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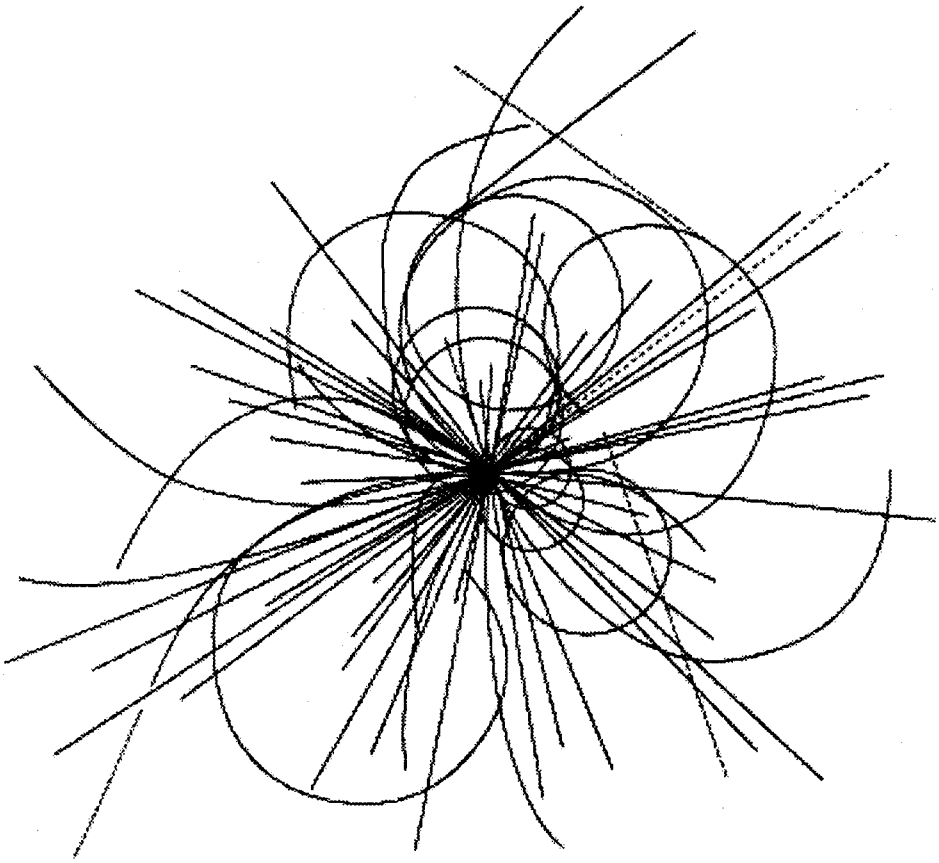

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A Study On Sector Nitrogen Inventory Emergency Venting*

B. Zhang

Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave.
Dallas, TX 75237

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A STUDY ON SECTOR NITROGEN INVENTORY EMERGENCY VENTING

Burt Zhang

Accelerator Systems Division
Superconducting Super Collider Laboratory*
2550 Beckleymeade Avenue
Dallas, Texas 75237

INTRODUCTION

The main ring of the Superconducting Super Collider consists of 10 sectors. Each sector has 4 strings and the total nitrogen inventory in a nominal string (4,320 m) is approximately 8,856 kg (2,894 gal)[1]. There are occasions when part of the collider nitrogen inventory needs to be vented in an emergency fashion. Due to the large quantity of the nitrogen inventory and the high elevation differential between the below-ground collider ring and the above-ground vent stack, it is essential to vent the nitrogen inventory in the vapor phase. Uninsulated dump tanks are provided at all sites to collect and vaporize liquid nitrogen expelled from the strings. Vapor nitrogen is then vented through a vent stack at surface level into the atmosphere. An emergency venting starts when a remote control valve in the nitrogen subcooler box opens. The string nitrogen inventory is then discharged into the dump tank. Around 100 kg nitrogen inventory will be discharged before the string inventory reaches a saturation state at certain location. After that, the static heat leak into the 80 K circuit (16,250 W per string) becomes the dominating driving force to expel the nitrogen inventory. Due to the length of the string, the boil-off bubbles are localized. The mass boil-off rate is translated into a much higher mass flow rate expelled from the string. The string saturation pressure is dynamically balanced by the total pressure drop between the string and the vent stack. The capacity requirement for the nitrogen dump tank reaches the maximum when the dump tank at each site has to handle the nitrogen inventory in two strings, which is approximately 17,712 kg (5,788 gal). This work is intended to analyze the volume capacity requirement for the nitrogen dump tanks for this worst scenario. A computer program is developed to numerically simulate the emergency venting process. The string, dump tank, and venting paths are modeled individually and then linked to impose the constraints.

ANALYSIS

In a venting process, the string pressure is first relieved from nominal operating pressure to a saturation pressure. The static heat leak vaporizes nitrogen at a rate $\dot{M}_v = \dot{Q}_s/L_s$, where $\dot{M}_v$ is the mass rate at which nitrogen is vaporized in the strings, and L_s is the latent heat of nitrogen evaluated at string pressure. Due to the slender geometry of the strings, the vapor generated in time is entrapped along the strings. The mass expelled per unit time $\dot{M}_e$ is much greater than that being vaporized, which is governed by the equation

$$\dot{M}_e = \dot{M}_v \frac{v_g - v_f}{v} \tag{1}$$

here $v = xv_g + (1-x)v_f$ is the specific volume, x is the quality, and v_g and v_f are the specific

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volumes of saturated vapor and liquid respectively. Equation 1 indicates that the driving force that expels the nitrogen inventory in the strings is the difference in specific volume between saturated vapor and saturated liquid. The dump tank collects, temporarily contains, and vaporizes nitrogen expelled from the strings. The venting mass rate from the tank to the vent stack is given by

$$\dot{M}_o = \frac{\dot{Q}_t + \dot{Q}_w}{L_t} + x\dot{M}_v \tag{2}$$

where L_t is the nitrogen latent heat at tank pressure, and x is the quality of nitrogen inventory in the strings. The first term in this equation represents the mass rate being vaporized in the tank, and the last term is the vapor portion of the mass rate into the tank. $\dot{Q}_t$ in Equation 2 represents the heat transfer rate to the bulk nitrogen in the tank from the underground enclosure environment. It has the form

$$\dot{Q}_t = (T_a - T_i)/\sum_{j=1}^{N} R_j, \qquad N = 4 \tag{3}$$

where T_a and T_i are ambient air and bulk nitrogen temperatures respectively. The heat transfer process between the ambient air and the liquid nitrogen in the dump tank includes conduction, convection and radiation modes. The denominator in Equation 3 is the sum of heat transfer resistance which includes the following four resisters

$$\sum_{j=1}^{N} R_j = R_o + R_f + R_w + R_i, \qquad N = 4 \tag{4}$$

where R_o denotes the heat transfer resistance between the ambient air in the tunnel and the outer surface of the frost formation on the dump tank, R_f is the frost conduction resistance, and R_w, and R_i represent the resistances through the tank wall and at the inner surface of the dump tank respectively. The heat transfer between the ambient air in the tunnel and the outer surface of the frost formation is due to free convection and radiation. The resistance is characterized by

$$R_o = \frac{1}{H_c + H_{rad}} \tag{5}$$

where $H_c = N_u k_a / L_c$, L_c is a characteristic length (tank height), k_a is the thermal conductivity of ambient air, and the Nusselt number is evaluated using the formula

$$N_u = \left[.825 + \frac{.387 R_a^{1/6}}{\left[1 + (.492/P_r)^{9/16}\right]^{8/27}} \right]^2 \tag{6}$$

The Prandtl number for air P_r is evaluated at tunnel ambient temperature, and the Rayleigh number $R_a = G_r P_r$ is calculated using

$$G_r = g\beta \frac{(T_a - T_o) L_c^3}{\nu_a^2} \tag{7}$$

$$\beta = \frac{2}{T_a + T_o} \tag{8}$$

T_o here is the temperature at the outer surface of the frost formation, ν_a is the kinematic viscosity of air, and g is the gravitational acceleration. The radiative heat transfer coefficient in Equation 5 is calculated using $H_{rad} = \epsilon\sigma \left(T_a^4 - T_o^4\right) / (T_a - T_o)$ where ϵ and σ are the emissivity of the frost formation surface and the Stefan-Boltzmann constant respectively. The second resister is due to the conduction resistance of the frost formation. The conduction resistance of the frost formation depends on the venting duration and moisture content of the ambient air in the underground enclosure. A value $R_f = 2 \times 10^{-4}$ K/W is used in this study. The third resister is the stainless steel tank wall. The evaluation of this resister involves an integral of the thermal conductivity of stainless steel over the temperature range between the outer and inner wall surface temperatures T_{wo} and T_{wi}

$$R_w = \frac{(T_{wo} - T_{wi}) W}{K} \tag{9}$$

in which K is the thermal conductivity integral for stainless steel over the given temperature range,

$$K = \int_{T_{wi}}^{T_{wo}} k_{ss} dT \tag{10}$$

W is the thickness of the tank wall, and k_{ss} is the thermal conductivity of stainless steel, which increases with temperature. This integration process is repeated at each iteration when the temperature range is updated. The fourth resister R_i represents the resistance to convective heat transfer between the inner surface of the tank wall and the contained bulk nitrogen. As the temperature difference $T_{wi} - T_i$ pass the Leidenfrost point and hence the heat transfer process under discussion falls in the film pool boiling regime, the correlation

$$N_u = .64 \left[\frac{g(\rho_f - \rho_g) L'_{N_2} L_c^3}{\nu_g k_g (T_{wi} - T_i)} \right]^{.25} \tag{11}$$

is used to yield the convective heat transfer coefficient with the corrected latent heat given by

$$L'_{N_2} = L_{N_2} + .4 C_p (T_{wi} - T_i) \tag{12}$$

Properties used to calculate the Nusselt number N_u are evaluated at the film temperature $T_f = (T_{wi} + T_i)/2$. The term $\dot{Q}_w$ in Equation 2 represents the heat ejected from the tank walls as the tank is filled and cooled down. It is given by $\dot{Q}_w = C\dot{M}\Delta T_w$, where C is the specific heat of the tank wall material (stainless steel) evaluated at the average wall temperature, $\dot{M}$ is the rate at which the tank wall mass comes in contact with the bulk nitrogen in the dump tank, and ΔT_w is the average temperature change of the tank wall during the initial cool-down. The equations listed in this section are solved to produce two nitrogen mass flow rates. The first is the mass rate expelled from the strings, the second is the one that leaves the tank being vented through the vent stack. Special interest is focused on the process before these two mass rates have the same magnitude when the accumulated liquid in the tank reaches the highest level, which determines the capacity requirement for the dump tank. Thermodynamic properties of nitrogen are generated using a computer subroutine[3]. They are updated at each iteration and time step.

RESULTS

The simulated time history of the venting is presented in Figure 1 in terms of masses in the strings and dump tank. In less than 15 minutes, approximately 7,500 kg (2,450 gal) of nitrogen

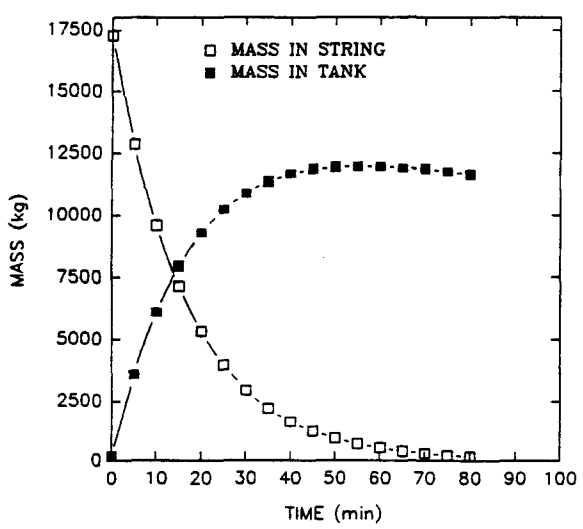

Figure 1. Time history of masses in string and dump tank

will accumulate in the dump tank, which equals to the remaining nitrogen quantity in the strings. The vented mass by this time is slightly over 2,700 kg (882 gal). The accumulated nitrogen mass in the tank reaches a maximum of 12,000 kg (3,921 gal) in less than 60 minutes after the venting started. At this time, over 96% of the string nitrogen inventory has been discharged, and approximately 29% of the inventory has been vented. The mass flow rates into and out the dump tank are compared in Figure 2 as functions of time. The initial mass flow rate into the dump tank is about 17 kg/s which drops rapidly as the string nitrogen reaches a saturation pressure. Further reduction of this mass flow rate is due to the variation of the string nitrogen inventory quality which increases from

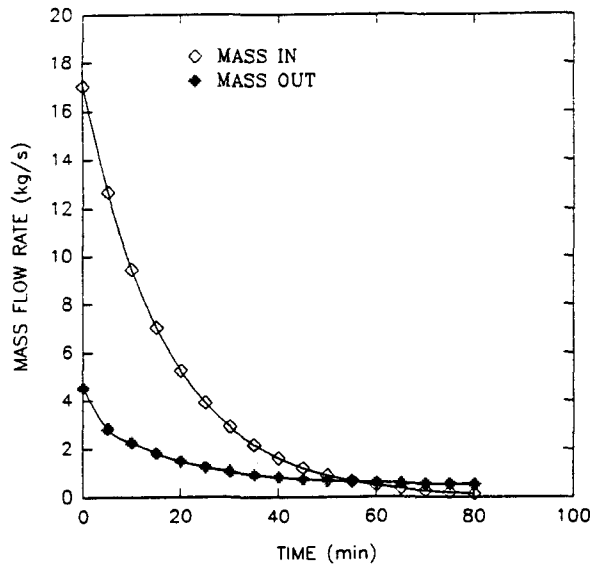

Figure 2. Mass flow rates into and out dump tank as functions of time

0 to over 0.8 within the first 80 minutes of venting. The venting mass flow rate has a starting value of less than 5 kg/s. It drops below 1 kg/s when the dump tank is cooled down and remains almost constant after 40 minutes of venting. The two curves intercept each other in about 55 minutes after the venting started, which corresponds to the moment when the accumulated liquid nitrogen reaches its highest level in the dump tank. After 80 minutes, the remaining mass in the strings falls below 160 kg which is less than 1% of total inventory. This may be considered as the end of the venting process. The subsequent venting of the accumulated nitrogen mass in the dump tank takes approximately 6 hours, which is of less concern.

SUMMARY

The dynamic process of the SSC tunnel nitrogen inventory emergency venting has been numerically simulated. Time histories of both the remaining string nitrogen inventory and the nitrogen accumulation in the dump tank are generated along with the mass flow rates into and out the dump tank. For a predetermined inner diameter of the dump tank, the minimum capacity requirement of the dump tank is determined. It corresponds to the highest liquid nitrogen accumulation level in the dump tank. Heat ejected by the tank wall during the initial flash-off and the subsequent cool-down vaporizes a large portion of the accumulated liquid nitrogen. Since the latent heat of nitrogen slightly decreases with increasing pressure, the string pressure during venting should be kept minimal, which requires a small pressure drop through the venting path. The string pressure will dynamically build up to a level required to overcome the resistance in the venting path. According to the simulation results, the minimum capacity requirement for the dump tank at each site should be 15.14 m^3 (4,000 gal).

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