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Thermal Acoustic Oscillation: Causes, Detection, Analysis and Prevention

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TAO Occurs



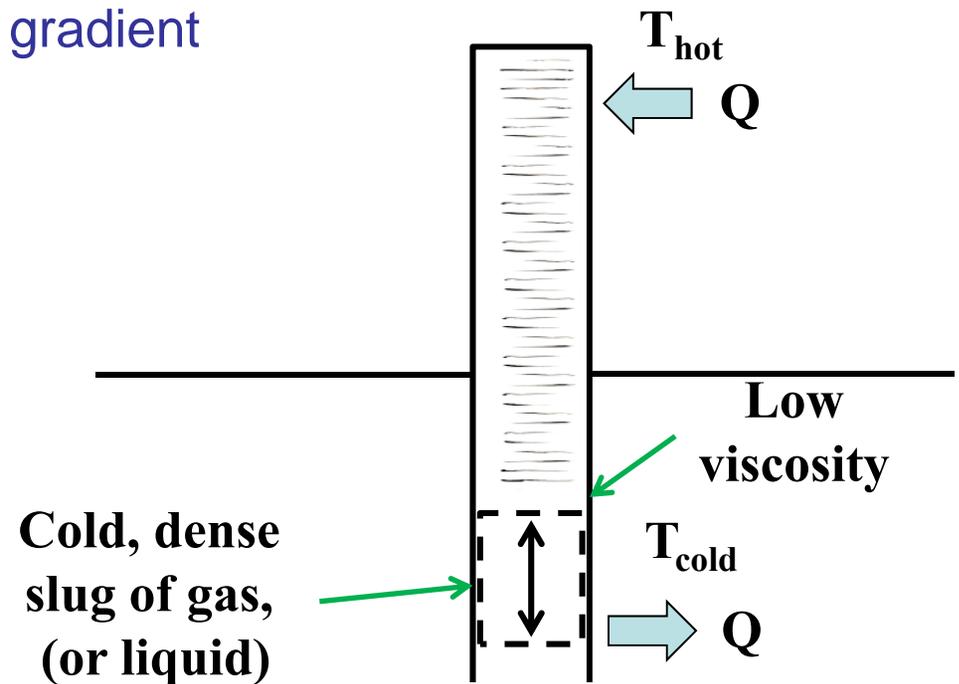
- Slender Half Tube
 - Closed at warm end (or slight flow)
 - Open at cold end (either in vapor or liquid)
- Spontaneous
- Critical temperature ratio needed to initiate TAO
- TAO transfers heat from the warm end to the cold end because gas absorbs heat from the walls as it expands at the warm end and 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

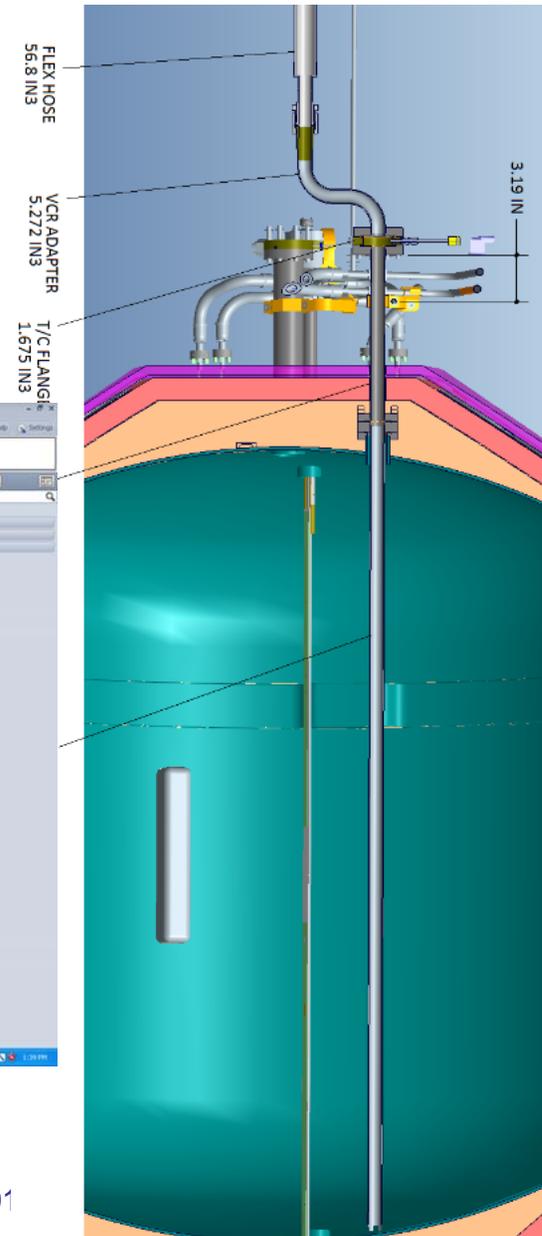
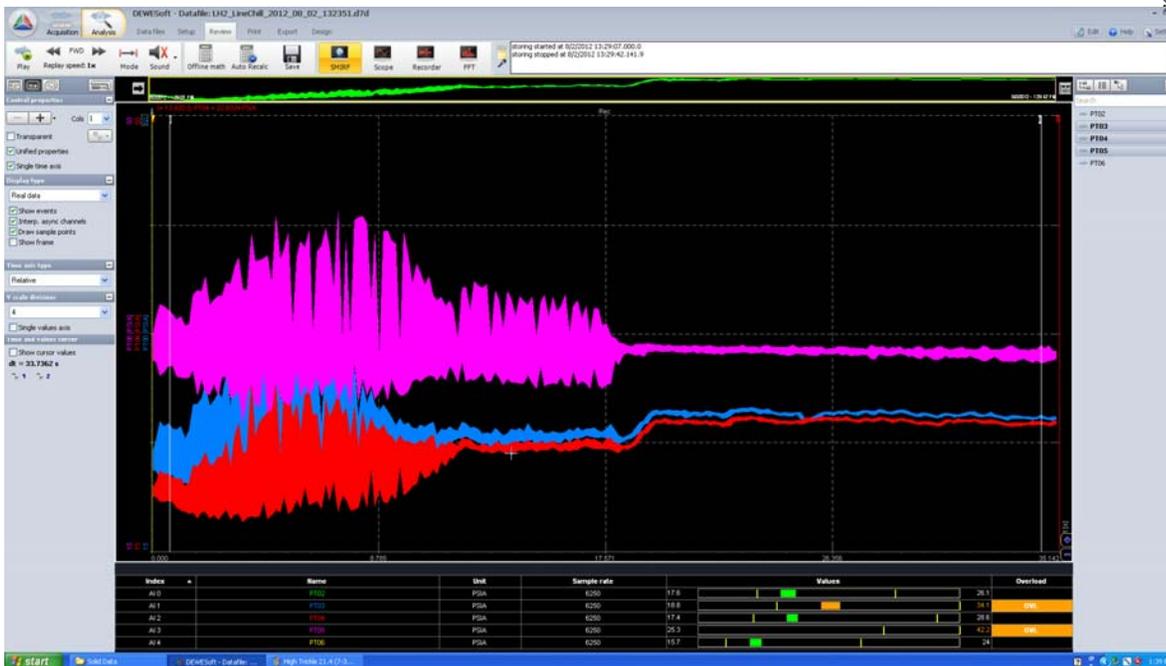




TAO Happens



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





TAO Frequency



- Tube acts as $\frac{1}{4}$ wavelength acoustic resonator
- $f = c / \lambda$
 - λ is the $4 \times \frac{1}{4}$ wavelength tube, for **lowest** frequency
 - without liquid in the tube
 - c is the speed of sound at vapor temperature



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



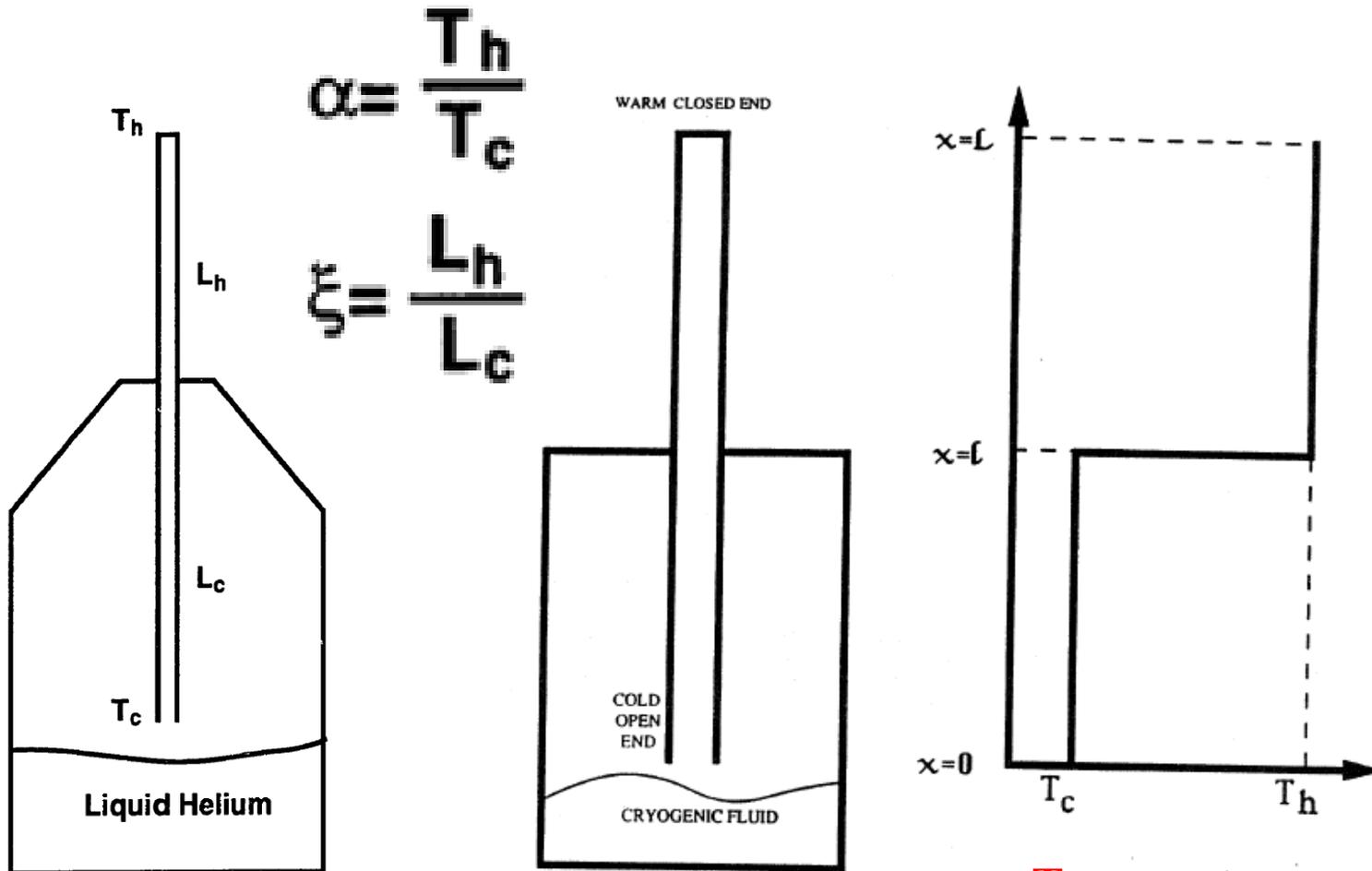
Where TAO Does Not Occur



- 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 $T_{\text{hot}}/T_{\text{cold}}$
 - e.g. $\alpha < 8$ for a 1m long tube
 - $300\text{K}/20\text{K} = 15$
- Very small inside diameter tubes
 - e.g. ID < 0.015 " for a 1m long tube



Typical Analytical Model



Temperature Step Change



The Equations



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

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \tilde{v} = 0$$

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

$$\rho C_p \frac{\partial T}{\partial t} = -\nabla \cdot \tilde{q} + \left. \frac{\partial \ln V}{\partial \ln T} \right|_P \frac{dP}{dt} - \tau : \nabla \tilde{v} + S$$

$$P = Z \rho R T$$

- Standard method of solution is a perturbation solution about the mean value for ρ, u, v, P, T :

- Example: $P = P_m + \hat{P}_1 \varepsilon + \hat{P}_2 \varepsilon^2 + \dots$

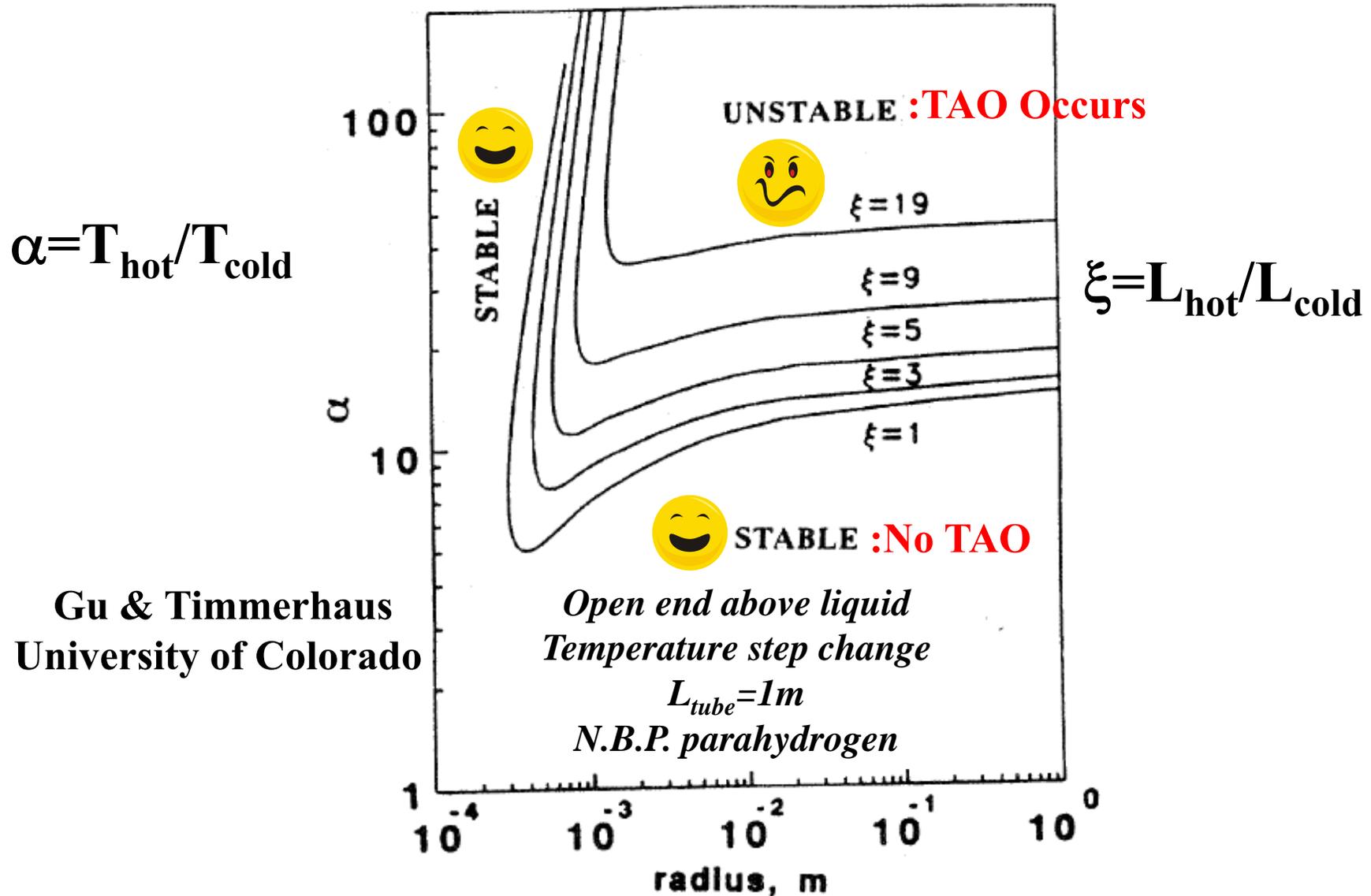
- If a sinusoidal wave is assumed, $P = P_m + \hat{P}_1 \varepsilon + \hat{P}_2 \varepsilon^2 + \dots$ only the first order term is retained, because $P_m = 0$ and higher order terms are small.

$\therefore P = \varepsilon P_1 \exp(i\omega t), u = \varepsilon u_1 \exp(i\omega t), etc.$ Real part of ω is oscillation frequency

- Substitute perturbed solutions into 5 equations, solve numerically



TAO Critical Conditions



Gu & Timmerhaus
University of Colorado

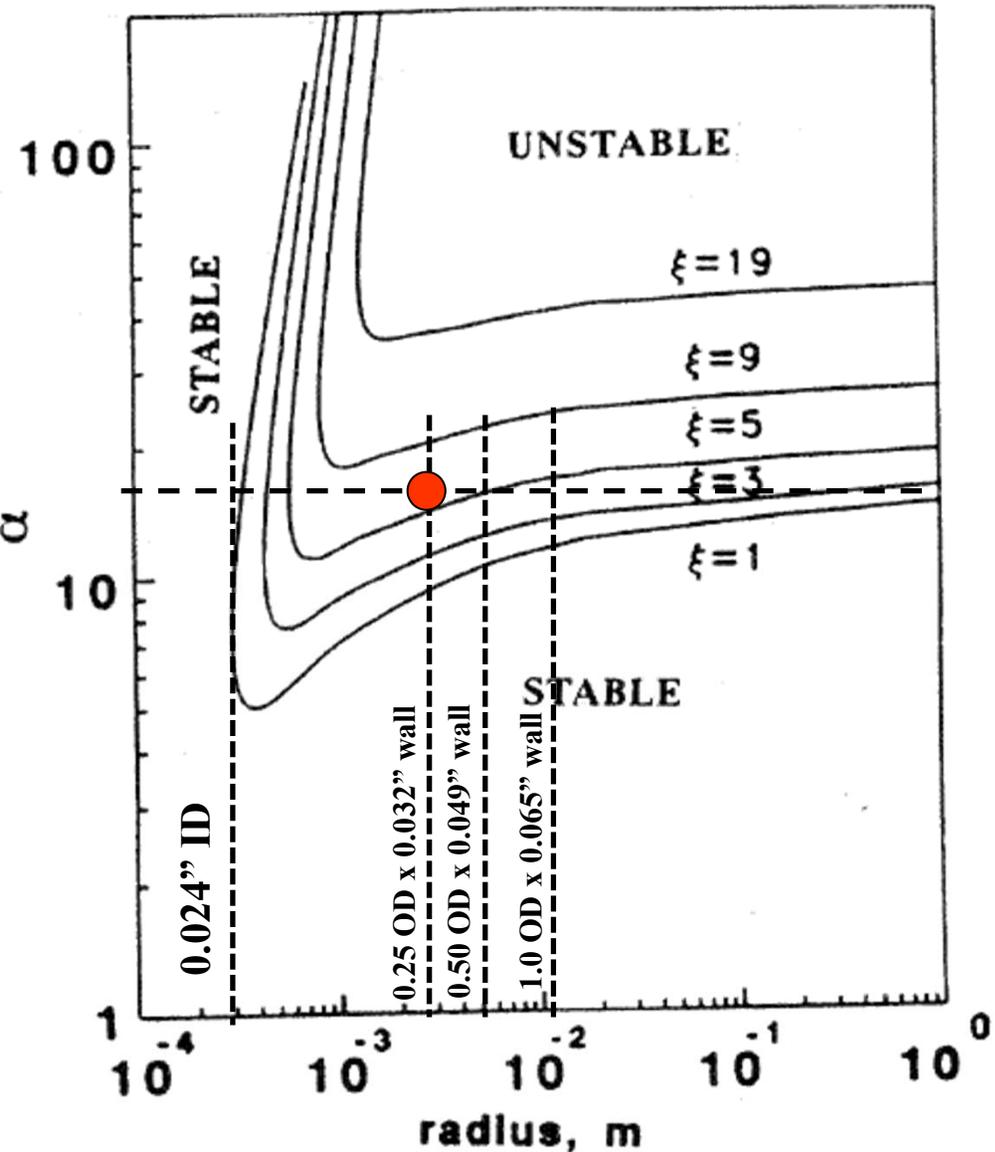


Effect of Changing Tube Size



- Example

- $L = 1\text{m}$
- Tube: 0.25 OD
 - 0.032" wall
- $\alpha = 15$
 - $300\text{K}/20\text{K}=15$
- $\xi = 5$
- Could make stable by:
 - Increasing tube size
(weak: requires big change)
 - Increasing ξ
 - Decreasing α

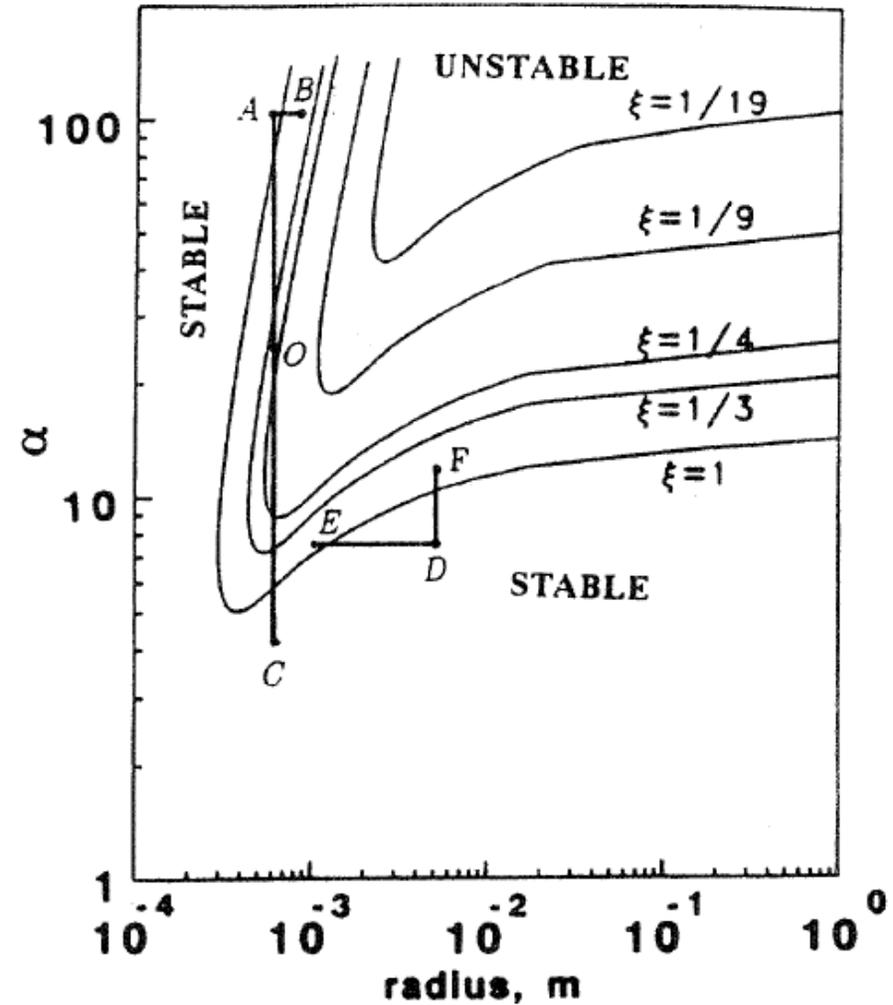
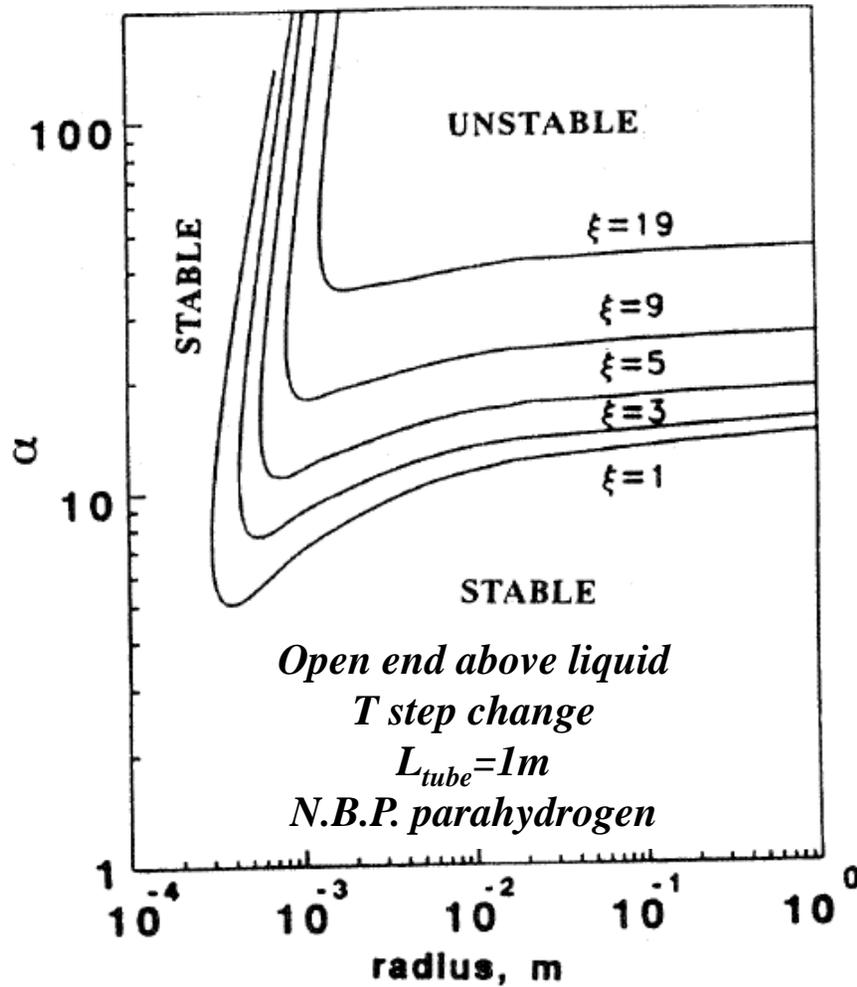




Effect of Length Ratio < 1



$\xi > 1$ **Open end in vapor** $\xi < 1$

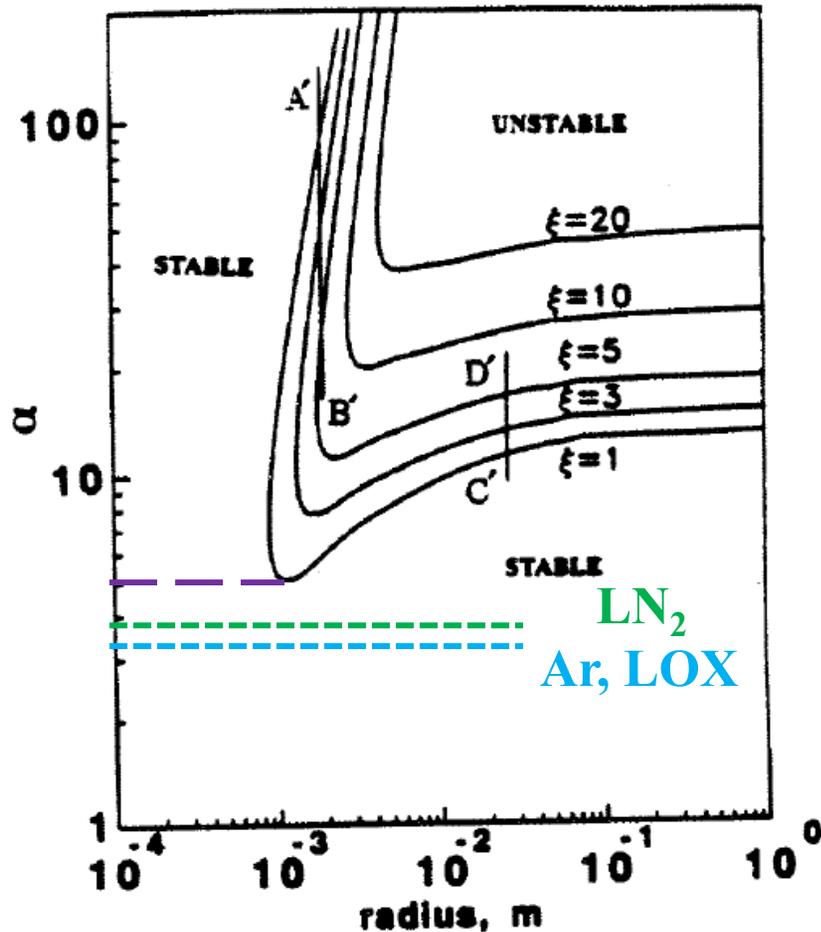




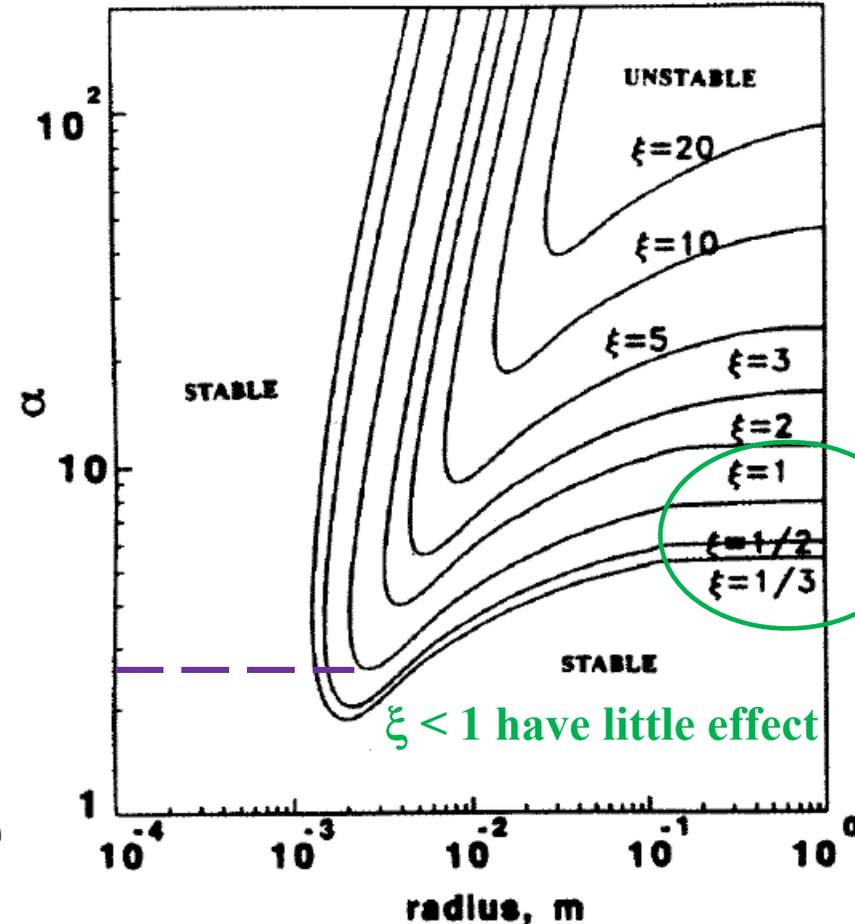
Dry vs Wet Open End



Open End in Vapor



Open End in Liquid

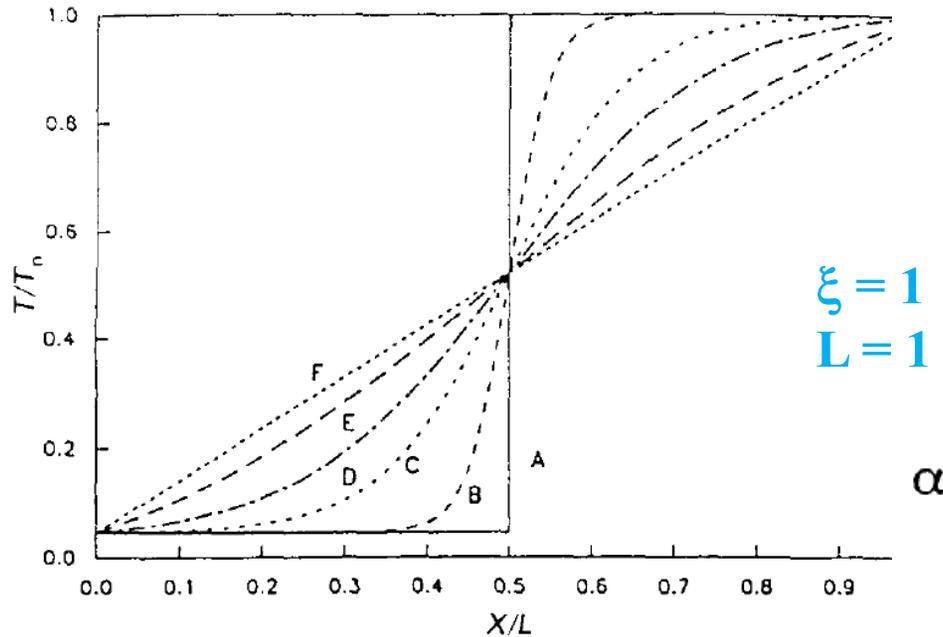


Open end 0.1m below liquid surface
Mass of liquid in tube will lower the
oscillation frequency

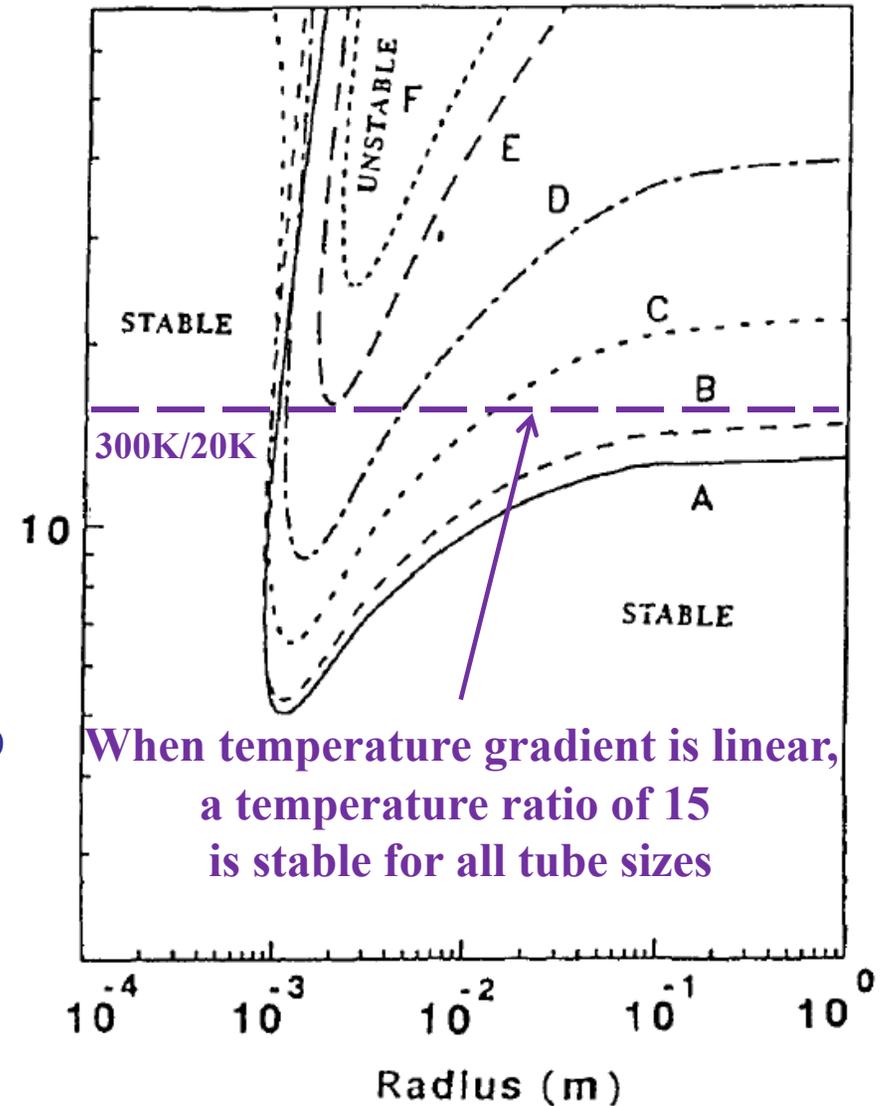
T.P. parahydrogen, $L_{\text{tube}}=1\text{m}$, Step change



Effect of Thermal Gradient

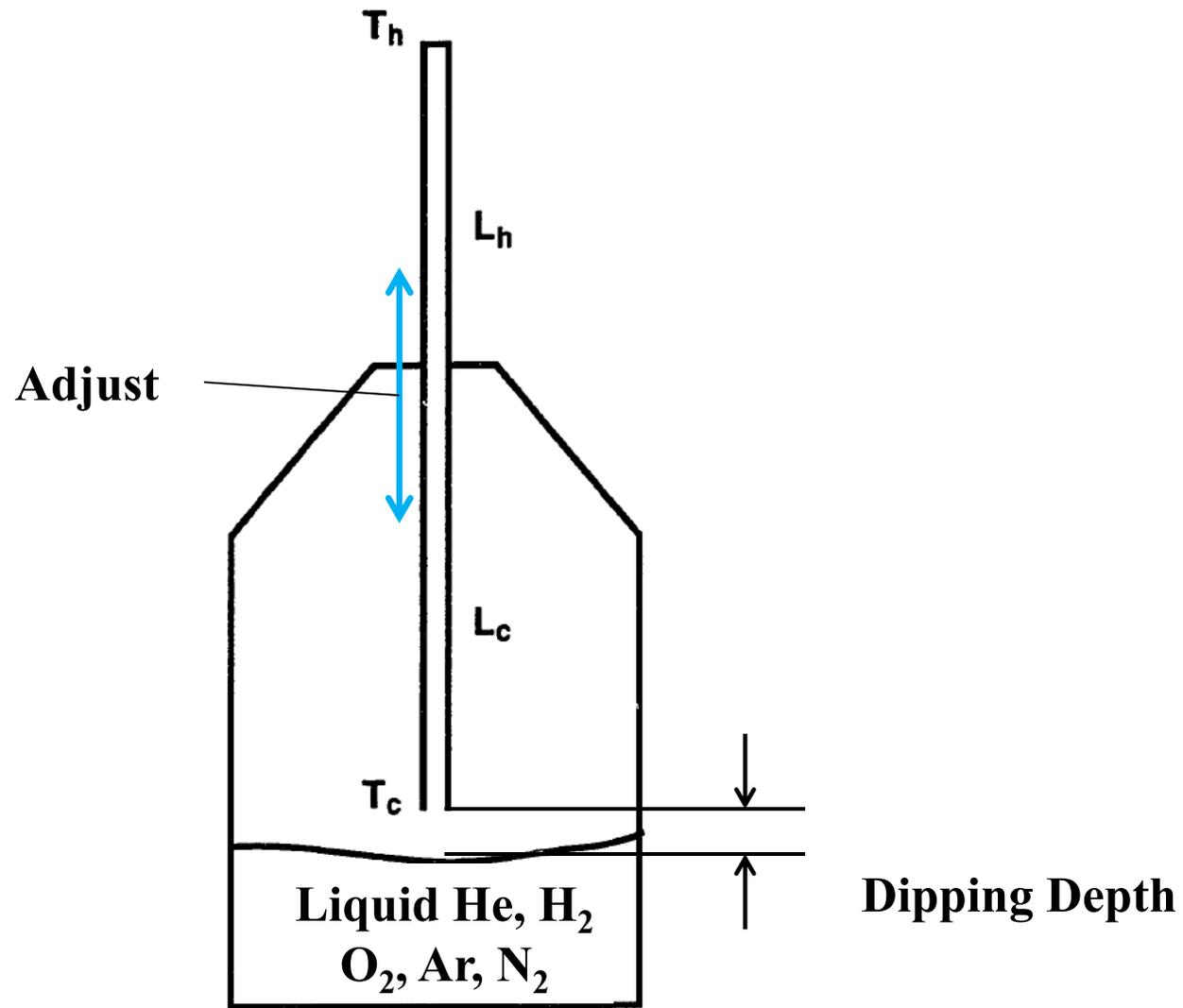


- Reducing temperature gradient raises temperature ratio needed to initiate TAO
- Step change is worst case
- Insulation is useful to linearize the temperature distribution





Dipping Effects

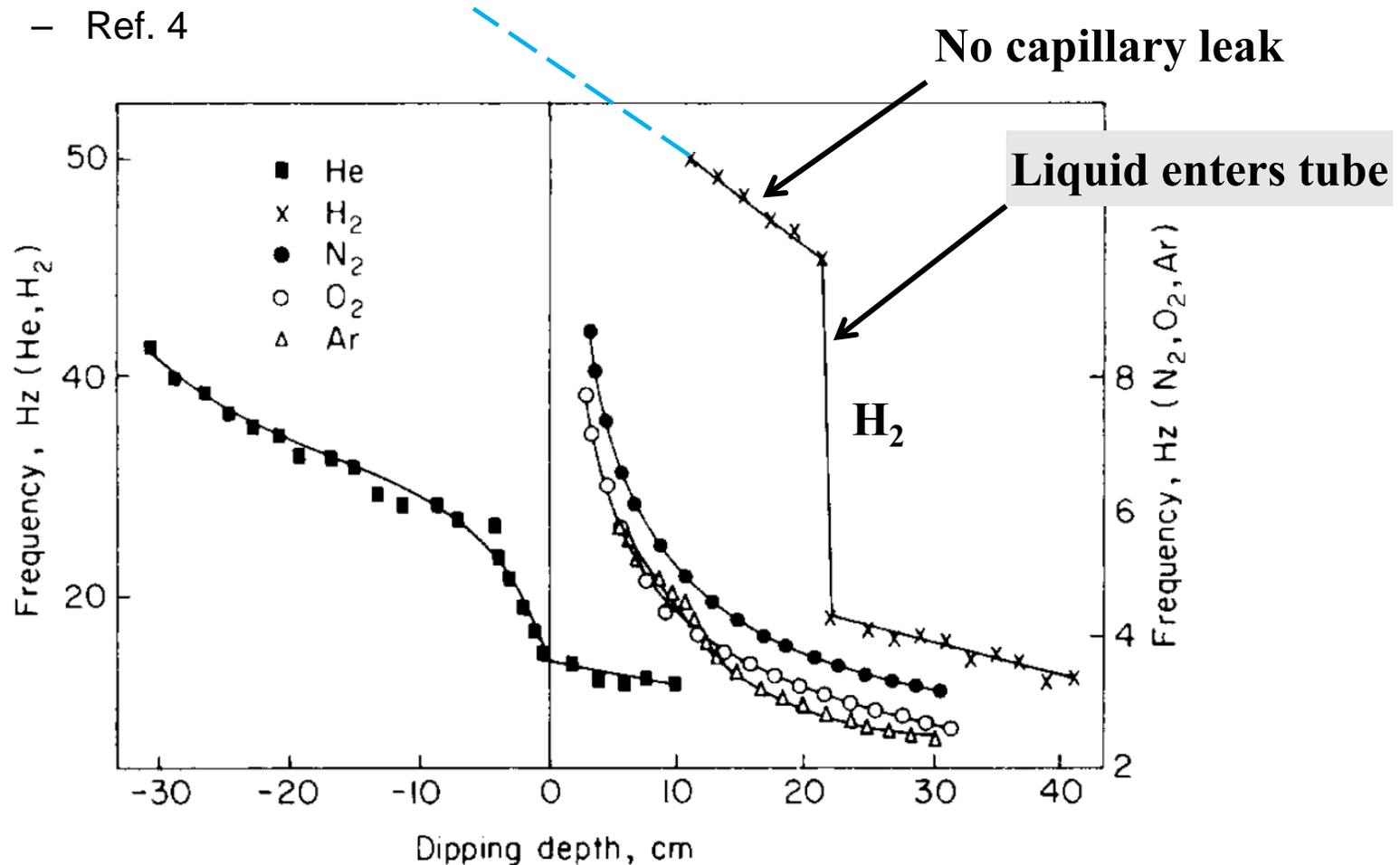




Dipping Effects



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



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



TAO Forces



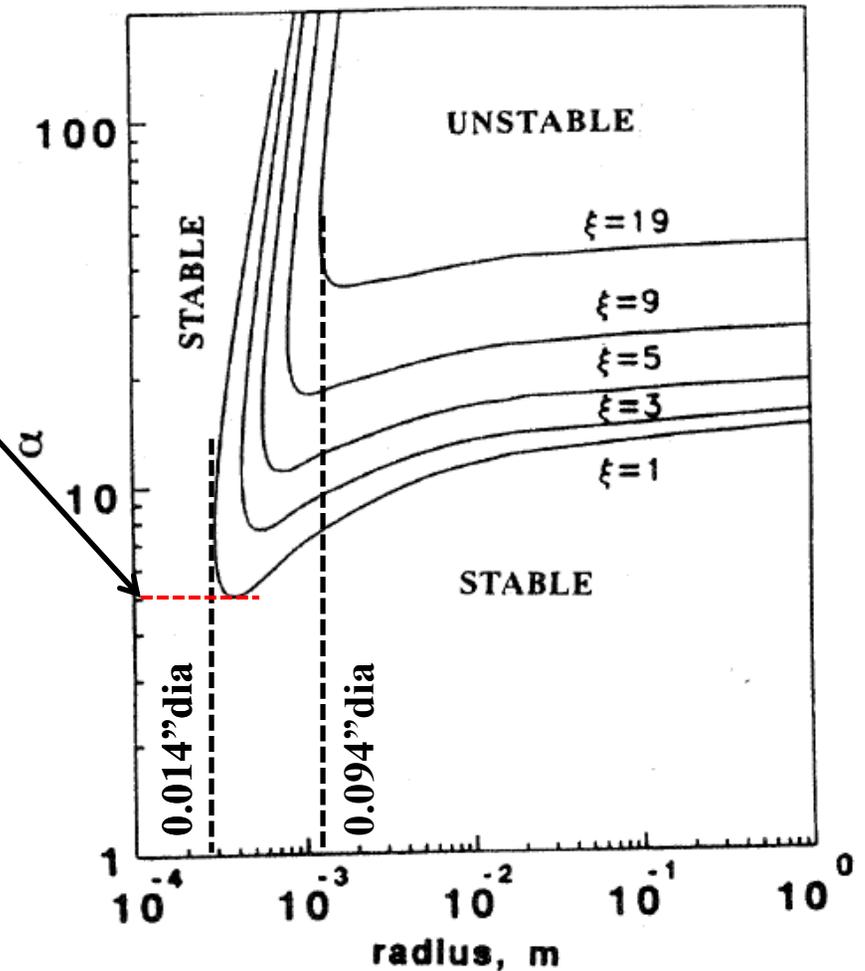
- Forces in TAO
 - Driving force
 - Temperature ratio and gradient
 - Heat transfer area
 - Length and radius of warm section
 - ‘Driving force is directly proportional to warm end tube length’
 - Viscous resistance
 - Viscosity in warm section predominates when $\xi > 1$
 - Length ratio critical
 - 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
 - $\alpha_{\min} = 5$ (end not in liquid)
 - $\alpha_{\min} = 2$ (end in liquid)
 - Increase length ratio
 - Applies to right hand region
 - Increase L_{hot}
 - Decrease L_{cold}



**N.B.P. parahydrogen $L=1\text{m}$
Open end not in liquid**



Changing Tube Size or Temperature Ratio



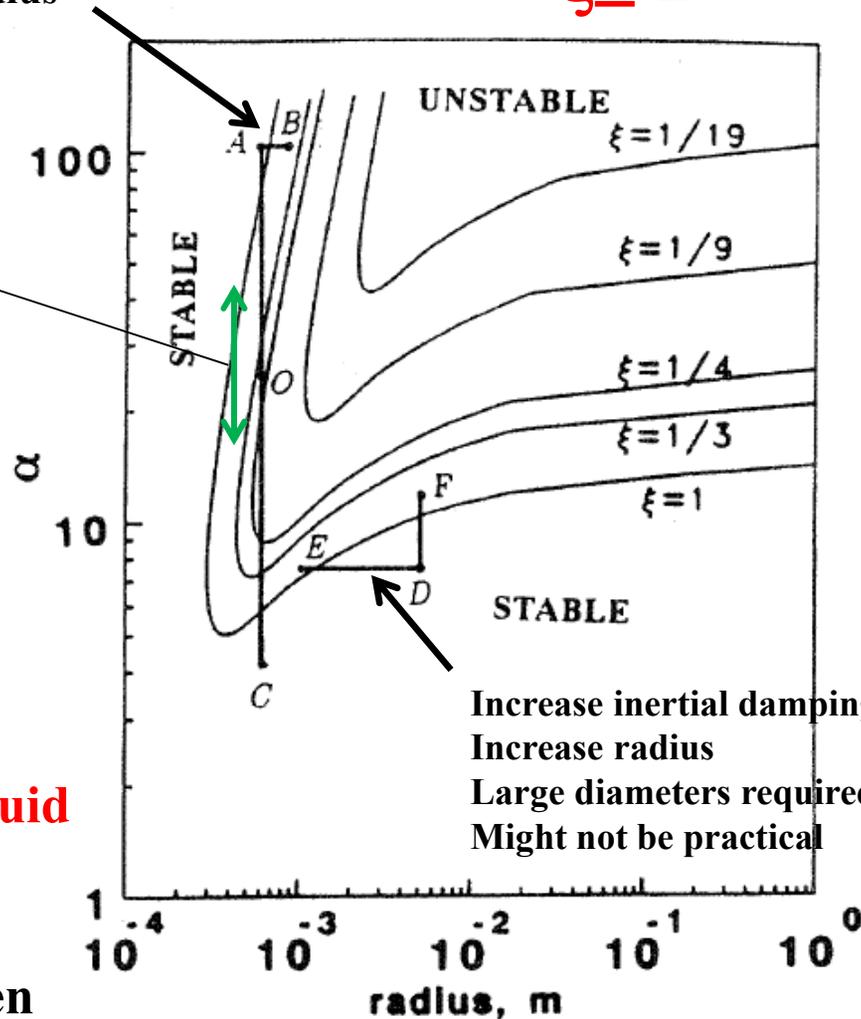
Increase viscous damping
Decrease radius

$$\xi \leq 1$$

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

Increase or decrease
temperature ratio

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



Examples:

- @ O $\xi=1$
- @ B $\xi=1$
- @ E $\xi=1$
- @ F $\xi=1$

Open end above liquid

T step change

$L_{\text{tube}}=1\text{m}$

N.B.P. parahydrogen

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



Mitigation Methods



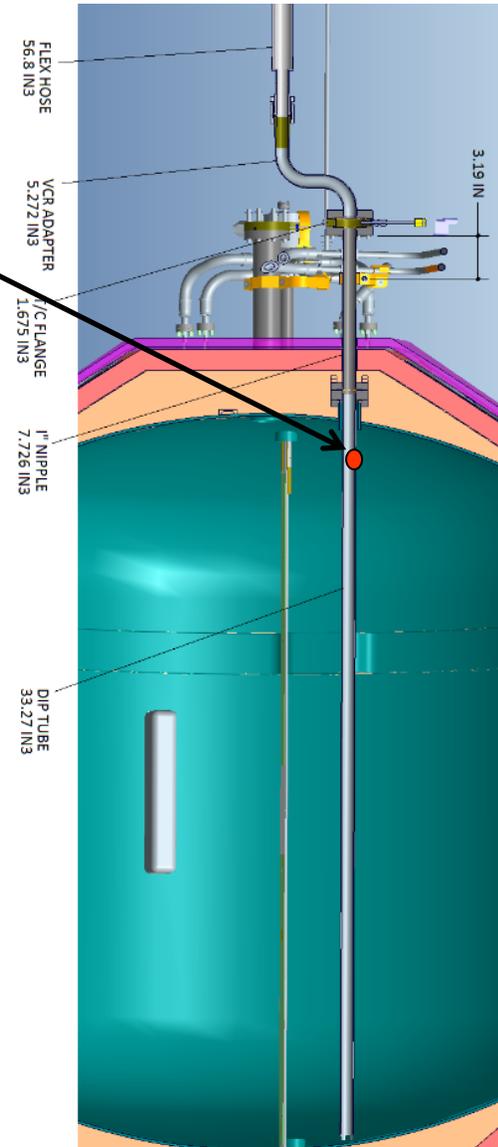
- Reduce driving force
 - Change temperature ratio α
 - Reduce temperature gradient
 - Make warm end colder
 - Insulation
 - Change length ratio ξ
 - Make warm end shorter
 - Reduces driving force
- Increase viscous damping
 - Reducing tube radius
 - e.g. add restrictor to cold end
- Increase inertial 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 $\frac{3}{4}$ wavelength tube
- Other
 - Get away from $\xi = 1$
 - 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

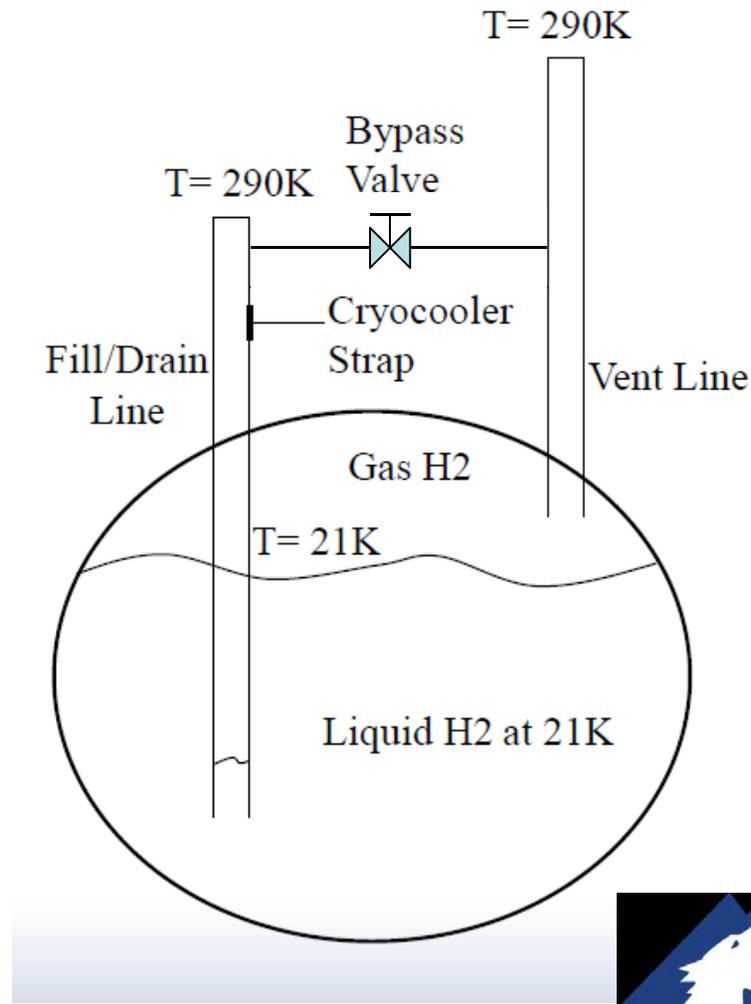


- Change effective length of dip tube by allowing liquid to fill it
 - Drill hole in warm end
 - Effective when tank is relatively full in 1g
 - When fluid level is low, vapor length will increase and TAO may return





Actual Fix: Cross Over Valve



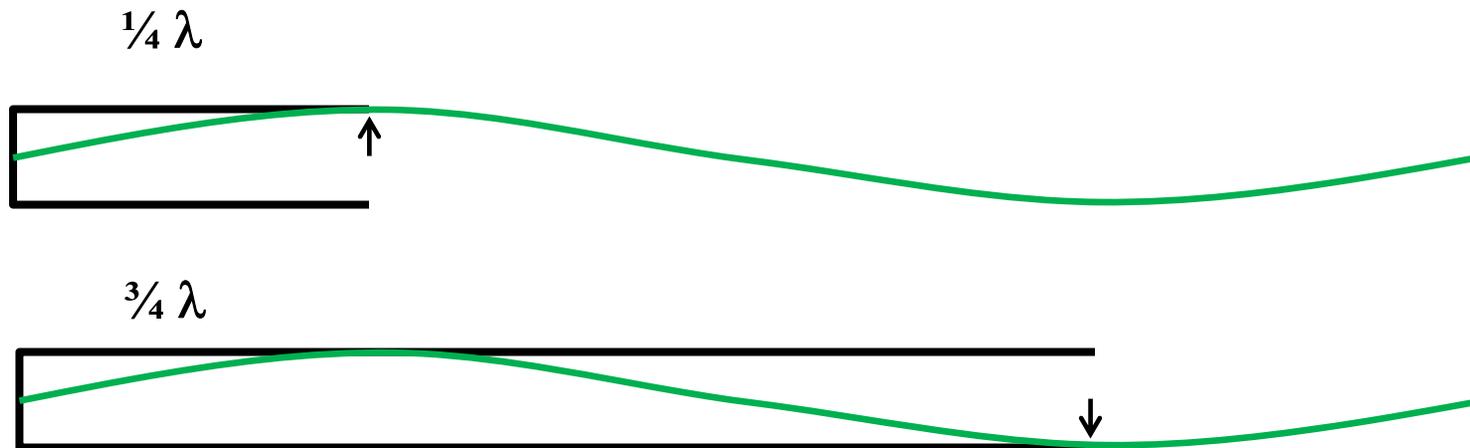
Ref. 7



Out-of-Phase Parallel Tubes

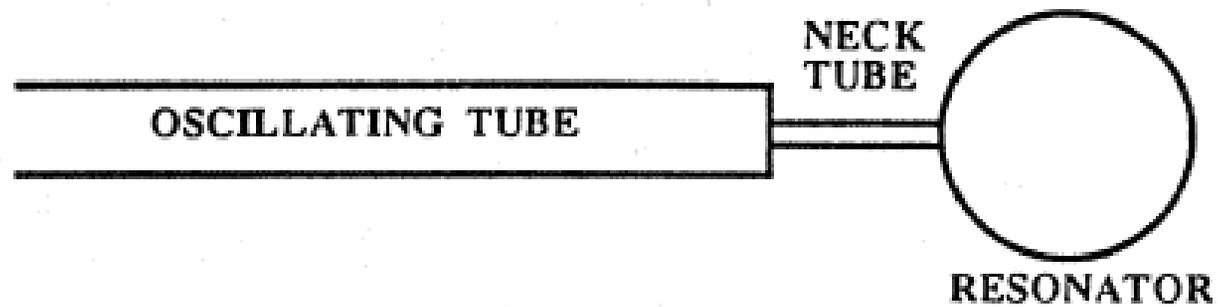


If a $\frac{1}{4}$ wave-length tube and a $\frac{3}{4}$ wave-length tube are in parallel, their out of phase oscillations will cancel each other





Warm End Resonator

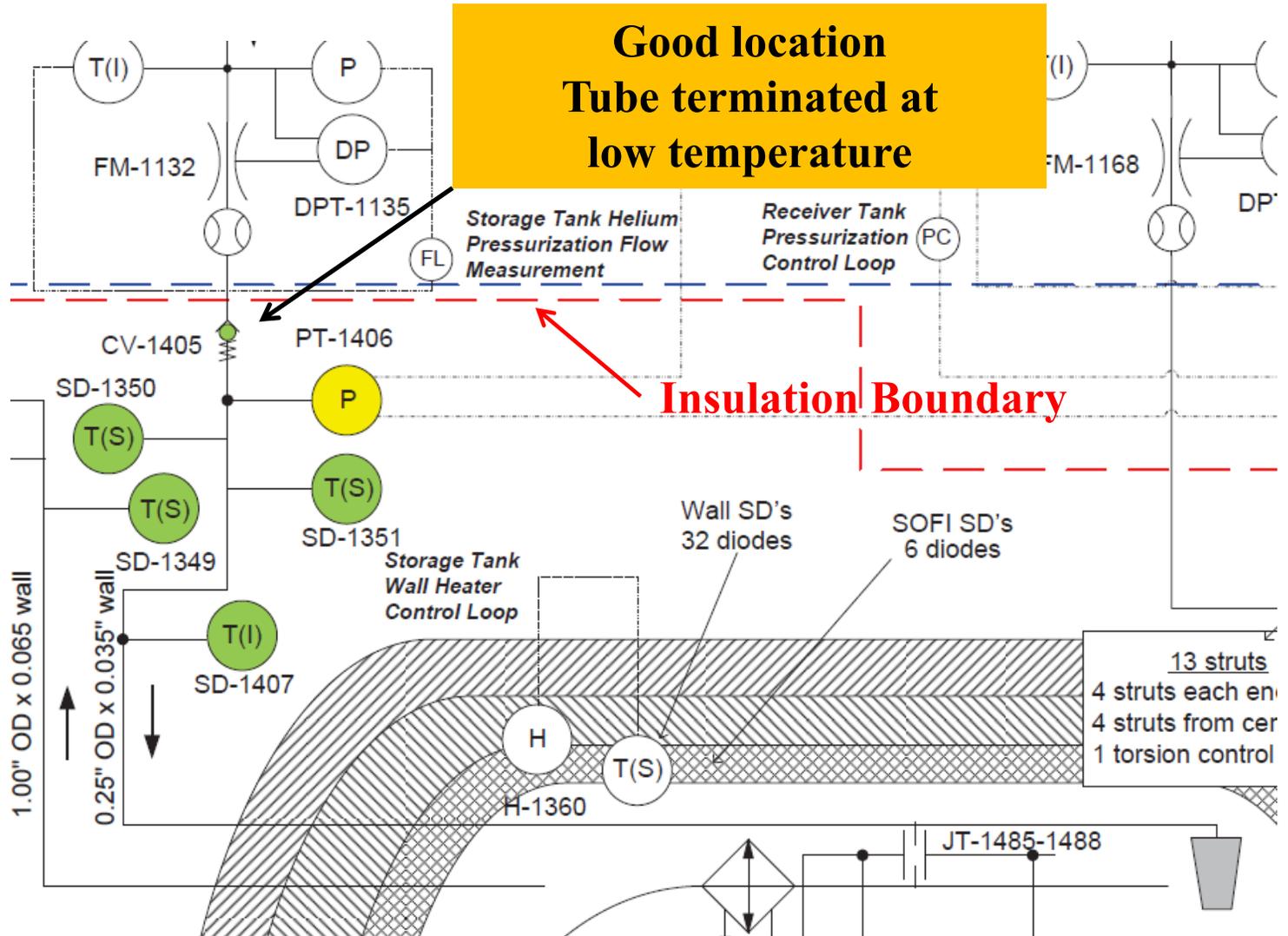


Shown to work theoretically

Ref. 1



Check Valve





References



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