INSULATION AGING & GREEN FOAM

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What is "green foam" and why is it good for my next insulated piping system project? Green foam is light cream in color and if you placed a chunk of it next to other rigid polyurethane foams, you wouldn't see any difference. In fact the foam itself has not changed. It is the addition by Perma-Pipe of an impermeable metal foil layer between the polyurethane insulation and the high-density polyethylene (HDPE) protective jacket that makes the new insulation system environmentally friendly and economically advantageous.

As long as we've been installing jacketed foam insulated piping systems, we've lived with the fact that their performance as an insulation deteriorate over time. This has been termed "foam insulation aging". The initial thermal conductivity of the pipe insulation, no matter how good, drifts upward over time from months to years, by as much as 25-30%. Some engineers have tried to specify the aged thermal conductivity along with the initial conductivity, but accelerated aging tests and predictions of insulation performance are based on extrapolation of limited information and experience. Most engineers prefer to specify the best foam they can get and use a conservative estimate of the average thermal conductivity over the useful life of the system of 20 to 30 years to calculate system performance and operating economics. Green foam changes all of this by effectively eliminating aging.

Cause of Insulation Aging

To understand how this is done, a short discussion of aging and its cause is needed. High quality rigid polyurethane foam insulation is made of billions of small, tightly closed, honeycomb-like cells filled with gas. The walls of the cells are solid polyurethane; thin but very strong due to the structural arrangement of the cells, which depend on the surrounding cells to distribute the load. In high quality closed cell foam, the gas pressure inside the cells also provides compressive strength. One can picture this arrangement as a box of mylar balloons packed tightly together. They can support quite a large load until the individual balloons begin to pop. Figure 1 is a photomicrograph showing the closed cell structure of rigid polyurethane foam. The best foams have small and uniform cells with typical sizes of one mil (0.001 inch or 0.3 mm).

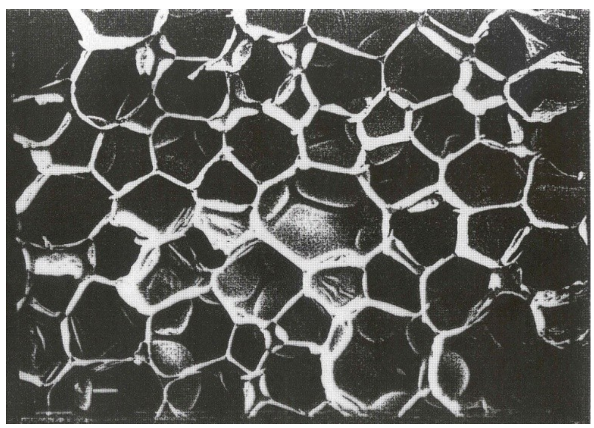


Figure 1 - Rigid foam cell structure

Cell gas and blowing agents

The greater part of the foam insulation is the gas contained inside the cells. Standard foam of density of 2.5 pounds per cubic foot (40 kg/m^3) is only 4% polyurethane and 96% gas, by volume. The importance of the gas can't be overlooked. To carry the box of balloons analogy further, compare the volume of the box of full balloons to the same box with all the balloons deflated and lying flat in the bottom of the box.

The gas inside the cells is a mixture of several gases. The most prevalent gas is the chemical blowing agent used to expand the foam from a liquid to the solid cellular structure pictured above. Choosing the blowing agent gas is one of the single most important choices in formulating a rigid foam insulation product. The blowing agent must mix well into one of the liquid polyurethane pre-components and remain a dormant liquid during shipping and handling of the chemicals. When ready, the mixing of the polyurethane chemicals creates an exothermic reaction that generates heat, which in turn changes the blowing agent from a liquid to a gas. If done properly with high quality chemical components, the result is cured rigid foam with small uniform size cells filled with the blowing agent gas under a small pressure. Over the past few decades, serious concerns and international treaties over ozone depletion chemicals and green house gases have changed the blowing agents of choice. The current dominant blowing agents used to produce polyurethane foam pipe insulation are hydro-fluoro-carbons (HFC's), hydrocarbons (pentanes), and carbon dioxide, a result of adding water to the chemical reactions creating the polyurethane.

Each blowing agent has different properties, some of which are beneficial and some not. The two key properties of the blowing agent gases are their thermal conductivity and the size of their molecules. Since the gas makes up the greatest part of the foam volume, the thermal conductivity of the foam insulation is largely dependent on the thermal conductivity of the gas. Analyses of rigid foams indicate that the thermal conductivity of the cell gas contributes approximately 65% of the overall thermal conductivity of the foam. The remainder is the thermal conductivity of the polyurethane cell structure walls and a small amount of radiation within each cell. The bottom line is that the better the thermal conductivity of the blowing agent, the better the *initial* thermal conductivity of the foam insulation. HFC's and pentanes have similar thermal conductivities and both are better than carbon dioxide.

With time, the *initial* thermal conductivity of the foam deteriorates; it ages. The mechanism that causes aging is the diffusion of blowing gas molecules *out* of the foam cells and the diffusion of atmospheric gases *into* the cells. This gas exchange occurs naturally but slowly, gas molecule by gas molecule, as anyone who's seen a three-week-old helium-filled balloon can agree. The diffusion path may be very torturous, but gas molecules always find a way to diffuse unless blocked by impermeable materials. There are atmospheric gases (air) in the soils surrounding buried piping systems and if there is a difference in concentration of one gas in an insulation cell and that gas in the soil and atmosphere, diffusion will take place until there are equal concentrations in both locations.

There is an excellent graphic animation that shows diffusion through a permeable barrier and the rates of diffusion leading to equilibrium. It may be found at the link below:

http://www.indiana.edu/~phys215/lecture/lecnotes/diff.html

Open cell and closed cell foam aging

Thermal aging is strictly a gaseous diffusion process and is inevitable unless blocked. The rate of aging is controlled by the rate of gaseous diffusion out of the cells *to* the soil and atmosphere and into the cells *from* the soil and atmosphere. In open-cell insulation systems, the only barrier to aging is the insulation jacket, and the initial thermal conductivity is much worse than closed cell insulation because convection of gases or air in the insulation contributes significantly to the insulation's thermal conductivity. For closed-cell insulations with small cell size typical of quality foams, convection is non-existent. In closed-cell insulation, the gas must pass from cell to cell to cell through the cell walls to reach the barrier of the insulation HDPE jacket. Aging is slower, but the diffusion through the jacket is the still the major barrier to diffusion. To best understand aging, the factors that control diffusion of the various gases through the high density polyethylene jacket need to be discussed.

Time and Temperature

Diffusion of gases through materials depends on four major factors. They are time, temperature, the permeability of the material to each specific gas, and the area and distance through the material. For a buried or above ground system, intended for twenty or more years of service, there is more than enough time for diffusion to reach completion, or near completion. When foam has fully aged, all the cells contain approximately 80% nitrogen and 20% oxygen. They are essentially now filled with air. All blowing agent gases have escaped the cells, and the aged thermal conductivity of the foam has increased above the initial thermal conductivity, often by more than 25%.

Temperature energizes the gas molecules, causing them to move faster. Thus hot insulated piping systems age faster than chilled systems. The higher the temperature, the faster the diffusion and aging proceed.

Jacket Gas Permeability

Permeability of each gas through the jacket material is an inherent property of each gas and specific material. High-density polyethylene is a very successful jacket material for electrical cables and thermal insulation, it is relatively inexpensive, extrudable, impervious to water and liquids, but not gases. Even at deep depths in the ocean, HDPE protected cable sheathing last decades without permitting the intrusion of water. PE of all densities can be used as liquid containers and HDPE is sometimes used as water pipe material. PE is not recommended for pressurized gases, and PEX pipe, which is used to convey water in European and other domestic water systems must have a barrier material added as a liner to prevent corrosion of the metal fittings by diffused oxygen and to prevent taste and odor problems from diffusion of other gases into the water systems.

Gaseous diffusion through the HDPE can be thought of as individual gas molecules passing through a thick screen whose holes are of single molecule size. The more holes there are in the material; the more diffusion. The smaller the gas molecules trying to slip through the material, the easier it is to get through and thus more diffusion. The higher the density of the polyethylene material, the fewer "diffusion holes" there are and therefore less diffusion. The larger the gas molecules are, the smaller the rate of diffusion. HFC's and pentanes are relatively larger and heavier molecules than carbon dioxide. This accounts for the much more rapid aging of water-blown foams than those foams blown with HFC's and pentanes.

Diffusion Distance

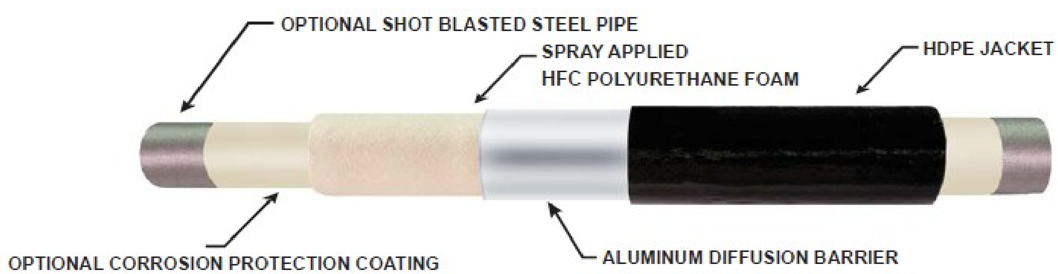
The blowing gas molecules must escape through the cells and jacket to cause the insulation to age. The thicker the jacket, the further each molecule must travel. A thicker jacket retards but can't stop aging. The blowing agent molecules are replaced in the cells by molecules of air diffusing through the jacket from the outside inward. Once this exchange has occurred, equilibrium has been reached. There are atmospheric gases both inside the cells and outside the jacket in equal concentrations. Diffusion and aging stop.

If the thermal conductivity of air was as good as the blowing agent used in the insulation, there would in fact be aging but it would be of no consequence, since the net effect of the diffusion processes on thermal conductivity would be zero. Unfortunately, air is not as good an insulating gas, so there is a significant rise in the thermal conductivity and loss of the insulating capacity of the foam, typically 25 to 28%.

Impermeable barriers

Imposing an impervious, impermeable barrier to the diffusion of gases can defeat insulation aging. One of the most effective barriers is metal. A foil layer of aluminum or other metal has no holes in its crystalline structure that permits diffusion. Perma-Pipe has developed a method of adding an aluminum foil barrier between the insulation and jacket, as part of their straight pipe continuous insulating process. Figure 3 shows the XTRU-therm Plus product with the barrier. Bands of continuous foil are wound helically around the insulation when the foam is fully expanded but not completely chemically reacted. The HDPE jacket is then extruded over the foil. By pre-coating both sides of the foil, a chemical bond forms between the foil and the foam insulation on the under side and a polyethylene fusion bond is created on the upper side.

This is critical for the successful performance of the foil barrier and the insulation system as a whole. Unless bonded, the foil under the HDPE jacket will act as a slip surface, allowing relative motion of the jacket to the insulation when shear forces are placed on the system during thermal expansion and contraction. A fully bonded system carries and restrains the shear forces from the carrier pipe experiencing the expansion and contraction through the insulation, bonding, and jacket to the soil packed around the piping system.



Comparison of Aged and Green foam insulations

If the foam insulation is allowed to age, it happens at its greatest rate earliest in the life of the foam. This is because the gas concentration differences between inside the cells and the outside atmosphere are at their greatest. Over time, the concentrations will equalize and diffusion and aging will stop. For high quality, uniform small cell size foams and tight thick HDPE jackets, aging of a low temperature hot water system may take twenty to thirty years, but the worst aging will take place in the first few years.

Figure 3 below shows a comparison of the thermal conductivity of standard foam and jacket with green foam in which diffusion has been effectively blocked.

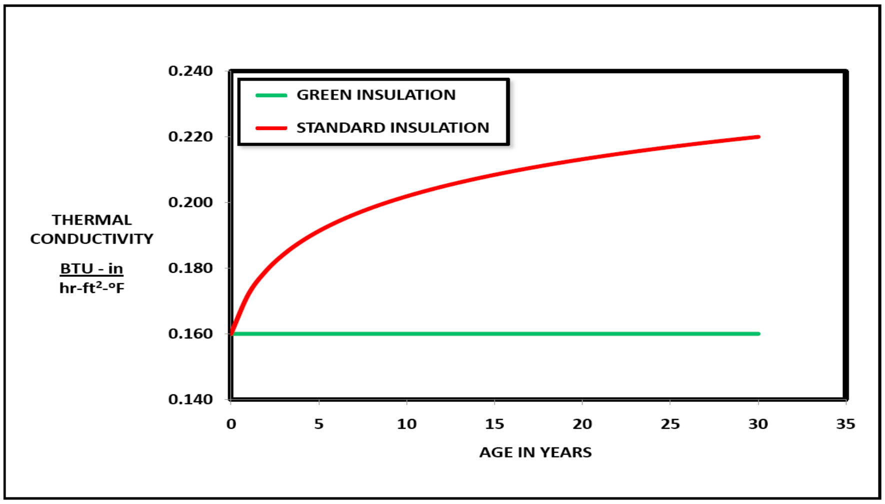


Figure 2 - Comparison of aging and green foam insulations

From the figure, the growth in thermal conductivity in the first five years is considerably higher than in the last years from twenty-five to thirty.

Benefit of Green Foam

To get a sense of the benefit provided by eliminating insulation aging over a 30-year life of the piping system, a simple side-by-side will be discussed. Assume a simple hot water system comprised of two direct buried hot water pipes, side by side and 500 feet in length. They are both nominal 12 inches diameter, standard weight steel pipes conveying 180ºF (82ºC) hot water from an oil-fired boiler to a service load. One of the parallel pipes is insulated with 2.0 inches (50mm) of standard rigid PUR foam protected with an HDPE jacket 0.120 inch (3mm). The other is identically insulated and jacketed, but has Perma-Pipe's diffusion barrier (green foam) bonded between the PUR insulation and the HDPE jacket.

The two pipes are side-by-side buried in average soil with a conductivity of 10 BTU-inch/hr-ft^2-^{o}F. The heat lost initially (before aging takes place) per foot of length from the each hot water pipe can be calculated to be 33.9 BTU/hr. The barrier foil does not affect the heat transferred from the pipe to the soil, because it is thin and perpendicular to the radial direction of heat flow. For each operating day, initially, 406,800 BTUs will be lost to the soil from each of the pipes.

(BTU/hr-ft) x (24 hours/day) x (500 feet) = 406,800 BTU/day

If we assume that the oil-fired boiler operates at 75% efficiency, then 542,400 BTUs must be expended to make up for the heat lost to the soil each day for each pipe, initially. The average heating value of fuel oil is 128,700 BTU/gallon, therefore it takes 4.2 gallons (16.0 liters) of oil each day to account for the loss from each pipe. At $3.50 per gallon for fuel oil, the daily expense is $14.75.

The fuel oil has a density of 6.94 lbs/gallon and is approximately 86% carbon by weight. The efficient burning of one pound of fuel oil with atmospheric oxygen will create 3.16 pounds of carbon dioxide (CO_2). The 4.2 gallons daily will therefore produce approximately 92 lbs (41.7 kg) of CO_2 daily, adding to the carbon burden in the atmosphere. If the system is operated all year, with two weeks of maintenance down time (8,400 hours), then each line will lose $5,163 and generate 16.1 tons (14,606 kg) of CO_2. Only changing the boiler efficiency or increasing the amount of insulation on the pipes to reduce the heat losses can change the cost and carbon burden.

Both pipes are losing costly energy to the soil, but it relatively small when compared to the cost and shortened system life of uninsulated or poorly insulated pipes. As time progresses, the situation will change and the two pipes will diverge in performance. The green foam pipe insulation will not age, as diffusion has been effective blocked. The losses calculated in this example will be the same in the tenth year, the twentieth year, and even the thirtieth year.

The same cannot be said of the standard foam insulated pipe. Each year, the heat losses to the soil will increase as the thermal conductivity increases. If its thermal conductivity follows the red line of figure 3, the thermal conductivity will have increased to approximately 0.200 by the tenth year. In that year, the extra heat losses to the soil will be 106,600 BTU/day from the standard insulated pipe when compared to the green insulated pipe. Over the whole tenth year, the extra cost operating the standard insulated line will be $ 1,450 and 4.5 tons of extra CO_2 will enter the atmosphere.

The difference effect grows over the thirty-year life of the systems. If each year's savings from operating the green foam line compared to the standard foam line were banked at 4% interest, the compounded total savings (future value) would exceed $74,000.

In addition to the operating expense saving of the green foam insulation, 138 tons of carbon dioxide would not be added to our atmosphere. It has been estimated that a full size tree can absorb approximately 50 pounds of CO_2 each year. Using this estimate, it means that the 138 tons of CO_2 each year saved by the green foam insulated line is equivalent to 184 trees in absorbing power.

Conclusion

The green foam question has now been answered. By preventing the foam insulation from aging, a significant operating cost can be avoided and your piping system will have a far less negative impact on our environment. You can let the trees in our forests absorb someone else's carbon dioxide.

The author is a retired vice president of Perma-Pipe, Inc. During his thirteen years at Perma-Pipe, he managed product development engineering projects and quality assurance. He is a Registered Professional Engineer and a Certified Quality Engineer.