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Helium Release Rates and ODH Calculations from RHIC Magnet Cooling Line Failure

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Abstract

A catastrophic failure of the magnet cooling lines, similar to the LHC superconducting bus failure incident, could discharge cold helium into the RHIC tunnel and cause an Oxygen Deficiency Hazard (ODH) problem. A SINDA/FLUINT® model, which simulated the 4.5K/ 4 atm helium flowing through the magnet cooling system distribution lines, then through a line break into the insulating vacuum volumes and discharging via the reliefs into the RHIC tunnel, had been developed. Arc flash energy deposition and heat load from the ambient temperature cryostat surfaces are included in the simulations. Three typical areas: the sextant arc, the Triplet/DX/D0 magnets, and the injection area, had been analyzed. Results, including helium discharge rates, helium inventory loss, and the resulting oxygen concentration in the RHIC tunnel area, are reported. Good agreement had been achieved when comparing the simulation results, a RHIC sector depressurization test measurement, and some simple analytical calculations.

INTRODUCTION

RHIC consists of twelve sextants in two rings [1] (see Fig. 1). Total helium inventory in each sextant is about 1365 kg (or 273000 SCF). Between adjacent sextants, isolation valves and pressure relief valves are installed on the Valve Boxes, outside the RHIC tunnel, to control the helium flow. Low pressure vacuum tank reliefs are installed along the magnet and the transfer line cryostats, inside the tunnel, to protect the tanks from over pressure. When a catastrophic failure of the magnet cooling lines occurs, similar to the LHC superconducting failure incident, a tremendous amount of helium could leak into the tunnel, causing an Oxygen Deficiency Hazard (ODH) problem [2].

In the past, Wu [3] had done an estimation of the helium release into the RHIC tunnel during a hypothetical accident. The calculations were based on an over conservative amount of helium into the insulating vacuum volume and a couple assumed helium heating processes: a constant density and a constant pressure heating process, inside the cryostat. Than [4] also did a preliminary calculation on the helium leakage into the RHIC tunnel from the magnet line catastrophic failure in the sextant arc area. The simple model had included the flow resistances along the magnet cooling lines. However, the effect of vacuum tank size and total relief area on the amount of helium release still could not be simulated.

In this paper, a more complete system model had been developed in SINDA/FLUINT®(S/F) [5] to simulate the 4.5K/ 4 atm liquid helium flowing through the magnet cooling system distribution lines, then through a line break into the insulating vacuum volumes and discharging via the reliefs into the RHIC tunnel.

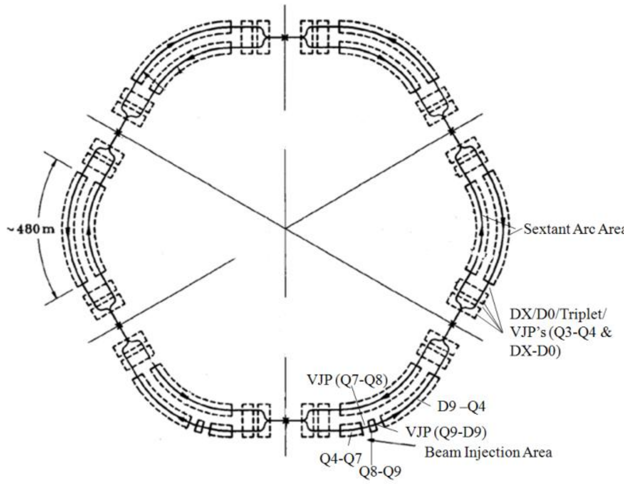

Fig. 1: RHIC Rings and Three Typical Areas

The model included as many details as practical: e.g. flow resistances of the magnet cooling circuit, inlet/outlet losses of the magnet end cans, re-coolers and valves to model the actual flow impedance accurately. Arc flash energy deposition, based on the injected electrical power, was applied to the helium flow at the line break. Heat load from the ambient was calculated based on the forced convection of the helium gas inside the tank, free convection of ambient air outside the tank, and the heat conduction through the wall thickness. Choked flow condition and fluid quality were detected and calculated by the program. Three typical areas: the sextant arc, the Triplet/DX/D0 magnets, and the injection area, with seven different sized insulating vacuum volumes had been analyzed (see Fig. 1). Results, including helium discharge rates, helium inventory loss and the oxygen concentration near the helium discharging location are presented below.

THE MODELS

Model for the Helium Release Simulations

Each sextant in RHIC consists of 42 dipole magnets, 41 quadrupole/ sextupole/ corrector magnet assemblies, 81 magnet interconnections, 5 re-coolers, 1 lead pot and a few transfer lines between cryostats and between sextants. There are typically four parallel cooling lines in each magnet, with a diameter of ~3 cm. The total length of the cooling line is around 880 m per sextant. A SINDA/FLUINT® model was developed to simulate the helium flow inside the system. The magnet cooling lines were divided into finite numbers of lumps (with constant

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pressures) and paths (with constant flow rates). Due to the large system size, only one sextant was modelled in details. A fluid lump was added to the model to account for the helium inventory inside the other five sextants and in the supply lines. The governing equations for the lumps are conservation equations for mass and energy [5]:

Mass: $\Sigma\, e_k \cdot FR_k = dM_i / dt$ (1)

Energy: $\Sigma\, e_k \cdot h_k \cdot FR_k + QDOT_i = dU_i / dt$ (2)

The governing equation for the path is conservation equation for momentum [5]:

$$dFR_k / dt = AF_k / TLEN_k \cdot (PL_{up} - PL_{down} + FC_k \cdot FR_k \cdot ABS(FR_k)^{FPOWk} + AC_k \cdot FR_k^2 - (FK_k \cdot FR_k \cdot ABS(FR_k)) / (2 \cdot \rho_{up} \cdot AF_k^2)) \quad (3)$$

where FR = mass flow rate [kg/s]; M = mass [kg]; h = enthalpy [J/kg]; QDOT = power input [W]; PL = pressure [Pa]; U = internal energy [J]; t = time [second]; TLEN = path length [m]; AF = flow path cross section area [m^2]; ρ = fluid density [kg/m^3]; FK = additional K-factor losses, 0.5 for the inlet and 1 for the exit and the U-bends; FC = friction coefficient; FPOW = 0 (for laminar flow) and = 1 (for fully turbulent flow); AC = recoverable loss coefficient; and e_k = coefficients. Sizes of the seven insulating vacuum tanks (VT), with a thickness of ~ 6 mm, and relief valves (RV), with a setting at ~1.2 atm (abs), are shown in Table 1.

Table 1: Sizes of Insulating Tanks & Relief Valves

	RV ID [mm]	RV Areas [m^2]	VT Vol [m^3]	VT Area [m^2]	VT Len [m]	VT OD [m]
Sext. Arc	4.8	.106	97	930	485	.61
Triplet/DX/D0	4.8	.0157	42	293	38	1.22
+VJP Q3-Q4	5.7				102	.51
Inj. Q8-Q9	4.8	.0035	4	35	18	.61
Inj. Q4-Q7	4.8	.0142	8	76	39	.61
Inj. D9-Q4	4.8	.0885	88	849	443	.61
Vjp. Q7-Q8	5.7	.0026	4	35	22	.51
Vjp. Q9-D9	5.7	.0026	2	17	11	.51

Liquid helium from the refrigerator is at 4.5K and 4 atm. The ambient air temperature is 297 K. Helium supply to the sextant was assumed to be isolated at 15 seconds after the line break. Heat load from the ambient onto the helium inside the cryostat was determined by the heat convections on the outer and on the inner surface of the tank and by the heat conduction through the tank's wall thickness. Heat convection coefficients on the inside (hi) and on the outside (ho) surface of the tank were calculated by Eq. (4) (Dittus-Boelter Equation [5]) and Eq. (5) respectively:

$hi = .023 \cdot Re^{0.8} \cdot Pr^{0.4} \cdot k/D_h$ [W/m^2-K] (4)

$ho = 10$ [W/m^2-K] (5)

where $Re = \rho \cdot V \cdot D_h / \mu$; $Pr = C_p \cdot \mu / k$; ρ = helium density [kg/m^3] [6]; μ = helium dynamic viscosity [Pa-s] [6]; V = flow velocity [m/s]; D_h = Hydraulic Diameter [m]; k = helium thermal conductivity [W/m-K] [6]; C_p = helium specific heat [J/kg-K] [6]. Thermal properties for the cryostat materials are as shown in Table 2.

Table 2: Thermal Properties of Cryostat Materials

	Density [kg/m3]	Thermal Conductivity [W/m-K]	Heat Capacity [J/kg-K]
Steel	7750	41.8	502
SST304L	7804	14	502

Arc flash energy deposition onto the helium flow is 0.5 MJ over 10 seconds, which is based on the 200 V/ 600 A power supply to the magnet during the injection, with consideration of the extraction resistors.

Model for the Oxygen Deficiency Hazard (ODH) Calculations

Oxygen concentrations in the RHIC tunnel after the helium release were calculated, using Eq. (6) and Eq. (7).

Case 1: When the exhaust fan is on

$V \cdot dC / dt = 0.21 \cdot (Q\text{-}R)\text{-}Q \cdot C$ (6)

Case 2: When the exhaust fan is off

$V \cdot dC / dt = -R \cdot C$ (7)

where V = Affected tunnel volume near helium discharge (~6% of the tunnel volume was assumed) = 17980 [ft^3]; C = Oxygen concentration (mole fraction); t = Time [minutes]; Q = Exhaust fan(s) flow rate inside affected volume (~ 1 exhaust fan's capacity) = 19800 [CFM]; Exhaust fan ramping time = 1 [minute]; Fan(s) turn on when C < = 18 % [7]; R = Helium gas spill rate into tunnel (see Fig. 2) plus 150 [g/s] to account for the boiled off liquid helium due to system heat leak [CFM]; Ambient oxygen concentration= 21 %.

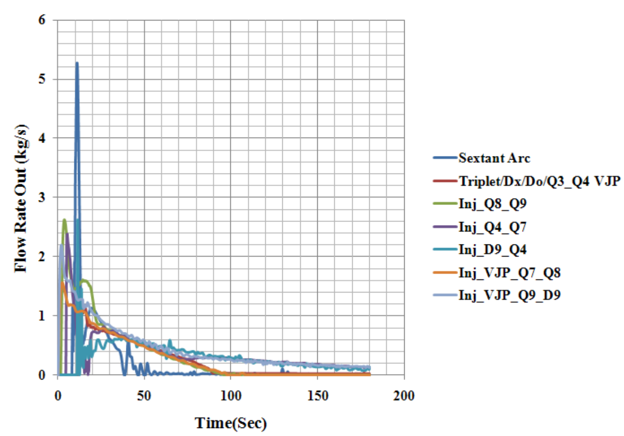

Fig. 2: Helium Release Rates out of Relief Valves

RESULTS AND VERIFICATIONS

Simulation Results

Fig. 2 and Fig. 3 are the simulation results from the S/F model, which show the helium release rates out of relief valves and helium inventory losses respectively. Fig. 4 is the simulation results, based on Eq. (6) and Eq. (7), which shows the oxygen concentration in RHIC tunnel around the helium discharging location.

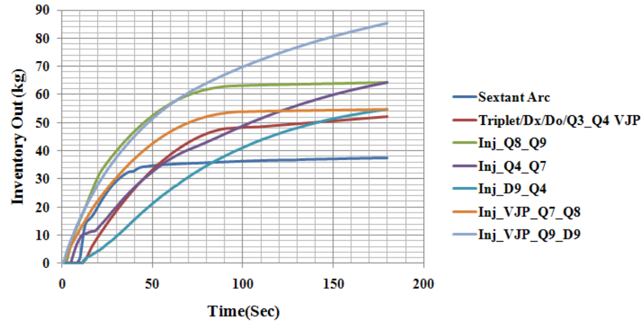

Fig.3: Helium Inventory Loss

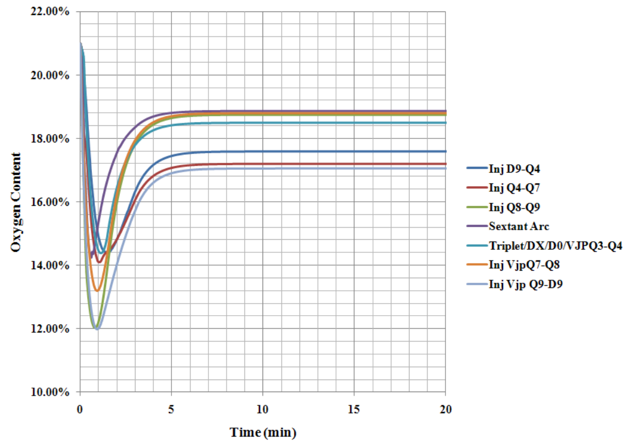

Fig. 4: Oxygen Content in RHIC Tunnel near the Helium Discharging Location

Result Verifications

The developed S/F model was used to simulate a RHIC system depressurization test [8]. Good agreement between the simulated and the measured result had been achieved. (See Fig. 5.) Simple analytical calculations had also been performed to check the results obtained from the S/F simulations, which included helium release rate and heat transfer through the insulating tank wall. Good agreement had also been achieved [9].

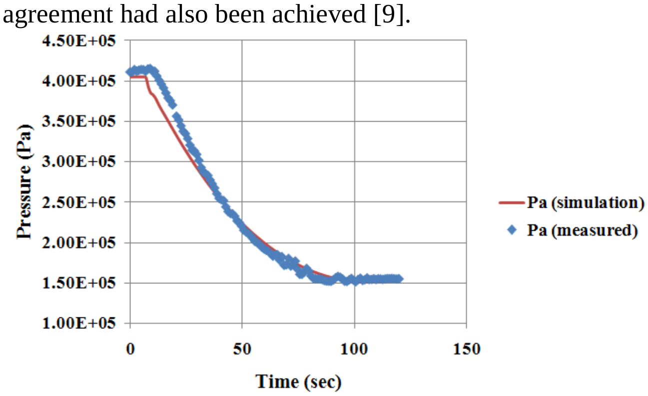

Fig. 5: RHIC Sextant Depressurization Test

CONCLUSIONS

Based on the simulations, the conclusions are as follows:

(1) When the magnet cooling line breaks inside the cryostat, the smallest cryostat tank with insufficient reliefs would release the largest amount of helium into the tunnel.

(2) Helium discharging rate from a cryostat is highest when the relief valves start to open and will approach the steady state expulsion rate due to heat leak (~150 g/s) in about 180 seconds.

(3) With the helium supply being isolated at15 seconds after the line break, the helium inventory loss from the depressurization process from a sextant volume would be around 90 kg. After this the out flow will be dictated by the heat leak into the remaining inventory, which would results into an exhaust rate of 150 g/s.

(4) Oxygen concentration in RHIC tunnel near the helium discharging location could drop to 12 % in ~1 minute and would be above 17% in 5 minutes, assuming that the ODH fans turn on at 18 %.

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