NASA JSC

Space Environment Simulation Lab (SESL)

Chamber A

New Helium Refrigerator

By
JLab Cryo Group

Presenter: Pete Knudsen

September 18, 2012

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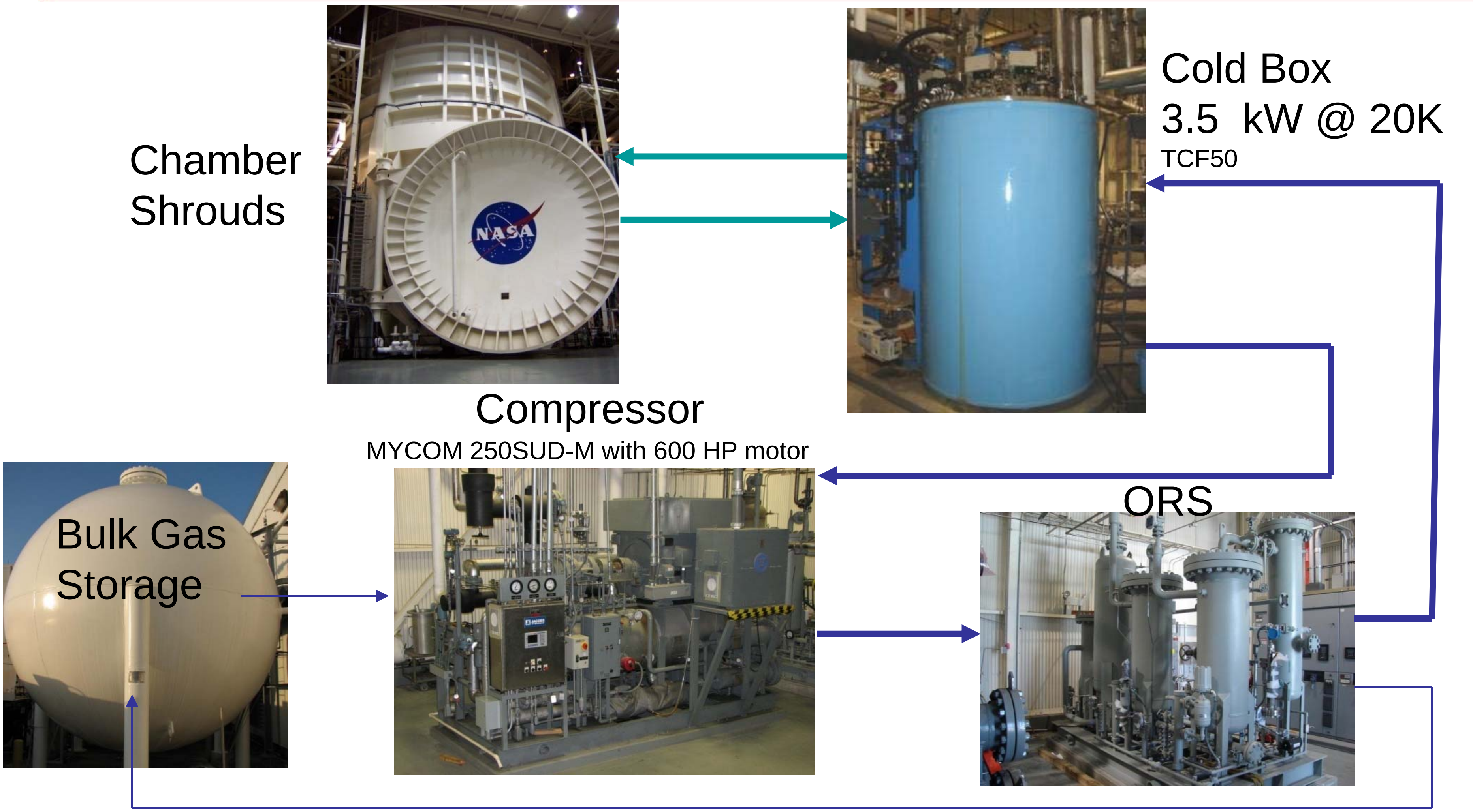
SESL Background

- Since being commissioned in 1965 and prior to modifications required for the James Webb Space Telescope (JWST), helium refrigeration system used to provide cryo-pumping via. helium cryo-panels (“shrouds”) – *NOT to simulate a colder (< 80 K) environment*
- Original helium refrigerators installed in the 1960’s used during Apollo program era
  - (4) units CVI each capable of ~1.5 -1.75 kW at 20 K
  - Refrigerator used piston expanders for refrigerator
  - Used reciprocating warm compressors
  - Decommissioned in 1996

SESL Background

- In 1997, NASA-JSC commissioned (2) Linde Kryotechnik TCF50's
  - Capable of 3.5 kW at 20 K
  - Only needed one unit; other served as a backup
  - Refrigerators used turbo-expanders
  - Used Mycom 250SUD-M (600 Hp) compressors
  - Refrigerators had a number of issues:
    - Oil carry over
    - Poor system efficiency at less than 100% of maximum capacity
    - Not very stable operation
    - Load temperature variation of ~ ± 2.5 K
    - Erratic and high liquid nitrogen consumption

SESL Background



New 12kW 20K Helium Refrigerator

- In 2006, NASA-JSC solicited JLab’s technical direction for the procurement of a new helium refrigerator to test the JWST
  - The new helium refrigerator would no longer serve to provide cryo-pumping to 80 K (liquid nitrogen) shield – *the refrigerator in conjunction with new helium cryo-panels (“shrouds”) would provide a 20 K environment*
  - Refrigerator system requirements:
    - Temperature stability of ± 0.25 K
    - “20K Mode”: 12.5 kW at 20 K
    - “100K Mode”: ~100 kW at 100 K

JLab Cryo Group Experience

- So, what experience does the JLab Cryo Group have in the process analysis and design of helium refrigerator systems?
  - All of JLab's plants (CHL-1, SBR, ESR, CTF)
    - Power reduction at CHL-1 from 6 to 4.2 MW
    - CTF process improvement: increased LHe supply to user by 40% and reduced input power by a factor of 2
  - 1998: MSU-NSCL upgrade
  - 2000: SNS
  - 2005: BNL-RHIC upgrade
    - Power reduction from 9.4 to 4.8 MW
  - 2006: 12 GeV CHL-2
    - 4 MW as compared to 6 MW for CHL-1 at max. capacity
  - 2008: ESR recovery HX (used for Qweak)
  - 2012: MSU-FRIB
  - Others…
    - Large & small 2K plants, LN pre-cooler optimization, 4-2K HX improvement, etc.

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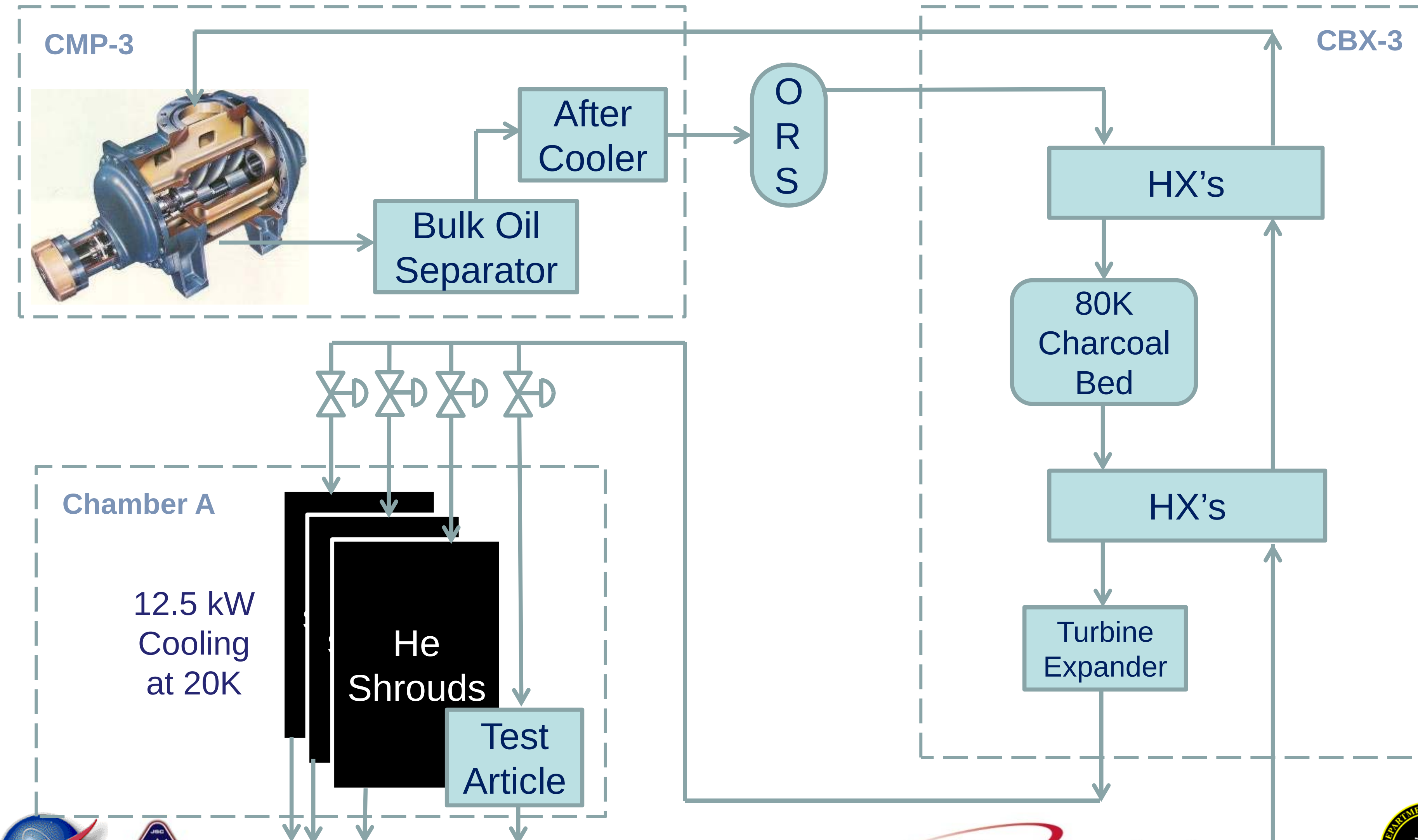
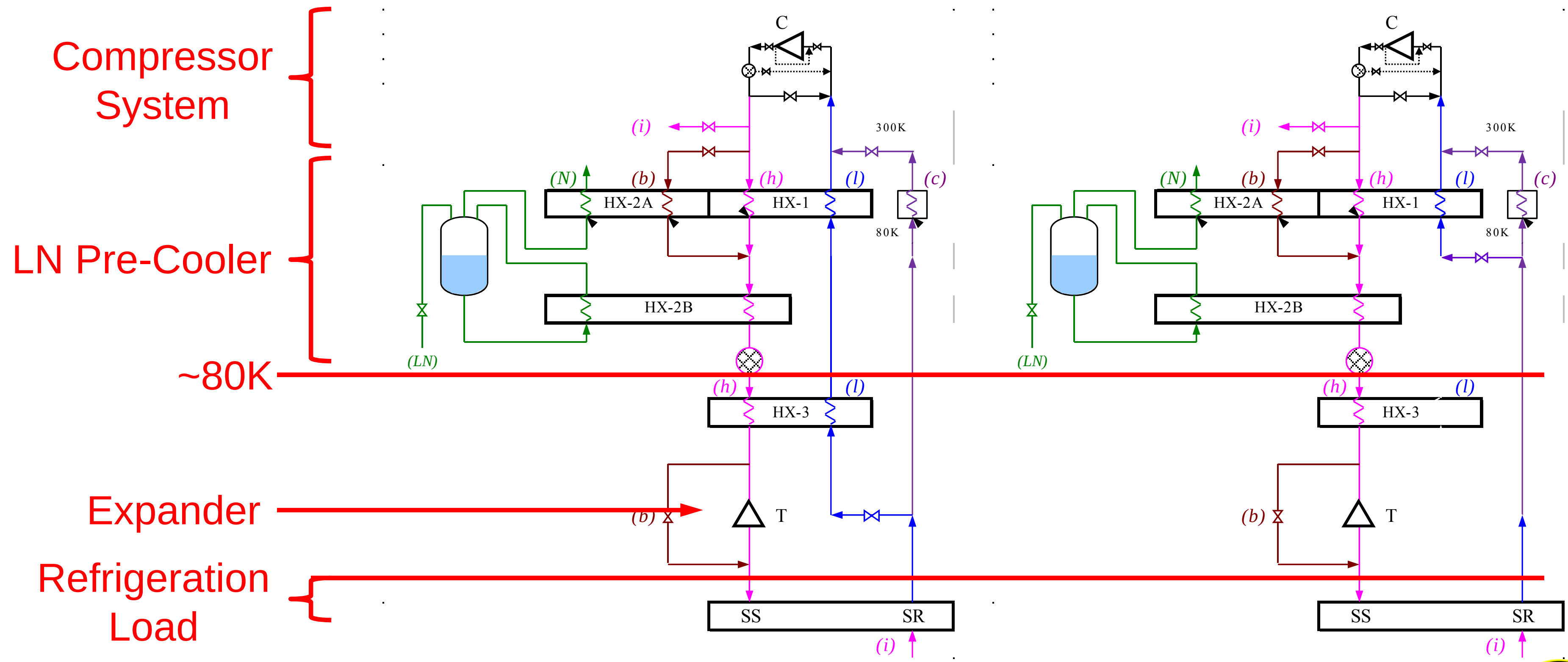
NASA-JSC New Helium Refrigerator System Basic Principle of Operation



New 12kW 20K Helium Refrigerator

"20K Mode"

"100K Mode"
Note: HX-3 is bypassed



New 12kW 20K Helium Refrigerator

- Preliminary JLab analysis indicated:
  - For an assumed 13.5 kW 20 K load (8% load margin)
    - Helium mass flow: 385 to 400 g/s
      - i.e.,13.5 kW at 20 K to 98 kW at 100 K
    - Compressor volumetric displacement: ~1260 to 1275 l/s
    - LN required:
      - 45 g/s at 13.5 kW at 20 K
      - 200 g/s at 98 kW at 100 K
    - Input power: ~1.2 MW (either mode)
    - Expander flow coefficient: 100 K mode = 2 * (20 K mode)

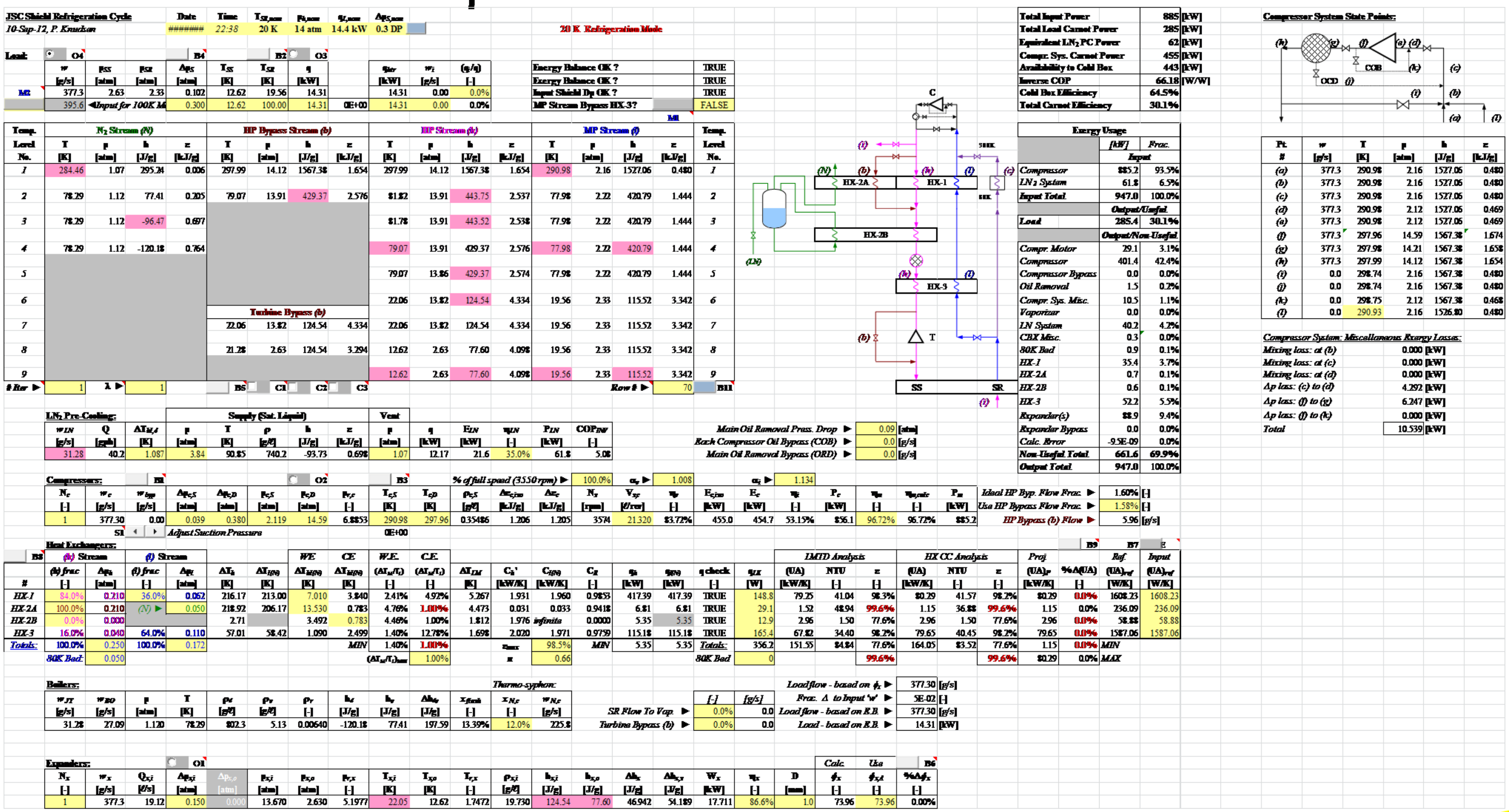
- Note: For basic ideas behind preliminary analysis, see:
- Knudsen, Ganni, “Simplified helium refrigerator cycle analysis using the ‘Carnot Step’,” Adv. Cryo. Eng., 51, AIP, 2006
- Ganni, Knudsen, “Optimal design and operation of helium refrigeration systems using the Ganni cycle,” Adv. Cryo. Eng., 55, AIP, 2010

New 12kW 20K Helium Refrigerator

- Detailed JLab analysis examined,
  - Real fluid effects
  - More precise compressor performance characteristics
  - More precise expander performance characteristics
  - HX cooling curves
  - Pressure drop vs. flow effects
  - Exergy losses
  - More precise input power & process efficiency estimates
  - Turn-down & off-design performance
- Determine trade-offs
  - Compressor frame size
  - HX arrangement for different modes of operation
    - i.e., layering, turn-down effects, imbalance vs. effectiveness, etc.

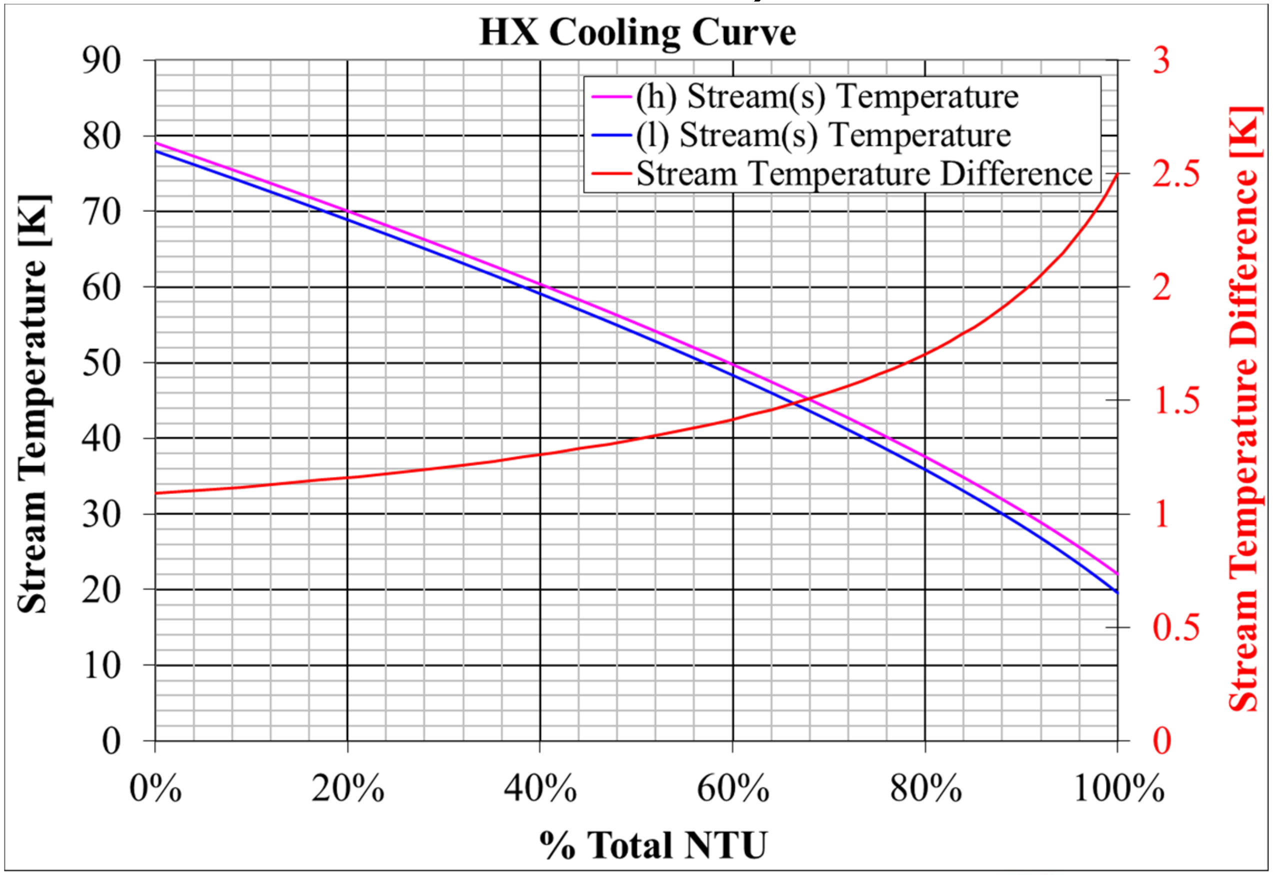
New 12kW 20K Helium Refrigerator

- Simulation of process…



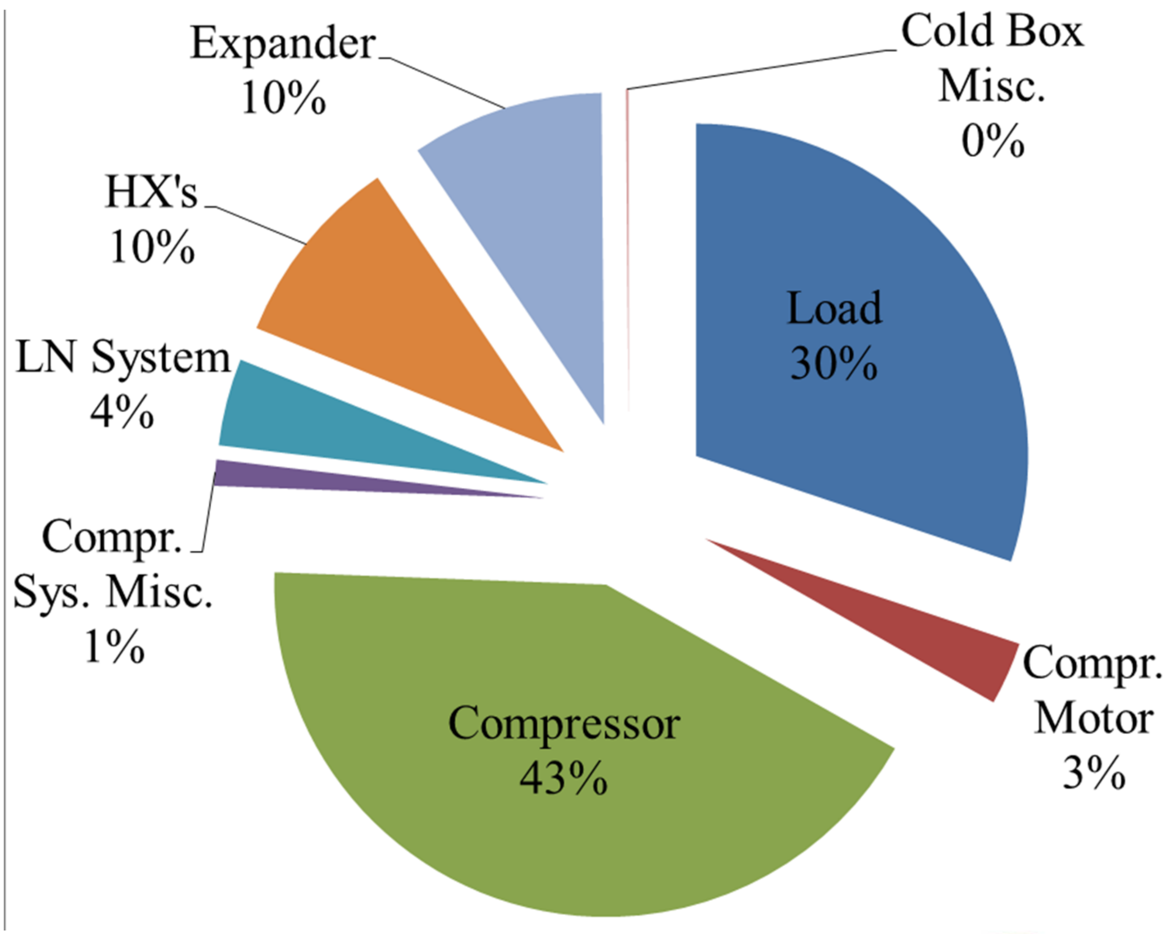
New 12kW 20K Helium Refrigerator

- Heat exchanger simulation – cooling curve…
  - (20K 14 atm 14.4 kW 0.3 DP)



New 12kW 20K Helium Refrigerator

- Exergy Usage (20K 14 atm 14.4 kW 0.3 DP)



New 12kW 20K Helium Refrigerator

- For modern helium systems, we typically use oil-flooded rotary screw compressors
- These are fixed displacement devices (as opposed to a centrifugal pump)

New 12kW 20K Helium Refrigerator

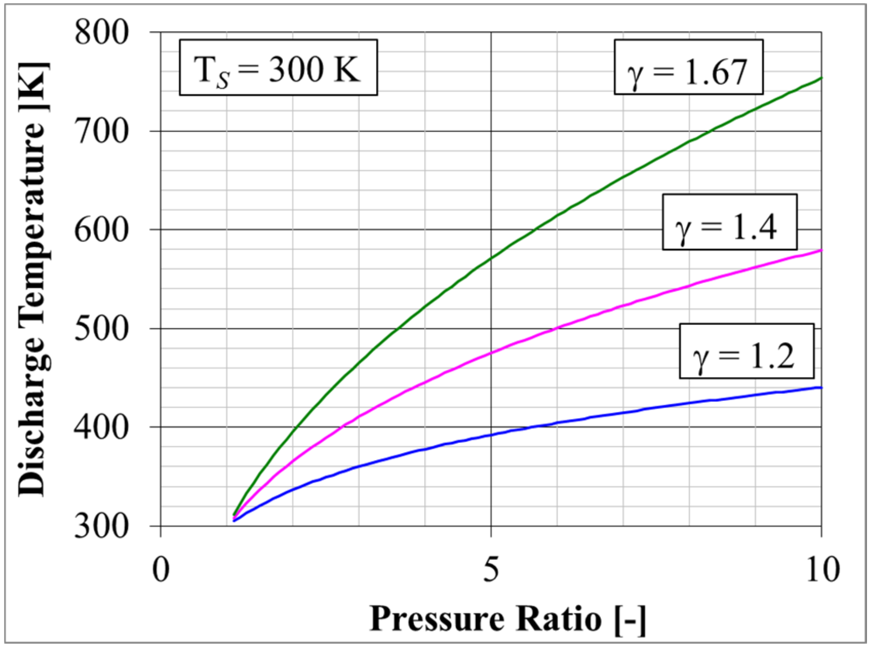
- Why use an oil-flooded (as opposed to "dry")?

  $T_D = T_S \cdot p_r^{\phi}$ where, $\phi = (\gamma - 1)/\gamma = 0.4$ for helium

  – Common refrigerants, $\gamma \approx 1.2$

  – Air, nitrogen, $\gamma = 1.4$

  – Helium, $\gamma = 1.667$



  – Note: above ~400 K, seals will tend to fail quickly

- Still need lubrication for the bearings!

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New 12kW 20K Helium Refrigerator

- How much oil is circulating with the helium?
  - Enough to keep the helium discharge temperature (out of the compressor) below 372 K
    - But if it runs too much cooler, the overall process will be consume more power due to increased oil viscosity
  - Typical of helium screw compressors:
    - Oil to helium mass flow ratio: ~ 10 to 25
    - But, volume ratio < 1%
    - Can use a polyalkylene glycol (PAG) or polyalphaolefin (PAO)
      - These don't mix!
    - JLab uses DOW/UCON LN-170X (PAG)

New 12kW 20K Helium Refrigerator

- How to we characterize the compressors?
  - Volumetric efficiency

    η_v = ratio of actual to theoretical mass flow rate

    - For a fixed displacement compressor (like a rotary screw or piston) compressor, the mass flow is primarily determined by the suction density
  - Isothermal efficiency

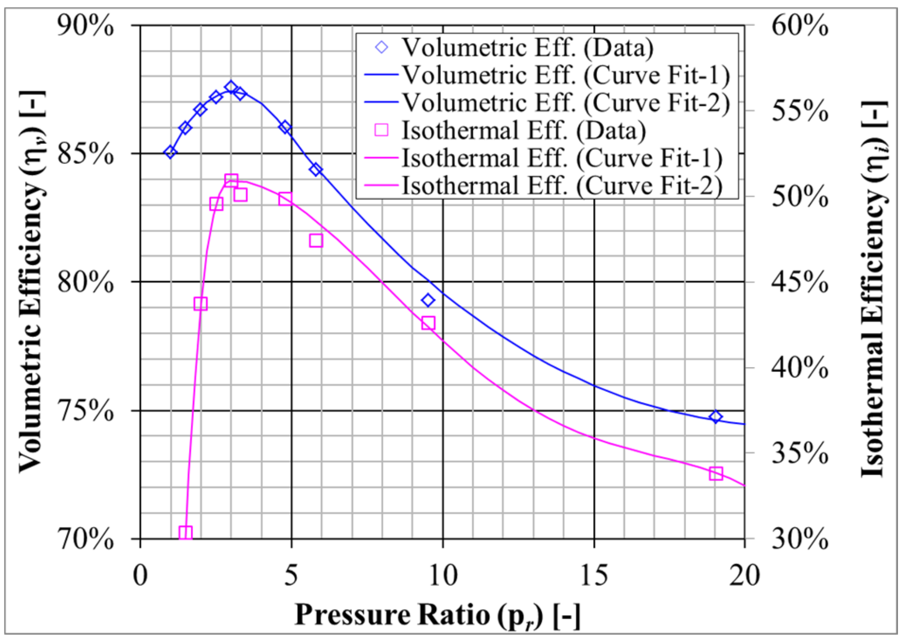
    η_i = ratio of theoretical (isothermal) to actual shaft power req'd

    - Use actual mass flow (not theoretical)
    - Could use adiabatic efficiency (they are related)…but,
    - For helium systems, the "ideal" warm compression process is isothermal…not adiabatic
  - These efficiencies are strong functions of the pressure ratio

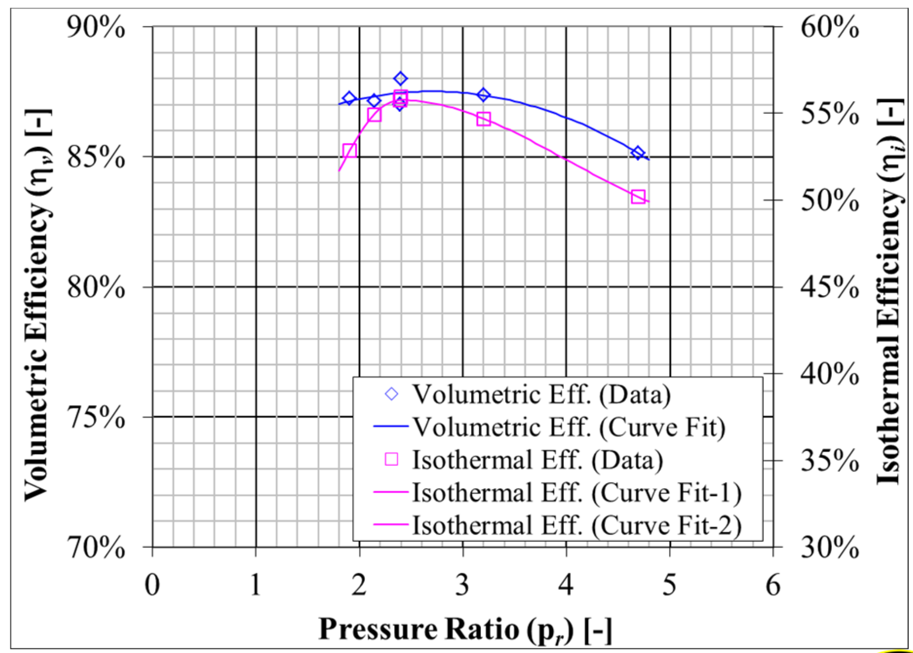
New 12kW 20K Helium Refrigerator

- Characterization of compressors…continued
  - Empirical values for η_v and η_i, derived from testing done at the SSC and SNS by present JLab staff
  - Note: Peak (maximum) volumetric and isothermal efficiency at a pressure ratio of ~2.5 to 3.5

LP Stage



HP Stage



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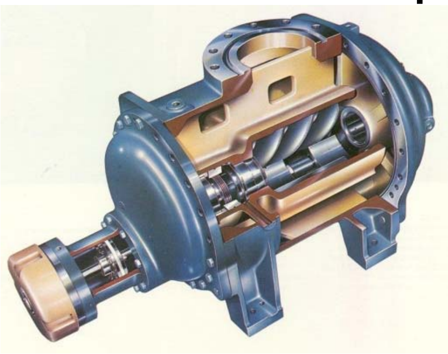
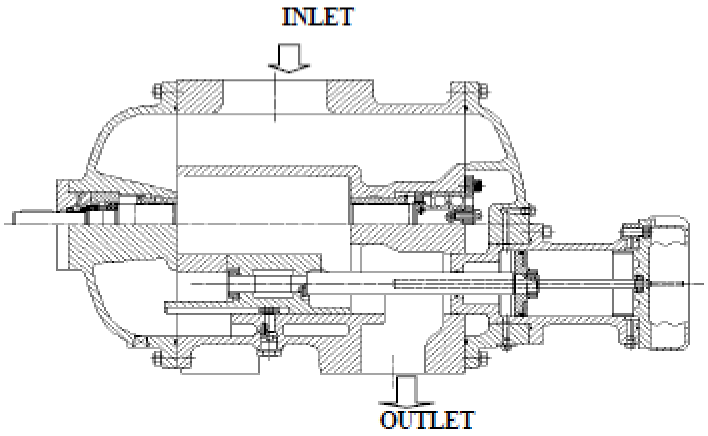
New 12kW 20K Helium Refrigerator

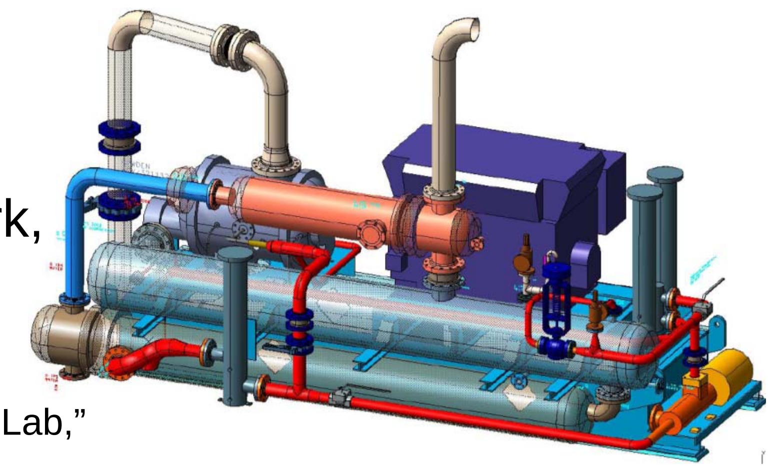
- For NASA-JSC, selected Howden WRVi 321/132
  - Rotary screw compressor – positive displacement
    - Male (4 lobes) & female (6 flutes) helical rotors
  - 321 mm diameter rotors (OD)
  - 1.32 Length to diameter ratio
  - Equipped with variable built-in volume ratio adjustment (manual)
  - 21.32 ℓ/rev of swept volume
    - 2673 CFM at 3550 rpm





New 12kW 20K Helium Refrigerator

- Compressor Development at JLab
  - Used compressor for NASA-JSC as a proto-type for 12GeV compressors
  - Implemented a number of fundamental compressor skid changes to improve efficiency, reliability and maintainability
  - For a description of the development work, refer to:



Ganni, et al, "Compressor system for the 12 GeV upgrade at JLab," Proc. ICEC-23

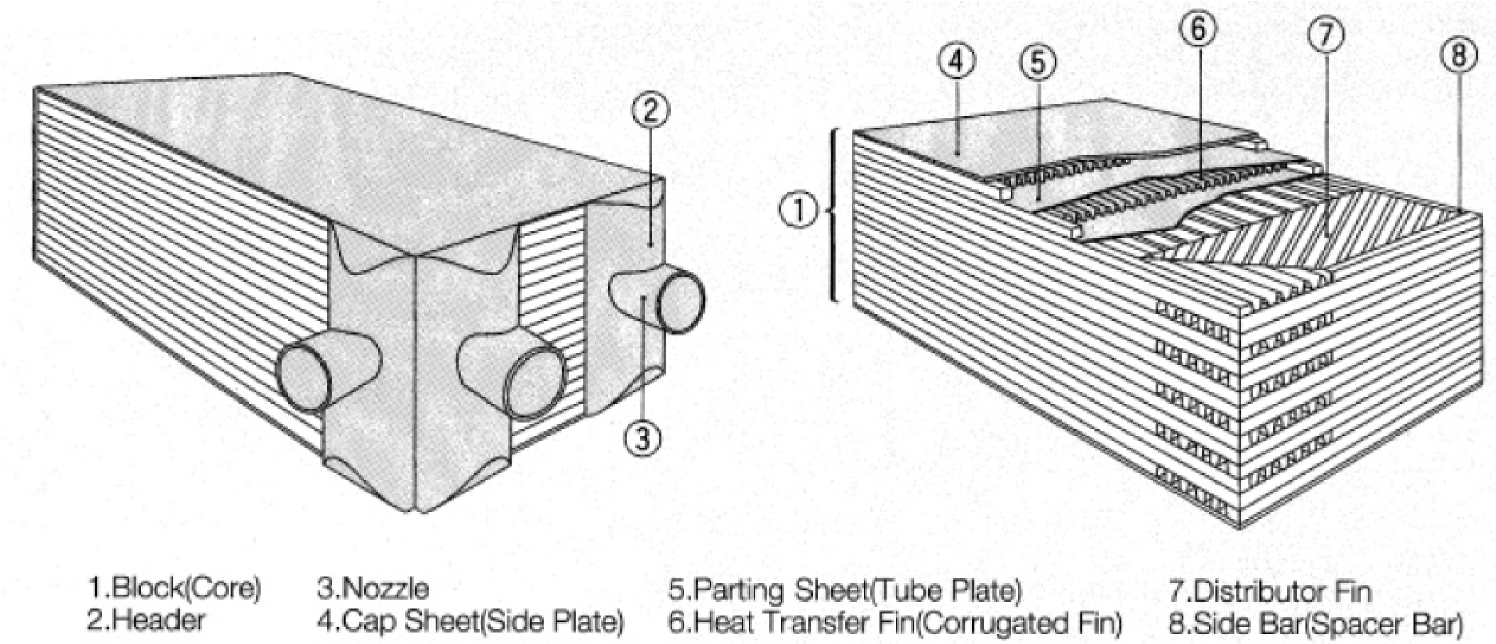
  - Compressor for new helium refrigerator built by Salof per JLab/NASA specifications and drawings

New 12kW 20K Helium Refrigerator

- CMP-3 at NASA-JSC

New 12kW 20K Helium Refrigerator

- Larger helium refrigerators typically use…
- Brazed aluminum plate-fin heat exchangers
  - Very “compact” (thermally)
    - Ratio of heat transfer surface area to total volume is typically ~1000 m^2 / m^3
  - Capable of yielding very high effectiveness (>98.5% for balanced capacity streams



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New 12kW 20K Helium Refrigerator

- How do we characterize heat exchangers?
  - (UA) is the overall heat transfer coefficient * heat transfer surface area
    - It is a measure of the *size* of the heat exchanger
    - (UA) = ratio of total duty (q) to effective temperature difference (ΔT_{LM})

      q is the heat transferred from one stream to the other

      ΔT_{LM} – the "log-mean" temperature difference
  - NTU or "no. of thermal transfer units"
    - It is a measure of the *length* of the heat exchanger
    - NTU = ratio of largest stream temperature difference (ΔT_{max}) to the effective temperature difference (ΔT_{LM})

New 12kW 20K Helium Refrigerator

- Heat exchanger specifications (JLab) vs. provided (SPP)

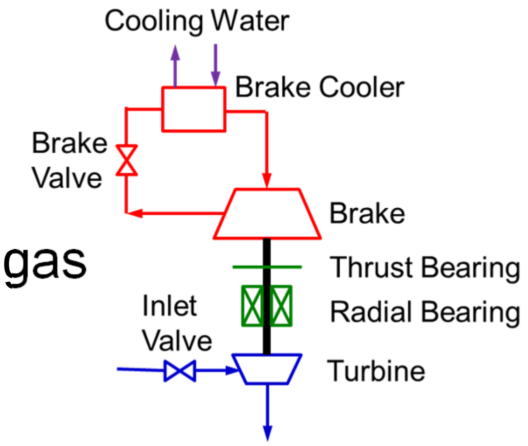
			q_h [kW]	(UA) [kW/K]	NTU [-]	L_{eff} [mm]	β [m^2/m^3]
HX-1	**Mode-1**	*JLab*	436.7	70.7	36.0	3320	1042
		SPP	450.8	90.6	46.3		
HX-2A	**Mode-2**	*JLab*	41.7	5.2	27.6	2240	1101
		SPP	45.2	4.8	24.6		
HX-2B	**Mode-2**	*JLab*	33.5	7.1	3.4	350	767
		SPP	35.7	7.4	3.7		
HX-3	**Mode-1**	*JLab*	117.0	72.4	36.0	4460	1311
		SPP	118.4	105.2	52.7		

Note:
1. L_{eff} is the effective length provided by SPP's HX design
2. β is from SPP's design

- HX's manufactured by Sumitomo Precision Products (SPP)

New 12kW 20K Helium Refrigerator

- Turbo-expanders are typically used (vs. reciprocating piston expanders)
  - Since they are more reliable and have higher capacity
- Turbo-expander basic components
  - Turbine wheel: extracts energy from process
  - Brake (compressor) wheel: compresses ambient gas
  - Brake valve: dissipates pressure exergy
  - Brake cooler: removes (brake) compression heat
  - Bearings: radial and thrust



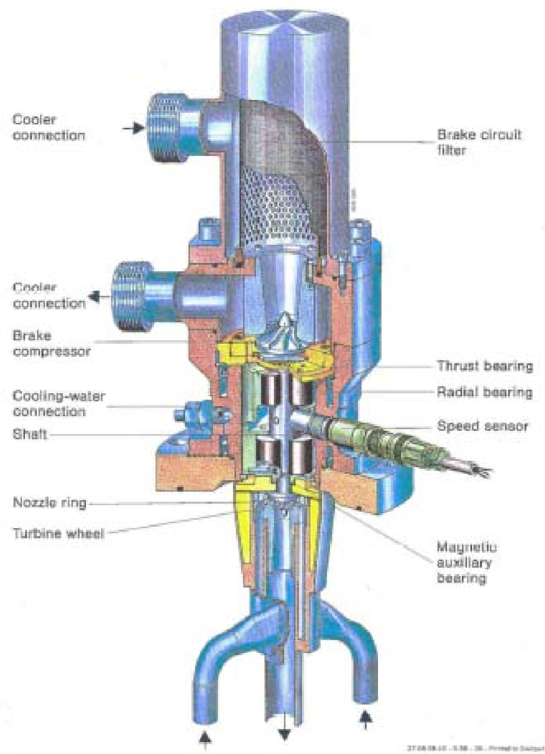
- Basic classifications for turbo-expanders used for helium systems
  - Wheel: more radial, less radial (more "3D")
    - i.e., increasing specific speed
  - Bearing type: oil, static gas, dynamic gas
  - Brake type: fixed, variable

New 12kW 20K Helium Refrigerator

- Turbine bearing types
  - Oil bearing
    - Can be used with a fixed or variable brake
    - Not used in modern helium systems due to contamination potential
  - Static gas bearing
    - Usually used with a fixed brake
    - Resilient to back-pressure surges and capable of higher bearing loads (at low and higher temperatures)
    - Usually lower adiabatic efficiency, since some of bearing gas must leak into process stream
  - Dynamic gas bearing
    - Usually used with variable brake
    - More vulnerable to back-pressure surges and lower bearing capacity (at low and higher temperatures)
    - Usually higher adiabatic efficiency

New 12kW 20K Helium Refrigerator

- For new refrigerator, we verified turbine expander number, size, efficiency with manufacturer (Linde)
  - This was actually a development project for Linde
  - Two turbines were required for,
    - Backup for 20K mode, and,
    - 100K mode
  - Required (approx.):
    - 30.5 kW max. power output
    - 158 J/g max. enthalpy drop
    - >80% adiabatic efficiency
  - Use two TED45-50KN
    - 50 mm dia. process (turbine) wheel
    - 80 mm dia. brake (compressor) wheel



Basic Design Ideas

- Cryogenic helium refrigerators tend to:
  - Have unique load requirements (from the end-users)
  - Operate at different load conditions than designed
    - Usually due to the uncertainly in loads
  - Have components that may (and often) operate differently than designed
    - Since these plants are so specialized
  - Have a long lifetime and are often used for more than one program or project
- Consequently we believe it is wise to:
  - Design the refrigerator around more modes than usually specified by the end-user
    - To establish a "well-balanced" plant

Basic Design Ideas

- Does it cost more to have a system designed for more than one mode?
  - Process analysis (to study the modes) is maybe $\approx$ 1% of the total project cost
    - So, invest the time and put the thought into it!
  - Variation in the actual size and complexity of 'passive' equipment is insignificant compared to the project cost
    - e.g., a heat exchanger cost is driven more by the number of separate 'cores' then by a core that is 50% larger.
  - A more (overall) efficient helium system *does*:
    - Cost less to build
    - Cost less to operate, and,
    - Have better reliability

Floating Pressure Process

- Traditionally, helium refrigerators have been design around the anticipated maximum capacity mode; e.g. a single, or maybe two modes
- At reduced or off-design loads, this typically results in "driving a car with the 'pedal to the metal' but adjusting the speed with the brake"

- The Ganni Cycle – Floating Pressure Process is essentially a *constant pressure ratio process* that allows the refrigeration system to automatically adjust its gas charge to match the load (as it varies) – *while maintaining high system efficiency*

Modification of NASA-JSC 20K 3.5kW Helium Refrigerator

- In 2008, JLab provided direction to modify TCF50 helium system
  - Implemented floating pressure process (patent pending)
    - Ref. Ganni, Knudsen, "Optimal design and operation of helium refrigeration systems using the Ganni cycle," Adv. Cryo. Eng., 55, AIP, 2010
  - Changed LN control to JLab standard
    - Ref. Knudsen, Ganni, "Helium refrigerator liquid nitrogen pre-cooler component parameter sensitivity analysis," Adv. Cryo. Eng., 55, AIP, 2010
  - *Required no new equipment*
  - Stabilized plant operation
  - Substantial improvement in plant turn-down efficiency
    - e.g., reduction in the inverse COP of ~ ½ at 50% of max. load
  - Reduced LN consumption
  - Improved load temperature to ±0.25 K (i.e. a factor of 10)

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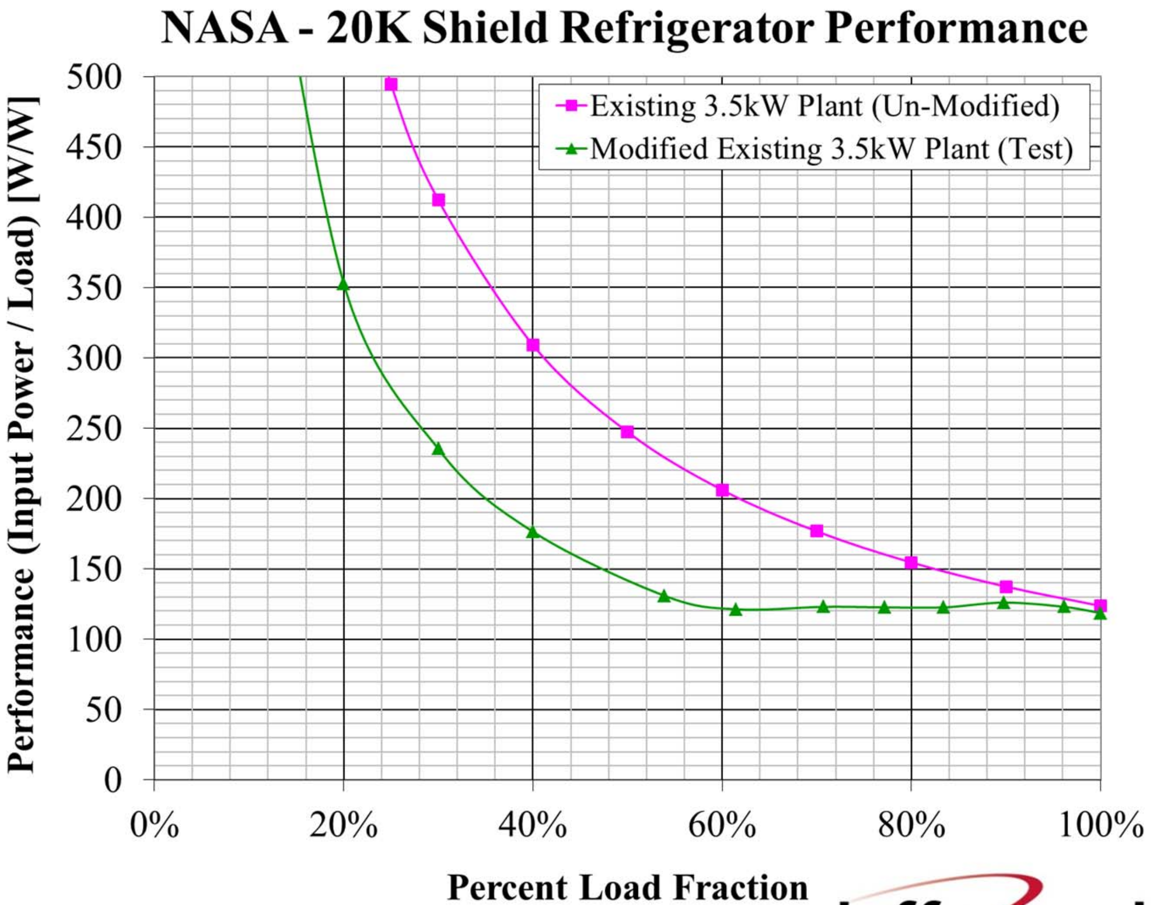
Modification of NASA-JSC 20K 3.5kW Helium Refrigerator

Inverse Coefficient of Performance,

COP_{inv} = total input power / refrigeration load



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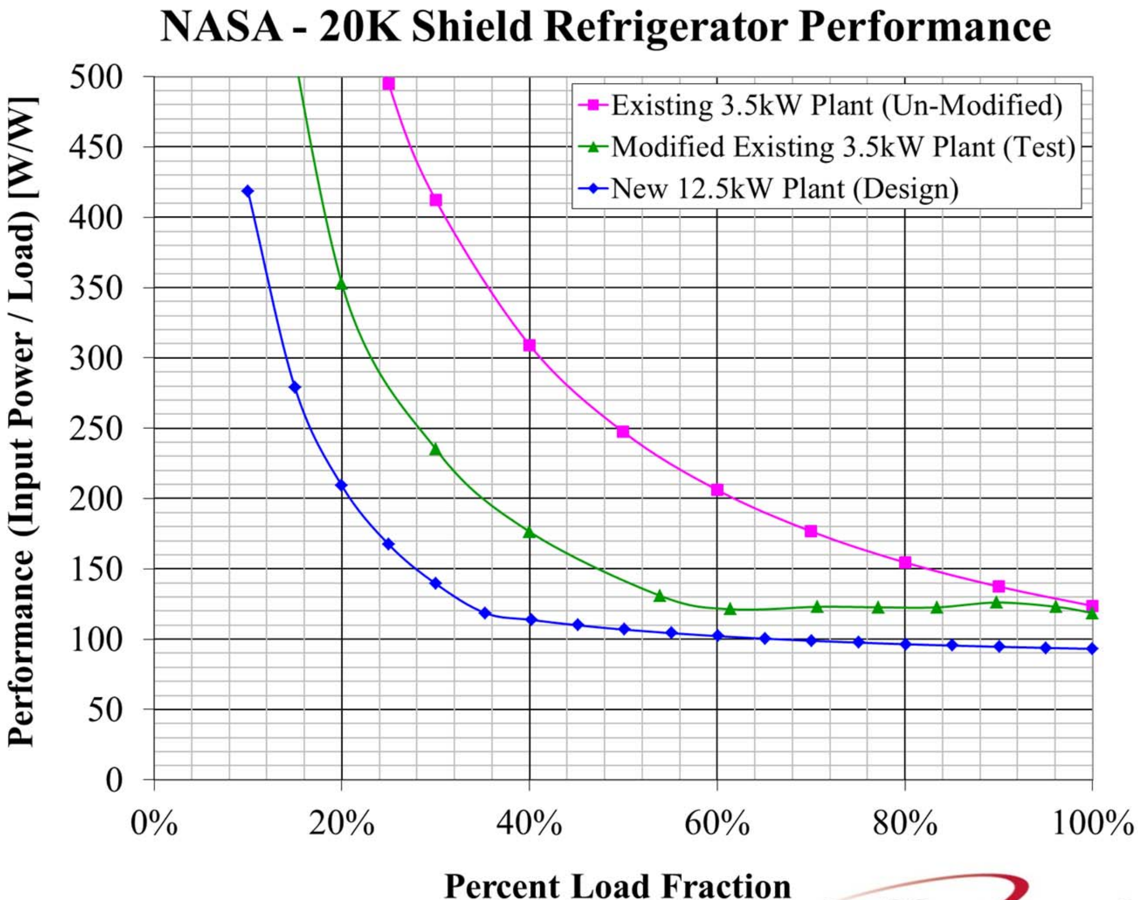
New 12kW 20K Helium Refrigerator

- Getting back to the new helium refrigerator…
- Anticipated performance



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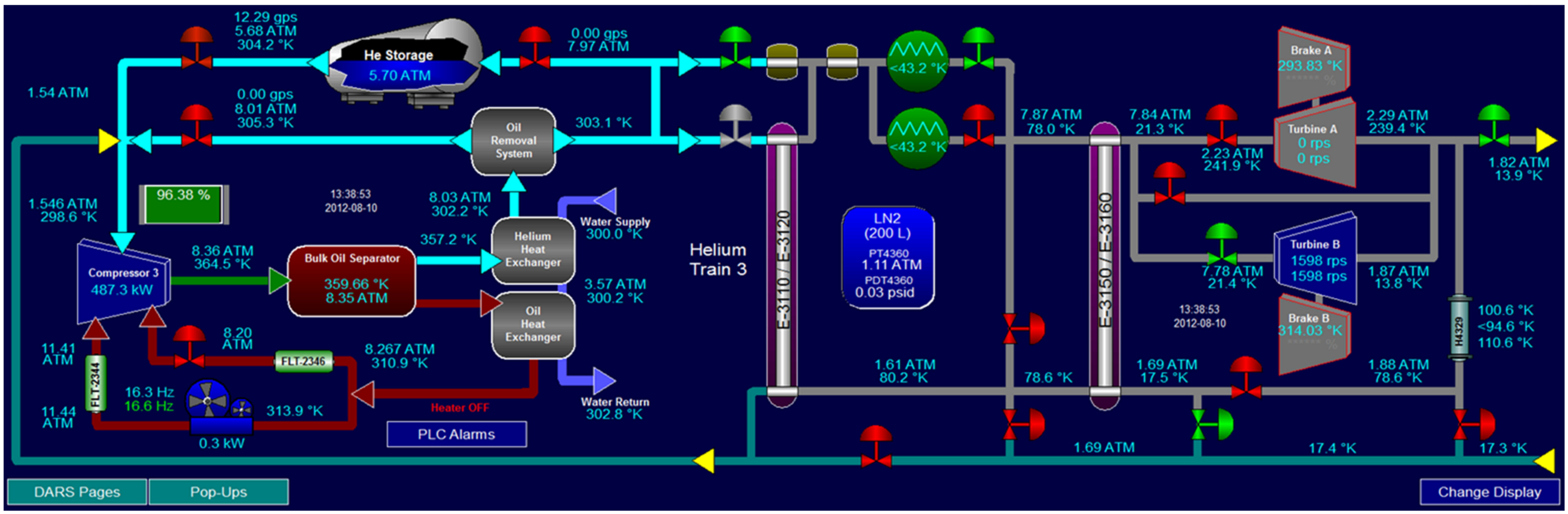
New 12kW 20K Helium Refrigerator

- Cold box built by Linde per JLab/NASA specification
  - Ref. Arnold, "Large Scale Refrigerator Plant for Ground Testing the James Webb Telescope at NASA Johnson Space Center," Adv. Cryo. Eng., 55, AIP, 2010

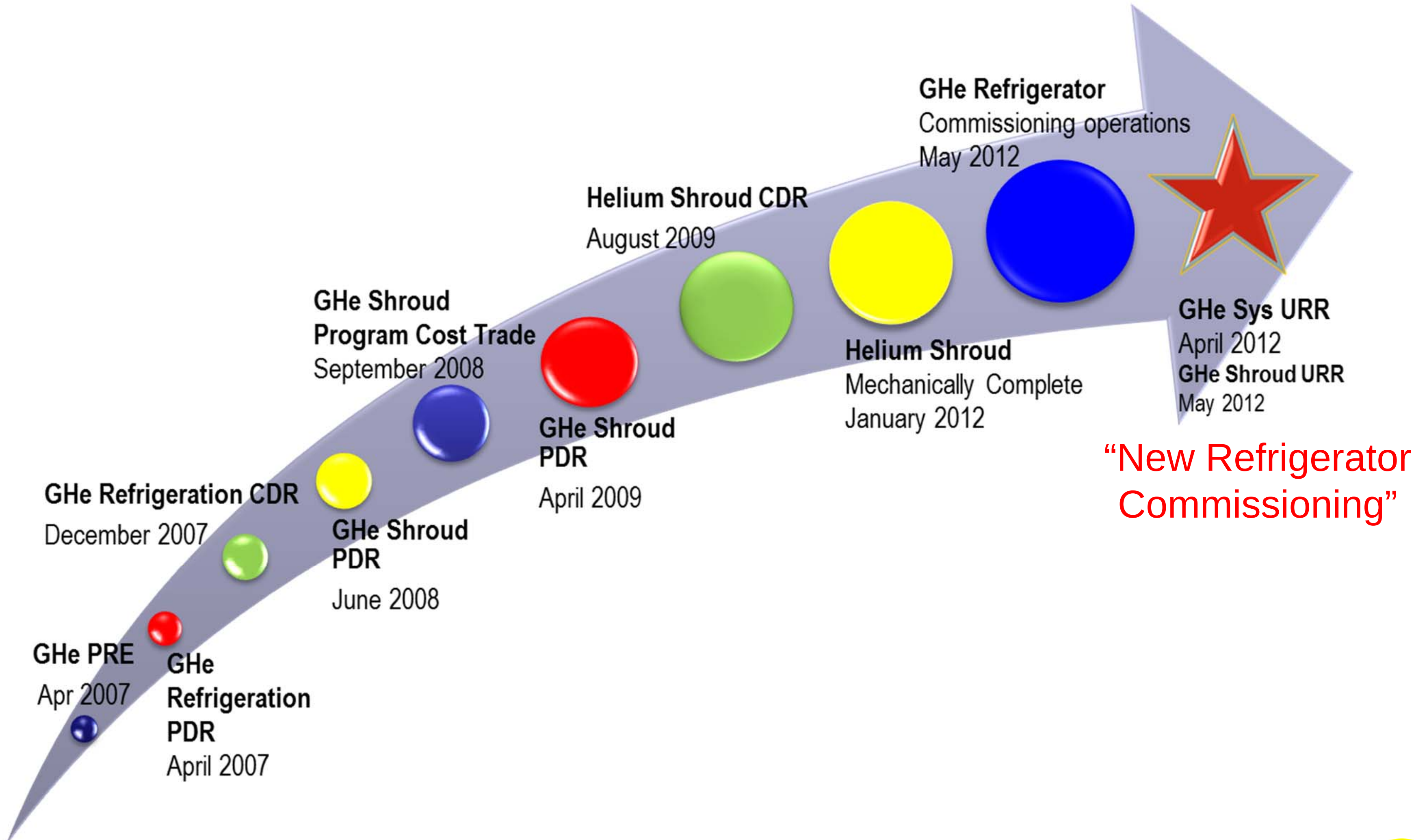
- Compressor system built by Salof per JLab/NASA fabrication drawings

New 12kW 20K Helium Refrigerator

- Control screen (example)



Chamber A – Helium System Project History



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Commissioning

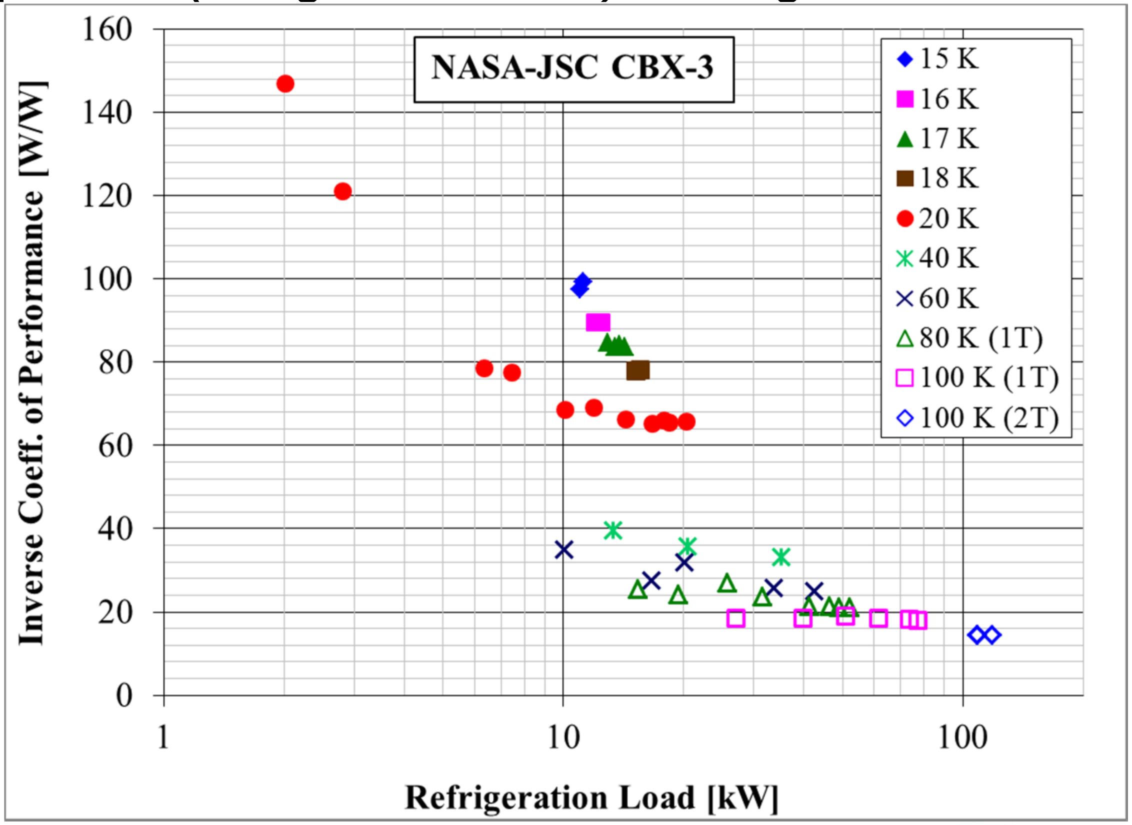
- Some general ideas in the analysis of test data
  - What are the most influential process parameters?
    - (1) Refrigeration load
    - (2) Mass flow
    - (3) Turbine output work: typically ascertained by inlet and outlet, pressures and temperatures
  - How to assure the above parameters are measured accurately?
    - Selection of instrument/device; e.g., venturi vs. orifice meter, SSR vs. SCR heater
    - Design of instrument/device for transducer used; e.g., sufficient venturi pressure difference over flow range to provide enough resolution for good accuracy?
    - Calibrate…properly! Is it being done under the correct conditions?
  - Cross-checked parameters during testing!

Commissioning of CBX-3

- Heat exchangers
  - Performed “well” (but still analyzing data)
- Turbines
  - Max. power output ~50 kW
    - Will not operate at this level (…will limit to ~40 kW)
    - As mentioned, these turbines were a development effort for Linde
    - Turbines were tested to find their limits
  - Operated at a pressure ratio of ~2.1 to 9.2
  - Adiabatic efficiency,
    - ~85% below an inlet temperature of 80 K
    - ~77.5% for single turbine operation above an inlet temp. of 80K
      - Note: pressure ratio across turbine is higher for single turbine operation than for two turbine operation
    - ~80.5% for two turbine operation at 100 K max. capacity

Commissioning of CBX-3

- Performance
  - Unprecedented load range: 11.2 kW at 15K…to…118 kW at 100K
  - *<u>Note</u>: x-axis (refrigeration load) is a log scale*



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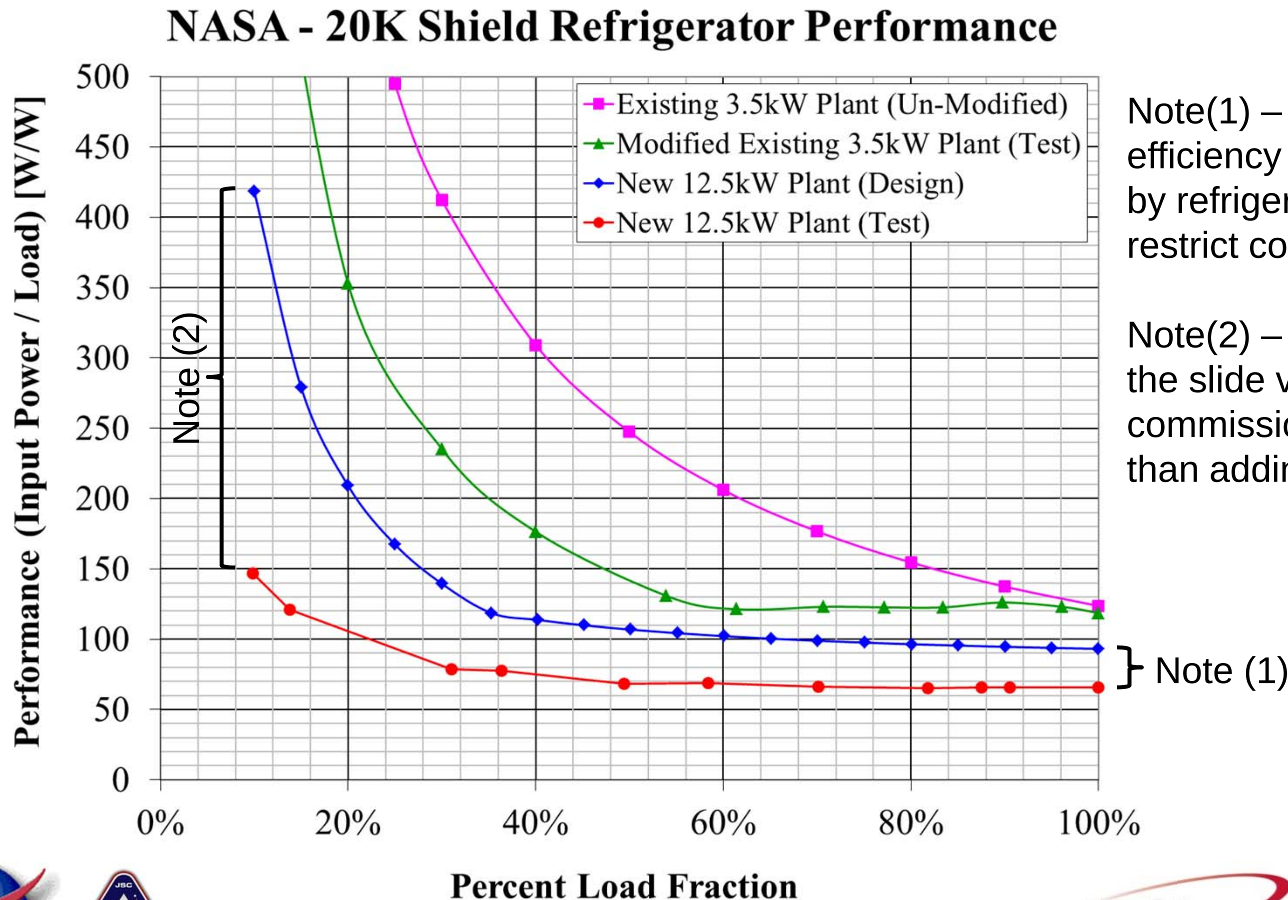
Commissioning of CBX-3

- Performance…continued
  - Essentially constant efficiency down to ~1/3 of max. 20K load!



Note(1) – Offset due to actual expander efficiency higher than minimum required by refrigerator specification (so as not to restrict competition).

Note(2) – Increased offset due to using the slide valve at low loads during commissioning (which is more efficient) than adding heat.

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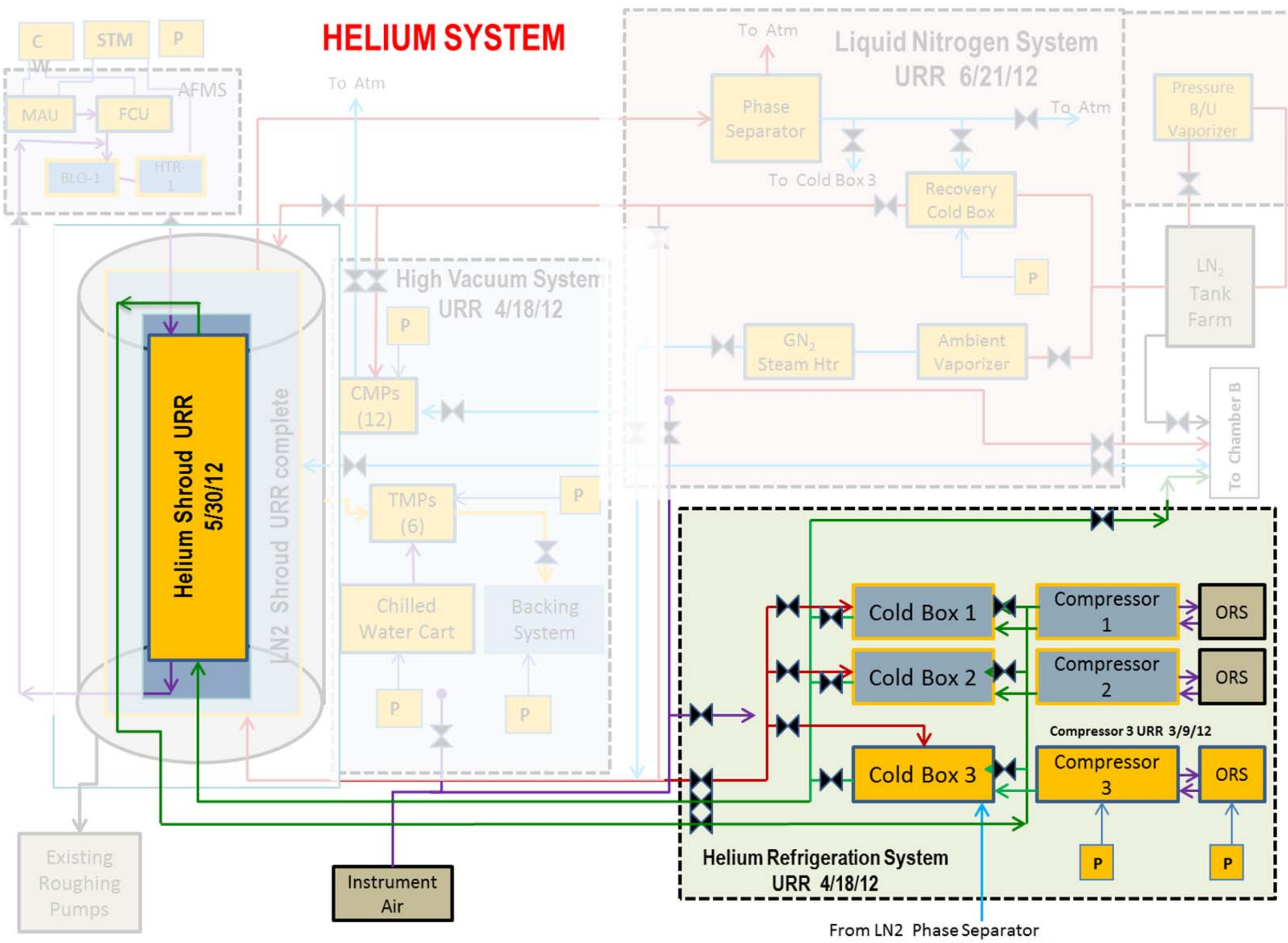
Chamber A – Helium System



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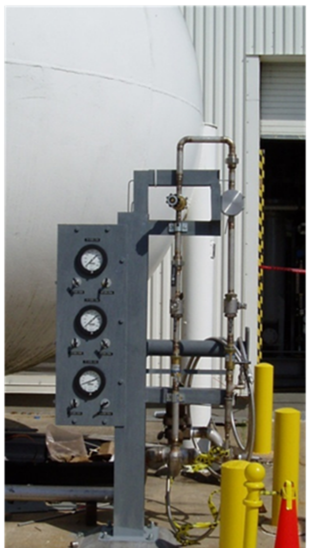
Chamber A – Helium System

Supply and Storage



Loading Station
2,500 psi reducing to 250 psi

Storage

Storage
4,000CF 250 psi

Tube Trailer

Chamber A – Helium System

Oil Removal System

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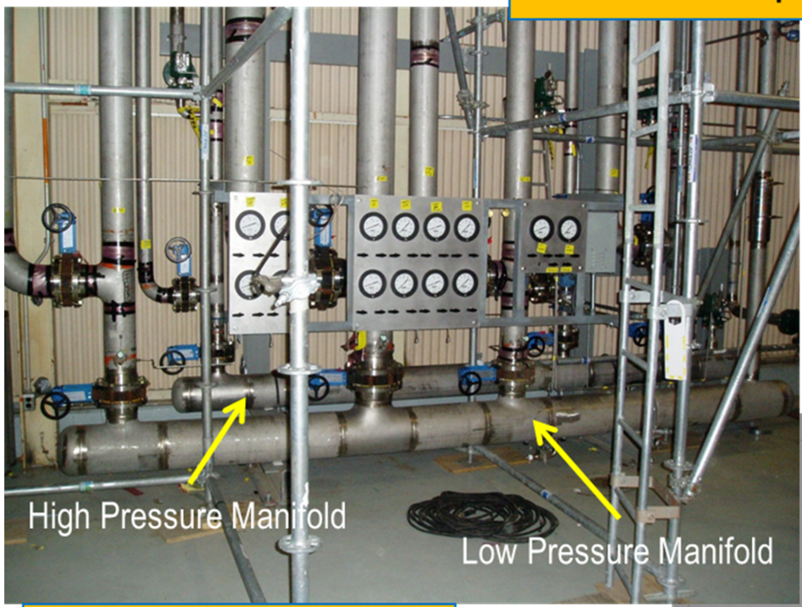
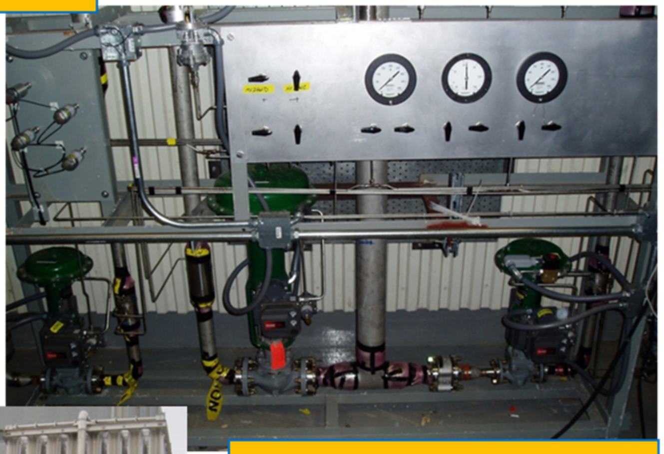
Chamber A – Helium System

Warm Piping



Warm Piping Manifolds
in R1904



Gas Management Skid
In R1904B

Ambient Heat
Exchanger 3

Chamber A – Helium System

Cold Box 1 & 2

Cold Box 3

Chamber A – Helium System

Cold Piping

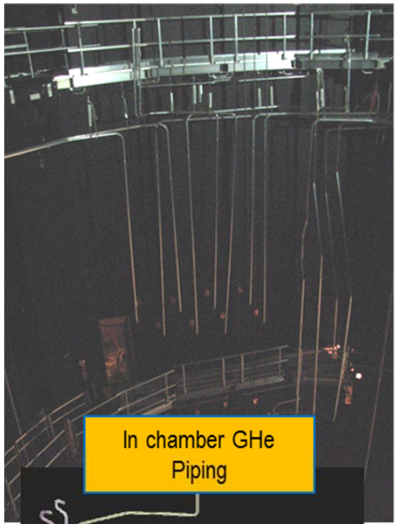
VJ Zone Supply Manifolds
North Platforms

VJ Manifold in R1904

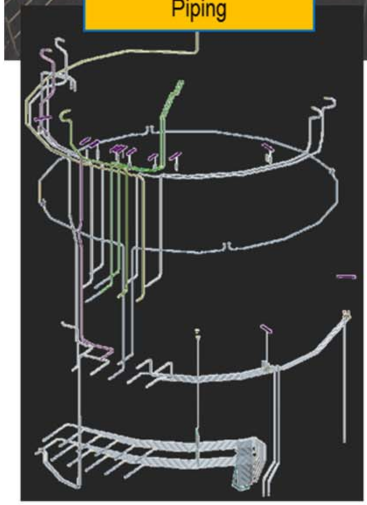
Bakeout Heater

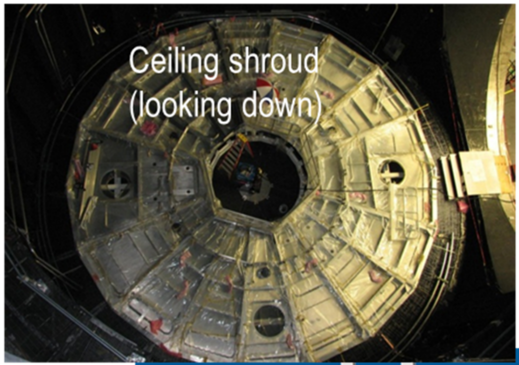
Chamber A – Helium System

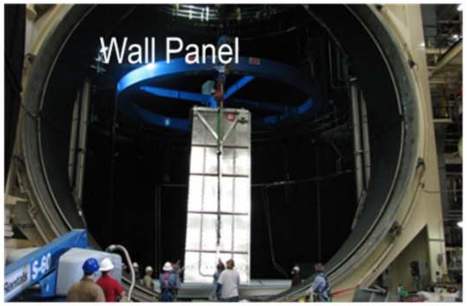
Internal Piping and GHe Shroud

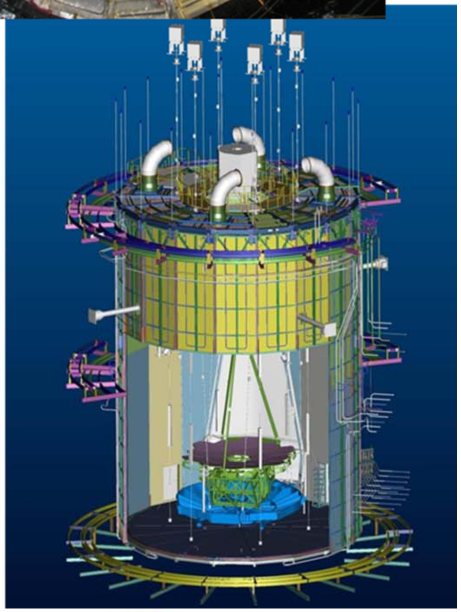


In chamber GHe Piping









Functional Test Summary (Aug. 2012)

- Objectives
  - Bakeout
    - Goal: average shroud temperature of 330 K
    - Results: achieved 332 K
  - Cool-Down
    - Goal: 48 hrs for shrouds to reach 20 K
    - Result: ~30 hrs
  - Cool-down “as low as possible”
    - Cooled shrouds below 15 K

Functional Test Summary (Aug. 2012)

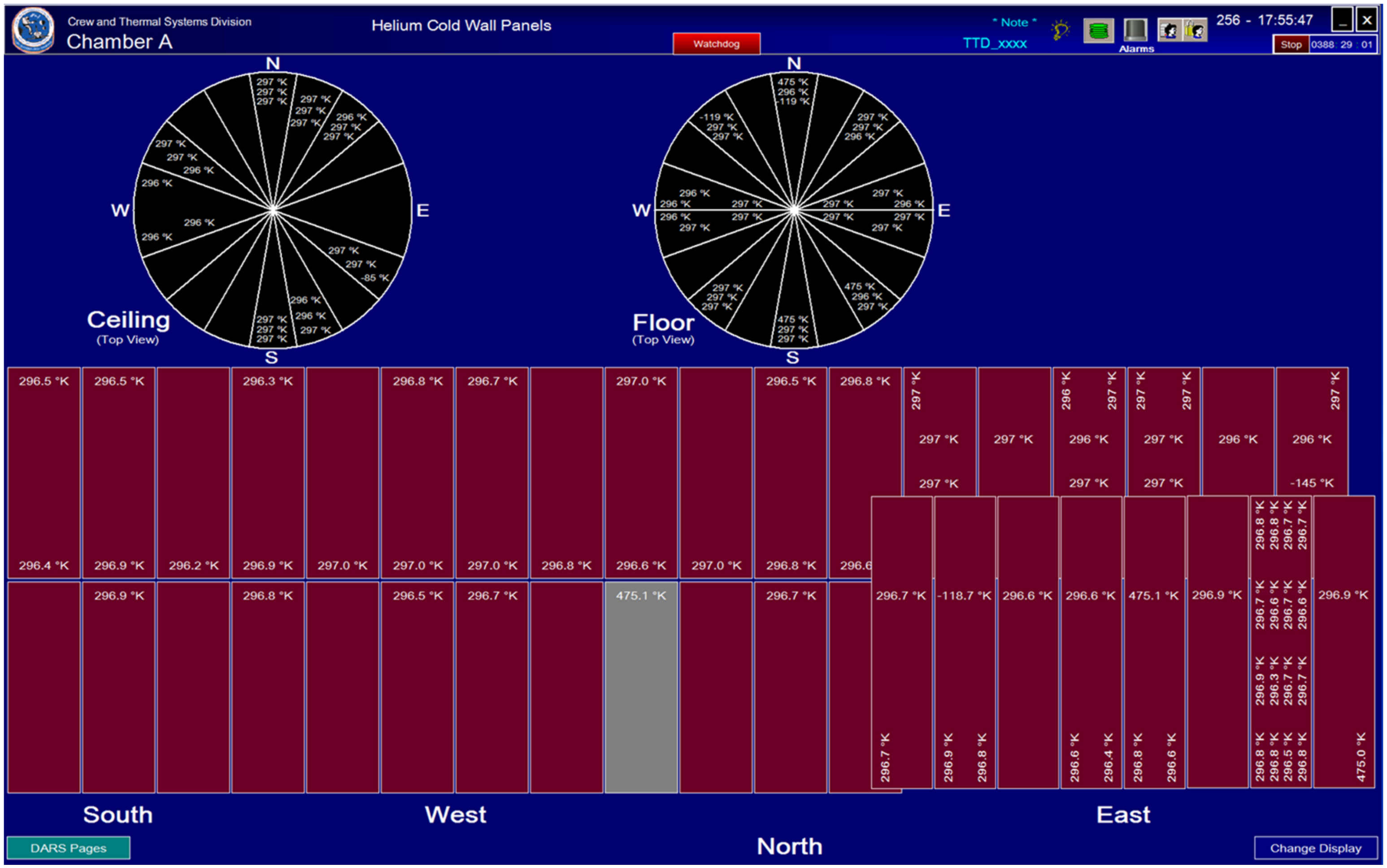
- Objectives…continued
  - Measure static load ("clean dry empty")
    - ~2.5 kW at 20 K
  - Measure load with helium backfill
    - Raised chamber pressure with helium to 10^{-3} Torr
    - Added ~5 kW of additional load (i.e., total ~7.5 kW load)
  - Control warm-up to allow slow release of condensed air
    - Controlled shroud to 26 K and observed release
  - Measure control temperature range
    - Able to vary helium shroud temperature anywhere between 16 to 330 K

Functional Test Summary (Aug. 2012)

- Objectives…continued
  - Verify helium tight
    - No helium loss
  - Verify temperature stability
    - Goal: ±0.25 K (at 20 K)
    - Stability ~ ±0.1 K
  - Verify refrigerator performance
    - Inverse coefficient of performance ~66 W/W at peak operation
    - Unprecedented turn-down capability: maintained essentially constant efficiency down to 1/3 of max. capacity
    - Unprecedented load range: 11.2 kW at 15K…to…118 kW at 100K

Functional Test – Helium Shrouds

- Helium shrouds (cryo-panels) initially (at start)



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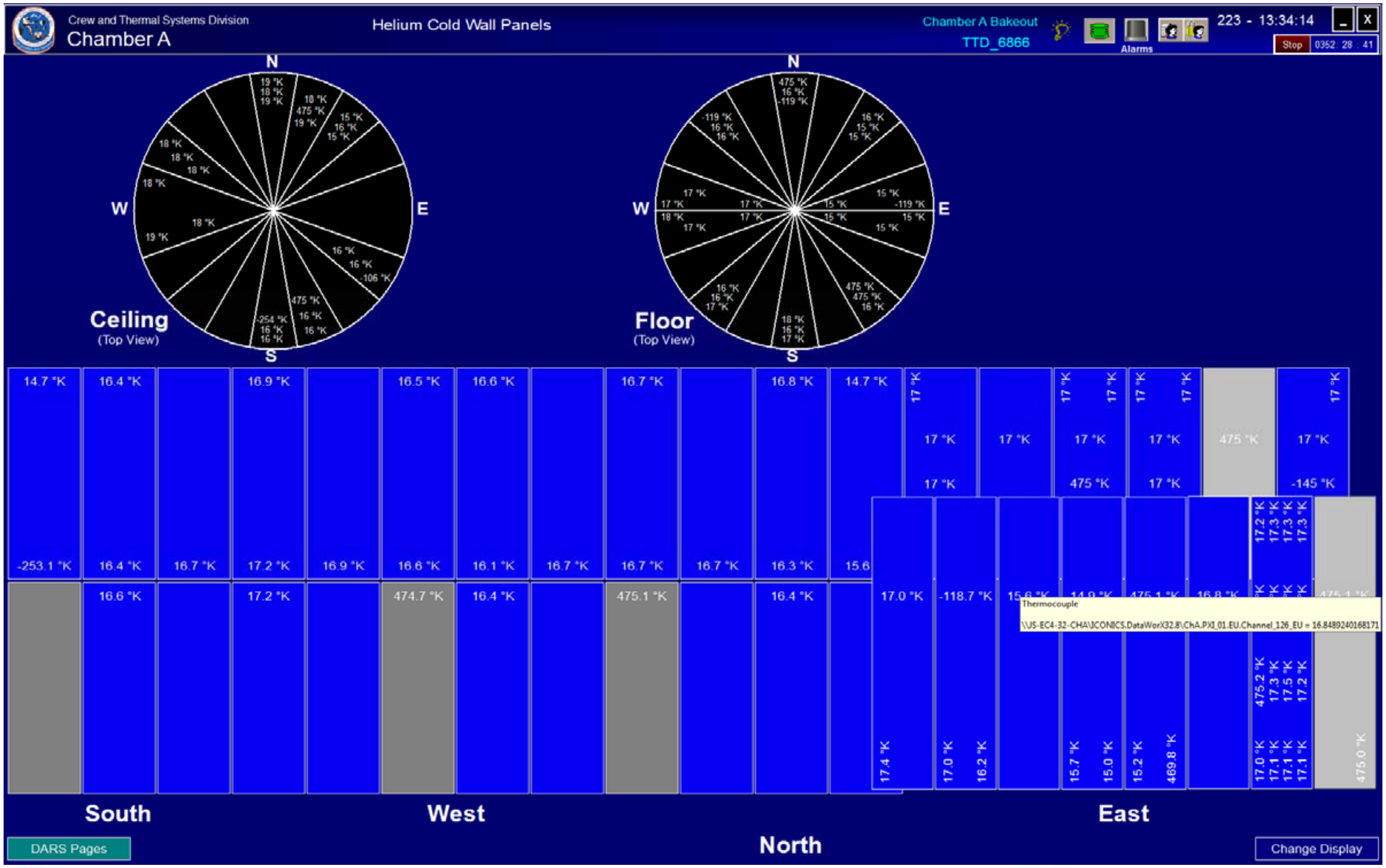
Functional Test – Helium Shrouds

- Helium shrouds (cryo-panels) at steady state



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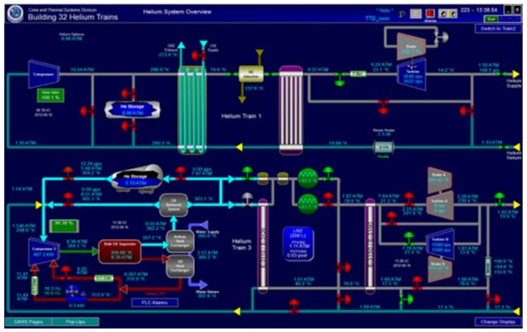
Conclusions



Chamber A Successfully Passed and Exceeded All Expectations for

August 2012 Functional Test

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