TECHNICAL BULLETIN 1220

INSULATION PERFORMANCE AT CRYOGENIC/COLD TEMPERATURES:

Logical Thinking Part 3

INTRODUCTION

This is the final in a 3-part series of Technical Bulletins to discuss "*Logical Thinking*" when specifying mechanical insulation for very cold/cryogenic applications. Dyplast® Technical Bulletins are intended to provide objective information on insulation (mostly pipe) and foam core challenges. It may be helpful to glance over Part 1 and Part 2 for background.

In this document we continue a discussion about how the environment at very low/cryogenic temperatures is very different from the ambient conditions sometime set by the test protocols of many standards organizations (ASTM, EU, DIN, ISO, etc.). We intend to offer a *logical thinking* process that considers *consequences* that correlate to the performance of insulants for low temperature or cryogenic applications such as Liquid Natural Gas (LNG). It is not possible within this short document to address all relevant physical properties, so we address the most important properties and briefly consider polyisocyanurate, cellular glass, aerogel, and elastomeric.

RECAP OF PART 2

In Part 2 we discussed:

- Heat Transfer
- Radial Dimension Effects
- Lambda Vs. Temperature Gradients
- Logical Thinking Quiz
- Due Diligence

Part 3 of this series of Technical Bulletins investigates other physical properties such as water absorption, water vapor transmission, strength, and dimensional stability at very low or cryogenic temperatures.

EMPIRICAL HISTORY: WATER VAPOR TRANSMISSION

Since the objective in this series of Technical bulletins is to consider physical properties of insulants at very low and cryogenic temperatures, issues related to water vapor, liquid water, and ice must logically be of interest. From the very beginning of below-freezing pipe and equipment applications, there has been a concern over frozen valves and moving parts - - and thus risk of immobility, and possible system failure - - increasingly compounded by the needs to improve process efficiencies and reduce energy loss.

Thermal insulation became the most obvious solution to frozen valves. Yet, practitioners quickly learned that there is a natural water *vapor drive* of the humidity in the air on the *warm side* attracted to the *cold side of the pipe*. Thermal insulants that did not adequately mitigate this infiltration of water vapor (*humidity*) would eventually result in:

1st: loss of energy as the outer surface temperature of the insulation dropped;

2nd: condensation or freezing on the outer surface of the insulation; indicating loss of thermal resistance as the insulant absorbed water;

3rd: condensation, then ice on the metal pipe and valves potentially leading to *stuck valves*.

Thus, low WVT of insulants became a priority (even though there was additionally an increasing utilization of an outer layer of vapor *barriers*[1]), since experience demonstrated outer vapor barriers may be compromised by poor quality of the material, improper installation, or mechanical abuse (e.g. getting bumped, punctured, or stepped on).

So let's ignore outer wraps of vapor barriers for the rest of this discussion and focus on insulants.

Logical Thinking, Introductory Quiz

We've already stated that inherently low WVT in insulants is important, so let's dig deeper into why and/or to what extent it's important in cryogenic applications. In preparation for the discussions that follow in this document, consider logical answers to the following questions related to very cold pipes (which we'll address in the following sections).

1. If the insulant has a positive WVT measured at 75ºF, what is the WVT when the temperature of the inner insulant drops below the dew point[2]? - - then below freezing?
2. To what extent does a "high" content of water vapor within an insulant reduce thermal performance?
3. If the insulant itself has zero WVT, can the insulant actually Absorb Water?[3]
4. Logically thinking, if '*vapor*' cannot exist at cryogenic temperatures, why is WVT important at all?

WATER VAPOR TRANSMISSION

In a more detailed examination of WVT, consider it is synonymous with water vapor permeability - - in other words, the rate at which water vapor permeates through a material (measured in *perm-inches*). To be clear, *vapor* is water (H_2O) in a gaseous form[4], and water vapor permeability can be a critical performance property of an insulant - - not in and of itself but rather the likelihood that WVT leads to Water Absorption, which can materially reduce thermal insulating performance.

So, in a cryogenic pipe application the question becomes, "At what point across the insulation cross-section does any infiltrating water vapor condense, thereby essentially nullifying the ability of water vapor to continue permeating through the insulant?" The simplest answer is, "when the temperature within an insulant drops below the *dew point*." Not only does this render as mostly irrelevant any WVT measurement obtained at 75ºF, but it translates to the fact that this will be in the outermost region of the insulant layer.

To visualize this, consider a cryogenic pipe at -265ºF (-165ºC) with 4 inches of insulation in an indoor application at 75ºF (24ºC) ambient temperature. Assume the insulant is installed properly with no gaps between layers, and for simplicity let's consider the temperature gradient is *generally* linear[5]. In this case, the temperature 2" from the pipe is just above -100ºF; and the temperature at 3" from the pipe is still roughly only -10ºF. So the *dew point* of the insulant (where the vapor condenses) may be reached quickly as any humidity may penetrate from the atmosphere; in fact the freezing point may occur within the outermost segment of the insulant.

So,

- The humidity (vapor) does not penetrate very far before it condenses.

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[1] A vapor barrier is defined as a layer with a permeance rating of 0.1 perm or less.
[2] Similarly to atmospheric dew point, the *dew point* in this context is the temperature to which the vapor within an insulant must be cooled to the point it condenses.
[3] Aerogels (such as Cryogel-Z) with an integral vapor barrier, are more complex when evaluating WA and WVT.
[4] Humidity and water vapor are synonymous in this context and are each gaseous forms of water; on the other hand moisture, mist, condensation, and fog are liquid forms of water in very fine droplets.
[5] Since the insulation has a radial dimension rather than linear, the gradient is not truly linear.

- When the vapor condenses to water, the further penetration of H_2O as a vapor must drop dramatically; note that the penetration of condensed water becomes subject to the "wicking/capillary action" which is primarily an issue within insulants rarely used in cold pipe applications - - and which in any case would be revealed from Water Absorption tests.
- Since the freezing point of water may also be reached within an inch or so of the surface if the insulant, the water absorption ceases entirely.

Quiz Question #2 posed whether any vapor that is permeating through the insulant actually lowers the thermal performance. The simplest answer is "*somewhat*" since *if* the vapor penetrates, the thermal degradation from vapor is of course less than that of condensed water. The complete answer is more complex since in closed cell foams such as polyisocyanurate, elastomeric, and cellular glass, any water vapor must penetrate into any interstitial spaces that may exist and/or penetrate the cell walls. In non-cellular aerogel, the fibrous filaments are advertised as hydrophobic, yet there may be more interstitial space for potential water vapor. The suppliers of aerogel insulants should be queried about the realities of the measurements of water sorption tests (ASTM C1104) and the realities and impacts of absorption and adsorption.

Regarding Quiz Question #3, above, if the insulant itself has zero WVT, the insulant will not have vapor penetration that could then condense to water. Yet, note WA is still possible if the insulant is immersed in water or is exposed to sustained rain - - both unlikely scenarios with properly installed vapor barriers and jacketing.

The essence of Quiz Question #4 "*why is WVT important at all*" has been partially answered within the above discussion that concluded WVT may only be of importance within the outermost segment of an insulant. The additional half of the answer is "*during shutdowns and cycling*" where portions of the insulant temperatures may be above the *dew point*, and thus more proximate to the WVT measured at ambient temperatures. The duration of any shutdown or cycling event (and the ambient temperatures) are very important since it takes time for the outer segments of insulant temperature to rise to above the dew point.

Measurement of Water Vapor Transmission

Fortunately, most cryogenic insulants utilize ASTM E96 to measure WVT; whereas they use multiple protocols to measure Water Absorption. In fact, all of the prior-mentioned insulants other than aerogels (e.g. Aspen Aerogel®) utilize ASTM E96. ASTM E96 measures the rate of transmission of vapor across the insulant caused by a difference in vapor pressure on either side of the insulant. Again, this measurement protocol is conducted at ambient conditions (e.g. 75ºF), and thus we can logically conclude that if WVT was measured at <32ºF, the resultant WVT would be zero.

Aspen Cryogel-Z® applies ASTM C1104 (Standard Test Method for Determining the Water Vapor Sorption of Unfaced Mineral Fiber Insulation) which some interpret as a combination of water absorption and vapor transmission. And while C1104 is for *unfaced* materials, the Cryogel-Z has *facers*; thus the actual WVT properties are not clear. Logically thinking, because the actual aerogel is quite fibrous and has interstitial space that could hold water vapor, or if there is no facer or if the facer fails, then water vapor could penetrate, condense and/or freeze.

WATER ABSORPTION

Water absorption within an insulant reduces thermal performance, since water has a much poorer thermal efficiency that blowing agents, air, or water vapor! While there is no doubt there is a correlation between higher WA and higher (poorer) thermal conductivity (i.e. lambda or k-factor) in a given insulant, it will likely vary for each insulant, and calculations using mathematical formulas are problematic. Thus, parties making statements such as "lambda is degraded by X% for each Y% of WA" should be asked for the rationale and evidence.

Let's continue this section by discussing the considerable differences in test methods used to measure water absorption (WA) in alternative products.

Consider, for instance:

- the CINI specification (for cryogenic applications) for unfaced polyiso[6] requires ≤5.0% WA by volume per ASTM D2842
- ASTM C591 (for polyiso Type II) requires ≤1.0% WA <u>by volume</u> measured per ASTM C272
- ASTM C552 for cellular glass requires **<** 0.5% <u>by volume</u> per C240
- There are several elastomeric insulants with different chemistries, where water absorption may be measured by D1056 with a maximum of 10% <u>by weight</u>, or C209 to establish a water absorption maximum of <0.2% <u>by volume</u>; or ASTM C534 requiring a water absorption of <0.2% <u>by volume</u> according to C1763 method B (with the presence of a skin on at least one surface)
- Aerogel insulant "water sorption" is measured per C1104 with a maximum of 5% <u>by weight</u> (note that it is not clear what it would be 'by volume'); note also, C1104 is not an immersion test protocol (as in the above tests) but rather an exposure to a high humidity atmosphere

  Notes:
  1. the above measurement protocols have up to three different "methods" (A, B and C) which can give different results.
  2. the above are conducted nominally at *ambient* temperatures
  3. there are additional caveats within ASTM standards with regard to rough surfaces, cracks in surfaces, and insulants with chemistries that may be altered after prolonged exposure to water!

Test protocols may also vary by sample (specimen) size[7], specimen shape (e.g. flat or cylindrical), pre-preparation, duration, immersion depth, and post-immersion handling. For example, water absorption measurements per D2842 require a 96-hour immersion period. According to C1763, the immersion times for Procedures A, B and C are 48 hours, 2 hours and 24 hours respectively. The comparable cellular glass test per ASTM C240 and C209 (for cellulosic) require only a 2-hour immersion[8]. The existence of (and allowance for) factory-installed vapor barriers will also of course affect water absorption tests. Aerogel insulants, for instance, have an integral vapor barrier - - without which the insulant could be assumed to have high WA as well as WVT values. Note that virtually all insulation installation guidelines for low temperature applications require vapor barriers (typically field-installed), so *logically* why do some ASTM test protocols allow factory-installed vapor barriers and some not? Thinking logically, each of these variants in testing protocols could affect the results.

<u>Given the above</u>, *thinking logically*, there are instances wherein it may not be possible to *think logically* through the data. Still, the data can inform us if logical questions are asked. For instance:

- Is the water absorption of a particular insulant within the maximums allowed by the overall ASTM or other standards? If so, a small amount of solace can be taken, but proper due diligence by end-users may prompt related questions.
- Does a selected insulant have a higher or lower water absorption than a competitive insulant per the applicable ASTM standard? If so, the end-user or engineer should request a rationalization by the alternative suppliers or the specifier/engineers.

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[6] Installation standards for cryogenic applications require an outer vapor barrier facing as an additional mitigant.
[7] Note that water absorption results within a 1" x 12" x"12" board may not be extrapolatable to a larger size.
[8] The logic of a comparable immersion time for insulants as different as cell glass and cellulose is not intuitively obvious.

- To what extent is there a likelihood for a compromised outer vapor barrier (e.g. poor installation, puncture, or tears)? A conservative approach would be to assume mechanical compromise is inevitable (particularly in heavily-trafficked areas of a facility), and thus selection of an insulant with inherently low WA (and WVT) is wise.

Next, let's consider WA at very low or cryogenic temperatures! *Logically thinking*, no insulant should absorb water when the H_2O is solid state. *So why worry about WA in any application below 32ºF (0ºC)?* The answers have already been discussed in the WVT sections:

1. WA is primarily of concern during cycling events or shutdowns where temperatures may exceed 32ºF (0ºC). The more time an insulant is above freezing conditions, the ASTM measurements at ambient temperatures become more relevant. Note also, that the WA at, say, 35ºF (2ºC), may logically not be the same as at 75ºF (24ºC). [Recall again, that in cryogenic applications there is always an additional mitigation against WA - - the vapor barrier[9]];
2. WA is relevant in the outermost portion of the insulant where temperatures are likely above freezing (assuming ambient temperatures are above freezing).

STRENGTHS AT CRYOGENIC TEMPERATURES

It is not unsurprising that many end-users surmise that compressive, tensile, flexural, shear, etc. strengths improve as temperature decreases. Yet the reality is quite different. For instance, compressive strength can improve as temperatures decrease, while flexural strength can degrade. The bottom line is that a detailed examination of the strengths of insulation materials at low and cryogenic temperatures is far beyond the scope of this Technical Bulletin - - and in fact may be unknown or at least unpublished.

Fortunately, *logical thinking* takes us back to an examination of empirical evidence, rather than ASTM tests that may not address low temperatures or may be inapplicable. There are decades of successful performance of polyisocyanurate and cellular glass insulation systems in low temperature and cryogenic applications. Increasingly, there are examples where elastomeric or aerogel insulants have been used successfully in very low temperature applications. End-users and specifier/engineers are simply cautioned to execute due diligence to ensure there is credible evidence of successful, sustained use of the desired insulant at very low or cryogenic temperatures.

DIMENSIONAL STABILITY

The dimensional stability test at the time of manufacture is intended primarily as a quality control test - - a method for comparing one small-scale sample to another or one type of cellular plastic to another.

Most insulation materials have some reference to testing requirements for dimensional changes in their particular ASTM standard specification, but the environmental exposure conditions and, in some cases, even the ASTM test method varies from one product to the next. Thus, the results of dimensional stability should generally not be used to compare unlike materials, even in a small-scale sample. For instance, while the standard specifications for polyiso products call for as many as three environmental exposure conditions, some other insulants have just one and call for different test methods. Additionally, cellular glass standards have no requirement for measurement of dimensional stability.

The conclusion is that as long as the dimensional stability of the insulant meets its specific ASTM and/or CINI (or other applicable) standards, it should be assumed acceptable for use as long as it meets other requirements.

A FINAL SUMMARY

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[9] A vapor barrier is generally defined as having a permeability of less than 0.1 perms; a vapor retarder more. (cont. next page)

In this three-part series of Technical Bulletins we examined how *logical thinking* can be used to consider an insulant's performance at very low or cryogenic temperatures even though ASTM, EN, and other standards may only measure properties under ambient conditions. Since *insulants* are intended to *insulate*, we initially spent considerable time addressing the complexities of thermal conductivity (lambda or k-factor) at very low temperatures, and offering some guidance on how, why, and to what extent the lambdas improve as temperature decreases - - and some guidance on how specifiers, buyers, and end-users can ask more informed questions about the actual thermal performance of each alternative insulant at cryogenic temperatures.

Fortunately, the lambdas of most commonly used insulants have been tested at cryogenic temperatures - - yet, note, some with important caveats that may affect performance, or at a minimum confuse the buyer[10]. Also, there is considerable empirical evidence of successful and demonstrable performance at cryogenic temperatures - - namely polyisocyanurate and cellular glass, and more recently and to a lesser extent aerogel and elastomeric.

In this final installment we went on to examine how water vapor transmission can lead to water/moisture absorption, a negative impact on lambda - - with the major qualification that water vapor can quickly condense and freeze in cryogenic applications. Thus, WA and WVT properties measured at or around 75ºF have limited impact in cryogenic applications where the bulk of the insulant is below the condensation point and/or freezing.

The strength and dimensional stability properties were also briefly addressed.

As an overall summary:

1) Consider empirical evidence regarding successful cryogenic performance over decades;
2) Closely review all literature available from insulant suppliers:
3) Insist on full disclosure of facts, independently verified by a qualified third party;
4) Understand the test conditions, such as ambient conditions, specimen size, durations, etc. and ask suppliers to logically compare their results to alternative insulants
5) Ask insulant suppliers about stated or unstated caveats that may impact the numbers or the interpretation of the numbers (e.g. the use of radial geometry rather than flat);
6) Challenge suppliers based on the most recent data that tied to product that is delivered;
7) When ASTM tests are at conditions that do not correlate to the actual, engage logical thinking to extrapolate to cryogenic conditions, given above deductions and the perspectives offered in this Technical Bulletin
8) Consider the physical properties of the insulants within the context of the entire insulation system;
9) Support standards organizations to increasingly address physical properties of insulants at cryogenic temperatures.

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[10] For example, Cryogel-Z (an aerogel) notes that its thermal conductivity is measured under a compressive load of 2 psi, yet does not address the impact of (say, a laborer) stepping in the insulant during/after installation, or the impact of multiple layers of 'wraps' each weighing 10 lb/ft^3 on top of the lower sheets.