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ACROSS LARGE DIFFERENCES IN ELEVATION

by

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Superconducting devices, installed in the deep underground tunnels of high-energy accelerators, can be fed with liquid helium from cryogenic plants located in accessible areas at ground surface or at intermediate levels. For this purpose, controlled transfer of liquid helium is required across large differences in elevation. Subsequent to demonstration of feasibility of this technique in a special test across a height of 25 m, a superconducting RF cavity, housed in a bath cryostat fed through a 100 m long transfer line, has been operated successfully in a real accelerator 60 m below ground.

INTRODUCTION

To comply with technical, economical and environmental constraints resulting from their large size and strong radiating beams, modern high-energy accelerators and colliders are installed in underground tunnels. At CERN, due to geotechnical reasons, the tunnels and experimental caverns of the SPS proton synchrotron and LEP electron-positron collider lie at depths ranging from 20 m to 150 m below ground. Although based on conventional (resistive) technology, these machines contain superconducting devices, such as low-beta (final focus) quadrupole magnets [1, 2] and accelerating cavities [3], operated in saturated liquid helium bath cryostats. In view of the high occupancy, limited access and technical inconvenience of locating the associated cryogenic equipment in the immediate vicinity of the accelerators, it is often desirable to feed these superconducting devices from surface buildings, or from platforms at an intermediate level, by means of long cryogenic transfer lines spanning large differences in elevation.

Two classes of problems frequently encountered in low-temperature engineering could hamper proper operation of such a transfer scheme, namely (i) parasitic heat loads, resulting in excessive loss of liquid due to the low latent heat of vaporization of helium, and (ii) flow instabilities, created by the coexistence of two phases in the pipe at proximity of the critical point.

Consequently, before any application to an operational device could be envisaged, it was necessary to assess the feasibility of the technique in a full-scale test.

FEASIBILITY TEST

Test set-up

The test was based on the reuse of an existing 50 m long, flexible vapour-screened transfer line [4], the flow and heat inleak characteristics of which had been previously measured in quasi even-level operation [5]. The line was reinstalled in the stairway of an eight-floor office and laboratory building, thus providing an elevation difference of about 25 m.

A schematic view of the test set-up appears in Fig. 1. Helium was transferred from a buffer dewar, situated on the higher floor, through the inner channel of the transfer line (corrugated pipe with a free inner diameter of 10 mm), and into a test cryostat equipped with an adjustable heat load (electric heater), located on the lower floor. The liquid level in the cryostat was measured by means of a continuous superconducting gauge, and controlled by throttling the liquid withdrawal from the dewar with a cold valve, actuated by an electric motor. A variable fraction of the cold vapour produced in the test cryostat by losses, as well as by the applied heat load, was returned through the line screen for thermal shielding. All gas flows out of the system were continuously measured using mass flowmeters, while the transfer pressure difference was read on a precision aneroid manometer.

The transfer losses were estimated by subtracting the flow of liquid vaporized in the test cryostat (heat inleak and applied heat load) from the flow of pure saturated liquid withdrawn from the dewar; in steady operation, the latter is just equal to the total gas flow out of the system. The origin of these transfer losses are discussed in the following.

Thermodynamics

The conservation of energy, as applied to the fluid flowing through the line, can be expressed as follows

$$\dot{\Delta H} + \dot{m}g \Delta z = \dot{Q}$$

with

$\dot{\Delta H}$	enthalpy variation rate of fluid
Δz	difference in elevation
g	acceleration of gravity
$\dot{m}$	mass flow-rate of fluid
$\dot{Q}$	line heat inleak

Expressing $\dot{\Delta H}$ as a function of the exit vapour quality x and of the enthalpy per unit mass of the liquid and vapour phases, yields

$$x = \underbrace{\dot{Q} / L_v \dot{m}}_{\text{boiling}} + \underbrace{\Delta H_1 / L_v}_{\text{flashing}} - \underbrace{g \Delta z / L_v}_{\text{potential energy}}$$

with

L_v	latent heat of vaporization of fluid
ΔH_1	enthalpy variation of liquid across transfer pressure difference.

Hence, liquid helium is vaporized in the line by three processes, the effects of which algebraically add up, namely (i) boiling due to heat inleak, (ii) flashing due to expansion and (iii) release of gravitational potential energy.

Considering the typical values encountered in the test of 50 mbar for the transfer pressure difference, and 25 m for the difference in elevation, it appears that the last two processes vaporize only about 1 % each of the transferred liquid. Consequently, for the flow-rates of interest (0.1 to 1 g s⁻¹), the heat inleak into the line remains the main source of transfer losses.

Level control

Due to the rather large inner diameter of the helium pipe, which is required to pass gaseous helium during cooldown, the average velocity in the line is small. A time delay is then observable between an opening of the control valve and the resultant level increase in the cryostat. A decrease of the proportional gain or of the bandwidth of the control loop such as to reach a non-oscillatory behaviour would result in a reaction time incompatible with consumption changes to be expected in magnets or cavities. The closed loop has then an essential nonlinearity giving oscillation periods of between half a minute for a horizontal line, and 20 minutes for a line

with a regular slope. The best adjustment of a normal PID controller is obtained with a high gain of the derivative to shorten the oscillation period. This delay problem is enhanced by the heat accumulation in the line when the valve is closed, resulting in a sharp level decrease at valve opening. Furthermore, a lower cryostat consumption increases the time needed to absorb the overshoot (see table below).

Besides artificially increasing the cryostat heat load, two strategies can be envisaged in case of excessive oscillations: (i) maintain a base flow lower than the minimum consumption of the system, or (ii) use a fully bang-bang control sending bursts of liquid at a faster rate than the normal oscillation period.

Results

Two series of tests were run, with two different line layouts across the same elevation difference: one with the line installed in a helical pattern along the staircase (Fig. 2), the other with the line going straight down for 25 m and then quasi-horizontally for the remaining 25 m. The results, summarized in the table below, call for the following comments:

- transfer losses always remain small; out of the measured 4 W, about 3 W are due to heat inleaks into the line and test cryostat 4, while the remaining fraction can be attributed to the control valve;
- in all cases, the level in the test cryostat can be adequately controlled, with maximum peak-to-peak oscillations of about 1 liter;
- the amplitude and period of the level oscillations decrease markedly as the applied heat load is increased from 5 W to 10 W;
- the vertical/horizontal layout definitely allows better level control than the constant slope helical layout; in the former case, the final quasi-horizontal section of line probably buffers flow surges which could occur in the vertical section, thus steadying the flow into the test cryostat.

SUMMARY OF TEST AND OPERATION RESULTS					
Height (m)	Layout	Cryostat heat load (W)	Transfer loss (W)	Level oscillation Amplitude (eq ^t lit)	Period (mn)
25	Helical	5	3.8	1.0	18
25	Helical	10	4.3	0.6	14
25	Vert/Horiz	5	4.1	0.4	11
25	Vert/Horiz	10	4.3	0.2	5
60	Vert/Horiz	~ 25	< 15	5	-

OPERATIONAL TEST OF A SUPERCONDUCTING RF CAVITY

An opportunity to gain experience in a realistic operating environment was provided by the need to install and test a prototype LEP superconducting accelerating cavity in the SPS accelerator [6]. To be able to perform early tests in autumn 1987, before a dedicated, remote-controlled helium refrigerator could be installed in the immediate vicinity of the cavity, liquid helium was supplied from dewars at ground level via a 100 m long coaxial transfer line, assembled from two 50 m long line recovered from a previous set-up [5]. The line layout featured a vertical section, going down a 60 m deep access pit, followed by a 30 m long quasi-horizontal section arranged in a gentle loop before entering the cryostat. The liquid helium level in the cryostat

was controlled from the surface by a throttle valve in a distribution box at the line inlet. Since almost all the cold vapour generated in the system was available for thermal screening, the transfer line exhibited good performance: the overall transfer losses (two unshielded laboratory transfer lines, distribution box, long coaxial transfer line) amounted to less than 15 W, of which 10 W can be attributed to the 100 m-long coaxial line. Moreover, due to the rather high heat load of the cavity (about 25 W static), helium transfer was very steady. Pressure oscillations in the cryostat, which could become critical for cavity operation, showed a maximum amplitude of 10 mbar over several hours of operation. The performance of this transfer line under variable operating conditions will be further investigated, using a dedicated test set-up presently under construction.

FUTURE PLANS

The preceding experience has demonstrated the feasibility and convenience of feeding saturated helium bath cryostats installed in deep accelerator tunnels from accessible surface facilities. In the near future, the low-beta superconducting quadrupoles equipping one experimental area of the LEP electron-positron collider, installed in a cavern at a depth of 44 m, will also be fed with liquid helium, through similar lines, across a difference in elevation of 23 m (Fig. 3).

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Fig. 1: Flow-scheme of transfer test set-up

Fig. 2: Transfer line installed in helical pattern along staircase

Fig. 3: Liquid helium transfer to superconducting quadrupole magnets at LEP experimental area No. 2