FREON REMOVAL SYSTEM FOR THE CERENKOV COUNTER.

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INTRODUCTION.
The CLAS spectrometer in end station B includes Cerenkov detectors. These detectors require the use of either Freon 12 (CCl₂F₂) or Freon 114 (C₂F₆H₂C₆F₂). This note describes a conceptual design approach for the filling and recovery of the Freon 114 gas.
A design objective is to minimize the release of Freon to the atmosphere during filling and recovery operations.

DESCRIPTION OF THE APPARATUS.
The system uses nitrogen as a carrier gas. During filling operations, the Cerenkov chamber is first filled with nitrogen. The Freon is then introduced and the exhaust from the Cerenkov flows through a cooling system to condensate the Freon. The remaining gas (nitrogen) is released to the atmosphere. The recirculation continues until the required purity of Freon is reached within the chamber.
When recovering Freon, nitrogen gas is introduced into the chamber and the exhaust flow passes through the heat exchangers. Freon gas is condensed and collected.
See section 5 for a schematic of the system. The system uses three heat exchangers, the first precools warm nitrogen to the required temperature, the second cools Freon and carrier gas to the temperature at which Freon liquifies and the third freezes the remaining Freon.
The liquid nitrogen is used as the coolant in all three heat exchangers. The system is sized to fill or empty the chamber (volume approx. 12.8m³) in approximately 12 hours. The detector maximum working pressure is about 2" of water, so the system must operate with near ambient pressure.
We expect that we would recover at least 99.9 percent of the Freon.

REQUIREMENTS FOR EACH HEAT EXCHANGERS.

1. THE HEAT EXCHANGER TO COOL FREON FROM ROOM TEM-
PERATURCE TO -80°C.

1.1. Nitrogen requirement to cool the incoming Freon.

1.1.2. Initial Freon flow rate from the system (one Cerenkov counter).

Since system must be empty from Freon within 12 hours, initial volumetric Freon flow rate must be:

\[ v = \frac{V}{t} = 3E - 4m^3/s \text{ or } 18.3in^3/s \text{ – initial volumetric flow rate of Freon for:} \]

\[ V=12.8m^3 \text{ – volume of the Cerenkov counter} \]

\[ t=12 \text{ hours – time to remove Freon from the system} \]

1.1.3. Flow rate of nitrogen required to cool Freon from ambient temperature (25°C) to -80°C (20°C off the freezing point).

Heat to be removed from the incoming Freon.

\[ Q = Q_1 + Q_2 + Q_3 = .54kW \]

where:

\[ Q_1 = m c_p(T_1 - T_2) = 0.036kW \text{ – heat removed to cool Freon to 3 deg C} \]

\[ Q_2 = m h_{f-g} = 0.31kW \text{ – heat removed to liquify Freon} \]

\[ Q_3 = m c_{pl}(T_2 - T_3) = 0.19kW \text{ – heat removed to cool liq. Freon to -80°C} \]

for:

\[ m = v \rho = 2.3E - 3kg/s = 5.1E - 3lb/s \text{ – mass flow rate of Freon} \]

where:

\[ \rho = 7kg/m^3 \text{ – density of Freon at 25°C and 1atm [1]} \]

\[ v = 3E - 4m^3/s \text{ – flow velocity of Freon (sec.1.1.2)} \]

\[ c_p = 0.71kJ/kgK \text{ – specific heat of Freon at 25°C and 1atm [1]} \]

\[ c_{pl} = 1.0kJ/kgK \text{ – specific heat of liquid Freon at -3 deg C [1]} \]

\[ h_{f-g} = 135kJ/kg \text{ – heat of liquefication [1]} \]

\[ T_1 = 25°C \text{ – ambient temperature} \]

\[ T_2 = 3°C \text{ – liquifcation temperature} \]

\[ T_3 = -80°C \text{ – required end temperature of liquid Freon} \]

Required flow rate of -100°F=200K nitrogen (assumed value) can be calculated as:

\[ m = \frac{Q}{c_p \Delta T} = 2.6E - 2kg/s \text{ or } 0.015m^3/s \text{ – flow rate of 200K nitrogen} \]

for:

\[ Q=540 \text{ W – heat to be removed (calculated above)} \]

\[ c_p = 1.043kJ/kgK \text{ – specific heat of nitrogen [2]} \]
\[dT = 20 \text{K} \quad \text{temperature rise of nitrogen (assumed value)}\]

1.2. Sizing of the heat exchanger.
The heat exchanger is counterflow type, with Freon flowing via .5” dia coiled tube and cooling gas flowing outside. The coiled tube is inserted in between two concentric tubes, forming the passage for the cold gas.
1.2.1. Required surface area of heat exchange to cool incoming Freon to -80°C.
The following assumptions are made:
- inside diameter of the tube for Freon flow (coiled to 2 in radii) – 0.5”
- inside diameter of the nitrogen container – 3”
- outside diameter of the nitrogen container – 5”

1.2.1.2. Heat transfer coefficient inside of the Freon tube.
\[h = \frac{N_u k}{d} = \frac{0.0156 \frac{W}{in^2}}{m_F} \quad \text{heat transfer coefficient [3]}\]

where:
- \[N_u = 0.023 Re^a P_r^{\frac{3}{2}} = 53 \quad \text{Nusselt number [3]}\]
- \[Re = \frac{123.9 \rho v d}{\mu} = 21000 \quad \text{Reynolds number [4]}\]

for:
- \[d = 0.5 \text{ in} \quad \text{tube diameter}\]
- \[\rho = 0.486 \frac{lb}{ft^3} \quad \text{density of Freon at 25°C [1]}\]
- \[\mu = 0.011 \text{cPoise} \quad \text{dynamic viscosity of Freon at 25°C [1]}\]
- \[v = 7.7 \frac{ft}{s} \quad \text{calculated flow velocity of Freon inside of the .5” tube (calculated as a ration of volumetric flow velocity over the tube cross section area)}\]
- \[P_r = 0.5 \quad \text{Prandtl number for freon at 25°C [1]}\]
- \[k = 1.46 E - 4 \frac{W}{m^2} \quad \text{thermal conductivity of Freon at 25°C [1]}\]

1.2.1.3. Heat transfer coefficient outside of the .5in tube – nitrogen passage.

Velocity of nitrogen within passage (the ring 3 in ID and 5” OD with .5” tube inside coiled to 2 in radii).
\[v = \frac{V}{A} = 146 \text{ in/s}\]

for:
- \[V = 1.5 E - 2 m^3/s = 915 in^3/s \quad \text{required volumetric flow rate of nitrogen (sec.1.1)}\]
- \[A = 6.28 in^2 \quad \text{cross section area of the nitrogen passage (area in between 3’ and 5” dia tubes minus 4” dia coil of .5” tube)}\]

Hydraulic diameter of the cooling passage.
\[r = A/P = 0.153” \quad \text{hydraulic radii}\]
for:

\[ A = 6.28 \text{in}^3 \] - calculated flow area

\[ P = 40.8 \text{in} \] - calculated perimeter of the ring and the tube inside

Calculated hydraulic diameter is \( d = 4r = 1.3 \text{in} \).

The heat transfer coefficient can be calculated from the following formula:

\[ h = \frac{0.6834}{d} \text{Re}^{0.466} \text{Pr}^{0.33} = 0.0167 \frac{W}{\text{in}^2 \text{F}} \]

where:

\[ \text{Re} = \frac{\rho \nu d}{\mu} = 7970 \] - Reynolds number [3]

\[ \rho = 0.1099 \text{lb/ft}^3 \] - density of nitrogen at 200K [2]

\[ \mu = 8.5E-6 \text{lb/ft s} \] - dynamic viscosity of nitrogen at 200K [2]

\[ k_f = 2.5E-5 \text{W/\text{in} F} \] - thermal conductivity of nitrogen at 200K [2]

\[ d = 0.61 \text{in} = 0.051 \text{ft} \] - calculated hydraulic diameter of the cooling passage

\[ v = 146 \text{in/s} = 12.1 \text{ft/s} \] - calculated flow velocity

\[ \text{Pr} = 722 \] - Prandtl number for nitrogen at 200K [2]

Required length of the Freon tube.

Since both nitrogen and Freon temperature are known, an effective heat transfer area can be found from the following formula:

\[ Q = UA\delta T_{\text{log}} \]

where:

\[ U = \frac{h_i h_o}{h_i + h_o} = 0.0081 \frac{W}{\text{in}^2 \text{F}} \] - overall heat transfer coefficient

\[ A = 3.14dl \] - heat transfer area to be calculated

\[ Q = 540W \] - heat to be removed (sec.1.1.3.1)

\[ \delta T_{\text{log}} = \frac{dT_1 - dT_2}{\ln(dT_1/dT_2)} = 77.4 \text{F} \] - average temperature across the films

for:

\[ h_i = 1.56E - 2 \frac{W}{\text{in}^2 \text{F}} \] - heat transfer coef. within the Freon tube

\[ h_o = 1.67E - 2 \frac{W}{\text{in}^2 \text{F}} \] - heat transfer coef. outside the Freon tube

\[ dT_1 = 300 - 220 = 80 \text{K} \] - temperature difference at the entrance of the Freon and exit of \( N_2 \)

\[ dT_2 = 220 - 200 = 20 \text{K} \] - temperature difference at the exit of the Freon and entrance of \( N_2 \)

The calculated required surface area of the Freon tube is 861\text{in}^2 or or 548 in of .5\text{in} dia tube or 44 turns, coiled to 2\text{in} radii.

In summary, the heat exchanger used to cool Freon from 300 to 220K or
-80°C can be built from two concentric 5" and 3" tubes, with volume in between those two cylinders filled with .5" Cu tube, coiled to 2 in radii with 44 turns.

2. THE HEAT EXCHANGER TO PRECOOL ROOM TEMPERATURE NITROGEN TO 200K.
This heat exchanger is used to cool warm nitrogen flowing thru the coiled Cu tube, immersed within liquid nitrogen bath. The cold nitrogen from this device is fed into heat exchanger evaluated in sec. 1.
Requested exit temperature of warm nitrogen (200K) will executed by adjusting level of liquid nitrogen. Nitrogen temperature will be adjusted according to a temperature sensor reading attached to the exit of the warm nitrogen tube.
Assumption for the calculation of the required tube length:
- tube diameter .5"
- warm nitrogen flow rate .026 kg/s or .057 lb/s or .67 ft³/s (at 250K), sec.1.1
- temperature of a warm nitrogen at the entrance – 300K
- temperature of a warm nitrogen at the exit – 200K
2.1 Heat transfer coefficient inside of the tube.
The same formulas as used in sec. 1 can be used with datas for a nitrogen.
\[ h = \frac{N_u^h}{d} = 55.2 \frac{mW}{cm^2K} \] [3]
where:
\[ N_u = 0.023 Re^a Pr^n = 317 \] – Nusselt number [3]
\[ Re = \frac{vd}{\mu} = 1.68E5 \] – Reynolds number [3]
for:
\[ \rho = 0.0853 lb/ft^3 \] – density of nitrogen at 250K [2]
\[ v = 491 ft/s \] – flow velocity of warm nitrogen within .5" tube, for required mass flow rate .057 lb/s (sec.1.1)
\[ \mu = 1.04E5 \frac{lb}{ft s} \] – dynamic viscosity of nitrogen at 250K [2]
\[ d = .5 in \] – tube diameter
\[ Pr = .733 \] – Prandtl number for nitrogen at 250K [2]
\[ k = 221 \frac{mW}{cm K} \] – thermal conductivity of nitrogen at 250K [2]

The required tube length, inside of the heat exchanger, can be evaluated under the initial assumption that heat transfer coefficient outside of this tube (within the liquid) is large. The correction for finite heat transfer outside (within the liquid) will be done at the final step.
Heat transferred across the boundary is:
\[ Q_1 = hA\delta T_{log} \]
Heat removed from the flowing nitrogen is:
\[ Q_2 = mc_p(T_1 - T_2) = 2693W \]
for:
\[ \delta T_{log} = \frac{dT_1 - dT_2}{\ln(dT_1/dT_2)} = 165K \quad \text{log mean temperature} \]
\[ dT_1 = T_1 - 80 = 300 - 80 = 220K \quad \text{temperature difference in between warm} \]
\[ dT_2 = T_2 - 80 = 200 - 80 = 120K \quad \text{temperature difference in between cold} \]
\[ c_p = 1.042 \frac{kJ}{kgK} \quad \text{specific heat of nitrogen at 250K} \ [2] \]
\[ m = .026 \frac{kg}{s} \text{ or } .0571 \frac{lb}{s} \quad \text{required mass flow rate of nitrogen (sec.1.1)} \]
\[ A = 3.14dL \quad \text{heat transfer area of the cooled tube to be calculated} \]
For steady state \( Q_1 = Q_2 \); calculated .5" dia tube length must be 74 cm for heat transferred across the boundary of 2693 W (calculated from \( Q_2 \)).

Since heat transfer coefficient from LN\(_2\) was taken infinitely large, correction at this stage must be taken. Heat flux from the wall to the liquid nitrogen:
\[ \frac{Q}{A} = \frac{2693}{3.14 \times 2.54 \times .5 \times 74} = 9.1 \frac{W}{cm^2} \]
Since boiling heat transfer of the nitrogen (for temperature difference 120 K) is \( 2 \frac{W}{cm^2} \) \[5\], the correction of 9.1/2 for tube length must be taken; the final .5" tube length must be about 674 cm.
If one assume bend radii of 2" required number of turns must be 22.

In summary nitrogen precooler can be made from 5in tube with 22 turns of .5" Cu tube coiled to 2in radii.

3. The FREON FREEZER.
A freezer tank is an container used to freeze a vapor released from the liquid Freon.
3.1. The required freezer volume to contain frozen Freon.
The vapor pressure of the Freon at required liquid temperature of -63F(220K) is 27.9 in Hg \[1\]. With ambient pressure of 29.92 in Hg, a portion of Freon vapor escaping the liquid Freon container is proportional to a difference in between these two pressure divided by an ambient pressure.
The portion of incoming gas escaping a liquid phase is:
\[ m = \frac{P_1 - P_2}{P_1} \]
\[ m = \frac{29.92 - 27.9}{27.92} = 0.067 \]

For the total liquid volume of the Freon within the one Cerenkov counter, a volume of the freezer for complete removal of the Freon from one counter should be:

\[ V_{fr} = 0.067V_f \]

for Freon liquid volume used for one Cerenkov counter eq. to 4400\text{in}^3, required volume of the freezer should be 300\text{in}^3 to contain the frozen freon.

3.2 Min liquid nitrogen flow to the freezer to freeze the vapor:

3.2.1 Heat to be removed from the Freon.

\[ Q = Q_1 + Q_2 = 31W \]

where: \( Q_1 = mc_p(T - T_e) = 2.25W \) - heat removed to cool freon down to freezing point

\[ Q_2 = mH_{fs} = 28.5W \] - heat removed to solidify Freon

\[ m = 1.5E-4\text{kg/s} \] - flow rate of freon vapor (for flow rate of Freon from the counter 2.3E-3\text{kg/s} (sec.1.1))

\[ c_p = 1.0kJ/kgK \] - specific heat of liquid [1]

\[ H_{fs} = 1.358E5J/kg \] - heat of fusion of Freon [1]

\[ T = 220K \] - vapor temperature, equal to liquid temperature

\[ T = 205K \] - freezing temperature of Freon at 1atm [1]

3.2.2. Required flow of the nitrogen.

\[ m_n = \frac{Q}{H_{vl}} \]

for:

\[ Q = 31W \] - heat removal rate

\[ H_{vl} = 199kJ/kg \] - heat of vaporization of LN

Calculated flow rate of the nitrogen to the freezing tank must be 0.16 g/s or 0.13\text{cm}^3/s

Probably reserve of 2h nitrogen flow interruption should be kept within the freezer eq. to 56\text{in}^3.

The total volume of the freezer should be about 500\text{in}^3, to contain all frozen Freon and reserve of liquid nitrogen for 2 hours.

4. Estimated pressure drop for Freon within the pipework.

Pipes length form the Cerenkov counter to the exit from the freezer:
- pipe length from the counter to the Freon removal station - 10 feet
- pipe length within the Freon removal station - 68 ft
- addition unknown length 5 ft. Pressure drop can be calculated according to 'Crane' formula:

\[ \frac{dP}{d} = \frac{0.001284}{f} \frac{\text{in}^2}{\text{ft}^2} \]  [4]

where:
\[ f = 0.316Re^{-0.26} = 0.026 \]

for:
\[ Re=21000 \] - Reynolds number calculated in sec.2
\[ v = 7.7 \text{ ft/s} \] - flow velocity calculated in sec.2
\[ \rho = 0.486 \text{ lb/ft}^3 \] - Freon density at 300K and 1 atm
\[ l = 83 \text{ ft} \] - estimated tube length
\[ d = 0.5 \text{ in} \] - tube diameter

Calculated pressure drop over entire system is 0.16 psi or 4.3 in of water. This pressure drop in on pessimistic side, since during the cooldown process, gas density increase very rapidly decreasing flow rate and pressure drop. If the system can’t tolerate such "high" pressure, small pump may be necessary to drive gas through system.

5. System schematic.
References:
1. Du Pont – Properties of Freon
2. R. Barron – Cryogenic System
3. J.P Holman – Heat Transfer
4. Crane Catalog
5. NBS TN317 – Boiling Heat Transfer of Nitrogen
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1 Vapor pressures are shown as PSIG. Red figures are shown as inches of mercury vacuum.
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<th>FREON 503</th>
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<td>Chemical Formula</td>
<td>CCl₂CClF₂</td>
<td>CCl₂F</td>
<td>CCl₂CCl₂F₂</td>
<td>CCl₄F₂</td>
<td>azeotrope⁹</td>
<td>CCl₂F₂</td>
<td>azeotrope⁹</td>
<td>CCl₂F₂</td>
<td>azeotrope⁹</td>
<td>CCl₂F₂</td>
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<td>47.57</td>
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<td>145.7</td>
<td>112.0</td>
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<td>lb/ft³</td>
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<td>90.91</td>
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<td>75.95</td>
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<td>at 25°C (77°F)</td>
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<td>39.47</td>
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<td>58.53</td>
<td>71.04</td>
<td>84.47</td>
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<tr>
<td>Liquid, 25°C (77°F)</td>
<td>Btu/(hr)(ft²)(⁰F)</td>
<td>0.0434</td>
<td>0.0506</td>
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<td>0.0373</td>
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<td>0.0444</td>
<td>0.0451</td>
<td>0.0060</td>
<td>0.00557</td>
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<td>0.00609</td>
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<tr>
<td>Liquid, 25°C (77°F)</td>
<td>cal/g (⁰F)</td>
<td>0.218</td>
<td>0.209</td>
<td>0.243</td>
<td>0.232</td>
<td>0.256</td>
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<td>cal/g (⁰C)</td>
<td>0.161</td>
<td>0.142</td>
<td>0.170</td>
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<td>0.175</td>
<td>0.157</td>
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<td>0.112</td>
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<td>Viscosity, 25°C (77°F)</td>
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<td>0.415</td>
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<td>0.192</td>
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<tr>
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<td>(60°C)</td>
<td>0.010</td>
<td>(1 atm)</td>
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<tr>
<td>Solubility, 25°C (77°F)</td>
<td>FREON in water (1 atm)</td>
<td>0.017²</td>
<td>0.013</td>
<td>0.028</td>
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<td>Water in FREON</td>
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<td>Max water content ppm (wt)</td>
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<td>Max non-absorbable gas % (v/v)</td>
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<td>-</td>
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<tr>
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<td>TLV-TWA ppm (v/v)</td>
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<td>1000²</td>
<td>1000</td>
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</table>

a. CCl₂CClF₂ (73.8/26.2% by wt).
b. CCl₂CCl₂F₂ (60.1/39.9% by wt).
c. CHF₂CCl₂F₂ (40.1/59.9% by wt).
d. CHF₂CCl₂F₂ (48.9/51.2% by wt).
e. At saturated press.
f. Ceiling limit.
g. Relative toxicity based on available data.