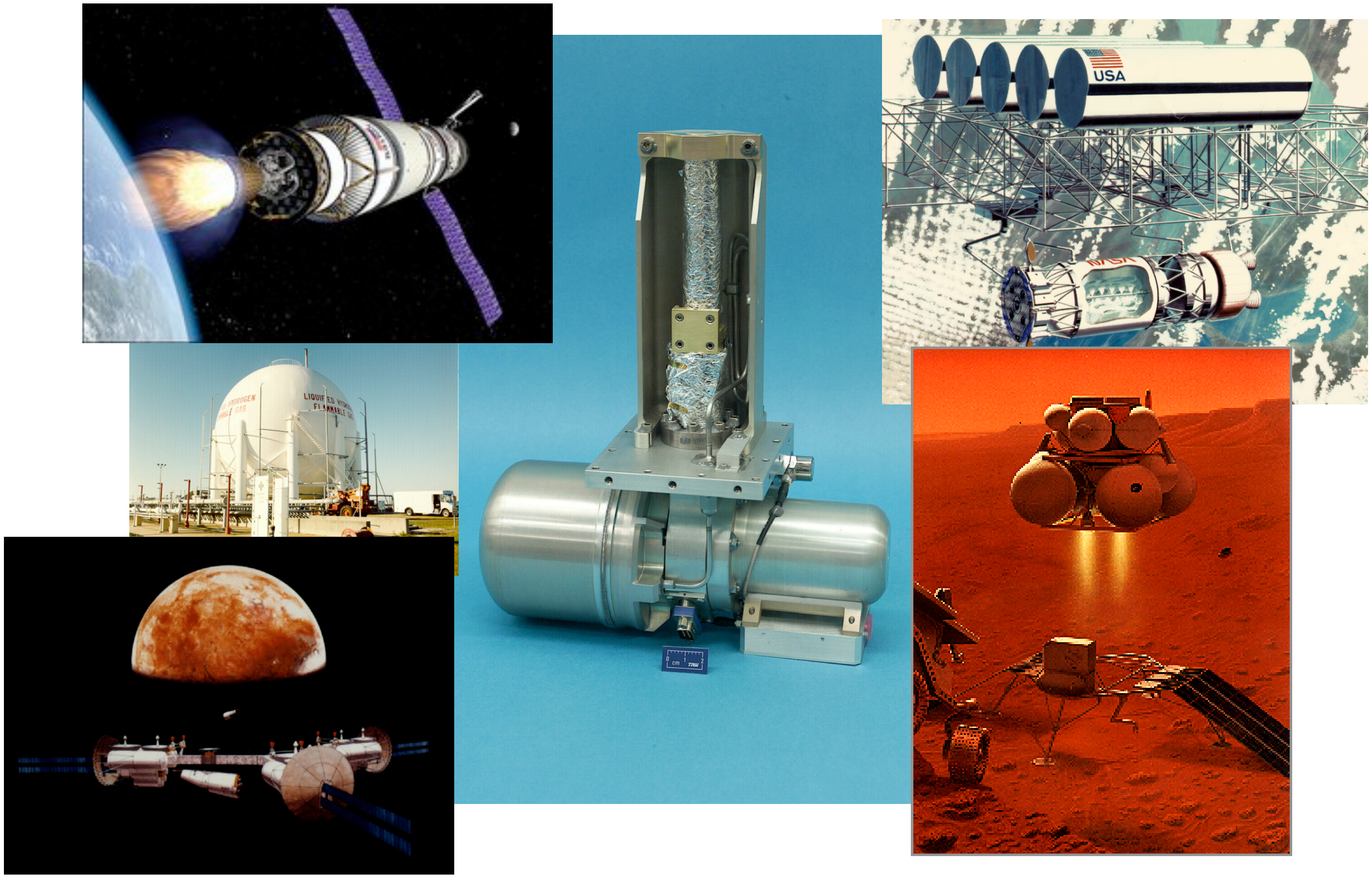
Cryogenics for Space Exploration

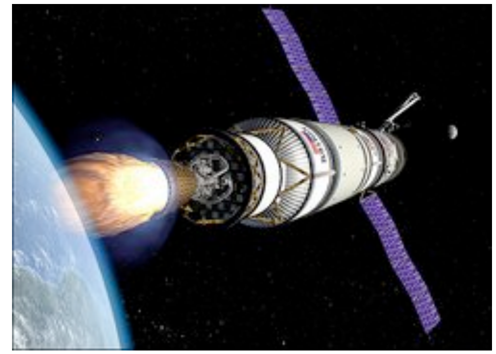


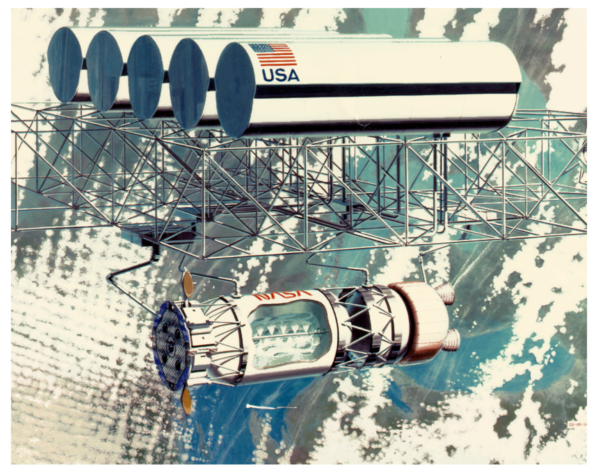
Louis J. Salerno
NASA Ames Research Center
CEA Saclay 20 October 2006

Need

Cryogenic Fluid Management (CFM) is critical to NASA's Advanced Space Transportation programs:

- Crew Exploration Vehicle (CEV)
- Orbital Transfer Vehicles (OTV)
- In Space Cryogenic Propellant Depots
- Planetary Exploration





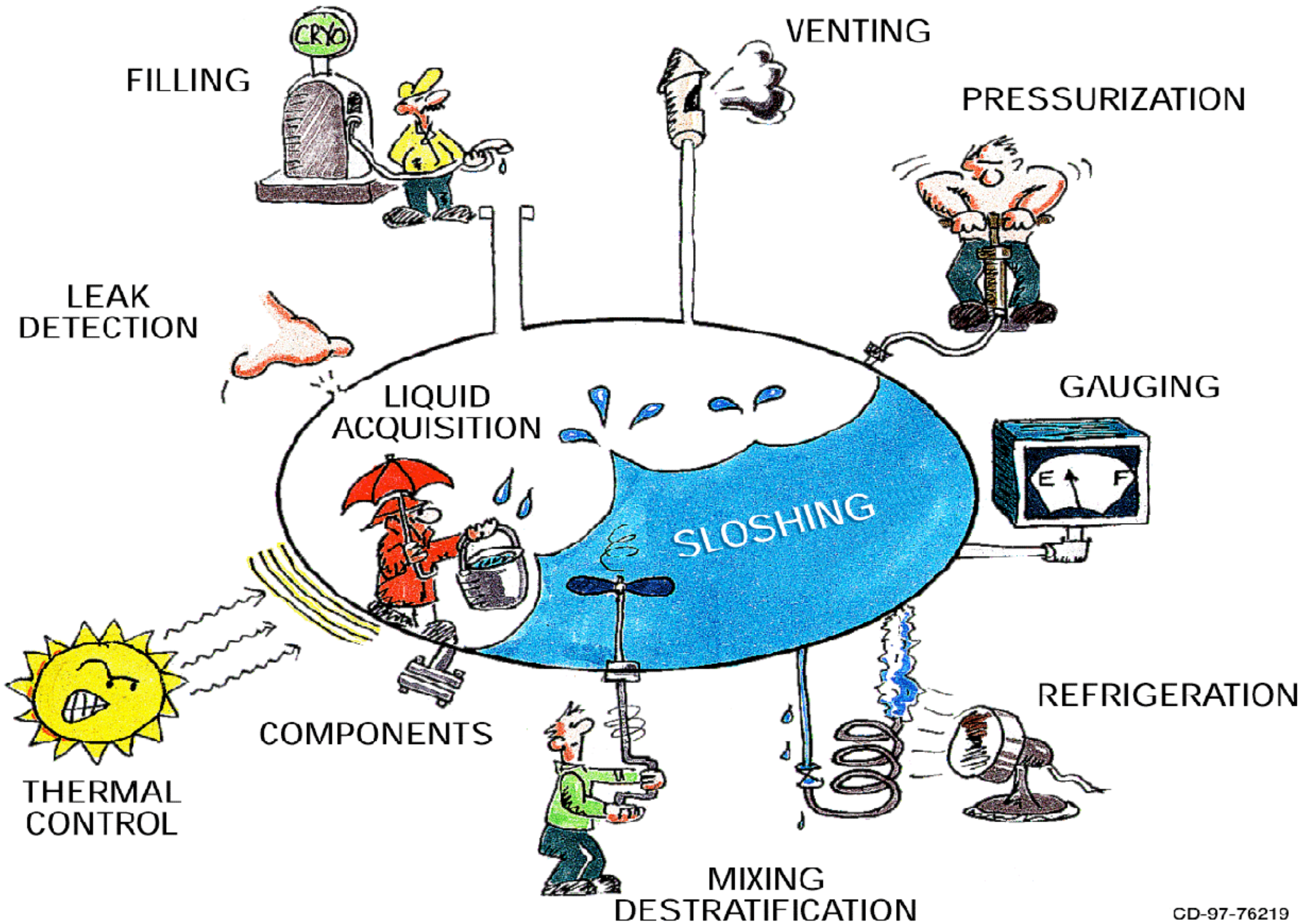
Ames Research Center

Technology Applicability

	CEV	OTV	Propellant Depots	Planetary Exploration
Lightweight, High Efficiency Coolers	⊕	⊕	⊕	⊕
Zero Boil Off Cryogen Storage	○	⊕	⊕	⊕
Liquefier Technology			⊕	⊕

Enabling ⊕ Enhancing ○

Cryo Fluid Management Simplified



CFM Technological Challenges

- NASA's planned Exploration Missions require sophisticated cryogenic propellant storage systems
  - Optimizing tankage and developing hybrid systems (passive and active cooling) reduces the initial mass to Low Earth Orbit (IMLEO)
  - Minimizing cryogenic propellant losses through zero boil-off (ZBO) is crucial to NASA's long duration exploration missions and on-orbit propellant storage in depots
- Long-term human presence in space requires *In-Situ Resource Utilization (ISRU)*
  - Propellant production, liquefaction, and storage on planetary surfaces is critical for making NASA's planned exploration missions economically feasible

Presentation Topics

- Zero Boil-Off (ZBO) Cryogen Storage
  - Long-term space missions
  - In-Space Cryogenic Propellant Depots
  - Lunar Surface
  - Commercial (Terrestrial) ZBO Applications
- Lightweight High Efficiency Cryocooler Development
  - 10 W, 95 K protoflight cryocooler
- Distributed Cooling Systems
  - Interface between cryocooler and propellant tanks
- Liquefier Technology
  - Laboratory demonstration showed that O_2 liquefaction requirements for 2003 Mars mission can be met with off-the-shelf hardware.

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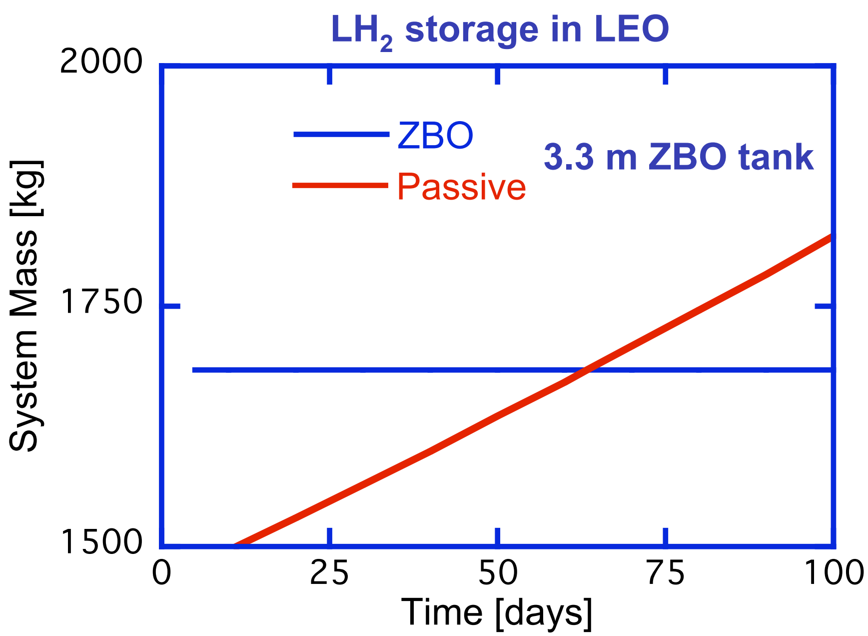
Zero Boil Off (ZBO)

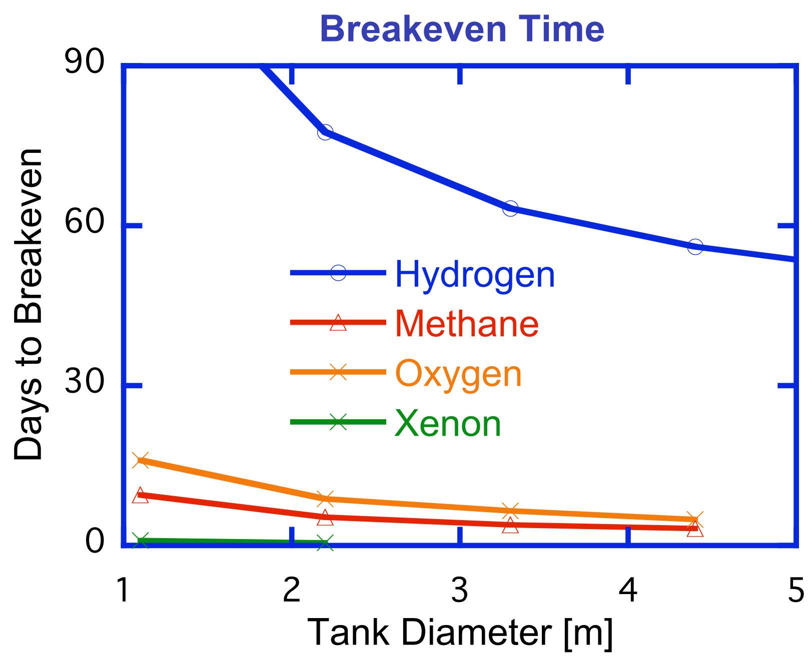
- ZBO = Zero Boil Off propellant (cryogen) storage
- Goal: Long term propellant storage in space (Exploration Missions, Propellant Depots, Lunar Surface)
- Traditional approach:
  - Passive storage with boil off
  - Up to 3%/month propellant loss - a killer for a 5 yr mission !!!
  - Launch excess propellant – reduce payload
- ZBO approach
  - Use cryocoolers to achieve ZBO – no propellant loss
  - Launch smaller tanks – increase payload
- NASA program to develop and demonstrate ZBO
  - ARC: cryocooler development
  - GRC: subsystem development and small scale testing
  - MSFC: subsystem development and large scale testing
- Future flight demonstration

The Case for ZBO

- Zero Boiloff (ZBO) storage
  - reduced system mass for long duration missions
  - model developed by ARC and GRC
  - Working with MSFC on new model



For equal amounts of propellant at end of storage period



For times longer than breakeven, ZBO has lower system mass

ZBO for Outer Planet Missions

- SOA outer planet missions require large Δv for insertion/landing

Mission Name	Total Design-Delta-V (m/sec)	Spacecraft Mass (kg) with Orbit Insertion Propulsion	Payload Fraction
Titan Explorer	5000	5580	9 %
Neptune Orbiter	4100	2980	17 %

- Cryo-propellants have high I_{sp}

$$I_{sp} = \frac{F}{\dot{m} g}\ , \quad \dot{m} = \frac{dm}{dt}$$

Fuel	Oxidizer	Isp (sec)
Monomethyl-hydrazine (MMH)	N_2O_4	325
N_2H_4	Liquid Oxygen (LOX)	344
N_2H_4	Liquid Fluorine (LF2)	380
Liquid Hydrogen	Liquid Oxygen	456

ZBO for Outer Planet Missions

- Benefits of high ISP cryo-propellant

Titan Explorer			
	using storables	using LOx/LH	Δ
Isp [s]	325	456	131
s/c mass [kg]	5580	2270	-3310

  - Mass eq:

$$m_{dry} + m_{propellants} = m_{dry} * exp\left(\Delta v / I_{sp}\, g\right)$$

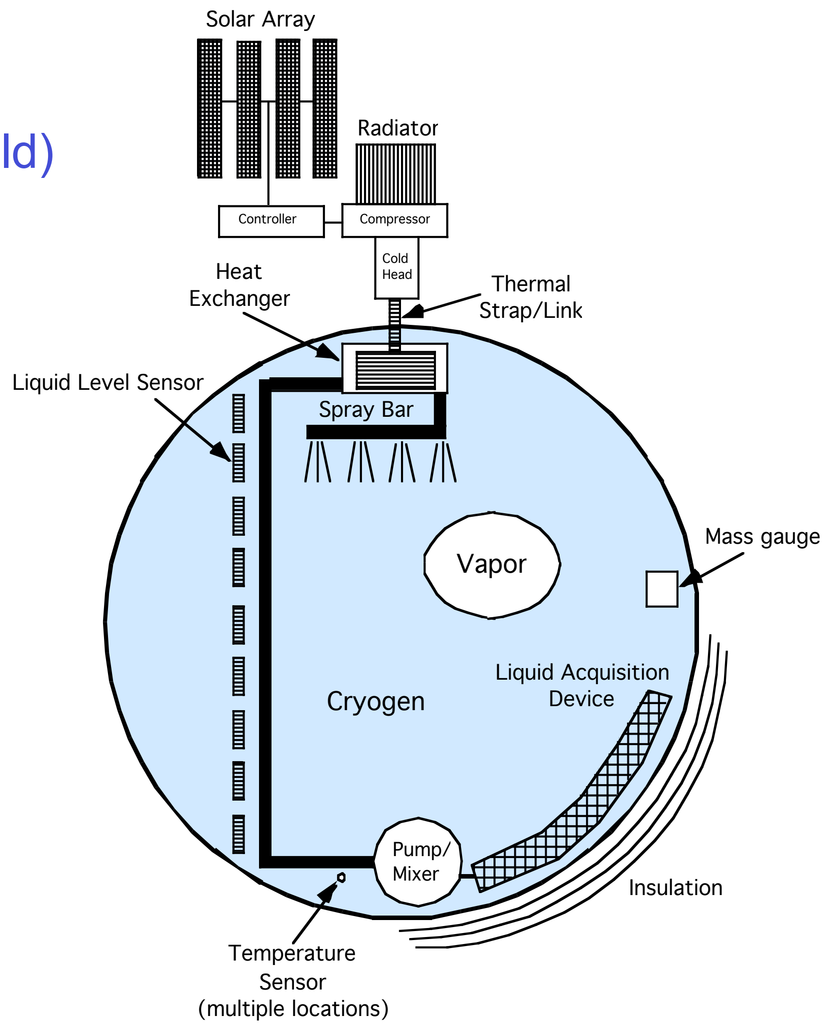
$$m_{dry} = m_{payload} + m_{spacecraft} + m_{tanks}$$

$$m_{tanks} = 0.15 * m_{propellants}$$

ZBO System Components

- Tank
- Insulation / cooled shields
- Condensation barrier* (ground hold)
- Cryocooler*
- Radiators
- Power source
- Controllers
- Heat exchanger
- Mixers / pumps*
- Flowmeters*
- Liquid acquisition devices (lads)
- Mass gauges*
- Thermometers
- Liquid level sensors
- Fill / drain systems

* development needed



ZBO System Demonstration

- Tested at NASA MSFC Oct/Nov 2001
- 18 m^3 liquid hydrogen tank
- 30 W @ 20 K G-M cooler
- Recirculation line
  - Heat exchanger inserted in line
  - Pump and Spray Bar mixer system.
  - Designed to provide intermittent destratification in 0-g environment
- Tested at 98%, 50%, and 25% fill levels
  - Flow required for heat removal order of magnitude less than required for mixing.
  - ZBO sustained at each fill level for durations of 3 to 5 days (steady state)

Multipurpose Hydrogen Test Bed Facility at MSFC

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Coolers for ZBO -- Lightweight High Efficiency Cryocooler Development

Objective

- Development of Lightweight, High Efficiency (LWHE) Cryogenic Coolers is crucial to NASA's Advanced Space Transportation Programs

Applications

- Coolers for ZBO propellant storage
- Coolers for liquefaction of propellant gases on planetary surfaces
- Backing coolers for dilution refrigerators, ADRs

Cooler Development Benefits

- **SOTA first stages for development of a 20 K second stage for ZBO Liquid Hydrogen coolers**
- **Combine with heat exchangers for SOTA ISRU Liquefiers**
- **Science instrument applications**
  - Backing coolers for Helium Dilution Refrigerators and Adiabatic Demagnetization Refrigerators
  - Replacing Solid cryogens in the 50K to 150 K range
- **LWHE cooler technology, plus advanced regenerator and aftercooler development will make two stage LH_2 coolers economically feasible for NASA's Exploration Missions**

How is cooler efficiency calculated ?

- Cooler efficiency is usually stated as a percentage of Carnot efficiency
- Carnot efficiency is given by: $\frac{T_H - T_L}{T_L}$
- For a cooler operating at a rejection temperature of 300 K and a cold tip temperature of 100 K, the Carnot efficiency is given by (300-100)/100 = 2 W/W (watts input power per watt of cooling). This represents the maximum possible efficiency that a cooler operating under these conditions could have.
- For a cooler operating at the above conditions and having a measured efficiency of 10 W/W, the efficiency is 2/10 or 20% of Carnot.

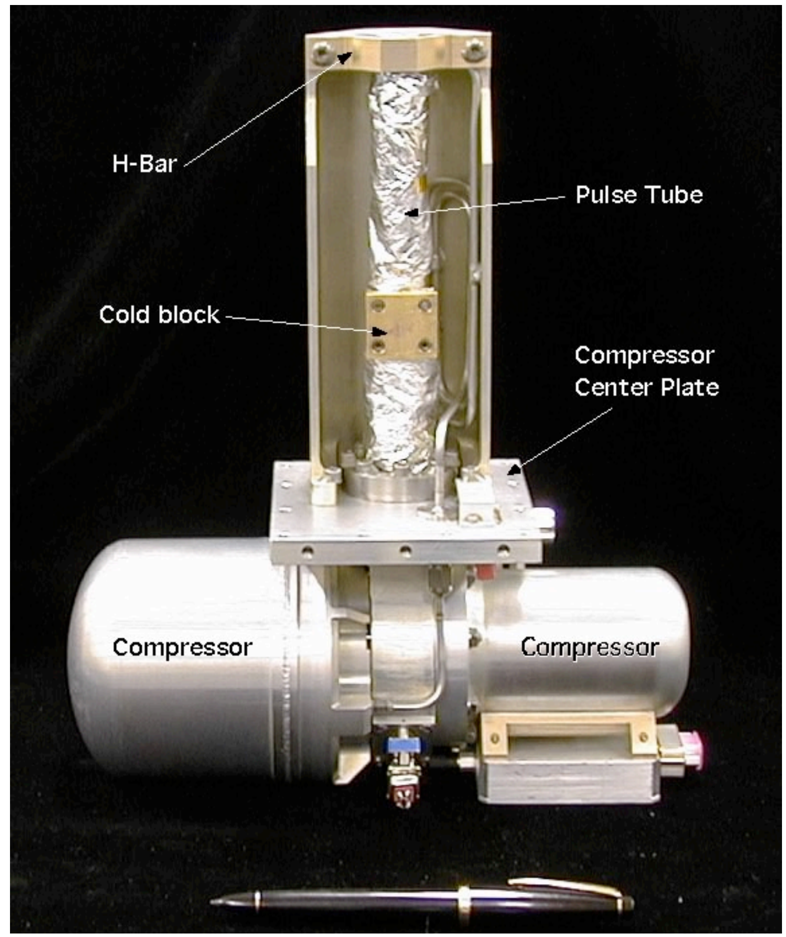
Lightweight High Efficiency Cryocooler Development

ARC teamed with Air Force Cryocooler Lab in March 1998

- To develop 95 K pulse tube cooler
- Goals: improve cooler efficiency, lower mass, and extend lifetime
- Subsequent Air Force contract was awarded to Northrop Grumman (formerly TRW)
    - Two coolers procured
    - Air Force funded $2.7M development cost
- Coolers delivered 6/01
    - 10 W, 95 K cooler for tactical applications
    - Mass = 4.0 kg (1/3 of SoA)
    - Efficiency = 12 W/W (nearly double SoA)
    - Cooler flight qualified (except electronics)
    - Estimated 10 yr lifetime

Northrop Grumman Cooler

- NASA, DoD, NGST team developed a 95K flight qualified cryocooler.
  - Increased efficiency x0.33 (17% of Carnot)
  - Reduced mass x 3
  - Suitable for O_2 and CH_4 ZBO storage



- Compressor
  - dual piston
  - flexure-bearing
  - gas-gap seals
- Pulse Tube
  - Single stage
  - Inertance tube

Cooler Testing

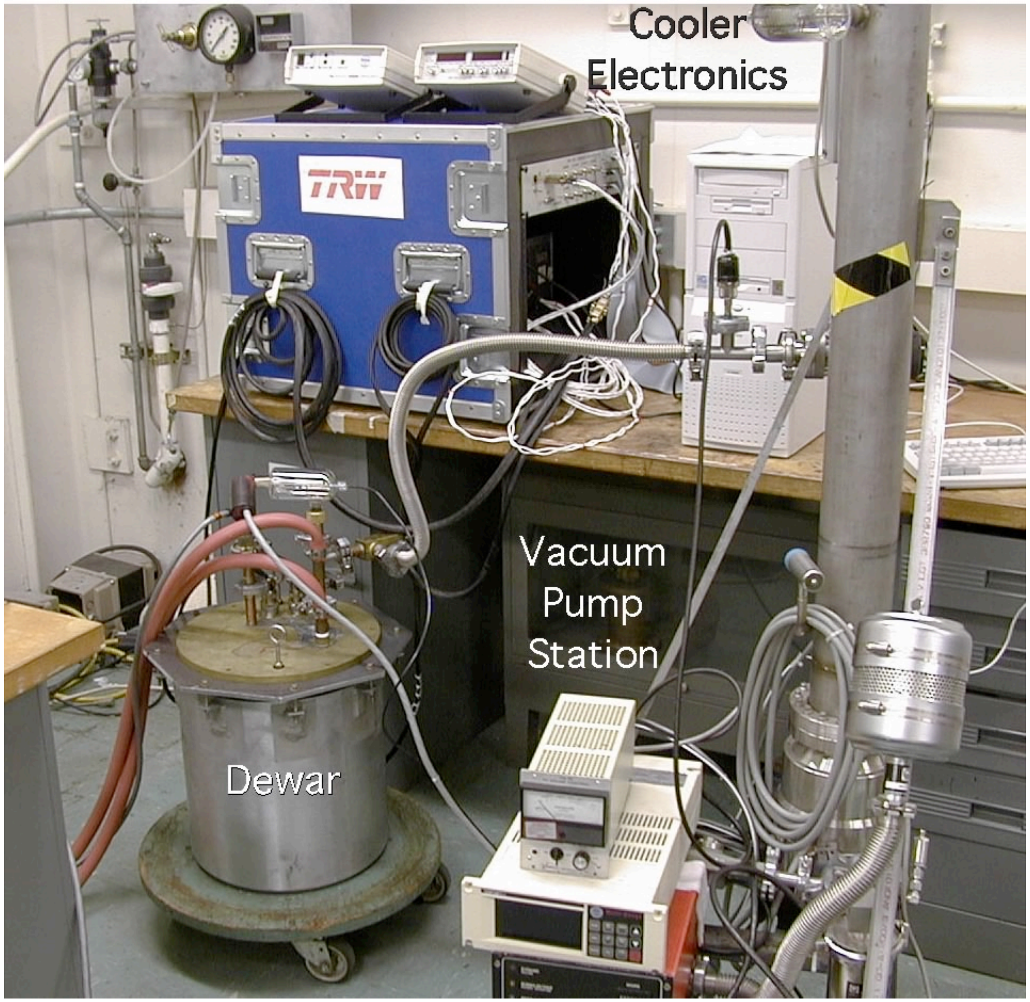
NASA Cooler HEC 201 tested

- Initial no-load tip temperature of 41 K recorded at 85% stroke
- Operated cooler at two different rejection temperatures
    - 280 K
    - 300 K
- Applied heat loads of 1, 5, 10, 15, 20 W
- Operated cooler at range of strokes
    - 40%, 60%, and 80%
- Operated cooler at maximum allowable stroke (94%) at 300 K and measure minimum no-load cold-tip temperature

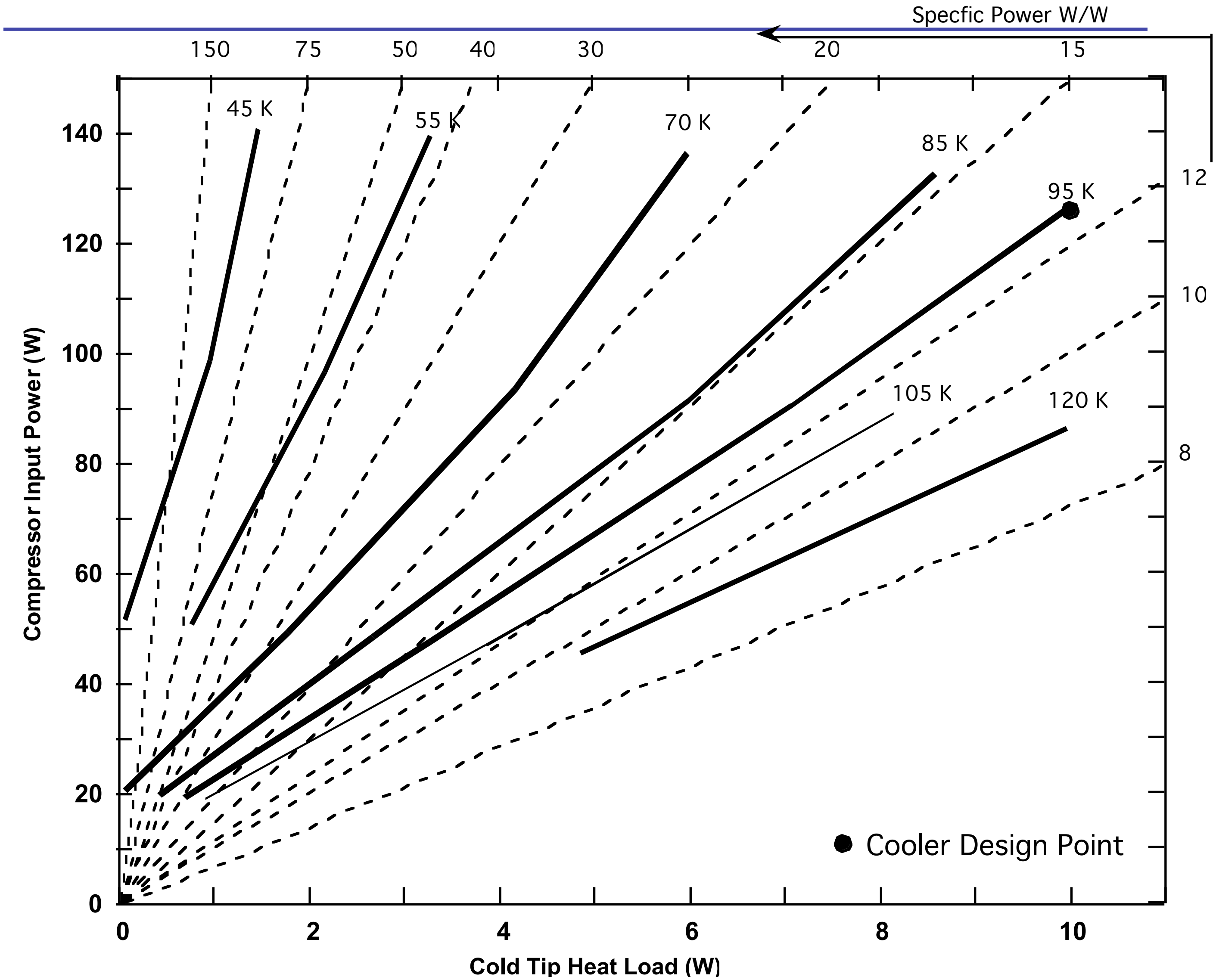
Cooler Testing

- Heater (25.6 ohm, 5W) resistor mounted on the cooler cold block
- MLI blanket - 16 layers
- Cooler mounted onto a water cooled copper heat exchanger
- External chiller
  300 K rejection temperature

HEC 201 Test Setup



Cooler Test Results

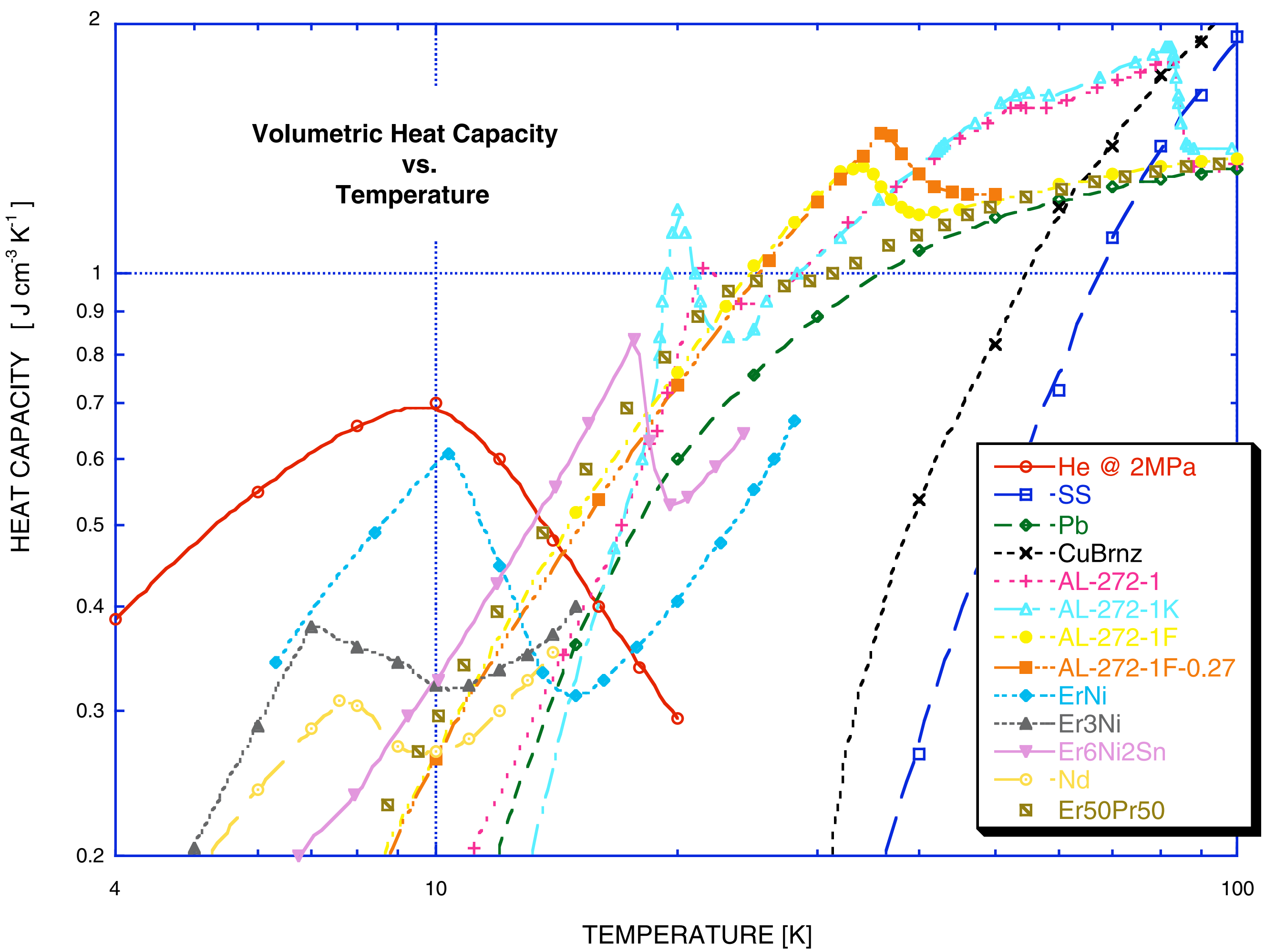


50 K+ Technical Challenges

- **Increased Performance**
  - Efficiency improvement
    - Cold head - Pulse Tube regenerator development
    - Compressor optimization
  - Mass reduction
  - Integration Issues
  - Improve thermal contact with load
- **Extended Lifetime**
  - 5-10 yr lifetime feasible with present technology
  - Continued development required to maintain reliability with increasing number of on/off cycles (multi-mission reusability)
- **Flight Electronics Development**
  - Radiation hardness
  - Mass reduction
  - Thermal Control
  - Estimates of Development cost approximately $3M

20 K Technical Challenges

- **Use regenerator materials with higher heat capacity**



Outer Planet Mission Benefits

- Benefits from improving cooler performance
  - Effect of changing 2ed stage regenerator from Pb to $Er_{50}Pr_{50}$
    - Increases efficiency x 1.4
    - Decreases input power x 0.7
    - Smaller compressor ⇨ reduced mass
    - Smaller radiator ⇨ reduced mass
    - Smaller power supply ⇨ reduced mass

Sub-system	SOA cooler (kg)	Δ with improved regenerator (kg)
Cryocooler	46	-13
Radiator	22	-6
Power supply	76	-22
Reduced tankage	-	-19
Reduced propellant	-	-126
TOTAL	**144**	**-186**

Other 20K Cooler Applications

- Densification of propellants
  - Enable reduced mass propellant systems
- ISRU (In-Situ Resource Utilization)
  - H_2 liquefaction and storage
- Tank chill down
  - Enable low-loss propellant transfer in 0-g

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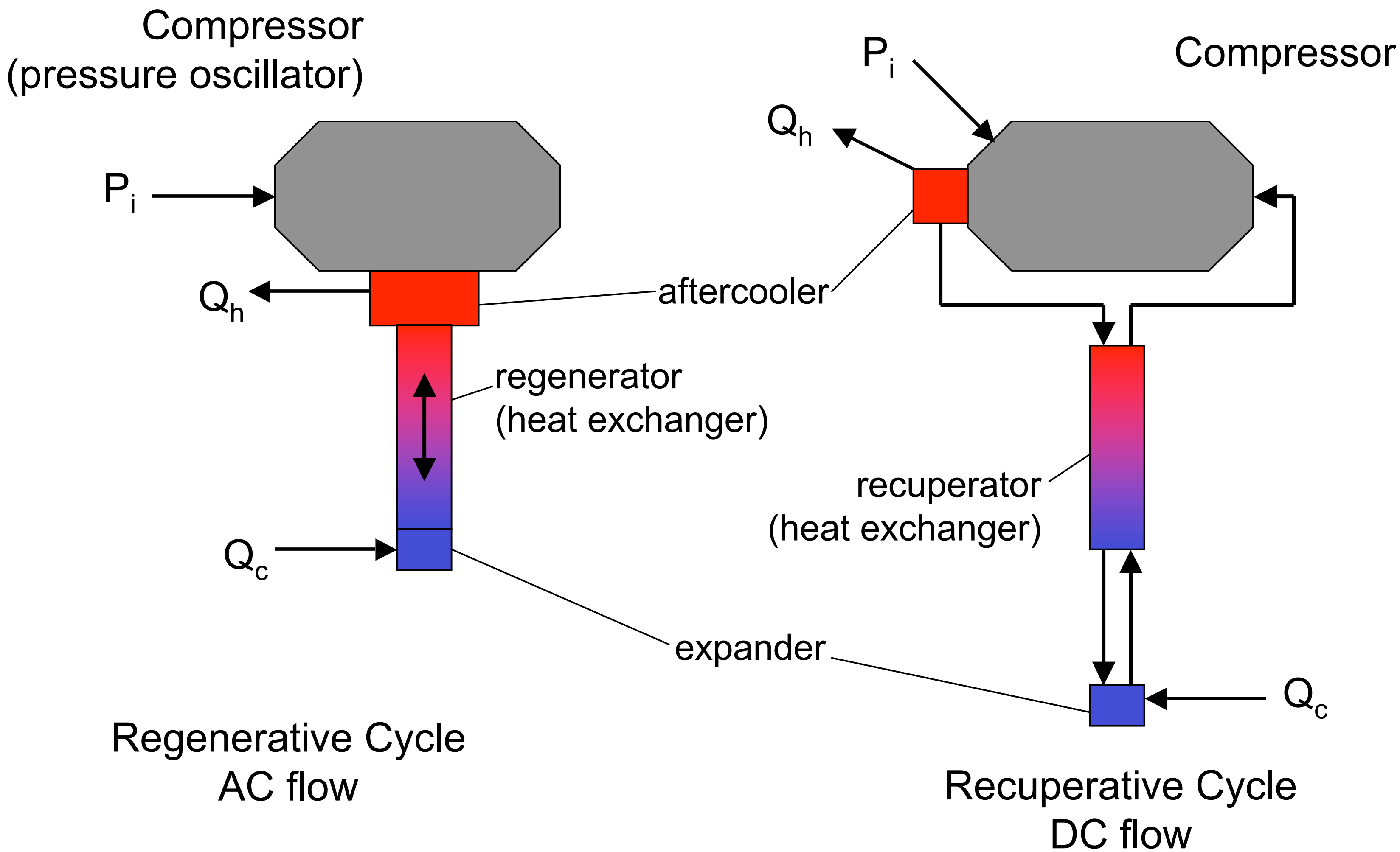
Distributed Cooling

Coupling the Cooler to the Propellant Tank

- Most cryocoolers produce cooling at a small point, the “cold head”, or “cold point”
- To effectively cool a propellant tank requires cooling over a large area
- A method of “distributing” the cooling needs to be provided
- This method is dependent upon the type of cooler

Distributed Cooling

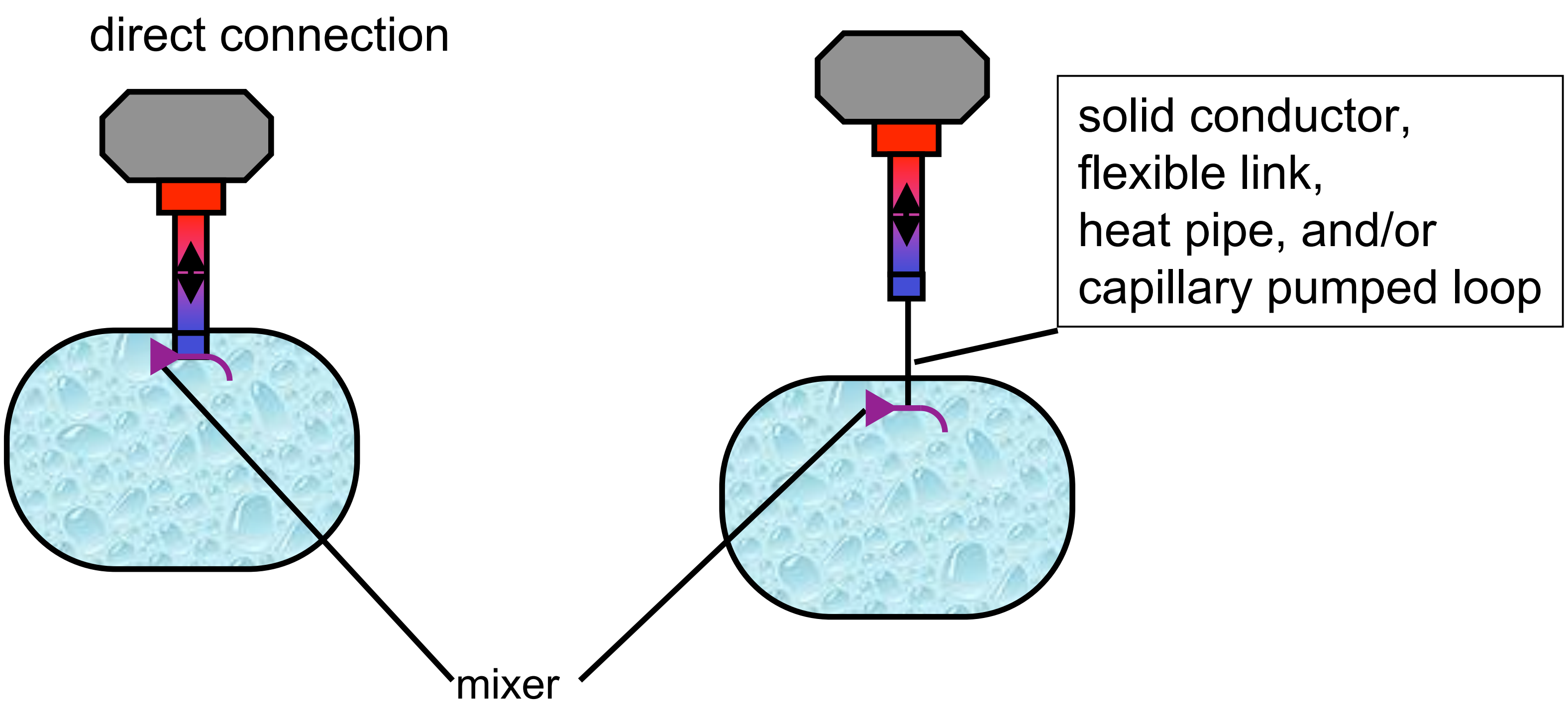
Types of Cryocoolers



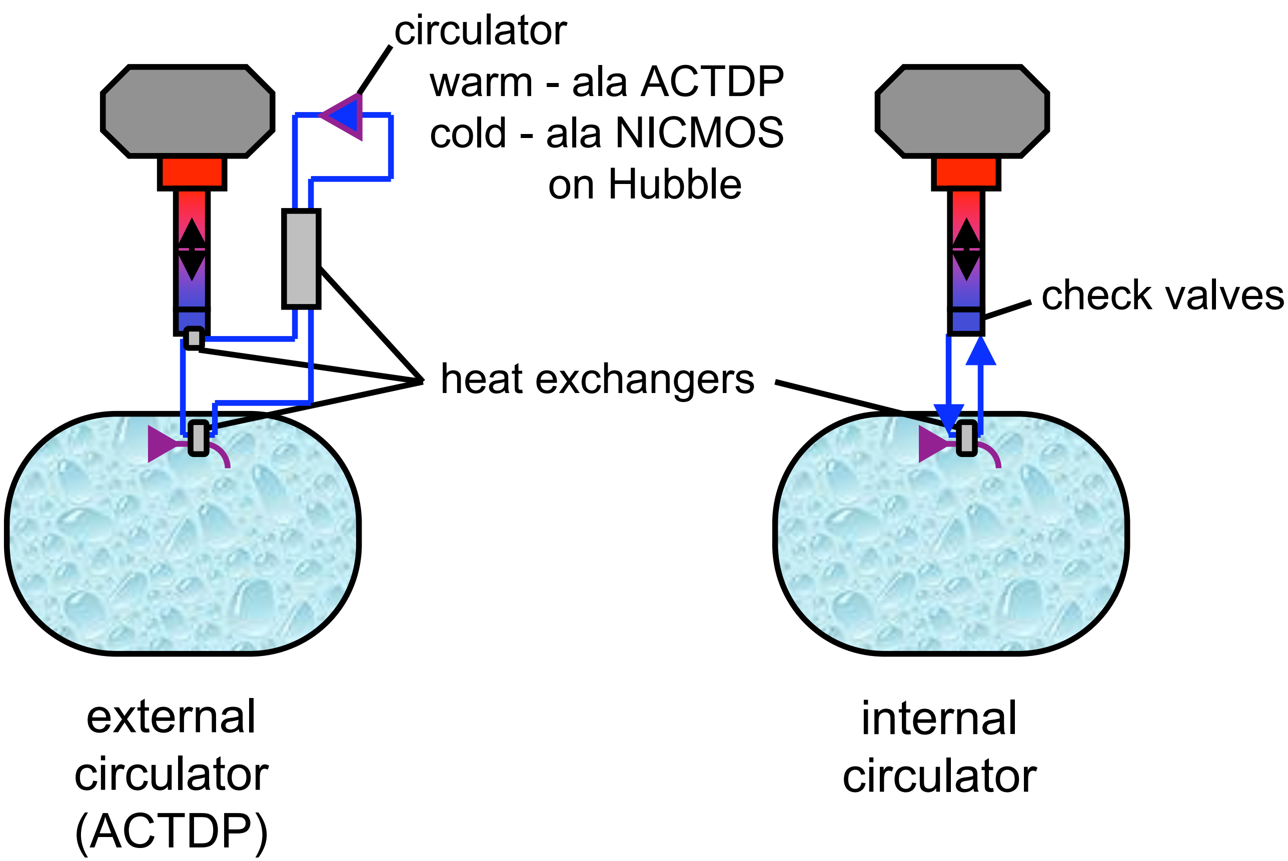
Integrating a Single Cryocooler

Cooler type	Cooler/Depot link	Cooling Distribution in Depot
Regenerative (pulse tube, Stirling)		
	• Direct connection (no additional link) • Solid conductor • Flexible link • Heat pipe • Capillary pumped loop • Circulator	• Point cooling –Integrated with tank's internal circulator • Distributed cooling (no internal mixer ?) –External circulator linked to cooler (as in ACTDP, NICMOS) –Integrated circulator (circulate gas from cold head using check valves)

Regenerative Configurations 1



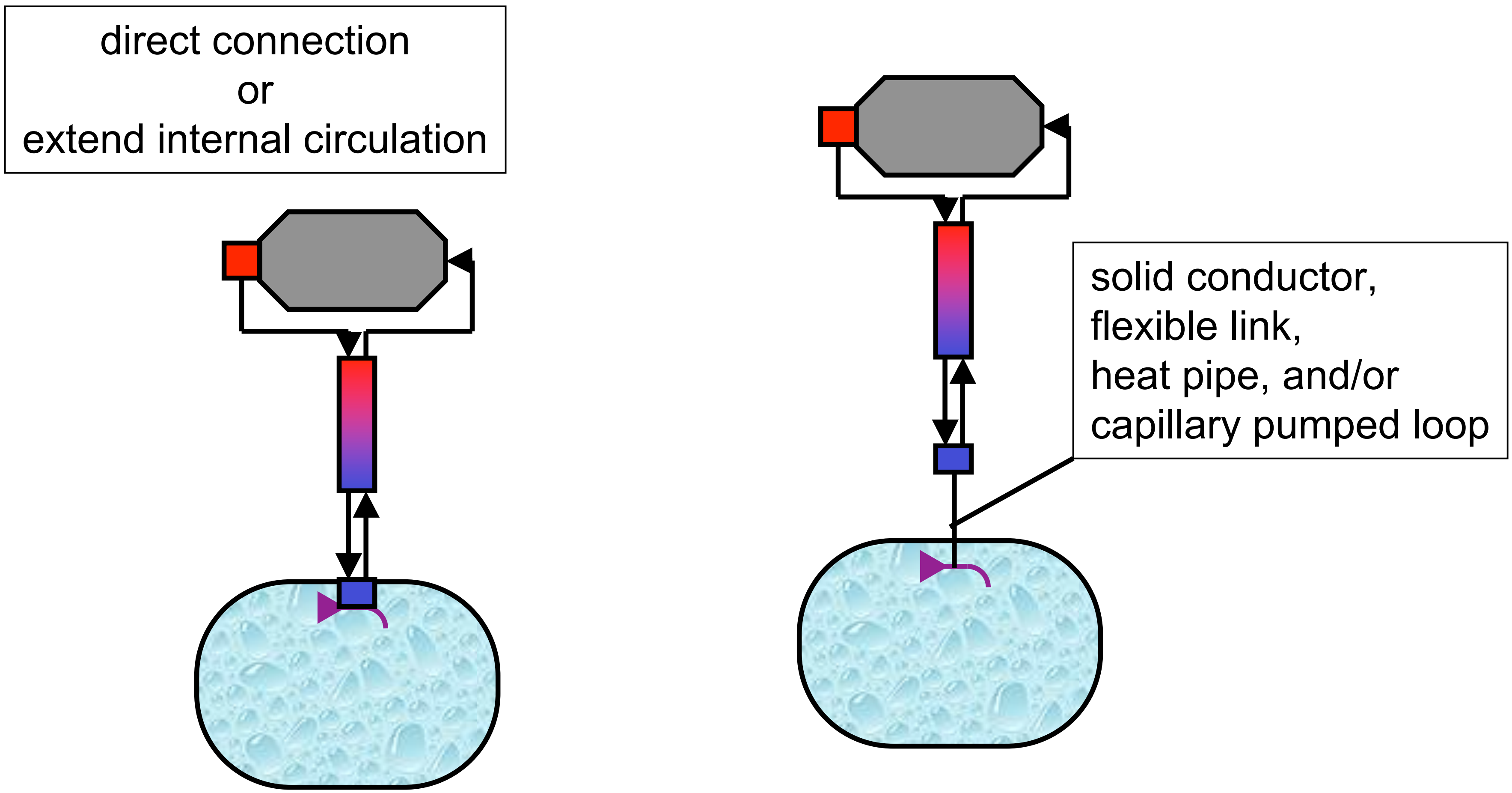
Regenerative Configurations 2



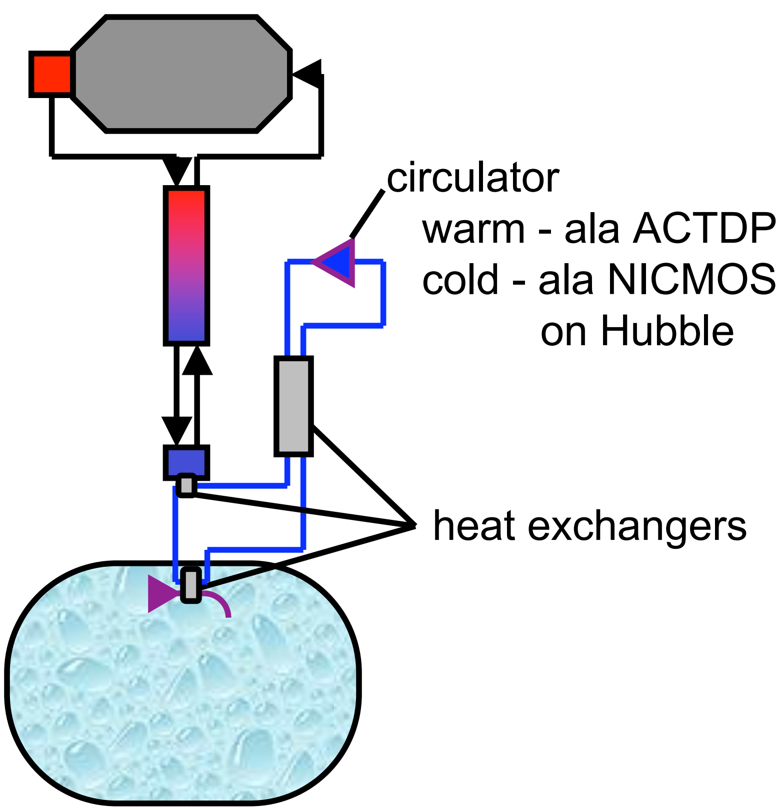
Integrating a Single Cryocooler

Cooler type	Cooler/Depot link	Cooling Distribution in Depot
Recuperative (turbo-Brayton)		
	• Direct connection (no additional link) • Solid conductor • Heat pipe • Capillary pumped loop • Circulator (extend circulation of working fluid) (external circulator as in ACTDP and NICMOS)	• Point cooling –Integrated with tank's internal circulator • Distributed cooling (no internal mixer ?) –External circulator linked to cooler (as in ACTDP and NICMOS) –Integrated circulator (circulate gas from cooler)

Recuperative Configurations 1



Recuperative Configurations 2

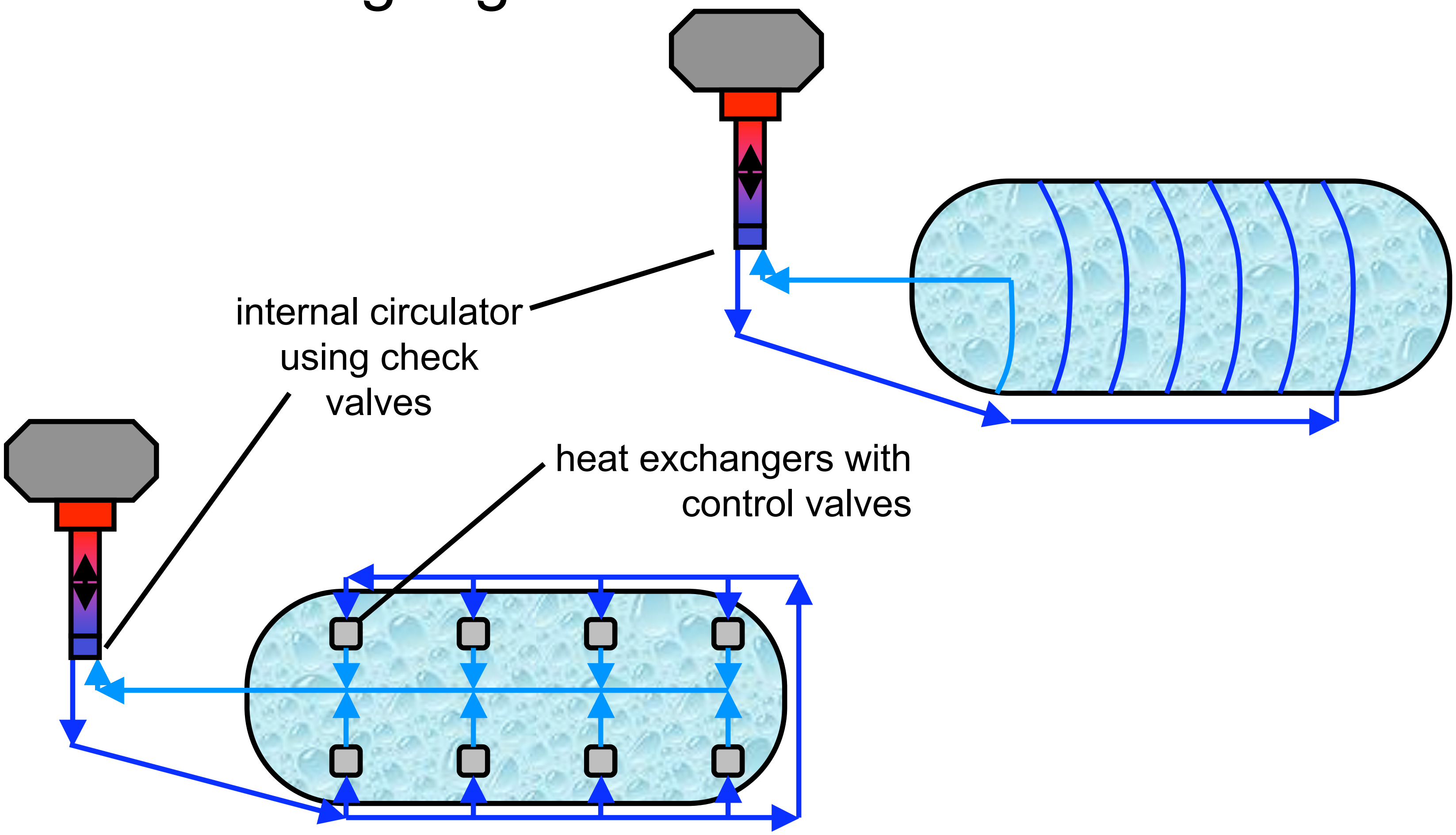


Distributed Cooling Concepts

- Where is cooling applied to tank ?
  - At high heat inflow points ?
    - Supports
    - Plumbing
    - But, in large tanks heating dominated by insulation
  - At internal circulator ?
  - Both ?

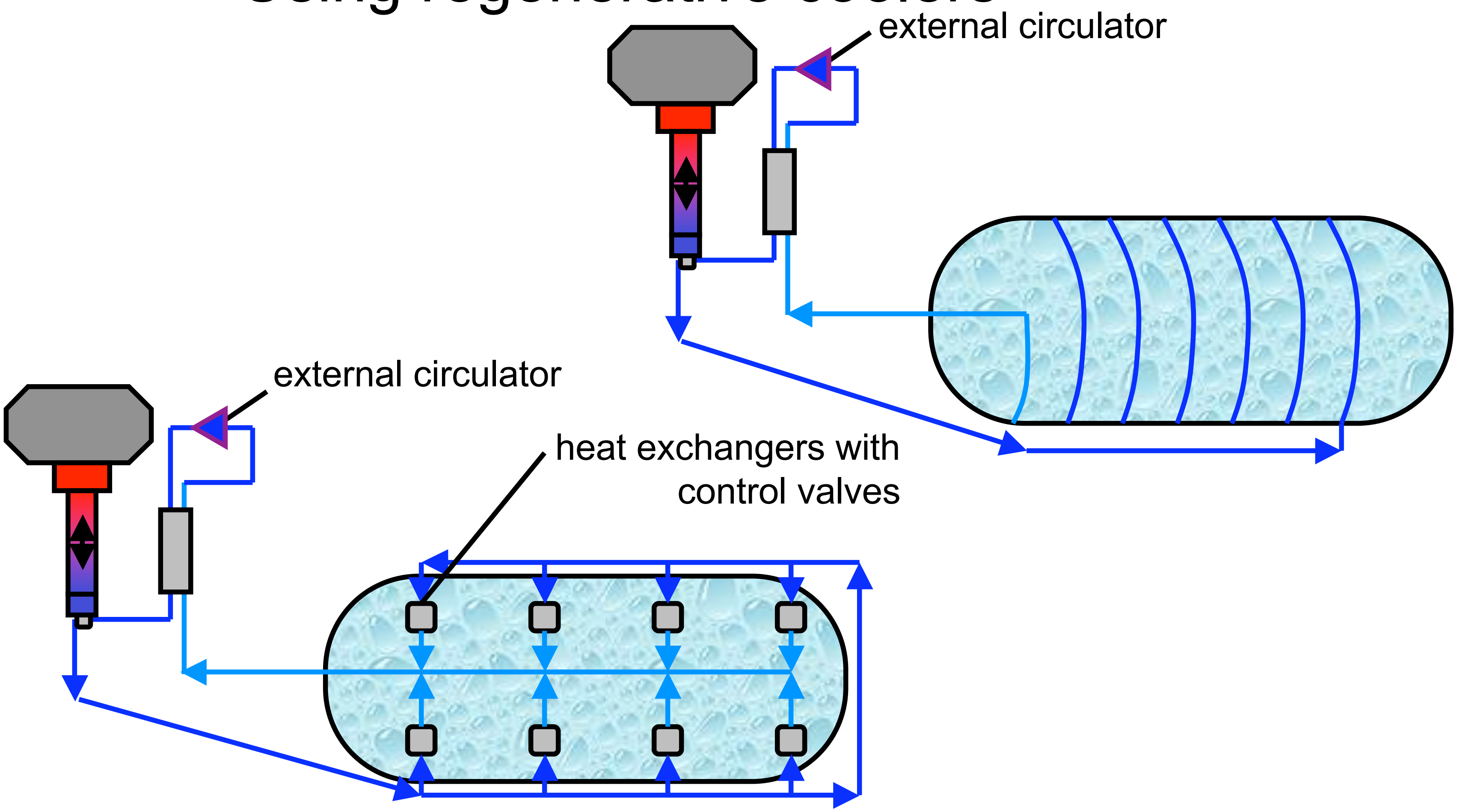
Distributed Cooling Concept 1

- Using regenerative coolers



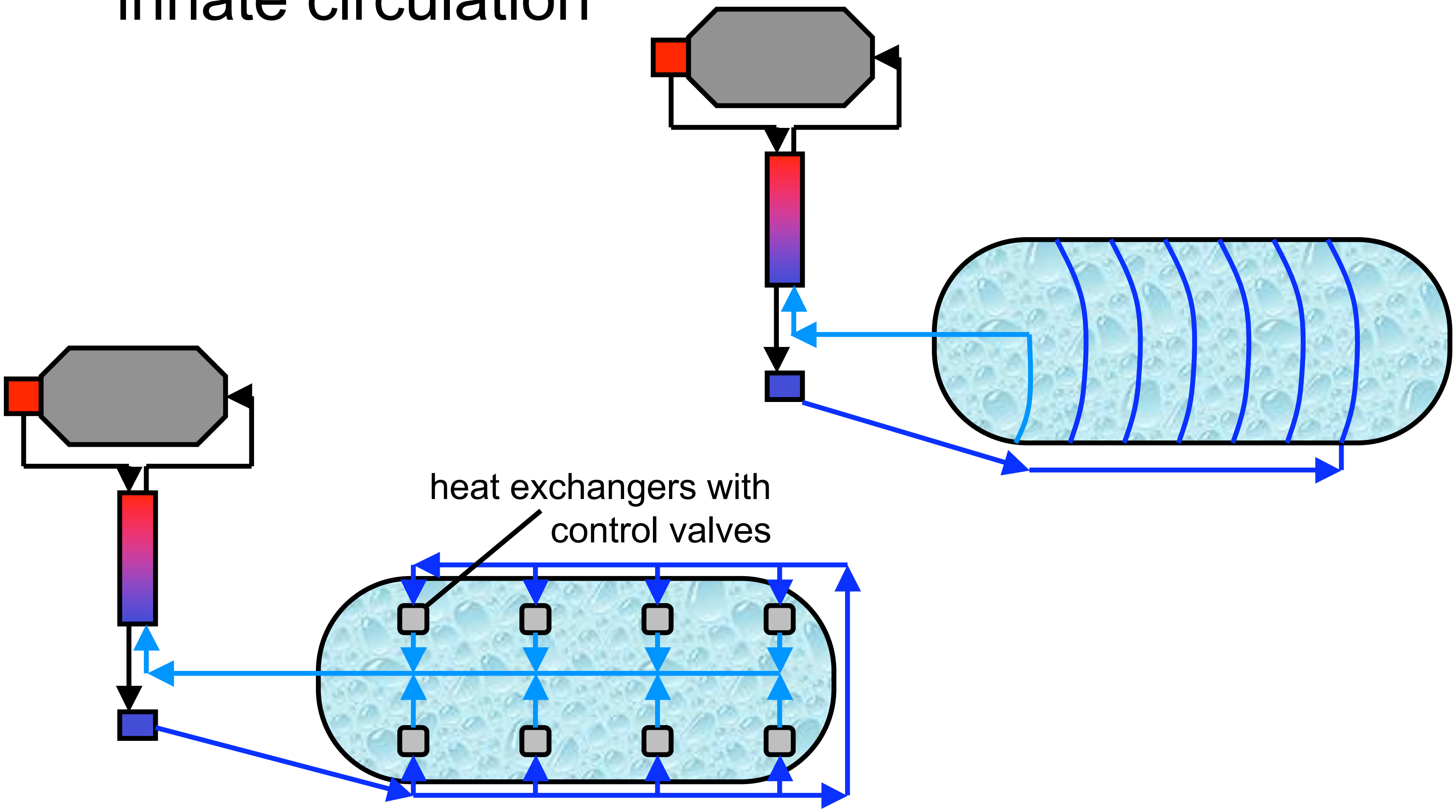
Distributed Cooling Concept 2

- Using regenerative coolers



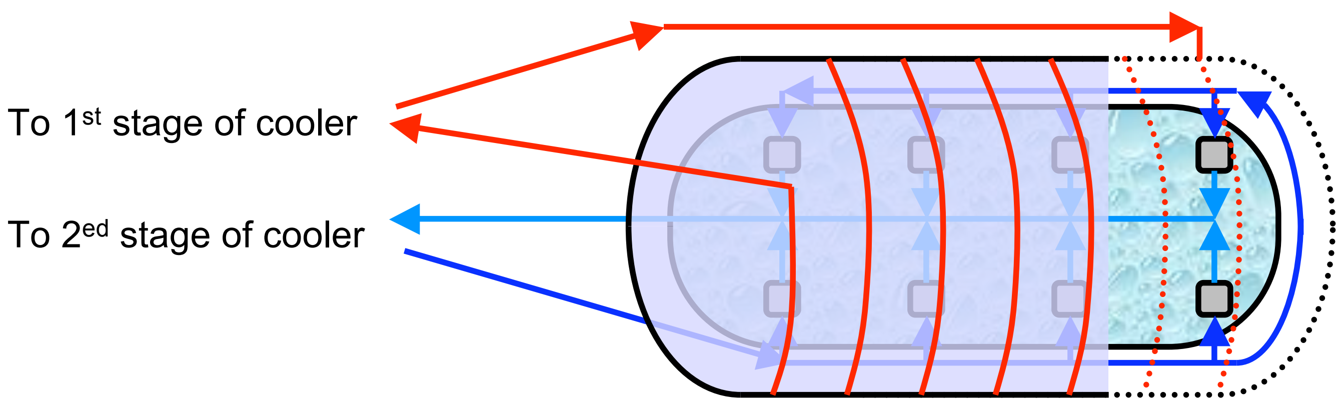
Distributed Cooling Concept 3

- Using recuperative cooler's innate circulation



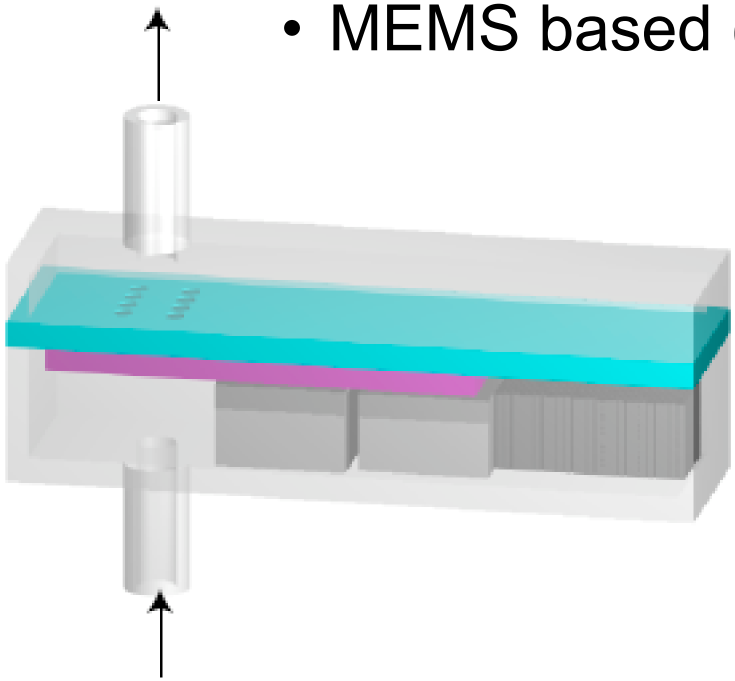
Example with Cooled Shield

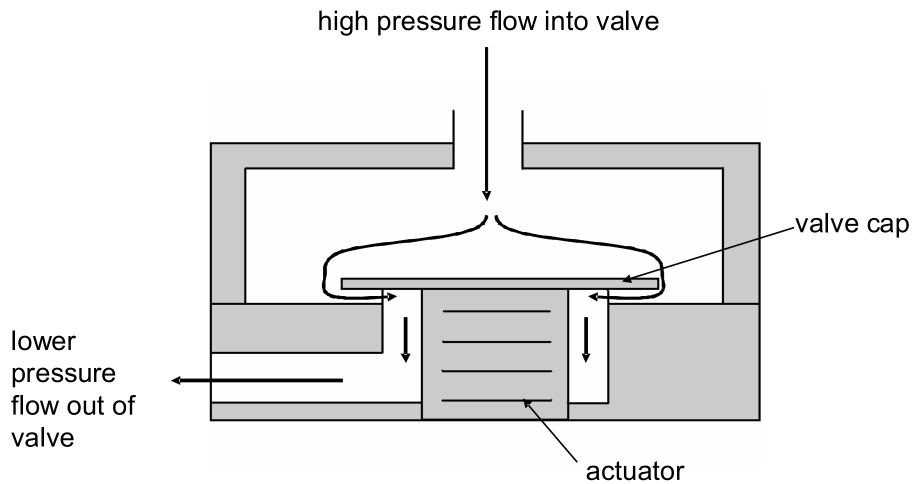
- Can use separate coolers or a 2-stage cooler



Time Dependent Loads

- Do the heat loads vary with time or mission ops ?
- Do the cooling requirements vary with time or mission ops ?
  - Cold variable distribution valves are being developed
    - MEMS based (ARC, U of WI, U of MI)





Commercial ZBO Applications

Commercial application of ZBO dewars will only be successful if it makes economic sense to implement

Cost assumptions based upon industrial rates:

Energy cost 0.04 $/kw-hr

Bulk cost of LN_2 0.113 $/liter

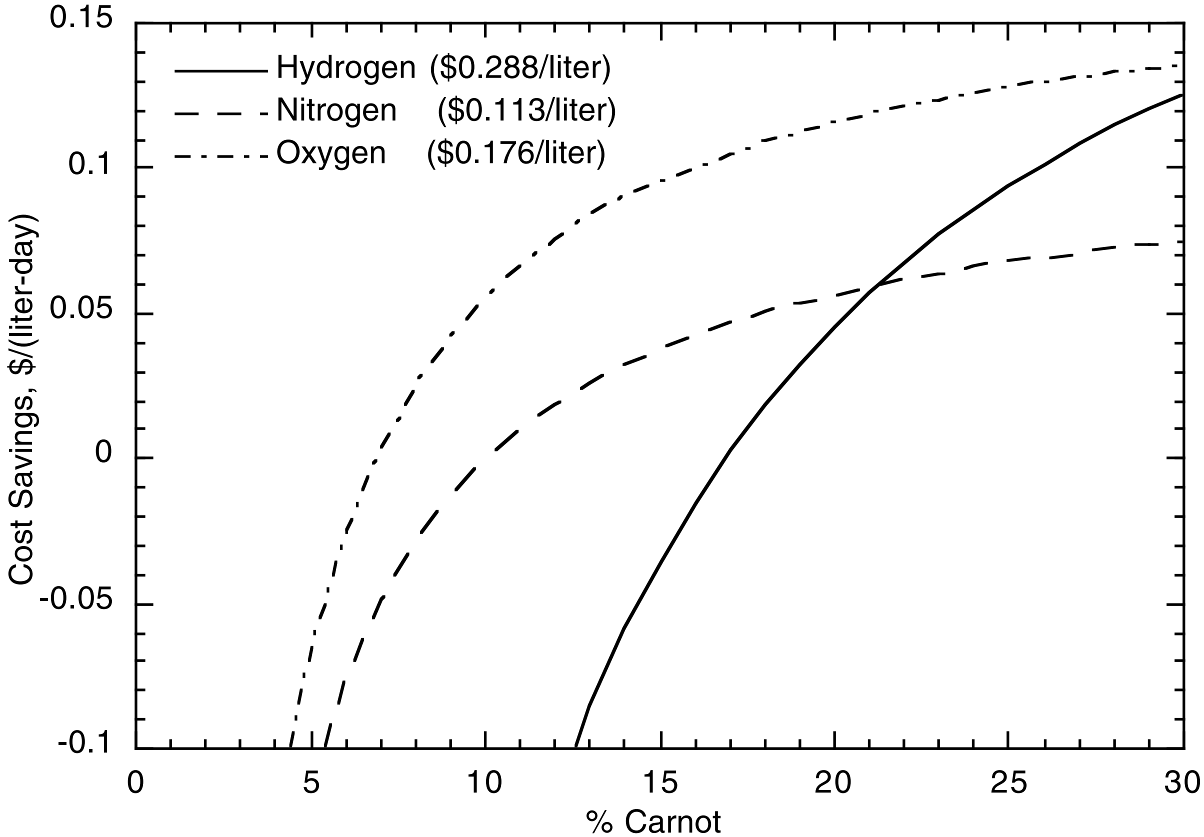
Bulk cost of LO_2 0.176 $/liter

Bulk cost of LH_2 0.288 $/liter

We can estimate the cost savings per day as a function of the percent of Carnot efficiency that the liquefier achieves.

Advanced low cost Gifford-McMahon cryocoolers can achieve efficiencies of approx 9% and 11% of Carnot efficiency at 20 K and 80 K respectively

Cost Savings Based on Liquefier Efficiency



ZBO Cost Savings Example

Example:

A typical oxygen dewar of 26,000 kg (6000 gallon) capacity may have a boil off rate of 1% per day

With an advanced cryocooler of 16% efficiency, we can save $22.71/day

(6000 x 0.01 x 3.785 x$ 0.10 = $22.71)

If we can buy the cooler for $15,000 the pay back period is under 2 yrs

Note: A hydrogen cooler must have an efficiency of 17% just to break even

Shield coolers may be required to implement a reduced boil-off system for hydrogen applications.

NASA Kennedy Space Center
Launch Site

3200 m^3 LH_2 storage tank

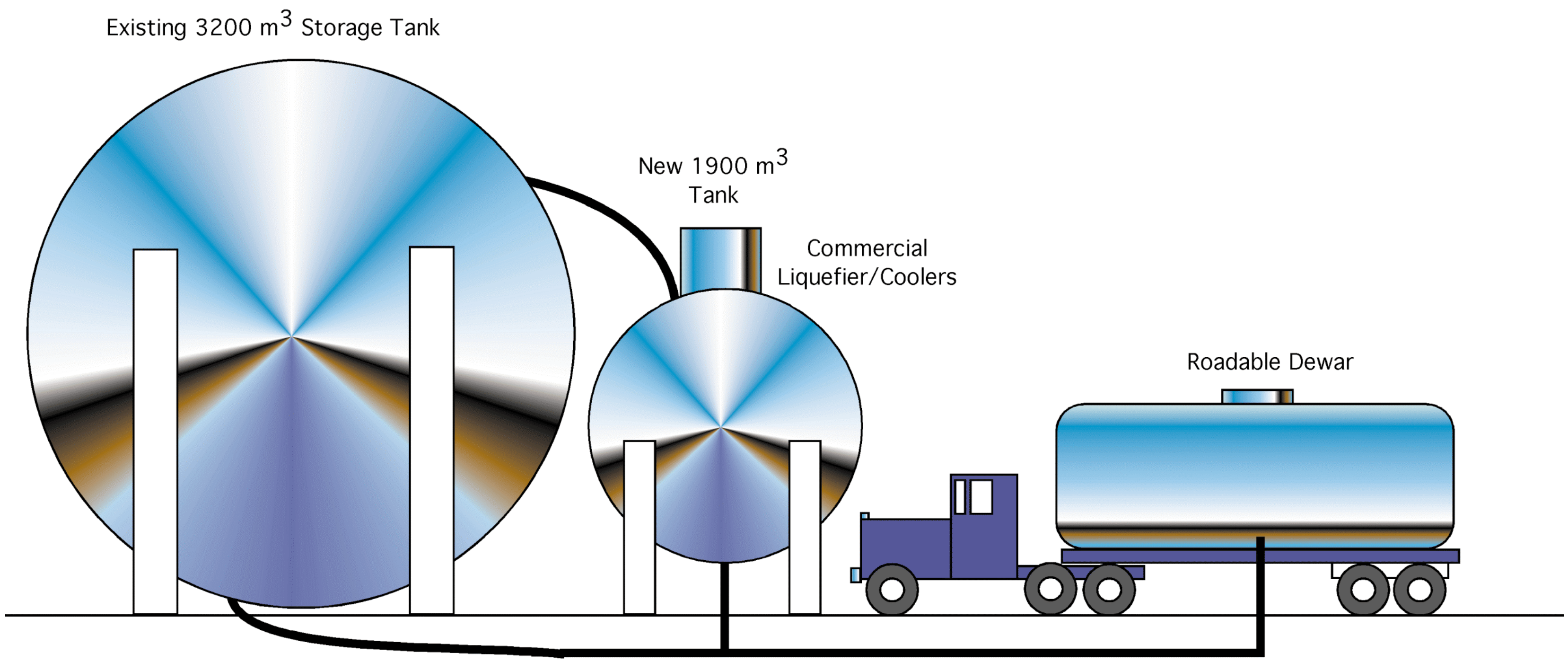
NASA Kennedy Space Center Launch Site

Launch pads at LC 39 A and LC 39 B each contain a 3200 m^3 (850,000 gallon) LH_2 storage tank

- Each tank loses 650 kg per day of hydrogen through boil off (475,000 kg/yr)
- Each tanker truck used to replenish the tank loses 1300 kg in transfer over 4 hr transfer period
- 450 tanker trucks are offloaded each year (585,000 kg/yr)
- Total loss 1 x 10^6 kg hydrogen
- If this could be prevented, $625,000 per year could be saved, with current shuttle launch frequency of 8/yr
- Increased frequency would result in more savings
- Savings based upon KSC rate of $0.21/liter of LH_2 -- 10 yr contract with supplier -- several million liters/yr usage

NASA Kennedy Space Center Launch Site

ZBO Approach



NASA Kennedy Space Center Launch Site

ZBO approach

Add Auxiliary 190 m^3 (50,000) gallon tank at each site

- Transfer every 30 to 45 days would correspond to over the road tanker (roadable dewar) delivery
- Transfer from aux to main tank would also precool line

Two cooling systems required:

- "Daily" cooling system to avert normal boil-off (800 watts continuous)
- "Surge" cooling system for tanker delivery (9 kW per 64 hrs every 30 days)

NASA Kennedy Space Center Launch Site

ZBO KSC approach (continued) - Use multiple coolers, staged, depending upon requirements

Costs

- Additional tank - $350,000
- 9 kW ‘surge’ coolers - $3,000,000
- 800 W ‘daily’coolers - $ 270,000
- Total Equipment Cost - $3,660,000 per pad , or $7,315,000 total

- Power input to 9 kW (588 kW input) coolers - 452,000 kW-hr
- Power input to 800 W (52 kW input) coolers - 455,000 kW-hr
- Total annual utility expenditure - $72,500
- Annual Savings - $552,000

Payback period for Equipment Acquisition - 13 years.

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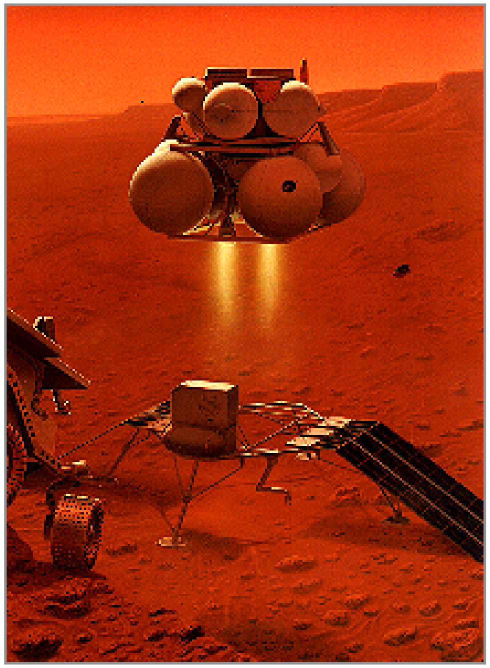
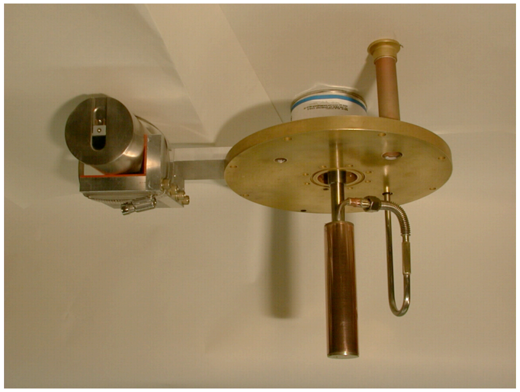
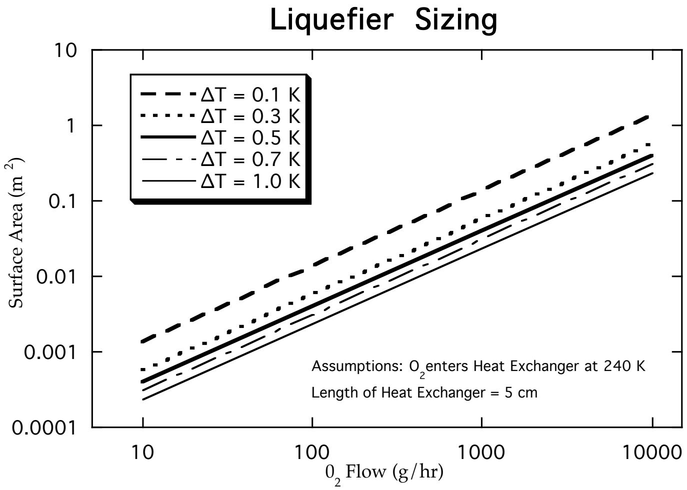
Liquefier Technology for In-Situ Resource Utilization (ISRU)

- Current SOA
  - Small oxygen liquefiers using existing coolers
    - Demonstrated at ARC and NIST
- Gaps
  - Hydrogen liquefiers require further development of compact, efficient heat exchangers and cryocoolers
  - Major technical challenge will be developing large capacity liquefiers (2500 g/hr) for human Mars missions





ARC Liquefier using BEI Tactical Cooler



Liquefier sizing

Liquefier sizing involves an energy balance between the incoming gas flow and the cooling through the heat exchanger/condenser

$$\dot{Q} = \dot{m}\left(h_{fg} + h_g \Delta T\right) = hA\delta T$$

$$h = C\left(\frac{g\rho(\rho - \rho_v)k^3 h_{fg}}{L\mu\delta T}\right)^{1/4}$$

A = surface area

δT = subcooling of wall

ΔT = temperature change of gas (ambient to condensation)

g = gravitational acceleration

h = enthalpy, heat transfer coefficient

k = liquid conductivity

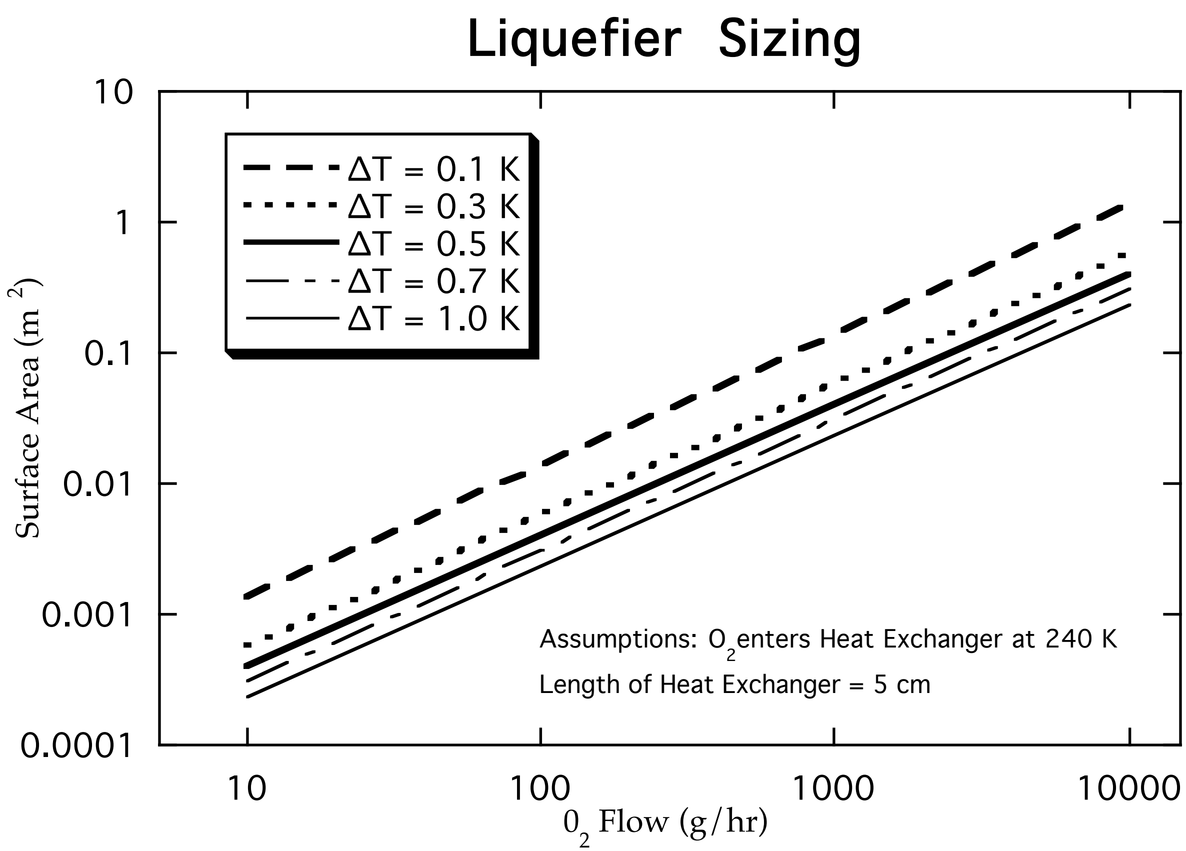
L = fin length

$\dot{m}$ = mass flow

μ = viscosity

ρ = density

Liquefier sizing



Are we there yet ???

- We're ALMOST there……
- The technical expertise exists, but key components require development now:
  - Although 90 K flight qualified cryocoolers exist in the capacities required for ZBO, 20 K coolers require development and demonstration
  - 20 K flight coolers with capacities of 5-20 W cooling are required
  - Distributed cooling systems require further development and demonstration
  - Large flight qualified liquefiers (2500 g/hr) require development and demonstration
- A ZBO flight system demonstration is needed to prove the technology for lunar and planetary missions and for in-space cryogenic supply depots

Conclusion

- Advanced Cryogenic Systems are critical to lunar and Martian missions as well as In-Space Cryogenic Propellant Depots
- Sustained human presence in space requires In-Situ Resource Utilization
- Cryogenic Fluid Management technology will help realize the vision for space exploration