assumed to vary slowly.

$a_V = \pi r_V^2$,

ℓ_V = length of vent line.

R_V = Reynolds number = $\frac{2r_V M_V}{\mu a_V}$ (where μ = viscosity).

ρ_{aV} = average density of helium in vent line.

n = number of velocity heads across valve and in connection of length ℓ_V to vent volume.

The term containing R_V varies very slowly with M_V. Some further estimating then leads to

$$M_V = 10^3 a_V \left[(p - p_V)\, \rho_3 \;/\; \left(6 \times 10^{-3} \ell_V / r_V + n\right)\right]^{1/2} \tag{35}$$

The first term in the denominator, with reasonable assumptions for ℓ_V and r_V, is $< n$ which can be taken as $n = 2$.

Finally, to take venting into account with sufficient approximation, it follows from eqs. 28, 33 and 35 that now

$$\frac{dp}{dt} = \left(\frac{m_1 \beta_1 q_{he1}}{\lambda_1} + \frac{g m_2 \beta_2 q_{he2}}{\lambda_2} - jw\,(p - p_V)^{1/2}\right) \frac{1}{\xi} \tag{36}$$

$$w = 10^3 a_V \left(\rho_3 \left(6 \times 10^{-3} \ell_V / r_V + n\right)^{-1}\right)^{1/2}$$

j = 0 before venting starts and =1 when it begins; if t_j is the time at which the vent valve opens: j=0 for $t \le t_j$ and j=1 for $t > t_j$. If t_j equals the quench duration time Δt, no venting occurs during this time.

7. Quench Pressure Calculation for Mixed State.

The derivations so far refer to the unmixed state of $m_{1,2,3}$. In Section 2 it was shown that for ideal gases there would be no difference between the pressures of unmixed and mixed states. It was also stated that at temperatures or pressures where the ideal gas law does not apply pressures for these states cannot be expected to be equal. It is unlikely that, during the short quench time, the helium masses m_1, m_2, and m_3 will mix. However, since any possible degree of mixing and therefore its effect on the pressure cannot be predicted with certainty, we should calculate the fully "mixed pressure" in order to (1) establish whether it could exceed the "unmixed pressure" and (2) establish a range of uncertainty.

Assuming no venting, we are dealing with constant density of the mixed gases, and therefore

$$\rho\,(p_m, T_m) = \rho\,(p_o, T_o) = \frac{m_1 + m_2 + m_3}{V} \tag{37}$$

where p_o, T_o are the given initial (t=0) values for pressure and temperature and p_m, T_m those for the mixed state. With venting one would have to specify whether only a fraction of the gas originally in the interconnection volume (and bypass volume) escapes or whether the mixture of m_1, m_2, and m_3 escapes. Assuming that only a part of m_3 is vented (likely because m_3 represents most of the helium in the magnet enclosure), leaving mass m_3' for mixing, we must write

$$\rho\,(p_m, T_m) = \frac{m_1 + m_2 + m_3'}{V} \tag{38}$$

The total internal energy is constant during the mixing process since the total volume is constant. Therefore, as in eq. 3,

$$U\,(p_m, T_m) = \frac{m_1 U\,(p, T_1) + g m_2 U\,(p, T_2) + m_3' U\,(p, T_3)}{m_1 + g m_2 + m_3'} \tag{39}$$

where p was the pressure found for the unmixed states. Since p, T_1, T_2, T_3, and m_3' are now known for the unmixed state from the calculations in Sections 5 and 6, eqs. 38 and 39 can be solved for p_m and T_m. If the "equation of state" for helium, namely the mentioned NBS program, lists only the enthalpy $H\,(p, T)$, then, by definition, U is replaced by the expression $H - \gamma p/\rho$.

Solution of eqs. 38 and 39 can be obtained by "trial and error" in a computer or, more systematically, by expressing eqs. 38 and 39 in the form

$$d\rho = 0 \tag{38a}$$

$$dU = 0 \tag{39a}$$

Then, by again introducing expressions for partial derivatives of ρ with respect to T and p, as in eqs. 22/23, and similar ones for the partial derivatives of U, one can obtain two first order differential equations for dT/dp, one corresponding to eq. 38a and the other to eq. 39a. Solution of these equations would result in two functions $T\,(p)$ which will intersect at the point p_m, T_m. In more detail,

$$\frac{dT}{dp} = -\frac{\alpha\,(p, T)}{\beta\,(p, T)} \tag{40}$$

from eq. 38a. Initial condition: p = "unmixed" pressure, T = temperature found from eq. 38, setting $p_m = p$.

From eq. 39a:

$$\frac{dT}{dp} = \frac{\gamma T \beta\,(p, T)}{c_p\,(p, T)\,\rho\,(p, T)} \tag{41}$$

Here c_p is the specific heat of helium at constant pressure. Initial condition: p = "unmixed" pressure, $T = T_m$ found by means of eq. 39, setting $p_m = p$.

8. Pressure Drop Along Coil Passage.

In addition to the general pressure build-up during a quench there is an additional pressure increase around the beam tube - trim coil assembly which is largest at the center of the magnet for a symmetrical quench. This pressure increase is required to force m_1 and gm_2 along the coil passage. Referring to equations of the type of eq. 34, pressure gradients along pipes are approximately

$$\frac{dp_c}{dx} \sim M^2$$

where p_c is the pressure along the coil passage. The later calculations show that for most of the time during a quench the pressure in the cable cavities is much greater than that in the coil passage. Therefore, referring to equations of the form eq. 35, the flow of helium from the coil cavities is distributed approximately uniformly over the quenched region, say, at the rate of μ_1 (g/sec cm). The flow along the coil passage also receives heat from the coil through the insulation which also results in a gradual acceleration. We will then set

$$\frac{dM}{dx} = \mu_1 \approx \ const \tag{42}$$

and

$$\frac{dp_c}{dx} = -kM^2 \tag{43}$$

where $k \approx const$. At the axial center of the magnet (x = 0), M ≈ 0 during a quench (symmetry assumed here). Therefore also $dp_c/dx = 0$ at x = 0. At x = $\ell/2$, at magnet ends, we use $p_c = p$, the pressure found from eq. 28.

We obtain

$$p_c = p + \frac{k\mu_1^2\ell^3}{24}\left(1 - 8x^3/\ell^3\right) \tag{44}$$

and for x = 0

$$p_{cmax} = p + \frac{k\mu_1^2\ell^3}{24} \tag{45}$$

$\frac{\mu_1\ell}{2}$ is the total flow exiting from the coil cavities $\left(0 \le x \le \frac{\ell}{2}\right)$ plus the total accelerating flow of the helium originally in the coil passage: $\mu_1\ell \approx 0.9m_1 + gm_2$. Therefore

$$p_{cmax} \approx p + k\left(0.9m_1 + gm_2\right)^2 \ell/24 \tag{46}$$

which allows one to estimate p_{cmax} from the results found from eqs. 24 to 28. Note that the total pressure drop along the coil passage is proportional to ℓ^3 (pressure gradient $\sim \ell^2$). If all of $\mu_1 \ell$ originated near the center of the magnet, one would find

$$p_{cmax} = p + k\,(m_1 + gm_2)^2\,\ell/8$$

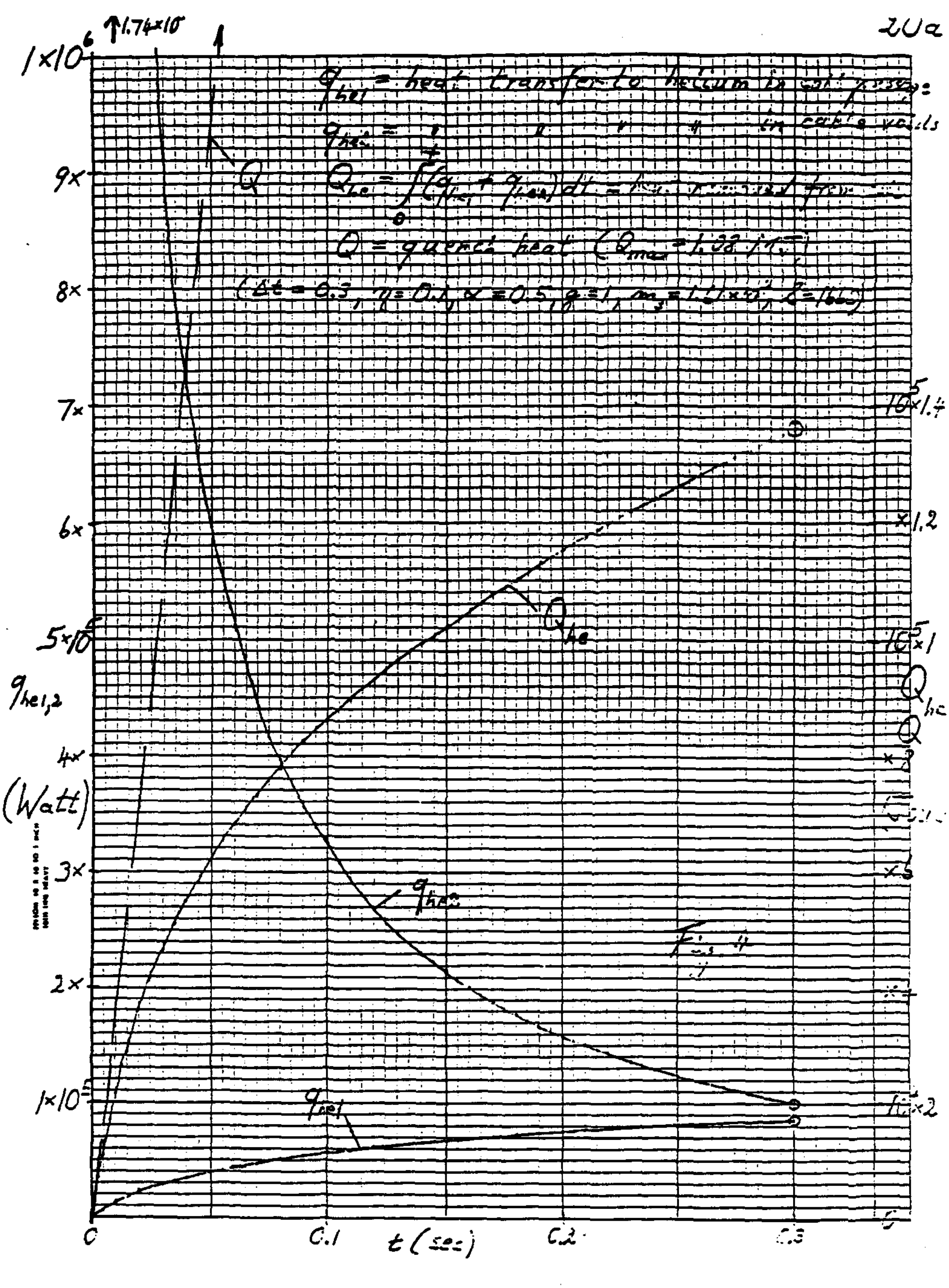
or 3 times the pressure drop for the case with distributed m_2. However, this comparison is not particularly valid since, for a quench concentrated near the magnet center, the resulting temperature distribution along the coil would be quite different. Equation 46 will suffice for an estimate of the maximum pressure build-up around the beam tube during a uniformly distributed magnet quench. The mentioned "dynamic calculation" will contain the properly calculated distribution of the pressure along the tube.

9. Results.

We proceed to discuss computer results making use of the parameters α, g, η, Δt, β, t_j, ℓ, ℓ_3, r_V and f defined in Sections 5 and 6.

The computer program was arranged and operated by Kurt Jellett to whom the author is very highly indebted.

Prior to presenting a number of Tables, varying essentially only one parameter at a time, we present 3 figures. Figure 4 shows the heat Q generated in the coil during a quench as a function of time t. Quench duration $\Delta t = 0.3$ sec. Coil cavity fraction $\eta = 0.1$, parameter for helium contact with quenched region $\alpha = 0.5$, fraction of helium exiting from coil cavities g = 1, helium mass in magnet bypasses and end volumes $m_3 = 1.61 \times 10^4 g$ magnet length $\ell = 1660 cm$. Plotted, as functions of t, are the heat q_{hc1} transferred through the cable insulation to the helium in the coil passage, q_{hc2} transferred to the helium in the coil cavities, and Q_{hc} = the sum of q_{hc1} and q_{hc2} integrated over t, or the total amount of heat removed from the coil. The heat (per second), q_{hc2}, transferred to helium in the coil cavities is large at small t because T_c increases fast for small t (see fig. 6), the heat transfer area is very large and the helium is not insulated from the conductor surfaces. q_{hc1} starts at small values because the heat transfer area is much smaller and there is insulation around the cables. The total heat Q_{hc} removed by the helium during the quench in this case



↑1.74×10
1×10^6
9×
8×
7×
6×
5×10^5
4×
3×
2×
1×10^5
q_he1,2
(Watt)
q_he1 = heat transfer to helium in
q_he2 = in cable voids
Q
Q = quench heat
Q_he
q_he2
q_he1
10^5×1.4
×1.2
10^5×1
Q_he
Q
10^5×2
0
0.1
t (sec)
0.2
0.3

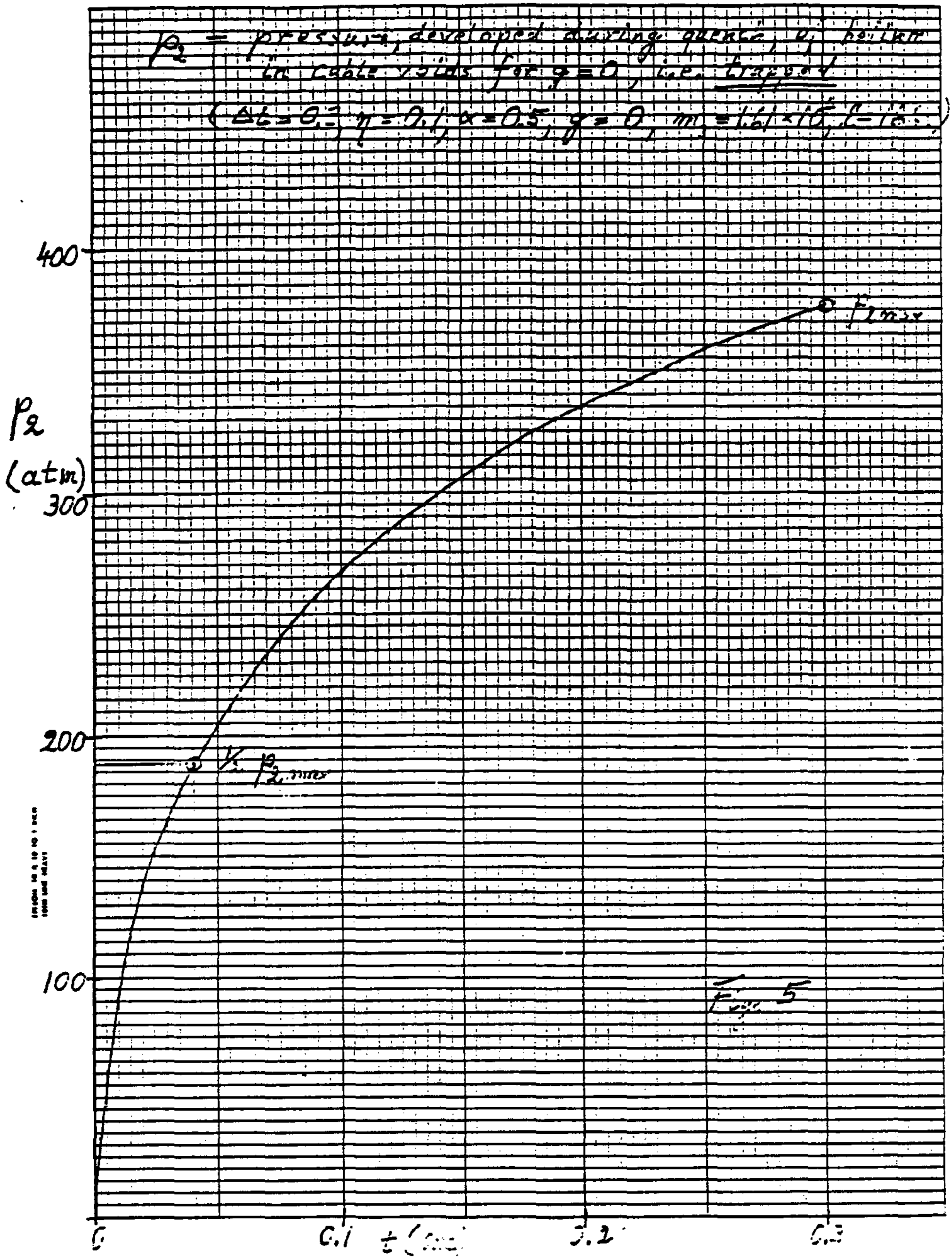
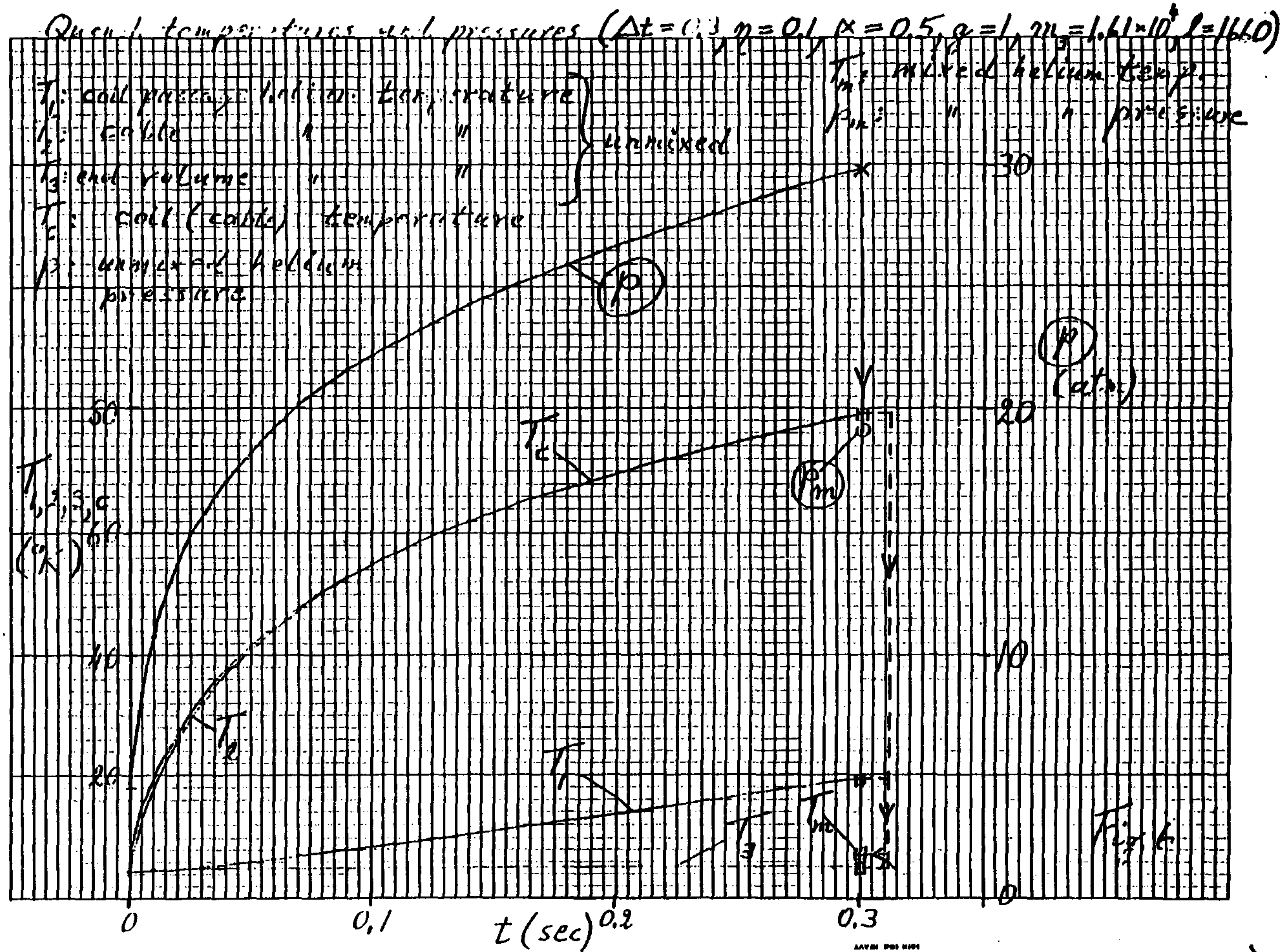

p_2 = pressure developed during quench of helium in cable voids for $q = 0$, i.e. trapped
($\eta = 0.1$, $\alpha = 0.5$, $q = 0$,
p_2
(atm)
400
300
200
100
$\frac{1}{2}\,p_{2,max}$
$p_{2,max}$
0
0.1
0.2
0.3
t (sec)

Fig. 5

20c


Quench temperatures and pressures ($\Delta t = 0.3$, $\eta = 0.1$, $\alpha = 0.5$, $a = 1$, $m_3 = 1.61 \times 10^4$, $l = 1660$)
T_1: coil passage helium temperature
T_2: cable " "
T_3: end volume " "
unmixed
T_c: coil (cable) temperature
p: unmixed helium pressure
T_m: mixed helium temp.
p_m: " " pressure
$T_{1,2,3,c}$ (°K)
p (atm)
t (sec)
0
0.1
0.2
0.3
20
40
60
80
10
30
p
p_m
T_c
T_1
T_2
T_3
T_m
Fig 6

amounts to only $\sim 13\%$ of Q at $t = 0.3$ sec. Q_{hs} rises very fast for $t < 0.05$ sec to almost half its value at $t = 0.3$ sec.

Figure 5 shows the pressure p_2 that would be reached in the coil cavities if the helium could not escape ($q = 0$). This pressure reaches half its final value at 0.3 sec in only 0.04 sec. The final pressure of $\sim 375 atm$ probably would burst the cable insulation, at least inward, towards the coil passage. This has never been observed. One can estimate that the exposed insulation at the edges of the cables could sustain a p_2 of about $100 atm$. Therefore a major fraction of the helium must be able to leak out from the cavities, through Kapton tape overlaps and through a multitude of small pores and cracks in the epoxy bonding.

Figure 6, again for the same parameters, shows T_1, T_2, T_3, and T_c, as well as pressure p. p rises extremely fast, in 0.025 sec, from its original value of 4.5 atm to half of its value of 30 atm at t = 0.3. Half of the pressure difference between 30 and 4.5 is reached in 0.04 sec. The coil temperature T_c reaches a maximum value of 80° K at the end of the quench. T_2, the helium temperature in the cable cavities deviates by at most 1° K from T_c up to 0.08 sec and then is essentially equal to T_c. The helium temperature T_1 in the coil passage (m_1) reaches 19° K, and the end volume temperature (m_3, unmixed) rises to $\sim 5.3°$ K. Mixing $(m_1 + gm_2)$ and m_3 would result in $p_m = 19$ atm and $T_m = 7°$ K. But it is very unlikely that much mixing can occur in the short time available. It is of interest that for all cases considered one obtains a value of about 10 atm for the difference $p - p_m$ between unmixed and mixed states at the low temperatures considered here, somewhat less at lower p and more at the higher p.

In Table I we vary g for the unvented ($t_j = \Delta t = 0.3$, $\Delta t =$ quench duration) and a vented case with $t_j = 0.1$ sec for the opening time of the vent valve. The aperture of the valve is $2r_V = 2.5$ cm. The magnet length is $\ell = 1660$cm and interconnection length is $\ell_3 = 90$ cm (this length has more recently been decreased, but the helium bypasses add a large amount of volume, so that the exact length ℓ_3 used for these calculations is not particularly important). We tabulate maximum pressures p_{max} and p_{mmax}, maximum coil temperature, and maximum mixed temperature. In this Table we also give p_{2max} for the maximum pressure in the coil cavities.

Table I

α	g	η	β	Δt (sec)	t_j (sec)	p_{max} (atm)	p_{mmax} (atm)	T_{cmax} (°K)	T_{mmax} (°K)	p_{2max} (atm)
0.5	0	0.07	0.3	0.3	0.3	8.3	5.4	128	4.6	374
	0.3					17.2	9.5	122	5.4	215
	0.5					23.3	13.4	122	6.2	135
	0.7					28.5	17.4	123	7.0	74
	1					35.7	23.3	124	8.2	36
0.5	0	0.07	0.3	0.3	0.1	6.7	3.4	128	4.5	-
	0.3					13.4	5.4	122	5.1	-
	0.5					17.9	7.8	122	5.8	-
	0.7					21.8	10.5	122	6.6	-
	1					27.1	14.7	123	7.7	-

$\beta = 0.3$ was chosen for the fraction of the length of the magnet that is quenched (passive quench protection). For $\beta = 1$ (active q.p.) we obtain about 3 atmospheres less without venting, for $\eta = 0.07$. Venting decreases p_{max} by substantial amounts but not as much as one might have expected for the assumed rather large aperture valves venting every interconnection. Varying g affects p_{max} considerably. As a matter of fact, the helium vessel design pressure of 20 atm is exceeded between g = 0.3 and 0.4. Almost 36 atm can be reached for p_{max} if g = 1 without venting, and still 27.1 atm with venting. p_{2max} decreases fast with increasing g. In order to obtain $p_{2max} < 100$ atm, $g \approx 0.6$ is required.

In the next Table we shall vary coil cavity size fraction η.

Table II

α	g	η	β	Δt	t_j	p_{max}	p_{mmax}	T_{cmax}	T_{mmax}
0.5	0.5	0.05	0.3	0.3	0.3	20.0	11.2	125	5.8
		0.07				23.3	13.4	122	6.2
		0.10				27.5	16.6	118	6.9
		0.05			0.1	15.4	6.3	125	5.4
		0.07				17.9	7.8	122	5.8
		0.10				21.1	10.0	118	6.4

One sees that, as expected, p_{max} increases with increasing η, but the dependence is not very strong.

Varying quench length ratio β, we obtain the following Table.

Table III

α	g	η	β	Δt	t_j	p_{max}	p_{mmax}	T_{cmax}	T_{mmax}
0.5	0.5	0.07	0.1	0.3	0.3	23.8	13.6	227	6.3
			0.3			23.3	13.4	122	6.2
			1			20.6	11.8	79	5.9
			0.1		0.1	18.5	8.2	227	5.9
			0.3			17.9	7.8	122	5.8
			1			15.9	6.7	79	5.5

While coil temperature T_{cmax} varies considerably with β, p_{mmax} varies quite slowly: higher coil temperature, but shorter quenched length, same stored energy deposited.

In Table IV we shall vary α which determines the amount of helium flowing through the quenched region (see the definitions given above).

Table IV

α	g	η	β	Δt	t_j	p_{max}	p_{mmax}	T_{cmax}	T_{mmax}
0.2	0.5	0.07	0.3	0.3	0.3	22.4	12.8	123	6.1
1						23.6	13.7	122	6.3
0.2					0.1	17.2	7.4	122	5.7
1						18.1	7.9	121	5.9

Somewhat surprisingly dependences on α over the given large range are very slight. Reason: less flow of helium can result in higher helium temperature and therefore higher pressure, as was confirmed in the detailed computer output.

In Table V we vary the quench duration Δt.

Table V

α	g	η	β	Δt	t_j	p_{max}	p_{mmax}	T_{cmax}	T_{mmax}
0.5	0.5	0.07	0.3	0.3	0.3	23.3	13.4	122	6.2
				0.6		16.8	6.5	121	5.8
				0.3	0.1	17.9	7.8	122	5.8
				0.6		14.5	4.6	121	5.6
0.5	0.7	0.07	0.3	0.3	0.3	28.5	17.4	123	7.0
				0.6	0.6	29.7	18.5	122	7.3

For the case with $\Delta t = 0.6$, but $t_j = 0.3$, the vent valve is open for $0.3 \leq t \leq 0.6$, while for $\Delta t = 0.3$, $t_j = 0.3$, it is closed. Two cases for $t_j = \Delta t$ (no venting) are given in the last rows of Table V, although here $g = 0.7$. It is seen that p_{max} depends very little on Δt without venting.

Although no very strong dependences on the parameters have been found so far, we wish to present an extreme, although unlikely case, just to illustrate that the pressure could become very high.

Table VI

α	g	η	β	Δt	t_j	p_{max}	p_{mmax}	T_{emax}	T_{mmax}
0.5	1	0.1	0.1	0.3	0.3	59.3	42.5	216	11.9
					0.1	43.9	28.8	213	11.4

Here even p_{mmax} becomes quite large for the unvented case.

Finally, in Table VII, we have varied the magnet length ℓ, the stored energy represented by fraction f, and the valve aperture $2r_V$.

Table VII

α	g	η	β	Δt	t_j	ℓ	$2r_V$	f	p_{max}	p_{mmax}
0.5	0.5	0.07	1	0.3	0.3	1660	2.5	1	20.6	11.8
						830			16.3	8.8
						1660		0.5	16.1	8.9
					0.1	1660	2.5	1	15.9	6.7
							5.0		9.7	4.3

In these calculations, halving the magnet length has about the same effect as halving the stored energy (lower field or single layer coil), and doubling the vent aperture certainly lowers the pressure but not by as much as one might expect from quadrupling the valve cross section.

In most cases discussed here p_{max} exceeds the 20 atm design pressure if no venting is provided, and even by installing a rather large aperture (2.5 cm dia) vent valve 20 atm is exceeded in some cases. The beam tube is exposed to an even larger helium pressure due to the pressure drop along the coil passage. From Section 8 we have estimated that this pressure drop can be at least 25 atm ($\sim \ell^3$!) but could be much higher depending on the details of the mass flow in the coil passage. Assuming now that by means of proper venting one has limited the pressure in the interconnection and bypasses to the design pressure of 20 atm, by adding the mentioned pressure drop, the beam tube could be exposed to a maximum external pressure of >45 atm. Resulting effects on the beam tube wall must be combined with effects due to the large eddy currents induced in the beam tube copper plating during a quench.

Simple addition of the calculated overall pressure p_{max} to the pressure drop in the coil passage is probably oversimplified. In fact, indications from early results of a dynamic calculation employing partial differential equations with independent variables for time and location show that pressures in the interconnections tend to be lower than calculated here, but pressure drops in the coil passage higher, so that the maximum pressure on the beam tube remains high. It is also indicated that, even without venting, all pressures can be reduced drastically by providing leakage paths between coil passage and bypasses, enabling a fraction of the warm helium $(m_1 + gm_2)$ to mix with the helium in the bypasses and for the mixture to deposit some of the heat in the yoke iron. These results will be discussed in later Notes. Generally, the simplified calculations discussed here appear to result in plausible estimates. However, the results of these estimates seemed to justify the more extensive effort to undertake the above-mentioned new calculations.

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