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PRESSURE CALCULATIONS FOR THE CRYOSTAT OF THE MILAN SUPERCONDUCTING CYCLOTRON

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ABSTRACT

In this paper we investigate the pressure behaviour in the cryostat following a quench of the superconducting coils. The main assumptions used in the calculations and the results relevant to the Milan Superconducting Cyclotron are discussed. The aim is to evaluate the helium discharge conditions so as to ensure the cryostat safety at all times. The typical pressure value reached in the cryostat for a quench of the whole coils, is about four bar absolute.

1. - COILS AND CRYOSTAT DESCRIPTION

A detailed description of the coils and the cryostat of the Milan Superconducting Cyclotron can be found elsewhere(1, 2). In this paragraph we describe briefly their structure, their most important parameters being listed in Table I.

The coils are wound with the double pancake technique and operate in a liquid helium bath at 4.2-4.3 °K and at nearly atmospheric pressure. They are wetted by liquid helium by means of vertical channels (0.35×5 mm^2 section and 13 mm height) and horizontal channels (20×165 mm^2 section and 1 mm height) as shown in Fig. 1.

The cryostat is cylindrical and consists of two parts essentially symmetrical with respect to the median plane of the cyclotron. The two parts, hereby called lower and upper vessel, are separated by a thick (120 mm) plate. A section of the upper vessel is shown in Fig. 2. Helium passage between the two parts is assured

TABLE I

Maximum magnetic field	4.8 T
Maximum stored energy	38 MJ
Maximum M.M.F.	6.5×10^6 A turns
Maximum current	1944 A
Superconducting insert	NbTi (46%)
Critical temperature (5T, 2000A)	4.9 °K
Cable	ETP copper (2% cold work)
Matrix dimension	13×3.5 mm^2
Overall Cu/NbTi	20 : 1
Total conductor length	22700 m
Internal coils radius	1000 mm
External coils radius	1165 mm
Internal helium vessel radius	969 mm
External helium vessel radius	1238 mm
Coils height	2 x 620 mm
Helium vessel height - upper	715 mm
- lower	700 mm
Maximum allowed pressure in the cryostat	7 bar absolute

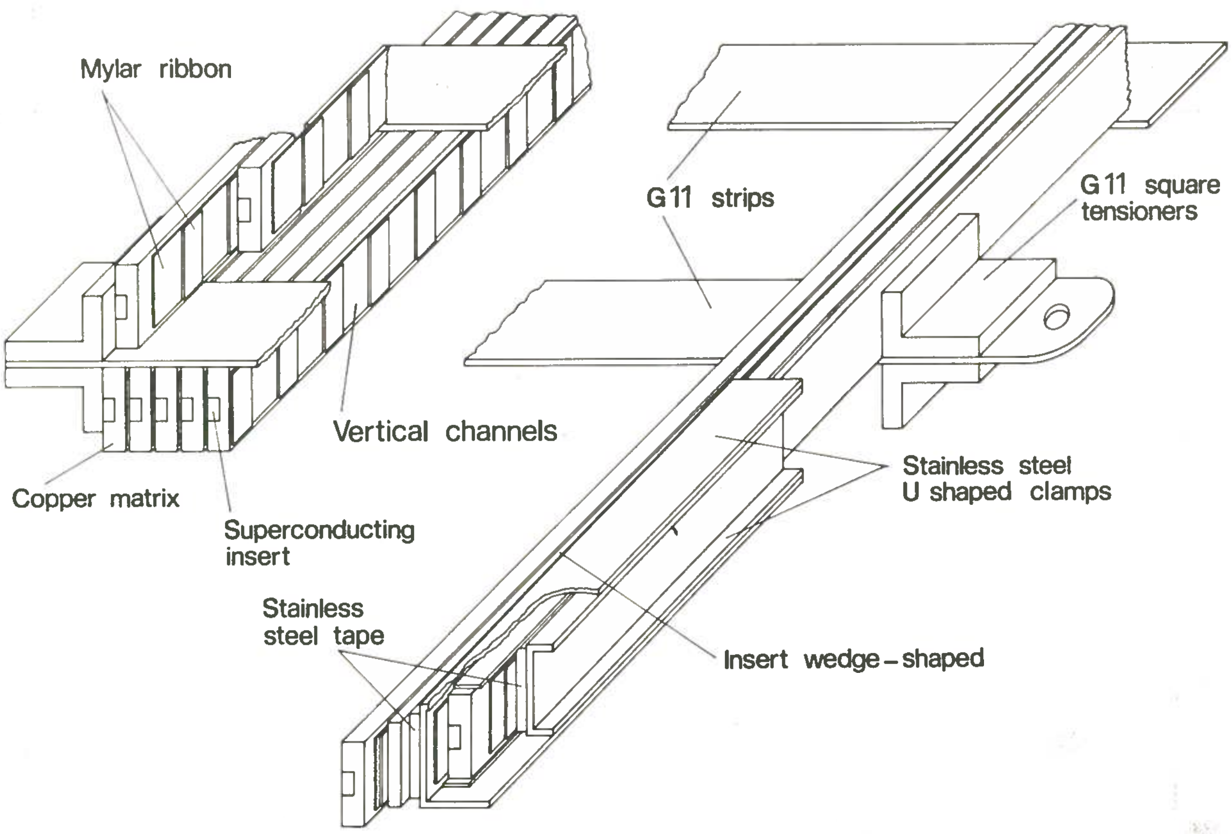

FIG. 1 - A sketch of the double pancake structure.

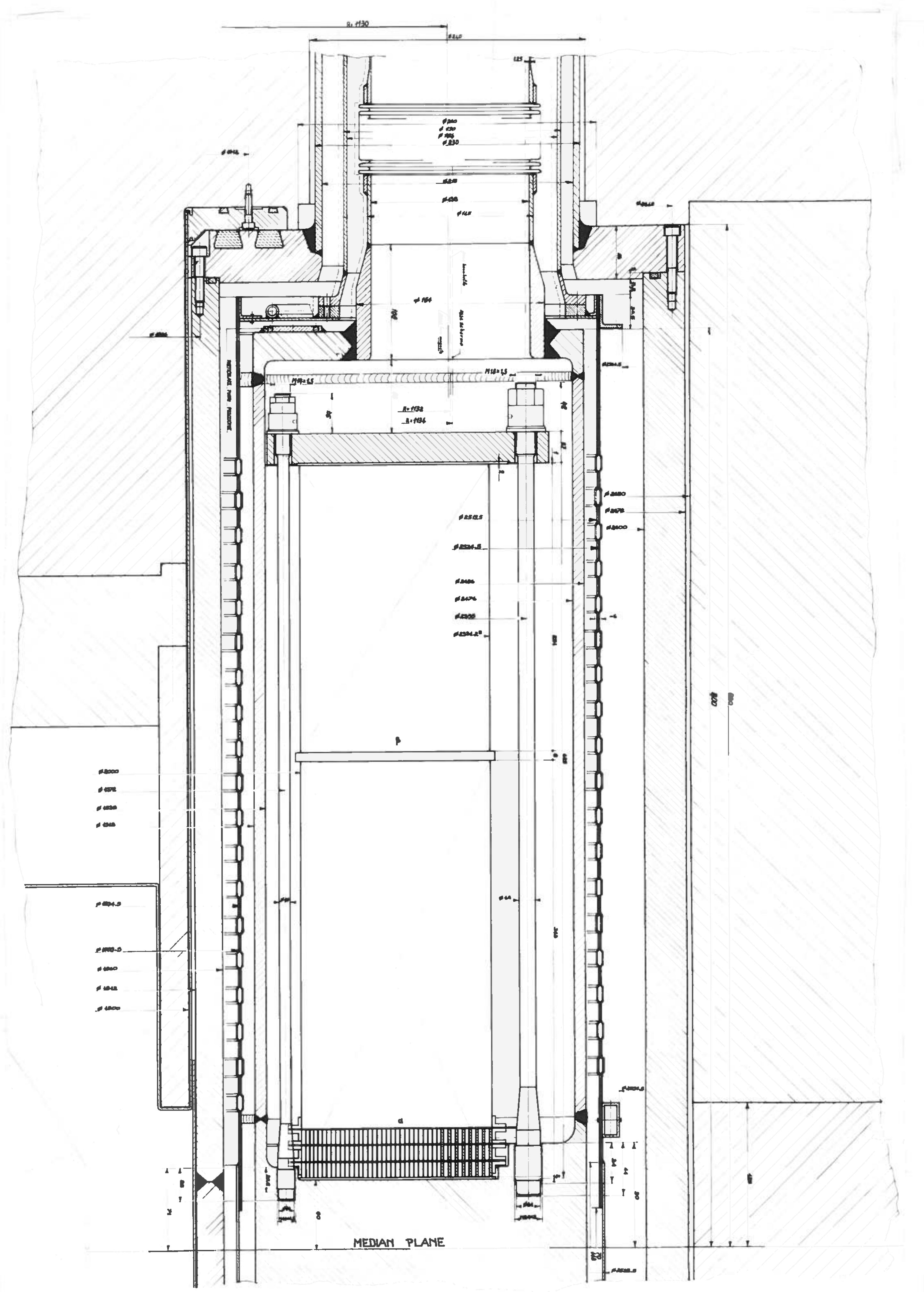

FIG. 2 - Coils and cryostat section.

through holes drilled in the midplane plate; the number of these holes, which may not be too high for geometrical constraints, has been studied with some accuracy in this work.

The cryostat, as shown in Fig. 2, is equipped with exit necks, which are used for various functions. A discharge valve is provided for the helium exit from the vessel. Also one or two rupture disks, which must assure the cryostat safety at all times, are provided.

2. - THERMODYNAMICAL BEHAVIOUR OF THE HELIUM

Under normal operating conditions, the helium is a saturated liquid at about 1050 mbar ($T = 4.26\ ^{o}K$), with a small amount of vapour on the top of the upper vessel. A perturbation in the coils, e. g. a mechanical movement, may cause a localized heating of the cable. Consequently a localized transition (quench) of the superconductor to the normal resistive state may occur. Eventually the superconductor recovers and goes back to the superconducting state but only if the energy involved in the perturbation is below the cryogenic stability limits. On the contrary, if the relevant energy passes these limits, the quench will spread and a large fraction of the coils, or its totality, may undergo the transition to the resistive state. Under these circumstances a large amount of Joule energy is transferred to the helium bath, causing a rapid passage of helium to the gas phase and therefore a large increase of the cryostat pressure.

The limiting pressure which can be reached in such an occurrence must be known with some accuracy, given the obvious danger for the cryostat structure. For this reason we have studied in some detail the case of a quench of the whole coils, this being the most pessimistic and most important case to insure the safety of the cryostat.

We assume that the helium is at uniform temperature and pressure in each vessel. Since any localized overheating of the helium with respect to the bulk is neglected, we assume that the energy transferred by the coils is uniformly distributed in the helium bath. Such an assumption may not be very realistic but should be regarded as a conservative one for the purpose of calculating the maximum pressure. This because the energy transfer from the coils to the helium bath, which determines the pressure in the cryostat, is greater than the actual one. Moreover, under this hypothesis we can study the helium bath as a simple thermodynamical system described by the following equation:

$$\frac{d}{dt}\, m(t)\, u(t) = W(t) + h(t)\, \frac{d}{dt}\, m(t) \quad ,$$

where:

t	is the time;
$m(t)$	is the helium mass contained at the time t in the vessel;
$u(t)$	is the specific internal energy of the helium;
$h(t)$	is the specific enthalpy of the helium;
$W(t)$	is the power transferred by the coils.

This equation, derived from the energy conservation principle, means that the increment of the helium internal energy, and therefore of its temperature, results from the balance between two opposite terms. The first one is the positive term $W(t)$, the other is the negative term $h\, dm/dt$ which represents the power lost via the helium outflowing from the helium vessel.

Actually this is true for the lower vessel only, because for the upper vessel the helium inlet from the lower one must be taken in account. So we obtain the following equations describing the helium behaviour at the time t:

lower vessel $$\frac{d}{dt} m_1 u_1 = W_1 + h_1 \frac{d}{dt} m_1$$

upper vessel $$\frac{d}{dt} m_2 u_2 = W_2 + h_2 \frac{d}{dt} m - h_1 \frac{d}{dt} m_1$$

where the subscript 1 refers to the lower vessel and 2 to the upper one. The term $m(t) = m_1(t) + m_2(t)$ represents the helium mass in the cryostat and so dm/dt is the rate of the mass escape from the cryostat.

The terms appearing in the previous equations depend on the helium temperature and density, which determine the helium state, and on the matrix temperature, which determine (together with the helium state) the power input W into the bath. Thus we need to write two other equations for each vessel. One equation, for computing the helium density, requires the calculation of the rate of the helium escape as shown in the next paragraph. The other equation, in order to know the matrix temperature, is given by the balance between the Joule power and the power transferred to the bath.

3. - TREATMENT OF THE HELIUM OUTFLOW

The helium flows out of the cryostat through the necks, which carry the valve and rupture disks, and acquires velocity by the expansion process. To compute the exit mass rate we assume that the helium flow is steady and the expansion is adiabatic. These assumptions neglect the initial moments of the helium outflow from the cryostat, when the warm vapours in the neck start to flow out and when the neck begins to be cooled by the expanding fluid. To take the transient outflow somehow into account, we consider in the calculation a delay time in the valve opening larger than the actual one. This delay time is fixed at 0.5 seconds (a delay time of one second was also tried and did not seriously affect the pressure value).

Indicating with h the helium specific enthalpy and with c the flow velocity at any section of the neck, by previous hypothesis we thus write:

$$h + \frac{c^2}{2} = \text{constant}$$

where the term $h + \frac{c^2}{2}$ is the generalized enthalpy.

To calculate the exit velocity of the helium we need one more hypothesis on how the energy is divided between the kinetic and the enthalpic terms. We assume the expansion process divided into two parts: namely an isoentropic expansion, and a dissipative adiabatic expansion. In the first phase the helium in the neck increases its velocity at the expense of enthalpy, in the second phase, when the final pressure is reached, the helium expands converting its drift velocity into dissipative motion and so increasing its entropy until reaching the initial value of enthalpy ($c_{final} = c_{initial} \simeq 0$).

The maximum velocity of the flow is therefore given by the difference of the helium enthalpy between the beginning and the end of the isoentropic path. It is very important to remark that, for a given initial thermodynamic state of helium, there is a minimum pressure value (critical pressure) that the helium can reach via an isoentropic expansion. If the final pressure is smaller than the critical one, as it often happens, only the enthalpy difference between the initial and critical pressure can be converted in drift velocity.

In the upper T-S diagram of Fig. 3 a case is shown when the total enhalpy difference between the initial and final pressure is converted in drift velocity during the exit flow, with formation of liquidid-vapour mixture. In this case the dissipative expansion is isobaric. The lower T-S diagram presents a case where the critical pressure limits the exit flow velocity of the helium.

Finally, the helium exit rate is given by:

$$\frac{d}{dt} m(t) = - A\,\delta(t)\,c(t)$$

where A is the exit surface and $\delta(t)$ and $c(t)$ are respectively the helium density and drift velocity at the end of the isoentropic expansion. The velocity is given, as previously stated, by the generalized enthalpy conservation equation:

$$h_o + \frac{c_o^2}{2} = h + \frac{c^2}{2}$$

where h_o and c_o are the specific enthalpy and velocity of the helium bulk in the vessel and h and c are the same quantities at the end of the isoentropic path.

Since the ring section of the cryostat is about two hundred times the exit surface, the c_o velocity can be neglected and we can write:

$$c(t) = \sqrt{2(h_o(t) - h(t))}.$$

This velocity must be compared with the sound velocity in the helium during the isoentropic expansion and, if the critical pressure is reached, the sound velocity in the helium is taken as exit velocity.

The same method (isoentropic path + isobaric path) is also used for computing the helium flow through the holes in the midplane plate. In this case the shorter length of the holes with respect to that of the exit necks and the smaller pressure drop between the lower and upper helium vessel, justify the isoentropic expansion.

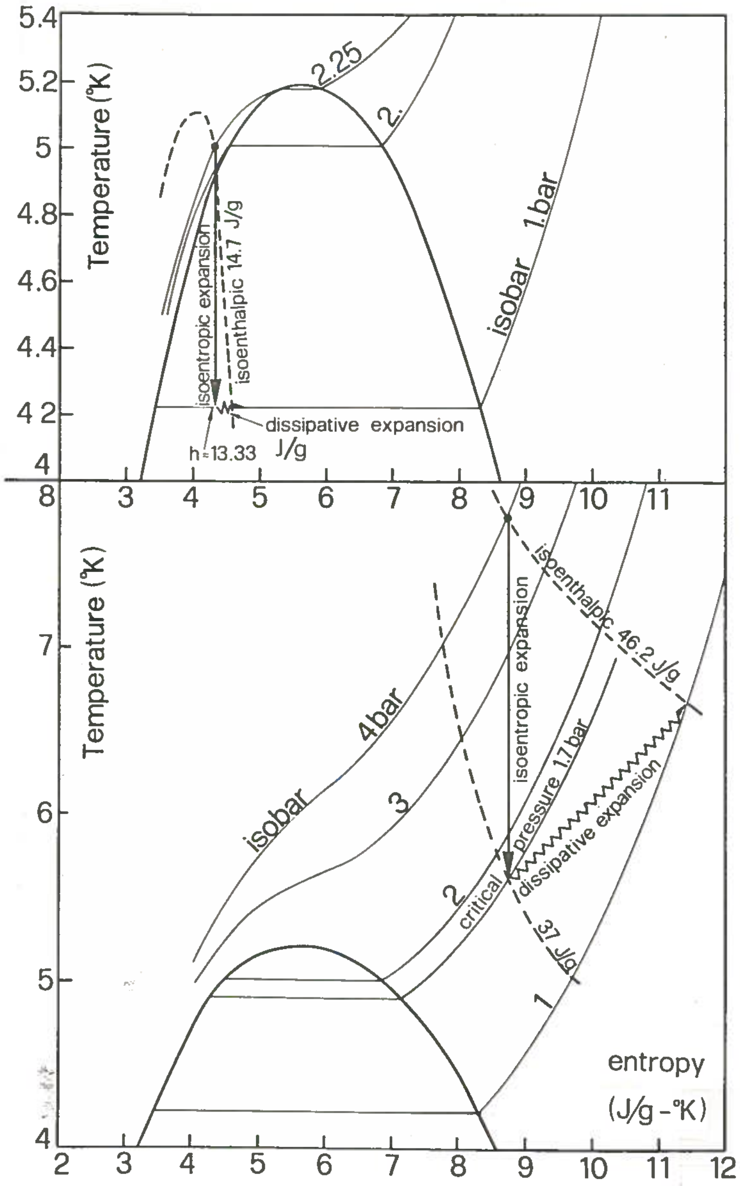

FIG. 3 - Thermodynamical path of the helium flowing out the cryostat. The upper graph is related to the earlier times of the process when helium nearly liquid phase flows at velocity smaller than the critical one. The lower graph shows the helium path at about the maximum pressure, when the velocity reaches its threshold at the critical pressure.

Finally, if the helium state is known at the time t, the exit mass rate can be computed. Then assuming the system parameters constant in the increment time Δt (i.e. neglecting second or higher order effects), the helium density is given by:

$$\delta(t + \Delta t) = \delta(t) + \frac{1}{V_o} \frac{dm(t)}{dt} \Delta t$$

where V_o is the vessel capacity.

By adding an equation of this kind for each vessel to the equations presented in the previous paragraph, we can determine the helium state and thus we need only to compute the power input into the bath.

4. - POWER INPUT AND COILS TEMPERATURE CALCULATION

When the coils begin to be heated, the heat transfer to the helium bath is governed by the nucleate boiling process[3,4] and quickly reaches the nucleate peak boiling value (0.6 W/cm^2 at ΔT = 0.3 °K for vertical surface). Then the heat transfer decreases down to 0.1 W/cm^2 at a metal temperature of about 1.5 °K above the helium bath temperature and then the heat transfer increases again governed by the film boiling process.

Since we are interested in the system evolution when a quench is large enough to propagate, we neglect the initial nucleate boiling heat transfer, because in this phase the cable can recover to the superconductive state. So we start computing the power transfer from the coils into the bath after the cable temperature is 6 °K, when the heat transfer is minimum (instead of starting when the cable temperature is 4.9 °K, beginning of the transition to the resistive phase).

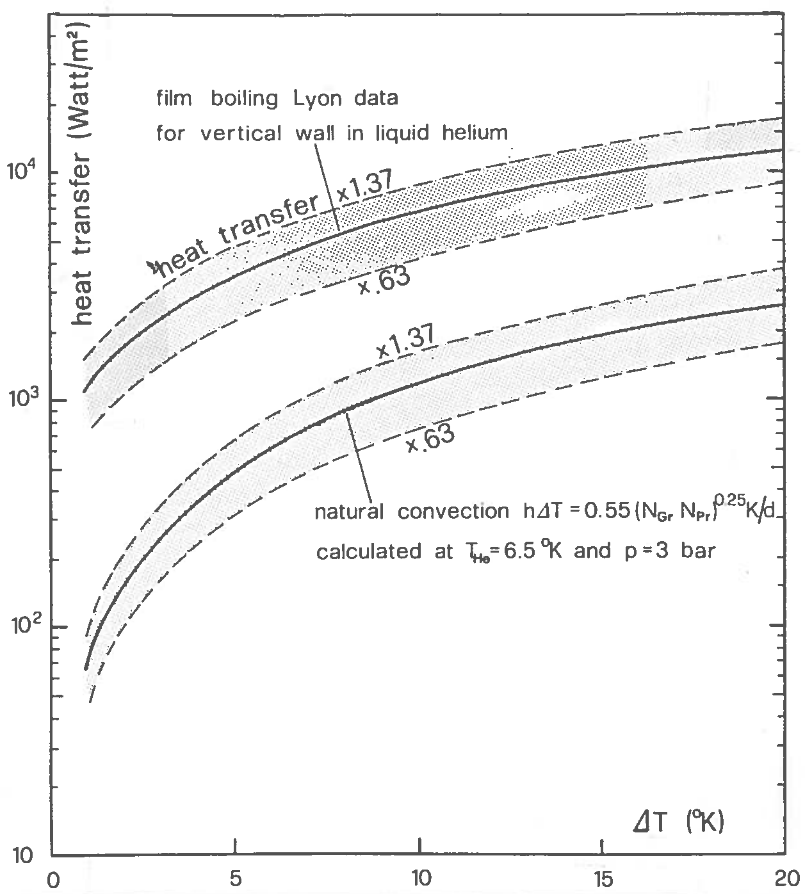

FIG. 4 - Heat transfer curves for metal surfaces in helium (full lines). Dashed areas are the heat transfer regions investigated.

Referring to Fig. 4, when the helium temperature is between 4.2 and 5.2 °K, i. e. nearly the liquid phase, the Lyon data for film boiling in liquid helium are taken as heat transfer. On the contrary when the helium temperature is larger than 6.5 °K, the heat transfer is calculated by means of the dimensional analysis method in the natural convection hypothesis:

$$N_{Nu} = 0.55\,(N_{Gr} + N_{Pr})^{0.25}$$

where N_{Nu}, N_{Gr}, N_{Pr} are the dimensionless Nusselt, Grashof and Prandtl numbers.

In the region of helium temperatures from 5.2 °K up to 6.5 °K, the film boiling curve and the natural convection equation are connected, to avoid discontinuity. So in this region the average between the two curves is taken as heat transfer (this procedure is justified by the fact that the natural convection formula approaches the film boiling data in this region).

Finally the power input per unitary surface of exchange, $h\Delta T$, is given by:

$$T_{He} < 5.2\,^{o}K \qquad h\Delta T = 600\,\Delta T + 500 \qquad (W/m^2)$$

$$T_{He} > 6.5\,^{o}K \qquad h\Delta T = 0.55\left[\frac{g\beta d\,\Delta T/2}{\nu^2}\right]^{0.25}\frac{k}{d}\,\Delta T \qquad (W/m^2)$$

where:

- g is the gravity acceleration in m/s^2;
- $\beta = v(\partial p/\partial T)_v/(\partial p/\partial \delta)_T$ is the thermal expansion coefficient;
- ν is the kinematic viscosity of helium in m^2/s;
- k is the thermal conductivity of helium in $W/m\text{-}^{o}K$;
- d is the equivalent diameter of the exchange channels (1.4 mm);
- ΔT is the temperature difference between copper and helium;
- h is the heat transfer coefficient in $W/m^2\,^{o}K$ (HTC in the following).

Because of the large spread in the experimental data concerning heat transfer and of the strong influence of the geometry of the exchange surface, we decided to carry out the calculation under the hypothesis of both a heat transfer larger than derived by the previous formulas and a smaller one. So every case was computed both with 1.37 multiplicative factor of HTC and with 0.63 one as shown in Fig. 4. These values are chosen because the Lyon data refer to the heat transfer for a free vertical wall. When the exchange surfaces are vertical channels, the heat transfer is reduced by a factor that depends on the height-length ratio of the channels. In our case this reduction coefficient is 0.63 and so 37% was chosen as enhancement or reduction factor of heat transfer curves.

The copper matrix temperature T_m is given by the energy balance:

$$\frac{d}{dt}T_m(t) = \frac{W_J(t) - W(t)}{M_m\, c_m}$$

where:

- $W_J(t)$ is the dissipated power for the Joule effect;
- $W(t)$ is the power transferred to the helium;
- c_m is the copper specific heat at the temperature $T_m(t)$;
- M_m is the cable mass.

The Joule dissipated power is initially given by: $W_J = R\,I^2$ and, when the dumping resistor circuit is activated, by:

$$W_J(t) = \varrho \frac{L}{S} \left[I \exp \left(- \frac{t - t_o}{\tau}\right)\right]^2$$

where t_o is the starting time of the coils discharge, τ is the time constant of the circuit, ϱ is the copper resistivity and L and S the conductor length and section. This equation neglects the effects on the current of the power transferred to the helium bath and of the increase of the matrix enthalpy, namely the current decrease is caused only by the dumping resistors. This is obviously a simplicative but also conservative hypothesis, according to the philosophy of our calculations.

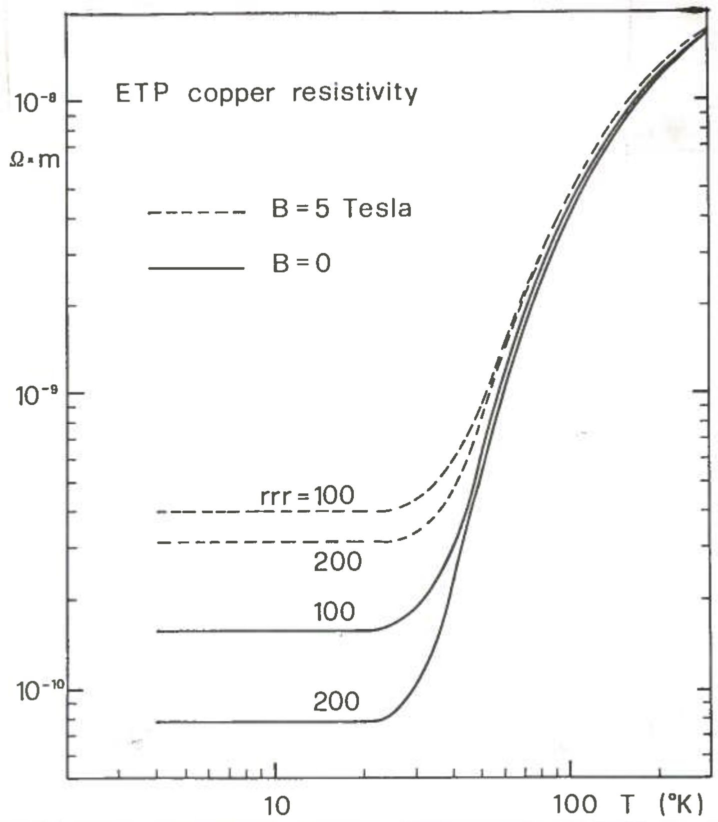

FIG. 5 - ETP copper resistivity versus temperature for different magnetic field and rrr values.

The copper resistivity is a function of the copper temperature T_m, of the magnetic field B in the coils and of the residual resistivity ratio rrr ($rrr = \varrho_{273^oK}/\varrho_{4.2^oK}$). It is shown in Fig. 5 as a function of temperature for different values of rrr and of the magnetic field. Analytical expression, for $T_m < 300^oK$, is :

$$\varrho(T_m, 0) = \varrho(273^oK, 0)\left[\frac{1}{rrr} + e^{\alpha(T_m - 273)/T_m}\right]$$

$$\varrho(T_m, B) = \varrho(T_m, 0) + KB\,\varrho(T_m, 0) \qquad (\Omega m)$$

where B is expressed in Tesla and α and K are 0.8 and 0.003 respectively. The average magnetic field in the coils is, at the maximum, 3 Tesla.

5. - CALCULATIONS

The main equations, see paragraph 3, can be expressed in terms of the helium temperature rate. Indicating with T_1, v_1, p_1 and T_2, v_2, p_2 the temperatures, the specific volumes and the pressures of the helium in the two vessels and with c_v its specific heat at constant volume, the process is described by the following system :

lower vessel

$$\frac{d}{dt} T_1 = \frac{W_1 + \left[p_1 v_1 + \frac{v_1}{m_1} (\partial p/\partial v)_T (\partial u/\partial p)_T \right] \frac{d}{dt} m_1}{m_1 c_v} ,$$

$$\delta_1 = \frac{M_{01} + \int_0^t (dm_1/dt)\, dt}{V_{01}} , \qquad \frac{d}{dt} T_{m_1} = \frac{W_{J1} - W_1}{M_{m1} c_m} ,$$

upper vessel

$$\frac{d}{dt} T_2 = \frac{W_2 + \left[p_2 v_2 + \frac{v_2}{m_2} (\partial p/\partial v)_T (\partial u/\partial p)_T \right] \frac{d}{dt} m - h_1 \frac{d}{dt} m_1}{m_2 c_v} ,$$

$$\delta_2 = \frac{M_{02} + \int_0^t (dm_2/dt)\, dt}{V_{02}} ,$$

$$\frac{d}{dt} m_2 = \frac{d}{dt} m - \frac{d}{dt} m_1 , \qquad \frac{d}{dt} T_{m2} = \frac{W_{J2} - W_2}{M_{m2} c_m} ,$$

where M_{01} and M_{02} are the initial helium masses in the two vessels.

A numerical integration of the two systems of differential equation was carried out. The time step of the integration was a 0.02 seconds. Indeed a longer time step of integration affects the results while a shorter one does not give serious differences in the results and increases heavily the computering cost.

The calculation begins when the coils temperature in the upper or/and in the lower vessel is larger than 4.9 °K (beginning of the transition of the superconducting cable to the resistive phase) and is truncated when the pressure returns approximately to the initial value. This regardless of the behaviour of other quantities in view of the main purpose of this calculation (calculations for the safety of the coils was carried out elsewhere(2)).

A numerical program, named PNEU, was written in Fortran language and used on the Univac 1100 computer of the Milan University.

To compute the thermodynamical and thermophysical properties of the helium, PNEU code uses the program HEPROP(5). This is a set of subprograms, in Fortran language, that are derived from the equation of state developed by McCarty which is valid from about 2 °K to 1700 °K and up to about 1000 bar. The programs are devised to calculate thermodynamical properties as a function of the temperature and density, but can also calculate the temperature as a function of density and pressure. Thus if the state of the system is defined by any two thermodynamical coordinates, all the other can be calculated. Equations for thermophysical properties of helium such as viscosity, thermal conductivity, sound velocity, etc., are included in HEPROP, too. The uncertainty on the PVT surface is estimated, in our region of interest, to be about 1%, except in the critical region, where it might as high as 8%.

The inputs of the PNEU code are: initial thermodynamical coordinates of the helium bath, rrr value of the copper and initial coils temperature, the surface of heat exchange, the multiplicative factor of the heat transfer (see previous paragraph) and the integration time step.

The output is the time evolution of: helium pressure and temperature, helium mass in the cryostat, exit velocity of the helium and power transferred to the helium. All input and output quantities are in MKS unities. Typical running time of the PNEU code is about 1 minute and 30 seconds.

6. - RESULTS ANALYSIS

First it should be emphasized that in the following, as in the graphs, all pressure values are in bar absolute: this applies as well to the valve and disks opening pressure.

A standard initial configuration was chosen and the most interesting quantities were plotted versus time for this configuration. Then the main parameters values were scanned over a reasonable range in order to understand the influence of each one on the process (especially on the maximum pressure reached in the cryostat).

The standard initial configuration data are:

helium in cryostat	: 1200 liters (about 145 kg)
initial saturated vapor	: ≃ 20 liters
initial cable temperature	: 6 ^{o}K
whole coil is quenched heat exchange surface	: 1 cm^2/cm of cable length (about 240 m^2)
rrr copper value	: 160
initial current	: 2000 A (40 MJ)
coils inductance	: 19.8 H (self + mutual)
current dumping resistors	: 0.5 ohm (total)
delay time of the quench detection system	: 0.5 s
average magnetic field in the coils	: 3 T

area of the passage holes through the median plane plate	:	70.7 cm^2 (corresponding to 20 holes with 27.4 mm of diameter when the 0.6 discharge coefficient of exit surface reduction is taken into account)
area of the valve	:	47.1 cm^2 (ϕ = 100 mm with 0.6 coefficient)
pressure of the valve opening	:	2 bar
delay time of the valve opening	:	0.5 s (after the opening pressure has been reached)
area of the rupture disks	:	23.6 cm^2 (2 disks with ϕ = 50 mm with 0.6 coefficient)
rupture pressure of the disks	:	5.5 bar.

The pressure versus time is plotted in Fig. 6, both for the lower and upper vessel in the case of a standard configuration. The pressure is plotted both for 1.37 x HTC case and for 0.63 x HTC case. With 1.37 x HTC, the worst case, the maximum pressure is four bar and is reached after about six seconds, with the entire process terminated after ten seconds, when the pressure drops below the opening pressure of the valve (2 bar). The initial narrow peak of the helium pressure is caused by the delay time in the valve opening and the following rapid decrease is caused by the expulsion of helium in a nearly liquid phase.

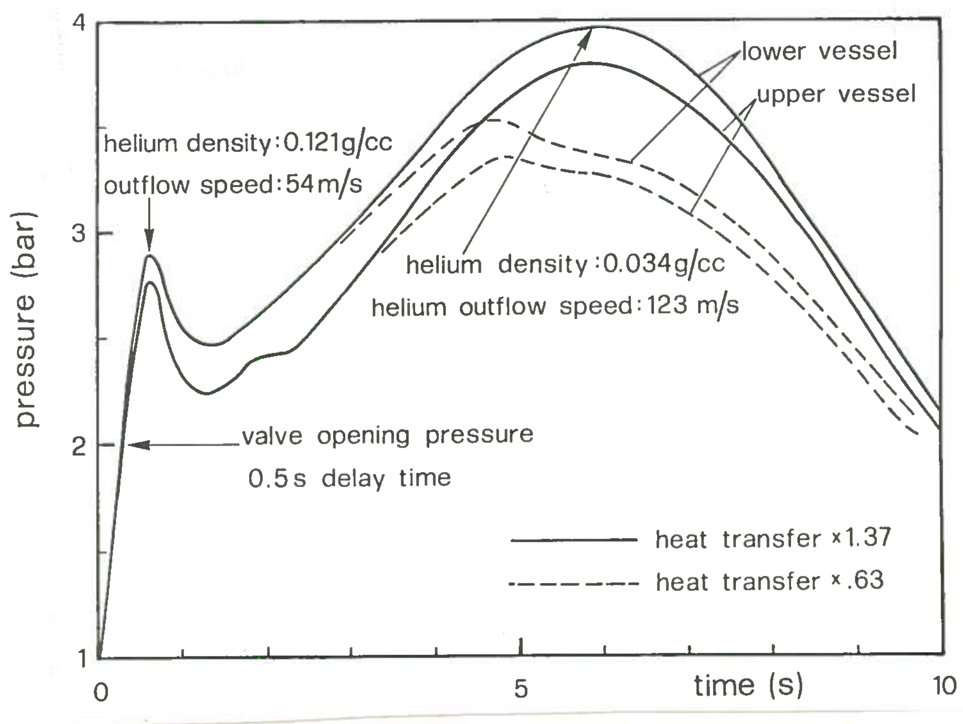

FIG. 6 - Helium pressure versus time in the lower vessel and in the upper one either with 1.37 enhancement factor for heat transfer either with 0.63 one.

To have a general picture of the process the thermodynamical path on the T - S helium chart is shown in Fig. 7 (dashed line).

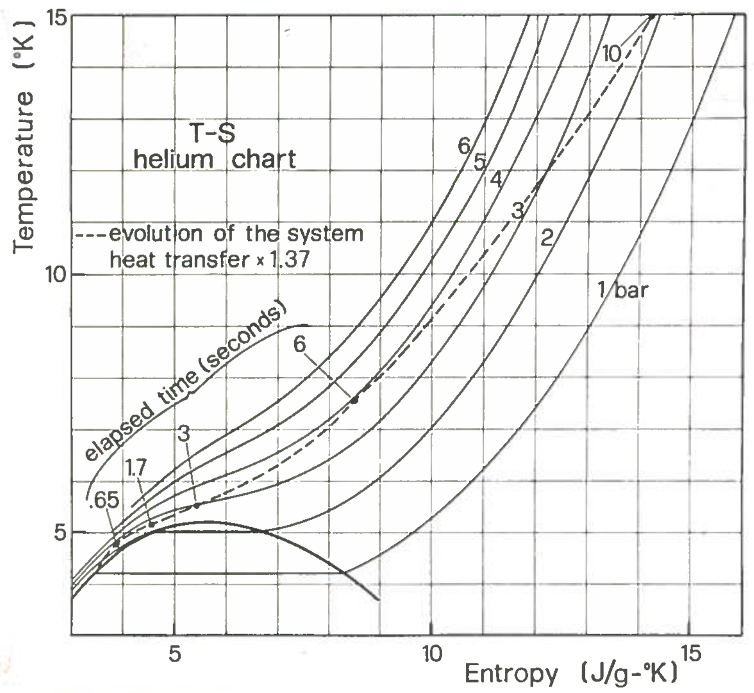

FIG. 7 - Thermodynamical path (dashed line) of the helium during the process for the standard configuration and 1.37 heat transfer (lower vessel). The dots indicate the time.

The helium mass in the cryostat decreases rapidly, see Fig. 8, showing that the process is very fast. The velocity of the helium flow, also shown in Fig. 8, quickly reaches its critical value, the sound velocity, in good agreement with the discussion of paragraph 3.

The short time of the whole process suggests that the maximum pressure is not affected seriously by delays in the activation of the dumping resistors (maximum pressure is 4.3 bar if the dumping resistors do not intervene).

The pressure in the lower vessel is just 0.25 bar over the upper one's. This is quite an acceptable value and indicates that no direct discharge of the lower vessel into the atmosphere is needed. Nevertheless different values of the total area for the helium passages through the midplane

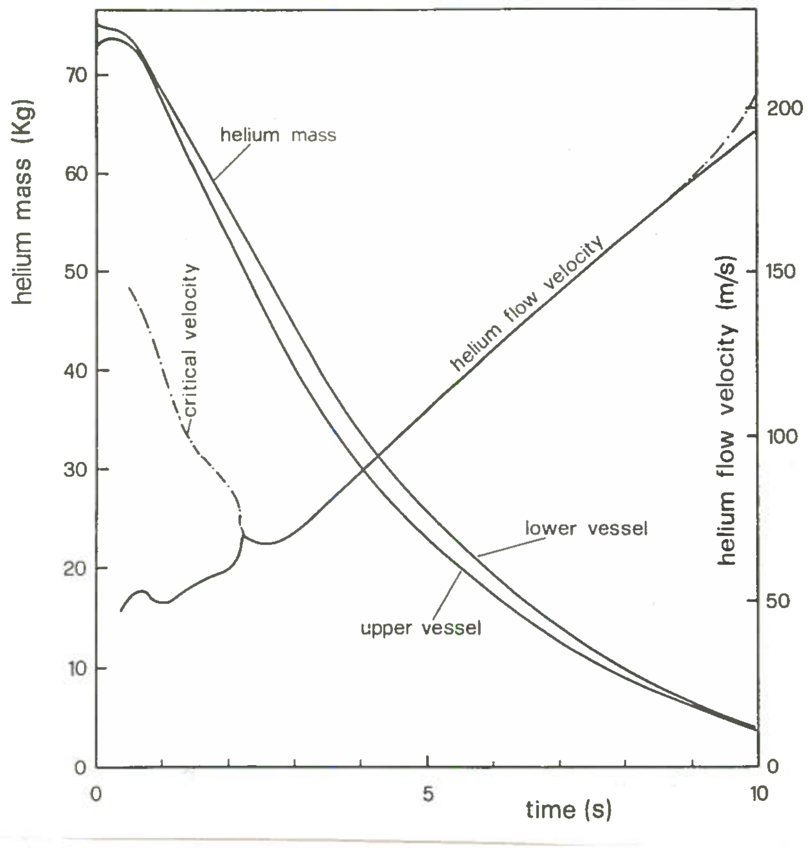

FIG. 8 - Helium mass in the cryostat and helium velocity in the discharge valve versus time. Sound velocity in the helium (dashed line) is also plotted versus time to show that it is early reached by the helium flowing out the cryostat.

plate were tested in order to understand their effect. The results for the case of 1.37 x HTC, are plotted in Fig. 9 and they show that reducing the effective area below 50 cm^2 will cause large differences in the pressure, a fact to be avoided.

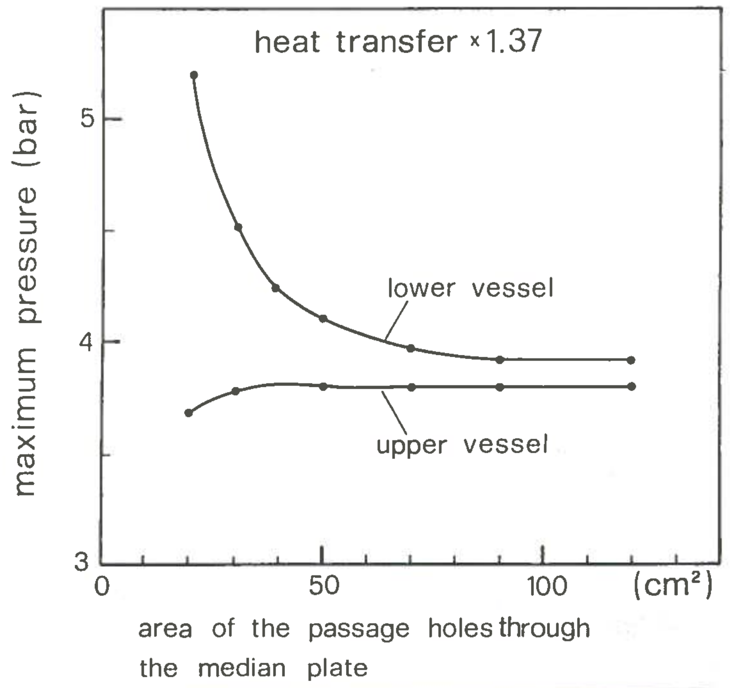

FIG. 9 - Maximum pressure reached in each vessel as a function of the area of the passage holes for the helium through the midplane plate.

Coming back to the standard configuration, see Fig. 6, we should remark the likeness of the pressure evolution in the two limiting cases with HTC differing by + 37% and - 37%, and note that the maximum pressure reached in the two cases differs by just 0.5 bar. This means that increasing the heat transfer by about 120%, i.e. enhancing from 0.63 to 1.37 the HTC the maximum pressure increases only by 15%. Considering the various uncertainties on the heat transfer model this result is a very reassuring one. The small difference in the pressure for the two cases can be explained with the following considerations. If the heat transfer coefficient is large a relevant fraction of the Joule power is initially transferred to the helium bath. Then the coils temperature remains low and the total power input into the bath, $h\Delta TS$, is not too large since the temperature difference ΔT between the coils and the helium is low. On the contrary, if the HTC is small, the temperature difference becomes larger than it does in the other case and so the total power input variation is smaller than the variation of the HTC. The coils and helium temperature for the lower vessel, for the case 1.37 x HTC, and the power input and the temperature difference ΔT are shown in Figs. 10 and 11 respectively.

The maximum pressure was investigated as a function of the various effective values of the exchange surface since the true value of the latter is very difficult to predict exactly. Actually the helium in the inner small vertical channels probably doesn't blend with the bulk and so only a fraction of the geometrical heat exchange surface must be taken into account. However a decrease of the effective heat exchange surface reduces the maximum pressure reached as shown in Fig. 12. Of course in this case the coils temperature increases faster than in the standard case (calculations of adiabatic heating of the coils were carried out previously[4].

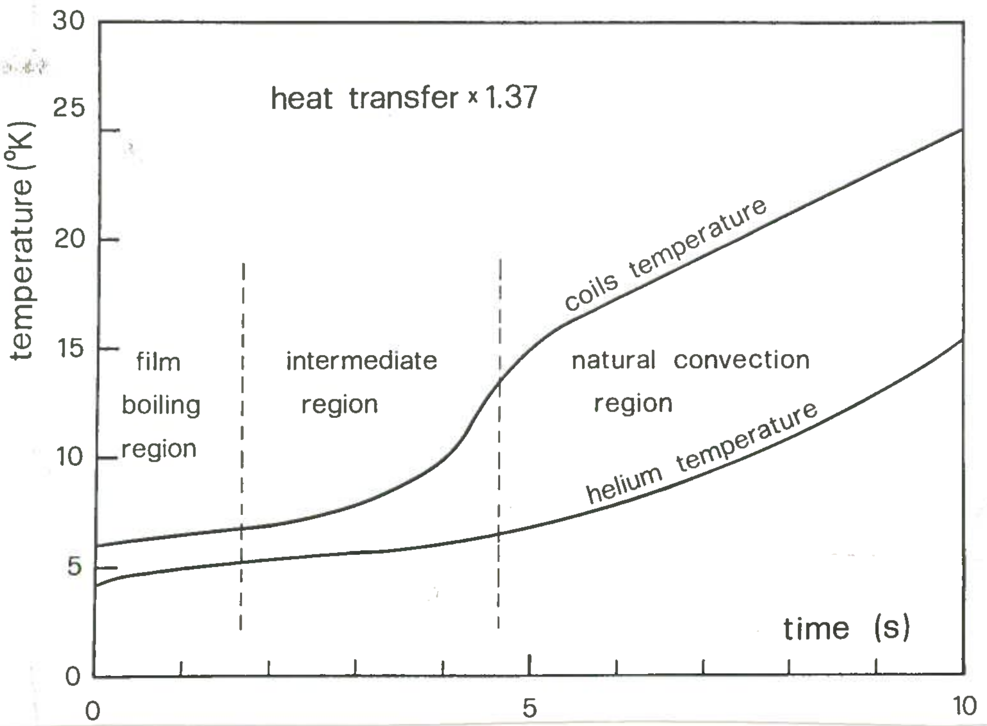

FIG. 10 - Coils and helium temperature versus time for the lower vessel in the standard cryostat configuration (for 1.37 heat transfer).

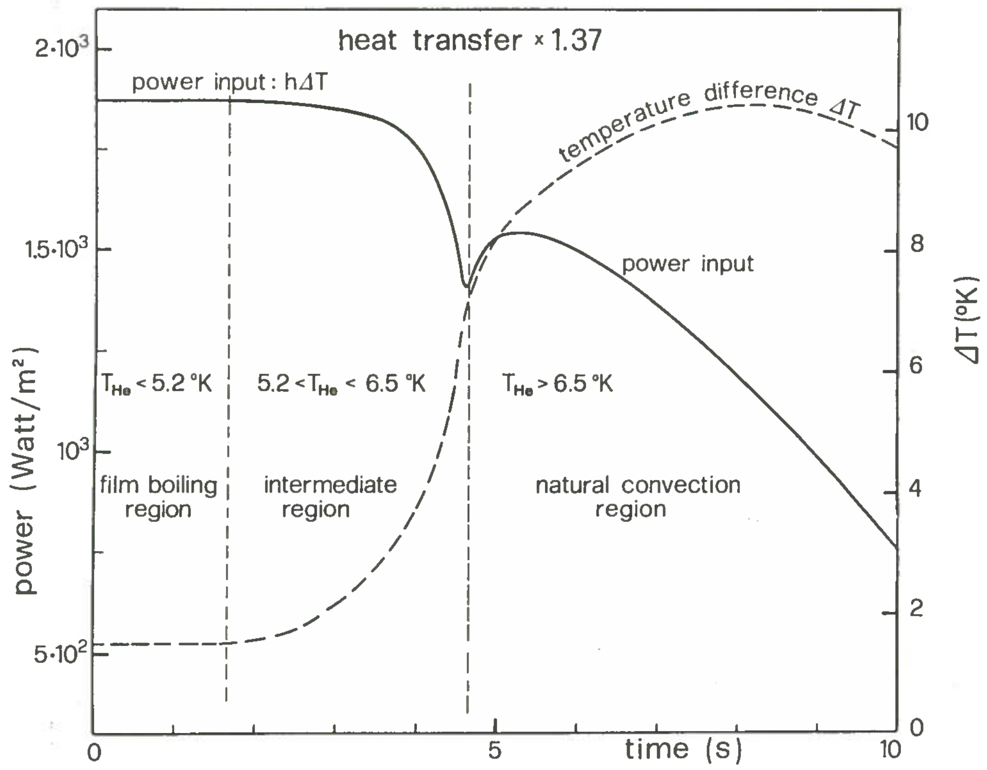

FIG. 11 - Temperature difference between the coils and the helium bath and power input into the bath per unitary surface (for 1.37 heat transfer).

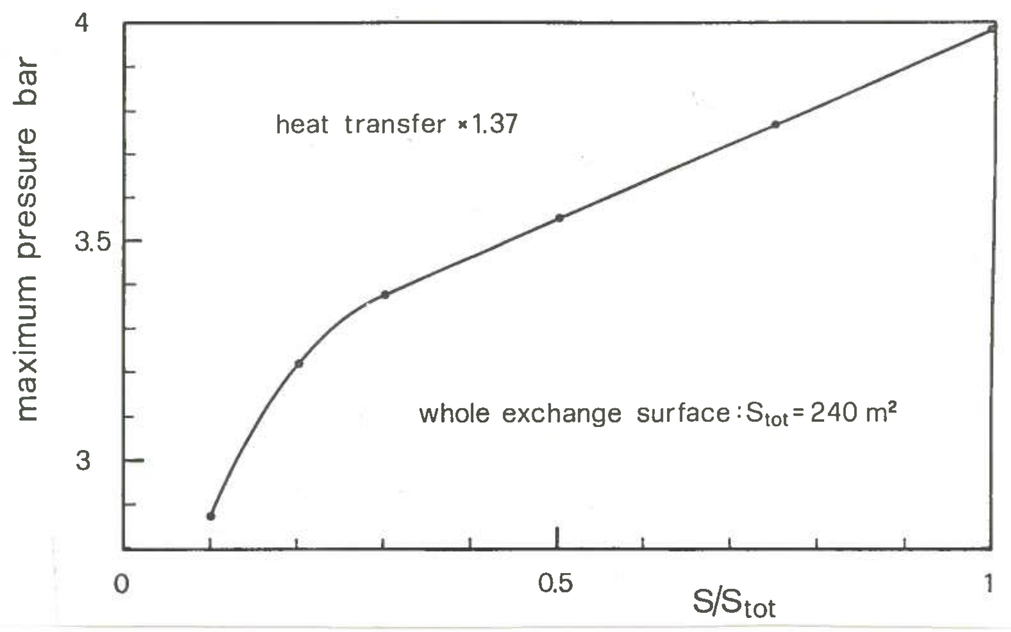

FIG. 12 - Maximum pressure versus the effective area of heat exchange.

Various values of the copper resistivity were scanned and its influence on the maximum pressure reached in the cryostat is shown in Fig. 13 in a selfexplanatory way.

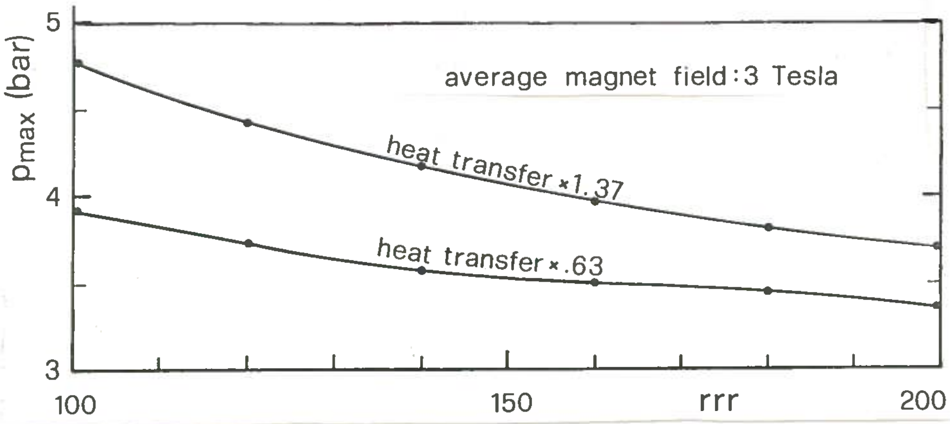

FIG. 13 - Maximum pressure versus the copper matrix resistivity.

The influence of the opening pressure of the discharge valve was studied and the results are plotted in Fig. 14. It is shown that, if the opening pressure is larger than four bar, the maximum pressure will approach the rupture pressure of the safety disks (5.5 bar absolute).

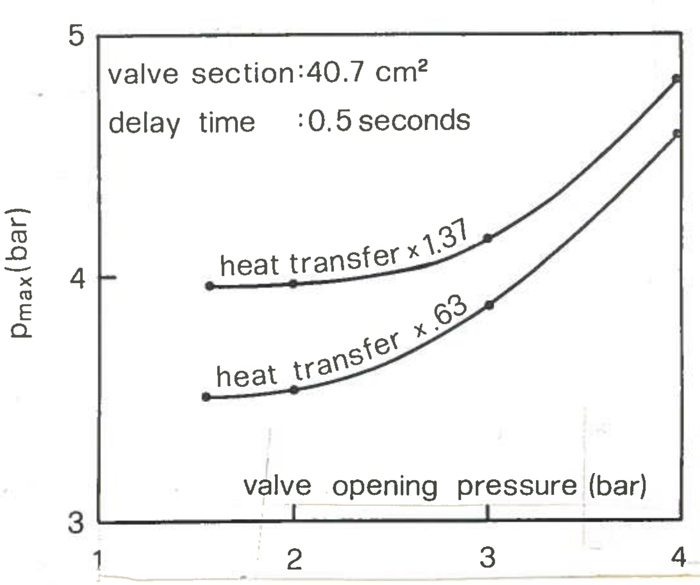

FIG. 14 - Maximum pressure versus the opening pressure of the discharge valve.

Finally the case of a failure of the discharge valve, with consequent expulsion of the helium via the rupture disks, was carefully examined. This is an interesting point both because of obvious safety considerations and because of the existence of two contrasting requirements. The first one is to have the rupture pressure of the disks low enough so that the pressure cannot reach the nominal maximum operating pressure for the cryostat safety which is about seven bar. The other is that the magnet cool-down requires reaching a pressure of about 5 bar. So the rupture pressure of the disks was fixed at 5.5 bar and the pressure behaviour was studied in this case as a function of the area of the disks. The results are plotted, for the more pessimistic case of 1.37 heat transfer coefficient, in Fig. 15. There it is shown that in order to have large safety margins two disks with 100 mm of diameters are needed. If just one disk were used the working point in Fig. 15 would be too close to the sudden increase noted in the left part of the curve and therefore such a solution would only offer a rather limited margin.

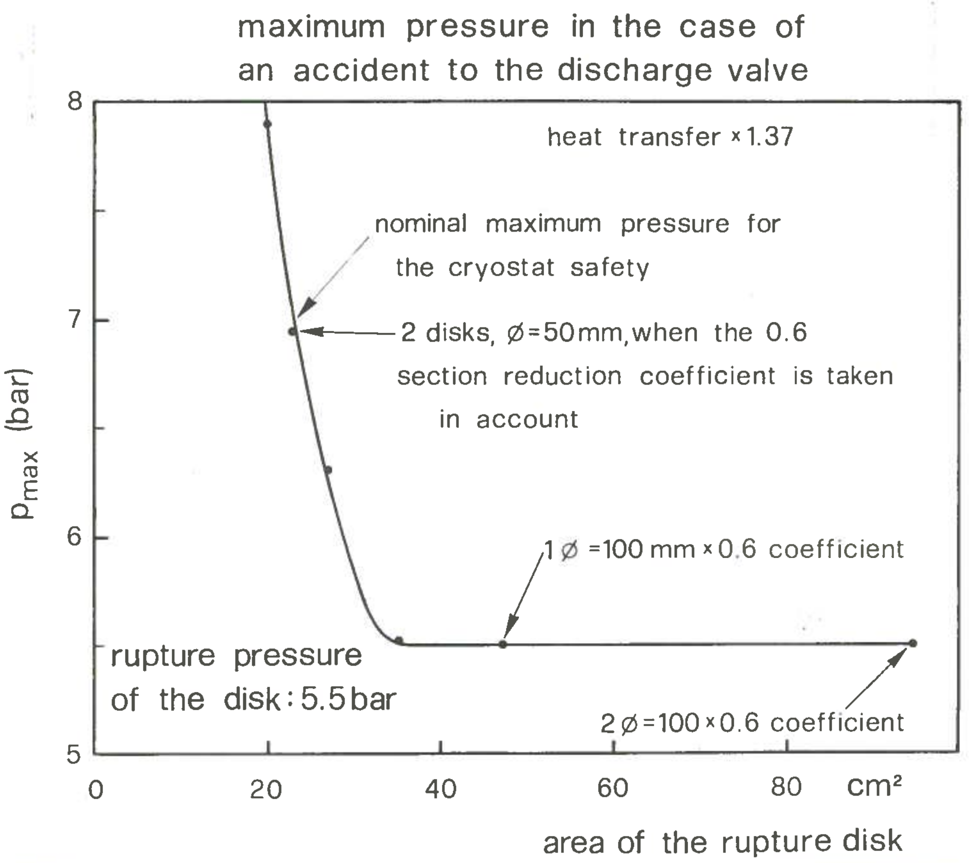

FIG. 15 - Maximum pressure reached in the cryostat when the discharge valve does not open, as a function of the area of the rupture disks (for 1.37 heat transfer).

7. - CONCLUSIONS

According to the results presented here it was decided that a direct discharge of the helium from the lower vessel into the atmosphere was not needed. So it was further decided to drill through the midplane plate 19 holes with ϕ = 30 mm, the latter being the maximum diameter that can be allowed in the plate. A valve of 100 mm of diameter and with 2 bar of opening pressure was also chosen. The number and section of the rupture disks are not yet frozen, but in principle we would like to have two disks with ϕ = 100 mm.

Nevertheless it should be remarked that a quench of the superconducting coils can be produced also by a very large air leak in the vacuum chamber. In this case the power input into the bath may be larger than in the case considered and slighty higher values of the maximum pressure are expected[6]. A study on this particular occurence, will be carried out as soon as possible.

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