Large 'pulse-tube' ~60 gallon/day oxygen liquefier for U. S. Navy carriers

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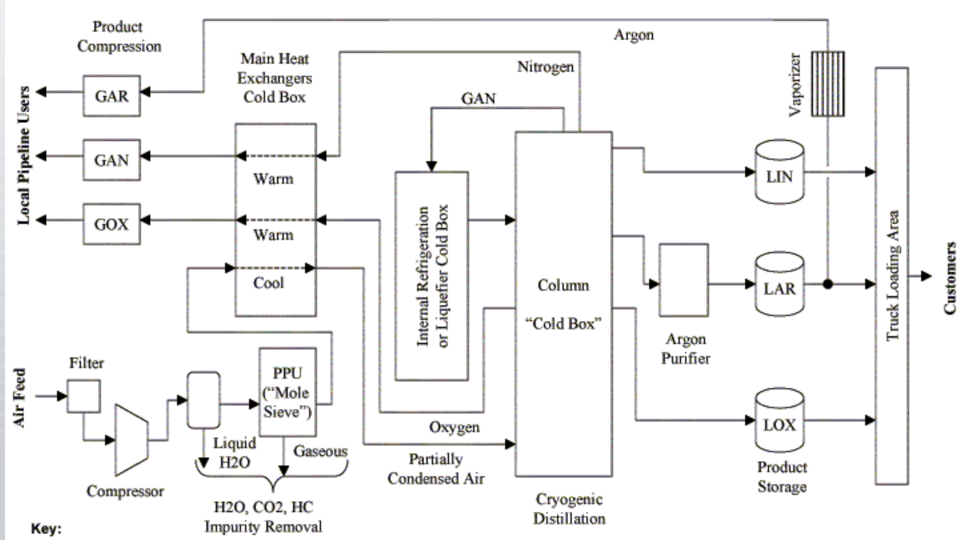
Shipboard LOX is a challenge for conventional technology

- LOX on warships has typically been provided by miniature air-separation plants
- Excellent technology for large-scale, permanent facilities, but
- Inconvenient for more compact, mobile enviroments

Most mini-airsep plants don’t produce LOX “on demand”…



Key:

Gaseous	Product	Liquid
GAN	Nitrogen	LIN
GAR	Argon	LAR
GOX	Oxygen	LOX
CO2	Carbon Dioxide	-
H2O	Water	H2O
HC	Hydrocarbons	-

Generic Air Separation Unit (ASU)

- Shows inter-relationship of major components
- Specific plants will vary

- Typical warmup time to produce LOX: **8 hours**

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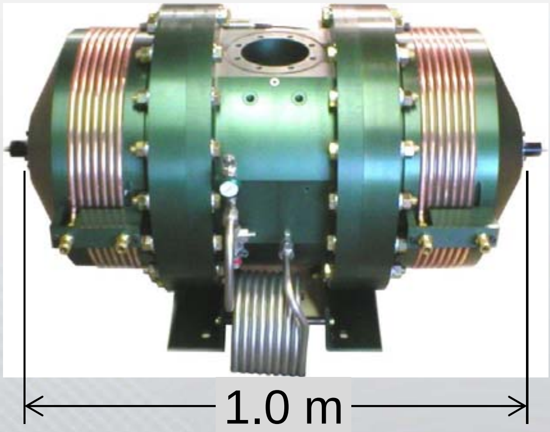
An oxygen plant built around an acoustic or Stirling cryocooler can start making LOX in < 30 min.

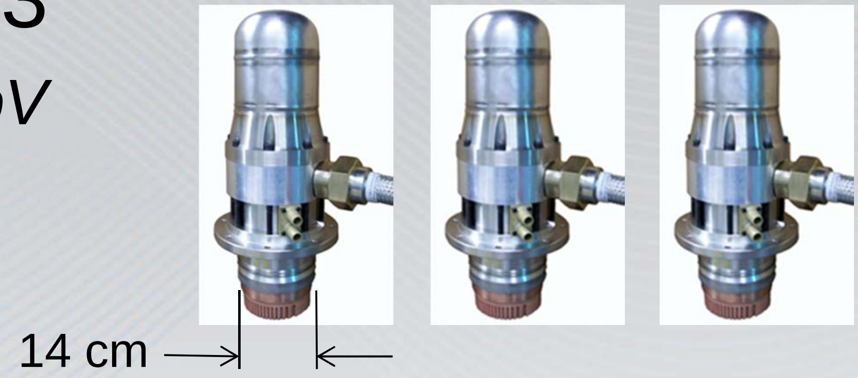
- Relatively simple to operate (compared to old Linde-style or turboexpander plants)
- Long life, relatively maintenance free, but-
- Unfamiliar to most of the customer base!
- Navy provided narrow window of opportunity to provide alternative technology—we responded with novel combination of existing parts.

Our liquefier is based on our "2S362K" product

- 2S362W pressure-wave generator
  - 20kWe in, ~15kW *pV* out



- 2S241K coldhead, X3
  - 200 W at 80K for 3 kW *pV* input, per coldhead



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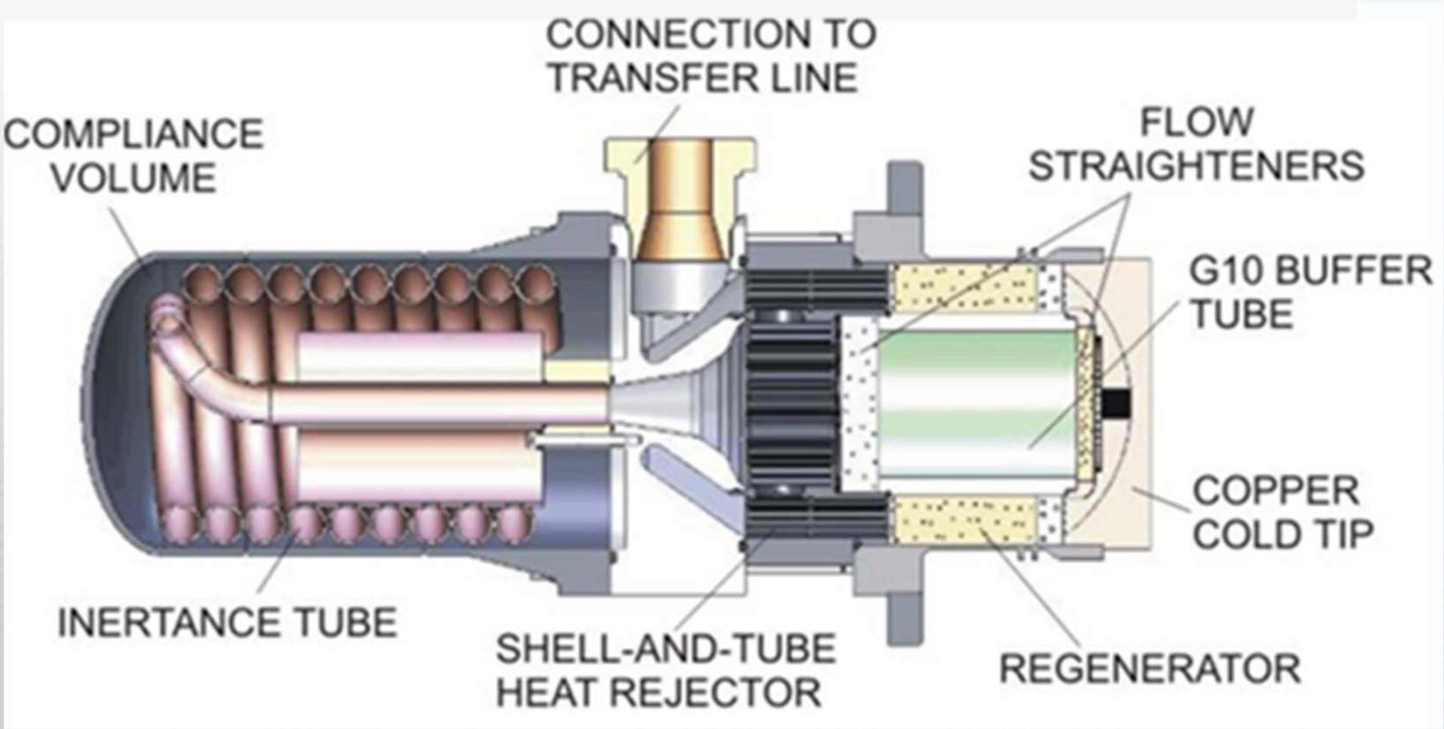
Simple, modular design

- Using existing parts shortens design cycle
- Simulation suggested ideal capacity of system would be 2X target
- Performance headroom allowed simplifications, compromises in order to get hardware into commission
- Performance targets met—but significant improvements are possible.

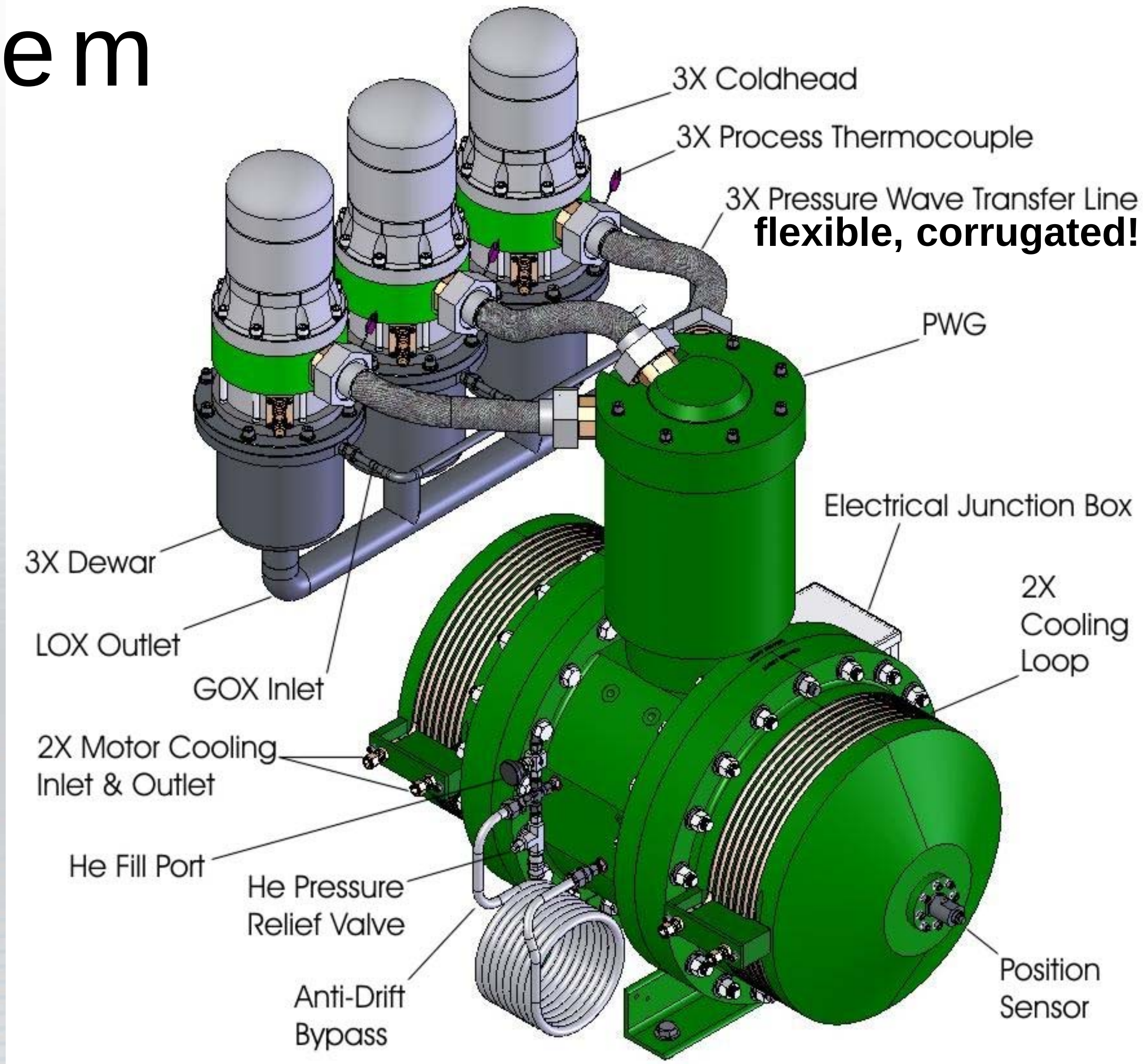
Coldheads are large, coaxial coldfingers:



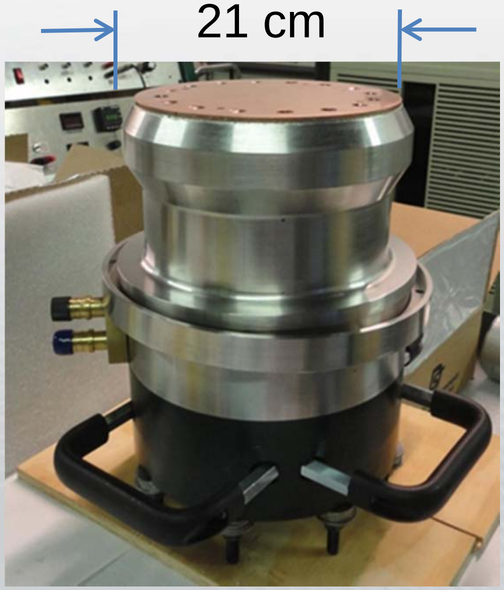
- Flow management can be a challenge in these (more about this later).

Core cryocooler system

Solid model shown; our customer prefers we not show the integrated system…



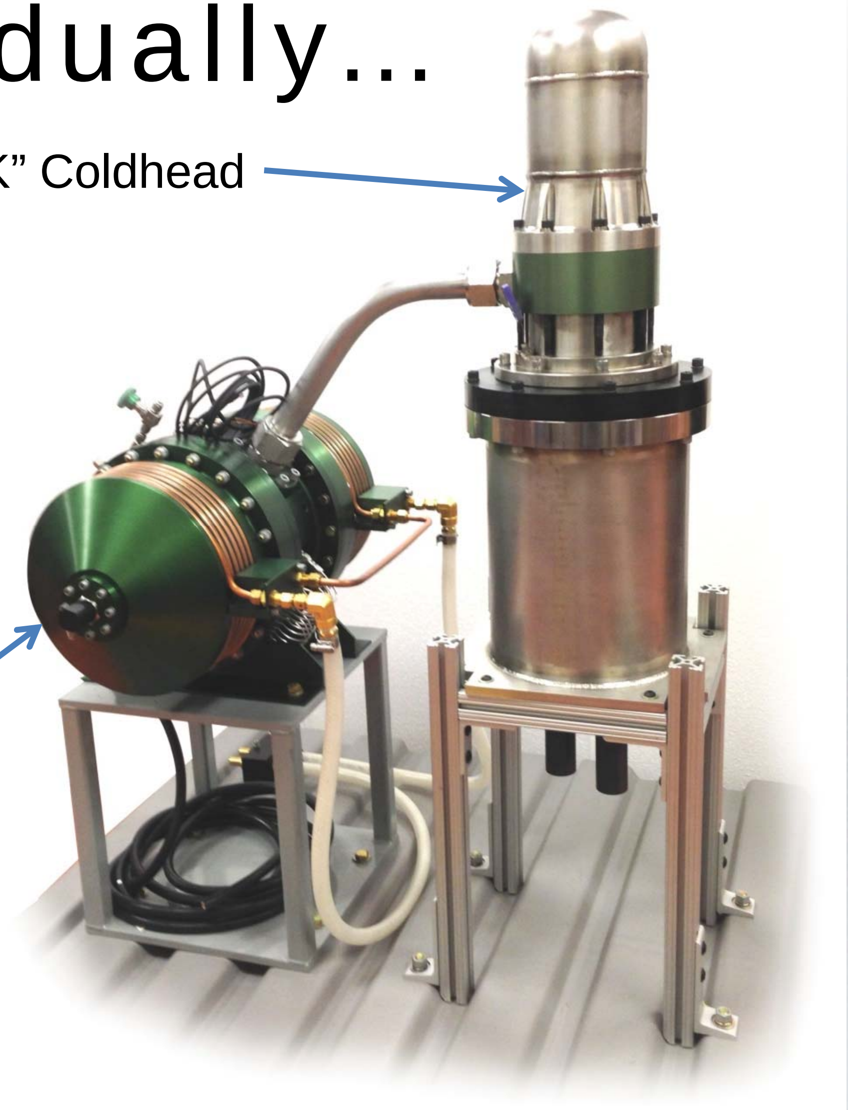
One coldfinger might be better…not quite there yet.



- "2S362K" coldfinger built for DOE project…Internal flow management issues with large "pulse tube".
- We might have it figured out—but no time, $ to check!

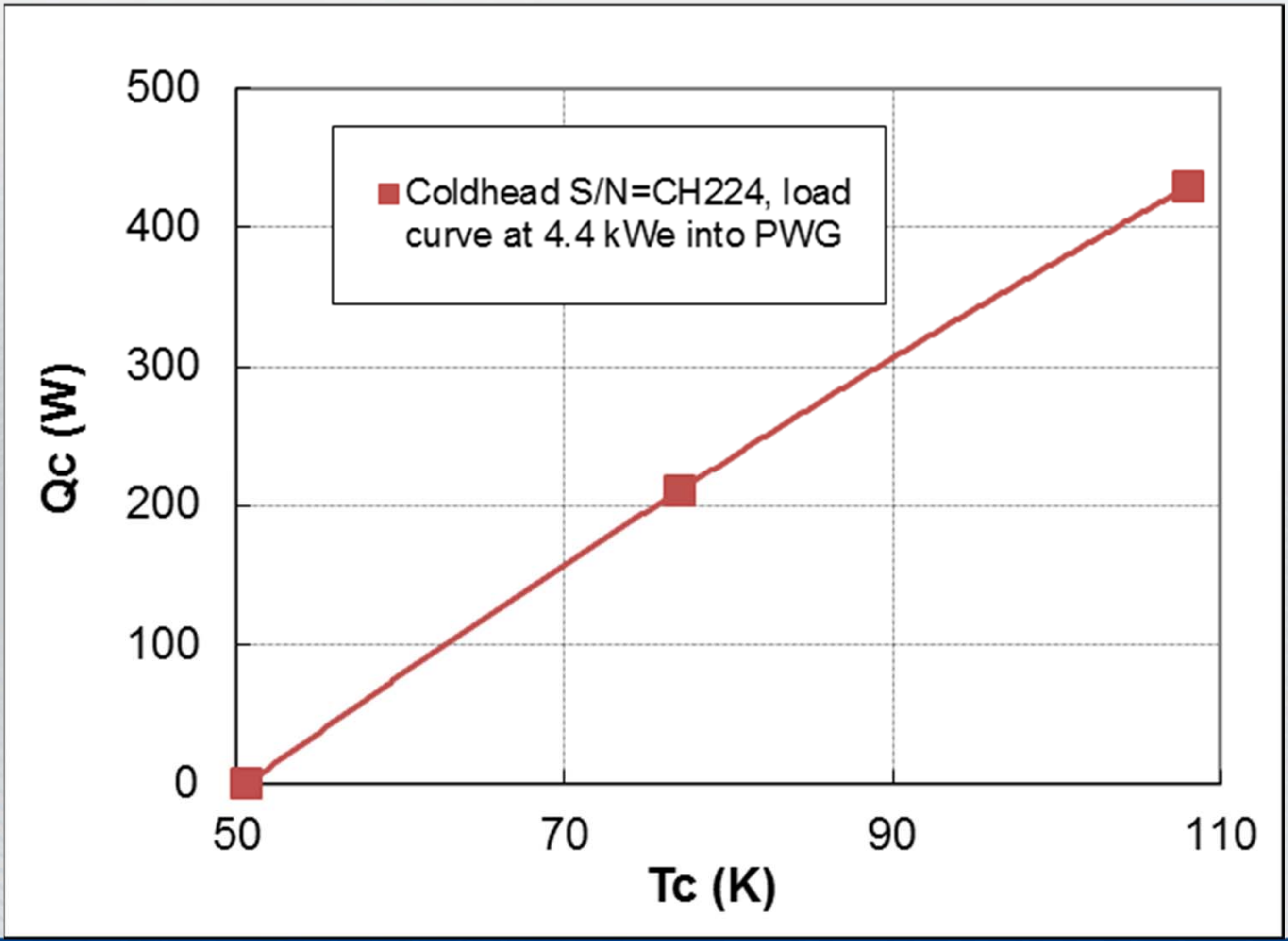
Coldheads qualified individually…

- Driven with matching PWG to get load curves.



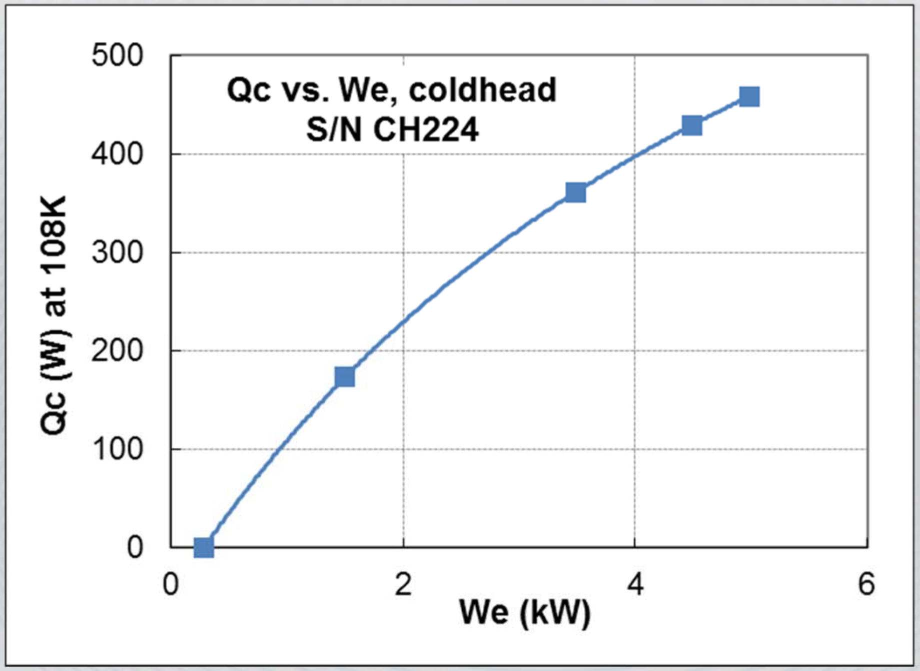
Performance measured up to 108K

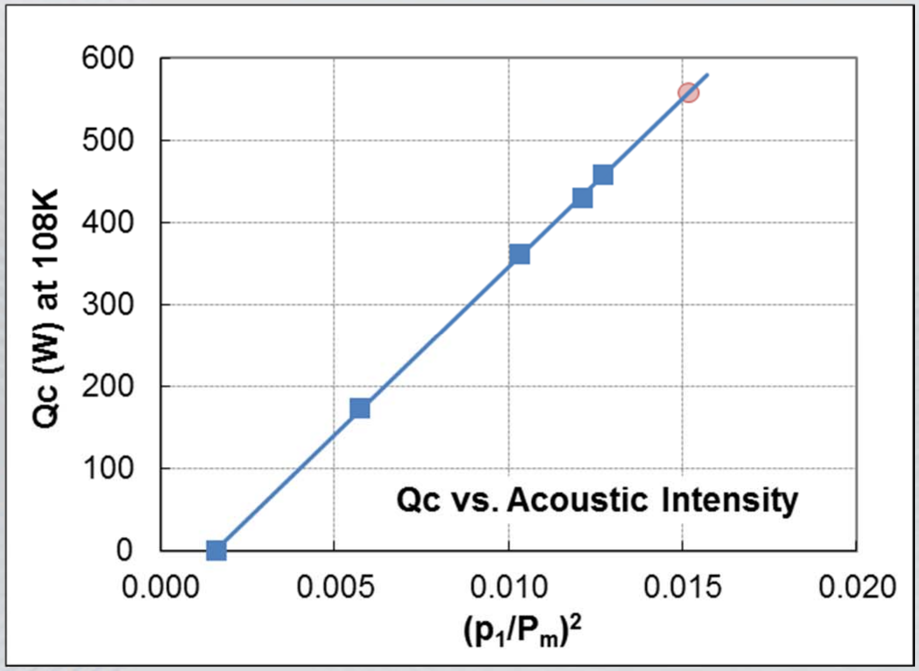
- Typical LOX storage dewar relief valve pressure = 50psig; so liquefaction takes place just below relief pressure



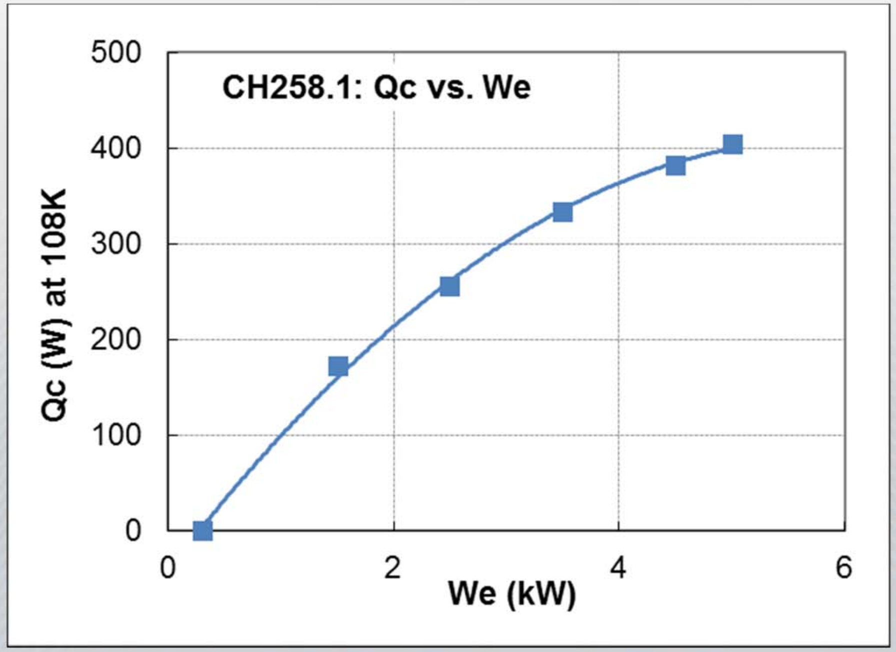
At 108K, find Qc vs. kWe input

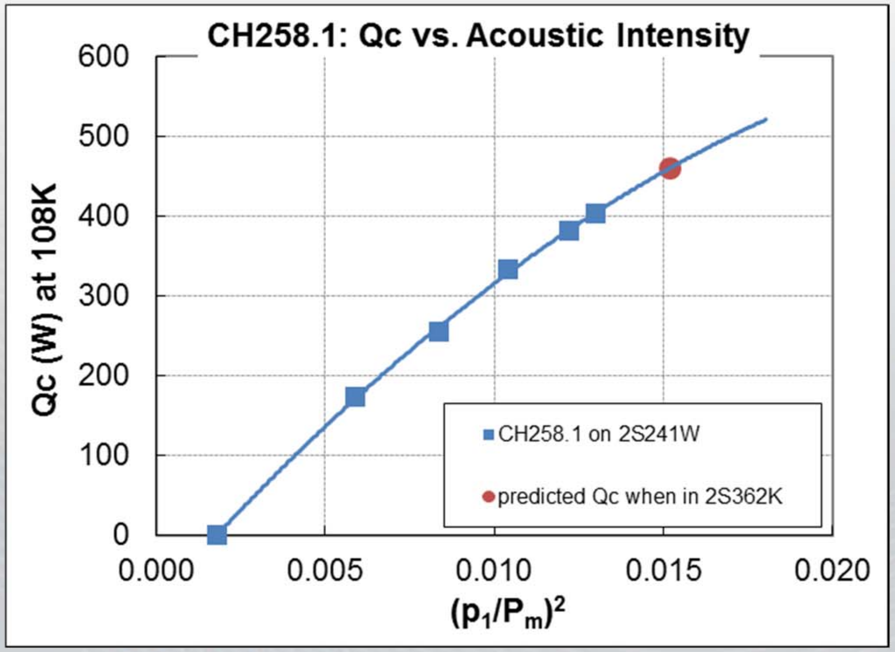
- 5 kWe PWG can't drive single coldhead as hard as 20 kWe can drive three; must extrapolate





Some coldheads more linear in $(p_1/P_m)^2$ than others:





- Small disturbances in buffer tube may be worse at higher amplitudes… (other causes?)

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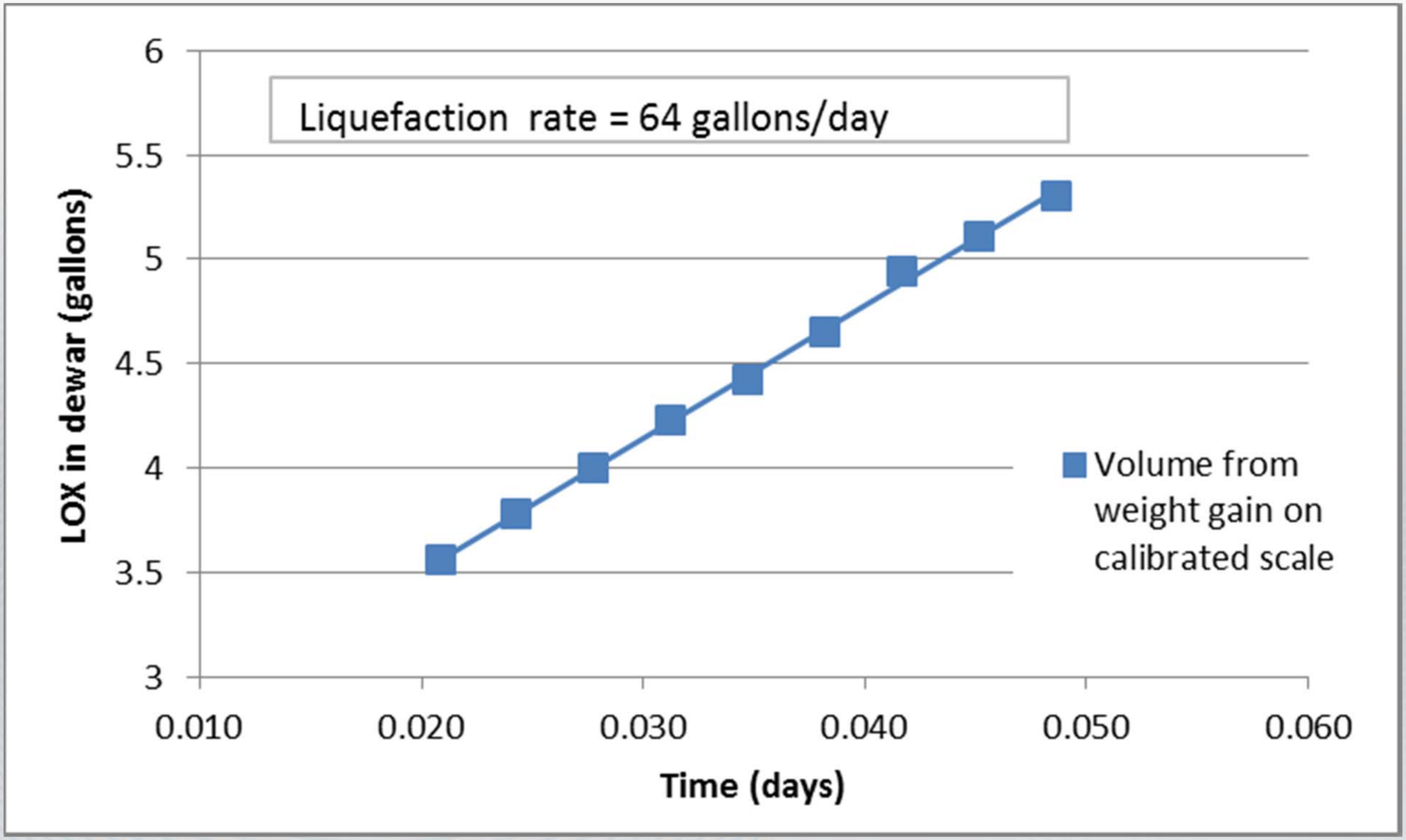
Cooling power of 3 heads at $(p_1/P_M)^2 = 0.015$ predicts cooling power of liquefier

- Cooling oxygen from ambient to 108K and liquefying requires 15 W per gal per day
- Example: for most recently built system, three heads together = **1360** W at 108K when driven by 2S362W;

implies **89.6** gal/day

(not counting boiloff, etc.)

In tests, got 64 gal/day



A few small losses:

- Dewar NER (only worth ~1 gallon/day)
- Heat leaks in transfer piping (also worth only ~1 gallon/day, we think)
- Actual coldtip runs colder than condensing gas, by 3K (worth < 1 gal/day)

Major losses:

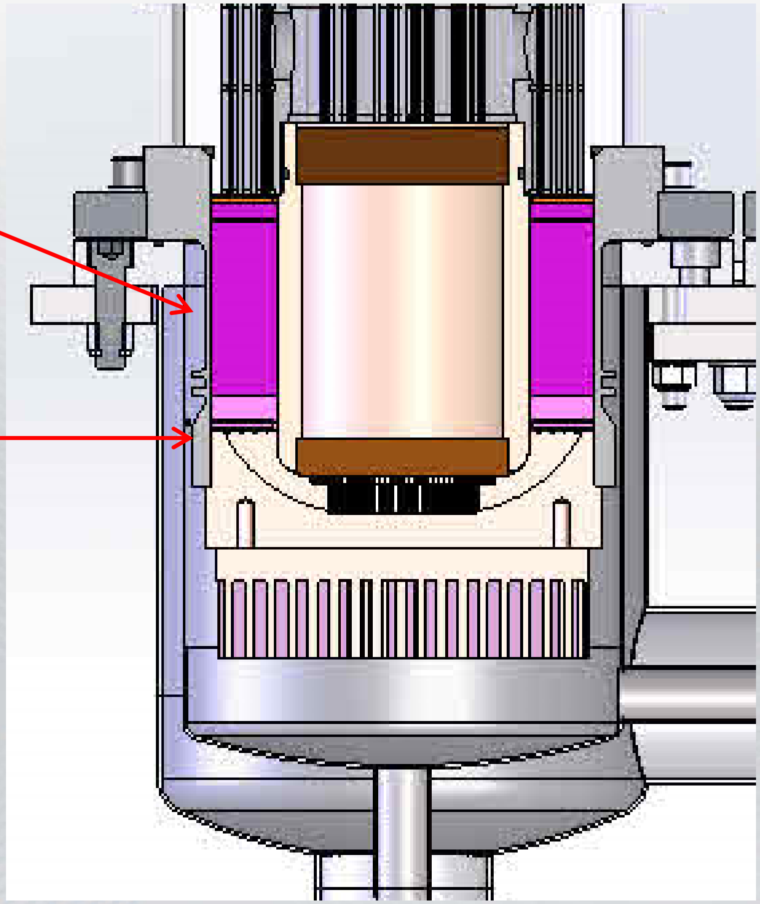
- **Pressure wave transfer lines** (see slide #7): These corrugated lines are flexible and take up any stacked-up tolerance error in the assembly; but such lines are known to induce high acoustic loss.
- **Process gas entry to liquefier**: The GOX enters via the annular space around the regenerator shell; since this space is full of warm process gas, not a vacuum and MLI, the coldhead performance is compromised. If the gas in this space does not stay stratified, then there are even bigger losses.

Detail of coldfinger in collection dewar

GOX enters at top; convection possible in this annular space

Regenerator shell has some wider O.D. features; possible cold-metal contact with dewar inner wall?

Vacuum system designed for simplicity rather than efficiency, in order to meet tight deadline in original schedule.



Short-term improvements

- Add instrumentation feedthrough to collection dewar (allow in-situ coldhead testing with calibrated heat loads)
- Measure acoustic loss in the short pressure-wave transfer lines; consider either solid pipes or incorporating a smooth liner
- Reconfigure annular space around regenerator to encourage spiral flow, eliminate turbulence

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Long-Term Improvements

- Move to single, integrated coldhead
  - Single coaxial coldhead would reduce parts count, cost, complexity of collection dewar.
  - Single inline coldhead would reduce parts count, but increase the complexity of vacuum vessel around head.
  - More complex vacuum vessel of inline coldhead would allow insulated lines directly to cold heat exchanger, while maintaining vacuum around the cold zones, increasing efficiency.

Thank you for your attention!

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