Cryogenic Safety

with Emphasis on Overpressure Protection of Low Temperature Helium Vessels

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USPAS

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MRI system event videos

- http://www.youtube.com/watch?v=1R7KsfosV-o
- https://www.youtube.com/watch?v=SWnXJFAGk2Y
- https://www.youtube.com/watch?v=CXWqIz68eqw
- http://www.youtube.com/watch?v=sceO38idjic&feature=related

Outline

- Introduction
- The basic hazards – selections from a general cryogenic safety training class
- Lessons learned from accidents
- Cryogenic pressure safety
- ODH analysis

Introduction

- The purpose of this lecture is to provide a review of cryogenic safety and pressurized gas hazards
- Most commonly used cryogenic fluids in accelerator work are argon (Ar), nitrogen (N2), helium (He) and hydrogen (H2). These fluids are used in liquid and gaseous form.
- These low temperature fluids have the potential for creating dangerous working environments.
- Everyone who works with cryogenic fluids must know their hazards and how to work safely with them.

The basic hazards due to helium and nitrogen

- Freezing, extreme cold
  - Burns skin, eyes
  - Embrittlement of material
- Pressure, force of blast, propelled objects
  - Dust, debris
  - Pipe cap, valve stem and bonnet
  - Expansion in a closed volume
- Noise
  - Compressors
  - Gas vents
- ODH--Oxygen Deficiency Hazard
  - Nitrogen
  - Helium
- Fire -- hydrogen burns easily and with a clear flame
- Oxygen enriched air -- enhanced burning of flammable materials

Oxygen Deficiency Hazard (ODH)

- Oxygen Deficiency Hazard (ODH) is caused due to oxygen displacement.
- ODH is a serious hazard usually occur without any warning
- ODH is addressed by Fermilab's FESHM 5064, which is available via the Fermilab web site.
- The cold, heavy gas from evaporating cryogenic liquid does not disperse very well and can group together in surrounding areas and will displace air.
- Some gases (He, H2) while cold may be lighter than air. They may partially mix with surrounding air, or stratify as they warm up.
- A hazard with helium and other inert gases is to have a pockets of trapped gas up high in a building, which may cause ODH. (A concern is that a person could pass out and fall off a ladder when replacing a lamp, for example.)
- Be aware of the hazards associated with large volumes of cryogens in a small space (for example, rolling a 160 liter LN2 dewar into a small room)

Extreme cold hazard

- Cryogenic liquids and cold vapors can cause a thermal burn injuries
- Brief exposures may damage delicate tissues (eyes, skin, etc).
- The skin, when not protected, can stick to metal that is cooled by cryogenic liquids and when pulled away the skin can tear
- Even non-metallic materials are very dangerous to touch at cryogenic temperatures

Fire Hazard

- Flammable cryogenic gases like H2 can burn or explode
- Hydrogen is colorless, odorless, non-toxic, highly flammable and explosive in the presence of air or oxygen in the right concentration. It forms a flammable mixture when it exists at 4 to 74%. Hydrogen, since it is lighter than air, will tend to form pockets of gas along ceilings, which can lead to an explosion or fire hazard.
- A flashing or rotating blue light is used at Fermilab to indicate that hydrogen is present in experimental apparatus in the area. Typically other institutions will also provide similar warning signals.
- Further training is required for qualification for working with hydrogen

Oxygen Enriched Air

- Cryogenic fluids like LHe, LN2 and LH2 can easily liquefy the air they come in contact with.
- Liquid air can condense on a surface cooled LHe, LN2 and LH2 .
- N2 has smaller latent heat than Oxygen (O2), thus evaporates more rapidly than oxygen from the liquid air. This action leaves behind a liquid air mixture which, when evaporated, gives a high concentration of oxygen.
- This O2 enriched air presents highly flammable atmosphere.

Over Pressurization or Explosion due to rapid expansion

- Without adequate venting or pressure-relief devices on the containers, enormous pressures can build up which can cause an explosion.
- Unusual or accidental conditions such as an external fire, or a break in the vacuum which provides thermal insulation, may cause a very rapid pressure rise.
- The pressure relief valve must be properly installed and free from obstruction.

Protection from cryogenic hazards

- Always wear personal protective equipment while handling cryogenic liquids. This includes: gloves, face shields, hearing protection, loose fitting thermal insulated or leather long sleeve shirts, trousers, safety shoes
- Only trained and qualified personal should be allowed to handle, transport or storing liquefied gases.
- Proper storage is essential for cryogenic fluids
- Depressurize system
- Stand aside from vent
- Be aware of closed volumes into which liquid cryogens might leak
- Do not leave open mouth dewars open
- Purge and evacuate all equipment before operation
- Use cryogens in a properly ventilated areas only

Lessons Learned

- The following are a set of "lessons learned" which have been compiled from various sources. One primary source of lessons learned is the American Industrial Hygiene Association, which has a section of their website describing several cryogenic accidents: http://www2.umdnj.edu/eohssweb/aiha/accidents/cryogens.htm has been used as a source of some different examples of cryogenic hazards.

Lessons Learned

- Empty 55 gallon drum (1999)
  - At the Nevada Test Site, a waste handler was opening new, empty 55 gallon open-top drums. Upon removing the bolt from the drum lid clamp, the ring blew off and the lid was ejected approximately 5 to 10 feet in the air, just missing the Waste Handler's face. The drum did not hiss or show signs of pressurization.
  - Because the Waste Handler had been properly trained to stand away from the drum while opening it, he was not injured.
  - The event was caused by the drums being manufactured and sealed at sea level in Los Angeles and subsequently shipped to a much higher elevation of approximately 6,000 feet at the Nevada Test Site. The increased elevation, combined with the midday heat, created sufficient pressure buildup to cause the lid to blow off when the ring was being released.
  - Lesson -- large force with small pressure times large area

Lessons learned (continued)

- 50 liter LN2 laboratory dewar explosion
  - Transfer of LN2 from 160 liter dewar to 50 liter “laboratory” dewar
  - Flex hose end from 160 l dewar would not fit in lab dewar neck (normally a “wand” is inserted for filling), so a connection was made with rubber hose over the OUTSIDE of the lab dewar neck and transfer hose end
  - “Slot” cut in rubber hose for vent
  - Failure not initially caused by overpressure, but by cooling of upper part of neck during fill! Seal between neck and vacuum jacket broke due to differential thermal contraction.
  - Seal to vacuum jacket broke after lab dewar nearly full, subsequent overpressure with lack of sufficient vent caused explosion of lab dewar
  - One person badly injured
  - Lesson -- rupture of insulating vacuum with restricted venting resulted in explosion

Lessons learned (continued)

- Two workers at a Union Carbide plant were inspecting a flange surface on a 48" diameter pipe with an ultraviolet light.
- They draped black plastic over the end of the pipe to create shade for seeing any glow from material in the ultraviolet.
- The workers did not know there were some sources of nitrogen connected to the pipe. In fact, one of the workers had helped to start a purge on another section of pipe. But the system was so complex, he did not know they were connected.
- When they went under the cover to do the inspection, both workers quickly passed out from lack of oxygen. One died; the other was seriously injured.
- OSHA ultimately cited the company for violation of the confined space entry standard.
- Lesson -- be aware of potentially confined spaces, possible unlabeled ODH hazards

Topics in cryogenic pressure safety

- ASME pressure vessel code, ASME pressure piping code
  - We will not discuss vessel or piping code details, just provide some references to relevant sections
- Sources of pressure
- Thermodynamics of cryogen expansion and venting
- Analytical methods for vent line and relief sizing
- Relief devices
- Example of a venting system analysis
- Examples of the impact on cryostat design
- Oxygen Deficiency Hazard (ODH) analysis
- Conclusions and references

Pressure vessel and piping codes

- ASME Boiler and Pressure Vessel Code and ASME B31 Piping Codes
  - I will not go into detail about the design of pressure vessels or piping per ASME code
    - Will focus on emergency venting and system issues
  - In general, we try to purchase vessels built to the code from code-authorized shops
  - Where code-stamping is not possible, we design (or specify designs) to the intent of the code and note implications of exceptions to the code
- Fermilab's ES&H Manual (FESHM) pressure vessel standard, FESHM 5031, is available online at http://esh-docdb.fnal.gov/cgi-bin/ShowDocument?docid=456

ASME pressure vessel code -- Section VIII, Division 1

- "Div. 1 is directed at the economical design of basic pressure vessels, intending to provide functionality and safety with a minimum of analysis and inspection. Rules are presented which, if applicable, must be used. Common component geometries can be designed for pressure entirely by these rules. Adherence to specified details of attachment eliminates the need for detailed analysis of these features for pressure loading. NDE of welds can typically be avoided by taking a penalty in overall thickness of a component."
- Quoted from "Guidelines for the Design, Fabrication, Testing and Installation of SRF Nb Cavities," Fermilab Technical Division Technical Note TD-09-005

ASME pressure vessel code -- Section VIII, Division 2

- "Div. 2 is directed at engineered pressure vessels, which can be thought of as vessels whose performance specifications justify the more extensive analysis and stricter material and fabrication controls and NDE required by this Division. Thus, while a Div. 2 vessel is likely to be more efficient than a Div. 1 vessel in terms of total material used, this efficiency is accompanied by increased design and fabrication cost."
- Quoted from "Guidelines for the Design, Fabrication, Testing and Installation of SRF Nb Cavities," Fermilab Technical Division Technical Note TD-09-005

Pressure protection

- Vessel and piping have a Maximum Allowable Working Pressure (MAWP) defined by the design of the vessel or system
  - A venting system and relief devices must be in place to prevent any event from pressurizing the vessel or piping above the MAWP (plus whatever code allowance may be available)
- Evaluate all pressure sources and possible mass flow rates
- Size the vent line to the relief device
  - Temperature and pressure of flow stream
  - Typically a pressure drop analysis for turbulent subsonic flow
- Size the relief device
- Size downstream ducting, if any
  - Downstream piping may be necessary to carry inert gas safely away from an occupied area or sensitive equipment

ASME pressure vessel code -- relief devices

- Section VIII of the ASME Code provides fundamental guidance regarding pressure relief requirements.
  - ASME Section VIII, Division 1, UG-125 through UG133, for general selection, installation and valve certification requirements
  - ASME Section VIII, Appendix 11 for flow capacity conversions to SCFM-air
- For Div. 2, relevant information is found in Part 9.

Compressed Gas Association publication, CGA S-1.3, "Pressure Relief Device Standards"

- Extensive guidance on requirements for relief devices consistent with ASME code
  - Applicable where MAWP and venting pressure exceed 15 psig
- I will not provide a detailed discussion of CGA S-1.3, but rather just point to a few key issues and most useful elements of the standard

Note: we take exception to paragraph 2.2 in CGA S-1.3

- "CGA believes that reclosing PRDs on a container shall be able to handle all the operational emergency conditions except fire, for which reclosing or nonreclosing PRDs shall be provided. The operational emergency conditions referred to shall include but not be limited to loss of vacuum, runaway fill, and uncontrolled operation of pressure buildup devices."
- Exception: we treat loss of insulating vacuum to air, with the very high heat flux resulting from condensation on the liquid helium temperature surface of a container, like the fire condition and may use nonreclosing relief devices for that situation

Compressed Gas Association publication, CGA S-1.3, "Pressure Relief Device Standards"

- From CGA S-1.3: Among the particular issues which must be addressed for low temperature vacuum jacketed helium containers are
  - the temperature at which liquid-to-gas evolution should be estimated for the supercritical fluid at its venting pressure *(CGA S-1.3 is very useful here; I'll discuss this)*
  - the warming of the cold fluid passing through a long vent line *(CGA S-1.3 also provides useful practical approximation methods here which I will discuss)*
  - the volume generated per unit heat added *(we have data from lab tests about this which provide useful numbers)*

Evaluating the venting flow rate and conditions

- Berkeley MRI magnet quench
- https://www.youtube.com/watch?v=QRahBusouRs

Sources of pressure -- mechanical

- Compressors, pumps
  - Screw compressors are positive displacement devices
  - Worst case flow may be with high suction pressure as limited by inlet-side reliefs or pump/compressor motor power
    - Calculate worst-case flow as highest inlet density combined with known displacement volume
    - Or consider power limitations of pump or compressor motor
- Connection to a higher pressure source, such as a tube trailer
  - Evaluate the mass flow as determined by the pressure drop from the highest possible source pressure to the MAWP of vessel to be protected

Sources of pressure -- heat

- Trapped volume, slow warm-up and pressurization with normal heat inleak
  - All possible volumes which may contain "trapped" (closed off by valves or by other means) cold fluid require small reliefs
  - Rate of warm-up may be evaluated, generally slow enough that trapped volume reliefs are not individually analyzed.
- Loss of vacuum to helium with convection and conduction through helium gas
- Sudden large heat influx to a liquid-helium temperature container due to condensation of nitrogen or air on the surface
  - Either through MLI or, worst-case, on a bare metal surface
- Stored energy of a magnetic field
  - May provide a larger flow rate than loss of insulating vacuum
- Fire, with heat transport through the gas-filled insulation space

Nominal heat loads

- Working numbers for making heat load estimates
  - ~1.5 W/m^2 from 300 K to MLI-insulated (typically about 30 layers) cold surface
  - ~50 mW/m^2 from 80 K to MLI-insulated (typically about 10 layers) 4.5 K or 2 K surface
- Note that support structures and "end effects" may dominate the total heat load

Heat flux due to loss of insulating vacuum as a source of pressure

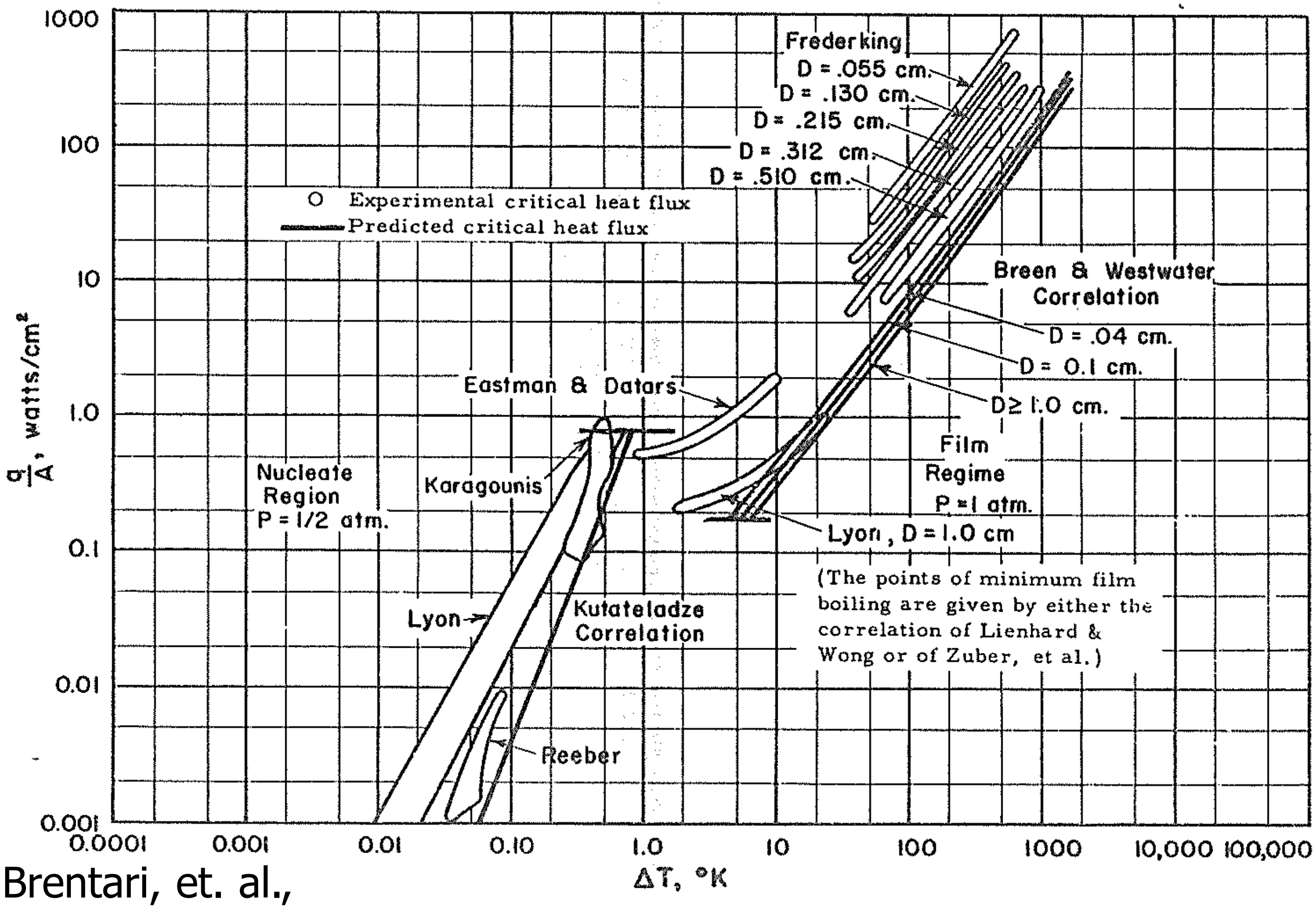
- W. Lehman and G. Zahn, "Safety Aspects for LHe Cryostats and LHe Transport Containers," ICEC7, London, 1978
- G. Cavallari, et. al., "Pressure Protection against Vacuum Failures on the Cryostats for LEP SC Cavities," 4th Workshop on RF Superconductivity, Tsukuba, Japan, 14-18 August, 1989
- M. Wiseman, et. al., "Loss of Cavity Vacuum Experiment at CEBAF," *Advances in Cryogenic Engineering*, Vol. 39, 1994, pg. 997.
- T. Boeckmann, et. al., "Experimental Tests of Fault Conditions During the Cryogenic Operation of a XFEL Prototype Cryomodule," DESY.

Heat flux conclusions

- Lehman and Zahn
  - 0.6 W/cm^2 for the superinsulated tank of a bath cryostat
  - 3.8 W/cm^2 for an uninsulated tank of a bath cryostat
- Cavallari, et. al.
  - 4 W/cm^2 maximum specific heat load with loss of vacuum to air
- Wiseman, et. al.
  - 3.5 W/cm^2 maximum peak heat flux
  - 2.0 W/cm^2 maximum sustained heat flux

Other heat flux comments

- T. Boeckmann, et. al. (DESY)
  - Air inflow into cavity beam vacuum greatly damped by RF cavity structures
- Various authors also comment about layer of ice quickly reducing heat flux
- Heat flux curves for liquid helium film boiling with a delta-T of about 60 K agree with these heat flux numbers (next slide)
- I use 4 W/cm^2 for bare metal surfaces

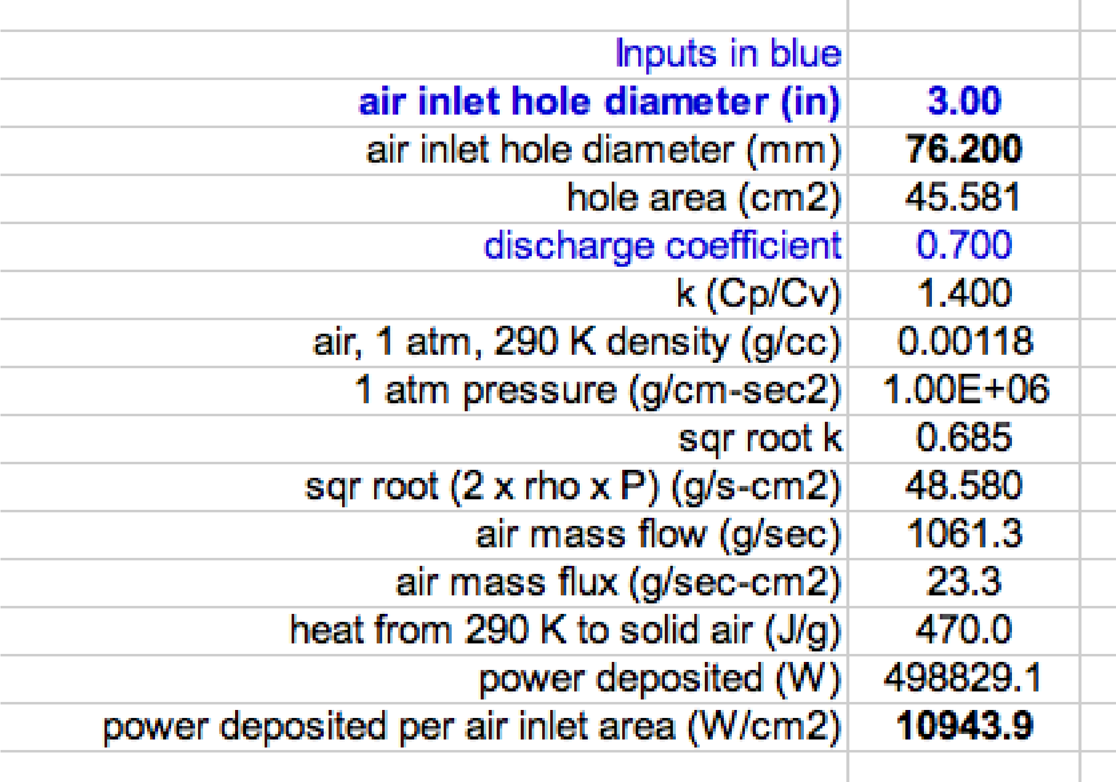


E. G. Brentari, et. al.,
NBS Technical Note 317

FIGURE 2.4

Experimental Nucleate and Film Pool Boiling of Helium Compared with the Predictive Correlation of Kutateladze and Breen and Westwater

Atmospheric air rushing into a vacuum space and condensing on a surface deposits about 11 kW per cm^2 of air hole inlet area. In many cases, heat flux will be limited by this air hole inlet size rather than low-temperature surface area.



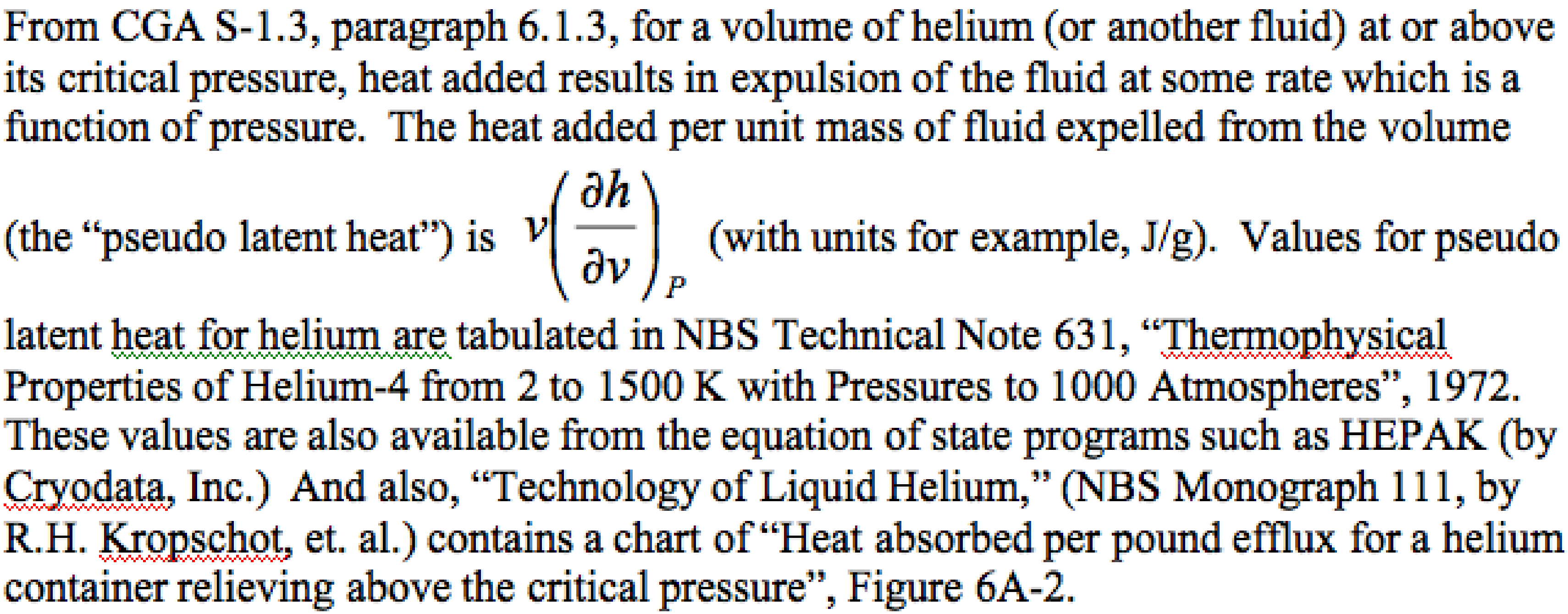
Inputs in blue	
air inlet hole diameter (in)	**3.00**
air inlet hole diameter (mm)	**76.200**
hole area (cm2)	45.581
discharge coefficient	0.700
k (Cp/Cv)	1.400
air, 1 atm, 290 K density (g/cc)	0.00118
1 atm pressure (g/cm-sec2)	1.00E+06
sqr root k	0.685
sqr root (2 x rho x P) (g/s-cm2)	48.580
air mass flow (g/sec)	1061.3
air mass flux (g/sec-cm2)	23.3
heat from 290 K to solid air (J/g)	470.0
power deposited (W)	498829.1
power deposited per air inlet area (W/cm2)	**10943.9**

Conversion of heat to mass flow

- Low pressures, below the critical pressure
  - Latent heat of vaporization
  - Net flow out is vapor generated by the addition of heat minus the amount of vapor left behind in the volume of liquid lost
- High pressures, above the critical pressure
  - Heat added results in fluid expelled
  - A "pseudo latent heat" can be evaluated

Supercritical fluid -- energy added per unit mass expelled

The pressure of a liquid helium container during venting will often exceed the critical pressure of helium (2.3 bar)



From CGA S-1.3, paragraph 6.1.3, for a volume of helium (or another fluid) at or above its critical pressure, heat added results in expulsion of the fluid at some rate which is a function of pressure. The heat added per unit mass of fluid expelled from the volume (the "pseudo latent heat") is $v\left(\frac{\partial h}{\partial v}\right)_P$ (with units for example, J/g). Values for pseudo latent heat for helium are tabulated in NBS Technical Note 631, "Thermophysical Properties of Helium-4 from 2 to 1500 K with Pressures to 1000 Atmospheres", 1972. These values are also available from the equation of state programs such as HEPAK (by Cryodata, Inc.) And also, "Technology of Liquid Helium," (NBS Monograph 111, by R.H. Kropschot, et. al.) contains a chart of "Heat absorbed per pound efflux for a helium container relieving above the critical pressure", Figure 6A-2.

Relief venting

- Up to now, we have discussed estimation of the venting flow rate
- In summary
  - We have a vessel or piping MAWP
  - We have a mass flow rate provided either by compressors/pumps or heating of low temperature fluid which must be removed from that vessel at or below the MAWP

Venting flow analyses

- Size piping to the relief device
- Size the relief device
  - Typically using the vendor-provided or standard relief device formulas and charts
- Size piping downstream of the relief device
- A somewhat different venting flow analysis -- estimate flow from a rupture or open valve into a room for an ODH analysis

Constraints and assumptions

- For relief and vent pipe sizing
  - Typically flow driven by a Maximum Allowable Working Pressure (MAWP, as defined by code requirements) at the vessel
  - Pipe size and relief device size are the free parameters
    - Perhaps also pipe routing
  - Flow rate may be determined by a compressor or pump capacity or heat flux to a low temperature vessel

Constraints and assumptions

- For ODH analysis
  - Pipe size may not be a free parameter
    - Analyses are often done for existing systems
  - A flow estimate is based on worst-case pressures and rupture or open valve assumptions
    - Worst-case in terms of maximum flow of inert gas

Venting and relief sizing analysis

- Conservative, err on the safe side
  - Venting is typically not steady-state, very dynamic
  - Make simplifying assumptions on the safe side
    - For example, flow rate estimate should be safely on the high side for relief sizing
- Reviewable
  - Simplest and most straightforward analysis which demonstrates requirement
  - Of course, more sophisticated analysis (such as FEM fluid dynamic simulation may be necessary for a system with sever constraints)

Vent sizing vs ODH flow estimate

- Vent sizing goal is to show that venting system (piping and relief devices) carry flow which starts at or below MAWP
  - So pressure drop estimate may be conservatively high so as to end with a conservatively low flow rate and verify safely large vent system size
- ODH venting analysis may be to estimate flow of inert gas into a space
  - So pressure drop estimate may be conservatively low so as to end with a conservatively high flow rate and verify safely large room ventilation

Vent line flow temperature

The temperature of the expelled fluid for analysis of the flow out the vent line is where

the quantity $\dfrac{\sqrt{v}}{v\left(\dfrac{\partial h}{\partial v}\right)_P}$ is a maximum for the specified venting pressure.

This exit temperature will typically be 5 K - 6 K for a liquid helium container venting at a somewhat supercritical pressure.

The temperature into the relief device may be higher than the exit temperature due to heat transfer to the flow via the vent pipe. For very high flow rates and a relatively short vent line, this temperature rise may be insignificant. A simple energy balance on the flow and stored energy in the vent line, with an approximate and conservatively large convection coefficient may provide a safely conservative estimate of the temperature rise. For a long vent line, a more detailed analysis may be required in sizing the relief device. CGA S1.3, paragraph 6.1.4 and following, provides some guidance for this analysis.

Vent line pressure drop evaluation

A general form of the Bernoulli equation.

Pressure drop for isothermal turbulent flow of a compressible fluid in a circular or non-circular conduit, neglecting gravitational effects, is

$$\int_{P_1}^{P_2} \frac{dP}{\rho} + \sum_i \left(\frac{v^2}{2} \frac{L}{R_h} f \right)_i + \sum_i \left(\frac{v^2}{2} e_v \right)_i = 0$$

where P_1 is pressure in, P_2 is pressure out,

ρ is fluid density, a function of pressure (temperature is assumed constant),

v is average fluid velocity within the i-th section of conduit or downstream of the i-th fitting,

L is conduit section length,

R_h is channel hydraulic radius (defined as flow area divided by wetted perimeter, which is D/4 for circular pipes),

f is friction factor based on hydraulic radius,

and e_v represents the resistance factor for fittings, elbows, tees, etc.

Notation and definition of friction factor f follows that in "Transport Phenomena," by R. Byron Bird, Warren E. Stewart, and Edwin N. Lightfoot (John Wiley and Sons, Inc., New York, 1960).

Considering just an increment of conduit where the pressure drop is dominated by pipe friction with constant flow area rather than fittings or cross-section changes, with pressure and density changing over the length dx of conduit, we have

$$\frac{dP}{\rho} + \frac{v^2}{2}\frac{f}{R_h}dx = 0$$

Substituting for v with $v = \left(\frac{\dot{m}}{\rho A}\right)$ where $\dot{m}$ is fluid mass flow and A is flow area (both are assumed constant),

$$\frac{dP}{\rho} + \frac{1}{2}\left(\frac{\dot{m}}{\rho A}\right)^2 \frac{f}{R_h}dx = 0$$

Thus, integration of the general equation, using the ideal gas approximation for a uniform section of conduit with large pressure drop, isothermal flow, and assuming a conservatively large constant friction factor, we have

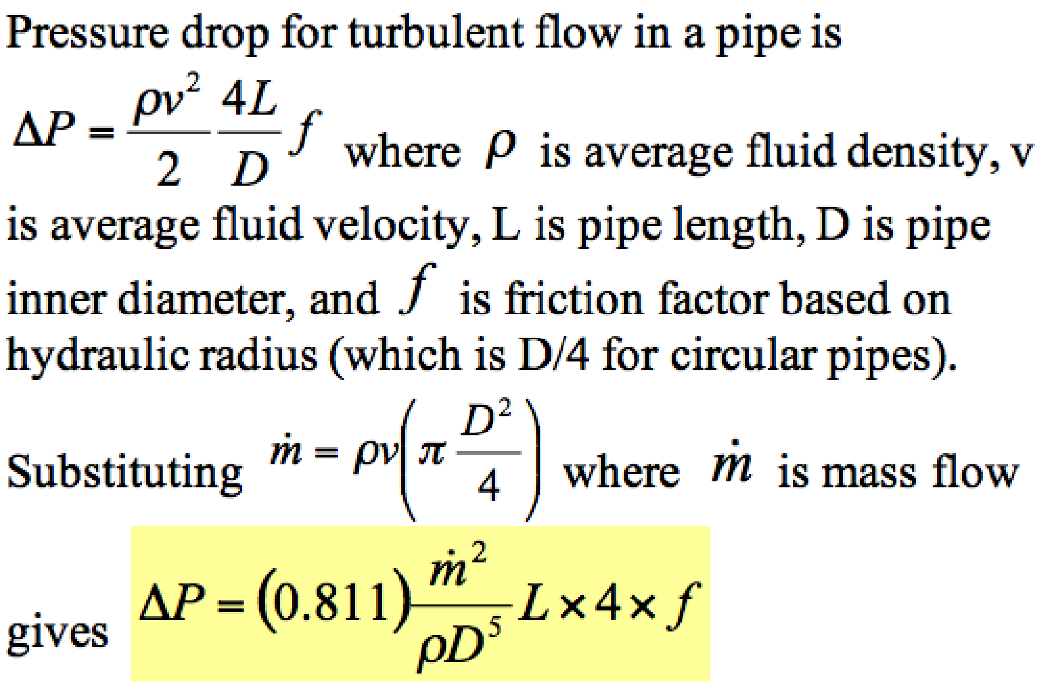
$$\rho_{avg}\Delta P + \frac{1}{2}\left(\frac{\dot{m}}{A}\right)^2 \frac{f}{R_h} L = 0$$

$$\text{where } \frac{(\rho_L + \rho_0)}{2} = \rho_{avg}$$

The point of this little derivation is to show that for sections of pipe with large enough pressure drop that density and velocity changes are significant, iterating pressure drop calculations to come up with a linear average density through the section of constant cross section gives a good estimate of pressure drop.

Pressure drop analysis, working formula for round pipes

This is a form of the D'Arcy-Weisbach formula. With pressure drop expressed as head loss, this is sometimes called simply the Darcy formula. (Note that delta-P changed signs here, to a positive number.)



Pressure drop for turbulent flow in a pipe is

$\Delta P = \frac{\rho v^2}{2} \frac{4L}{D} f$ where ρ is average fluid density, v is average fluid velocity, L is pipe length, D is pipe inner diameter, and f is friction factor based on hydraulic radius (which is D/4 for circular pipes).

Substituting $\dot{m} = \rho v \left(\pi \frac{D^2}{4} \right)$ where $\dot{m}$ is mass flow

gives $\Delta P = (0.811) \frac{\dot{m}^2}{\rho D^5} L \times 4 \times f$

Rupture disk and relief valve sizing

- Flow will typically be choked (sonic) or nearly choked in a relief valve or rupture disk
  - Inlet pressure is at least 15 psig (1 atm gauge) for ASME approved relief devices
  - Discharge is to atmosphere
- This makes analysis relatively simple
  - Relief valve catalogues and rupture disk catalogues have good, practical working formulas and charts for sizing relief devices

Choked flow in a nozzle

Choked (sonic) flow of an ideal gas through a nozzle (from Ascher H. Shapiro, “The Dynamics and Thermodynamics of Compressible Fluid Flow) is

$$\dot{m} = C_D A \left(\sqrt{k \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}} \right) \left(\sqrt{\rho P} \right)$$ where $k = \frac{c_p}{c_v} = 5/3$ for helium, C_D is the coefficient of discharge, A is minimum area, and P is the absolute inlet pressure.

Thus, for helium, $\dot{m} = 0.726 C_D A \sqrt{\rho P}$

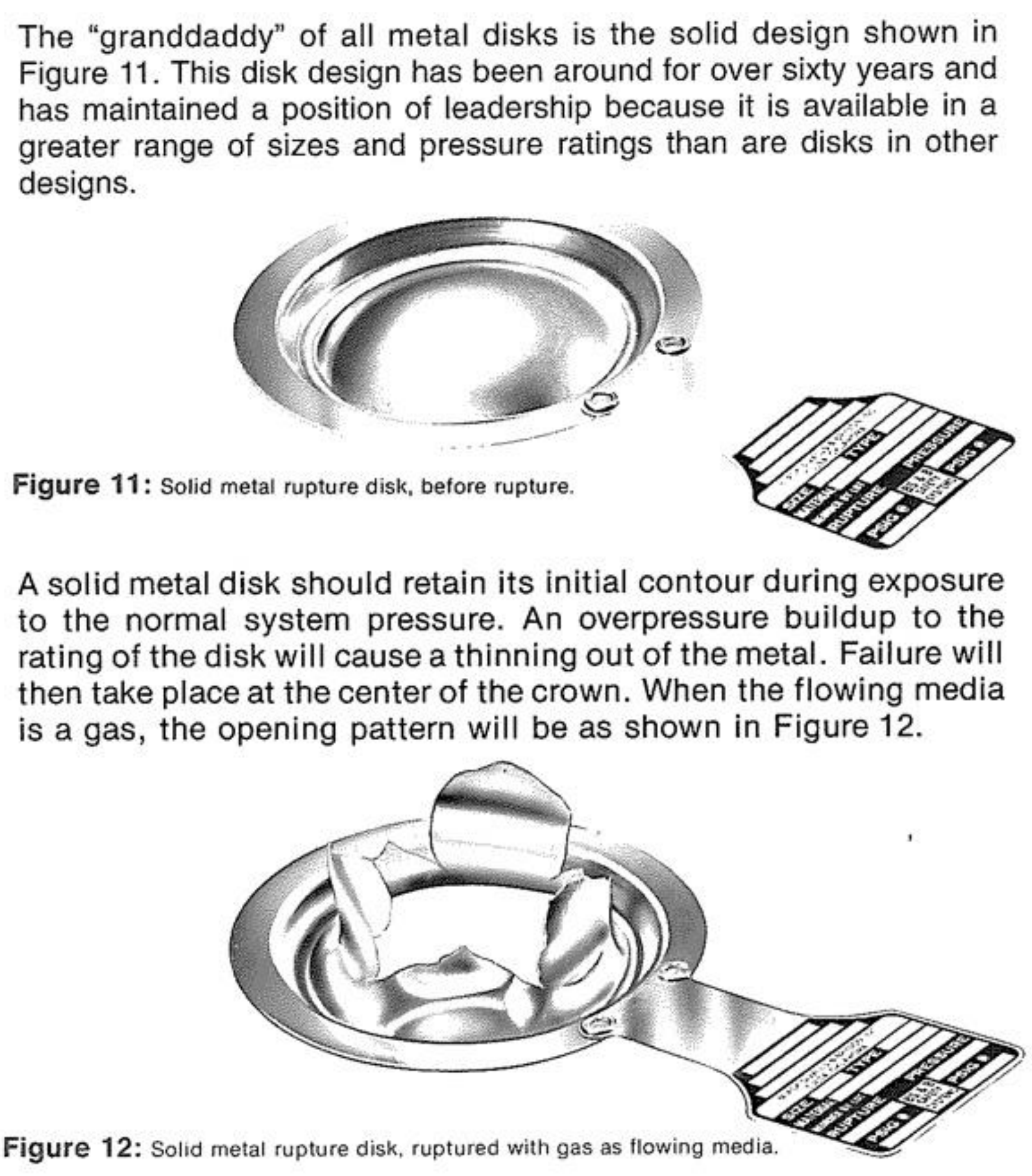
Crane Technical Paper #410

- Crane Technical Paper #410 “Flow of Fluids through Valves, Fittings, and Pipes”
- A classic reference, still available in updated forms
- Contains many forms of Bernoulli Equation and other formulas for both compressible and incompressible flow
- Relief valve and rupture disk catalogue formulas often reference Crane Technical Paper #410
- My only criticism (and strictly my personal opinion) -- I do not like the incorporation of unit conversions into formulas, which is too common in these engineering handbooks

Relief devices

- For cracking pressures of 15 psig or higher, ASME-approved (UV- or UD-stamped) pressure relief devices may be used.
- For vessels with a differential pressure of more than 15 psid within the vacuum jacket but a gauge pressure of less than 15 psig, ASME-approved reliefs are not available.

From the BS&B rupture disk catalogue



The "granddaddy" of all metal disks is the solid design shown in Figure 11. This disk design has been around for over sixty years and has maintained a position of leadership because it is available in a greater range of sizes and pressure ratings than are disks in other designs.

Figure 11: Solid metal rupture disk, before rupture.

A solid metal disk should retain its initial contour during exposure to the normal system pressure. An overpressure buildup to the rating of the disk will cause a thinning out of the metal. Failure will then take place at the center of the crown. When the flowing media is a gas, the opening pattern will be as shown in Figure 12.

Figure 12: Solid metal rupture disk, ruptured with gas as flowing media.

Rupture disks

- Various types, some pre-etched or with knife edge, or failure in collapse (pressure on the dome) and other designs and materials
  - Difficult to set a precise opening pressure
- A last resort device since they do not close
  - You don’t want these opening in normal operations
  - Switching valves available for dual disks such that one can be replaced while the other holds pressure and provides protection
- Inexpensively provide very large capacity, so typical for the worst-case loss of vacuum
  - Operational reclosing relief valves set at a safely lower pressure (80% of RD or less) prevent accidental opening of the rupture disk

Relief valves

- Even though valve at room temperature, will cool upon relieving, so need cold-tolerant material and design
- Take care to provide ASME UV-stamped valves for code-stamped vessels

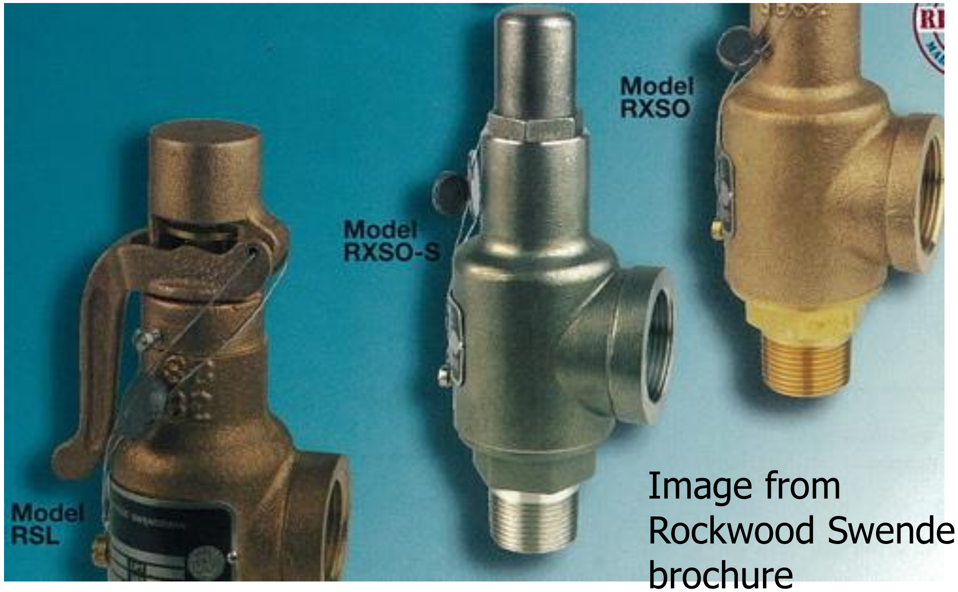
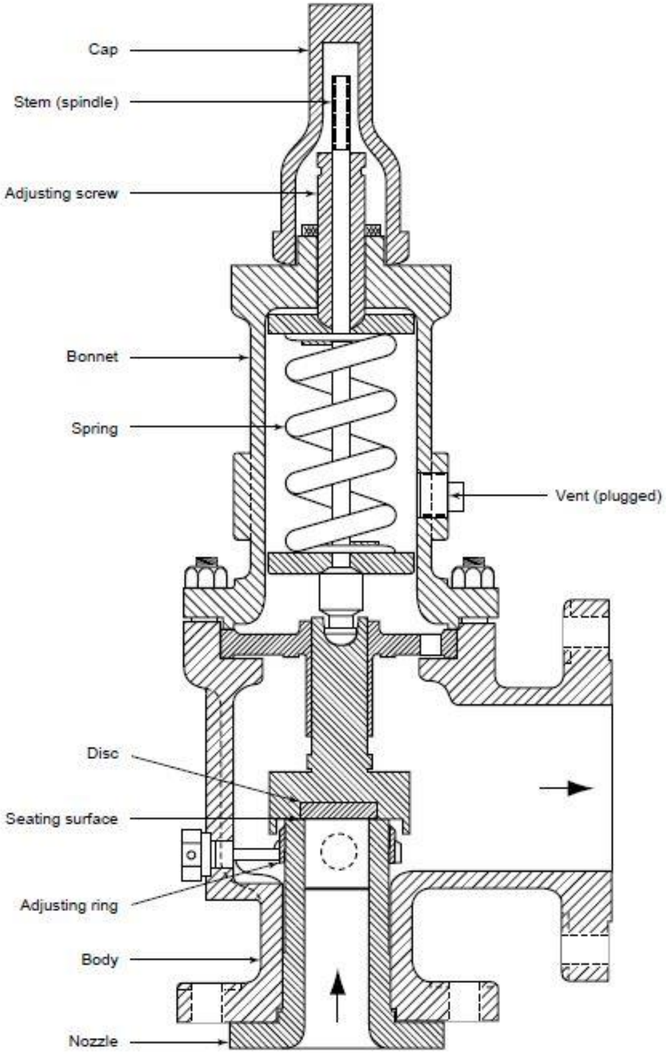


Image from Rockwood Swendeman brochure



Conventional safety relief valve, figure from API Standard 520, Part 1, Fig 2

Gas pressure operates against a spring. Set pressure may be adjusted via spring compression.

Relief valves

- Sizing best done via valve manufacturer information
  - Shape of valve body, type of plug make sizing unique to the valve design
  - Manufacturers certify flow capacity for UV-stamped (ASME approved) valves

Venting system analysis example

- The following spreadsheet shows a stepwise pressure drop analysis through a venting system
  - Piping to a rupture disk via various straight lengths and fittings
  - Rupture disk
  - Piping downstream of the rupture disk
- A piecewise analysis such as in this Excel spreadsheet can be quite good since isothermal flow and the use of average density are good assumptions for analysis within each piece of conduit, which tend to be relatively short

Sample spreadsheet for large pressure drop

Mass flow rate helium	865.73	g/sec											
Vessel's helium pressure	2	bar at helium vessel, start of calc's											
Helium temperature	8	K											
absolute viscosity	2.00E-05	gr/cm-sec	assumed constant										
	Fitting ev	L (in)	L (cm)	d (cm)	pressure (bar)	(Adjusted for pressure) Helium density (g/cm^3)	Velocity head (bar)	Reynolds	(Based on Re and on Rh) Friction factor	Beta	K	Pressure drop (bar)	Pressure drop due to friction in straight sections (bar)
Piping within HTC													
Entrance into vent pipe	0.45			5.49	2.000	0.013	0.052				0.45	0.023	
Mitre	1.50			5.49	1.977	0.013	0.053				1.50	0.079	
Straight run		2.00	5.08	5.49	1.898	0.012	0.056	1.01E+07	1.40E-03		0.0052	0.000	0.000
90 deg bend	0.70			5.49	1.898	0.012	0.056				0.90	0.051	
Vent line to LL dewar		42.43	107.77	5.49	1.847	0.011	0.059	1.01E+07	1.40E-03		0.1104	0.007	0.007
Thru LL dewar	1.45			5.49	1.840	0.011	0.059				1.45	0.086	
straight run		3.80	9.65	5.49	1.754	0.010	0.065	1.01E+07	1.40E-03		0.0099	0.001	0.001
tee thru	0.30			5.49	1.753	0.010	0.065				0.30	0.019	
2-90 deg bends	1.40			5.49	1.734	0.010	0.066				1.40	0.092	
straight run		2.40	6.10	5.49	1.642	0.009	0.072	1.01E+07	1.40E-03		0.0062	0.000	0.000
Sudden contraction	0.06			5.08	1.641	0.009	0.072			0.86	0.06	0.005	
Flexhose assy		25.70	65.28	5.08	1.637	0.009	0.099	1.09E+07	1.38E-03		0.0708	0.028	0.028
Sudden expansion	0.03			5.08	1.609	0.009	0.102			0.86	0.03	0.003	
Pumping line weldment													
helicoflex flange		1.20	3.05	5.49	1.606	0.009	0.075	1.01E+07	1.40E-03		0.0031	0.000	0.000
90 deg bend	0.70			5.49	1.606	0.009	0.075				0.7000	0.052	
straight run		6.30	16.00	5.49	1.553	0.008	0.079	1.01E+07	1.40E-03		0.0164	0.001	0.001
tee branch	1.00			5.49	1.552	0.008	0.079				1.0000	0.079	
Helium vent line branch													
straight run		13.10	33.27	5.49	1.473	0.008	0.087	1.01E+07	1.40E-03		0.0341	0.003	0.003
90 deg bend	0.70			5.49	1.470	0.008	0.087				0.70	0.061	
straight run		22.25	56.52	5.49	1.409	0.007	0.094	1.01E+07	1.40E-03		0.0579	0.005	0.005
Expansion 2 to 3-inch	1.63			5.49	1.403	0.007	0.094			0.439008	1.63	0.154	
3-inch diameter piping													
BS&B LPS burst disk	0.16			7.62	1.249	0.006	0.031			0.846852	0.16	0.005	
Straight run		72.00	182.88	8.28	1.244	0.006	0.022	6.66E+06	1.56E-03		0.1376	0.003	0.003
Expansion 3 to 4-inch	0.50			8.28	1.241	0.006	0.022			0.58562	0.50	0.011	
4-inch diameter piping													
Straight run		216.00	548.64	10.82	1.230	0.006	0.008	5.10E+06	1.66E-03		0.3377	0.003	0.003
90 deg elbow	0.70			10.82	1.227	0.006	0.008				0.70	0.005	
90 deg elbow	0.70			10.82	1.222	0.006	0.008				0.70	0.006	
90 deg elbow	0.70			10.82	1.216	0.006	0.008				0.70	0.006	
90 deg elbow	0.70			10.82	1.211	0.006	0.008				0.70	0.006	
Expansion 4 to 6-inch	1.51			10.82	1.205	0.005	0.008			0.449071	1.51	0.012	
6-inch diameter piping													
Straight run		96.00	243.84	16.15	1.193	0.005	0.002	3.42E+06	1.84E-03		0.1111	0.000	0.000
Exit	1.00			16.15	1.193	0.005	0.002				1.00	0.002	
Total	15.89368				1.19							0.809	0.052
													6.39%

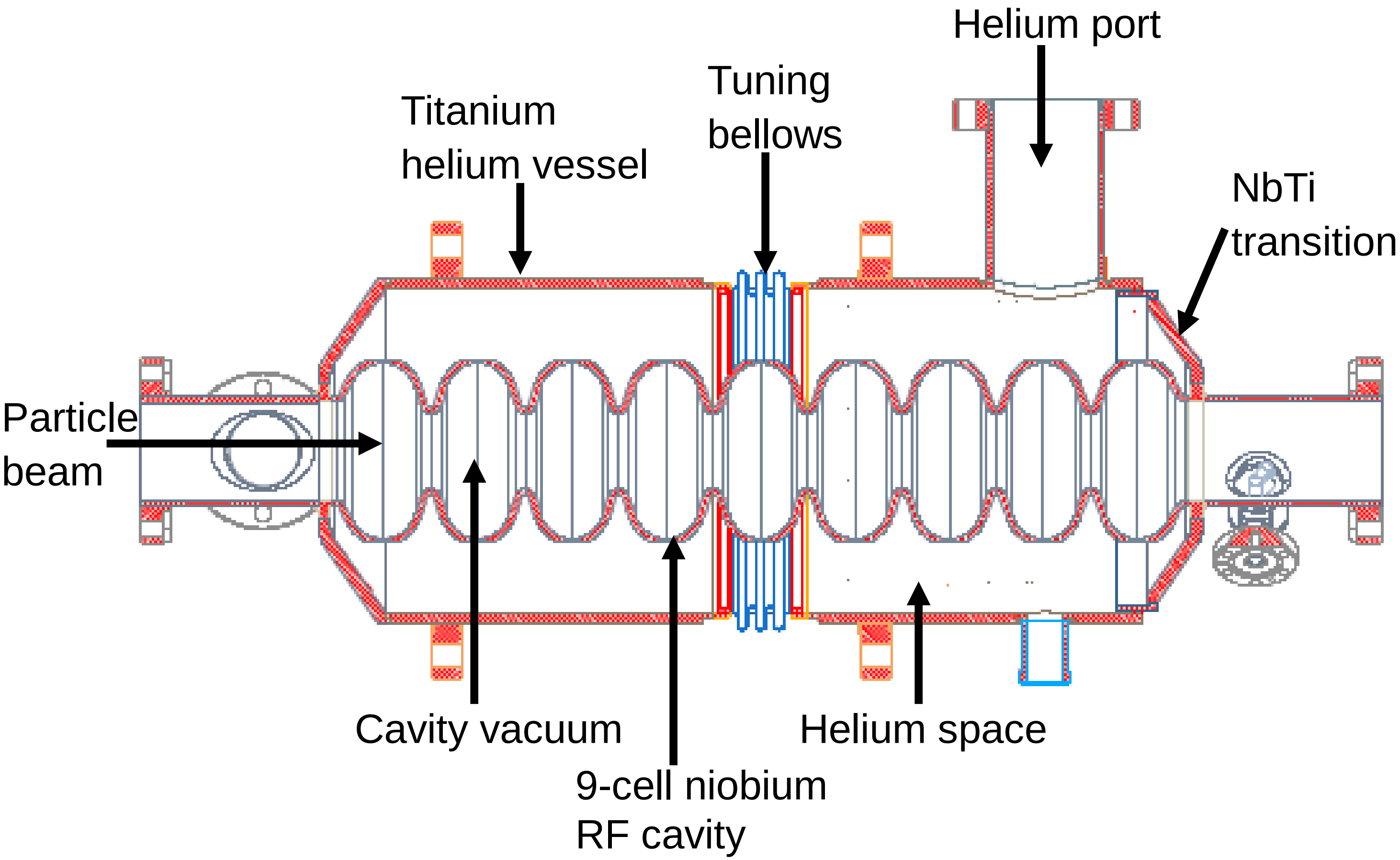
More examples

- We have talked about relief systems
- Venting for the loss of vacuum to air incident with associated high heat flux and venting flow rate, combined with a low MAWP, can be the determining factor for pipe sizes all the way into the cryostat (not just the pipes connecting to the reliefs)
- Superconducting RF cavity helium vessels have these traits
  - Low MAWP of as little as 1 bar gauge due to the delicate nature of the RF cavity
  - Large bare metal surface area for air condensation within the cavity vacuum, on the RF cavity surface
- The following examples illustrate some of these design issues

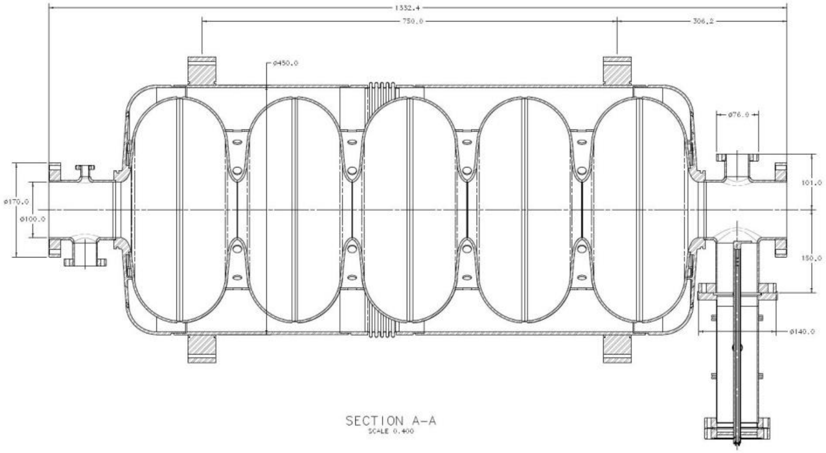
Cryomodule Pipe Sizing Criteria

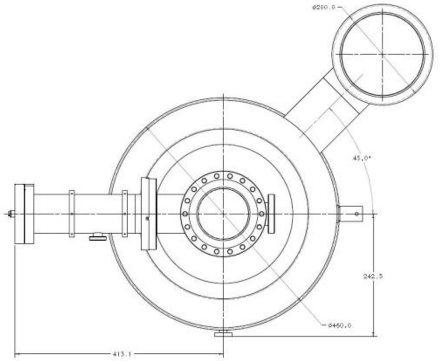
- Heat transport from cavity to 2-phase pipe
  - 1 Watt/sq.cm. is a conservative rule for a vertical pipe (less heat flux with horizontal lengths)
- Two phase pipe size
  - 5 meters/sec vapor "speed limit" over liquid
  - Not smaller than nozzle from helium vessel
- Gas return pipe (also serves as the support pipe in TESLA-style CM)
  - Pressure drop < 10% of total pressure in normal operation
  - Support structure considerations
- Loss of vacuum venting P < cold MAWP at cavity
  - Path includes nozzle from helium vessel, 2-phase pipe, may include gas return pipe, and any external vent lines

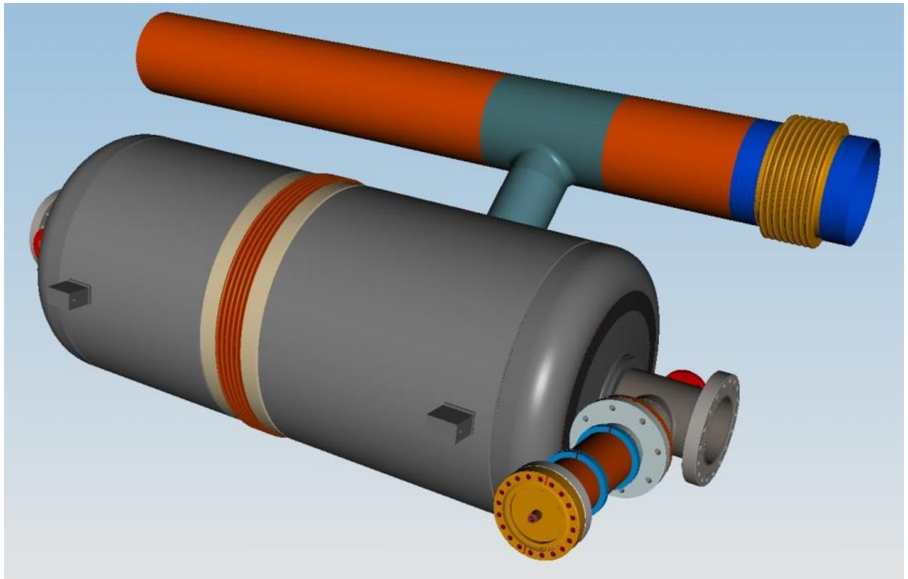
Superconducting RF Helium Vessel



Dressed cavity 650 MHz. (proposal) with MC cold-part

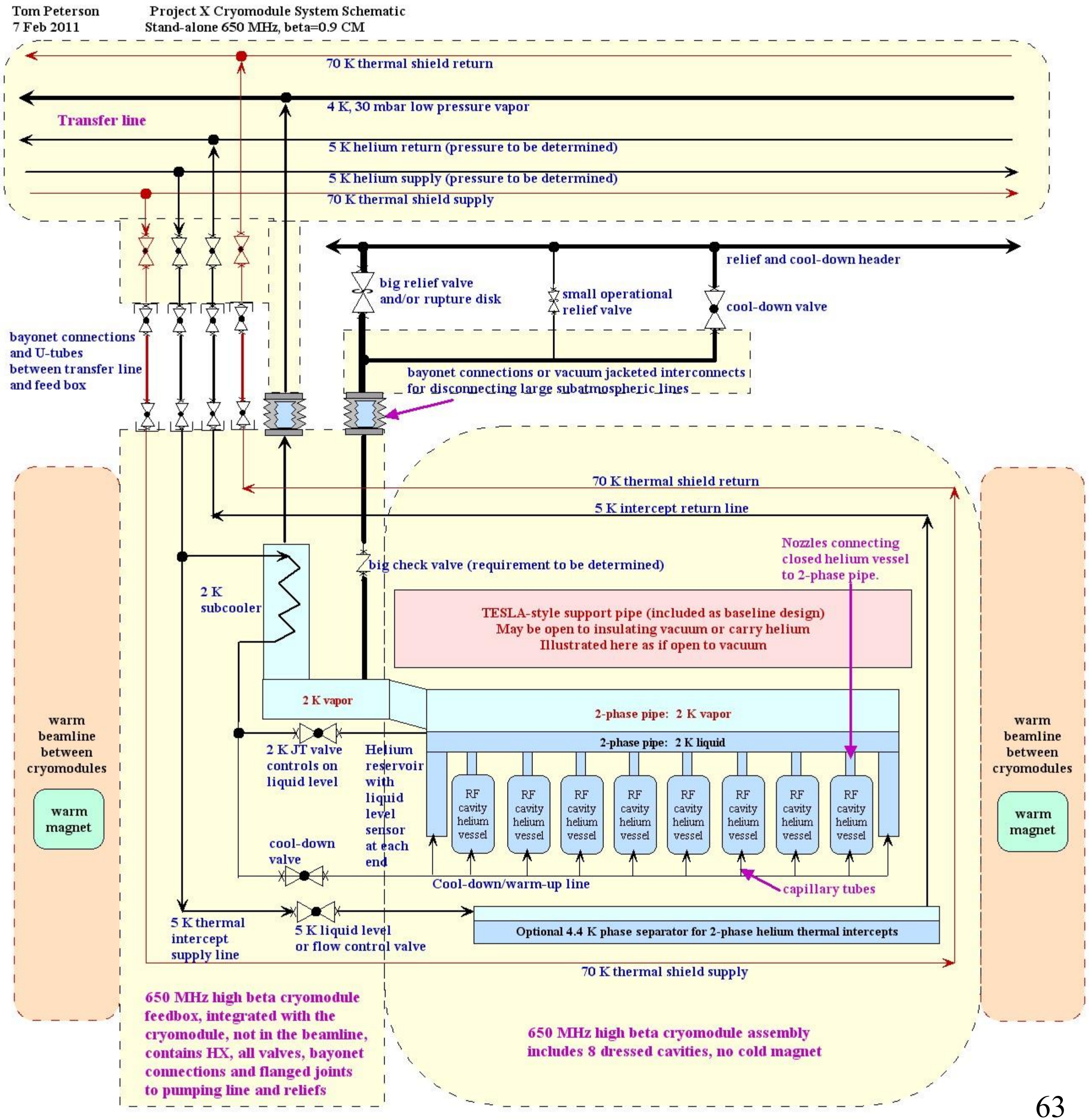




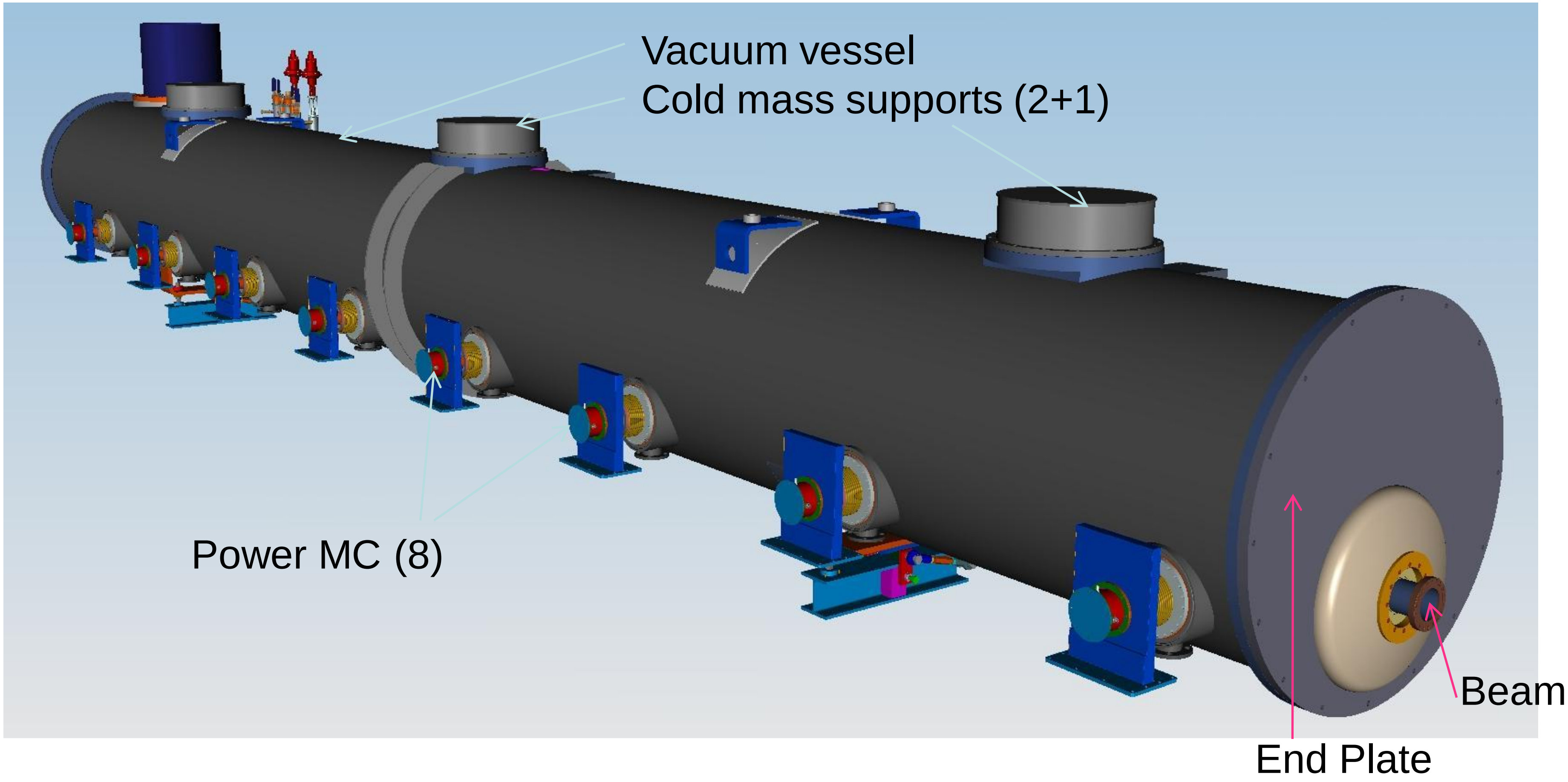


Ti Helium vessel OD-	450.0 mm
Ti 2-Phase pipe ID-	161.5 mm
Ti 2-Phase chimney ID-	95.5 mm

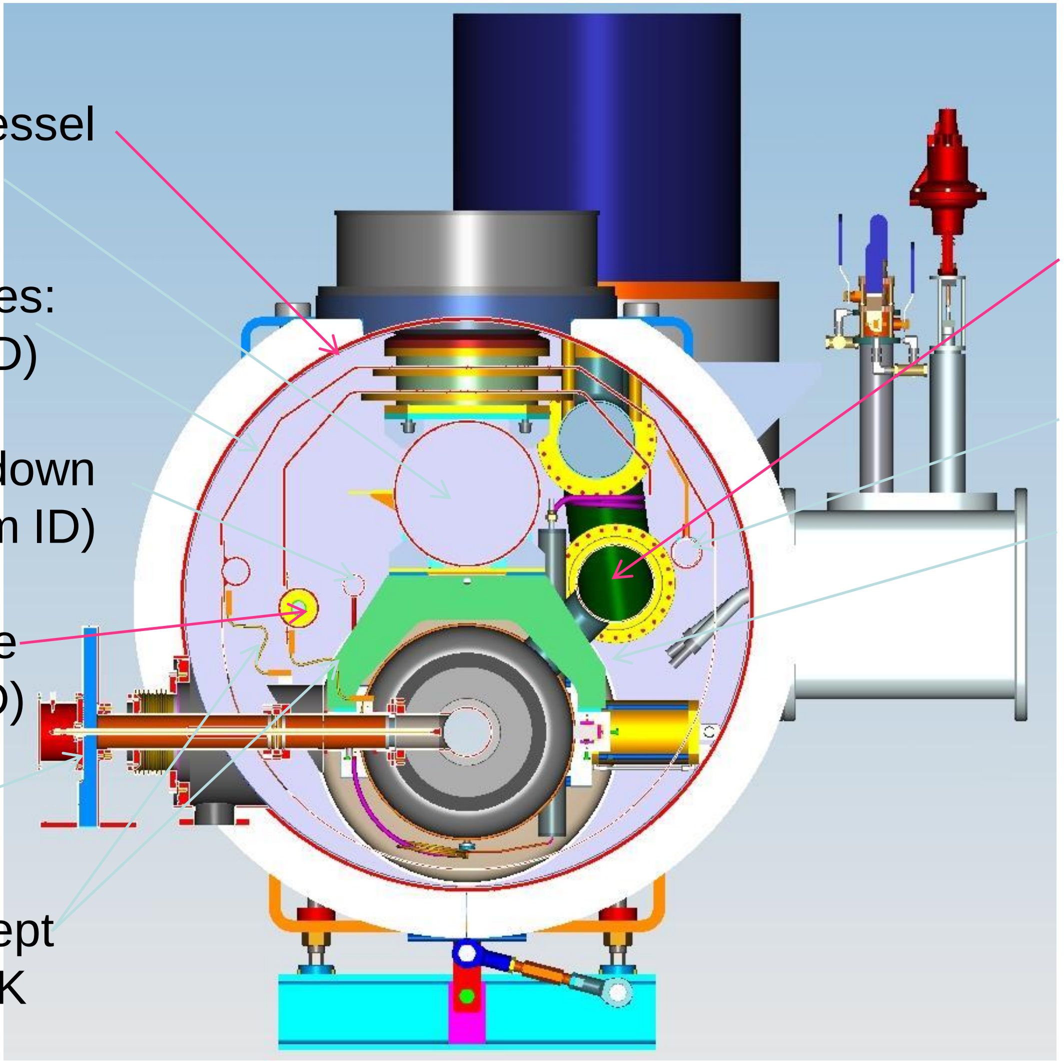
Stand-alone cryomodule schematic



650 MHz Cryomodule (Tesla Style-Stand Alone)



X-Y section



-48" vacuum vessel

300 mm pipe

-80K shield, pipes:
(Nom: 35mm-ID)

-Warm up-cool down
pipe (nom 25mm ID)

-4K return pipe
(nom 25mm ID)

-650 MC

-Thermal intercept
to MC 80k & 4K

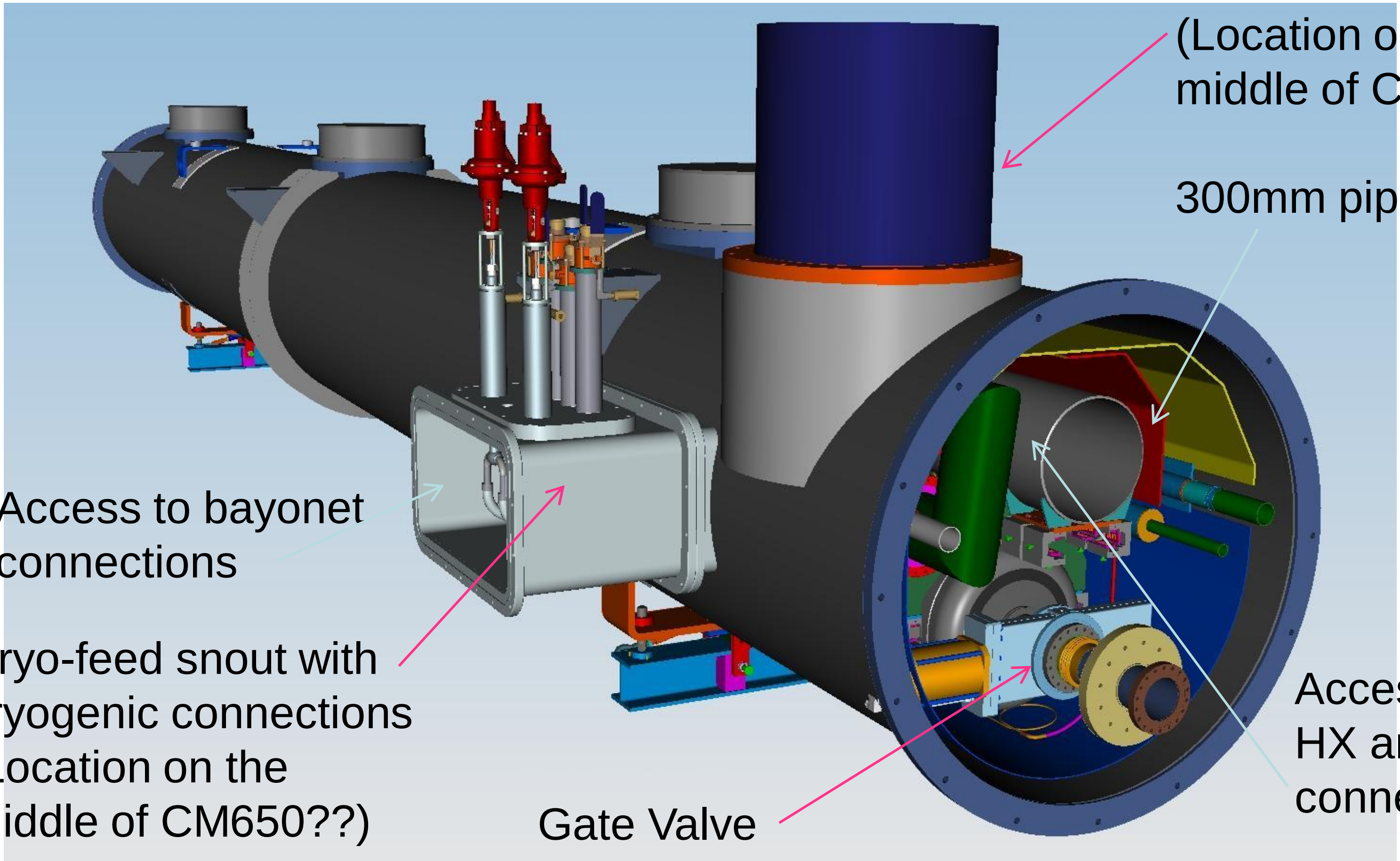
-2-Phase pipe
(161mm-ID)

-80K Forward pipe

-4K Forward pipe
(?)

-Thermal intercept
2-phase pipe to
300mm pipe (?)

650 MHz cryomodule. End plate not shown.



Heat exchanger (Location on the middle of CM650??)

300mm pipe

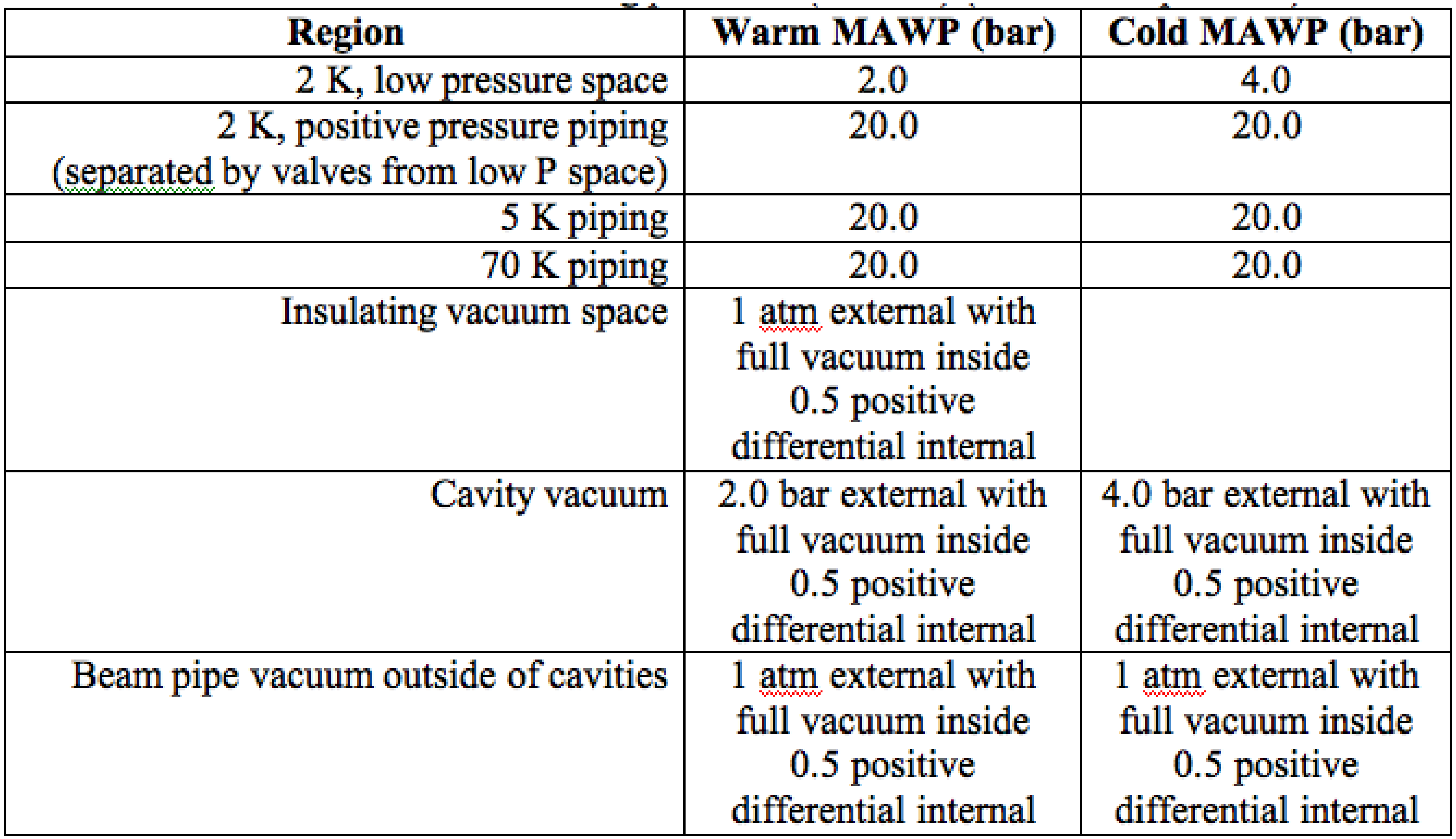
Access to bayonet connections

Cryo-feed snout with cryogenic connections (Location on the middle of CM650??)

Gate Valve

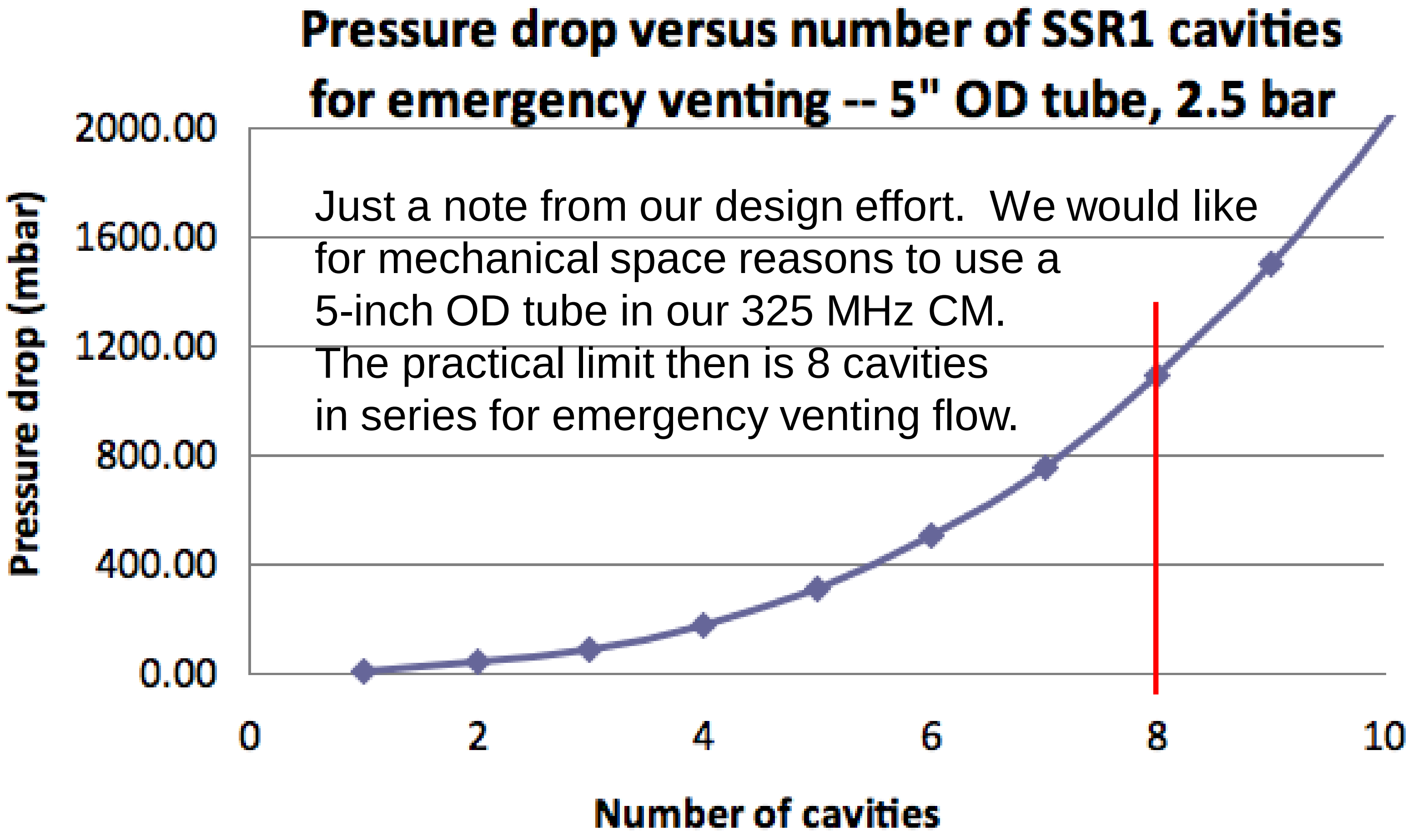
Access to HX and U-turn connections

Cryomodule requirements -- vessel and piping pressures



Region	Warm MAWP (bar)	Cold MAWP (bar)
2 K, low pressure space	2.0	4.0
2 K, positive pressure piping (separated by valves from low P space)	20.0	20.0
5 K piping	20.0	20.0
70 K piping	20.0	20.0
Insulating vacuum space	1 atm external with full vacuum inside 0.5 positive differential internal	
Cavity vacuum	2.0 bar external with full vacuum inside 0.5 positive differential internal	4.0 bar external with full vacuum inside 0.5 positive differential internal
Beam pipe vacuum outside of cavities	1 atm external with full vacuum inside 0.5 positive differential internal	1 atm external with full vacuum inside 0.5 positive differential internal

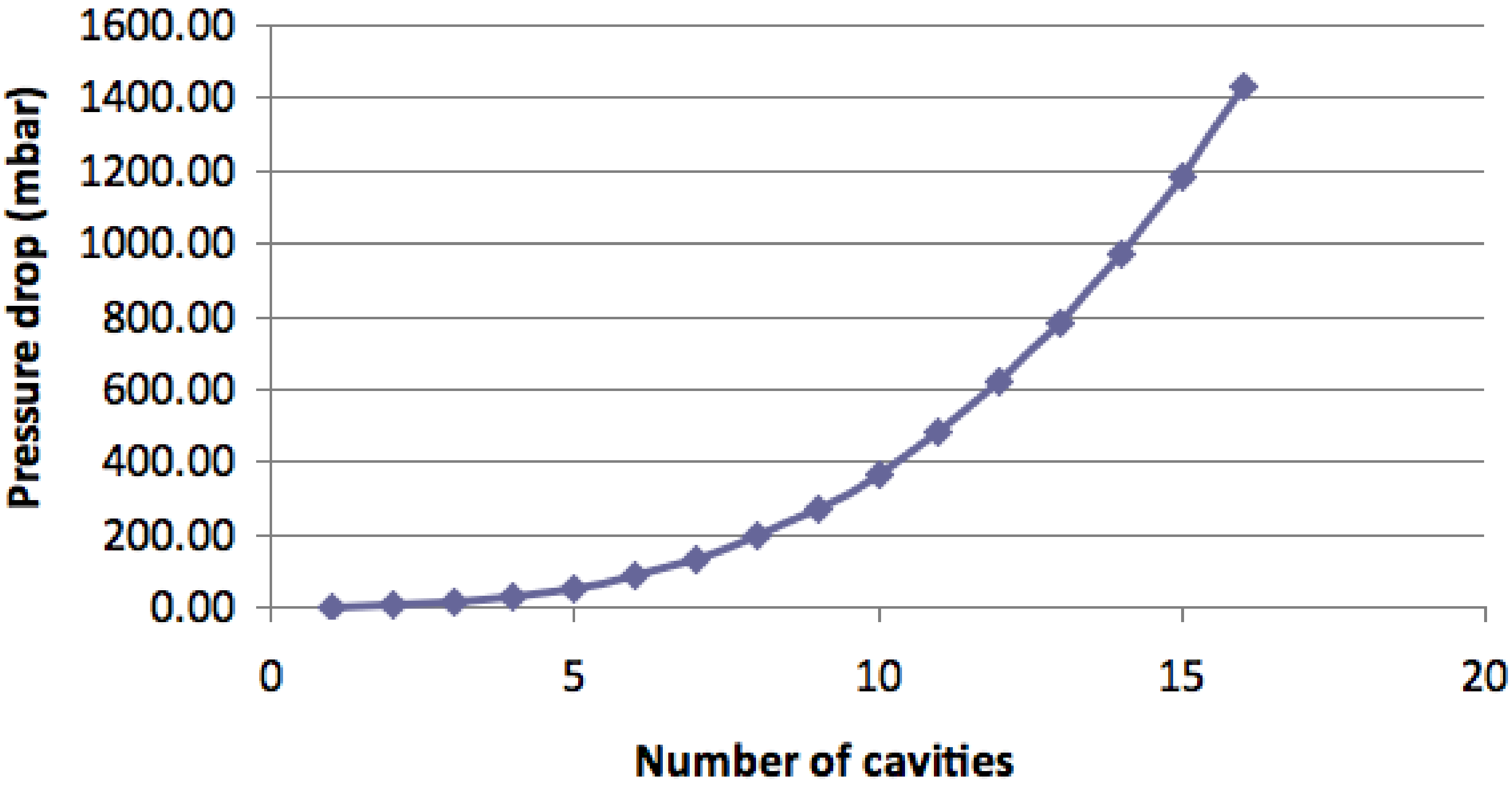
325 MHz loss of vacuum venting



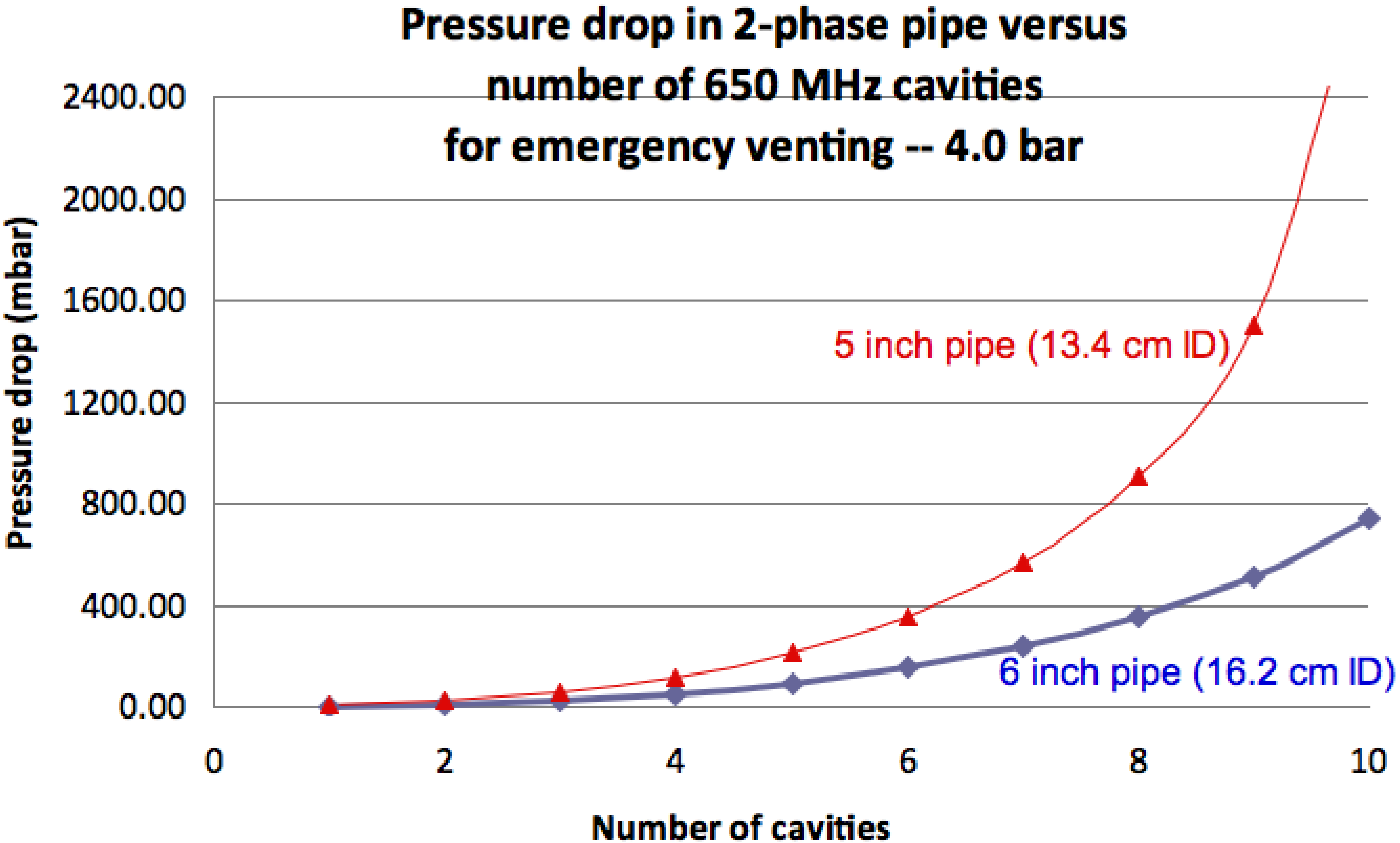
Just a note from our design effort. We would like for mechanical space reasons to use a 5-inch OD tube in our 325 MHz CM. The practical limit then is 8 cavities in series for emergency venting flow.

Pressure drop versus number of cavities for emergency venting -- 20 cm pipe

Note: a 3-inch air inlet hole results in a mass flow equivalent to ~ 8 beta=0.9 650 MHz cavities. Checking the feasibility of venting a CM string of cavities with a large 2-phase pipe. Looks OK but still need frequent cross-connects to a larger pipe.



Pressure drop in 2-phase pipe versus number of 650 MHz cavities for emergency venting -- 4.0 bar



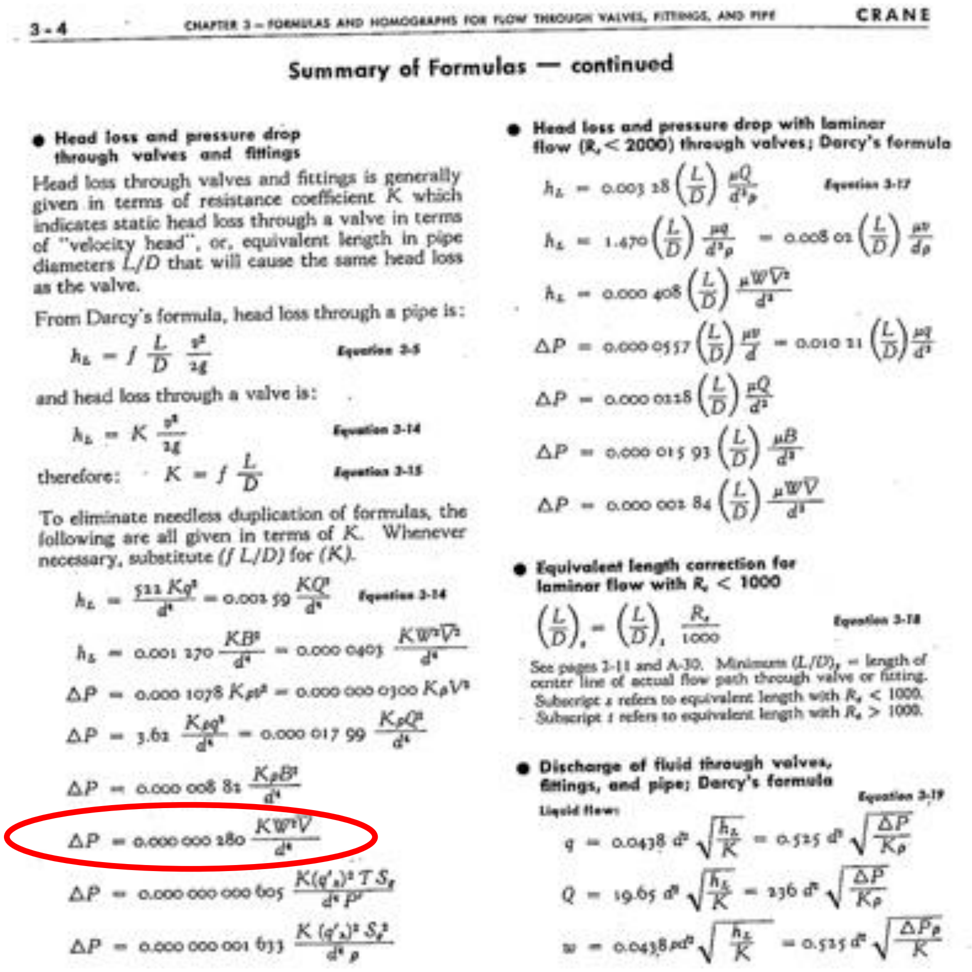
A comment about engineering

- Note that the previous slides showing some examples of cryomodule pipe sizing for emergency venting situations could have been placed in the cryomodule design lecture.
- Off-design allowances and safety considerations are part of the design process!

Subatmospheric systems

- In cases where normal operation is subatmospheric, a rupture disk is generally preferred, since a valve may allow air to leak back into the system.
- Back leakage must be prevented not only to avoid contamination of the helium during normal operation, but because frozen air in a vent line could block the relief flow path.

Crane Technical Paper #410 "Flow of Fluids through Valves, Fittings, and Pipes"



3 - 4 CHAPTER 3 — FORMULAS AND NOMOGRAPHS FOR FLOW THROUGH VALVES, FITTINGS, AND PIPE CRANE

Summary of Formulas — continued

- **Head loss and pressure drop through valves and fittings**

Head loss through valves and fittings is generally given in terms of resistance coefficient K which indicates static head loss through a valve in terms of "velocity head", or, equivalent length in pipe diameters L/D that will cause the same head loss as the valve.

From Darcy's formula, head loss through a pipe is:

$$h_L = f\,\frac{L}{D}\,\frac{v^2}{2g} \qquad \text{Equation 3-5}$$

and head loss through a valve is:

$$h_L = K\,\frac{v^2}{2g} \qquad \text{Equation 3-14}$$

therefore:

$$K = f\,\frac{L}{D} \qquad \text{Equation 3-15}$$

To eliminate needless duplication of formulas, the following are all given in terms of K. Whenever necessary, substitute $(f\,L/D)$ for (K).

$$h_L = \frac{522\,Kq^2}{d^4} = 0.002\,59\,\frac{KQ^2}{d^4} \qquad \text{Equation 3-14}$$

$$h_L = 0.001\,270\,\frac{KB^2}{d^4} = 0.000\,0403\,\frac{KW^2\bar{V}^2}{d^4}$$

$$\Delta P = 0.000\,1078\,K\rho v^2 = 0.000\,000\,0300\,K\rho\bar{V}^2$$

$$\Delta P = 3.62\,\frac{K\rho q^2}{d^4} = 0.000\,017\,99\,\frac{K\rho Q^2}{d^4}$$

$$\Delta P = 0.000\,008\,82\,\frac{K\rho B^2}{d^4}$$

$$\Delta P = 0.000\,000\,280\,\frac{KW^2\bar{V}}{d^4}$$

$$\Delta P = 0.000\,000\,000\,605\,\frac{K(q'_h)^2\,T\,S_g}{d^4\,P'}$$

$$\Delta P = 0.000\,000\,001\,633\,\frac{K\,(q'_h)^2\,S_g^2}{d^4\,\rho}$$

- **Head loss and pressure drop with laminar flow ($R_e < 2000$) through valves; Darcy's formula**

$$h_L = 0.003\,28\left(\frac{L}{D}\right)\frac{\mu Q}{d^4\rho} \qquad \text{Equation 3-17}$$

$$h_L = 1.470\left(\frac{L}{D}\right)\frac{\mu q}{d^3\rho} = 0.008\,02\left(\frac{L}{D}\right)\frac{\mu v}{d\rho}$$

$$h_L = 0.000\,408\left(\frac{L}{D}\right)\frac{\mu W\bar{V}^2}{d^3}$$

$$\Delta P = 0.000\,0557\left(\frac{L}{D}\right)\frac{\mu v}{d} = 0.010\,21\left(\frac{L}{D}\right)\frac{\mu q}{d^3}$$

$$\Delta P = 0.000\,0228\left(\frac{L}{D}\right)\frac{\mu Q}{d^3}$$

$$\Delta P = 0.000\,015\,93\left(\frac{L}{D}\right)\frac{\mu B}{d^3}$$

$$\Delta P = 0.000\,002\,84\left(\frac{L}{D}\right)\frac{\mu W\bar{V}}{d^3}$$

- **Equivalent length correction for laminar flow with $R_e < 1000$**

$$\left(\frac{L}{D}\right)_s = \left(\frac{L}{D}\right)_t \frac{R_e}{1000} \qquad \text{Equation 3-18}$$

See pages 2-11 and A-30. Minimum $(L/D)_s$ = length of center line of actual flow path through valve or fitting. Subscript s refers to equivalent length with $R_e < 1000$. Subscript t refers to equivalent length with $R_e > 1000$.

- **Discharge of fluid through valves, fittings, and pipe; Darcy's formula**

Equation 3-19

Liquid flow:

$$q = 0.0438\,d^2\sqrt{\frac{h_L}{K}} = 0.525\,d^2\sqrt{\frac{\Delta P}{K\rho}}$$

$$Q = 19.65\,d^2\sqrt{\frac{h_L}{K}} = 236\,d^2\sqrt{\frac{\Delta P}{K\rho}}$$

$$w = 0.0438\,\rho d^2\sqrt{\frac{h_L}{K}} = 0.525\,d^2\sqrt{\frac{\Delta P\rho}{K}}$$

For example from previous list

$$\Delta P = 0.000\,000\,280\,\frac{K W^2 \bar{V}}{d^4}$$

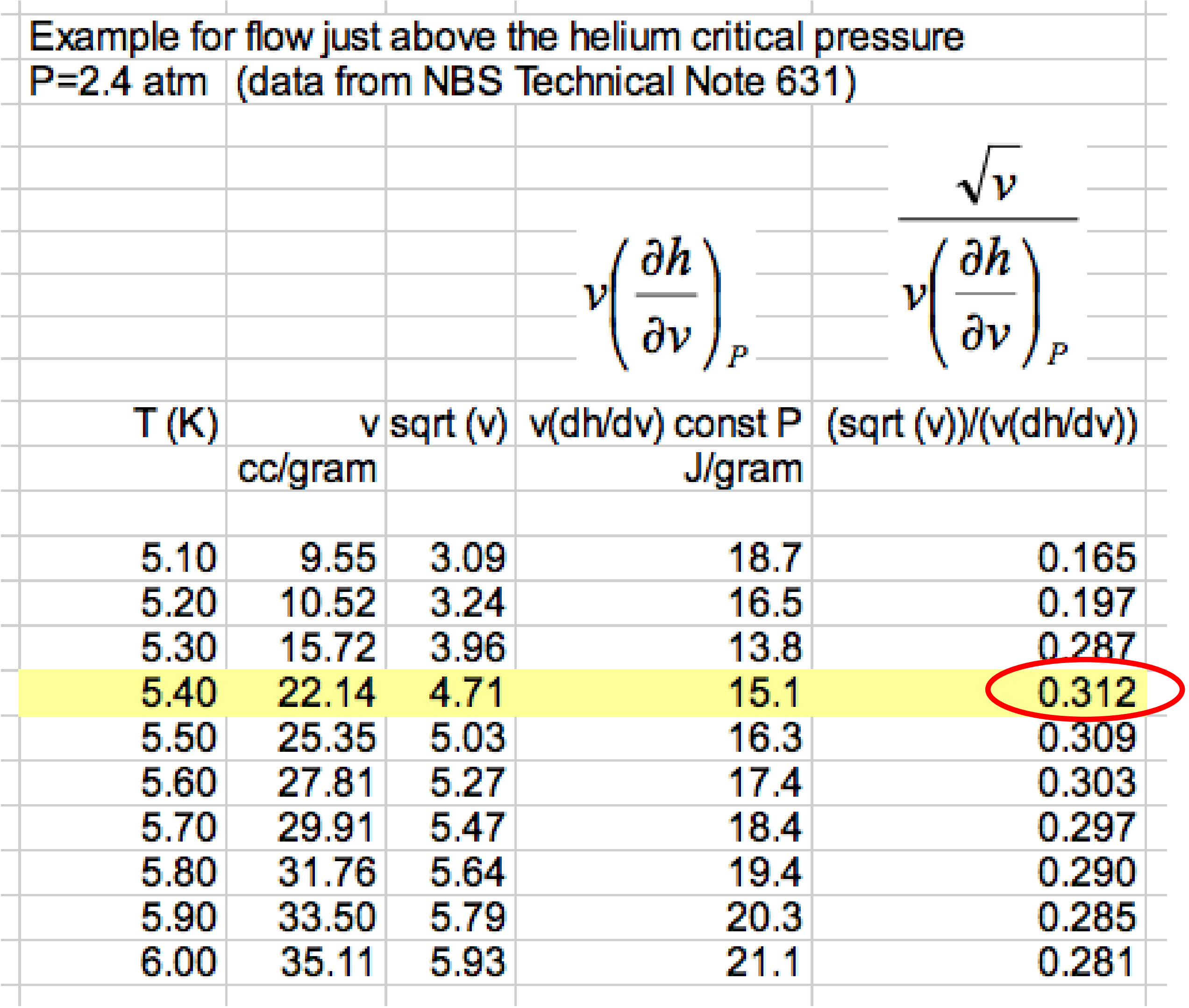
Where ΔP is pressure drop in psi, V is the specific volume (in^3/lbm), K is the total resistance coefficient = fL/d so is dimensionless, W is the mass flow rate (lbm/hr), and d is the pipe inner diameter (in).

Compare to

$$\Delta P = (0.811)\frac{\dot{m}^2}{\rho D^5} L \times 4 \times f$$

from slide 34 -- no unit conversions, and a different definition of friction factor. Note! Some sources define f based on hydraulic radius and some on diameter, a factor 4 difference for pipes!

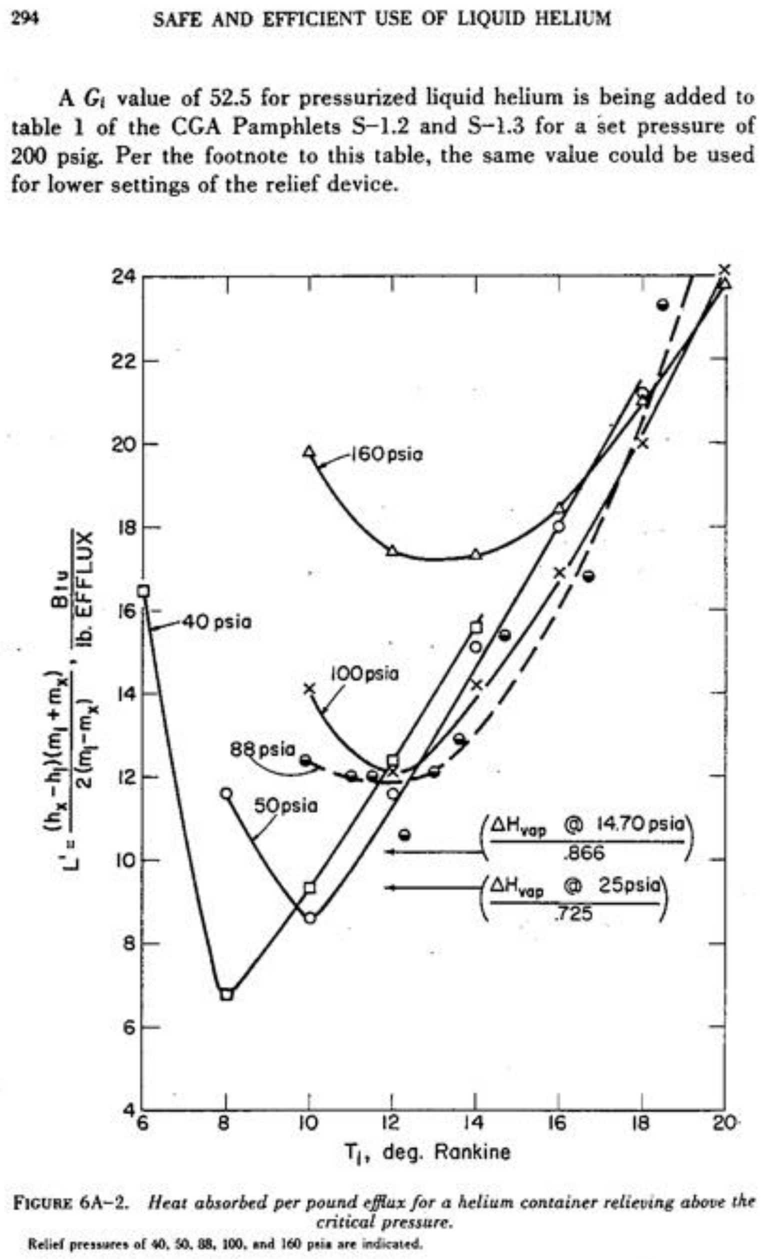
An example from CGA S-1.3—2005 for evaluation of the discharge temperature and effective latent heat (or “pseudo latent heat”)



Example for flow just above the helium critical pressure
P=2.4 atm (data from NBS Technical Note 631)

			$v\left(\frac{\partial h}{\partial v}\right)_P$	$\frac{\sqrt{v}}{v\left(\frac{\partial h}{\partial v}\right)_P}$
T (K)	v	sqrt (v)	v(dh/dv) const P	(sqrt (v))/(v(dh/dv))
	cc/gram		J/gram	
5.10	9.55	3.09	18.7	0.165
5.20	10.52	3.24	16.5	0.197
5.30	15.72	3.96	13.8	0.287
5.40	22.14	4.71	15.1	0.312
5.50	25.35	5.03	16.3	0.309
5.60	27.81	5.27	17.4	0.303
5.70	29.91	5.47	18.4	0.297
5.80	31.76	5.64	19.4	0.290
5.90	33.50	5.79	20.3	0.285
6.00	35.11	5.93	21.1	0.281

Maximum, so venting temperature is about 5.40 K and effective latent heat is 15.1 J/g



294 SAFE AND EFFICIENT USE OF LIQUID HELIUM

A G_i value of 52.5 for pressurized liquid helium is being added to table 1 of the CGA Pamphlets S-1.2 and S-1.3 for a set pressure of 200 psig. Per the footnote to this table, the same value could be used for lower settings of the relief device.

FIGURE 6A-2. *Heat absorbed per pound efflux for a helium container relieving above the critical pressure.*

Relief pressures of 40, 50, 88, 100, and 160 psia are indicated.

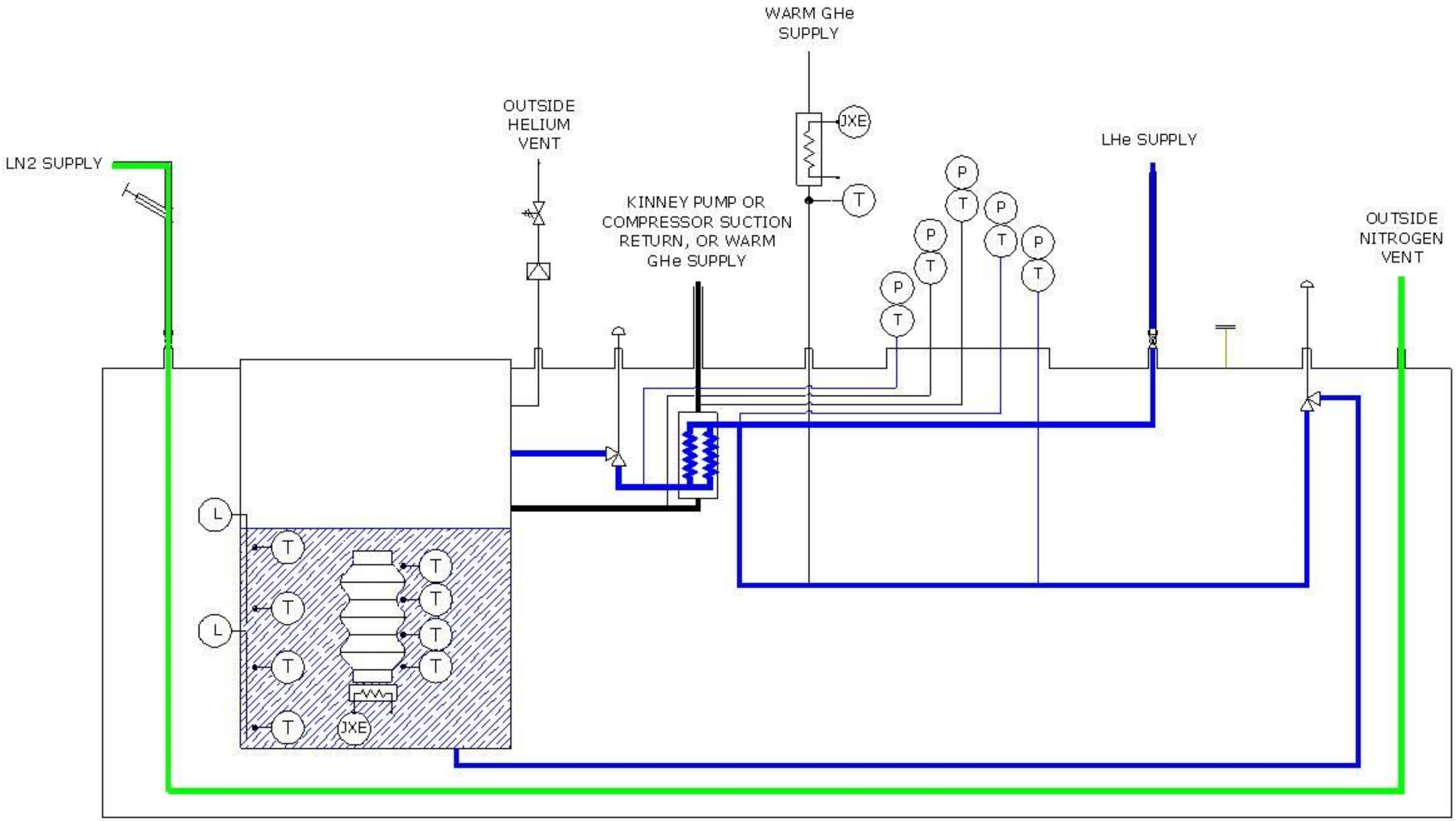
Another source of pseudo latent heat -- a plot of effective latent heat of helium as a function of temperature and pressure from R.H. Kropschot, et. al., "Technology of Liquid Helium," NBS Monograph 111

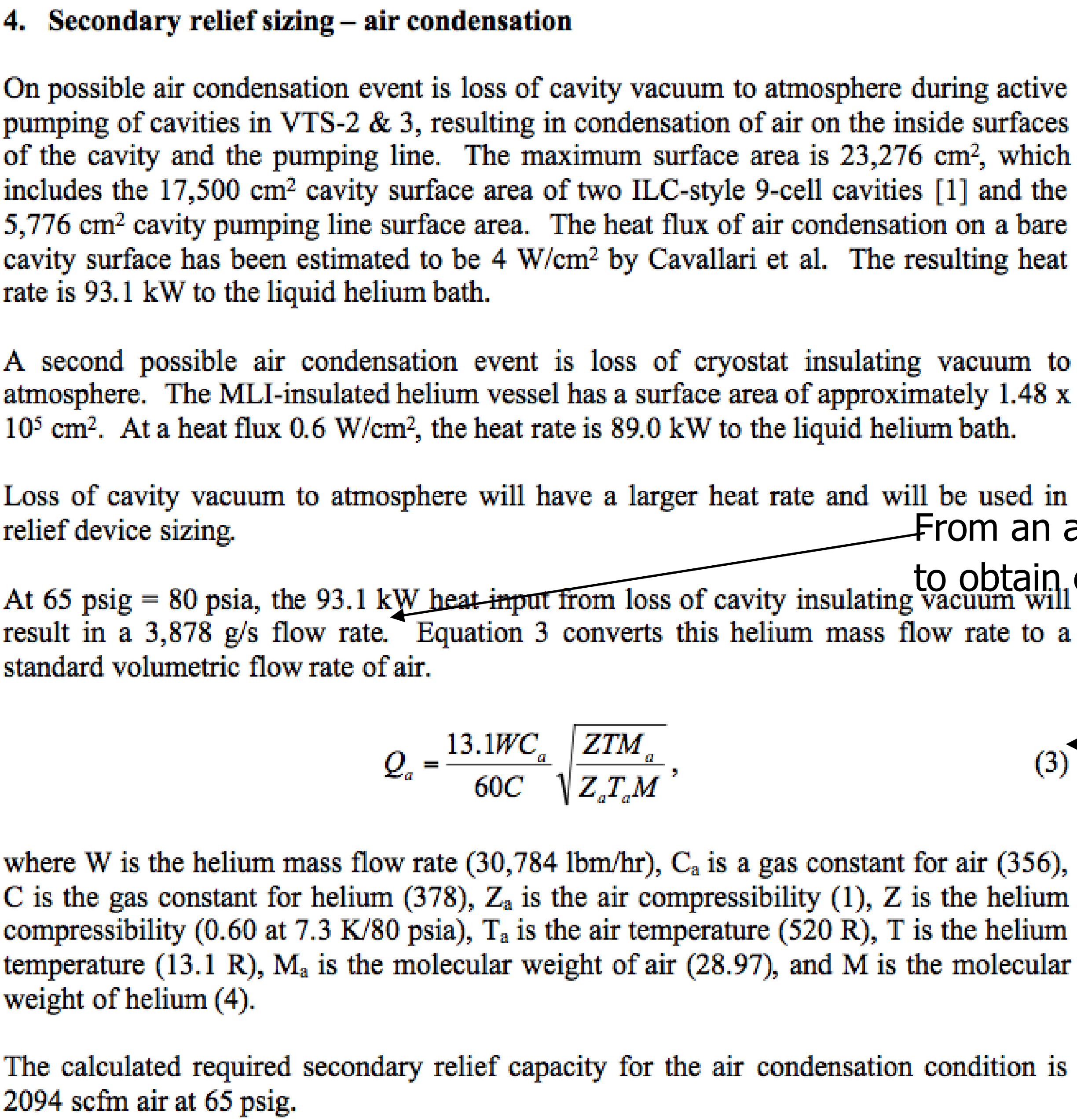
Fire relief sizing (CGA S-1.3—2005 paragraph 6.3.2) -- a suggestion

- I received a suggestion from an engineering note review panel at Fermilab with which I agree:
  - "For the fire condition, it is suggested that the argument be made that this case is identical to the loss of cryostat vacuum since it is an uninsulated vessel. For an uninsulated vessel, the heat load to the vessel is driven by air condensation/freezing as opposed to insulated vessels considering a temperature gradient across the insulation resulting gas conduction. The fact that there is a fire externally does not affect the vessel since it is shielded from the radiation; only the resulting letting up of the cryostat vacuum and resulting condensation and/or freezing drives the relieving requirements."

Example from an engineering note analysis for a superconducting RF cavity vertical test dewar

Vertical Test System (VTS)





4. Secondary relief sizing – air condensation

On possible air condensation event is loss of cavity vacuum to atmosphere during active pumping of cavities in VTS-2 & 3, resulting in condensation of air on the inside surfaces of the cavity and the pumping line. The maximum surface area is 23,276 cm^2, which includes the 17,500 cm^2 cavity surface area of two ILC-style 9-cell cavities [1] and the 5,776 cm^2 cavity pumping line surface area. The heat flux of air condensation on a bare cavity surface has been estimated to be 4 W/cm^2 by Cavallari et al. The resulting heat rate is 93.1 kW to the liquid helium bath.

A second possible air condensation event is loss of cryostat insulating vacuum to atmosphere. The MLI-insulated helium vessel has a surface area of approximately 1.48×10^5 cm^2. At a heat flux 0.6 W/cm^2, the heat rate is 89.0 kW to the liquid helium bath.

Loss of cavity vacuum to atmosphere will have a larger heat rate and will be used in relief device sizing.

At 65 psig = 80 psia, the 93.1 kW heat input from loss of cavity insulating vacuum will result in a 3,878 g/s flow rate. Equation 3 converts this helium mass flow rate to a standard volumetric flow rate of air.

$$Q_a = \frac{13.1 W C_a}{60 C} \sqrt{\frac{Z T M_a}{Z_a T_a M}}, \qquad (3)$$

where W is the helium mass flow rate (30,784 lbm/hr), C_a is a gas constant for air (356), C is the gas constant for helium (378), Z_a is the air compressibility (1), Z is the helium compressibility (0.60 at 7.3 K/80 psia), T_a is the air temperature (520 R), T is the helium temperature (13.1 R), M_a is the molecular weight of air (28.97), and M is the molecular weight of helium (4).

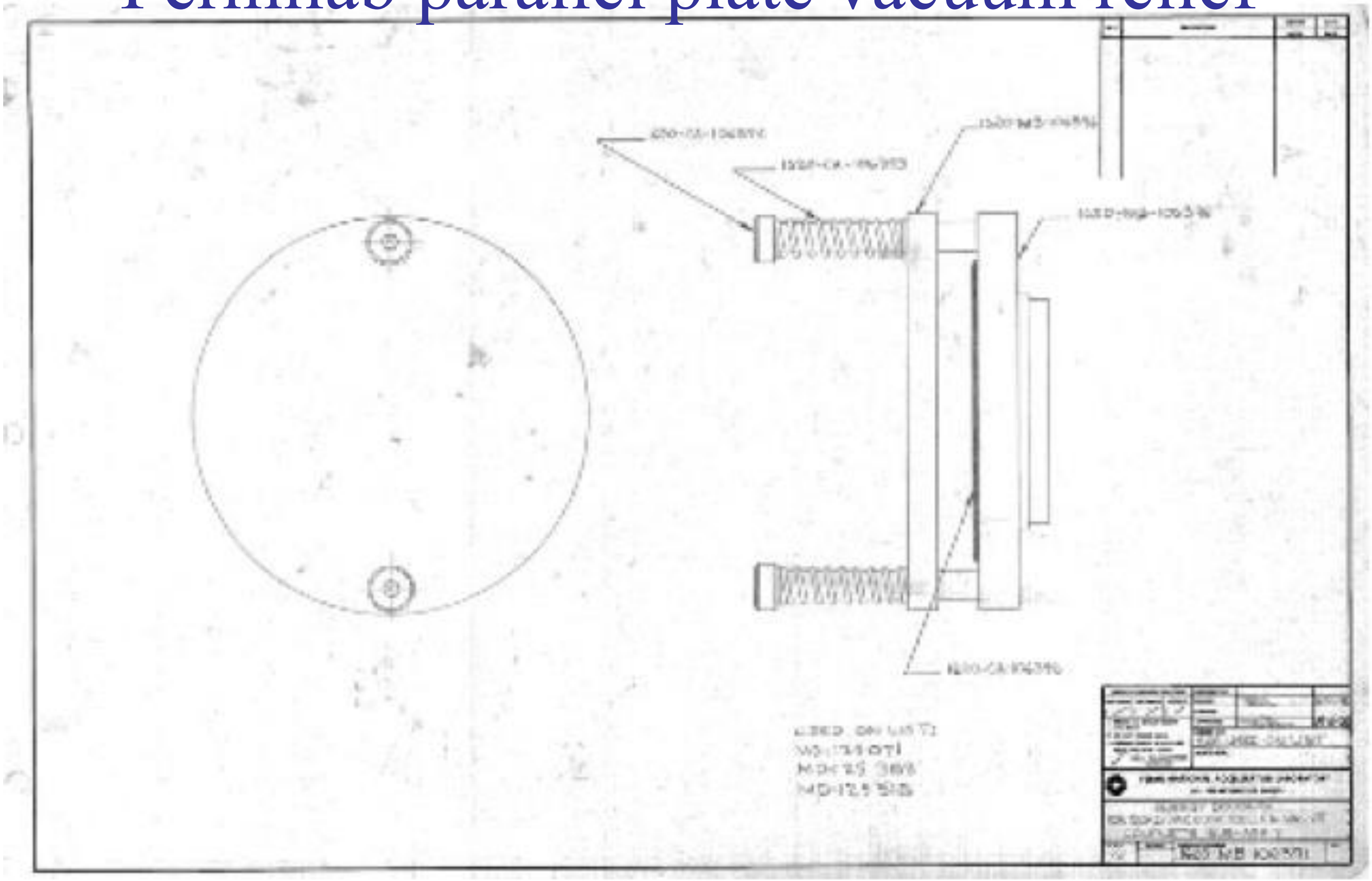
The calculated required secondary relief capacity for the air condensation condition is 2094 scfm air at 65 psig.

Note comparison of loss of cavity vacuum with condensation on smaller area of bare metal to loss of insulating vacuum with smaller heat flux on larger area.

From an analysis like on slide 75 to obtain effective latent heat

From CGA S-1.3

Fermilab parallel plate vacuum relief



Vacuum relief

- Typically very low pressure
  - Vacuum vessel not a code-stamped pressure vessel, so < 0.5 - 1 atm MAWP
  - Flow may be subsonic
  - Valve not officially approved
  - Sizing may be difficult, must be conservative
- But the most difficult task may be deciding on the worst-case incident for which the vacuum valve must be sized

EUROPEAN
SPALLATION
SOURCE

Oxygen Deficiency Hazards

J. G. Weisend II

www.europeanspallationsource.se
June 2019

Example Accident

In March of 1981, three technicians working at the Kennedy Space Center entered a compartment in the aft section of the space shuttle Columbia that had been purged with gaseous nitrogen. Due to a combination of poor communication and inadequate procedures, the technicians were unaware of the presence of an oxygen deficient environment in the compartment. All three technicians collapsed immediately. Two other workers entering the compartment in an attempt to rescue the first three also collapsed. Two of the three initial technicians died and one of the collapsed rescuers died several years later due to complications from the accident

This illustrates several typical features of ODH accidents:

- Rapidity of event
- Presence of fatalities
- Multiple fatalities
- Impact on would be rescuers

What are Oxygen Deficiency Hazards?

- Gases used in cryogenic systems such as He, N_2, Ar, H_2 can displace oxygen in an area causing the area to be unsafe for human life
  - Any oxygen concentration less that 19.5 % is considered oxygen deficient (OSHA)
- There are several aspects to this problem
  - Large volume changes from cryogenic liquids to room temperatures gases
  - Even small amounts of liquid can be a hazard is the if released into a small enough volume e.g. small rooms, elevators or cars
  - Little or no warning of the hazard at sufficiently low O_2 concentrations
  - Consequences can easily be fatal
- <u>This is not just a problem in large cryogenic installations</u>
  - It can easily be a problem in small labs and university settings – in fact, complacency in smaller settings may be an added risk factor

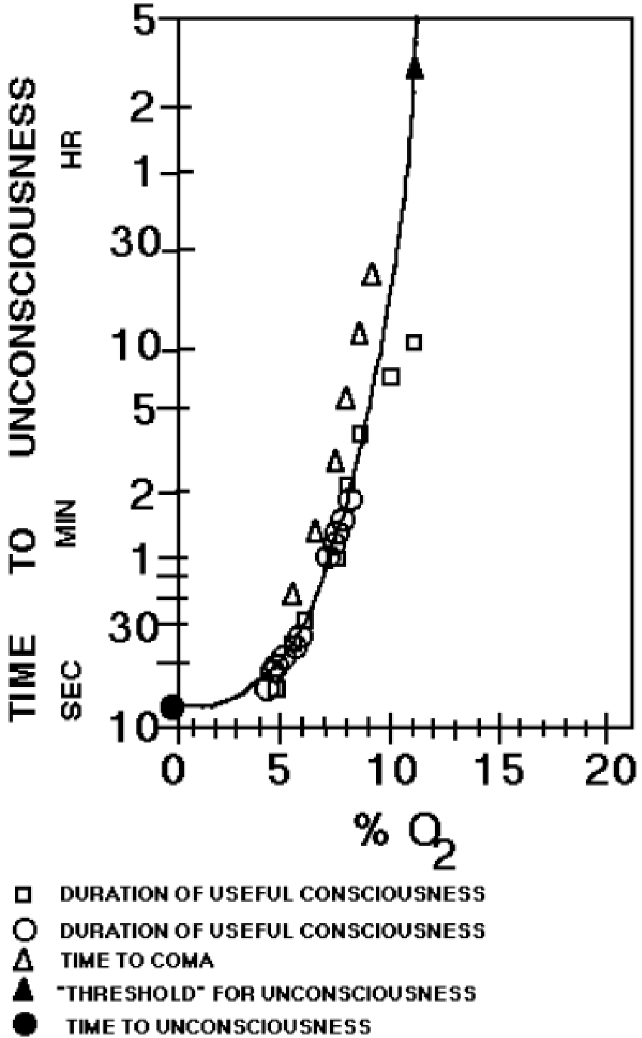
Recall from Lecture 1
Volume Changes for Cryogenic Fluids from Normal Boiling Point to 300 K & 1 Bar

Fluid	(Volume of gas at 1 Bar, 300 K) / (Volume of liquid at normal boiling point)
Propane	323
Ethane	446
Xenon	556
Krypton	711
Methane	660
Argon	861
Oxygen	879
Nitrogen	720
Neon	1488
Hydrogen (Para)	875
Helium	783

Effects of Oxygen Deficiency

Volume% Oxygen (at sea level)	Effect
17	Night vision reduced Increased breathing volume Accelerated heartbeat
16	Dizziness Reaction time for novel tasks doubled
15	Impaired attention Impaired judgment Impaired coordination Intermittent breathing Rapid fatigue Loss of muscle control
12	Very faulty judgment Very poor muscular coordination Loss of consciousness Permanent brain damage
10	Inability to move Nausea Vomiting
6	Spasmodic breathing Convulsive movements Death in 5-8 minutes

Approximate time of Useful Consciousness for a seated subject at sea level vs % O_2



At low enough concentrations you can be unconscious in less that a minute with NO warning

This is one of the things that makes ODH so dangerous & frequently results in multiple fatalities

ODH Safety Basics

- Understand the problem
- Determine level of risk
  - For each use of cryogenic liquids or inert gases a formal written analysis of the risk ODH posed should be done. The details of this may vary from institution to institution and may be driven by regulatory requirements.
  - One technique used by many laboratories (ESS,Fermilab, Jlab, SLAC, BNL) is the calculation of a ODH Fatality Rate. The size of this rate is then tied to a ODH class and each class is linked to specific required mitigations
- Apply mitigations to reduce the risk
- Have a plan to respond to emergencies
- <u>ALL users of cryogenic fluids no matter how small should analyze their risk and consider mitigations</u>
  - At a minimum, everyone should be trained to understand the hazard

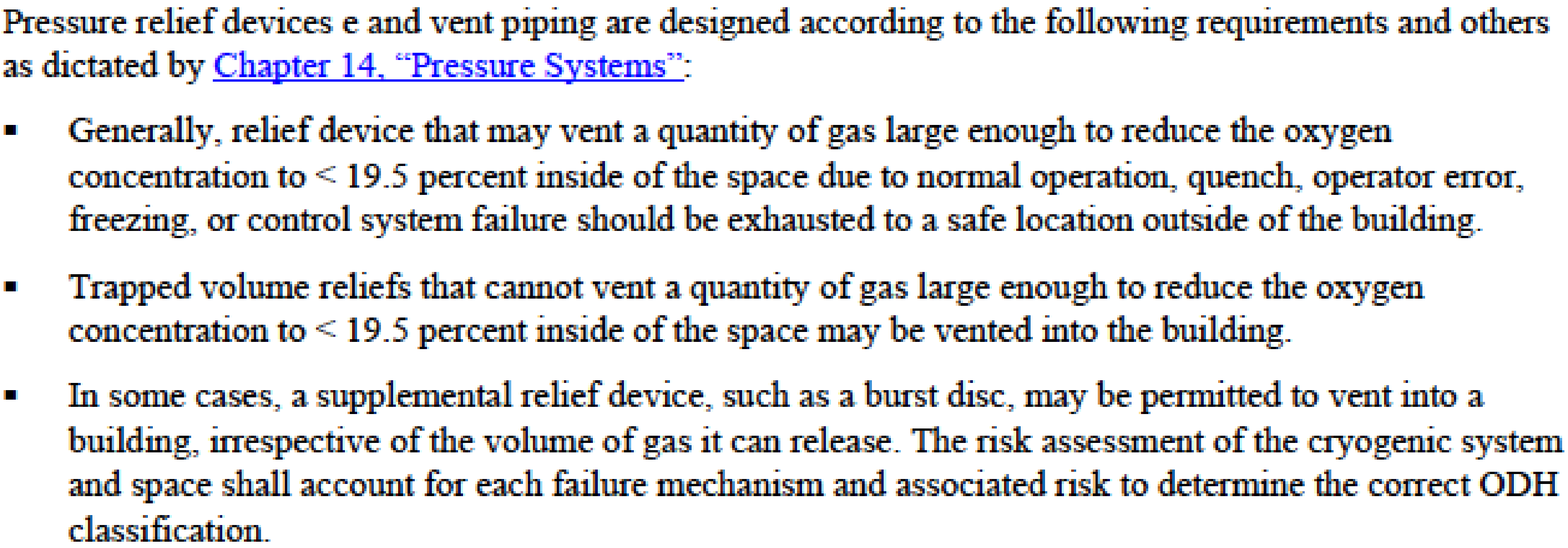
ODH Mitigations

- Best solution: Eliminate the hazard by design choices
  - Reduce inventory of cryogenic fluids & compressed gases
    - Use minimum amounts of cryogens or oxygen displacing gas
    - Restricted Flow Orifaces (RFOs) passive devices used in conjunction with compressed gas systems to reduce the amount of oxygen displacing gas that can enter an area.
  - Do not conduct cryogenic activities in small spaces
  - Do not transport cryogens in closed vehicles or in elevators with people
  - Do not use LN_2 underground
- Training
  - Everyone working in a possible ODH area should be made aware of the hazard and know what to do in the event of an incident or alarm
    - This includes periodic workers such as security staff, custodial staff and contractors
    - Visitors should be escorted
- Signs
  - Notify people of the hazard and proper response
  - Indicate that only trained people are authorized to be there

ODH Mitigations

If at all possible vent relief devices outside of buildings

An example policy from SLAC is shown below



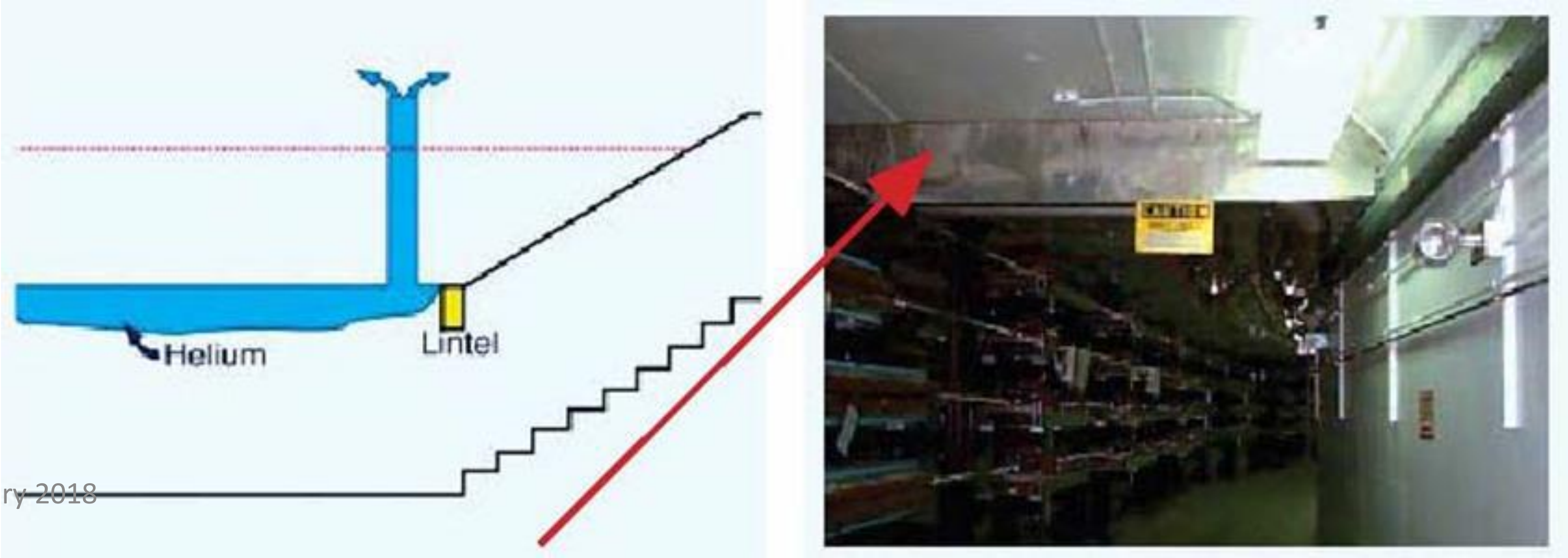
Pressure relief devices e and vent piping are designed according to the following requirements and others as dictated by Chapter 14, "Pressure Systems":

- Generally, relief device that may vent a quantity of gas large enough to reduce the oxygen concentration to < 19.5 percent inside of the space due to normal operation, quench, operator error, freezing, or control system failure should be exhausted to a safe location outside of the building.
- Trapped volume reliefs that cannot vent a quantity of gas large enough to reduce the oxygen concentration to < 19.5 percent inside of the space may be vented into the building.
- In some cases, a supplemental relief device, such as a burst disc, may be permitted to vent into a building, irrespective of the volume of gas it can release. The risk assessment of the cryogenic system and space shall account for each failure mechanism and associated risk to determine the correct ODH classification.

Note that this last point can be challenging in tunnel environments

ODH Mitigations

- Work Rules
  - Prohibit activities that increase risk of an accident
    - ESS & CERN: No tunnel entry during cool down and warm up of accelerator
  - Two Person Rule
  - Three Person Rule (unexposed observer)
- Use of lintels and vents to keep helium away from escape routes
  - For example at Jlab



ODH Mitigations

- Ventilation systems to increase air exchange and reduce the possibility of an oxygen deficient atmosphere forming
  - **Warning** If this approach is taken, the ventilation system must now be treated as a safety system with appropriate controls and redundancies
    - What happens during maintenance or equipment failure?
    - How do you know ventilation system is working?
- ODH Monitors and Alarms
  - A very common and effective mitigation. Commercial devices exist.
  - Indicates when a hazard exists
  - Very valuable in showing if a area has become dangerous during off hours
  - Alarms generally set to trip at 19.5% Oxygen
  - Alarms should include lights & horn as well as an indicator at entrance to area
  - Alarms should register in a remote center (control room or fire dept) as well
  - As a safety system it requires appropriate controls & backups (UPS, redundancy etc.)
  - In some cases personal monitors will add additional safety

Response to ODH
Alarms & Emergencies

- In the event of an alarm or other indication of a hazard immediately leave the area
- Do not reenter the area unless properly trained and equipped (e.g. supplementary air tanks)
    - Don’t just run in to see what the problem is
- <u>Only properly trained and equipped professionals should attempt a rescue in an ODH situation</u>
- Response to alarms should be agreed upon in advance, documented and be part of training

ODH Risk Analysis

In many labs e.g. ESS, SLAC, CERN, Fermilab this is done in two steps:

First: a simple calculation that determines if there is any problem at all. This approach compares the volume of the space containing the cryogen with the volume occupied by the inert gas if the entire cryogenic inventory is released, warmed up to 300 K and 1 Bar and uniformly mixed. The resulting oxygen concentration (C) in percent is given by:

$$C = \frac{21(V_R - V_C)}{V_R}$$

Where V_R is the volume of the space and V_C is the volume of the inert gas at 300 K and 1 Bar

ODH Risk Analysis

In the case where the inert gas is coming from outside the space, such as in the case of a helium compressor, the oxygen concentration is

$$C = \frac{21(V_R - Q)}{V_R}$$

Where V_R is the volume of the room and Q is the volumetric flow rate of the inert gas at room temperature and pressure. This calculation assumes 1 exchange of the room air per hour.

- If either of these oxygen concentrations are less than 19.5% under normal operating conditions or less than 18% under abnormal conditions then a more sophisticated risk analysis is required
- Even the simple analysis above (which should be done whenever inert gases or cryogens are used – no matter how small the amount) should be reviewed by an independent analyst and formally documented.
- Keep in mind the underlying assumption of uniform mixing. Be aware of helium being trapped at a high level, argon gas concentrated in pits or trenches and the possible effect of gas colder than 300 K

Step 2: A More Detailed Risk Assessment

EUROPEAN SPALLATION SOURCE

- This is done by calculating a probable fatality rate (without mitigations) for each possible failure in the system being studied
- These are then summed up for a total fatality rate which gives an ODH class
- Each ODH class has a set of predefined mitigations
  - Required mitigations by class may vary from institution to institution
- A key component of this approach is the review of the calculations and mitigations by others (for example an ODH or cryogenic safety committee)

ODH Fatality Rates

$$\Phi = \sum_{i=1}^{n} P_i F_i$$

where: Φ = the ODH fatality rate (per hour)
P_i = the expected rate of the ith event (per hour), and
F_i = the probability of a fatality due to event i.

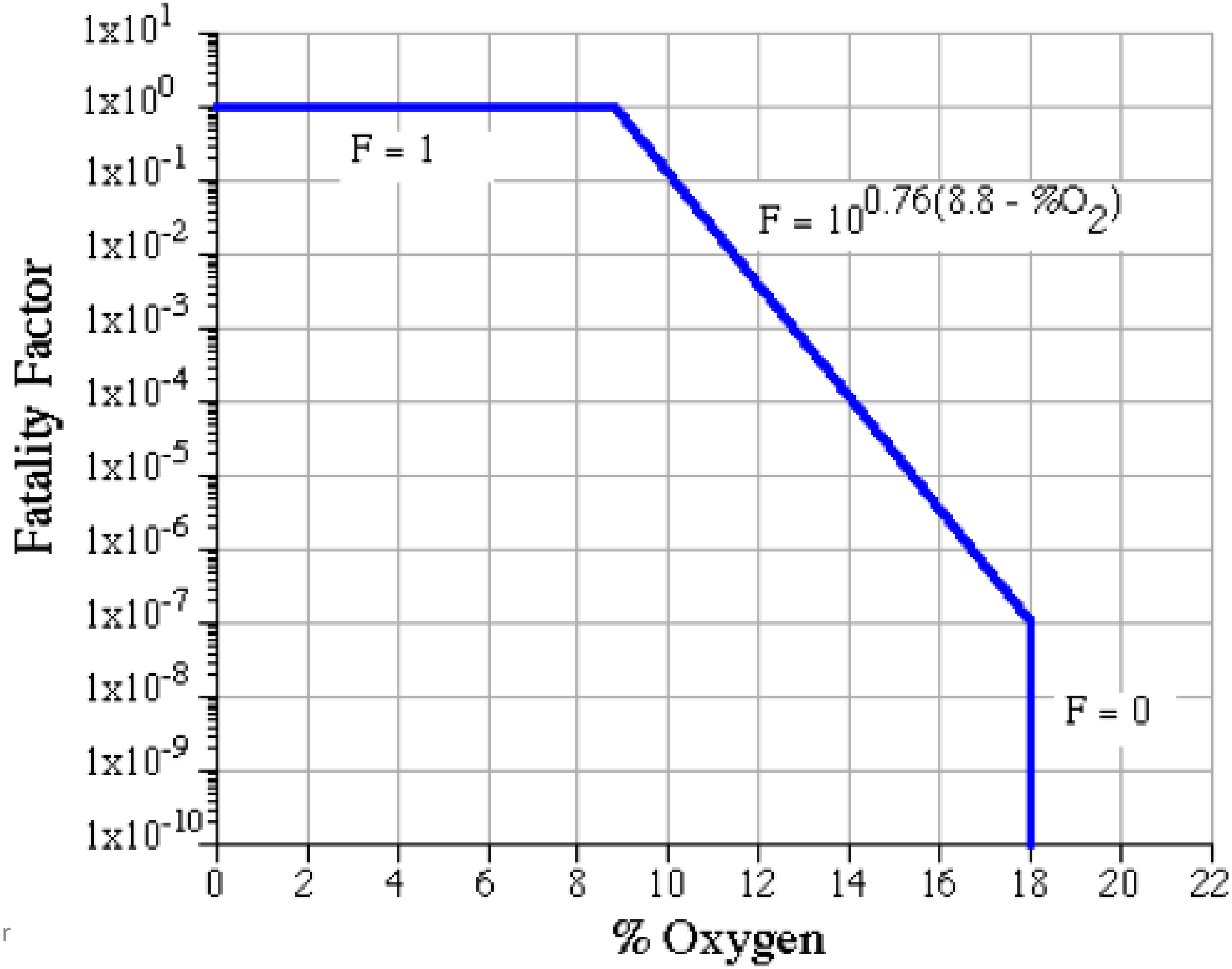
Sum up for all n possible events

ODH Fatality Rates

- Probability of an event (P_i) may be based on institutional experience or on more general data (see handouts)
- Probability of a given event causing a fatality (F_i) is related to the lowest possible oxygen concentration that might result from the event

F_i vs. Oxygen Concentration (note limits)

This is the same for ESS, SLAC and Fermilab



Note below 8.8% the fatality factor is taken to be 1 as this is the point at which useful consciousness is 1 minute

ODH classes at ESS

ODH Class	[Φ] (hr^{-1})
0	$\leq 10^{-7}$
1	$>10^{-7}$ …but… $\leq 10^{-5}$
2	$>10^{-5}$ …but… $\leq 10^{-3}$
Forbidden area Not permitted at ESS	$>10^{-3}$

Note these are fatality rates without any mitigations

Once the mitigations are applied, the fatality rate should be class 0 or better

ESS Mitigations vs. ODH Class

(note these are minimum mitigations,
additional ones may be required
by the safety committee)

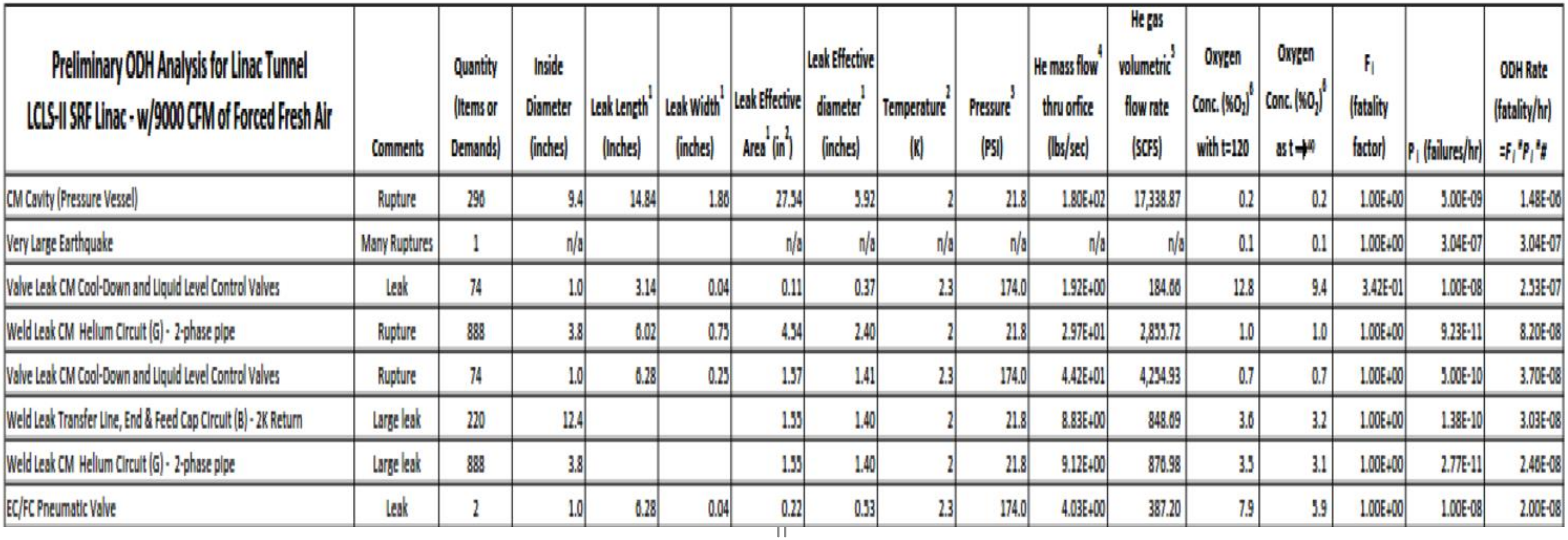
ODH Class	0	1	2
Technical Safety measures			
Warning signs	X	X	X
Ventilation		*	*
Area (fixed) Oxygen Monitoring	*	X	X
Organizational Safety measures			
Medical approval as ODH qualified		*	*
ODH training (e-learning)	X	X	X
Personal oxygen monitor		X	X
Self-rescue mask		*	*
Presence of minimum 2 persons			X
Administrative Safety measures			
Access restricted to authorized personnel only		X	X
Emergency procedure		X	X
Operating procedure	X	X	X

* To be evaluated case by case with the help of ES&H

Example Calculation

“ LINAC Coherent Light Source II (LCLS-II) Project Preliminary Oxygen Deficiency Hazard Analyses” - LCLSII-1.1-PM-0349-R1 (see handouts)

- **This is a very detailed analysis using the SLAC procedures and well worth using as a model**
- **Final result was that the Linac housing (tunnel), Gallery and Cryogenics building were rated as Class 1**
- **Work restrictions on entry into tunnel during cool down and warm up.**



Preliminary ODH Analysis for Linac Tunnel LCLS-II SRF Linac - w/9000 CFM of Forced Fresh Air	Comments	Quantity (Items or Demands)	Inside Diameter (inches)	Leak Length^1 (Inches)	Leak Width^1 (inches)	Leak Effective Area^1 (in^2)	Leak Effective diameter^1 (inches)	Temperature^2 (K)	Pressure^3 (PSI)	He mass flow^4 thru orfice (lbs/sec)	He gas volumetric^5 flow rate (SCFS)	Oxygen Conc. (%O$_2$)^6 with t=120	Oxygen Conc. (%O$_2$)^6 as t→∞	F$_i$ (fatality factor)	P$_i$ (failures/hr)	ODH Rate (fatality/hr) =F$_i$*P$_i$*#
CM Cavity (Pressure Vessel)	Rupture	296	9.4	14.84	1.86	27.54	5.92	2	21.8	1.80E+02	17,338.87	0.2	0.2	1.00E+00	5.00E-09	1.48E-06
Very Large Earthquake	Many Ruptures	1	n/a			n/a	n/a	n/a	n/a	n/a	n/a	0.1	0.1	1.00E+00	3.04E-07	3.04E-07
Valve Leak CM Cool-Down and Liquid Level Control Valves	Leak	74	1.0	3.14	0.04	0.11	0.37	2.3	174.0	1.92E+00	184.66	12.8	9.4	3.42E-01	1.00E-08	2.53E-07
Weld Leak CM Helium Circuit (G) - 2-phase pipe	Rupture	888	3.8	6.02	0.75	4.54	2.40	2	21.8	2.97E+01	2,835.72	1.0	1.0	1.00E+00	9.23E-11	8.20E-08
Valve Leak CM Cool-Down and Liquid Level Control Valves	Rupture	74	1.0	6.28	0.25	1.57	1.41	2.3	174.0	4.42E+01	4,234.93	0.7	0.7	1.00E+00	5.00E-10	3.70E-08
Weld Leak Transfer Line, End & Feed Cap Circuit (B) - 2K Return	Large leak	220	12.4			1.55	1.40	2	21.8	8.83E+00	848.69	3.6	3.2	1.00E+00	1.38E-10	3.03E-08
Weld Leak CM Helium Circuit (G) - 2-phase pipe	Large leak	888	3.8			1.55	1.40	2	21.8	9.12E+00	876.98	3.5	3.1	1.00E+00	2.77E-11	2.46E-08
EC/FC Pneumatic Valve	Leak	2	1.0	6.28	0.04	0.22	0.53	2.3	174.0	4.03E+00	387.20	7.9	5.9	1.00E+00	1.00E-08	2.00E-08

ODH and Visitors

Visitors and occasional staff (guards, custodial, delivery, visiting contractors etc.) should always be trained in ODH hazards and procedures or escorted by trained staff

Accident Studies - CERN

- In the last few years, CERN conducted a series of full scale, well instrumented, He spill tests in the LHC tunnel.
- 3 different release flow rates were used 1 kg/s, 0.34 kg/s and 0.1 kg/s
- The results, particularly the video coverage are impressive.
- A published summary paper (see also handouts) may be found at:

http://iopscience.iop.org/article/10.1088/1757-899X/101/1/012123

Accident Studies - CERN

An example of the video from one of these tests is shown here:

Accident Studies – CERN

From “Final report on the Controolled Cold Helium Spill Tests in the LHC Tunnel at CERN” Dufay-Chanat et al.

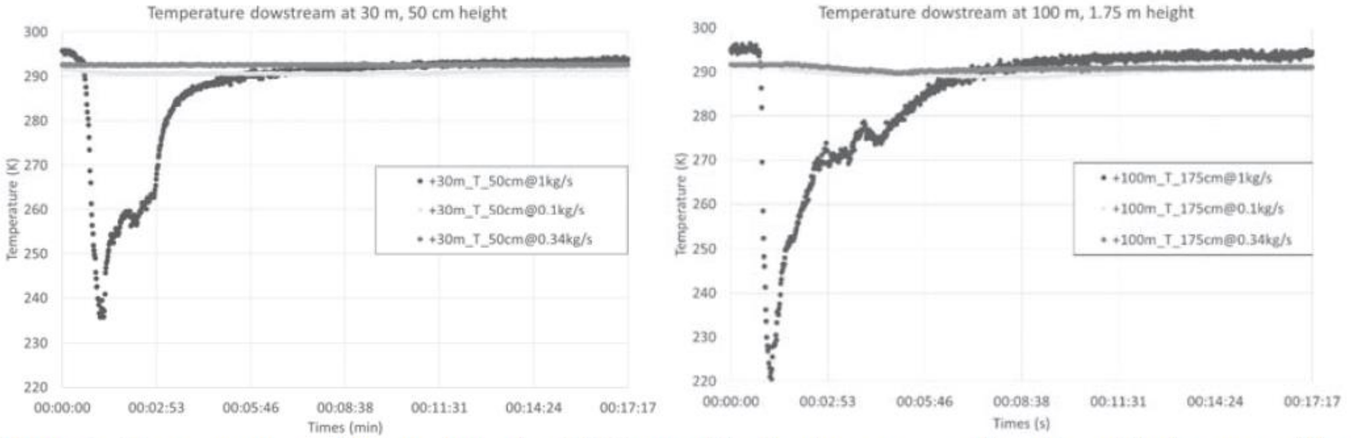


Figure 2. Temperature evolution along the LHC tunnel in the downstream direction with the start of the He spill at timestamp 0 s.

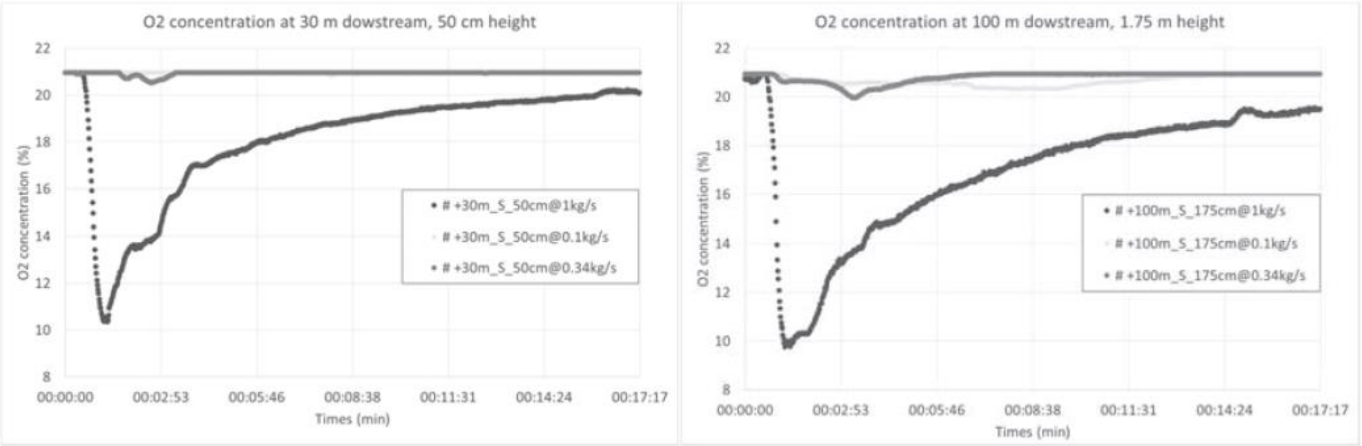
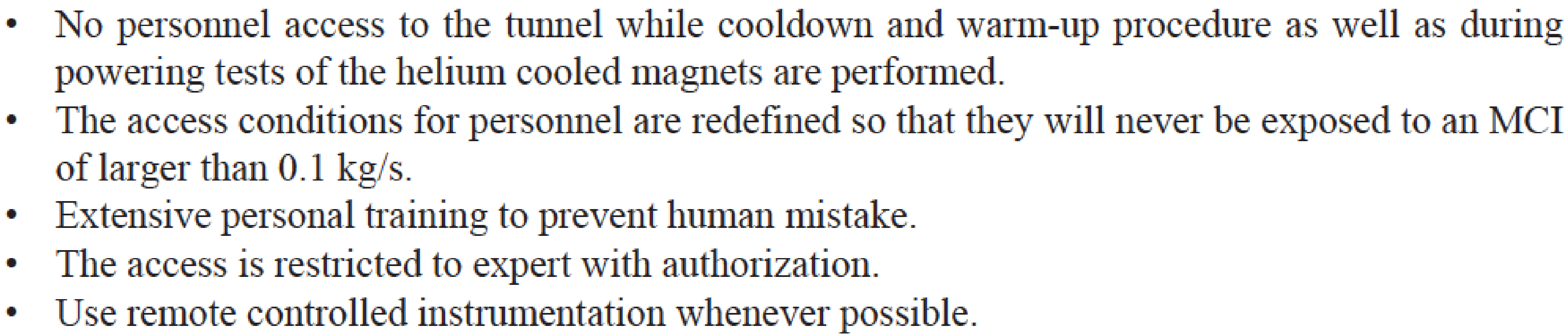


Figure 3. Measured oxygen concentration during the helium spill test in the downstream direction. Start of the pressurization of the dewars at t=0 s.

Accident Studies - CERN

There were many findings in this work. One interesting one was that at the highest spill rates, even outside the visible vapor cloud the O_2 levels were dangerously low

As a result of these tests, CERN put into place the following work rules for the LHC tunnel



- No personnel access to the tunnel while cooldown and warm-up procedure as well as during powering tests of the helium cooled magnets are performed.
- The access conditions for personnel are redefined so that they will never be exposed to an MCI of larger than 0.1 kg/s.
- Extensive personal training to prevent human mistake.
- The access is restricted to expert with authorization.
- Use remote controlled instrumentation whenever possible.

Accident Studies ESS

- Thanks to D. Phan & E Lundh of ESS for this content and these studies
- At ESS we employed CFD analysis of venting into the tunnel to look for issues and make design choices

- My (John Weisend) opinion – This work has been valuable in highlighting problems and making high level decisions but without some sort of bench marking, care should be taken to use these results for precise predictions.
  - Still we have made valuable and important choices based on these simulations

Accelerator tunnel
CFD simulations

Failure scenarios considered (during access)

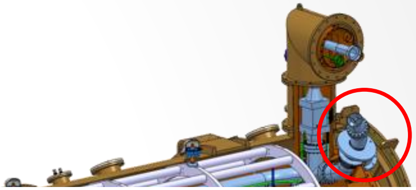
Scenario 1

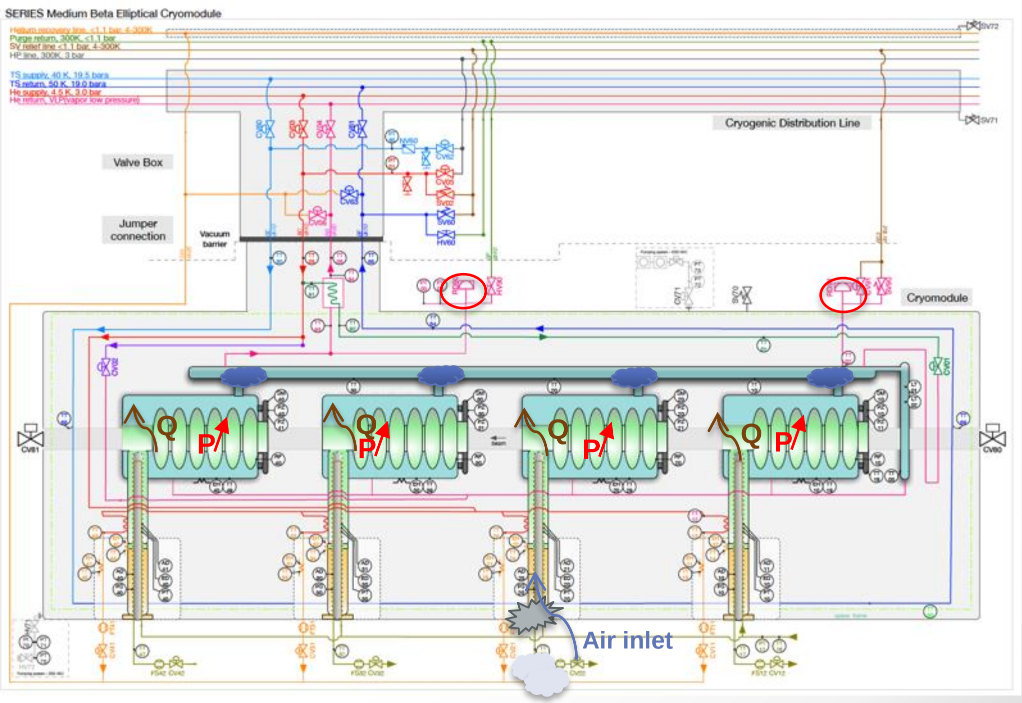
Rupture of the power coupler’s window or beam line

Loss of the content of 1 High-β* cryomodule (**28,4 kg at 2 K and 2. bara**)

Discharge of GHe through the 2 ru disks located on the LHe line (**1,9 s**

Max. mass flow rate = **15,2 kg.s^{-1}**





*the loss of 2 High-Beta has not be considered thanks to the CLOSE position of the gate valves in-between cryomodules during access

ACKNOWLEDGEMENT : J.P THERMEAU & D. PHAN – WP5_SAFETYSIZING_SAFETY_DEVICES

Accelerator tunnel

CFD simulations

Failure scenarios considered (during access)

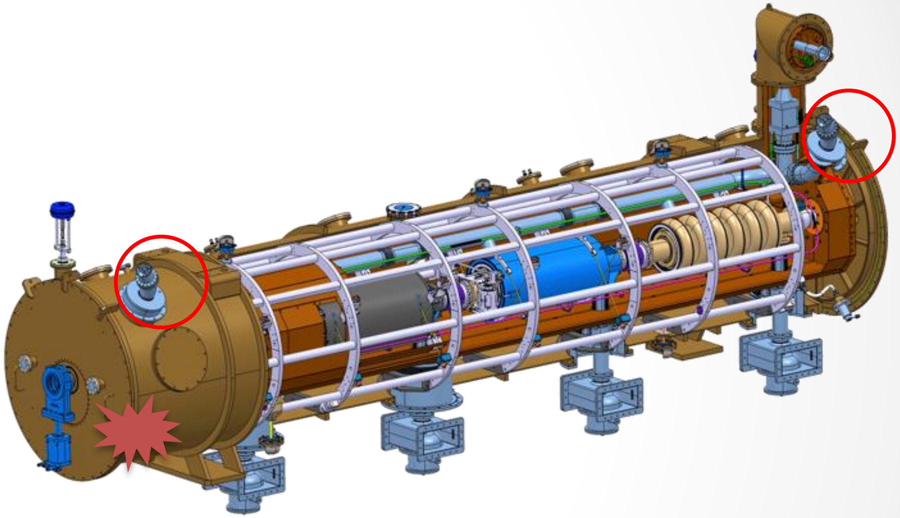
Scenario 2

Rupture of the insulation vacuum vessel of 1 High-β cryomodule

Loss of the content of 1 High-β* cryomodule (**28,4 kg at 2 K and 2.04 bara**)

Discharge of GHe through the 2 rupture disks located on the LHe line (**11,8 s**)

Max. mass flow rate = **2,4 kg/s**



*the loss of 2 High-Beta has not be considered thanks to the CLOSE position of the gate valves in-between cryomodules during access

ACKNOWLEDGEMENT : J.P THERMEAU – WP5_SAFETYSIZING_SAFETY_DEVICES

Accelerator tunnel

CFD simulations

Failure scenarios considered (during access)

Scenario 3

Helium leakage from the VLP line in the insulation vacuum of the Cryogenic Distribution System (CDS)

↓

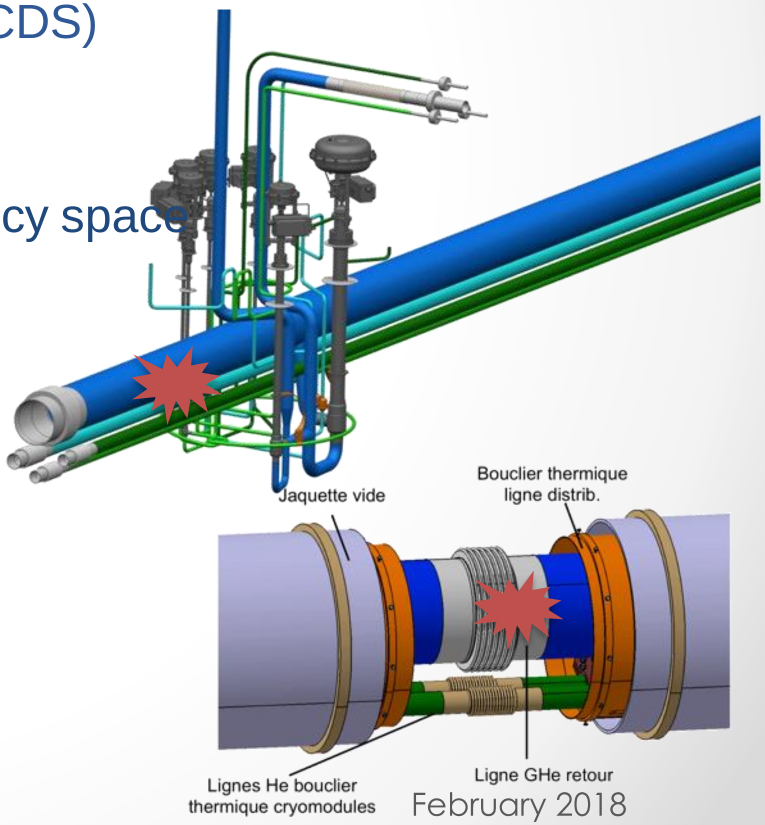
Loss of the content of the CDS in the contingency space (**60 kg at 3 K and 6 bara**)

↓

Discharge of GHe through the pressure relief device on the insulation vacuum jacket (**4 s**)

↓

Max. mass flow rate = **15 kg/s**



ACKNOWLEDGEMENT : J.FYDRYCH

Accelerator tunnel

CFD simulations

Assumptions

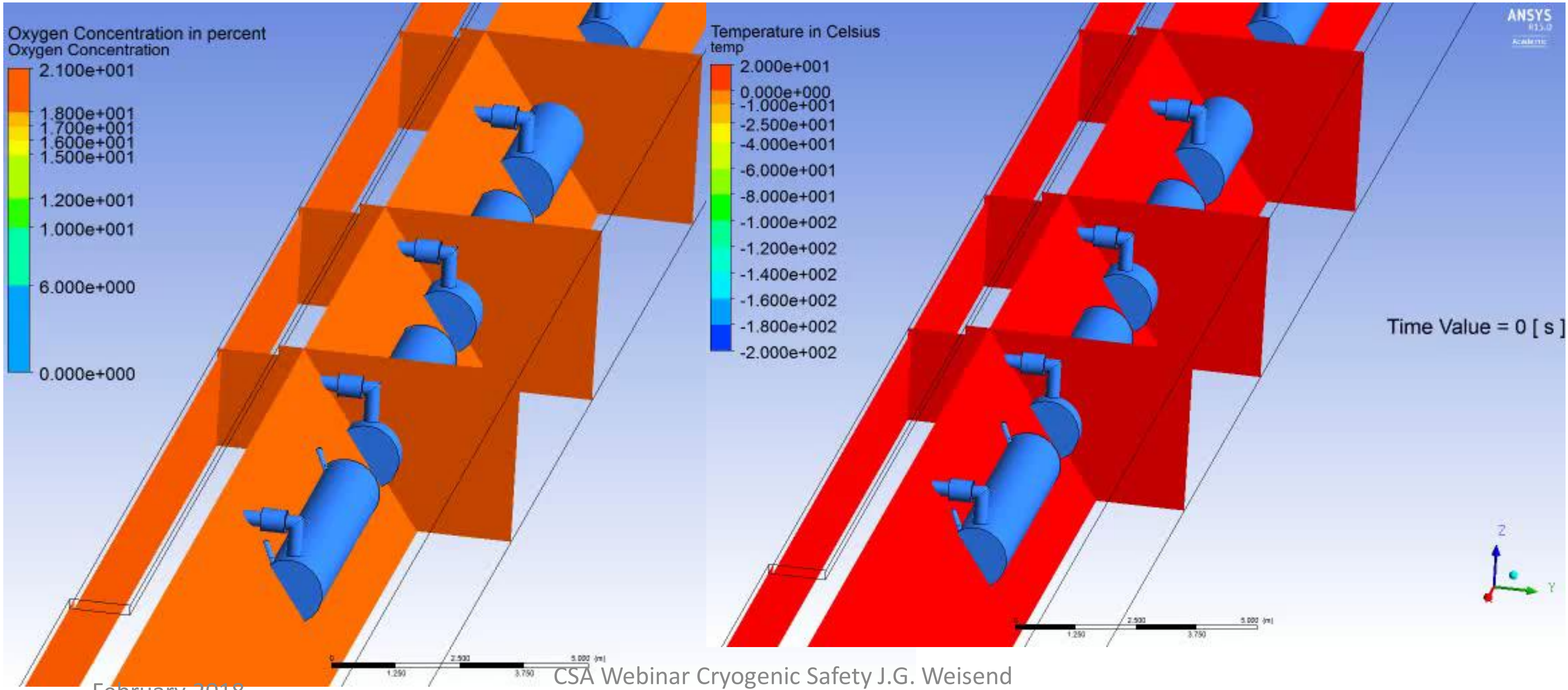
- GHe released at **5 K** (coldest value from the designer)
- **Constant mass flow rates** from the burst disks
- **Atmospheric pressure** in the tunnel
- **100% leak tightness** in the tunnel
- Walls and equipment held at a constant temperature of **22.5 ° C**
- Constantly forced ventilation (about **0.3 – 0.4 m.s^{-1}** in the tunnel)
- **Simplified geometry**
- CDS and cryomodules installed in the **contingency space**
- **Cryogenic helium properties** from the *NIST Chemistry WebBook*
- The simulation software **CFX** (ANSYS) is used

ACKNOWLEDGEMENT : E.LUNDH D. PHAN

Accelerator tunnel

CFD simulations

Scenario 1 (15.2 kg.s^{-1} during 2 s) – rupture of the beam line

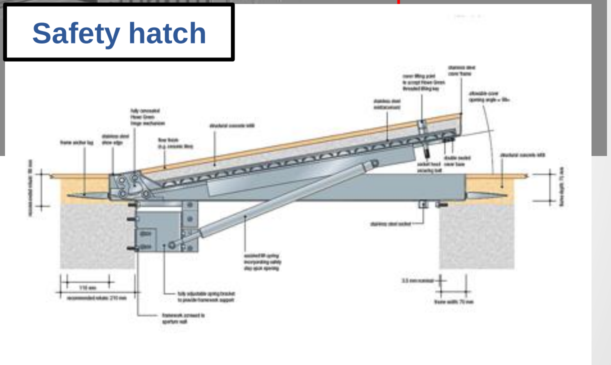


Accelerator tunnel

CFD simulations – Preliminary conclusions

1 Implementation of a **safety hatch** in the A2T area to facilitate evacuation

→ The minimum time needed to reach the nearest exit from the A2T area (64 seconds) does not allow a safe evacuation



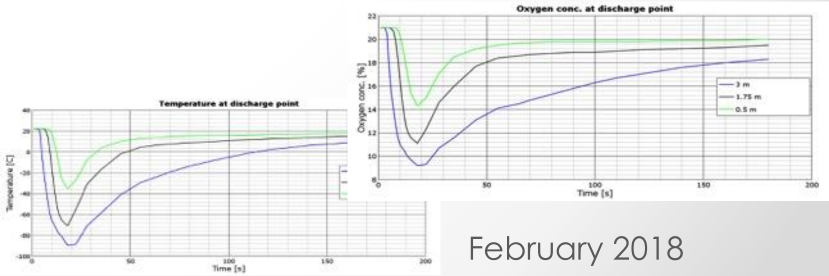
2 Reinforcement of the **hinges** of the emergency exit doors

→ The force applied on the doors in case of a failure of the CDS would be around 41 kN.m^{-2} (417 kg.m^{-2})

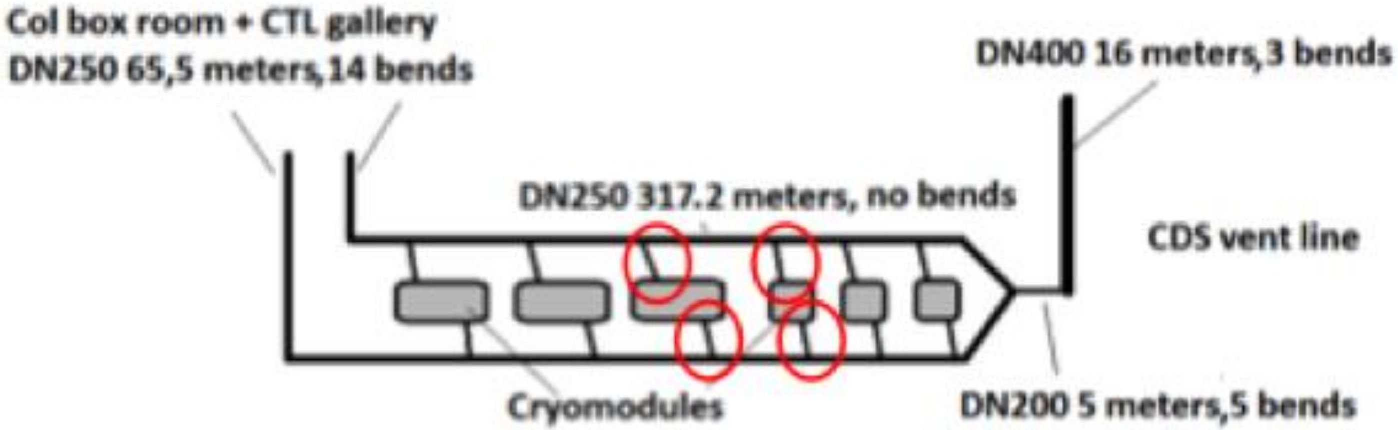
3 Investigation on **compensatory measures** close to the discharge points (e.g. deflector, screens, etc.)

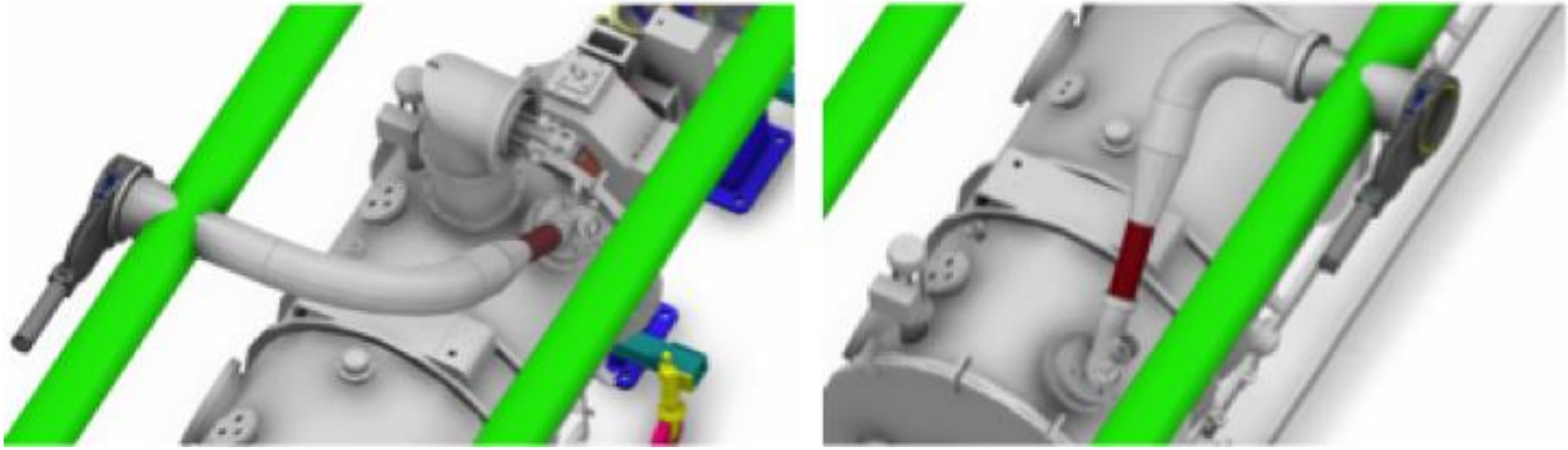
→ Lowest attainable O2 concentration = 6%

→ Lowest attainable temperature = -135° C



Ultimately, it was decided to add an additional helium header connected to the Burst disks to remove the helium from the tunnel





ODH Summary

- Oxygen Deficiency Hazards are a significant threat and can lead to fatal accidents even with small amounts of cryogens or oxygen displacing gases
- ODH can, however, be properly managed to allow safe work in cryogenic facilities
- Significant experience with ODH safety exists and resources exist at labs such as ESS, SLAC, Fermilab, Jlab etc. (see handouts)
- Do not become complacent!

Conclusions

- Cryogenic vessels and piping generally fall under the scope of the ASME pressure vessel and piping codes
- Protection against overpressure often involves not only sizing a rupture disk or relief valve but sizing vent piping between those and the vessel, and also perhaps further ducting downstream of the reliefs
- Loss of vacuum to air with approximately 4 W/cm^2 heat flux on bare metal surfaces at liquid helium temperatures can drive not only the design of the venting system but pipe sizes within the normally operational portions of the cryostat
- Piping stability due to forces resulting from pressure around expansion joints is sometimes overlooked and may also significantly influence mechanical design

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