TECHNICAL BULLETIN 0116
INSULATION PERFORMANCE ON LNG PIPE AND OTHER CRYOGENIC APPLICATIONS

INTRODUCTION

Get ready for a somewhat *mind-bending* ride if you desire to better parse the world of cryogenic insulation. As Elon Musk (re: Tesla, SolarCity, and Space-X) is fond of saying, if your brain does not hurt at the end of every day, you're not doing your job!

Albert Einstein, arguably the most accomplished physicist ever, was fond of *gedankenexperiment* (German for "thought experiment") - - which in essence considers *logical principles* for the purpose of *thinking* through *consequences*. Then he of course validated his conclusions via *scientific measurements*, *empirical evidence*, and *mathematical proofs*.

Since insulation performance in cryogenic applications, although not *theoretical physics*, is indeed a complex subject, the approach in this article is somewhat along the lines of *gedankenexperiment*. In other words, the objective is to logically examine the complex issues that surround insulant performance at cryogenic temperatures - - a different approach than simply examining and comparing *numbers advertised in datasheets*, particularly those measured under ambient conditions with the hope or trust that they accurately represent insulant performance at -265ºF (-165ºC).

BUYING INSULATION VERSUS STAINLESS STEEL

Specifying insulation is not like specifying stainless steel wherein performance expectations are essentially defined by the elemental content of iron, chromium, molybdenum, manganese, and so forth. To the contrary, evaluation of alternative insulants using elemental analysis is neither realistic nor helpful; and even the comparison of published physical properties can be challenging for multiple reasons.

Let's begin by affirming the objective of this article is <u>not</u> to promote any particular cryogenic insulant over others, but rather to offer a *logical thinking* process that considers *consequences* that correlate to the performance of LNG insulants:

1) often examined only within ambient conditions without considering actual in-situ performance, <u>or</u>

2) unfortunately sometimes "selected" by pulling an *old binder* off the shelf to determine which insulant, or even which single brand, "is specified". [Fortunately, this latter practice is gradually being replaced with more comprehensive *due diligence* by engineers and specifiers.]

Regarding the point #1 above, physical properties are often the influenced by:

- different standards and test protocols (e.g. different ASTM, CINI, EN, DIN, or others),
- different measurement temperatures,
- other test environments not representative of the application,
- manufacturers sometimes offering less-than-full-disclosure,
- data or performance claims often not validated by independent third parties, and very rarely audited.

DUE DILIGENCE

The aforementioned *due diligence* is indeed part of the solution, since a thorough understanding of each standard and test protocol better enables an engineer to make credible comparisons. A case in point is the considerable difference in test methods used in measuring water absorption (WA) in alternative insulants. There are at least four different ASTM standards for the four different insulants referenced herein, with varied preparation, durations, temperatures, immersion depths, post-immersion processing, and/or measurement per volume versus weight. Then consider the CINI-2014 requires ≤5.0% measured per ASTM D2842 while ASTM C591-2015 requires ≤1.0% measured per C272 in order to be *compliant*. Then consider the physics of water absorption at cryogenic temperatures*!!!*

The above *case-in-point* is not atypical - - which brings to the fore-front the use of *empirical evidence* as a good place to start in the *logical thinking* process. For instance, the vast majority of LNG facilities in the world have utilized either cellular glass or polyisocyanurate insulants (or a combination thereof). Other insulants have indeed played more minor yet undeniable roles. Polyiso and cell glass each have decades of successful performance - - as some would say: *proof has been in the pudding*. More recently aerogel sheet insulant[1] has been marketed as a *better* alternative - - ostensibly as a replacement for cell glass and polyisocyanurate. Similarly, elastomeric suppliers have increasingly marketed their product for cryogenic applications. Regarding the latter two insulants (with presumably less empirical evidence to demonstrate acceptable performance at cryogenic temperatures) the debate over suitability in cryogenic application is more highly influenced not only verified physical properties, but also the *logical* extrapolations into cryogenic applications, and of course as biased by any recent *failures*.

DIFFERENT ANIMALS IN THE ZOO

While polyisocyanurate (“polyiso” or “PIR”) and cellular glass are similar to the extent they are each classified as rigid and closed cell, they each have quite different physical properties - - namely thermal conductivity, dimensions (without gluing), moisture resistance, density, strength, and so forth.

The aerogel[1] referenced in this article is described as a silica aerogel integrated with a fiber blanket, open cell, with an integral factory-applied vapor retarder. The elastomeric insulant datasheet[2] indicates it is a closed cell elastomeric foam based on synthetic rubber, and inherently a vapor retarder with a Water Vapor Transmission of ≤0.10 perm-inches (0.15 ng/Pa·s·m[3]).

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[1] The term “aerogel” insulation can be applied to multiple and varied products, yet the use of the “aerogel” in this article should be considered synonymous with Aspen Aerogels®’ Cryogel®-Z. See Technical Bulletin 1215.

[2] Armacell’s brand product: Armaflex® LTD.

[3] An Armaflex LTD datasheet notes that “For some applications below -110°C the system is installed with an anti-abrasive foil, bonded to the inner surface layer.

DATASHEETS WITH PROPERTIES AT AMBIENT TEMPERATURES?

Traditionally, datasheets portray physical properties measured at or near ambient temperatures. Engineering-minded readers using *logical principles* will readily conclude it's likely that physical properties of insulants at cryogenic temperatures may be different than under ambient conditions. Yes, but which ones, by how much, and why should we care?

In a perfect world ASTM, EN, CINI, ISO, DIN and other standards would establish minimum/maximum values for all physical properties for all insulants across the range of temperatures. In an ideal world insulant manufacturers would offer comprehensive, verifiable, test data for not only their own insulant's physical properties but also for each comparative insulant across all temperature ranges from -165°C to 50°C (possible *cycling* temperatures). Within an even better scenario there would be an end-user database of *lessons-learned*[4]. In the most optimal case, engineers would have prioritized, order-ranked, and shared the physical properties of cryogenic insulants with attendant lessons-learned.

Unfortunately, none of the above is the case!

Yet there is some good news! International standards appear to increasingly require that physical properties be measured across a temperature range that includes cryogenic. For instance, ASTM C591-15 (applicable to polyiso) requires thermal conductivities to be measured for select temperatures from +200°F to -200°F (93°C to -129°C). CINI[5]-2014 similarly requires certain physical properties to be measured at -265°F (-165°C). Since LNG facility designers depend on either or both, it can be stated that failure of an insulant supplier to comply with the new reporting would mean exclusion from bidding. While not yet a prerequisite of either ASTM or CINI, *logical thinking* by engineer/specifiers may also consider being proactive in assessing to what extent *third party auditing* of the product/process additionally reduces risk exposure by ensuring the *product delivered* is the same as the *product referenced* in datasheets.

A COMPLICATION: THE TEMPERATURE GRADIENT

Any insulant in contact with a pipe or vessel containing liquid natural gas at -265°C (-165°F) can be assumed to be at that cryogenic temperature within at least a few millimeters (maybe a few centimeters) of the inner surface of the insulant. So assuming the insulant manufacturer has used ASTM or CINI tests to determine certain physical properties at -265°F and additionally at +75°F, there may be some certainty about the insulant's inner-most and the outer-most segments of the insulation system. Yet, in between there is inevitably a significant temperature gradient spanning roughly 340°F (190°C).

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[4] Such as OEM (Original Equipment Manufacturer) user groups that voluntarily form *groups* to share information about a particular product.

[5] CINI (Committee INdustrial Insulation) is the International Standard for Industrial Insulation for LNG

How does one determine the in-situ temperature at each layer of insulant in between, and then consequently average (or integrate?) (or interpolate?) the net physical properties of the insulation system? One logical conclusion is that you can’t. Another is that you don’t need to since there are decades of empirical evidence for the performance of the dominant LNG insulants. Additionally, with respect to polyiso, CINI established Cryogenic Thermal Stress Resistance factor[6] to ensure sufficient *margins of error* with respect to stresses potentially resulting from the temperature gradient.

Another “*plus*” is that most credible engineering organizations have modeled <u>the most important physical property: *thermal conductivity* (k-factor or lambda value λ)</u> for multiple insulants across multiple temperatures and environments - - or have adopted internet-based models such as 3E-Plus as sufficiently credible. Engineers and specifiers can therefore design the entire insulation system using proven software.

THIS MOST IMPORTANT PROPERTY: *k-factor*

Fortunately, for the vast majority of cryogenic applications the issues boil down to life-cycle k-factors - - assuming parameters such as strength, dimensional stability, etc. meet the minimum standards set by code authorities or the system design engineers. Also fortunately, thermal conductivity of all common LNG insulants improves (i.e. the k-factor lowers) as temperature decreases, although not at the same rates; and each insulant begins its improvements by starting at a different ambient k-factor.

The following chart was developed based on the latest internet-accessible datasheets from leading manufacturers of the product-types: namely, Dyplast ISO-C1®/2.5 for polyisocyanurate, FOAMGLAS® for cellular glass, Armaflex®LTD for elastomeric, and Cryogel®-Z for aerogels:

[6] ISO-C1/2.5’s CTSR is 5.8, while the CINI minimum is 1.5.

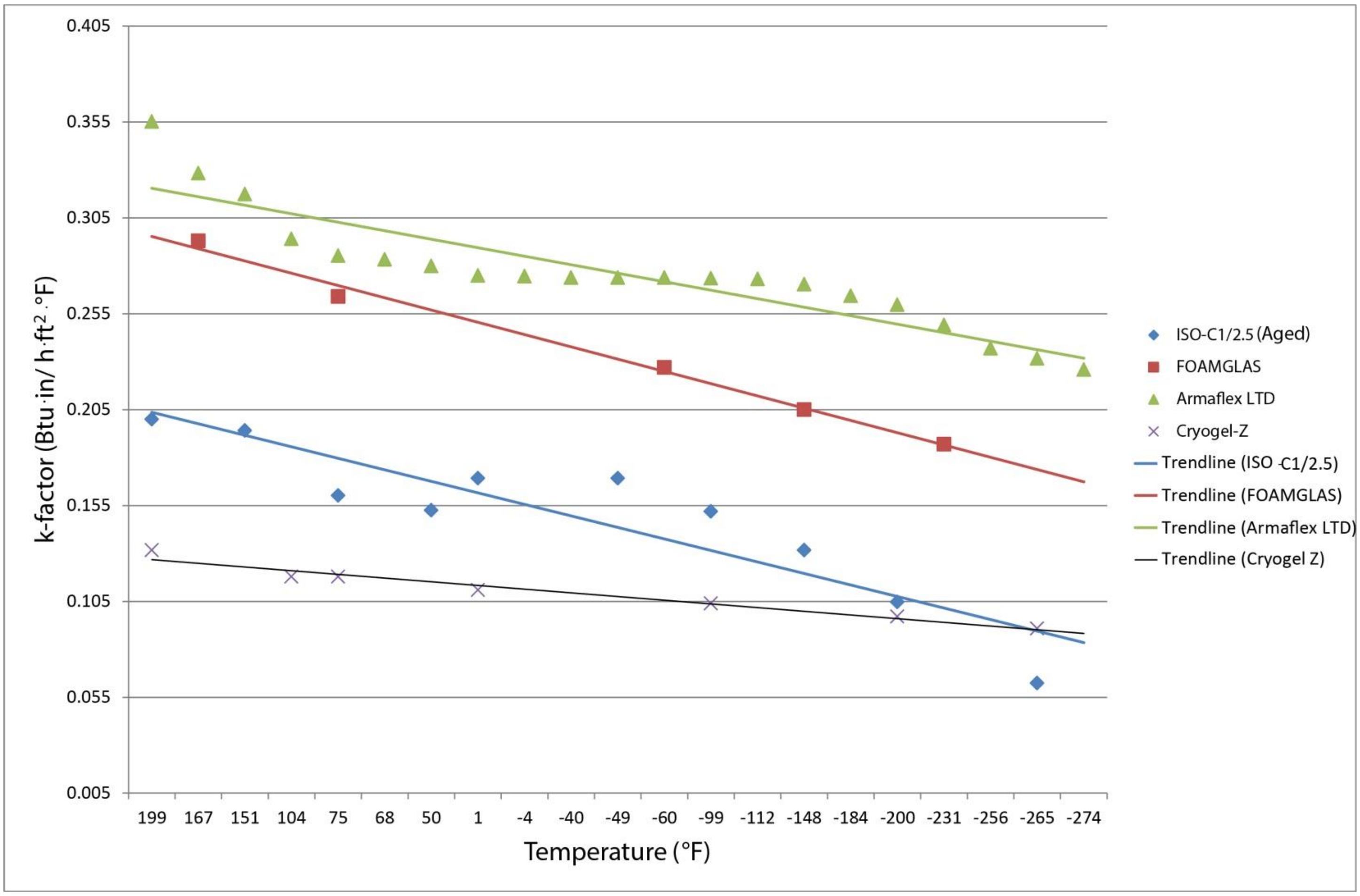

Chart notes:

1) *This chart includes k-factors for cellular glass and elastomeric insulants for comparison purposes.*
2) *Readers are cautioned to request demonstrable/verifiable information from manufacturers, and should not depend on this chart.*
3) *Thermal conductivities may vary between manufacturers of "the same" product.*
4) *Trend-lines are linear representations of potentially non-linear functions; for actual k-factors between points, the manufacturer should be contacted.*
5) *ISO-C1/2.5 polyiso's points are "180-day Aged at +/-75°F" (discussed later).*
6) *Thermal conductivities of Cryogel Z are typically measured at a compressive load of 2 psi, implying they may be worse are higher compressive loads.*

The above chart suggests that polyiso and aerogel insulants achieve materially better k-factors than either cellular glass or elastomeric insulants. So why not logically exclude the latter from future projects, especially since earlier paragraphs in this article offered that thermal insulation's ultimate objective is to "insulate". Wouldn't *logical thinking* conclude that *thermal conductivity* "k-factor" is the paramount indicator.

The obvious counter-argument is that "*extenuating circumstances*" may legitimately change the conclusion.

While all *extenuating circumstances* cannot be addressed in this brief article, it may be instructive to consider why polyiso and aerogel, each purportedly and based on different characteristics, have better k-factors.

Polyiso achieves its higher thermal efficiencies via the low-k-factor *blowing agents* incorporated within a trimerized rigid cell structure. The "aging" parameters discussed in the next section are often posed as a point of debate within the selection criteria. Thinking through the issues logically, one must consider the rationale applied by ASTM and other standards organizations striving to "level the playing field" amongst insulants being evaluated. Consideration must also be given to the fact that engineer/specifiers have for decades calculated a thickness for polyiso on LNG pipe based on *aged* k-factors. Any "*aging*" beyond predicted by ASTM protocols would have been clear, since failure would have otherwise resulted – the absence of which appears to validate the premise that material aging does not occur after installation in an LNG system.

The science behind the low k-factor's advertised for Cryogel-Z is less clear, and ostensibly more *rocket science* that cannot be addressed herein. As stated in prior paragraphs, aerogel as a more recent entrant into the decades-old cryogenic industry strives to demonstrate its advantage over incumbent insulants. The Cryogel-Z datasheet lists k-factors identical to the *maximums* specified under ASTM C1728, so it's not clear that those are third-party verified k-factors. The manufacturer should be able to readily resolve the lack of clarity. The often-heard challenges to aerogel use in cryogenic systems typically reference concerns over Water Absorption and/or Water Vapor Transmission - - discussed in more detail below.

COMPRESSION OF CRYOGEL Z AND K-FACTOR

Cryogel Z's datasheet notes that "Thermal conductivity typically measured at a compressive load of 2 psi". This raises several questions such as "*what are the k-factors at higher compressions?*", and what is the compression on the inner layers of a multi-layer application?

AGED K-FACTORS

It is well known that thermal insulants using the *next-gen* blowing agents such as hydrocarbons and indeed *older-gen* fluorocarbons lose a small amount of their insulating value over time since air can displace the insulating gases within the cells. ASTM has designed a testing protocol (C591) that "ages" the target insulant for 180-days at approximately 75°C prior to measuring k-factor. CINI specifies *aging* measurements per ASTM C591. As mentioned elsewhere, since polyiso has been successfully demonstrated in LNG application for several decades, the *aged* k-factors can be assumed to be representative of the average performance of the insulant over the life of the insulation system.

An important nuance is that k-factor values for polyiso listed at, for instance, -265°F were measured *at -265°F* from samples *aged 180-days at 75°F*. Thus engineering-minded folk may ask "to what extent does polyiso *age* at lower temperatures?" and/or "does a vapor barrier slow aging?" Good questions! Regarding vapor barriers and jackets, they will slow the aging process; and indeed thick insulant or multiple layers of insulant on an LNG pipe will slow the aging of the inner layers.

Regarding lower temperatures, the *aging* process slows dramatically and can be considered as nil at cryogenic temperatures. In other words, in theory, if *initial* (i.e. prior to aging) polyiso is promptly installed on cryogenic pipe, the inner layers of the insulant nearer the pipe may not age; and layers operating at less than ambient temperatures will age more slowly than they would an ambient temperatures.

Of course this cannot be measured or guaranteed since factors such as outages, cycling up to ambient temperatures, and so forth would result in the insulant being above cryogenic temperatures.

WATER ABSORPTION/WATER VAPOR TRANSMISSION

High Water Absorption (WA) and Water Vapor Transmission (WVT) have each historically been associated with poorer thermal efficiencies. *Critical thinking* is particularly important when considering WA and WVT! Conventional wisdom is that WA/WVT concerns originated from failures with primarily fiberglass, fibrous, and/or cellulose-based insulant systems in less-than-ambient temperature applications under humid conditions. A *root cause* of many of the problems has been typically either the lack of incorporation of an adequate vapor retarder, or the selection a vapor *retarder* when there should have been a zero-perm vapor *barrier*. Yet an additional *lesson learned* is that a fibrous and/or open-cell insulant offers no *second-line-of-defense* - - increasing the risks for the engineer that may have specified or the contractor that may have installed[7].

Note that there is no predictable, quantitative correlation between WA or WVT and k-factor in a given insulant, and will vary for each insulant. Thus parties making statements such as "k-factor is degraded by X% for each Y% of WA" should be challenged.

From another perspective, governing authorities such as ASTM, CINI, ISO, etc. often set standards for compliance; in other words an insulant that does not meet the applicable standard should not be utilized in LNG applications. CINI-2014 for instance establishes a maximum WA of ≤5% by volume for polyiso (tested of course with no vapor retarder/barrier installed). The maximum WVT per CINI-2014 is 0.8 $g/m^{2} \cdot h$, similarly tested with no vapor retarder or barrier. At least one polyiso manufacturer[8] posts compliant values of, respectively, 0.0% and 0.47.

Unfortunately, the standards (e.g. ASTM, CINI, etc.) may have different WVT/WA maximums based on the type of insulant. Stakeholders must conduct appropriate due diligence to parse the differences. Additionally, one can debate the extent to which stakeholders receive value for measurements that are better than minimum requirements!

Food for thought:

- Cellular glass manufacturers often quote a Water Absorption of <0.2% with the note on datasheets that most of the water is clinging to the outer, rough, surface. Logical thinkers will conclude this could be a reasonable explanation.

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[7] The old adage in the insulation industry still holds true! It's never the insulant's fault. It's always either the designed who mis-designed or the installer who mis-installed.

[8] Dyplast Products' ISO-C1/2.5.

- A polyiso insulant WA tested under CINI requirements (via ASTM D2842, a 96 hour immersion period) yielded the exceptional WA of "zero". CINI's current requirement is ≤5.0% by volume! On the other hand, ASTM C591-15 establishes a maximum WA of ≤1.0% as measured under C272 protocols. Under C272 (with an immersion period of 24 hours) the subject polyiso exhibits water absorption of 0.6%. Go figure!

- Aerogel insulation advertises a Water Vapor Sorption via ASTM C1104 of ≤5% by weight, with Water Retention after Submersion in Water per C1511of ≤5% by weight. Water Vapor Transmission of the aerogel insulant is posted at 0.00 perm - - yet with the caveat "with vapor retarder installed". [Note that if all insulants were tested with vapor barriers installed, they would all would have a WA and WVT of *zero*.] Critical thinking may conclude that the fibrous nature of the aerogel itself could pose higher risks of WA or WVT in LNG applications if there is any failure of the vapor barrier. It is up to the design engineers of course to validate the suitability for each application.

STRENGTHS AT CRYOGENIC TEMPERATURES

Logically, many will surmise that compressive, tensile, and likely other *strengths* increase as temperature decreases - - which is generally a good thing. From the engineer's perspective worried about *margins of error*, such margins relating to strengths should only improve. As example, measurement of polyisocyanurate (density 2.5 lb/ft^3) yields a compressive strength at 73°F of 43 psi[9], which increases to 72 at -265°F. Similarly, tensile strength increases, albeit less dramatically, from 59 to 70. There is no reason to believe cellular glass by itself would behave qualitatively differently, yet the properties of adhesives, mastics, cappings, etc. can influence the performance of the insulant; and brittleness of any insulant at cryogenic temperatures must be also considered.

But wait!

What about aerogels and elastomerics, which are quite different *animals*? Each is advertised to some extent as "flexible" down to cryogenic temperatures; yet are they? Cryogel Z's datasheets state "Resilient Flexible" (a step down from "Flexible") per ASTM C1101. Claims by elastomeric insulant manufacturers are less clear, yet insulant installers familiar with elastomeric insulants generally express doubt about any flexibility at LNG temperatures. Also, since the *glass transition temperature* for elastomeric insulants is approximately -94°F (-70°C), it would appear flexibility at -265°F (-165°C) is unlikely.

Cryogel Z is also described as compressible, and presented as at least partially resilient after repeated compression. At least one logical conclusion in this case is that compressive/tensile/flexural strengths of these insulants at cryogenic temperatures may be worthy of separate investigation. Obviously Cryogel Z and elastomeric insulants would not be suitable for the vast majority of pipe hangar applications.

Other logical questions may arise with respect to thermal conductivity resilience after mechanical abuse. , and these insulants' use in pipe hangars - - which as this stage must be ruled out.

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[9] Measured parallel to rise.

EXPANSION/CONTRACTION

Engineering-minded readers may also logically consider "shrinkage" as temperatures decrease. Coefficients of linear expansion (CLE) as well as Dimensional Stability represent different aspects of this concern. The good news is that the CLEs of cellular glass and polyiso are exceedingly low at 5 x 10^{-6} and 34 x 10^{-6} in/in·°F, respectively. Put into perspective, if 30 feet of insulated pipe went from an operational temperature of -265°F to an ambient 75°F, the polyiso would expand linearly by 4 inches. While cellular glass will expand less, the fact is that expansion joints within the insulation system compensate for such expansion/contraction; yes cell glass should require fewer expansion joints.

While CLE represents the *elastic* side of the equation, Dimensional Stability represents the *inelastic* perspectives. Again, ASTM and CINI among others have established limiting criteria for dimensional stability -- for which cell glass and polyiso each comply.

Yet what about aerogel and elastomeric? Even though they are "flexible", they expand/shrink by measureable amounts as temperature changes. ASTM C534 for instance measures linear shrinkage of elastomerics, measuring % linear change after exposure to -150°C over seven days. 7% is the maximum allowed, which is equivalent to 7 feet 100 feet of pipe.

A Final Summary

Even though there may not be a *perfect world* with respect to predicting performance of insulants at cryogenic temperatures, there should indeed be optimism within the ranks of informed LNG engineers, specifiers, and end-users:

- Insulant technologies are advancing while incorporating more sustainable chemicals and strategies.
- Life-cycle optimization (operations, finance, and sustainability) is replacing CapEx as primary determinant.
- Standards organizations are increasingly addressing cryogenic applications.
- The specifiers' *old-binder-on-the-shelf* of *who-is-specified* is being replaced by an expectation of current, third-party-verified data on the products.
- Conventional *wisdom* (which is inevitably past tense) is being supplemented by proactive (future tense) due diligence.

Informed stakeholders increasingly acknowledge "the buck must stop *somewhere* - - or at least *some places*". While the complexities of insulation system design, fabrication, and installation make it difficult to hold insulant manufacturers accountable, end-users must apply more due diligence in the selection of insulants. Again:

- Consider empirical evidence or decades of successful employment
- Challenge the incumbents based on fully-disclosed facts, independently verified
- Make logical leaps to extrapolate to cryogenic conditions
- Depend on informed engineers, while using *gedankenexperiment* to challenge.