TECHNICAL BULLETIN 1115 (0414 update)

What You Should Know About Thermal Conductivity and Aging of Low-Temperature Mechanical Insulation

PURPOSE

TB 1115 is an update to TB 0414 and another in Dyplast's series to provide objective information to decision-makers and end-users on important issues related to mechanical insulation (i.e. insulation for equipment and piping). This Technical Bulletin strives to objectively encapsulate more than can be gleaned from other documents generally available.

To set the context, there are many insulants with initially[1] "*poor*" thermal efficiencies that exhibit no "*thermal aging*", and alternatively there are insulants with initially "*superior*" thermal efficiencies that even after *aging* continue to have superior thermal efficiencies. Thus over the lifetime of the insulation system this latter class of insulants generally offers energy savings that outweigh any incremental premium in capital cost, and if any premium exists at all.

Consider at one extreme fiberglass pipe insulation which does not *thermally age*. Ignoring water infiltration or other degradation fiberglass maintains a constant thermal conductivity at 75°F of approximately 0.23 Btu•in/hr•ft^2•°F. This is 44% worse than *aged* polyisocyanurate from the best suppliers. Also consider cellular glass with roughly a 0.29 thermal conductivity that similarly does not age, yet exhibits even poorer thermal performance over the life of the insulation system.

BLOWING AGENTS

The manufacture of polyurethane (PUR), polyisocyanurate (PIR or polyiso), spray-foam polyurethane (SPF), extruded polystyrene (XPS), phenolic foam (PF), cellular glass, and elastomeric rubbers[2] each utilizes blowing agents. While the manufacturing process for each is quite different, in essence the process depends on the expansion of a liquid or mixture of liquids into a "foam" using blowing agents that become trapped in cells. Blowing agents can be a hydrofluorocarbon, hydrocarbon, carbon dioxide, air, or steam (each of which has successively poorer thermal conductivity). Over the past few decades, the Montreal Protocol has mandated incrementally staged phase-outs of CFCs and HCFCs from insulation foams because of their high ozone depletion potential. Hydrocarbons or the few HFCs still in use have typically replaced HCFCs, but now due to concerns about climate change and global warming regulations are being proposed to entirely phase-out HFCs. In time it is expected that current users of HFCs will switch either to hydrocarbons or to new fourth-generation blowing agents called Hydrofluoroolefins (HFOs).

---

[1] Measured within a few days of manufacture.

[2] See Dyplast's Technical Bulletin 1015 for a discussion of aerogel insulants.

THERMAL CONDUCTIVITY PRIMER

Thermal Conductivity is defined in ASTM C168 as the time rate of steady state heat flow through a unit area of a homogeneous material induced by a unit temperature gradient in a direction perpendicular to that unit area - - typically expressed as the symbol "*k*" in units of Btu·in/hr·ft²·°F[3]. In other words *k*-factor is the number of BTUs per hour that pass through a one inch thick by one foot square section of insulation with a 1°F temperature difference between the two surfaces. It is important to also note that the thermal conductivity of insulation materials varies with temperature among other factors discussed more thoroughly below. Typically, *k*-factors improve (get lower) at lower temperatures, and the insulation's thermal performance thus improves. Most ASTM material specifications subscribe to thermal conductivity measurements at a mean temperature of 75°F; yet increasingly standards, such as ASTM C591-15, are requiring that *k*-factors be tested across a wide range of temperatures, including cryogenic.

Thermal conductivity (*k-factor*) is essentially the inverse of thermal resistance (*R-value* per inch).

THERMAL AGING

Thermal aging is a term that refers to the tendency of some insulants to lose a percentage of their thermal resistance over time due to the very slow diffusion of low-thermal-conductivity (*non-air*) blowing agents out of the cells within the insulation, combined with the inward diffusion of air which has a higher (poorer) thermal conductivity than the *non-air* blowing agents. Since thermal aging is so often used as an argument for or against a particular insulation, it is important to understand this somewhat complex phenomenon.

The process governing gas diffusion in cellular foams is dependent upon, among other things, the *partial-pressure gradients of the different gases* across the cell boundaries which creates a "drive" for the gases to diffuse through cell walls. As the partial pressure gradient across a cell boundary for a particular gas is reduced, the rate of diffusion for that gas slows down and eventually an equilibrium condition is achieved across the cell wall. There are, however, many situations where the diffusion of the gases across cell boundaries is impeded: for example, at lower temperatures, and when the cells are in the interior of the foam and not exposed to air, covered with vapor barriers, and so forth (more on this later).

If "air" or an "air-equivalent" is used as the blowing agent, there may be no/minimal *aging*[4]since the insulant begins and ends with the same low-thermal-resistance levels.

VARIABLES IN THERMAL AGING

Thermal aging occurs very gradually over many years, is not linear (occurring mostly in early years),

---

[3] Thermal conductivity in metric units is lambda (λ) with units in W/m·°K.

[4] FOAMGLAS® advertises the cells are approximately 2/3rd vacuum and 1/3rd CO_2, implicitly stating that in combination with its cellular walls made of glass does not age.

and is mitigated by a number of variables.

A PREFACE: While the intent of this Technical Bulletin is to provide information and insight, the fact is that engineers and specifiers are typically faced with datasheets from competitive products that:

- may not present apples-to-apples comparisons even at ambient temperature applications,
- rarely offer comprehensive performance at cryogenic conditions,
- often do not have physical properties verified by independent third-parties, and
- sometimes tend toward non-disclosure.

Engineers/specifiers must execute due diligence by insisting on full compliance with the latest ASTM and other applicable (e.g. CINI) standards, verifiable physical properties and full disclosure.

Very roughly in order of priority, the sometimes interdependent factors that mitigate thermal aging include:

1) The process temperatures: the rate of diffusion of blowing agents out of the cells occurs much more slowly at low temperatures, and even more slowly at very low (e.g. cryogenic) temperatures. .

    a. Consider that at cryogenic temperatures such as liquid natural gas (LNG) most blowing agents are solids, and may be liquids even at temperatures as high as ~32°F; thus the "diffusion" across cell boundaries is no longer determined by *partial pressures* of gases.

    NOTE: In several earlier papers we noted the importance of Critical Thinking[5] *when parsing the unfortunate and avoidable complexities of insulation selection. Consider that typical ASTM aging protocols require for instance a one-inch thick bare specimen (no skins or vapor retarders) to be aged at ambient conditions for six months, whereby the partial pressure scenarios are active. Then consider that the aged sample is lowered to -265°F and measured for thermal conductivity. For contrast, consider the opposite approach of aging the specimen at -265°F for six months and measure the thermal conductivity at -265°F. Obviously, the measured thermal conductivity would be exceptional.*

    Also, contrary to conventional wisdom, as blowing agents liquefy or freeze at very low temperatures there is not a corresponding degradation of k-factors. The complexities of insulant performance at cryogenic temperatures cannot be addressed in this short Bulletin. Engineers, specifiers, and end-users should rather simply request third-party-verified k-factors for insulants at the temperature ranges being considered. Hard empirical evidence sometimes

[5] http://www.dyplastproducts.com/dyplastproducts-blog/item/dyplast-mission-critical-article-in-lng-industry-magazine

supersedes the need to understand the physics.

Of course another reality is that a multi-inch thick insulant has a rather steep temperature gradient across its boundaries. Various software programs strive to offer objective advice to engineers and specifiers on heat loss and thickness calculations; suffice to say the most informed engineer offers the best advice to his/her clients.

2) Insulation thickness and geometry: Since thermal conductivity measurements are typically made using thin, flat specimens, they can be conservatively characterized as optimizing the aging process from all surfaces of the insulant. The reality is that a one-inch-thick insulant applied on a cylindrical pipe surface has only the "outside" potentially exposed to a *partial pressure* - - to the extent a *partial pressure* may even exist when cellular glasses may be liquids [and ignore vapor barriers for the moment]. The *inside* surface of the insulant is not only adjacent to *steel* pipe but has less surface area exposed to the pipe, thus the geometries of the test protocols do not fit the *in-situ* conditions.

The thickness of the insulant (e.g. up to six to eight inches) additionally mitigates *aging* since interior cells are not exposed to "air", and thus there may be no/minimal diffusion. The ASTM testing protocols (although striving to establish an *apples-to-apples* at ambient and at non-in-situ conditions) inevitably fall far short of reality.

3) The blowing agent molecular structure: different blowing agents are used by different manufacturers; the larger the molecule, the less likely it is to diffuse across cell boundaries.
4) Insulant density: very generally (and there are caveats[6]), the higher the density of the insulant the more mass there is to transfer thermal energy via conductance; consider for instance cell walls of glass - - the higher the density the more glass there is, which has very poor thermal resistance;
5) Thermal conductivity of cell walls: plastic (i.e. thermoplastic) cell walls conduct less thermal energy than for instance glass walls;
6) Cell wall permeability: this varies with the cell wall chemistry of each insulant in relation to each specific blowing agent;
7) Closed Cell Content: (as a percentage) broken cell walls leak blowing agents more readily;
8) Space between the cells: interstitial space can "short circuit" heat flow [such as with Expanded Polystyrene (EPS)]
9) Voids or holes in the foam: Like the interstitial space between the cells, these can short circuit heat flow, and/or provide a pathway for the escape of the blowing agents contained within the cells;
10) The solubility of the blowing agent in the polymer: blowing agents must be retained within the

[6] Under the assumption that some cell walls could have a thermal conductivity lower than or similar to the gases contained therein, the higher densities should not have poorer thermal performance.

cells to be effective; if it is absorbed into the cell wall structure the equation becomes complex;

11) Physical enclosures over the insulation: vapor barriers, jackets, laminates, or "skins" dramatically retard the rate of gas diffusion.

"PREDICTING" THERMAL AGING

The practical problem for many years has been how to accurately predict the long-term thermal performance of the insulant. This problem has been largely solved for insulants operating at ambient conditions, yet remains problematic at lower and cryogenic temperatures. There are several approaches utilized for different insulants and in different countries to accelerate thermal aging in a laboratory environment to predict thermal conductivity over the lifetime of the insulation. The approach for mechanical/pipe insulation has been based on *aging* a specimen under *ambient* conditions over six months. More specifically, ASTM C591 prescribes the preparation (e.g. size and thickness[7]) of polyiso *specimens* and the subsequent *aging* of the specimen for 180 days in a controlled environment at ~75°F. Recent changes (i.e. ASTM C591-15) now dictate the specimen's k-factor is then measured at mean temperatures ranging from negative 200°F to positive 200°F in accordance with the testing protocols of ASTM C177. Note again that different manufacturers may use different test protocols; independent engineers/specifiers must execute due diligence to ensure, first of all, compliance with the governing standard, and secondly the measurement errors and variability inherent in each testing protocols.

CONCLUSIONS

1) Insulants manufactured with hydrocarbons, HFCs, or HFOs generally have better (i.e. lower) thermal conductivities than those blown with air or air-equivalents;
2) Insulants with non-air blowing agents *thermally age*, yet even after aging typically thermal performance superior to those blown with *air*;
3) Testing methods such as those used by ASTM strive to predict thermal aging and provide *apples-to-apples* comparisons between alternative insulants, yet it is incumbent on engineers/specifiers to execute *due diligence*;
4) Thermal aging protocols typically *age* specimens at ambient conditions that vary rarely reflect the conditions present at the actual application;
5) Thermal aging is mitigated by a number of factors: particularly low process temperatures and physical impediments to gas diffusion such as insulant layers, vapor barriers, and jackets.

[7] 12 x 12 x 1-inch samples cut from the bun/block.