PRESSURE PROTECTION AGAINST VACUUM FAILURES ON THE CRYOSTATS FOR LEP SC CAVITIES

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Abstract

Three types of moderate vacuum failure were studied experimentally on a prototype of the sc cavity cryostats developed for LEP. The observations were interpreted using a simplified description of the LHe bath and extrapolated to the worst possible pressure rise. This was verified in a last test by breaking the cavity vacuum in a fraction of a second with an 80 mm diameter valve. It was concluded that this simulated indeed the worst case and that, as a minimum, a rupture disk of 20 cm² is required on a low-impedence safety pipe to exclude excessive peak pressures and damage to the cavity.

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1. Introduction

A series of safety tests was undertaken to understand the **pressure risks** for the superconducting cavities under construction at CERN for LEP. A fast pressure rise in the liquid helium tank around the cavity can occur due to the entry of helium or air into the vacuum either inside the cavity or in the surrounding vacuum tank.

4 **successive tests** were made of increasing initial rate of heat input to the LHe bath and hence increasing risk of pressure peak.

The purpose of this series of tests was to first collect the necessary experimental data within the range of the provisional pressure protection of the prototype cryostats for an extrapolation to a safe handling of the worst credible case, and then to check this prediction.

The first test simulated a **helium leak into the vacuum tank** with heat input to the LHe tank due to gas conduction across the superinsulation surrounding the tank.

The second test simulated **a moderate air leak into the vacuum tank** (10 mm dia. hole) with heat input from latent heat of the air condensing on the tank surface, but limited by the presence of the superinsulation.

The third and much severer test was the **fast breaking of the cavity vacuum with air** (25 mm dia. hole) and heat input from condensing air on about 5 m^2 of unprotected surface in contact with the liquid He bath.

The **worst case** was finally simulated in the forth test where the cavity vacuum was broken with air using a 80 mm i.d. pneumatic valve and the helium bath protected by a 50 mm i.d. rupture disk.

2. Description of LEP1 parameters relevant to the tests

The prototype cryostat *LEP1* was used for the tests. Its cavity for 352 MHz with surrounding liquid helium (LHe) bath tank and top manifold for phase separation is shown in Figure 1 on page 3. Figure 2 on page 5 displays a section of the LEP cavity cryostats, for which a more detailed description can be found in earlier reports, e.g. in [1].

The cavity is surrounded by an ondulated stainless steel tank for a minimum volume liquid helium bath and installed in a cylindrical vacuum tank, together with a radiation screen cooled by cold helium gas and operated, during these tests, at about 120 K. 16 layers of superinsulation are directly wrapped around the helium tank, 40 layers cover the cylindrical radiation shield and the circular end shields.

For the present tests, the helium tank was cooled and filled from LHe dewars up to the normal level in the lower part of the manifold, but then disconnected from this supply.

Figure 2 on page 5 also displays the special features installed for each of the first 3 safety tests.

The parameters of the LEP cryostat relevant for the discussion of the tests are listed in Table 1 on page 4.

The LHe tank has originally been protected against accidental pressure rises by a 25 cm long, 40 mm i.d. safety pipe, ending in two 1.25-inch **safety valves** adjusted for breaking at 0.7 bar overpressure. This was also the bath protection used for TESTs 1-3.

For the most critical TEST 4, one of the safety valves was replaced by a 50 mm i.d. **rupture disk.**

For the protection of the insulation vacuum, a 110 mm dia. non-return valve was installed.

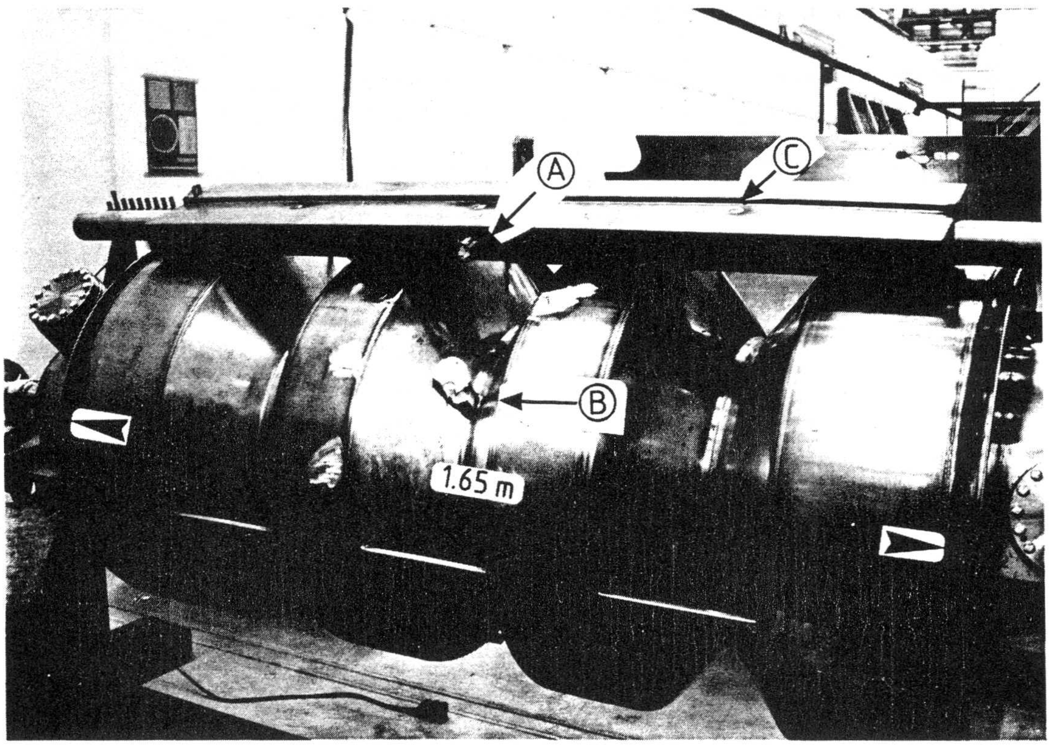

Figure 1: **View of the LEP1 cavity with LHe tank and top manifold.** (A) and (B) are the 35 mm i.d. connections available for a safety exhaust line. The leak into the vacuum tank during TEST 3 developed at welding (C).

Table 1: Parameters of the LEP1 cryostat important for pressure safety

Cavity volume	573 dm^3	Vacuum tank volume	1.5 m^3
LHe volume at start	180 dm^3	LHe mass at start	22.2 kg
GHe volume at start	28 dm^3	GHe mass at start	0.5 kg
Niobium mass in contact with LHe	145 kg	St.steel mass in contact with LHe	131 kg
Niobium surface in contact with LHe	5.6 m^2	St.steel surface in contact with LHe	7.3 m^2

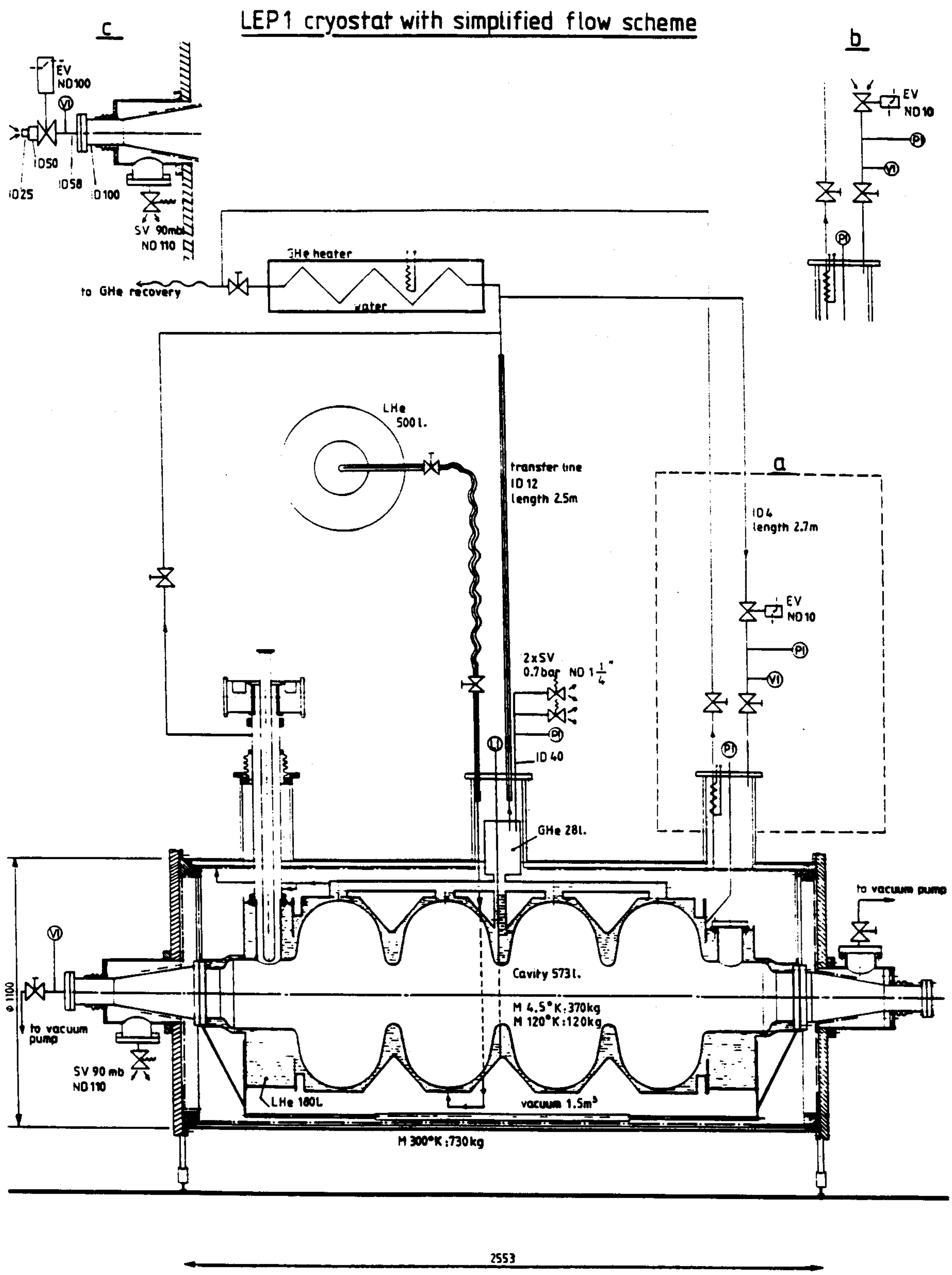

Figure 2: **LEP1 cryostat with simplified flow scheme.** Dimensional parameters relevant for the safety tests are indicated. The specific arrangments for each of the first 3 tests are shown: a) for TEST 1; b) for TEST 2; c) for TEST 3.

3. TEST 1: Loss of the insulation vacuum by a leakage of helium gas

3.1 Set-up

The specific set-up for the first accident simulation (TEST 1) is shown in Figure 2 on page 5, detail a. The vacuum tank was connected by a solenoid valve (EV) and a small pipe to the He recovery line. During the test, with a pressure of about 2 bar[1] at the entry of the recovery line, the pipe delivered a **helium flow** of about 0.6 g/s into the vacuum tank.

The cavity was cooled, the He tank filled up to its normal level of some 850 mm height and then the LHe dewar disconnected. The cavity was kept at a vacuum of a few 10^{-9} mbar and sealed off.

At start time $t_0 = 0$ the vacuum tank was sealed off with a few 10^{-6} mbar and the solenoid valve opened for some 35 s. This resulted in a helium pressure of almost 40 mbar[1] (which increased later to about 60 mbar due to the warm-up of the LHe tank). As a consequence of heat conducted by the helium gas between the warm vacuum tank walls and the outer wall of the LHe tank, the pressure in this tank increased quickly. The safety valves opened after 11 s and blew off cold helium for about 7 min until all liquid helium was evaporated.

3.2 Observations

The most interesting observations are summarized in Table 2 on page 7.

The development of **LHe tank pressure, vacuum tank pressure** and **LHe level** over the first 600 s after the start of helium admission at t_0 are shown in Figure 3 on page 8.

The **cool-down of the vacuum tank** envelope as a consequence of the heat transfer turned out to be rather limited. The temperature of the top of the vacuum tank dropped from 292 K to a minimum of 283 K and that of the bottom to 277 K.

The **cavity pressure** remained below 10^{-8} mbar until all LHe was evaporated and then rose close to 10^{-5} mbar (from $t_0 +$ 15 min).

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[1] Pressures values quoted are absolut or identified as differential.

Table 2: Summary of vacuum failure tests 1 & 2 carried out with LEP1

	TEST 1	TEST 2
Simulated accident	He gas into vacuum tank	Air into vacuum tank
Size of leak	≈3 m of 4 mm i.d. line	10 mm dia. valve
Gas flow	About 20 g (120 dm3) over 35 s	About 10 dm3/s (12 g/s) for 4 short intervals, then continuous flow
Pressure rise		
- At 1.2 bar abs.	≈0.2 bar/s	≈0.1 bar/s
- At 1.7 bar abs.	<0.1 bar/s	≈0.08 bar/s
Safety valves start blowing at	to + 11 s	to + 14 s (not counting interruptions)
Pressure maximum at	2.02 bar abs. to + 36 s	2.08 bar abs. to + ≈40 s
Pressure below safety v. setting	to + 420 s	to + 270 s
Apparent LHe level <50% of start level	to + 140 s	to + 135 s
LHe tank empty, bottom temp.rising	to + 510 s	to + 240 s
Coldest temperat. on vacuum tank	292 K -> 277 K at to + 20 min	292 K -> 271 K at about to + 1 h
Estimated heat input at start	≈10 kW ≈0.15 W/cm2	≈5 kW ≈0.07 W/cm2

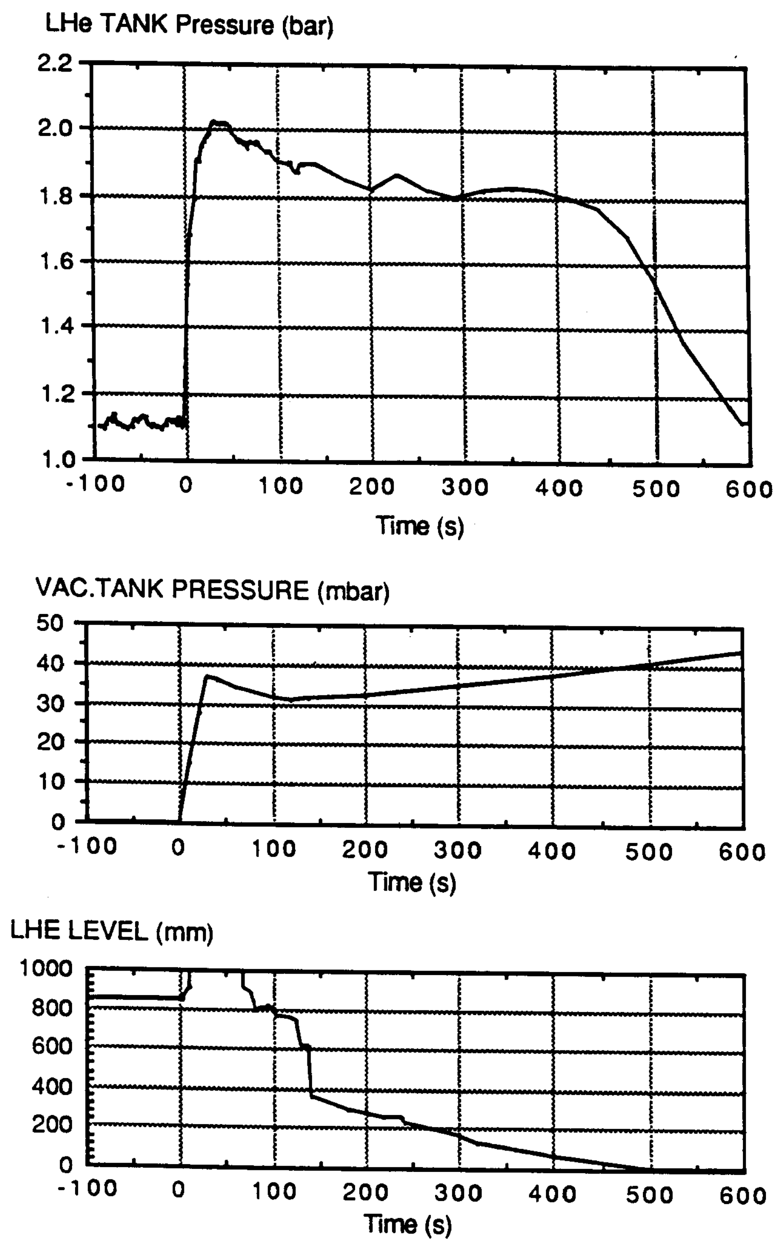

Figure 3: **TEST 1, 20 g of He gas into the vacuum tank.** LHe tank pressure, vacuum tank pressure, and level of LHe versus time since start of He injection.

4. TEST 2: Loss of the insulation vacuum by an 10-mm air hole

4.1 Set-up

The specific set-up for the second accident simulation (TEST 2) is shown in Figure 2 on page 5, detail b. The helium line of TEST 1 was replaced by a solenoid valve of 10 mm nominal diameter permitting the breaking of the insulation vacuum with ambient air. At room temperature with this set-up a pressure rise of about 7 mbar/s was observed in the 1.5 m^3 vacuum tank, corresponding to a an **air flow** of some 10 dm^3/s at STP or 12 g/s.

After cooling and filling the He tank, the cryostat was separated from the supply dewar and kept connected to the warm gas recovery line, stabilizing the pressure at 1.1 bar.

The air admission to the vacuum tank was then opened for 4 short periods (2+3+4+14 = 23 s), separated by observation times between 30 s and 60 s , before the valve was kept continuously open. Each time there was a sharp rise of the pressure by several hundreds of millibars in a few seconds, followed by a slower pressure drop over about one minute due to the evacuation of the evaporated helium through the recovery line. At the 4th valve opening the safety valve started blowing for about 10 s and then blew, during the continuous opening, for about 4 min.

4.2 Observations

The most interesting observations from TEST 2 are summarized also in Table 2 on page 7.

Graphs for 3 key parameters recorded during TEST 2 are shown in Figure 4 on page 10. The start time t_0 = 0 was chosen at 23 s before the continuous opening, so that from then on the time t was equal to the total duration of air entry into the vacuum tank.

The development of the **LHe tank pressure** reveals that the safety valves had no problem in handling heat loads of the kind simulated in TEST 2. The pressures measured in the safety pipe just in front of the safety valves were very similar, apart from superimposed oscillations, showing that the pipe had ample size for use with the safety valves. These were set for a breaking pressure of 0.7 bar gauge; they opened and re-sealed well between 1.7 and 1.8 bar.

Figure 4 on page 10, bottom, displays the **vacuum tank pressure** as recorded in the filling line between solenoid valve and tank. The real pressure in the tank could only be seen while there was no flow, whereas, when the valve was open, a dynamic value appeared between atmospheric pressure and tank pressure. It is interesting to note that, within the 1-second time resolution of the monitoring system, the air line pressure dropped below the detection limit of 1 mbar at each closing of the air valve. This shows how very efficiently the **cryopumping** operated at the air flow rates of TEST 2. In fact, only after more than 500 s of air blowing into the tank at the maximum rate of 12 g/s was a clear sign of rising static pressure in the vacuum tank visible on top of the dynamic line pressure. Only at this moment did the surface of the frozen air seem to have reached the triple point temperature (63 K) with vapour presssures of more than 0.12 bar. Thus some 6 kg of air must have been condensed, almost 3 times what was needed to fill the vacuum tank with all its contents at ambient temperature. At t_0 + 16 min the atmospheric pressure was reached, and 3 min later the vacuum tank safety valve opened to blow off the excess air.

The third parameter shown in Figure 4 on page 10 is the **temperature of the LHe tank**; there is a sharp rise at the end of LHe evaporation some 250 s after t_0.

Also during TEST 2 only a moderate cool-down of the vacuum tank walls was observed.

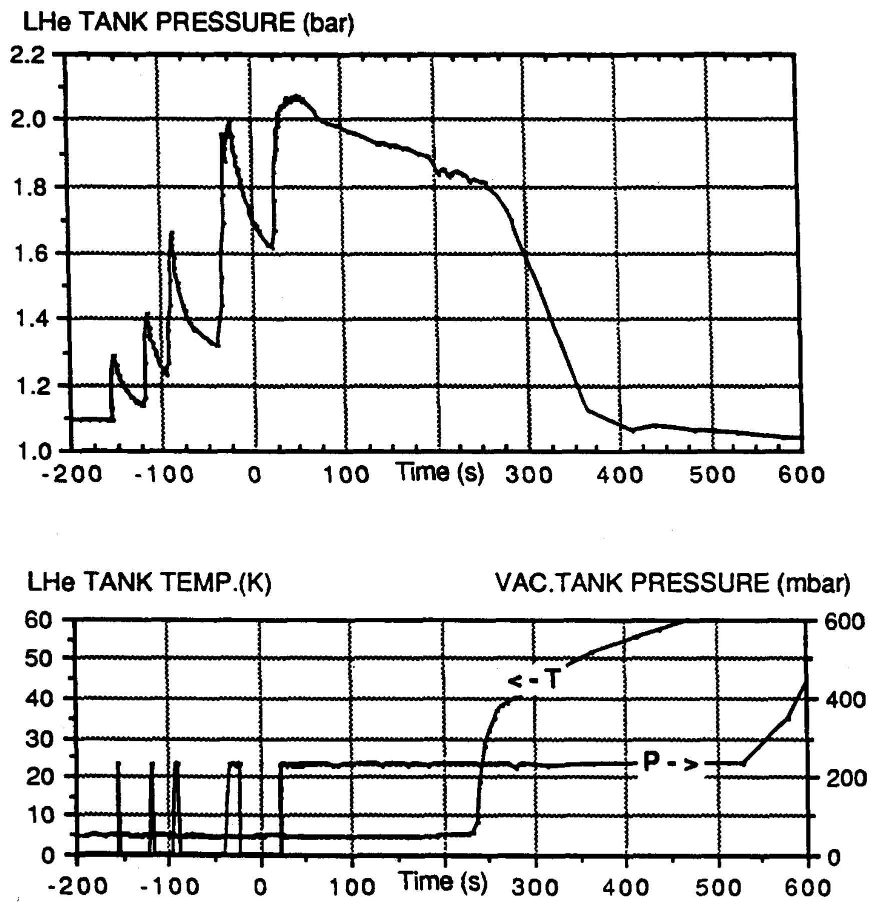

Figure 4: **TEST 2, 10 dm³/s STP of air into the vacuum tank.** Top: LHe tank pressure. Bottom: Vacuum tank pressure and temperature of coldest point on the LHe tank. The air admission was interrupted 4 times before it was maintained permanently.

5. TEST 3: Loss of cavity vacuum by air leaking through a 25 mm hole

5.1 Set-up

The specific set-up for the third accident simulation (TEST 3) is shown in Figure 2 on page 5, detail c. A large pneumatic valve was installed on the beam line flange of the cavity and equipped with an **orifice of 25 mm i.d.** to break the cavity vacuum with ambient air. The result of a room temperature calibration was that the orifice limited the air flow into vacuum to about 100 dm^3/s at STP or 120 g/s.

When the air valve was opened with LHe around the cavity, a very fast pressure rise occurred (Figure 5 on page 11). The safety valves started blowing violently less than 2 s after the opening of the cavity valve, without having any noticeable effect on the rising pressure. At $t_0 + 3$ s, when the LHe tank pressure reached almost 5 bar, a hollow sound was heard from inside the vacuum tank, and almost immediately afterwards cold helium started blowing fiercely from the vacuum tank protection valve. The pressure in the LHe tank dropped within 10 s to less than 2.5 bars, while a rain of particles of superinsulation come down from the hall roof.

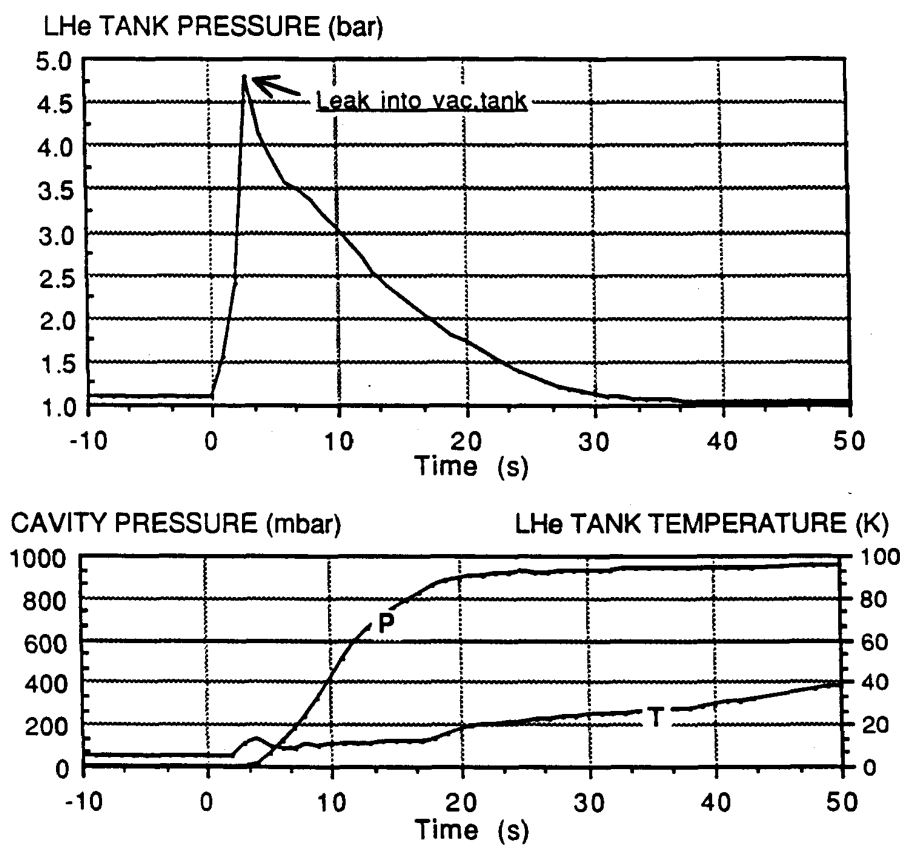

Figure 5: **TEST 3, 100 dm³/s STP of air into the cavity vacuum.** Top: LHe tank pressure versus time. Bottom: Cavity pressure and temperature of the lower part of the LHe tank.

5.2 Observations

The most interesting observations made during TEST 3 are summarized in Table 3 on page 12 and graphs for LHe tank and cavity pressures displayed in Figure 5. The warm-up of the LHe tank wall by the condensing air is also shown.

Fast analog recordings had to be used to get exactly the **sharp pressure peak** in the LHe tank: a maximum of 4.9 bar was reached 3.2 s after valve opening time t_0. The safety valve blowing started at $t_0 +$ 1.5 s and stopped already at $t_0 +$ 20 s.

The **cavity pressure** (bottom graph of Figure 5 on page 11 started rising surprisingly early, from $t_0 +$ 4 s); this is an indication of a fast saturation of cryopumping at the air flow rates used. This point will be analyzed in more detail in Chapter 6.

The **temperature of the LHe tank** bottom, as shown in the same graph, rose this time rather continuously without a clear jump at the end of LHe evaporation, due probably to the strong temperature gradient existing across the layer of solidified air and the cavity wall.

Table 3: Summary of vacuum failure tests 3 & 4 carried out with LEP1

	TEST 3	TEST 4
Simulated accident	Air into cavity vacuum	Air into cavity vacuum
Size of leak	25 mm dia. orifice	80 mm i.d. pneum. valve
Gas flow	About 100 dm3/s (120 g/s) continuous flow up to atmospheric pressure	About 1 m3/s (1.2 kg/s)
Pressure rise - At 1.2 bar abs. - At 3-4 bar abs.	 ≈0.8 bar/s ≈2.5 bar/s	 ≈8 bar/s
Safety valves start blowing at	to + 1 s	Safety v. : to + 0.2 s Rupt.disk : to + 0.35 s
Pressure maximum at	4.9 bar (rupture bath to + 3 s tank welding)	8.9 bar abs. to + 3 s
Pressure below safety v. setting	to + 20 s	to + 12 s
Apparent LHe level <50% of start level	to + 12 s	to + 1.2 s
Coldest temperat. on vacuum tank	292 K -> 253 K at about to + 45 min	No loss of insulation vacuum
Estimated heat input at start	≈50 kW ≈1 W/cm2	≈200 kW ≈4 W/cm2

5.3 Discharge into vacuum tank

Although this time most of the cold helium was directly blown across the vacuum tank, again only a rather limited cool-down of the **vacuum tank walls** occurred. At the coldest point observed on the bottom of the cylindrical envelope, the temperature reached 253 K at about $t_0 +$ 45 min. Everywhere else on the envelope (thickness 10 mm of aluminum and 1 mm of st.steel) and on the flanges (thickness 36 mm of aluminum) the temperatures remained higher. The minimum seen at the top of the shell was 271 K. The corresponding maximum **temperature gradient** across the height of the vacuum tank ($\approx$18 K) can probably be considered as close to the worst case possible. This is important for an estimate of the risk of deformations on longer modules combining several cryostats.

Already from the beginning there was no doubt that the safety valves installed on LEP1 were too small for major insulation accidents; nevertheless, we were struck by the fast pressure rise beyond 3 bar in the case of air leaking into the cavity through a 25 mm diameter hole only. It was rather fortunate that the pressure was finally prevented from rising further by some weak points in the LHe tank outer shell. After TEST 3, the vacuum tank was opened to know what **damage** the pressure peak had done, where the outer shell of the LHe tank had yielded and whether the niobium cavity had been deformed.

The first observation after opening the vacuum tank was the impressive destruction of the superinsulation produced by the discharge of the cold helium. This reminded us that special attention must be given to the fixation of the superinsulation upstream of the safety exhaust to exclude a partial obstruction.

The LHe tank itself had suffered very little. The leak across which the helium was blown into the vacuum tank consisted of three 14 mm dia. holes produced by the rupture of reinforcement struts welded into the walls of the rectangular helium gas collector ("C" in Figure 1 on page 3). It had already been replaced by a more solid solution in the cryostats built later.

The resonant frequency of the niobium cavity had also been re-measured. No clear frequency shift was observed ($\Delta f <$ 100 kHz) and thus no noticeable deformation of the wall geometry occurred.

6. Analysis of initial pressure rise and estimate of heat loads

6.1 Initial pressure rise

Figure 6 on page 14 shows the pressure values recorded during the first seconds after the start of the 3 tests. For the lowest curve with the initial pressure development in TEST 2, the 4 intervals between the 4 short periods of air admission to the vacuum tank were suppressed to fit all interesting data points to the same time range covered on the graph. The comparison of initial pressure slopes provides very useful qualitative information; however, in view of the sampling interval of 1 s and the limited number of measurements, only rough quantitative information can be extracted.

TEST 1 He into vacuum tank: The slope between the LHe tank initial pressure and the opening of safety valves is not constant. During the first 2 s there is an initial slope of 0.2 bar/s, falling then to less than 0.1 bar/s.

TEST 2 10 dm^3/s of air STP into vacuum tank: The air valve was opened 4 times on a trial basis and then left open continuously. The pressure slopes for the 5 start situations are surprisingly close to each other at about 0.1 bar/s.

TEST 3 100 dm^3/s of air STP into cavity vacuum: Only 4 valid digital readings are available between t_0 and $t_0 + 3$ s. Comparison with the analog recording confirmed that the pressure maximum occurred indeed just at $t_0 + 3.3$ s with about 4.9 bars, but showed also that the real start of pressure rise occurred slightly later than t_0 at about $t_0 + 0.3$ s. The initial slope is therefore about 0.8 bar/s, increasing to about 2.5 bar/s above 3 bars.

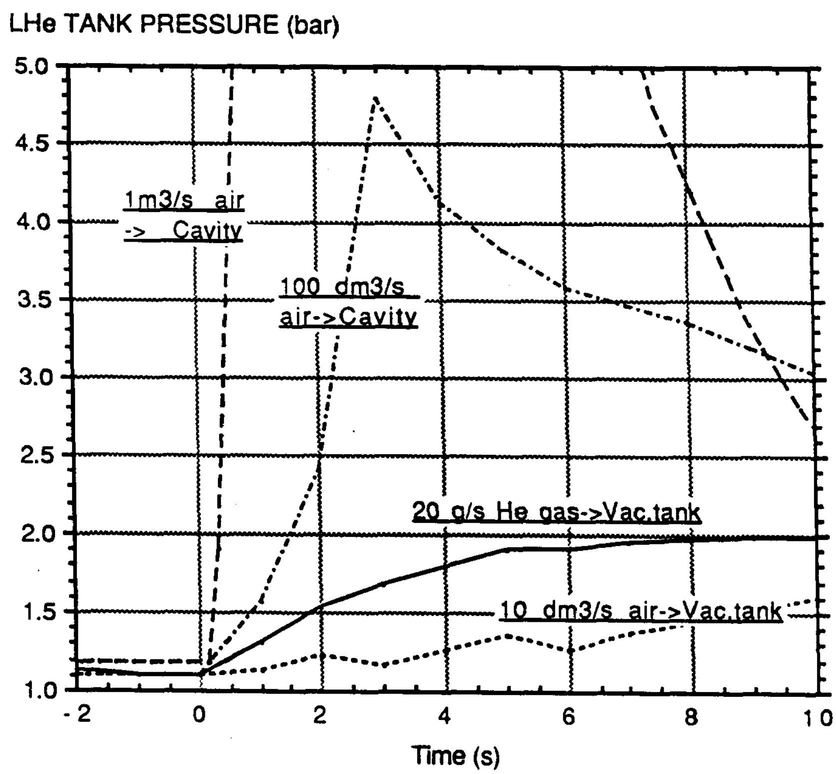

Figure 6: **Comparison of the initial pressure rises observed in TESTS 1-4.** The interruptions of air admission in TEST 2 were suppressed to fit into the 30 s interval displayed.

6.2 An estimate of initial heat loads

In order to be able to compare the observed test situations to a thermodynamic model for the behaviour of the cold helium in the LHe tank, it is useful to make an estimate of the heat load contributing to the pressurization of the tank filling. This can only be reasonably done for the initial phase before the opening of the safety valves with liquid helium in contact with most of the 6-7 m^2 of surface exposed to either the vacuum tank or the cavity side.

An estimate of the initial heat load is quite simple in the case of complete cryopumping of air. The full enthalpy of air between room temperature and the solid state (450 J/g) is then transmitted to the tank surface and, in view of the very low specific heat of metal below 20 K, to the helium inside. It thus can be concluded that TEST 2 corresponded to an initial heat load of about 5 kW ($\approx$0.07 W/cm^2) and TEST 3 of about 50 kW ($\approx$1 W/cm^2).

The case of helium gas in the vacuum tank (TEST 1) is not so simple for making an estimate, but typical values for practical cases are quoted in cryogenics textbooks. With helium pressures of 1 - 50 mbar in the vacuum tank and many layers of superinsulation, the heat transmission is mainly determined by simple gas conduction (thermal conductivity at 150 K: 0.1 W/m.K) over distances of typically 3 cm. Assuming a temperature difference of 280 K, we can roughly expect a steady state specific heat load of 0.05 W/cm^2.

On the other hand we can, for this simple qualitative analysis, use the similar initial pressure rise in TEST 1 and TEST 2 and conclude from the known heat load in TEST 2 that there was in TEST 1 an initial heat load of about 10 kW ($\approx$0.15 W/cm^2), falling later to a steady state value of less than 5 kW. This is in reasonnable agreement with our estimate for the specific heat load.

6.3 The development of air condensation in TEST 3

In order to be able to extrapolate from TEST 3 the safety requirements of a **worst case**, it is necessary to make also an estimate of the maximum heat load which has to be expected from air condensation. This question had been studied at the IEKP Karlsruhe in 1976 [2]. They found that the specific heat load to niobium surfaces at 4.2 K developed during 6 s after the start of air admission (32 mm i.d. line for 0.5 m^2 of cold surface) up to a maximum specific load of 3.8 W/cm^2, but falling then quickly to less than 2 W/cm^2 (from 10 s after start). Covering the cold surfaces with 10 layers of superinsulation reduced the peak heat load to about 1.8 W/cm^2. The slow development of the heat load over more than 5 s is probably mainly due to the specific arrangement used at Karlsruhe with evaporation near atmospheric pressure and presence of a gas volume ($\approx$30 dm^3) similar to the liquid volume.

We can conclude from TEST 2 that there is no noticeable heat load limitation due to the presence of superinsulation in the LEP1 vacuum tank, at least with air flows of 10 dm^3/s and complete cryopumping for quite some time. TEST 3 showed further that with stronger air leaks, heat loads of 1 W/cm^2 develop very quickly, at least for the geometry used with the LEP cryostats. The steepening of the initial slope in the upper graph of Figure 6 on page 14 is mainly due to the thermodynamics of cold helium around the critical point, as will be clear from the following model discussion.

We have, however, to assume from the measurements at Karlsruhe that peak values of heat load around 4 W/cm^2 without superinsulation and around 2 W/cm^2 with a few layers of superinsulation are possible if air leaks are produced with cross-sections of more than 10 cm^2.

On the other hand, TEST 3 revealed also that such peak loads cannot last for more than a few seconds. The early rise of the cavity pressure in Figure 5 on page 11 is an indication that the heat transfer is quickly limited by the heat resistance of the developing layer of solid air. Using this argument, we tried to extract from the observed cavity pressure the time dependance of the total heat load. This is done in Figure 7 on page 16.

We can assume that the cavity pressure is, for values below the critical pressure of nitrogen (0.12 bar at 63 K), identical to the vapour pressure of the gas-solid interface. For pressures between 0.12 bar and atmospheric pressure, liquid instead of solid air is formed until the LHe tank walls are warmer than 77 K. We can further interpret the rising pressure in the cavity as corresponding to air at a mean temperature between room temperature and that of the solid surface. The balance between the air flowing into the cavity at a constant rate (as long as the cavity pressure is below 50% of the atmospheric pressure) of $\approx$120 g/s and the air contributing to the gas pressure must have been cryopumped with heat transmission of 450 J/g.

The distribution of the air quantities are shown in Figure 7 on page 16, b, the corresponding integrated heat in Figure 7 on page 16, c and the time development of the instantaneous power input to the cavity in Figure 7, d.

Our conclusion is that, at air flow rates higher than those used in TEST 3, probably peak powers of up to 200 kW can occur, but they last only for 1-2 s, and from an accumulated heat load of 200 kJ on, the power load should already have dropped to less than 50 kW.

This seems not unreasonnable, looking at the equivalent thicknesses of air "snow". 200 kJ total load corresponds to 4 J/cm^2 or 10 mg of solid air per cm^2 and an equivalent thickness of a compact solid layer of 0.1 mm.

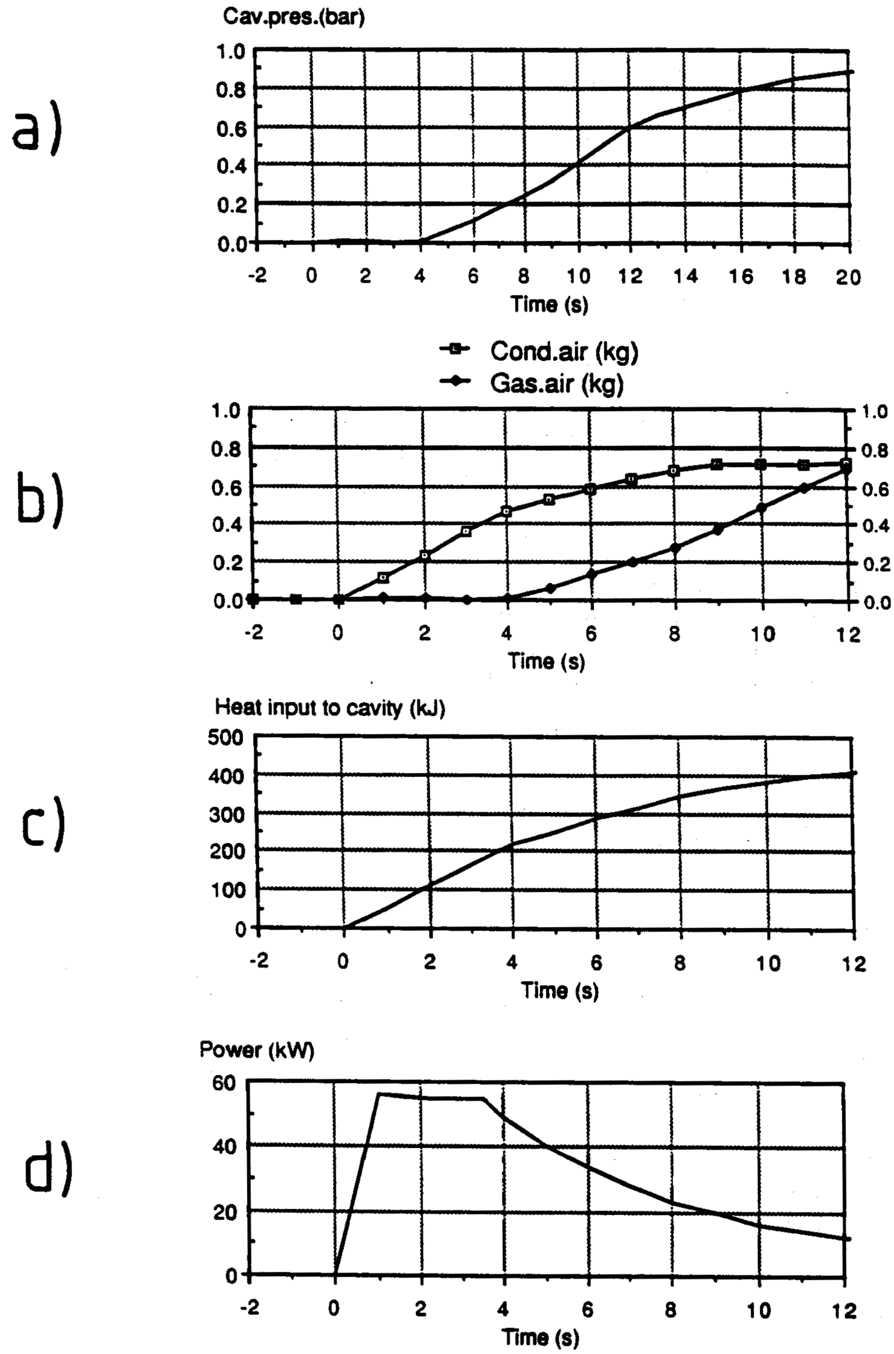

Figure 7: **Analysis of the cavity pressure during TEST 3**

7. Study of a thermodynamic model for the discharge from the LHe tank

To understand the relation between the instantaneous heat input to the cold helium and the pressure build-up, we studied the thermodynamics of a **simple model**. It consists of a closed volume of 205 dm^3 with, at start, 180 dm^3 of liquid and 25 dm^3 of gaseous helium at 4.3 K. We introduce heat into this volume and assume equal distribution and good mixing, such that a uniform temperature is maintained over the full volume. Once a given pressure ceiling is reached (2, 3 or 5 bar are studied), discharge through a safety valve at constant pressure is assumed. The helium flowing into the safety valve is supercritical at 3 and 5 bar; at 2 bar it is first liquid and then gaseous as soon as with the rising temperature a gas phase can again exist.

The model seems, despite its simplifying assumptions, to correspond quite well to the observed behaviour our LHe tank. The assumption of temperature uniformity is certainly close to reality during the first 100 s in TESTs 1/2 and during the first 10 s in TEST 3, where distribution of the incoming heat over a very extended surface and violent convection prevail. This is no longer true, once the apparent liquid level dropped, but this second phase is anyhow of secondary interest for our risk evaluation.

In order to have results which can be interpreted independently of specific test conditions, the development of all properties studied for the model system are shown as function of the total heat input to the helium present. The solid lines in Figure 8 on page 19 correspond to a pressure ceiling of 3 bar. In addition a few points are shown for comparison at 2 and 5 bar

The first phase of the pressure increase from 1.1 to 1.6 bar Figure 8 on page 19, a+b) corrresponds to the **warm-up** of the liquid helium from 4.3 to 4.8 K and the recondensation of the gaseous helium present at the beginning; it requires 50 kJ. Then follows a much faster pressurization without gas phase, resulting at {2 bar, 4.9 K} with a total of 58 kJ, at {3 bar, 5.16 K} with 74 kJ and at {5 bar, 5.76 K} with 111 kJ.

Then starts the **discharge** of helium as shown in Figure 8 on page 19, c. This happens at constant temperature for pressure ceilings below the critical pressure of 2.3 bar and at increasing temperature for higher pressures. At 3 bar, half of the helium mass is ejected by a total heat input of 300 kJ; at the 5 bar limit, 430 kJ are necessary. The difference in energy is due to the fact that at higher pressure more energy is converted into the kinetic energy of the helium jet. The He temperature has risen, at 50% discharge, to 5.8 K in the 3 bar case and to 7.3 K at 5 bar.

Figure 8 on page 19d gives the **heat content of the metal** (145 kg of niobium + 131 kg of st.steel) in contact with the helium (temperatures as in Figure 8 on page 19, b). It becomes evident that below temperatures of 20 K, no delay of heat transfer can be expected from the heat capacity of the metal walls on either side of the tank.

At heat loads of 1-2 W/cm^2, the limited thermal conductivity across the wall thickness certainly produces a temperature difference, but the effect on the heat load is small, as the enthalpy difference for air between room temperature and solidification is very much the same, whether the solidification occurs at 50 K or at 5 K. At an extreme heat load of 4 W/cm^2, the temperature of the air-side wall surface would be about 8.5 K for the cavity (3 mm of niobium, typical conductivity 0.3 W/cm.K) and 40 K for the LHe tank (2mm of st.steel, 0.8 W/cm integrated conductivity).

The most important information for our safety discussion is in Figure 8 on page 19, e+f. For Figure 8 on page 19e we calculated the **maximum fluid speed** one can achieve when expanding the cold helium from the ceiling pressure to atmospheric pressure. It is equal to the square root of twice the enthalpy difference between the 2 pressure levels, assuming an isentropic expansion. After expansion, a 2-phase mixture is formed with, at the beginning, a high fraction of liquid. Speeds are typically below 80 m/s for 3 bar and below 100 m/s for 5 bar, which is in good agreement with the fact that cold helium has a sound velocity only slightly above 100 m/s.

Combining the excess mass ejected of Figure 8, c with the maximum speed possible, we obtain the **minimum effective cross-section** per unit input power, required for venting to atmospheric pressure without exceeding the given pressure ceiling. The results are shown in Figure 8, f. The values are slightly above 0.1 cm^2/kW for a 5 bar limit, reach 0.2 cm^2/kW for 3 bar, and go close to 0.3 cm^2/kW for 2 bar if phase separation and ejection of gaseous helium is assumed.

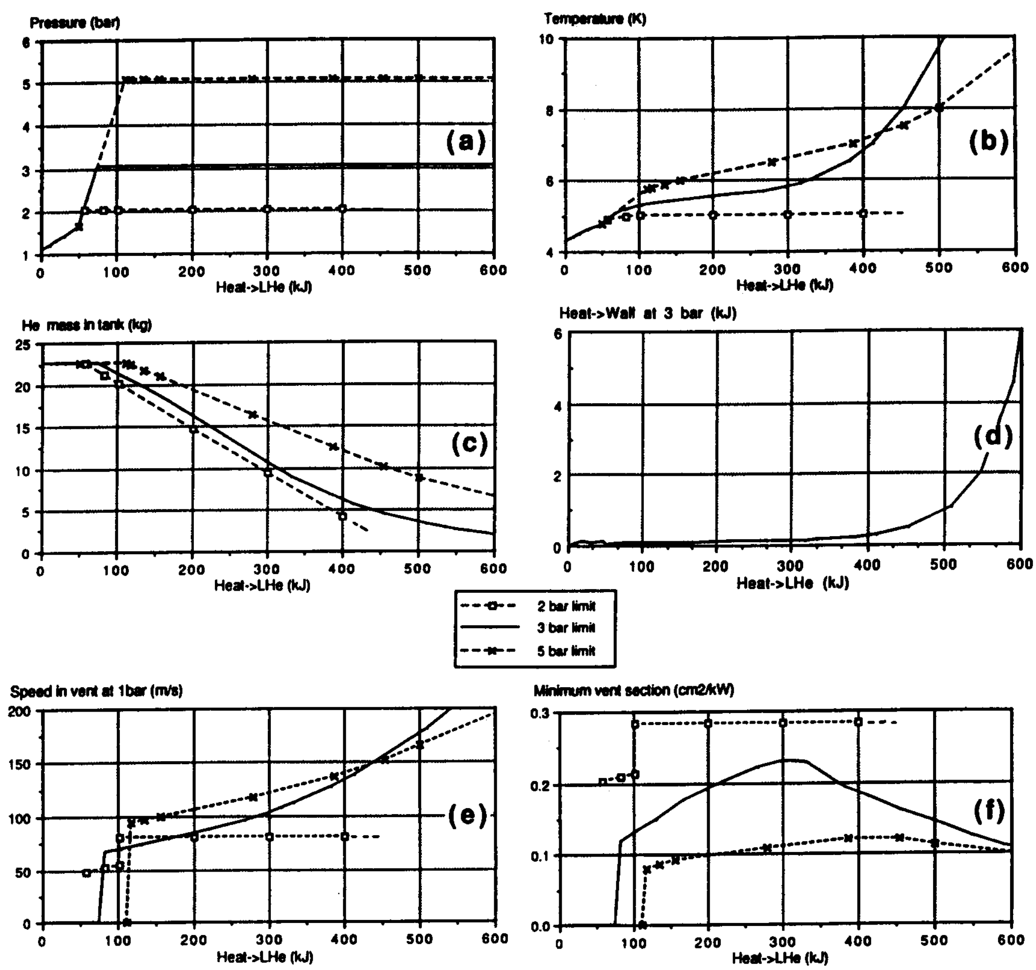

Figure 8: **Study of a thermodynamic model for the discharge from the LHe Tank of LEP1.** Are shown as function of the integrated heat input to the He in the LHe: The pressure in the LHe tank (a); the temperature of the He assumed uniform (b); the mass of the helium left in the tank (c); heat absorbed by the tank walls (d); average speed of the helium after expansion to atmospheric pressure (e); required vent line cross – section per unit of power input (f). In general a pressure limit of 3 bar abs. is assumed. For comparison some results are shown with limitation to 2 or 5 bar

8. TEST 4: 80 mm air leak into cavity as worst case

8.1 Set-up

To achieve heat loads and pressure rise times close to the worst possible case, a fast-acting pneumatic valve of 80 mm i.d. was installed on the beam pipe of the test cavity and one of the safety valves replaced by a 50 mm i.d. rupture disk. However, for reasons of constraints imposed by other tests, its connection to the LHe bath had to be done via a 1-m long pipe of generally 40 mm i.d., which however had only 35 mm i.d. on the first 10 cm (connection "B" in Figure 1 on page 3) and consisted for other 45 cm only of ondulated bellows. The flow capacity of the rupture disk was thus considerably influenced by this safety line.

Preliminary tests showed that the valve opened within 0.2-0.3 s and that at room temperature the cavity pressure rose in 1 s from vacuum to close to atmospheric pressure. The equivalent initial air flow rate is about $1 m^3/s$.

8.2 Observations

When the air admission valve was opened on the cold cavity with the LHe tank filled to normal level, a very violent discharge through the rupture disk occured within a fraction of a second and, nevertheless, a peak pressure of almost 9 bar was reached in the tank. No leak into the vacuum tank was observed and, after warm-up, no measurable shift of the cavity resonance and only a limited deflection of the safety line bellows was found.

The main observations are summarized in right column of Table 3 on page 12 and the fast rise of the pressurse in cavity and LHe tank are displayed in Figure 9.

8.3 Analysis of pressure rise in TEST 4

The cavity pressure reached nearly atmospheric pressure in only 2 s. There was no appreciable delay in the initial pressure rise. This means that the air inflow is faster than the initial cryopumping and more flow would hardly influence any more the heat load. The load reached in TEST 4 can be considered as worst case.

The initial slope of the LHe tank pressure, as shown in Figure 6 on page 14 with an increase from 1.2 bar to 5 bar in about 0.5 s corresponds in our model (Figure 8 on page 20, a) to a heat input of about 100 kJ, a power of 200 kW and a specific load of $\approx$**4 W/cm²**.

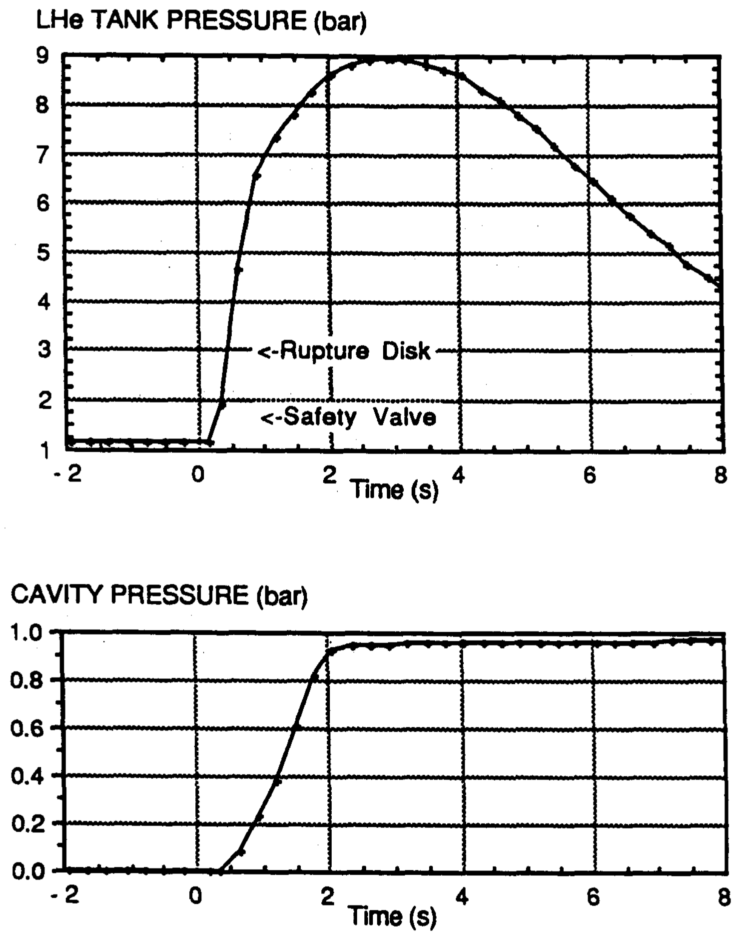

Figure 9: **TEST 4, ≈1 m^3/s of initial air flow into the cavity vacuum.** Top: LHe tank pressure versus time. Bottom: Cavity pressure.

9. Conclusions for the pressure protection of the sc cavities at LEP.

- Maximum specific heat loads of **4 W/cm²** into the LHe bath can occur when the vacuum of LEP type niobium cavities is broken with air through a hole of more than about 50 mm diameter. Such accidents are unlikely in normal operation, but can happen either by damaging the beam pipe or by a complete failure of the ceramic window in the main rf coupler.

- A simple isothermal **model** for the fast heating of the LHe tank gives satisfactory agreement with test results.

- For handling the **worst case**, we have to combine a maximum heat load of 200 kW with a value of 0.1-0.2 cm^2/kW as minimum requirements for the specific safety line cross-section as found from the model calculations. The result for the necessary vent line cross-section of the LHe tanks surrounding the sc LEP cavities is 20 cm^2, if peak pressures of 5 bar can be tolerated for the very unlikely worst case, or 30-40 cm^2 for peak pressures below 3 bar.

In addition, the vent line pipe must be short and wide enough with smooth transitions to assure that the helium discharge is mainly determined by an isentropic expansion to the atmosphere.

- The LEP1 cavity with 3-mm thick niobium of RRR < 50 resisted to a **peak overpressure** of almost 8 bar, apparently without damage. The first series of cavities in LEP will be made of niobium with higher RRR and accidental overpressures must therefore not exceed 4 bar.

- With the present design, it turned out to be very difficult to fit a safety line with more than 20 cm^2 cross-section. A 50-mm **rupture disk** will therefore be fitted to the safety line of each of the first 32 sc cavities, which will be installed in LEP by groups of 4 during the next 2 years.

  It is, however, expected that the peak overpressure seen in TEST 4 can be reduced to half by using all possibilities to lower the line impedance. This will be checked in a final safety test with LEP1.

- TESTs 1 and 2 showed that all current accidents with heat load to the LHe bath, such as a helium leak into the insulation vacuum and air leaks into cavity or insulation vacuum through holes of up to 10 mm diameter, can safely be handled by a 1.25-inch **safety valve.** Such a safety valve with a 1 bar breaking pressure will be maintained for the LEP cavities to protect the rupture disk with its 2-bar set point.

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