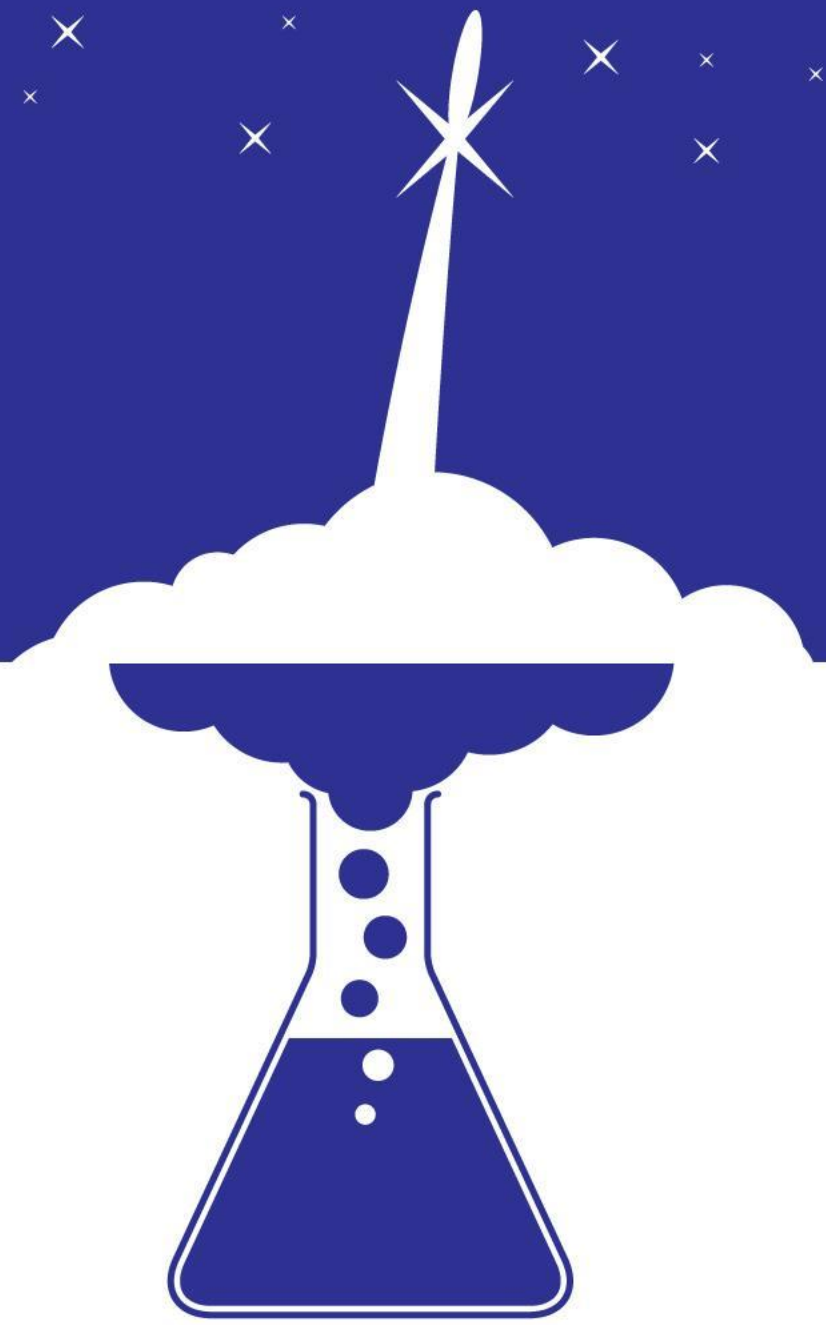

# Cryogenics

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Huntington Beach, CA, VESM109-001

ACADEMIC-INDUSTRY LIQUID ROCKET SYMPOSIUM 2023

# Cryogenics

- Hazards, Personal Protection Equipment
- Properties of Interest
  - BLEVE
  - Transferring
  - Boiling and Vapor Production

Texas A&M University Dewar Explosion

ref. http://www.tdi.texas.gov/fire/documents/fmred022206.pdf

The information provided in the seminar is not meant to be inclusive of all information needed to understand cryogenics. The information provided is meant as a guide to assist in education. The referenced information as is not inclusive of all pertinent information about cryogenics. VES holds itself harmless from any action that results from the use of this information. VES holds itself harmless from any errors provided in this seminar. The information in this seminar is incomplete without the oral portion of the presentation.

# Hazards

- Cold
  - Frostbite, cryo burns
  - Eye damage
- Vapor generation
  - Oxygen depleted clouds and spaces (LN2)
  - Oxygen enriched clouds and spaces (LO2, covered by O2 presentation)
  - Explosive and flammable atmosphere (LNG, LCH4, LH2)
- Trapped cavities
  - Overpressure and rupture of equipment, valve traps, ball valves, others
  - BLEVE
- Uninsulated LH2 surfaces produce oxygen enriched air liquification, fire hazard

# Personal Protection Equipment

https://www.aps.anl.gov/files/APS-Uploads/SECTOR29/Cryo.pdf

<u>Typical Cryo PPE</u>

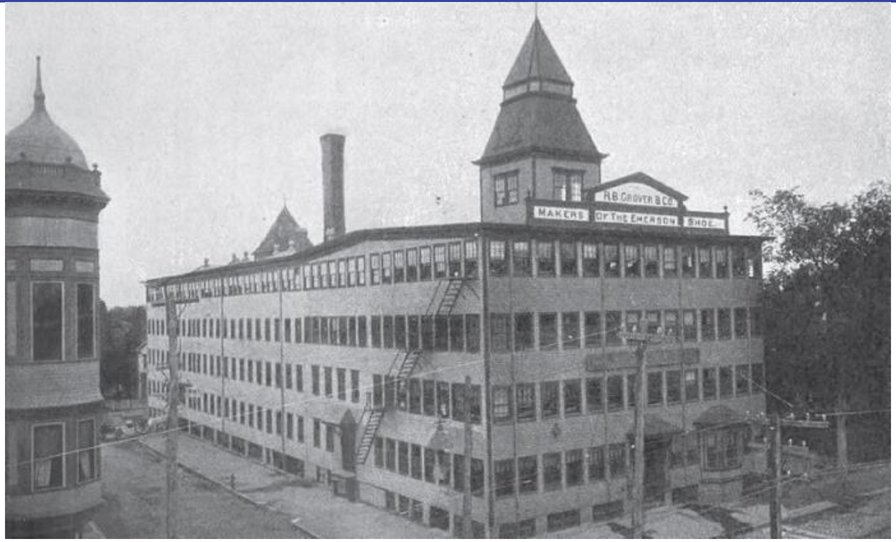
Goggles/splash protection
Face shield
Cryo gloves
Cryo apron/smock
Footwear
Ear protection
No exposed skin

Other related equipment
Oxygen sensor
Flammable gas sensor
Grounding

# Boiling Liquid Expanding Vapor Explosion (BLEVE)

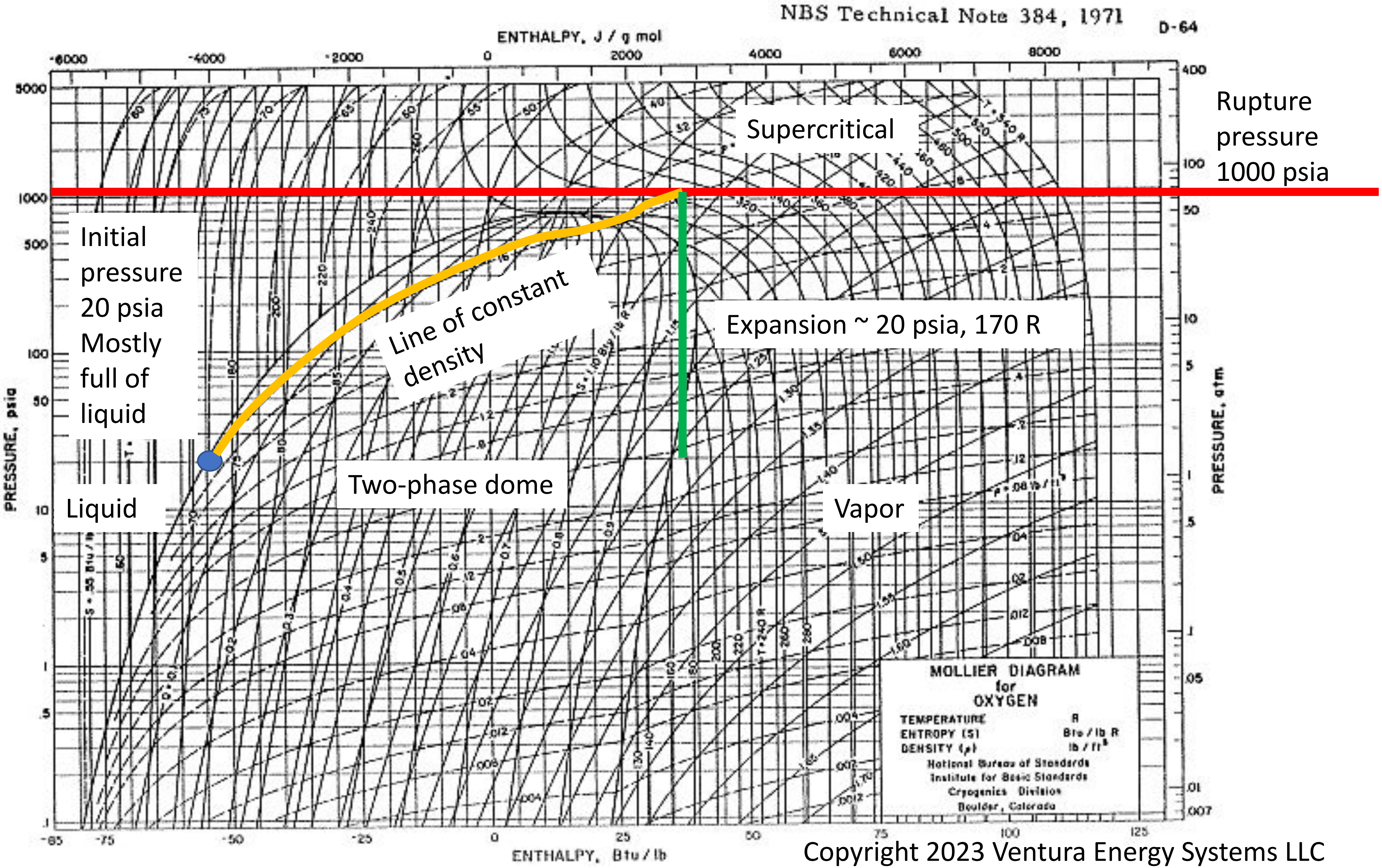
- Thermal energy is absorbed by contained fluid
- Fluid pressure rises to vessel burst pressure

- Vessel rupture lowers the fluid pressure
- State changes generate large amounts of gas
- Expanding vapors produce work
- Work ~ explosion




Grover Shoe Factory Explosion, 1905
(660 lbm dynamite equivalent)
https://en.wikipedia.org/wiki/Grover_Shoe_Factory_disaster

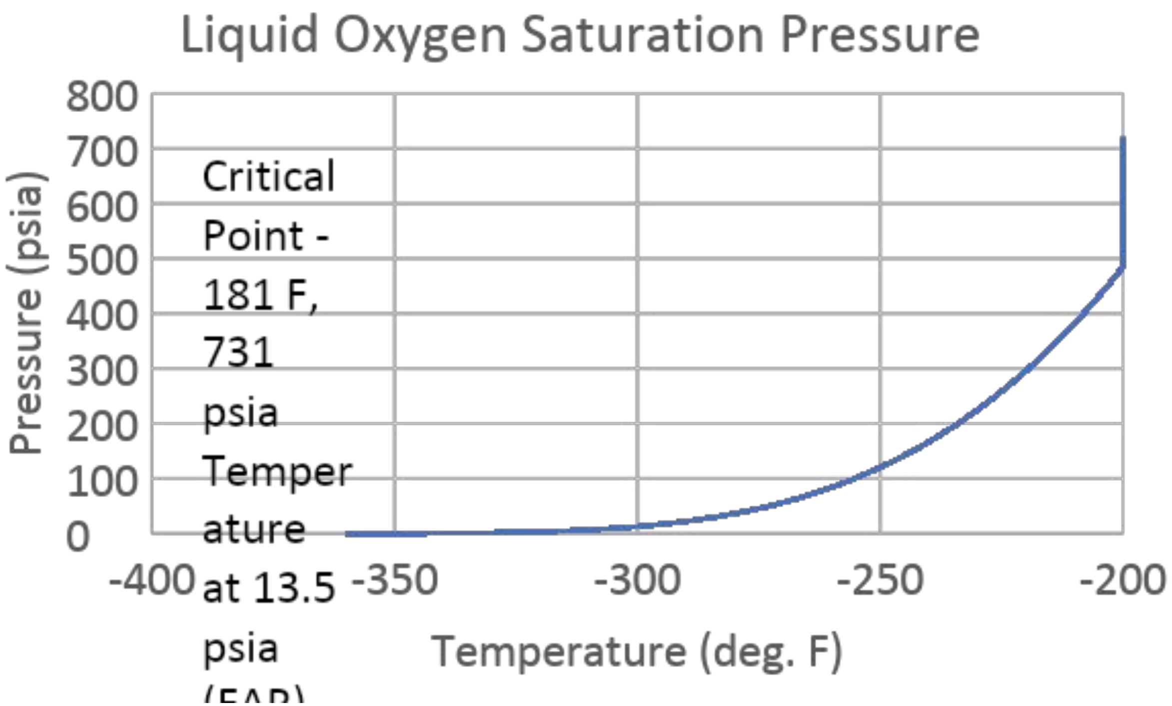

# BLEVE
# Example at FAR

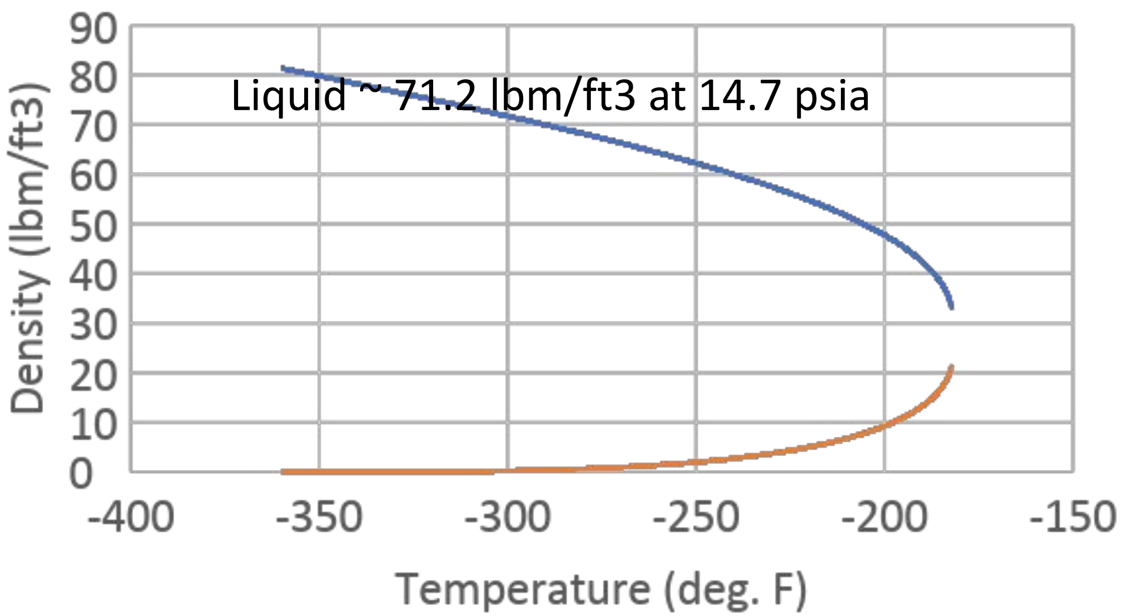

NBS Technical Note 384, 1971
D-64
ENTHALPY, J / g mol
Rupture pressure 1000 psia
Supercritical
Initial pressure 20 psia Mostly full of liquid
Line of constant density
Expansion ~ 20 psia, 170 R
Two-phase dome
Liquid
Vapor
PRESSURE, psia
PRESSURE, atm
ENTHALPY, Btu / lb
MOLLIER DIAGRAM for OXYGEN
TEMPERATURE R
ENTROPY (S) Btu / lb R
DENSITY (ρ) lb / ft³
National Bureau of Standards
Institute for Basic Standards
Cryogenics Division
Boulder, Colorado

# Transferring Cryogenics

- Liquid is typically saturated at the storage container pressure
- Fluid flow has a negative pressure gradient and flows from a cold soaked system to a hot system
- Fluid flow is transient, and multi-phase, typically two-phase: liquid/vapor

- Small amounts of vapor dramatically change the hydrodynamic behavior of two-phase flow
- Process entails large amounts of vented gases to absorb the heat of the hot equipment
- Vent systems need to be designed to allow this vent rate, too small of a vent system will limit fill rate and resulting bulk density

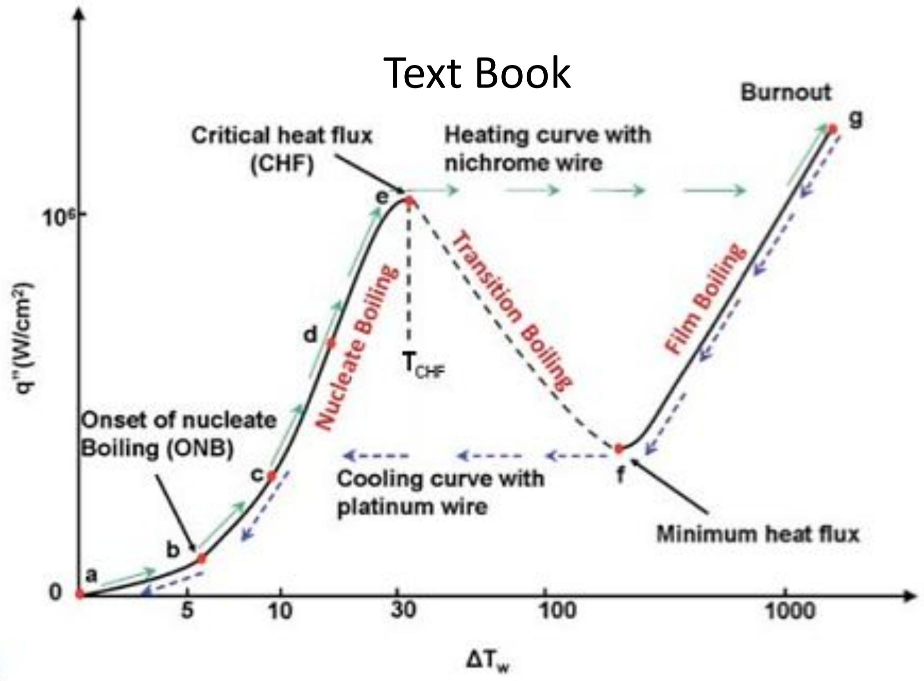


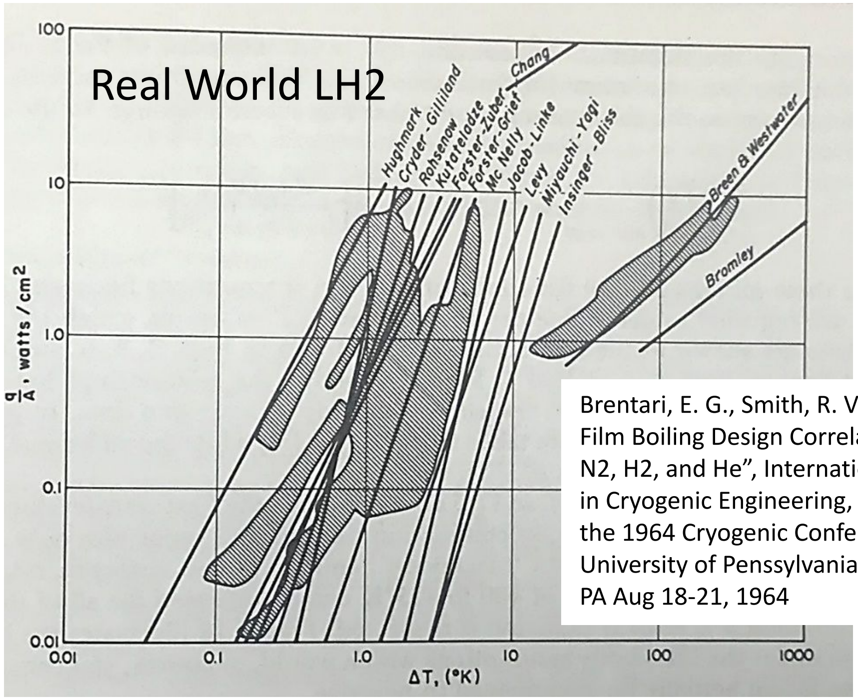



# Boiling & Clouds

- Boiling is hard to understand without experiential test data due to large dispersions in the boiling curve
- Cryogenic operations require an understating and analysis of how to manage vapors, oxygen deficient, oxygen enriched, and flammable vapors

- Vapors are clear, visible vapors are from water condensation which is highly variable based on the air ***specific*** humidity and thermodynamic state of the air
- Visible vapor clouds do not represent a good proxy for the actual vapor cloud due to large dispersions in water condensation behavior



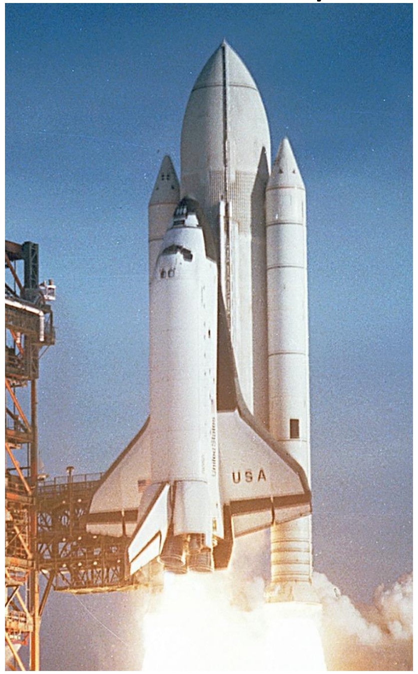




Brentari, E. G., Smith, R. V., Nucleate and Film Boiling Design Correlations for O2, N2, H2, and He", International Advances in Cryogenic Engineering, Proceedings of the 1964 Cryogenic Conference University of Pennsylvania, Philadelphia, PA Aug 18-21, 1964

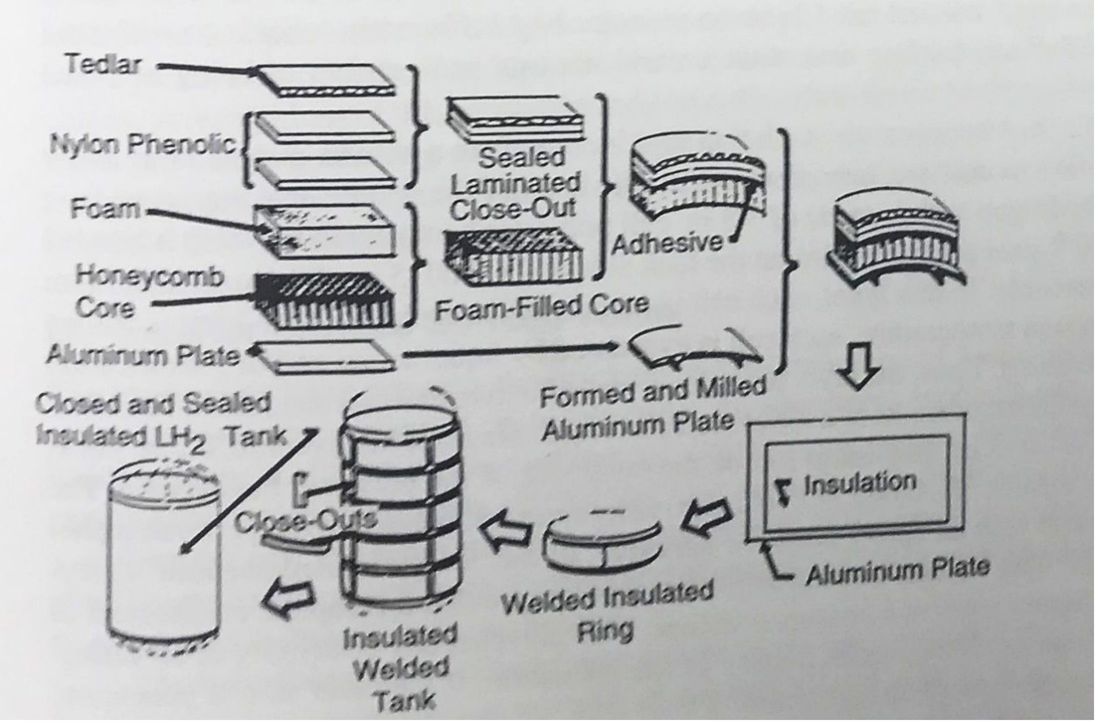
# Heat Transfer, Insulation

- Fluid operations are always transient
- Ice adds weight, heat lowers bulk density
- Condensable species, LH2 special case

PU/SOFI insulation






- Cold surfaces can cryopump moisture
- Creates partial pressure gradient
- Can infiltrate valves and causing jamming

Flynn, T., Cryogenic Engineering, Marcel Dekker, New York, 1996

# Common Problems

- Valve freezing from residual water or other condensable species
  - Valves can freeze in various states, open, closed, partially open
- Dewar vacuum jackets can be degraded, variable dewar boil-off
- Fill rate needs to be fast enough to overcome heat transfer

- Fluid system pressure drop and back pressure create a fill pressure balance
- Process is two-phase and transient
- Two-phase flow pressure drop is not easy to predict
  - It can be very large
  - Unsteady
  - Changes with time

- Tank back pressure controls tank saturation conditions and tank average density
- Axial and radial density gradients effect bulk density and are always transient
- BLEVE demo

# Start reading these authors

- R. V. Smith
- E. G. Brentari
- P. J. Giarratano
- And people they co-author with

- Advances in Cryogenic Engineering 1960's +/- 20 years
- NBS Technical Notes, various same time period

NIST Refprops source data, plus a lot more

# Questions

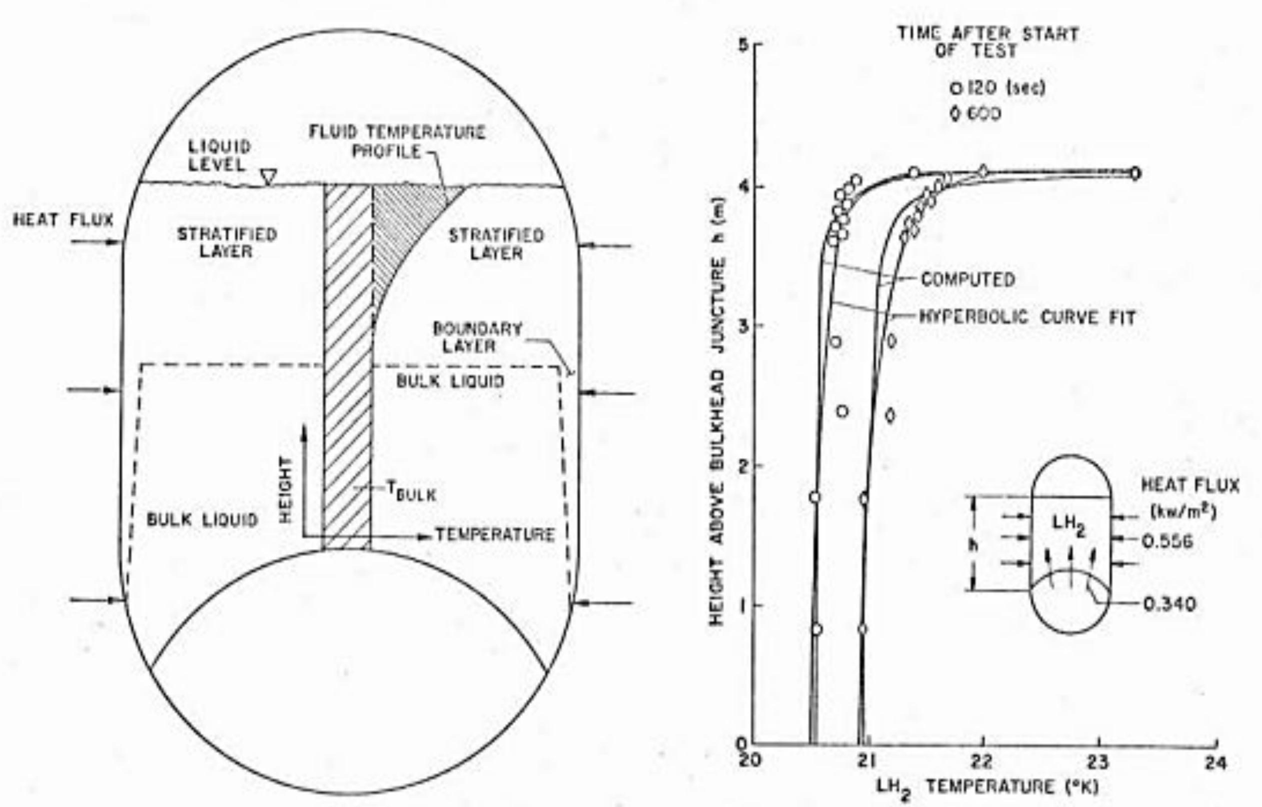
- For a tank loaded with a single cryogenic fluid saturated at local ambient pressure, what percentage of the tank fill maximizes the explosive BLEVE energy?
- What thickness of polyurethane foam reduces the heat load into a cryogenic tank by a factor of ten versus an uninsulated tank?

- What is the difference between para and ortho hydrogen?
- What happens to uninsulated LO2 equipment? And LH2 equipment? How are they the same and different?

- Are the mole/mass fractions of LNG species the same in a saturated state for liquid and vapor?
- Does LNG species blend change during transfer?
- What happens if you mix liquid oxygen with kerosene?

# Liquid Level, Stratification, and Densification

- A filled tank will be at some pressure between the loading pressure and ambient pressure aka a saturated fluid at a higher vapor pressure than ambient
  - Liquid will boil until itself-cools to lower saturation pressure
  - Self-cooling lowers saturation pressure/temperature and increases density
- Tank internal density is non-uniform and time dependent (stratification)
- Liquid surface level and location is unsteady and non-uniform

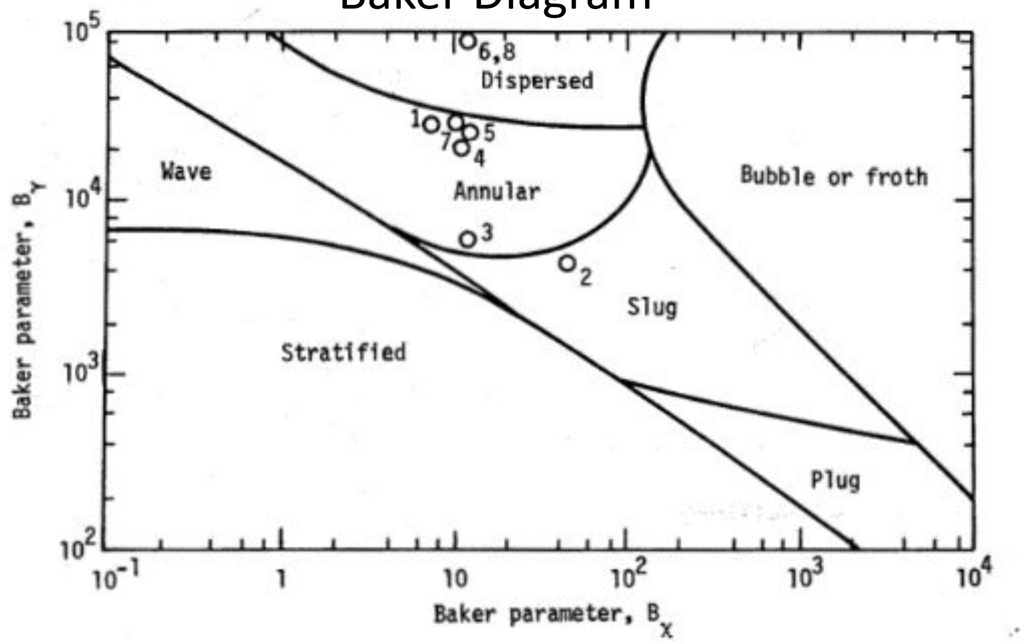


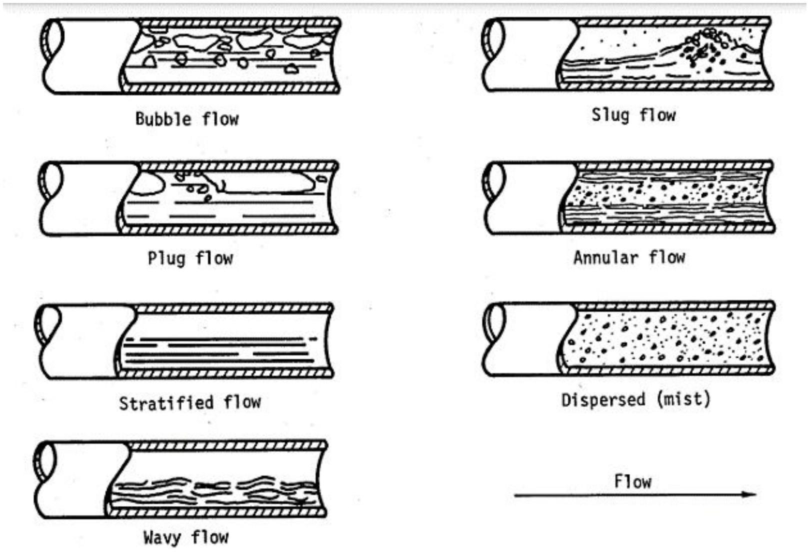

Woods, C., A REVIEW OF CRYOGENIC TECHNOT,OGY ASPECTS OF SPACE FLIGHT, INVITED PAPER for THE INTERNATIONAL CRYOGENIC ENGINEERING CONFERENCE Kyoto, Japan April 9 - 13, 1967

# Multi-phase flow

- Very hard to perform accurate engineering calculations, modeling, and simulation
- Flow regime dependent, typical operations have multiple regimes
- Inherently unsteady, pulsating
- Geometry, scale, fluid, species mixture, and orientation dependent
- Develop experiential data on systems, control variables and learn
- Multiple sources of analytic tools and methods

Baker Diagram






Calder, C., FLOW-REGIME CHARACTERIZATION FOR HORIZONTAL TWO-PHASE STEAM FLOW , LLNL, UCRL-52186, Livermore, CA October 5, 1976

# Embrittlement

- Some materials structurally unsuitable at low temperatures
- Material becomes brittle and will fracture
- Materials to avoid
  - Steels
  - Plastics
- Materials that work better
  - 300 series stainless steels
  - Teflon, however Teflon will cold flow under load
  - Polymers will go through the glass transition and become brittle
- H2 will also cause chemical embrittlement which is different but also common in cryogenics due to LH2
  - Exposure to H2 cause migration of H2 into certain materials which change their physical properties and some become brittle

LNG Facility Failure – East Ohio Gas Co., 1944

128 deaths

Cause unknown

Possibly due to brittle tank material

https://uspas.fnal.gov/materials/21onlineSBU/Cryo/2021%20USPAS%20Lecture%2016.pdf