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ADVANCED CRYOGENIC INSULATION SYSTEMS

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INTRODUCTION

- What is the "best insulation system" for a given design situation?
  - System design, engineering analysis, and thermal testing (materials) go hand-in-hand
- Conducting analysis and calculations according to standard methods:
  - Essential for fair comparison of different materials and accurate applications of results
- Testing to measure of the total heat transmission (Q) into a cryogenic system
  - Relevant conditions typically include a large temperature difference (ΔT) and a controlled, steady-state test environment or vacuum level
- Examples of cryogenic storage tanks and transfer piping are analyzed:
  - Determine the relative importance of both insulation and structural materials for achieving designs of highest energy efficiency

CALCULATIONS OF HEAT TRANSMISSION

- Follow the guidance given in ASTM C1774 *Standard Guide for Thermal Performance Testing of Cryogenic Insulation Systems*
  - Large ΔT: Warm Boundary Temperature (WBT) - Cold Boundary Temperature (CBT)
- The heat flow rate* (Q) in J/s and the effective thermal conductivity (k_e) in mW/m-K are calculated as follows:
  - Where $\dot{m}$-dot is the mass flow rate in g/s, h_{fg} is the heat of vaporization in J/g, A_e is the effective area for heat transmission in m^2, ΔT is the temperature difference in K, and Δx is the thickness in m
  - The system thermal conductivity (k_s) is defined as the thermal conductivity value through the total system including all ancillary elements such as packaging, supports, seams, joints, piping penetrations, feedthroughs, structures, etc.

$$Q = \dot{m} h_{fg} = k_e A_e \frac{\Delta T}{\Delta x}$$

$$k_e = \frac{Q}{A_e} \frac{\Delta x}{\Delta T}$$

*Heat leak or heat load or heat transmission

CALCULATIONS OF HEAT TRANSMISSION

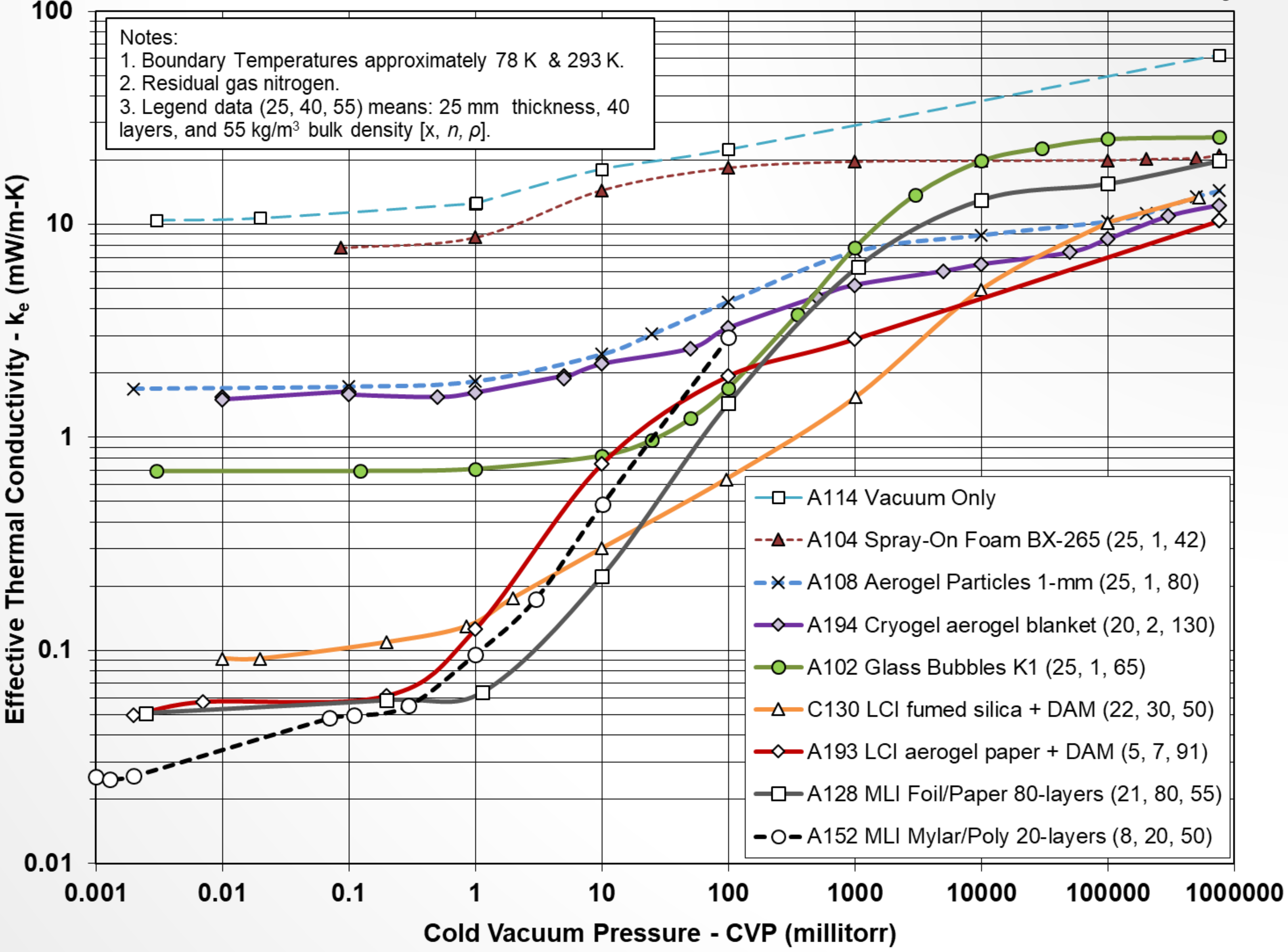
- The Q is obtained in a *direct* way by boiloff calorimetry
- Effective area of heat transmission (A_e):
  - For flat plate geometry, the A_e is constant through the thickness of the thermal insulation system
  - For cylindrical or spherical geometries, the A_e is the log-mean area between the inner and outer diameters of the thermal insulation system
- From the Q, the heat flux (q) in W/m^2 is calculated:
  - Heat flow rate, under steady-state conditions, through the A_e in m^2, in a direction perpendicular to the plane of the thermal insulation system
- For all calculations in this study, the k_e or k_s (as applicable) and the q are based on a standard ΔT of 215 K (that is, for 293 K WBT & 78 K CBT)

$$q = \frac{Q}{A_e}$$

CRYOSTAT-100 TEST DATA FOR THERMAL INSULATION SYSTEMS

- Spray-On Foam (NCFI)
- Aerogel Particles (Cabot)
- Aerogel Blanket (Aspen Aerogels)
- Glass Bubbles (3M)
- Layered Composite Insulation (LCI)
- Multilayer Insulation (MLI)

✓ Boundary Temperatures = 78 K & 293 K
✓ Residual gas = nitrogen
✓ Thickness = as noted
✓ No. of Layers = as noted
✓ Bulk Density = as noted



Notes:
1. Boundary Temperatures approximately 78 K & 293 K.
2. Residual gas nitrogen.
3. Legend data (25, 40, 55) means: 25 mm thickness, 40 layers, and 55 kg/m^3 bulk density [x, *n*, *ρ*].

SELECT THERMAL CONDUCTIVITY DATA (CRYOSTAT-100) FOR CRYOGENIC THERMAL INSULATION SYSTEMS

- High vacuum (<0.1μ)
- Soft vacuum (~100 μ)
- No vacuum (760,000 μ)

Note: 1 μ = 1 millitorr = 0.133 Pa

Thermal Insulation System	**Ref. No.**	**†Density**	**CVP**	**$*k_e$**
		kg·m^{-3}	μ	mW/m-K
Glass Bubbles Type K1	A102	65	<0.1	0.70
			100	1.7
			760,000	26
Aerogel Particles (1-mm diameter)	A108	80	<0.1	1.7
			100	4.3
			760,000	14
LCI with fumed silica & Mylar	C130	50	<0.1	0.09
			100	0.64
			530,000	13.4
MLI 80-layers Foil and Paper	A128	55	<0.1	0.051
			100	1.5
			760,000	20
MLI 20-layers Mylar and Poly Net	A152	50	<0.1	0.026
			100	3.0
			760,000	18 (est.)

†As-tested *For boundary temperatures of 293 K and 78 K

STRUCTURAL-THERMAL MATERIALS

- Included are polyimide aerogel AeroZero®, Ultem®, Foamglas®, Divinycell®, and Rohacell®
- Included for reference: G10 composite, Teflon™, balsa wood, and polyisocyanurate spray foam
- k_e data from Macroflash (Cup Cryostat), per ASTM C1774 Annex A4, boundary temperatures of 78 K / 293 K, compressive load of 34 kPa
- Combined properties: Thermal Conductivity + Density + Strength

Thermal-Structural Figure-of-Merit (F_{ST})

where:

σ = compressive strength [MPa]

k_e = effective thermal conductivity [mW/mK]

ρ = bulk density [kg/m^3]

$$F_{ST} = \frac{\sigma}{\rho k_e} \text{ x } 10^6 \qquad \left[\frac{\mathrm{K \cdot m \cdot s}}{\mathrm{g}}\right]$$

THERMOPHYSICAL DATA FOR STRUCTURAL-THERMAL MATERIALS USED IN CRYOGENIC SYSTEMS

- Effective thermal conductivity data by **Macroflash**
- Bulk density
- Compressive strength

Material	†σ	ρ	*k_e	F_{ST}
	MPa	kg·m^{-3}	mW·m^{-1}·K^{-1}	K·m·s·g^{-1}
G-10 (transverse direction)	448	1,939	467	495
Ultem® 2300 Glass Filled PEI	221	1,500	212	695
Ultem® 9185 PEI (3-D printed)	100	1,199	145	575
Teflon™ PTFE	24.1	2,120	253	45
Rohacell® WF-300 PMI foam (14 kPa)	17.8	324	42.1	1,305
Balsa Wood (transverse direction)	7.0	166	45.9	919
AeroZero® polyimide aerogel	1.6	150	28.1	380
Foamglas® Cellular Glass Foam	0.8	118	32.3	210
Divinycell® H45 PVC Foam (14 kPa)	0.6	50	23.8	504
Spray Foam Polyiso BX-265 (14 kPa)	0.4	37	22.6	483

†At ambient temperature *Boundary temperatures 293 K / 78 K; compressive load 34 kPa or as noted.

CRYOGENIC SYSTEM HEAT LEAK ANALYSIS

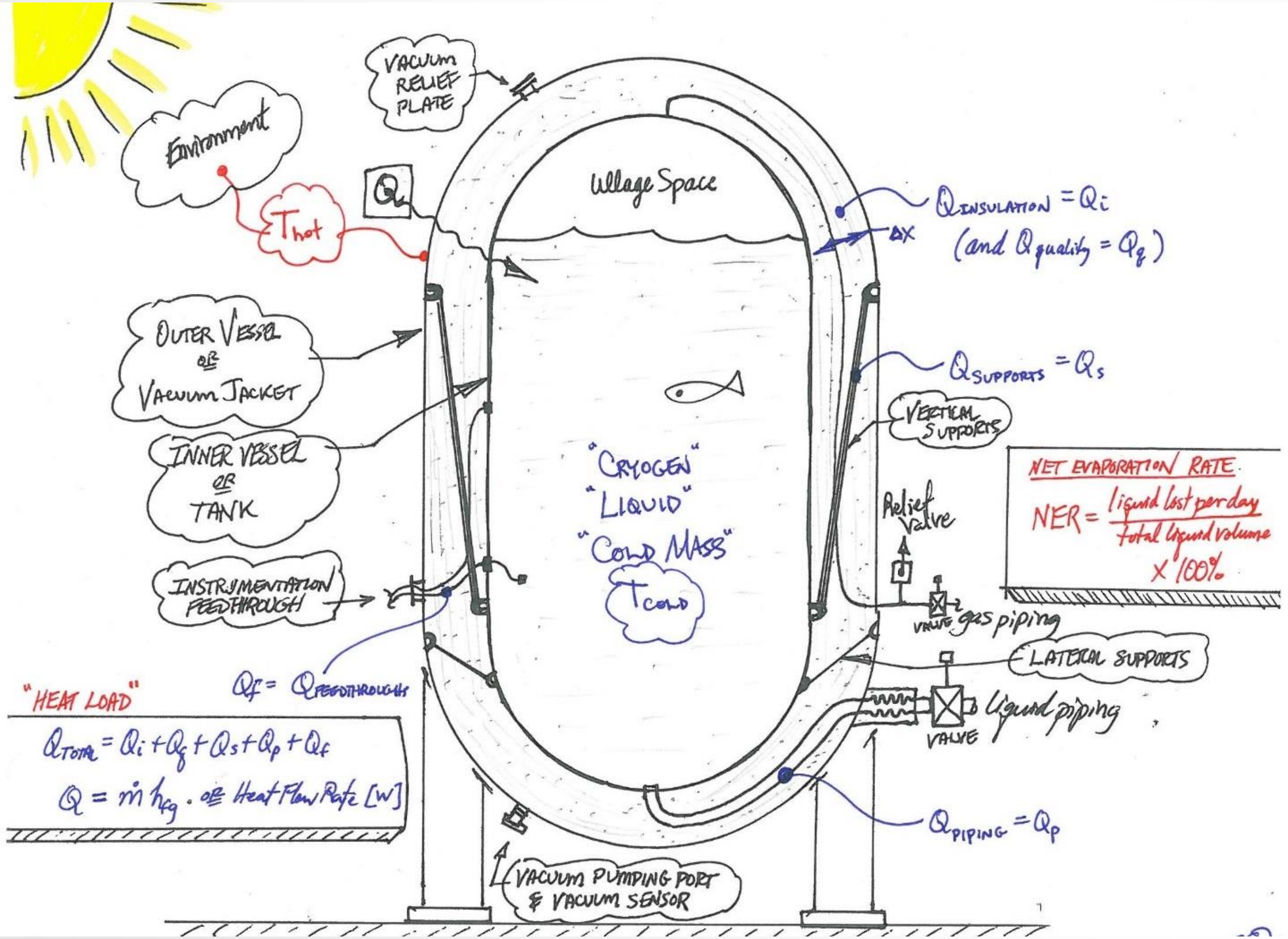
- Optimum design involves a different combination of materials for each specific case
- For simplicity and comparison, uniform hot and cold surfaces are assumed (testing includes data for LN_2 at 77 K and LH_2 at 20 K)
- Wide range of different cold vacuum pressures (CVP) represent actual working systems
- Cryogenic system example cases:

1.	Cylindrical tank	high vacuum (<0.1μ)
2.	Large spherical tank	moderate vacuum (~10μ)
3.	Small composite tank	soft vacuum (~100μ)
4.	Transfer piping	normal vacuum (~1μ)
5.	Piping field joint	no vacuum (760,000μ)

CRYOGENIC SYSTEM EXAMPLE CASES

- Three storage tank systems (LH_2) analyzed:
  1) Medium-size 125,000-liter cylindrical SST tank with a carbon steel outer jacket and a 200-mm annular space
  2) Large-size 3,200,000-liter spherical SST tank with a carbon steel outer jacket and a 1,200-mm annular space
  3) Small-size 100-liter carbon composite tank with a stainless steel (SST) outer jacket and an annular space of 23-mm thickness
- Two transfer piping systems (LH_2) analyzed:
  4) Transfer line consisting of a DN25x80-mm all SST vacuum-jacketed (VJ) pipe segment of 18-m length
     - Ends are disregarded for the reference case of a very long pipeline
  5) One-meter overall length field joint connection between two DN250x300-mm VJ pipe segments

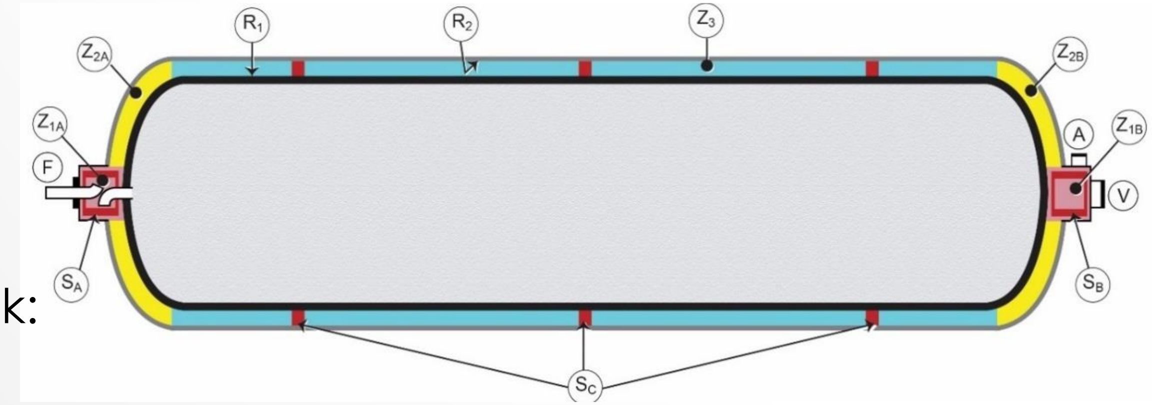
VACUUM-JACKETED (VJ) TANK BASICS



CRYOGENIC SYSTEM EXAMPLE CASES: VJ STORAGE TANKS

1) Medium cylindrical tank: high vacuum (<0.1μ)

2) Large spherical tank: moderate vacuum (~10μ)

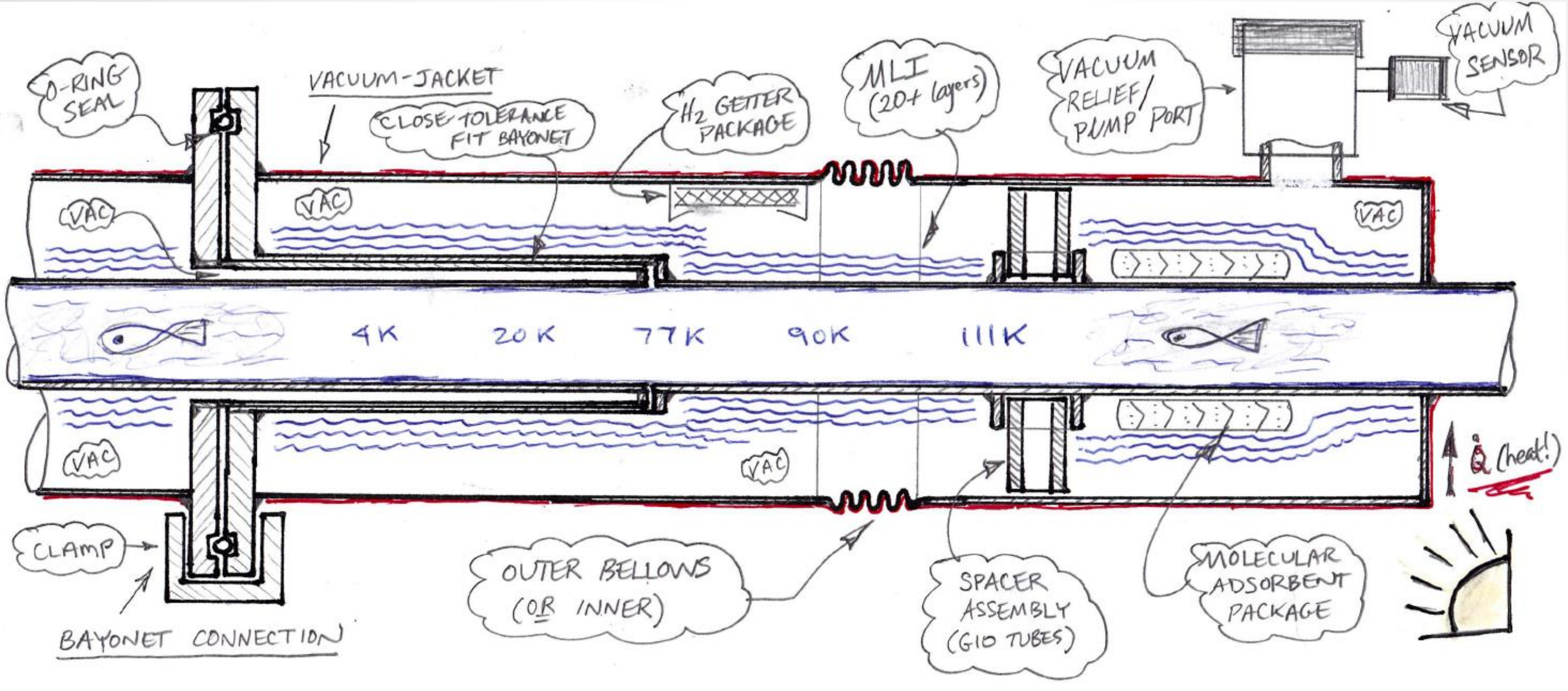


3) Small composite tank: soft vacuum (~100μ)

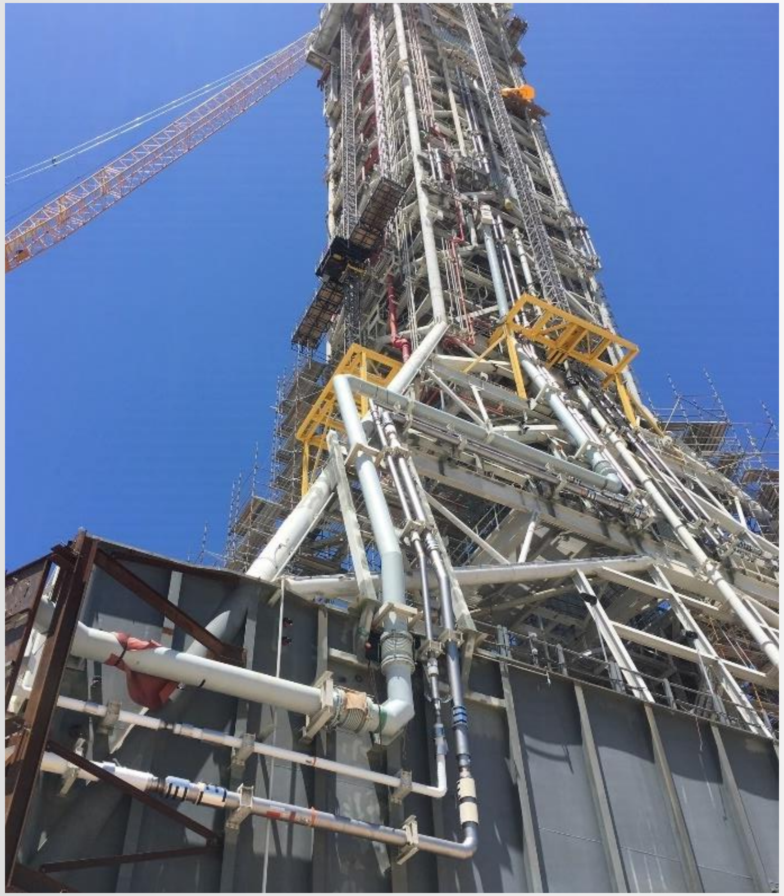
VJ STORAGE TANKS (LH_2) AT NASA/KSC LAUNCH COMPLEX 39B

Existing 3,200 m^3 sphere (right); new 4,700 m^3 sphere under construction (left)

VACUUM-JACKETED (VJ) PIPING BASICS



CRYOGENIC SYSTEM EXAMPLE CASES: VJ TRANSFER PIPING



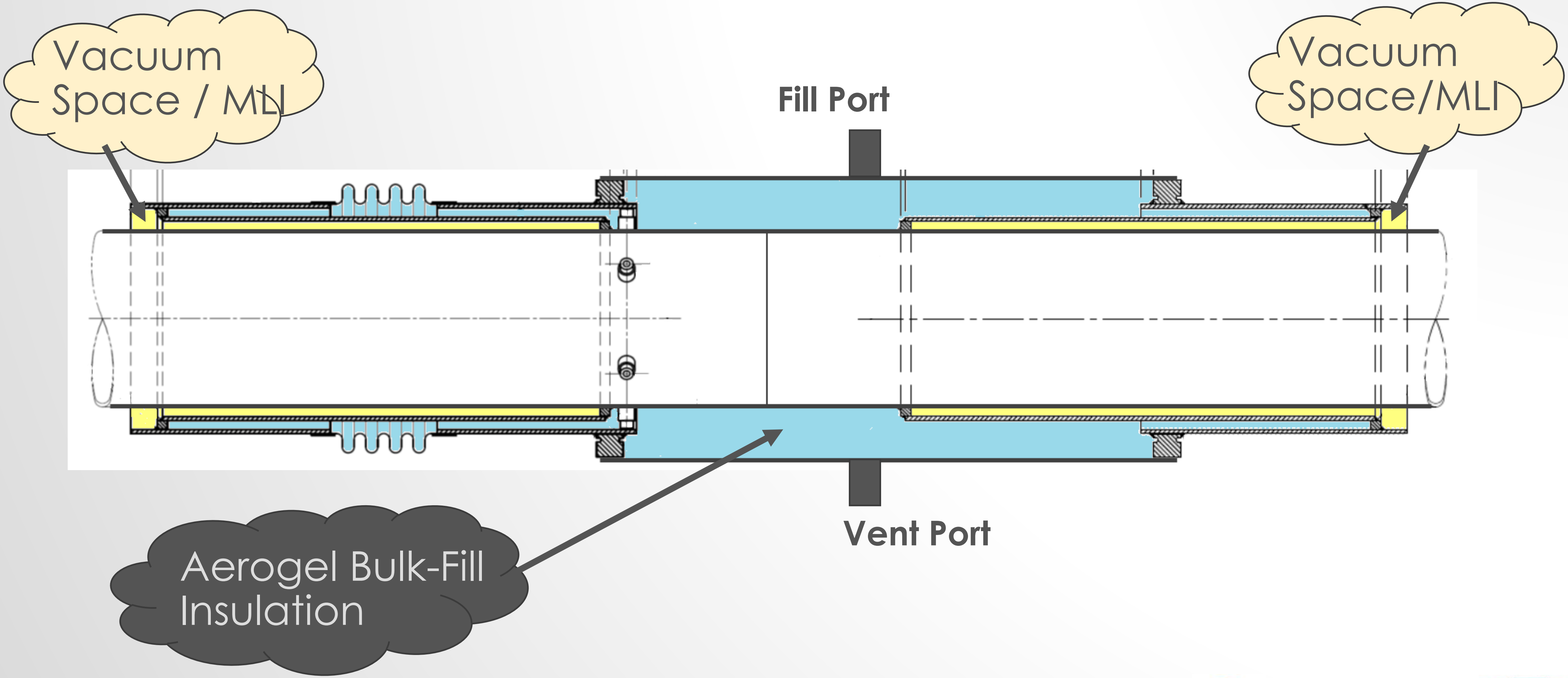
MLI wrapping in the shop

Before close-out with cans and aerogel in the field

Transfer piping: normal vacuum (~1μ)

Piping field joint: no vacuum (760,000μ)

FIELD JOINT FOR VJ PIPING CONNECTION


Vacuum Space / MLI

Fill Port

Vacuum Space/MLI

Vent Port

Aerogel Bulk-Fill Insulation

COLD TRIANGLE DESIGN APPROACH

The total heat leak into any cryogenic tank or piping assembly is comprised of three parts in addition to the baseline heat leak through the insulation (Q_i):

1) Heat leak through the structural supports (Q_s)
2) Heat leak through piping connections, penetrations, and feedthroughs (Q_p)
3) Insulation Quality Factor or IQF (Q_{IQF})
   a. Heat leak due to practical constraints of fabrication, installation, and assembly of the insulation system on the cold mass
   b. Heat leak due to the negative effects of the supports and connections on the insulation performance
   c. Other parasitic heat leaks or real-world factors

Cold Triangle

Insulation +
Supports +
Piping +
IQF

$$Q = Q_{total} = Q_i + Q_s + Q_p + Q_{IQF}$$

Cold Triangle

$$\longrightarrow \quad Q_{total} = Q_i + Q_s + Q_p + Q_{IQF}$$

USE OF THE COLD TRIANGLE

- Provides a basis for:
  - Evaluating performance benefits of new materials
  - Analyzing the cost effectiveness in overall system design
- Insulation Quality Factor (IQF) for IQF HEAT LOAD or Q_{IQF}
  - $Q_{IQF} = 0$ is perfection or perhaps idealized laboratory conditions
  - $Q_{IQF} = 0$ means no additional heat leak
- Use of the IQF:
  - Determined by testing or estimated by analysis
  - Represents the true additional heat load of real systems
  - Set up as an individual parameter or individualized for the insulation, the piping, and the supports
    - Account for as a percentage of each part, if data are available
    - Or use as a placeholder, if data are not available

ANALYSIS: FIVE EXAMPLE CASES

- Breakdowns of the total heat leaks for the five different systems (LH_2 and/or LN_2) are summarized in the following table
- The insulation materials chosen and the data given represent preferred solutions in each case (or context) among this vast array of different applications
- The heat leakage rate (Q) for each system is comprised of three main parts: insulation, supports, and piping penetrations:
  - Plus another crucial part: the insulation quality factor (IQF)

Total heat flow rate analysis for different examples of cryogenic systems

Cryogenic System Description	**Thermal Insulation System**	**CVP**	**Dimensions**		**Q_i**	**Q_s**	**Q_p**	**^Q_{IQF}**	**Q_{total}**	**q**	**k_s**
			t	***A_e**							
		μ	mm	m^2	%	%	%	%	W	**W/m^2**	**mW/m-K**
1) Medium tank, VJ, factory built (125-m^3)	MLI (80 layers) for high vacuum	**<0.1**	250	229	33.7	17	43.3	6.3	**300**	1.3	1.5
2) Large tank, VJ, site-built (3,200-m^3)	Bulk-fill glass bubbles, moderate vac	**10**	1200	1194	74.1	12.9	12.9	0.0	**240**	0.2	1.1
3) Small composite tank, VJ, conceptual (0.1-m^3)	LCI for soft vacuum	**100**	23	1.6	68.9	21	10.4	?	**14.4**	9.0	1.0
4) Piping System, DN25x80-mm, VJ, with 2 bayonet joints, factory built (18.3-m)	MLI (20 layers) for normal vacuum	**1**	26	3.2	12.0	15	38.3	34.4	**20.9**	6.5	0.8
5) Piping Field Joint, DN250x300-mm, double-wall, field fabricated (1-m)	Bulk-fill aerogel for non-vacuum	**760000**	50	0.88	54.1	27	19	0.0	**49.0**	55.7	12.9

* Effective surface area for heat transmission between inner and outer shells

^ IQF = Insulation Quality Factor

† ΔT = 293 K - 78 K = 215 K

ANALYSIS: SUMMARY

- These examples give first order approximations and the interplay among materials, design, installation, and manufacturing
- There are many more details and materials choices to be made in the final design for the optimum solution
- The IQF is a first order way to quantify the combined effects of the insulation's thermal performance due to:
  a) Practical limitations of its installation and
  b) Increased heat transmission due to supports and piping
- Note: the IQF is not a degradation factor but a very real heat load

DESIGN + ANALYSIS + TESTING

- Standardized laboratory testing of materials/systems is the start
- Thermophysical data for aerogels, aerogel composites, multilayer insulation, novel layered composites, and glass bubbles for standard test conditions of 293 K / 78 K under conditions from high vacuum to ambient pressure
  - Reference materials data are included for direct analytical comparison
  - Basic data for structural-thermal materials, including ranking of their structural-thermal figure of merit (FST) are given
- Testing of VJ tanks and VJ piping systems with LN_2 and LH_2 under real-world conditions (prototypes and field demonstrations)
- Cold Triangle analysis of a cryogenic storage tanks system shows the total heat load and its constituent parts
  - Heat load (Q) in W and heat flux (q) in W/m^2
  - Total system k-factor (k_s) in mW/m-K

CONCLUSION

- System design, engineering analysis, AND thermal testing (materials):
  - These go hand-in-hand for determining the "best insulation system" for a given design situation

- Practical methodology for cryogenic system design: "cold triangle" approach of insulation, supports, and piping plus the insulation quality factor (IQF)
  - Total heat leak is what matters: to minimize it in a cost-effective way, the thermal performance must understood as a summation of its parts
  - Basis for evaluating performance benefits of new materials and analyzing the cost effectiveness in the total system design

- Examples of different cryogenic storage tanks and transfer piping systems:
  - These show the relative importance of both insulation and structural materials for achieving designs of highest energy efficiency

440-LITER LH2 TANK WITH LN2-COOLED SHIELDS (B. BIRMINGHMAN,1957)

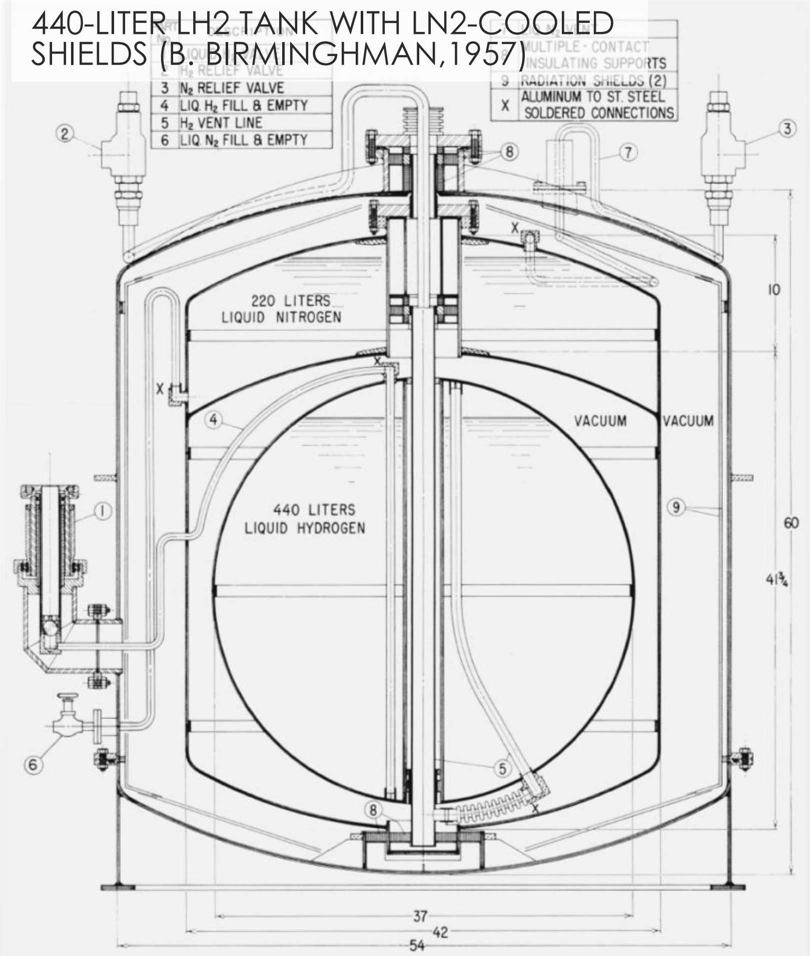


FIGURE 1. *440-liter liquid hydrogen Dewar.*

END

Advanced cryogenic insulation systems

- The elements of heat transmission into a cryogenic system are highly interdependent
- Analysis of the total heat leak is an iterative process
- The right design approach depends on....everything* and, of course,

….the economic objectives

*The shape, the size, the components, the environment, the materials, the temperatures, the process, the cryogen, the fabrication constraints, the operational objective, the duty cycle, etc., etc.

THANK YOU

for your attention

Questions?

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