Thermal Acoustic Oscillation: Causes, Detection, Analysis and Prevention

Robert Christie & Jason Hartwig
NASA Glenn Research Center

Presented By
Robert Christie

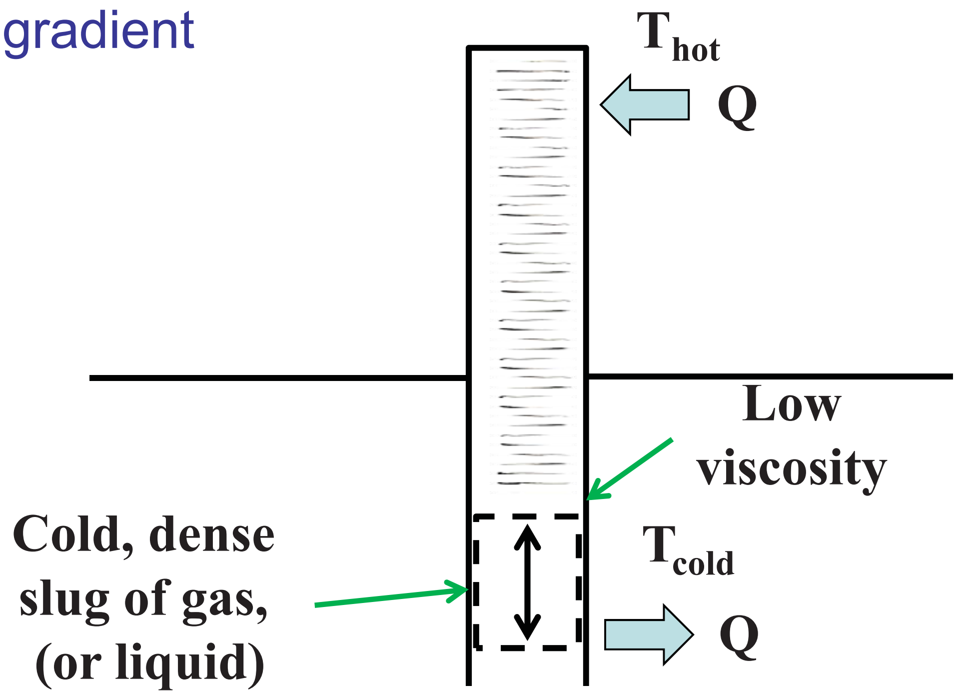
Thermal & Fluids Analysis Workshop
TFAWS 2014
August 4 - 8, 2014
NASA Glenn Research Center
Cleveland, OH

TAO Occurs

- Slender Half Tube
  - Closed at warm end (or slight flow)
  - Open at cold end (either in vapor or liquid)
- Spontaneous
- Critical temperature ratio needed to initiate TAO
- TAO transfers heat from the warm end to the cold end because gas absorbs heat from the walls as it expands at the warm end and gives up heat to the walls as it is compressed at the cold end
- Can increase heat transfer 1- 3 orders of magnitude over that of conduction

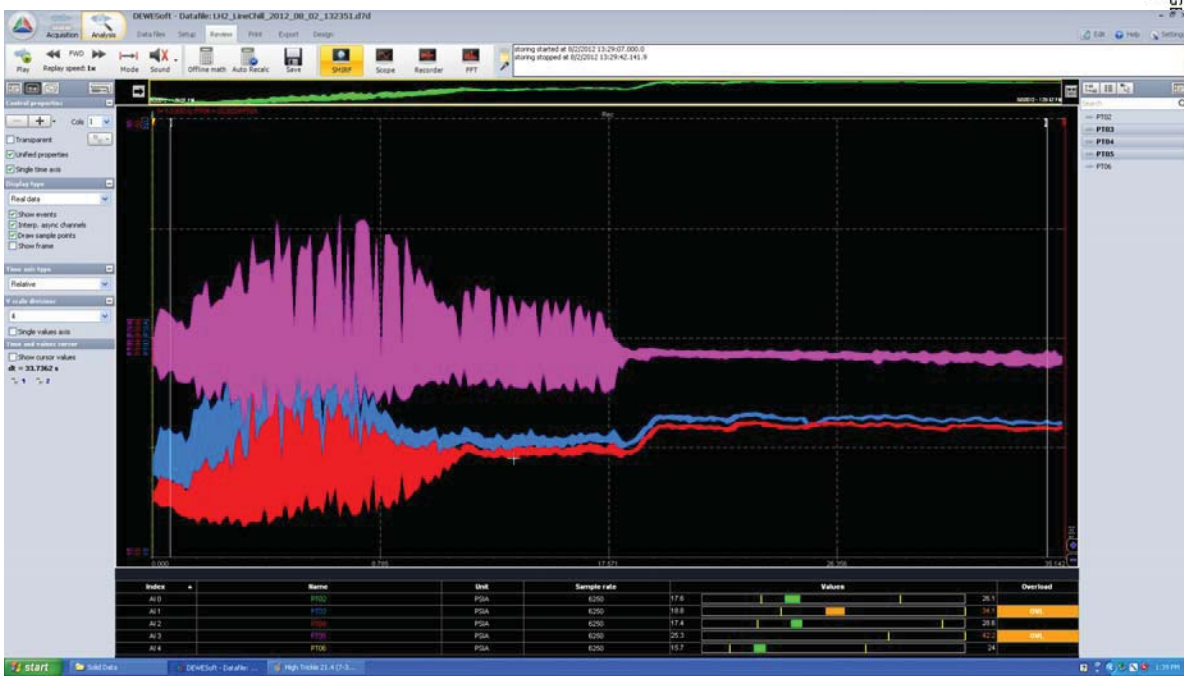
TAO Process

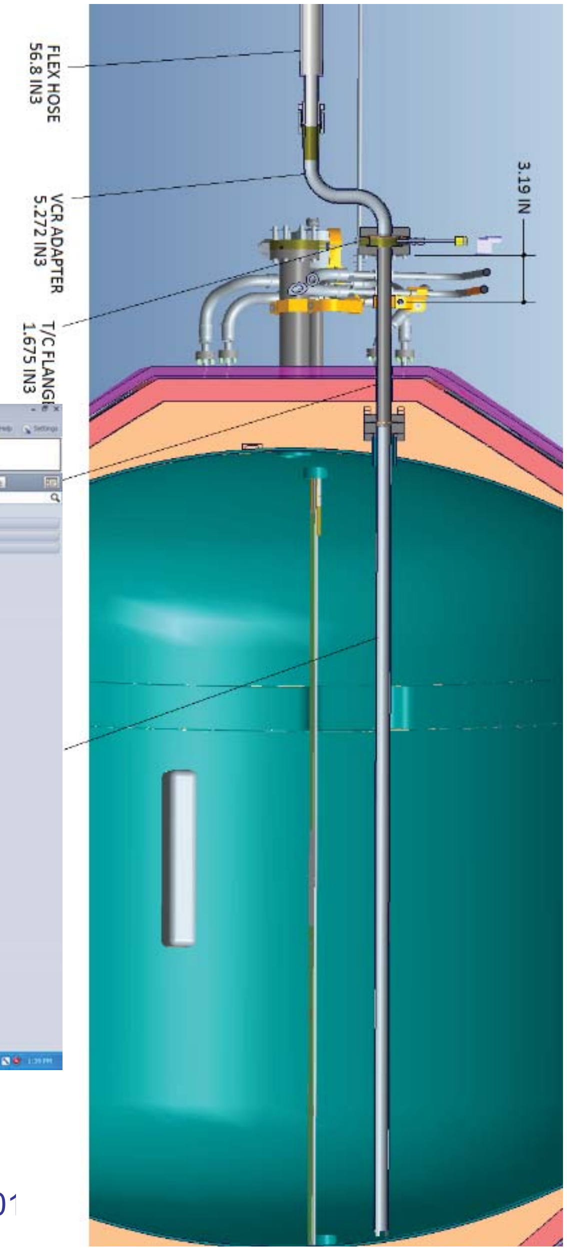
- Cold gas enters the warm end and rapidly expands
- Expanding gas pushes warmed gas into the cold open end
- Inertial forces cause a low pressure to form in warm end
- The low pressure causes the flow to reverse
- Cold dense gas moves into warm end
- Creates large radial temperature gradient
- Cold gas gets heated
- Process repeats
- Ref. 5



TAO Happens

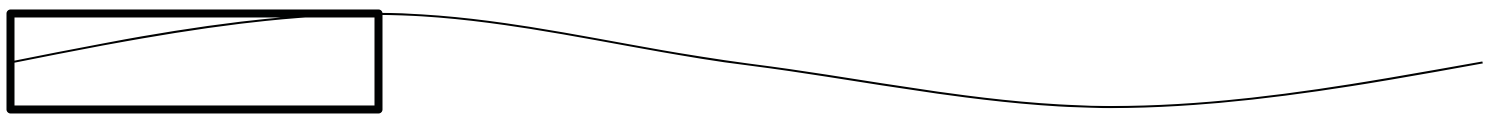
- Cryogenic Boil Off Reduction System
  - Unexplained heat
  - Oscillation observed with high-speed pressure-transducer





TAO Frequency

- Tube acts as ¼ wavelength acoustic resonator
- $f = c / \lambda$
  - λ is the 4 x ¼ wavelength tube, for lowest frequency
    - without liquid in the tube
  - c is the speed of sound at vapor temperature

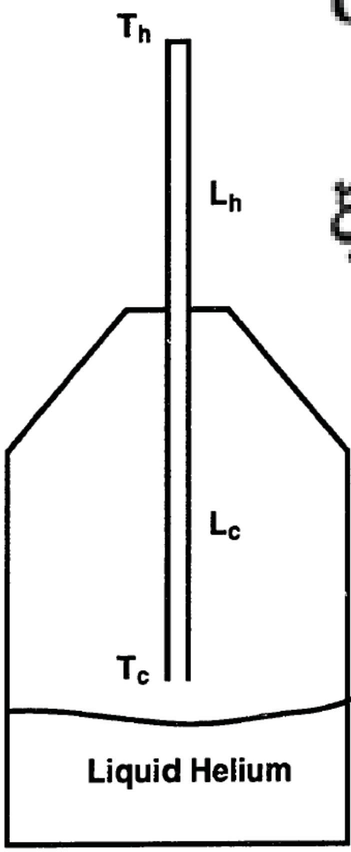


  - Example
    - Hydrogen at 20K, R = 4124J/kgK, k = 1.41
    - $c = 341$ m/s
    - $\lambda = 4$m
    - $f = 85s^{-1}$

Where TAO Does Not Occur

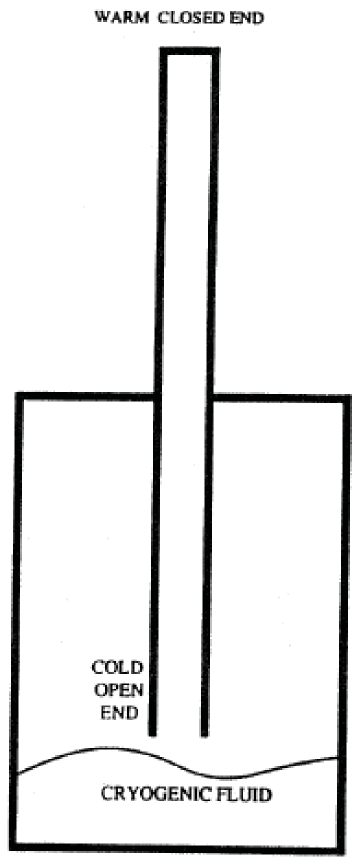
- Closed system
  - e.g. between two valves
  - Can occur after a valve is open
- Open at both ends
  - e.g. an open vent
  - Very small openings may appear as closed
- Small ratios of T_{hot}/T_{cold}
  - e.g. $\alpha < 8$ for a 1m long tube
  - 300K/20K = 15
- Very small inside diameter tubes
  - e.g. ID < 0.015” for a 1m long tube

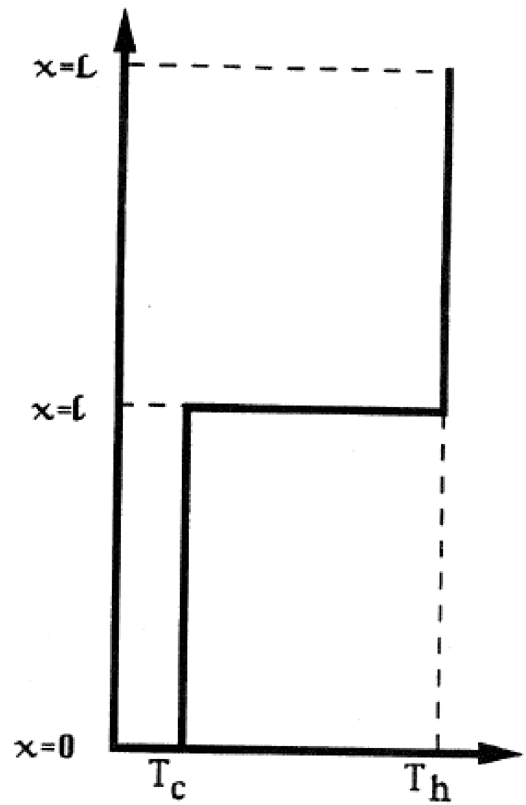
Typical Analytical Model



$$\alpha = \frac{T_h}{T_c}$$

$$\xi = \frac{L_h}{L_c}$$





Temperature Step Change

The Equations

- Solution of TAO stability curves depends on solution of combined mass, momentum, energy for a compressible fluid:

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \rho \underset{\sim}{v} = 0$$

$$\rho \frac{\partial \underset{\sim}{v}}{\partial t} = -\nabla P + \underset{\sim}{F_B} + \mu \nabla^2 \underset{\sim}{v} \qquad (2D)$$

$$\rho C_P \frac{\partial T}{\partial t} = -\nabla \bullet \underset{\sim}{q} + \left.\frac{\partial \ln V}{\partial \ln \mathrm{T}}\right|_P \frac{dP}{dt} - \tau \colon \nabla \underset{\sim}{v} + \underset{\sim}{S}$$

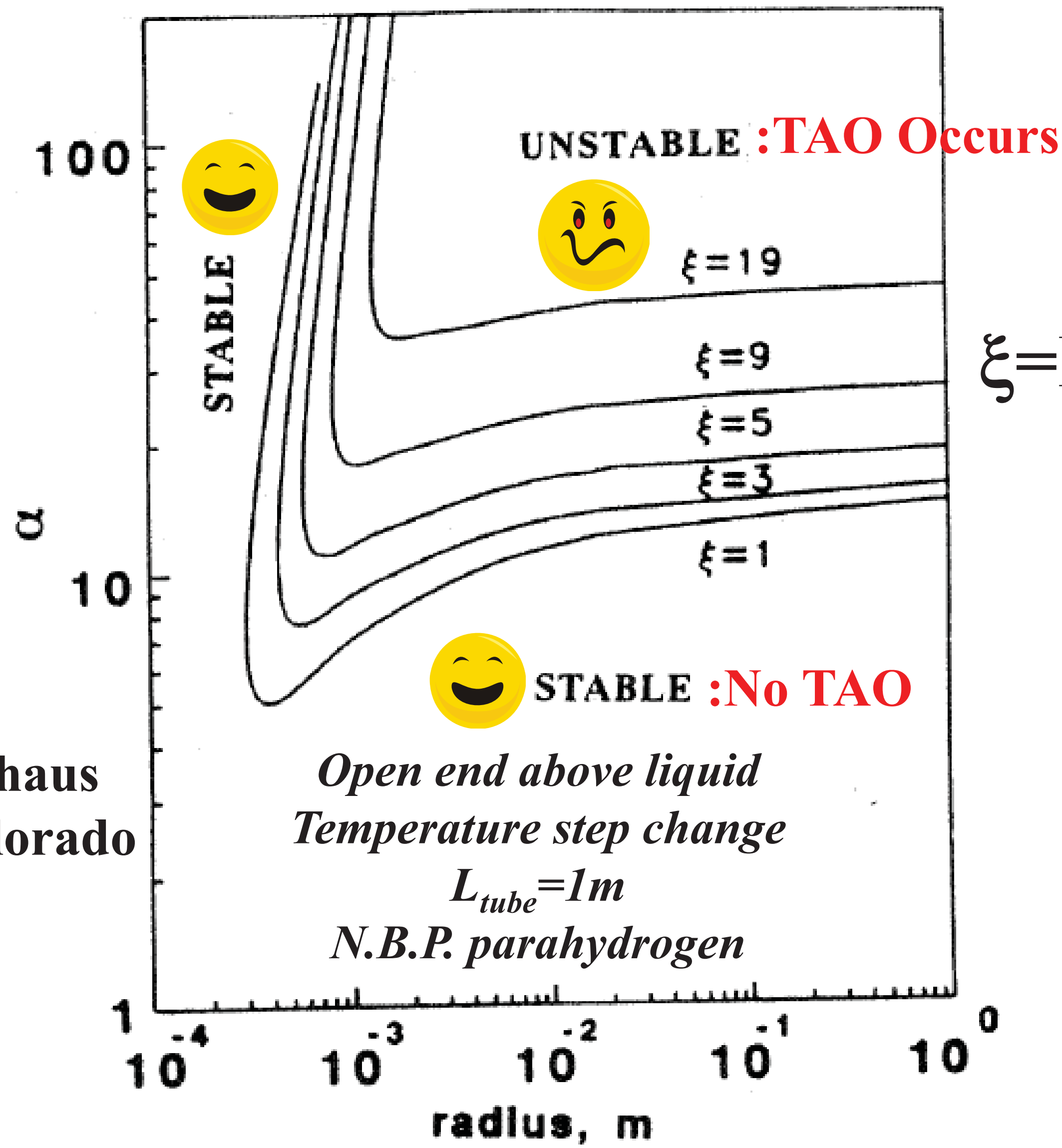
$$P = Z \rho R T$$

- Standard method of solution is a perturbation solution about the mean value for $\rho, u, v, \mathrm{P}, \mathrm{T}$:
- Example: $P = P_m + \hat{P}_1 \varepsilon + \hat{P}_2 \varepsilon^2 + \ldots$
- If a sinusoidal wave is assumed, $P = P_m + \hat{P}_1 \varepsilon + \hat{P}_2 \varepsilon^2 + \ldots$ only the first order term is retained, because $P_m = 0$ and higher order terms are small.

  $\therefore P = \varepsilon P_1 \exp(i\omega t), \mathrm{u} = \varepsilon u_1 \exp(i\omega t), etc.$ Real part of ω is oscillation frequency
- Substitute perturbed solutions into 5 equations, solve numerically

TAO Critical Conditions

$\alpha = T_{hot}/T_{cold}$



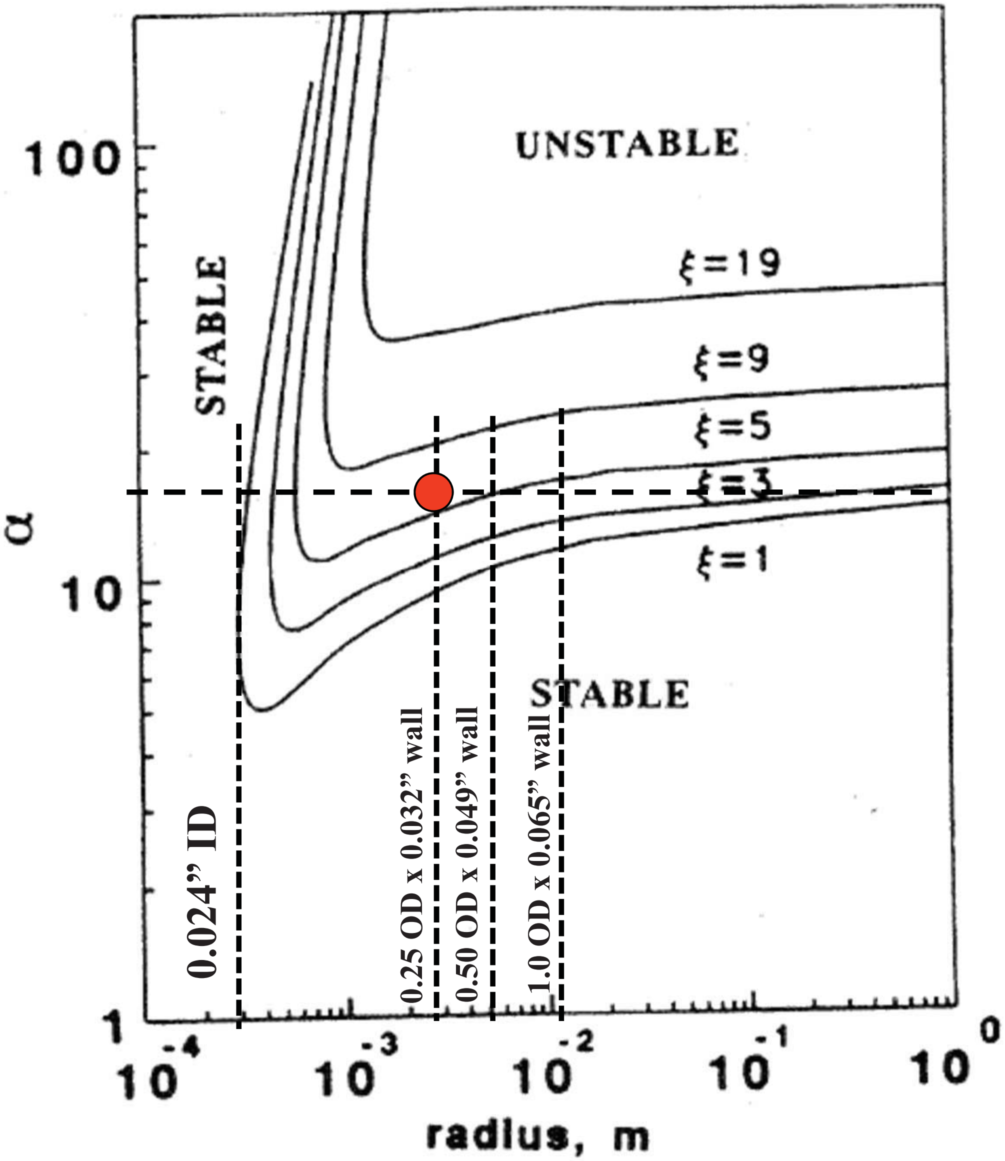
$\xi = L_{hot}/L_{cold}$

Gu & Timmerhaus
University of Colorado

Open end above liquid
Temperature step change
$L_{tube}=1m$
N.B.P. parahydrogen

Effect of Changing Tube Size

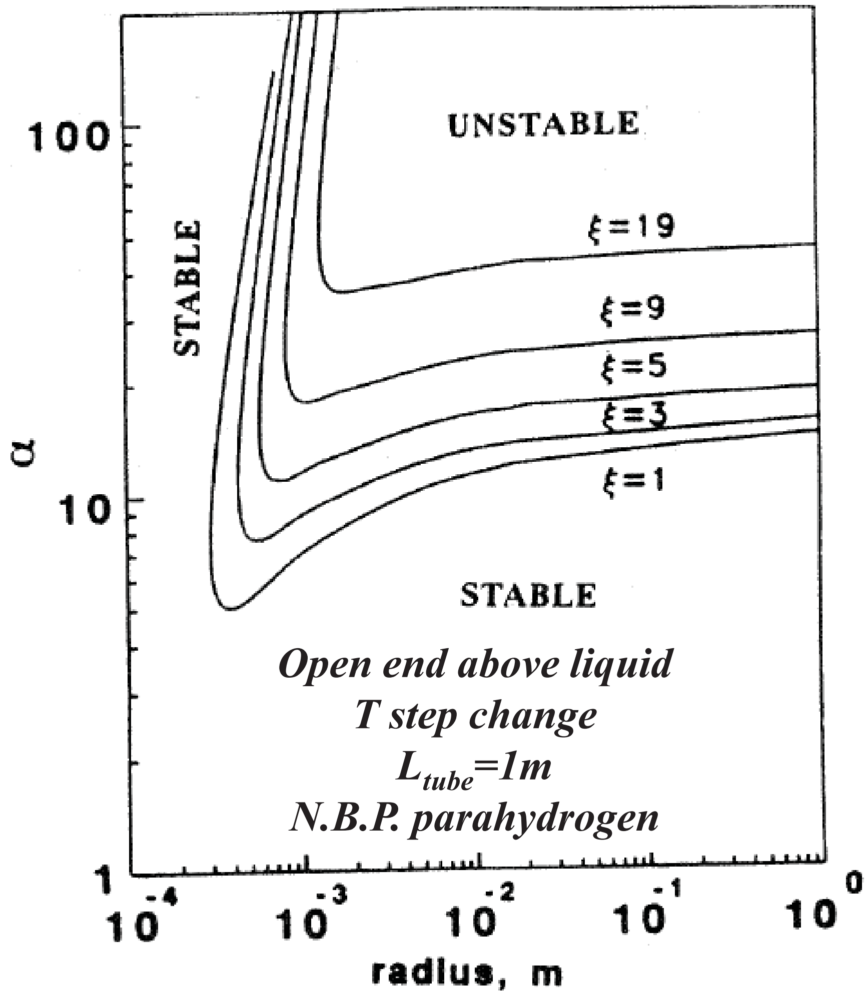
- Example
  - L= 1m
  - Tube: 0.25 OD
    - 0.032” wall
  - α = 15
    - 300K/20K=15
  - ξ = 5
  - Could make stable by:
    - Increasing tube size (weak: requires big change)
    - Increasing ξ
    - Decreasing α



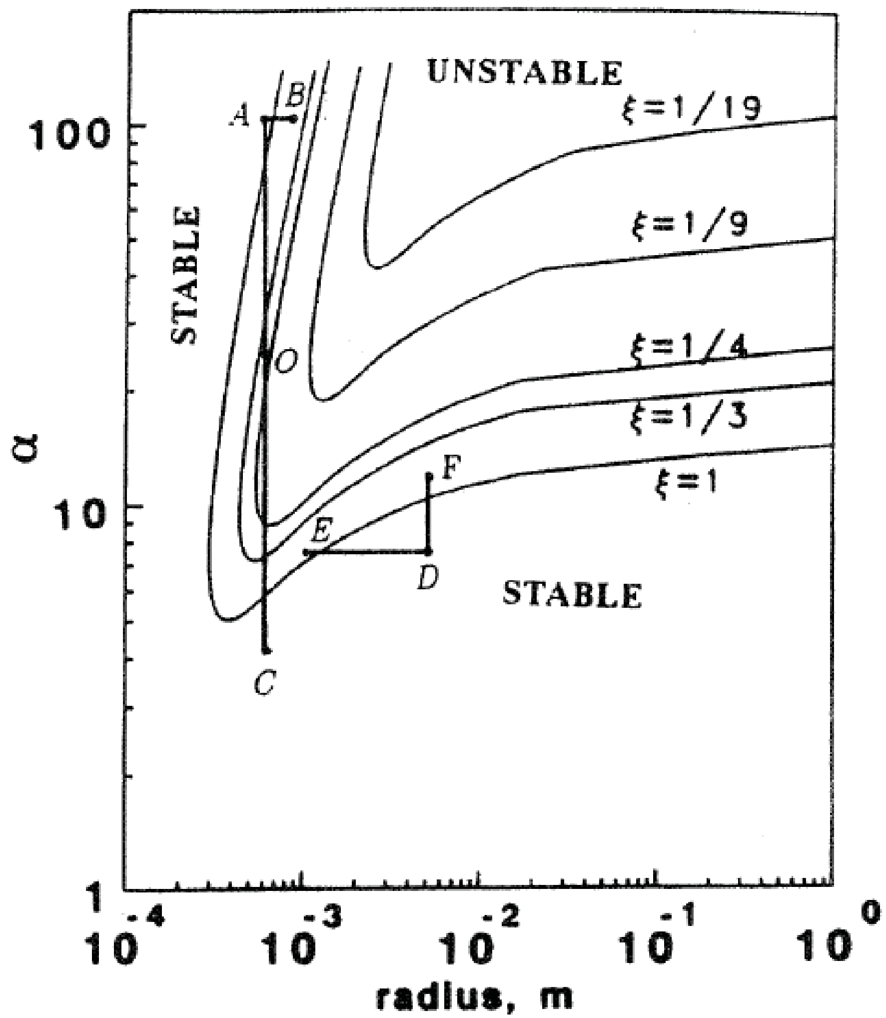
Effect of Length Ratio < 1

Open end in vapor

$\xi > 1$

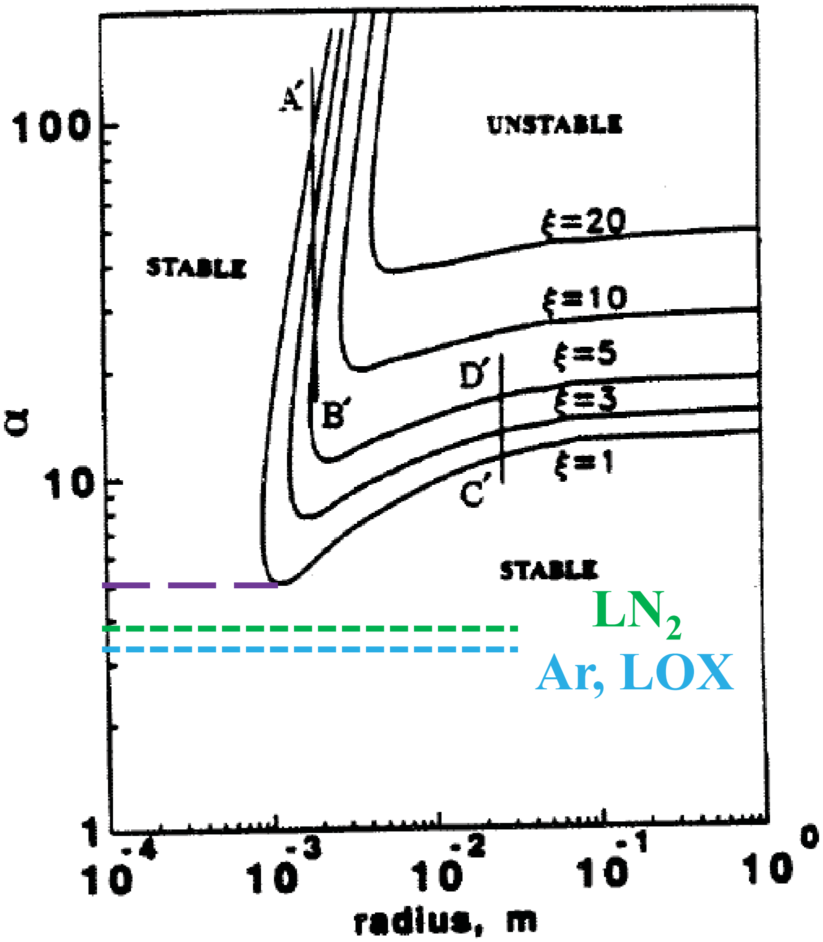


$\xi < 1$

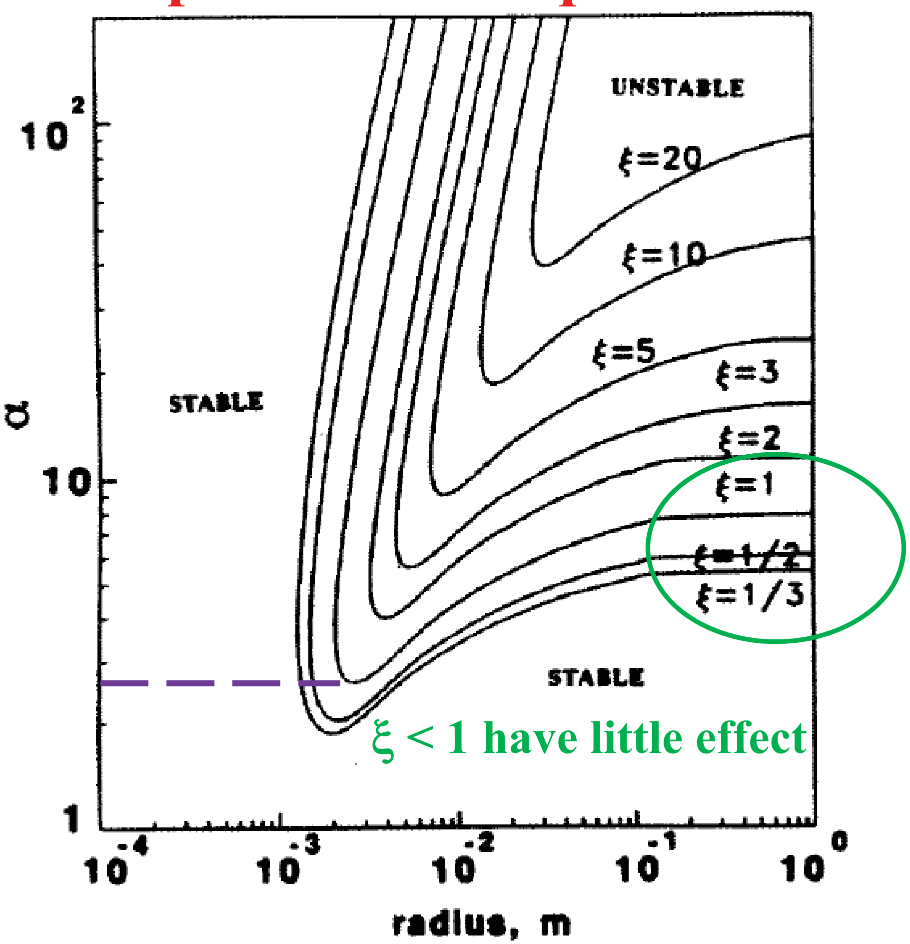


Dry vs Wet Open End

Open End in Vapor



Open End in Liquid

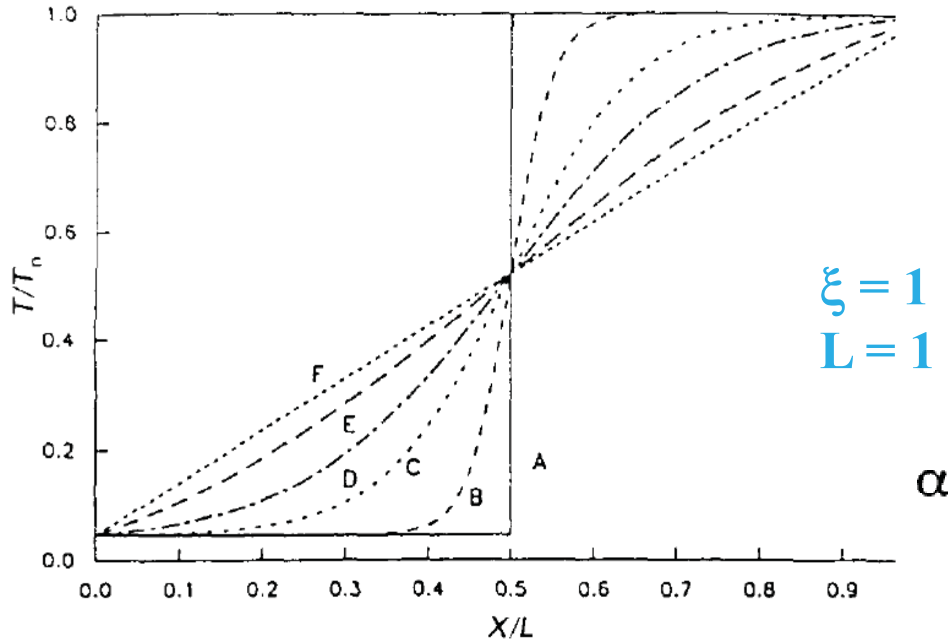


Open end 0.1m below liquid surface

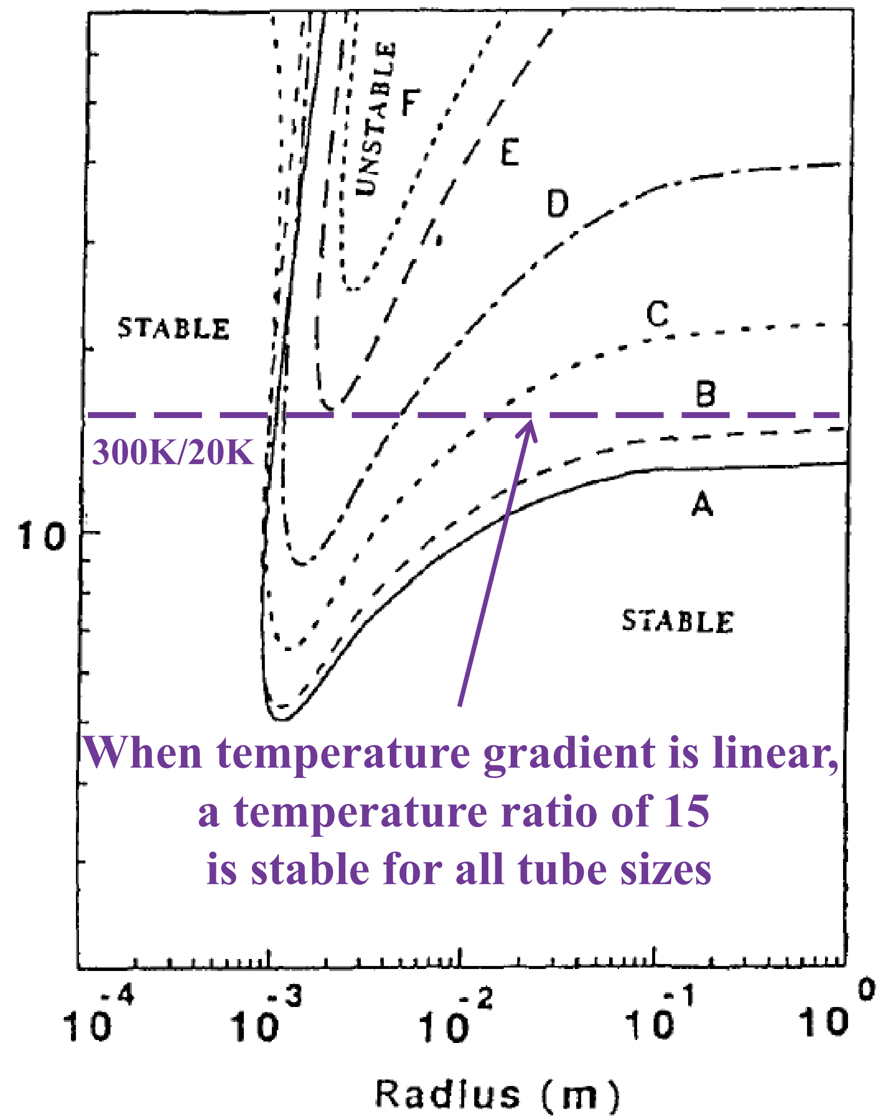
Mass of liquid in tube will lower the oscillation frequency

T.P. parahydrogen, L_{tube}=1m, Step change

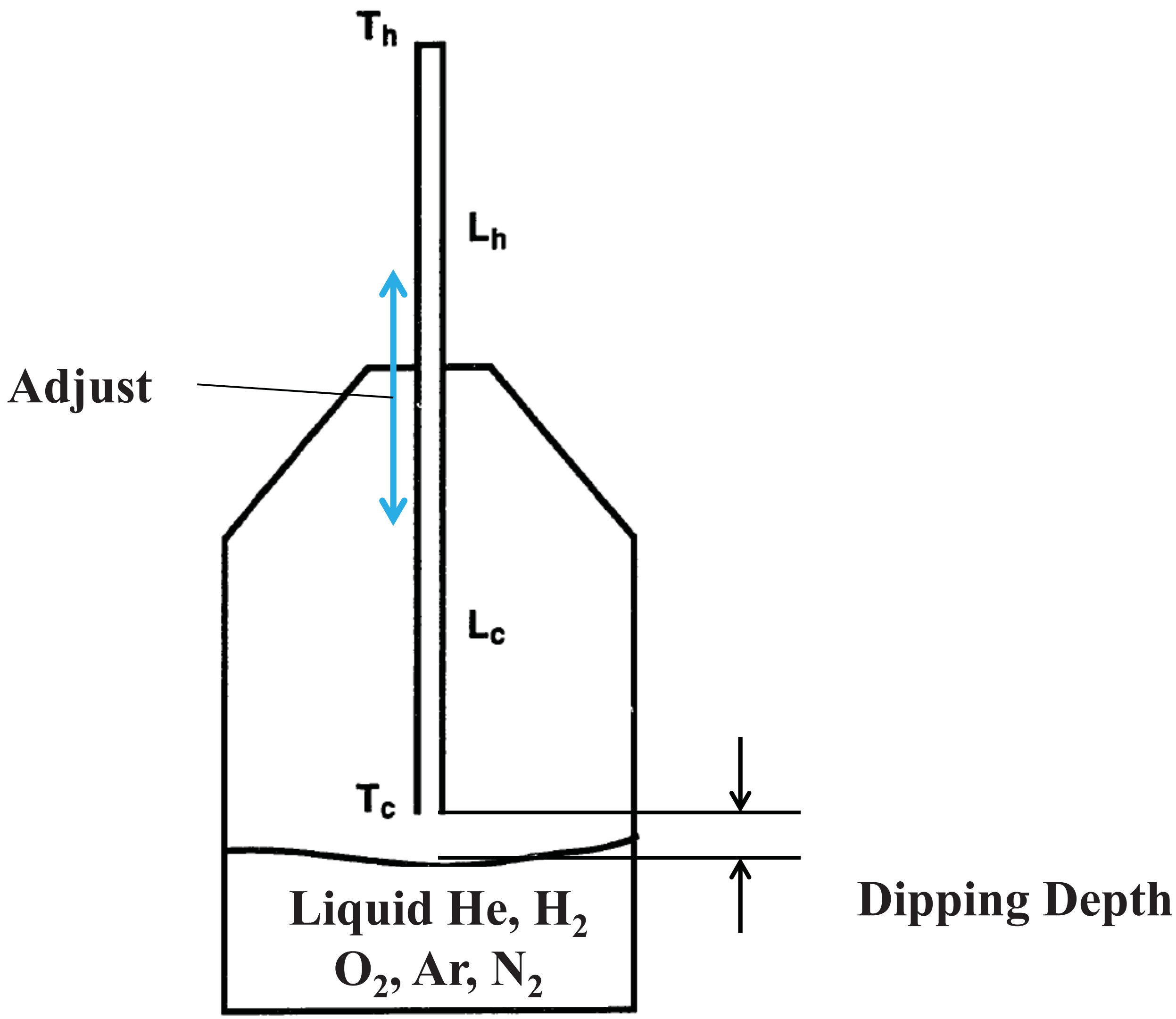
Effect of Thermal Gradient



- Reducing temperature gradient raises temperature ratio needed to initiate TAO
- Step change is worst case
- Insulation is useful to linearize the temperature distribution

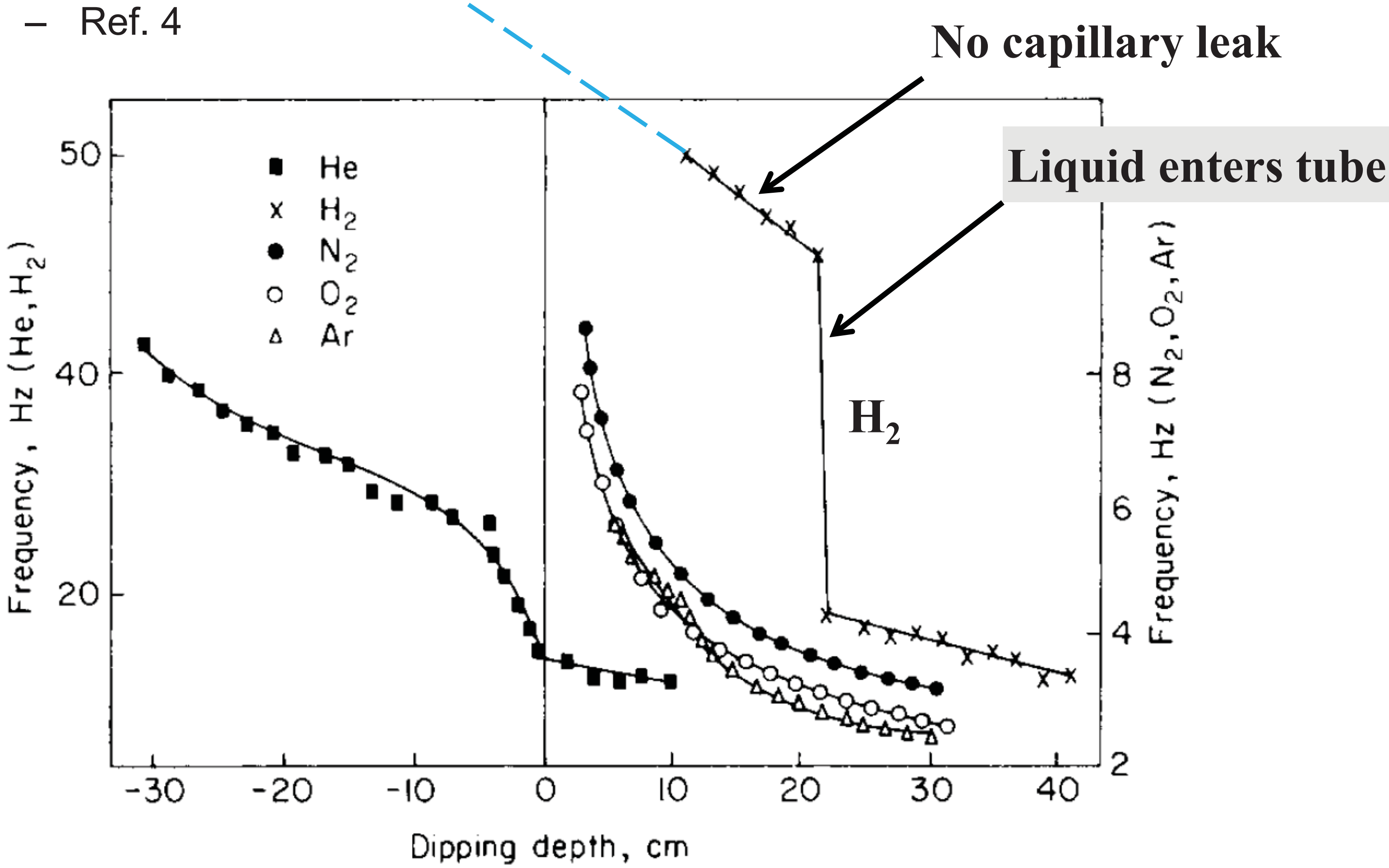


Dipping Effects



Dipping Effects

- LH2 did not enter tube until submersed 20cm
  - Ref. 4



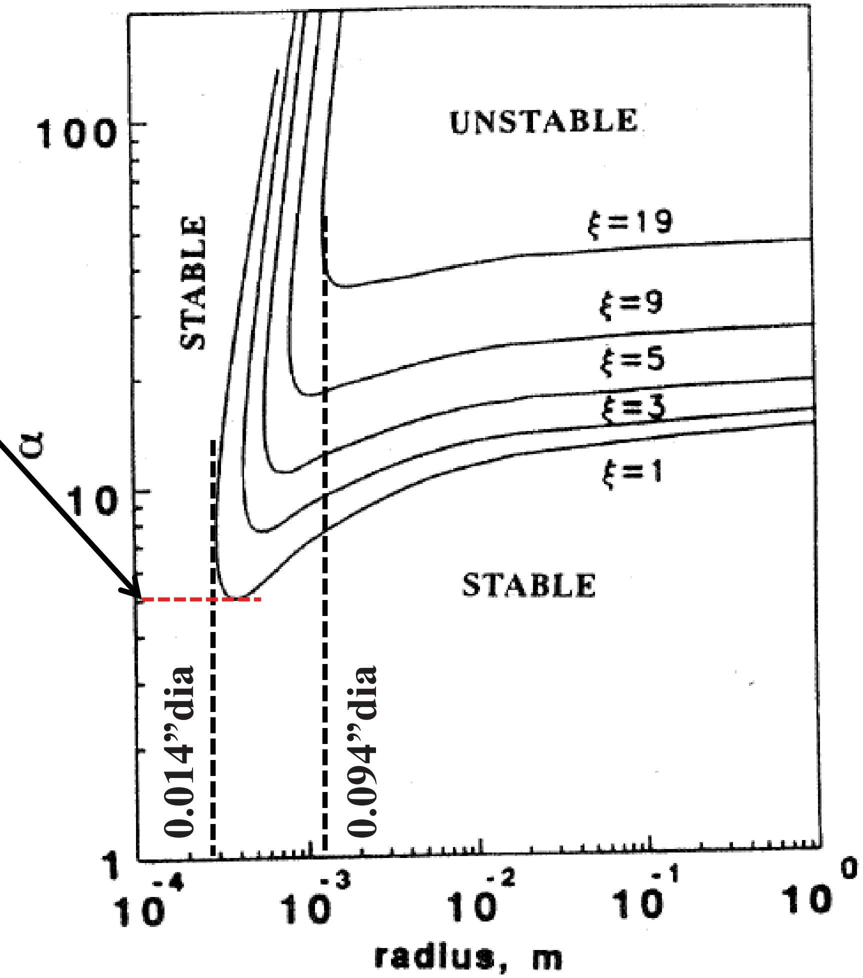
Note difference in behavior between He and H2. Use caution when applying He findings to H2 applications

TAO Forces

- Forces in TAO
  - Driving force
    - Temperature ratio and gradient
    - Heat transfer area
      - Length and radius of warm section
      - ‘Driving force is directly proportional to warm end tube length’
  - Viscous resistance
    - Viscosity in warm section predominates when $\xi > 1$
    - Length ratio critical
  - Inertial force
    - Oscillating Mass
    - Pressure, temperature, volume
- Features
  - More easily excited when cold end is in fluid
  - Lower frequency when fluid is in fluid

TAO Stability Limits

- To increase stability
  - Reduce temperature gradient
    - α_{min} = 5 (end not in liquid)
    - α_{min} = 2 (end in liquid)
  - Increase length ratio
    - Applies to right hand region
    - Increase L_{hot}
    - Decrease L_{cold}



N.B.P. parahydrogen L=1m
Open end not in liquid

Changing Tube Size or Temperature Ratio

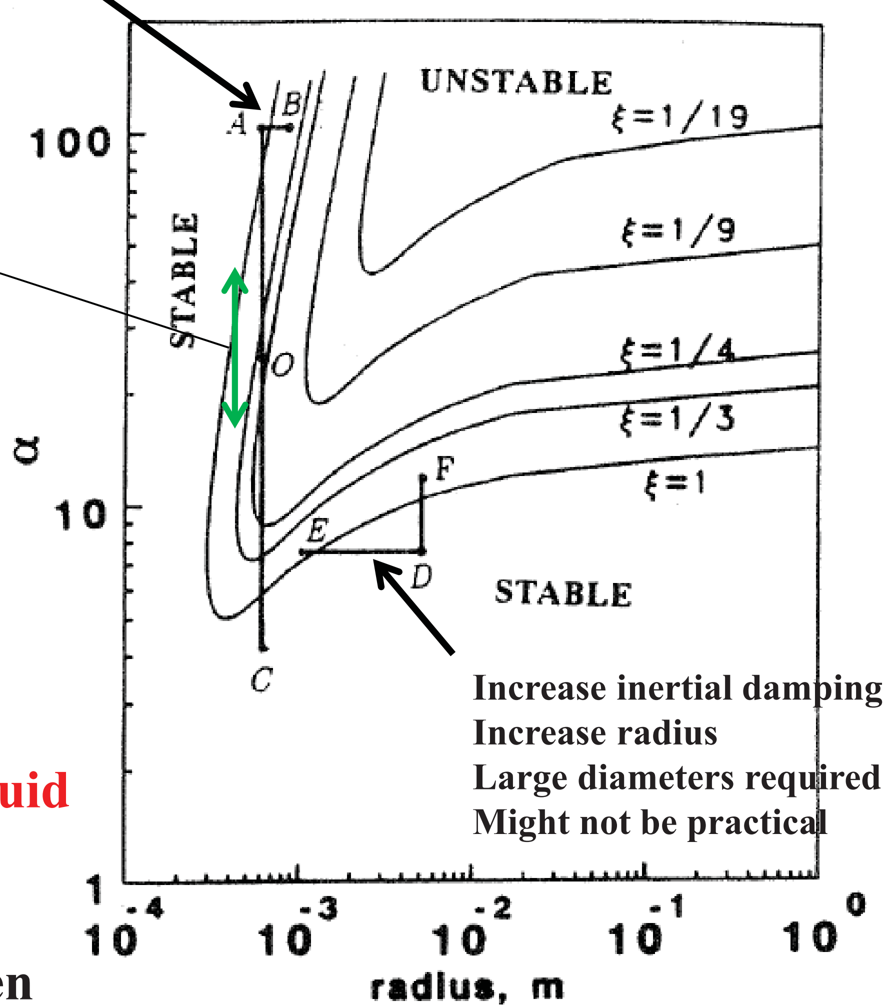
Increase viscous damping
Decrease radius

$\xi \leq 1$

$\xi = L_{hot}/L_{cold}$

Increase or decrease temperature ratio

$\alpha = T_{hot}/T_{cold}$



Increase inertial damping
Increase radius
Large diameters required
Might not be practical

Examples:
@ O $\xi=1$
@ B $\xi=1$
@ E $\xi=1$
@ F $\xi=1$

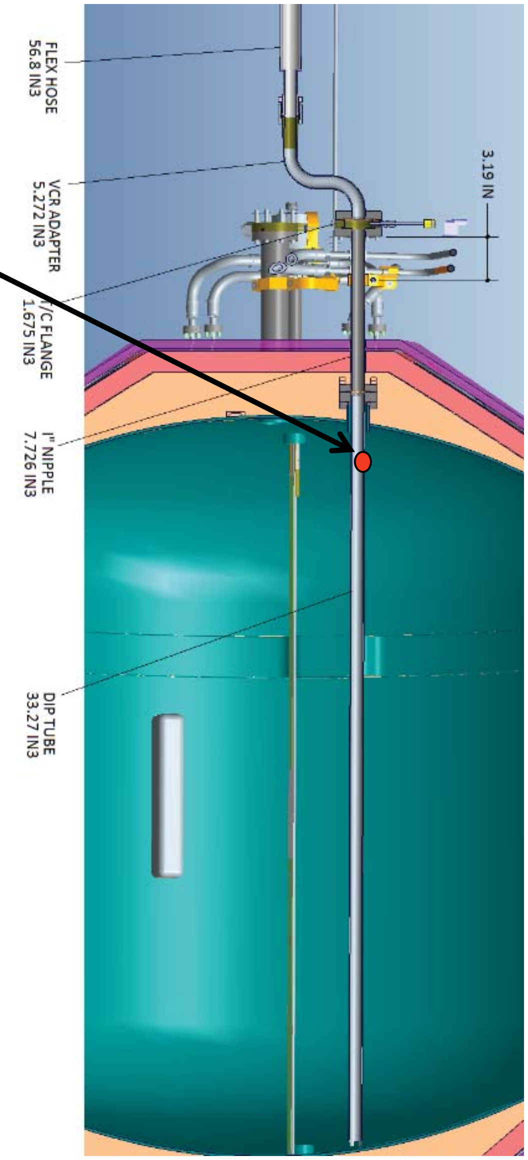
Open end above liquid
T step change
$L_{tube}=1m$
N.B.P. parahydrogen

Mitigation Methods

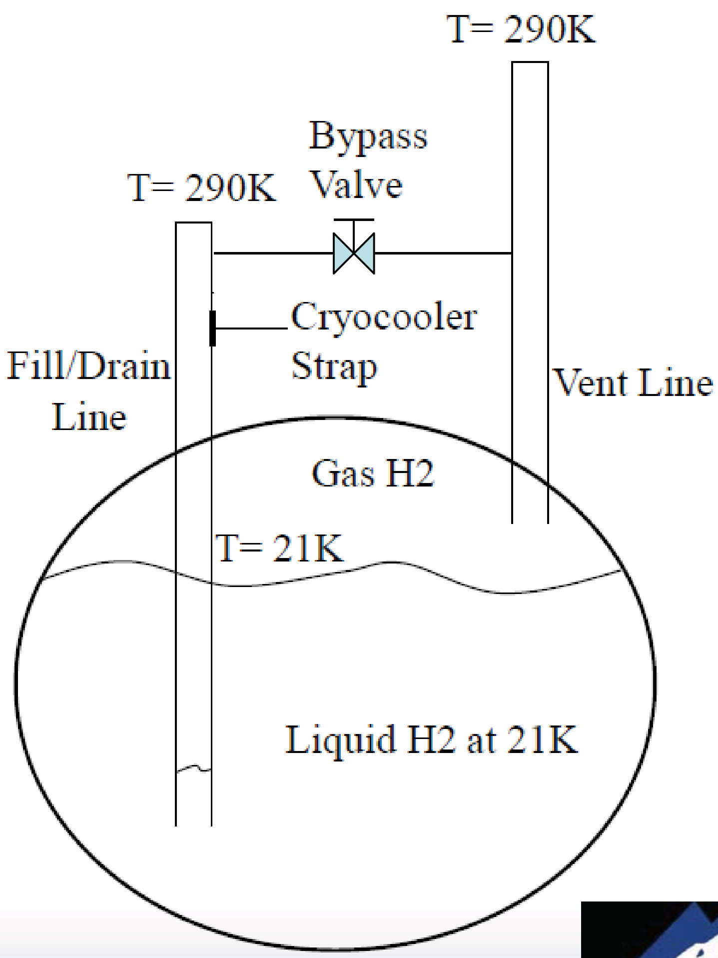
- Reduce driving force
  - Change temperature ratio α
    - Reduce temperature gradient
    - Make warm end colder
      - Insulation
  - Change length ratio ξ
    - Make warm end shorter
      - Reduces driving force
- Increase viscous damping
  - Reducing tube radius
    - e.g. add restrictor to cold end
- Increase inertial damping
  - Increase tube radius
  - Change temperature gradient
    - Insulation
- Block line
  - Check valve
  - Add filter
    - Use as acoustic absorber
- Connect Fill with Vent
- Resonator
  - Add resonator to warm end
  - Works theoretically
- Parallel ¾ wavelength tube
- Other
  - Get away from ξ =1
  - Adding a large cavity to warm end can have the same effect as opening the closed end
    - e.g. add a vent
  - Get open end out of liquid
    - Raises minimum critical temperature ratio
  - Fill tube with liquid
    - Oscillations would need to drive a large mass
    - e.g. add vent to warm end of dip tube

Possible Fix: Vent Hole

- Change effective length of dip tube by allowing liquid to fill it
  - Drill hole in warm end
  - Effective when tank is relatively full in 1g
  - When fluid level is low, vapor length will increase and TAO may return



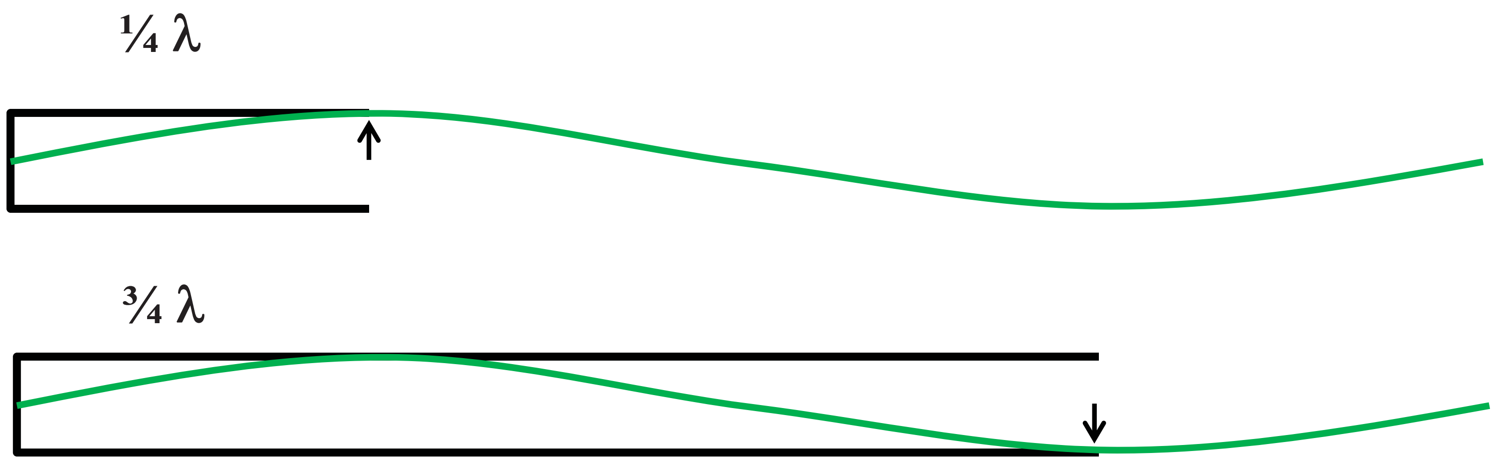
Actual Fix: Cross Over Valve



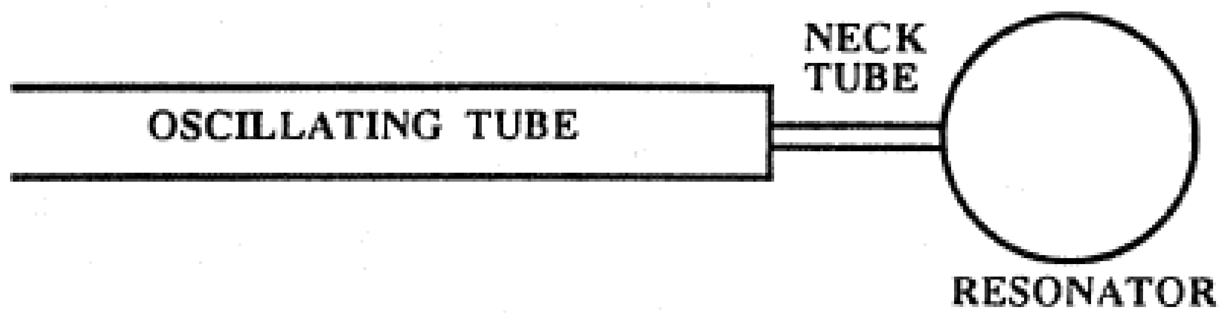
Ref. 7

Out-of-Phase Parallel Tubes

If a ¼ wave-length tube and a ¾ wave-length tube are in parallel, their out of phase oscillations will cancel each other



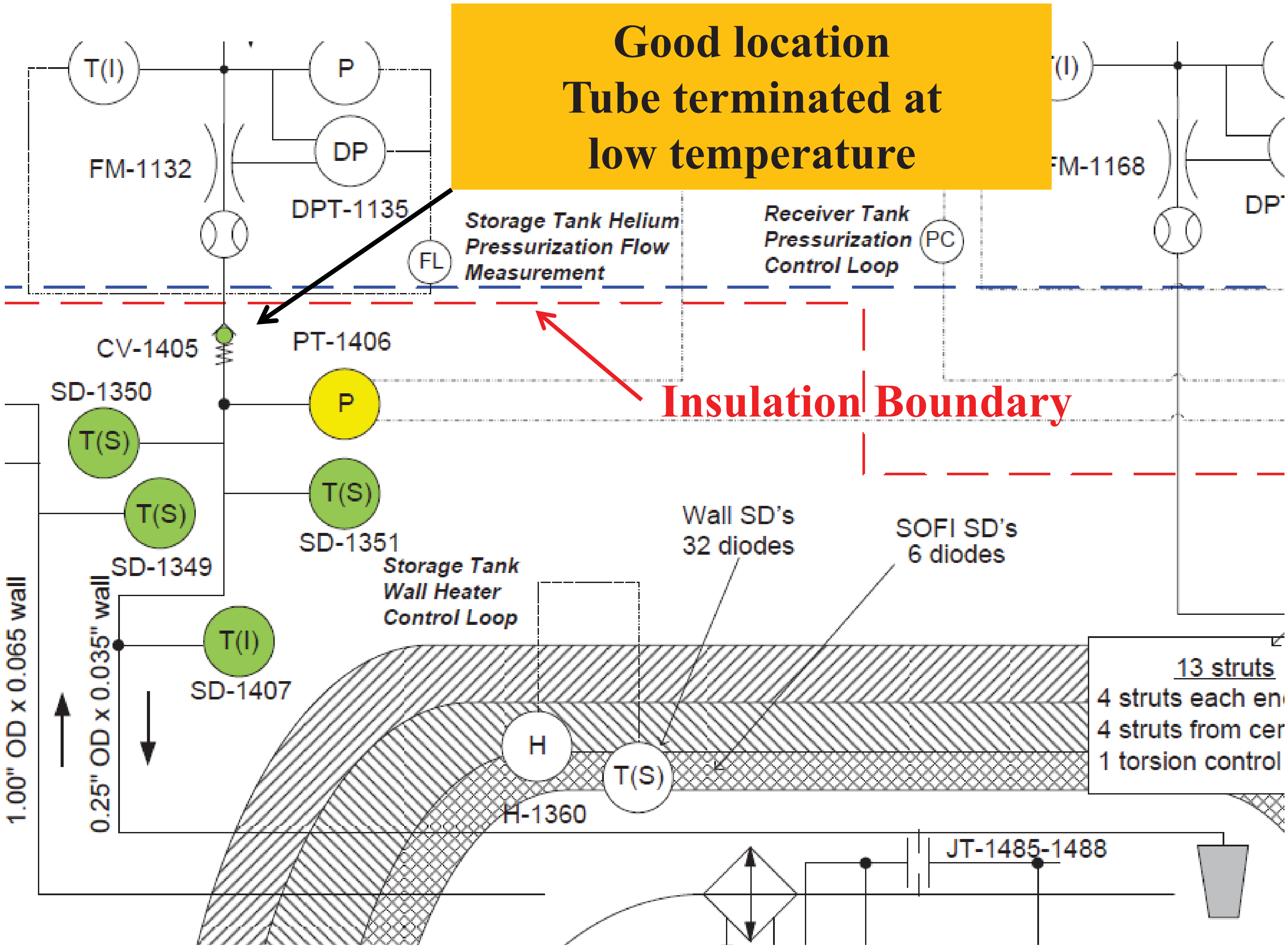
Warm End Resonator



Shown to work theoretically

Ref. 1

Check Valve



Good location
Tube terminated at
low temperature
Insulation Boundary
T(I)
P
DP
FM-1132
DPT-1135
FL
Storage Tank Helium Pressurization Flow Measurement
Receiver Tank Pressurization Control Loop
PC
FM-1168
CV-1405
PT-1406
SD-1350
T(S)
SD-1349
SD-1351
SD-1407
Storage Tank Wall Heater Control Loop
Wall SD's
32 diodes
SOFI SD's
6 diodes
H
H-1360
13 struts
JT-1485-1488
1.00" OD x 0.065 wall
0.25" OD x 0.035" wall

References

1. Y Gu & K Timmerhaus, Damping of Thermal Acoustic Oscillations in Hydrogen Systems, NASP CR 1137, 1992
2. Y Gu & K Timmerhaus, Damping Criteria in Slush and Liquid Hydrogen Systems, Space Cryogenics Workshop, 1991
3. Y Gu, Thermal Acoustic Oscillations in Cryogenic Systems, Doctorial dissertation, University of Colorado, 1993
4. Dmitrevskiy Y.P & Melnik Y.M, Observation of Thermal Acoustic Oscillations in Hydrogen, Nitrogen, Oxygen and Argon, Cryogenics Jan 1976
5. T. Miller & Y. Gu, Elimination of Thermal Acoustic Oscillations in Cryogenic Pumps, Advances in Cryogenic Engineering, CEC, Vol. 51, 2006
6. R. Haycock, Techniques for Eliminating Thermal Acoustical Oscillation in Cryogenic Instrumentation, SPIE Vol. 245 Cryogenically Cooled Sensor Technology, 1980
7. C. Nguyen, Thermal Acoustic Oscillation Heat Pump in Cryogenic System Modeling
8. J. Hartwig, Thermal Acoustic Oscillation Analysis, NASA GRC