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CHARACTERIZATION OF SYNTACTIC FOAM PACK-IN-PLACE AND POUR-IN-PLACE INSULATION FOR ULTRA-DEEPWATER

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ABSTRACT

A major challenge facing deepwater production of oil and gas is the insulation of subsea equipment to prevent cooling and formation of hydrates or paraffin precipitates. A variety of new syntactic foam insulating materials are now available, but the problems remain of testing and qualifying these materials for long-term performance under demanding conditions. This paper describes evolving industry practice and equipment.

INTRODUCTION

Offshore production of hydrocarbons has spread rapidly into deep water, moving from a thousand meters or less to depths well in excess of two thousand meters. As the water depth has increased, so too has the temperature of the product, from under 100º C to more than 150º C. At the same time, the size of fields and length of transport are growing, worsening the risk of blockage due to thermal precipitates. In response, a number of different flow assurance measures have evolved, including insulation of flowlines, risers, and especially wellhead equipment. At the same time, methods have been evolving to test and qualify new insulation materials based on syntactic foam.

Figure 1. Epoxy Insulation Applied to Subsea Sled

SYNTACTIC FOAM

Syntactic foam is a lightweight composite material made from tiny hollow microspheres in a polymeric resin binder, along with other fillers and additives. Because the microspheres are filled with air, syntactic foam is low in both density and thermal conductivity. The choice of syntactic materials typically includes the following:

Rigid Binders: A rigid binder will add support and reinforcement to the microspheres, giving greater strength. However, excessive rigidity may result in cracking under thermal shock and cycling. The most common rigid binder resin choice is epoxy, because of its superior strength and resistance to hot, wet conditions.

Flexible Binders: Flexibility is desirable in many applications, and can offer some protection against cracking. However, flexible binders must be carefully designed to avoid degradation under hot, wet conditions, and they do not strongly reinforce microsphere fillers, detracting from their effectiveness in density and thermal conductivity.

MATERIAL VARIABLES

Many different kinds of materials can be used for subsea insulation, including epoxy, hydrocarbon resins, polyurethane, silicone, polypropylene, and various rubbers. Each material has distinct advantages and disadvantages. Extensive testing has shown that thermosetting epoxy resins have superior properties in hot, wet applications in ultradeep service. The most commonly used fillers in epoxy resin are glass microspheres. The typical sizes of glass microspheres range from 15 to 120 microns, and their density varies from 0.125 to 0.6 g/cc.

Glass microspheres sometimes show solubility effects under extreme conditions. These effects can be mitigated by careful selection of glass chemistry and addition of appropriate coatings and coupling agents. **Figure 2** illustrates the effect of glass surface treatment. Sample 1 is an epoxy syntactic foam sample with untreated glass microspheres, and Sample 2 is the same, but with glass surface treatment. After 22 weeks of exposure, Sample 1 gained over four times as much water as did Sample 2.

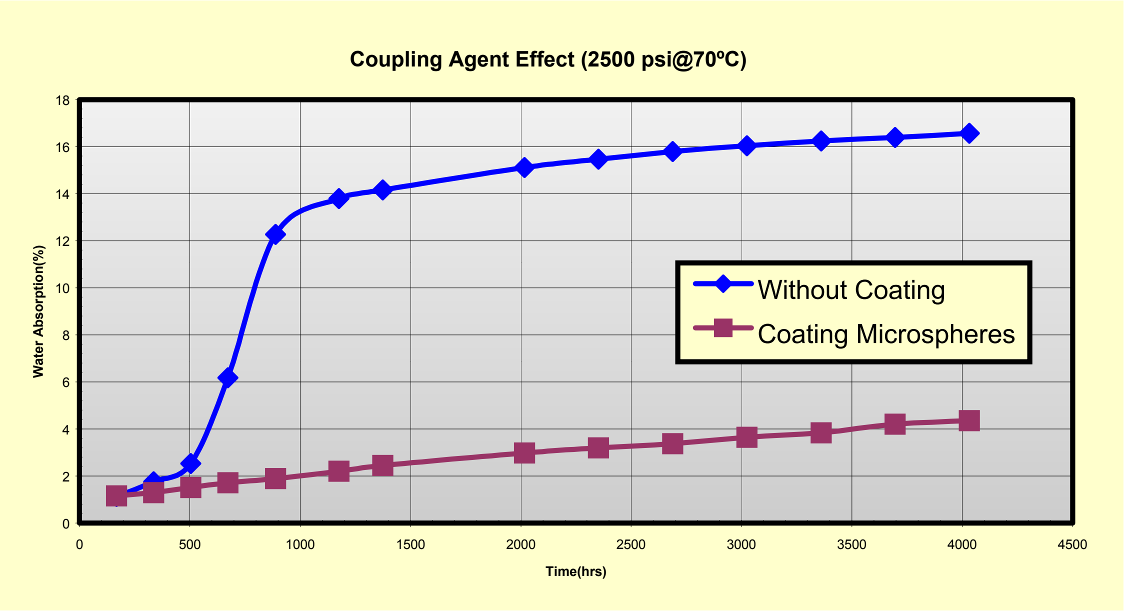

Figure 2. Glass Surface Treatment Effect

Ceramic microspheres have also found favor in some applications, although their greater density and conductivity are often serious drawbacks. The main advantage of ceramic fillers is that they exhibit much less solubility under “hot, wet” conditions. This is illustrated in **Figure 3**, in which Sample 1 is an epoxy syntactic foam made with untreated glass microspheres, and Sample 2 is an epoxy syntactic foam made with ceramic microspheres. After nearly 10 weeks of exposure, Sample 1 absorbed nearly twice as much water as Sample 2.

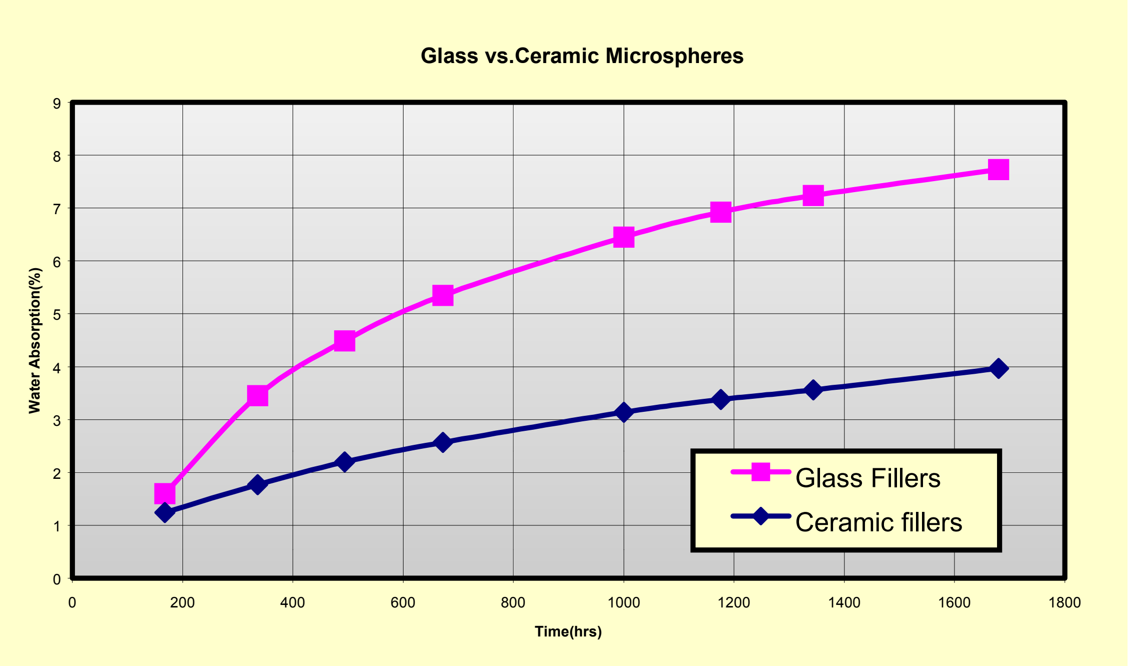

Figure 3. Glass vs. Ceramic Microspheres

WATER ABSORPTION

There has been much debate about the effects of air bubbles entrained in the insulation, especially when evacuated precast or poured-in-place molding are inconvenient, due to the complicated shape of the equipment. Two common approaches are “pack-in-place” and “pour-in-place” materials. **Figure 4** and **Figure 5** illustrate these two systems applied on subsea equipment. In **Figure 6**, we see that the inherent porosity of the pack-in-place material causes a great deal of initial water uptake, but then weight gain remains unchanged out to 6000 hours. In contrast, the water absorption of non-porous poured-n-place syntactic foam is expected to be in the 5-10% range.

The advantage of the pack-in-place material is that it can be applied by hand and does not require molds, and therefore is both faster to install and usually less expensive. When insulating very complex shapes in confined spaces, it may be the only practical way to apply insulation. Often, a combination of the pour-in-place and pack-in-place systems is the optimal solution to insulating large subsea equipment.

In most hydrothermal testing, the amount of water absorbed by the insulation material is taken as the principal order of merit. This is because it is easy to measure (weight before test is compared to weight after test) and equates very closely to the resulting decline in insulating value. **Figure 7** illustrates this behavior, showing that water absorption over a very wide range causes a very linear response in thermal conductivity.

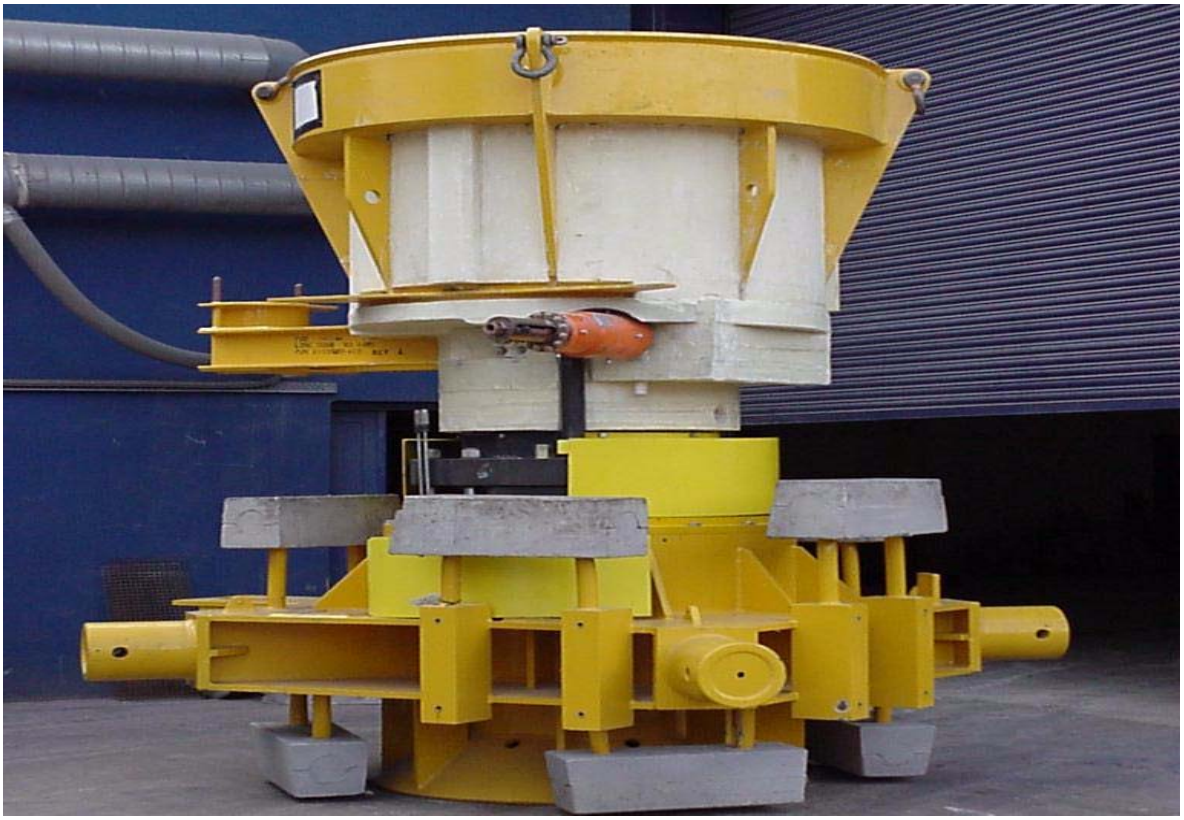

Figure 4. Pour-in-Place Insulation

Figure 5. Pack-in-Place Insulation

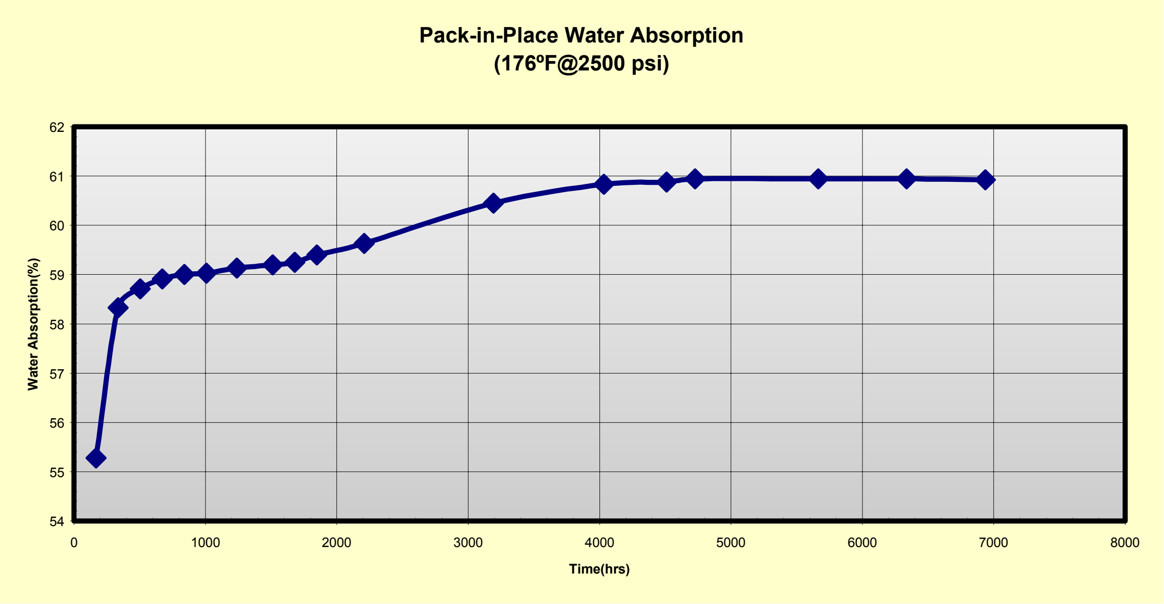

Figure 6. Water Absorption of Pack-in-Place Insulation

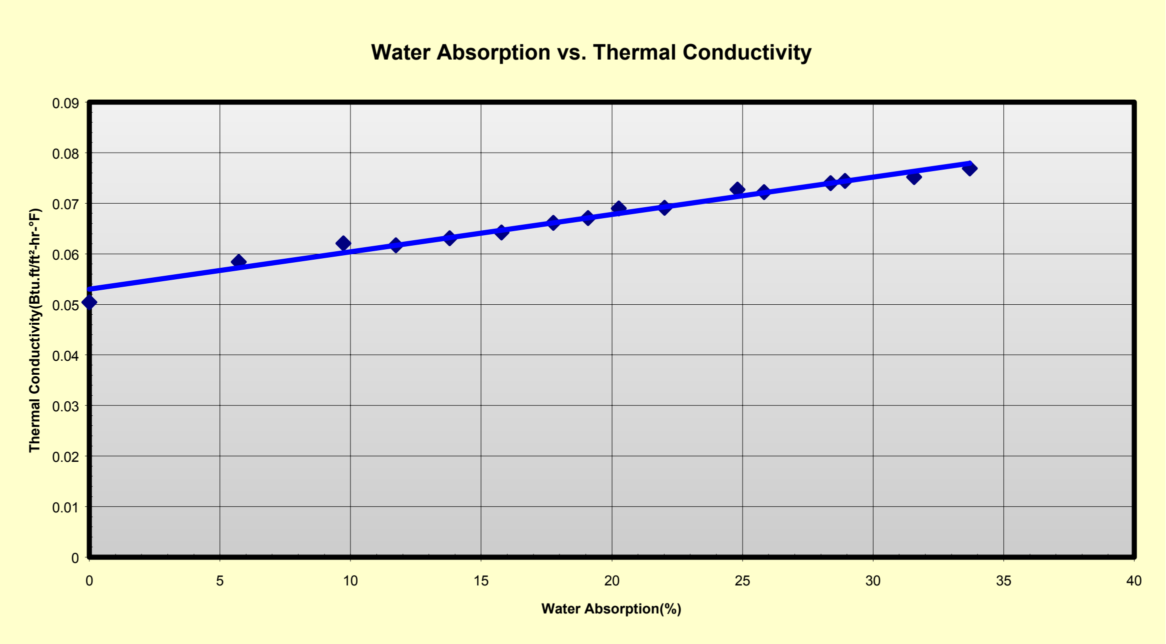

Figure 7. Water Absorption vs. Conductivity

TESTING METHODS AND EQUIPMENT

First stage: Screening Test: Three different temperature (50, 70, 95ºC) water baths to measure water absorption at atmospheric pressure for different formulation samples (similar to ASTM D570)(4). Test durations range from 24 hours to 10,000 hours.

Second stage: Properties Tests: including mechanical properties (density, hardness, compression, tensile, creep, shear and impact), thermal properties (thermal conductivity, glass transition temperature, specific heat), hydrostatic properties (water absorption at different temperatures and pressures, crush pressures) and aging properties (thermal and humid aging).

Third stage: Simulated Service Test: performed under the most realistic conditions possible, such as the testing service provided by Heriot-Watt University: hot inside, cold outside. A standard test is 28 days, although longer periods are desirable.

INTERPRETATION OF TEST DATA

EFFECTS OF TEMPERATURE

In screening testing, small samples are subjected to hot water for varying periods. This kind of information is often extrapolated by exponential methods, such as the *Arrhenius* equation, to simulate accelerated aging. However, it is difficult to apply this rule to syntactic foam materials, because the aging process is complex, involving the base material, fillers, glass transition temperature, pressure, and so on. In **Figure 8**, we see identical formulations tested in small samples at three different temperatures. At the beginning, the higher temperature sample shows more water absorption, but as time goes on, the results tend to approach each other.

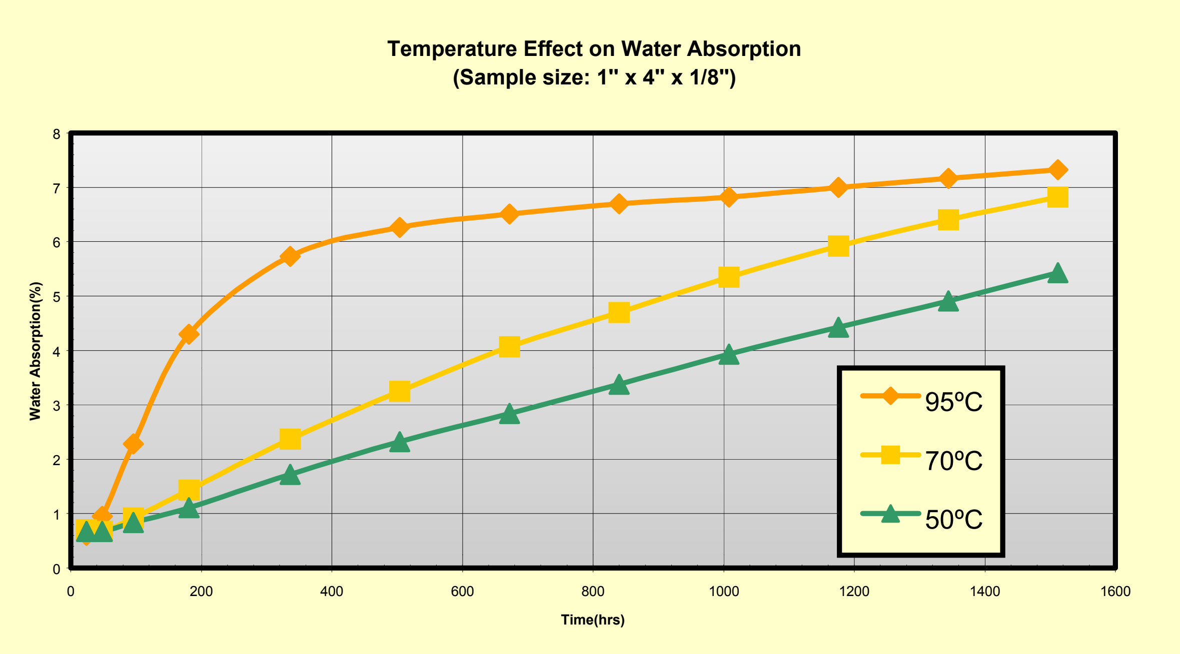

Figure 8. Temperature Effect on Absorption

The tendency of higher temperature to cause greater initial water absorption persists under pressure, as shown in **Figure 9**. Two samples of syntactic foam, larger than the samples tested above, both under hydrostatic pressure at 2,500 psi, exhibited different weight gains due to temperature. After 14 weeks exposure, Sample 1 gained 2.5 times as much water as did Sample 2, even though the difference in the water temperature was only 10^{o} C.

EFFECTS OF THICKNESS

Another issue has to do with sample size and test method. Are ASTM standards really appropriate for this new application? It seems at this point that no one has the “perfect” method or model for predicting insulation material performance after twenty years in the ocean. However, speed and economy of testing are still desirable. To that end, the atmospheric pressure water bath test is most often used as the initial screening test. The key is to set up the test and establish an acceptance range that is both accurate and realistic. To do that, we must understand the mechanism of water absorption.

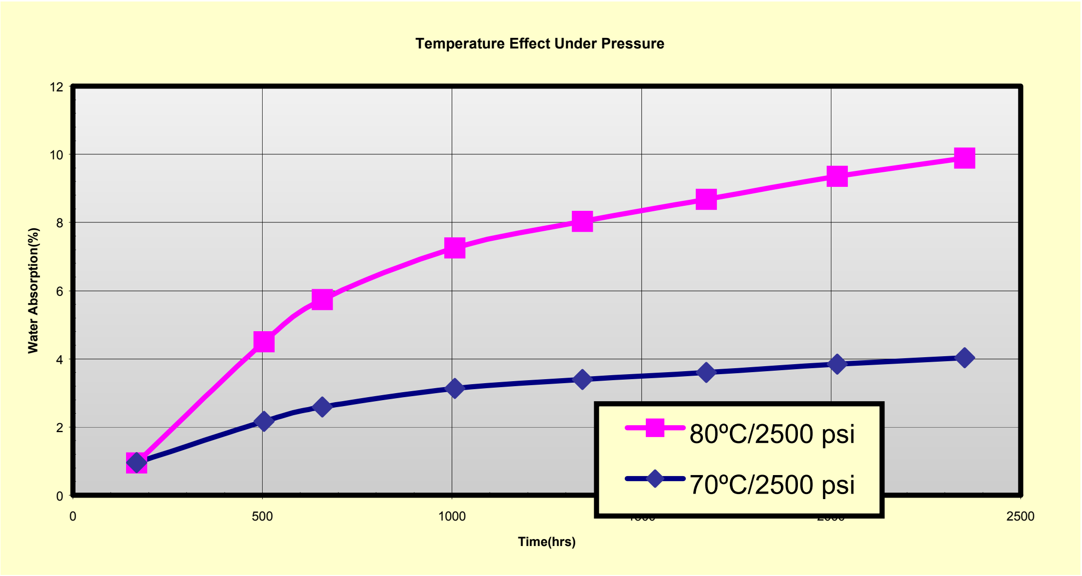

Figure 9. Effect of Two Temperatures Under Pressure

THE MECHANISM OF WATER ABSORPTION

As the binder material cures, a number of "micro-voids" form in the resin matrix. When the material is immersed in water, water molecules fill these voids. Most commonly used models estimate the rate of water absorption according to Fick's laws of diffusion (3), in which only one phase is considered, and the filling rate is governed by diffusion. Obviously, the thickness and area-to-volume ratio of the sample are important variables. For example, a sample that had been already exposed to high temperature water for a long period of time (85ºC / 1,848 hrs) was examined under a SEM. The water was seen to have penetrated no more than 50 microns. In another example, as shown in **Figure 10**, the thickness of the sample is seen to dramatically affect both water absorption and long-term performance. This is why larger-scale tests are preferred.

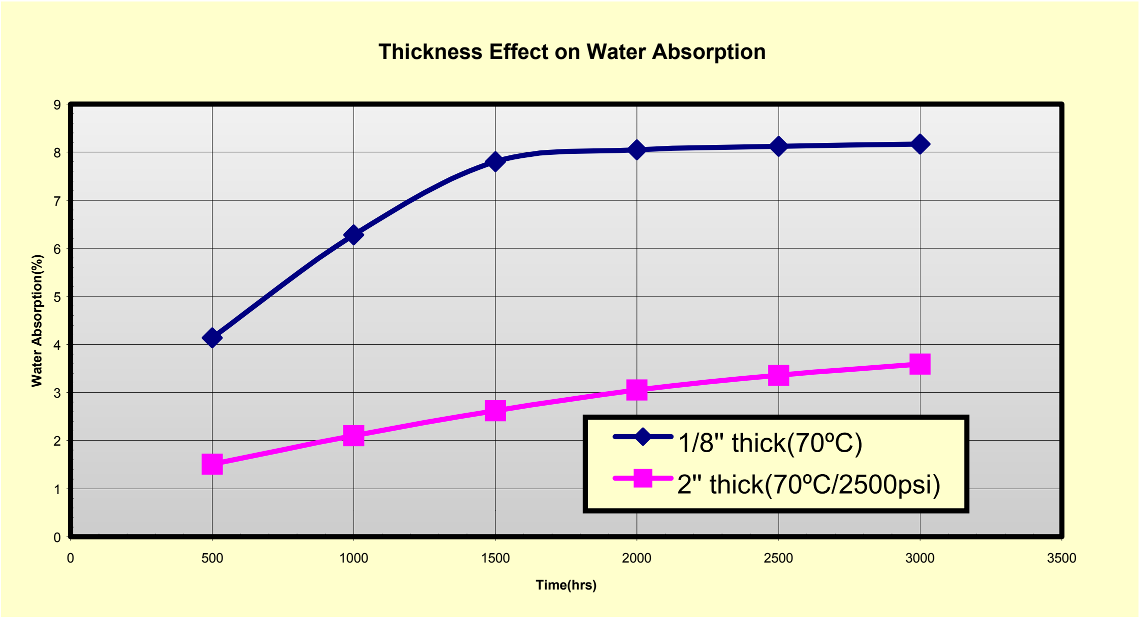

Figure 10. Effect of Sample Thickness

MEASURING THERMAL CONDUCTIVITY

An instrument commonly used to measure thermal conductivity is the Holometrix Lambda 2000 Series Heat Flow Meter, operated in accordance with ASTM C518. Other equipment and standards are also used, and care must be taken to calibrate the different tests to verify accurate measurement of thermal properties. As discussed above, increasing pressure and/or temperature will increase the rate of water absorption and loss of thermal properties. However, these methods of accelerated testing often yield suspect results, since the binder resin is sensitive to the relationship between test temperature and its inherent glass transition temperature (Tg), and the microsphere filler has fixed and finite crush strength. A more promising approach is to employ fatigue testing (rapidly repeated cycles of pressure and/or temperature) to speed the loss of properties. Testing to verify the accuracy of this method is currently under way.

EFFECTS ON OTHER PROPERTIES

Exposure to heat and pressure affects other insulation properties, including strength and flexibility, often in unexpected ways. For example, **Figure 11** shows the behavior of an epoxy/glass syntactic foam under hydrothermal (hot, wet) aging over a range of temperatures. Tensile strength declines, as expected, with rising temperature. Surprisingly, elongation at break actually increases under the same conditions. The reason, of course, is that the elastic modulus of the material also falls with rising temperature, resulting in much “softer” material. This kind of benign behavior cannot be expected to go on forever, of course, but it does illustrate that the interrelatedness of physical properties must be kept in mind when evaluating test results.

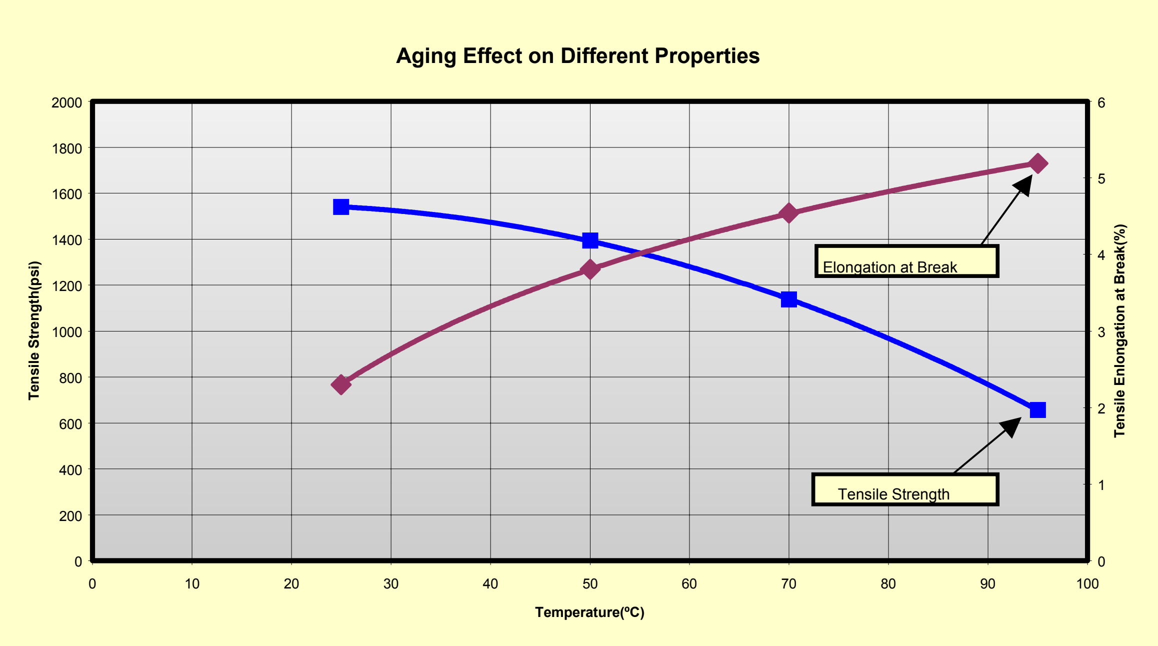

Figure 11. Aging Effect on Mechanical Properties

SIMULATED SERVICE VESSEL

The most realistic testing method is the “Simulated Service Test” which attempts to duplicate actual conditions: hot oil flowing inside the pipe and pressurized cold water outside the insulation. Because this test is expensive and time consuming, and not suitable for screening large numbers of materials, it must be part of a comprehensive program of screening and evaluation by other methods. The SSV that we use in our testing operates up to 175 ºC and 20 MPa. The vessel can test insulation samples cast onto 8’’ nominal pipe (219 mm) up to 1.65 m long. In order to generate more data per unit time, we normally limit our samples to 0.55 m long each, and test three samples simultaneously. The apparatus, which is shown in **Figure 12**, consists of five major parts: pressure vessel, oil heater, water chiller, temperature and pressure controller, and emergency pressure relieve valve.

Figure 12. Simulated Service Vessel

Figures 13 and **14** illustrate typical SSV tests, one of pour-in-place material, and the other of pack-in-place material. The vessel was opened every week to visually inspect the insulation material and weigh the samples to calculate water absorption. During the opening and closing process, the insulation materials experienced both thermal shock and pressure cycling. As result, the SSV test is more severe than its intended application, and the data collected therein tends to be conservative.

SUMMARY AND CONCLUSIONS

1. Syntactic foam insulation materials are available to meet most present subsea insulation requirements, with epoxy/glass-based materials being the most versatile and capable systems known at this time.

2. Long-term materials behavior can be predicted by testing small size samples under appropriate conditions. However, the conditions and procedures must be very carefully selected, and the results properly analyzed.

3. Materials performance is driven by both temperature and pressure. Temperature is the key driver in short-term “ hot, wet” conditions. Hydrostatic pressure, so long as it is well below the crush pressure, primarily impacts long-term performance. (Conclusions are continued on Page 11.)

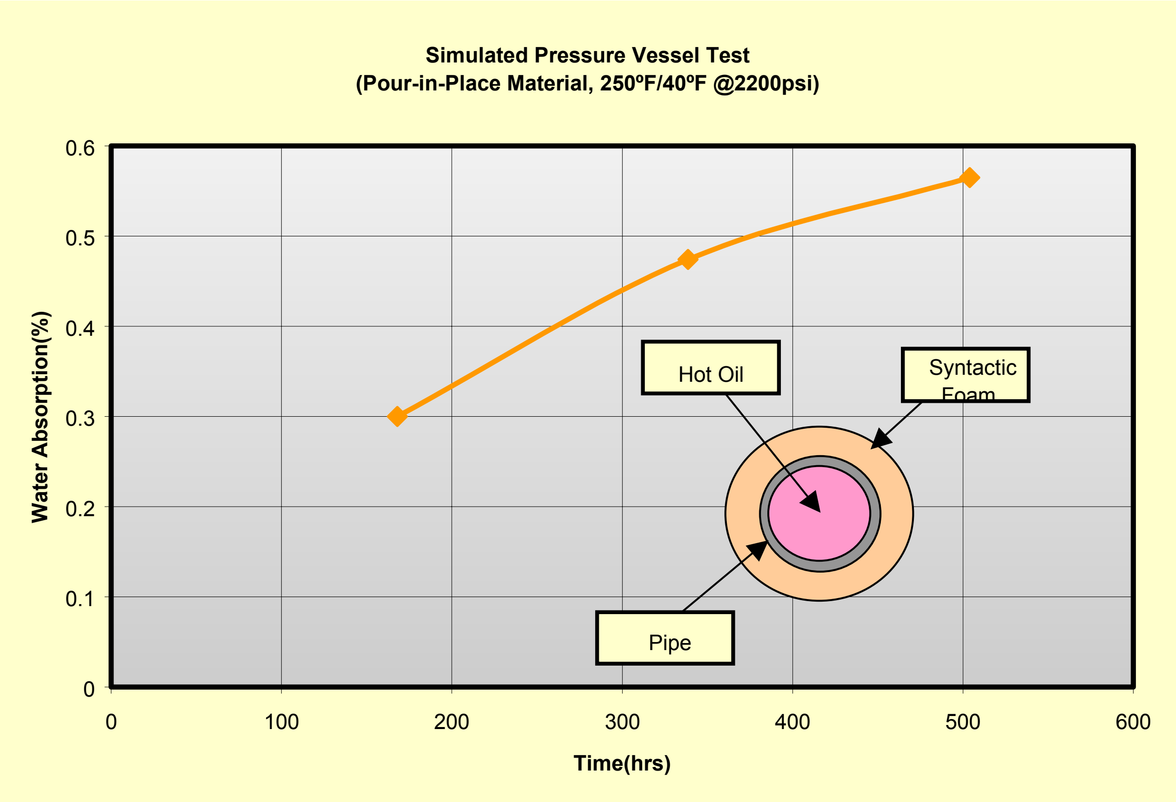

Figure 13. SSV Test of Pour-in-Place Insulation

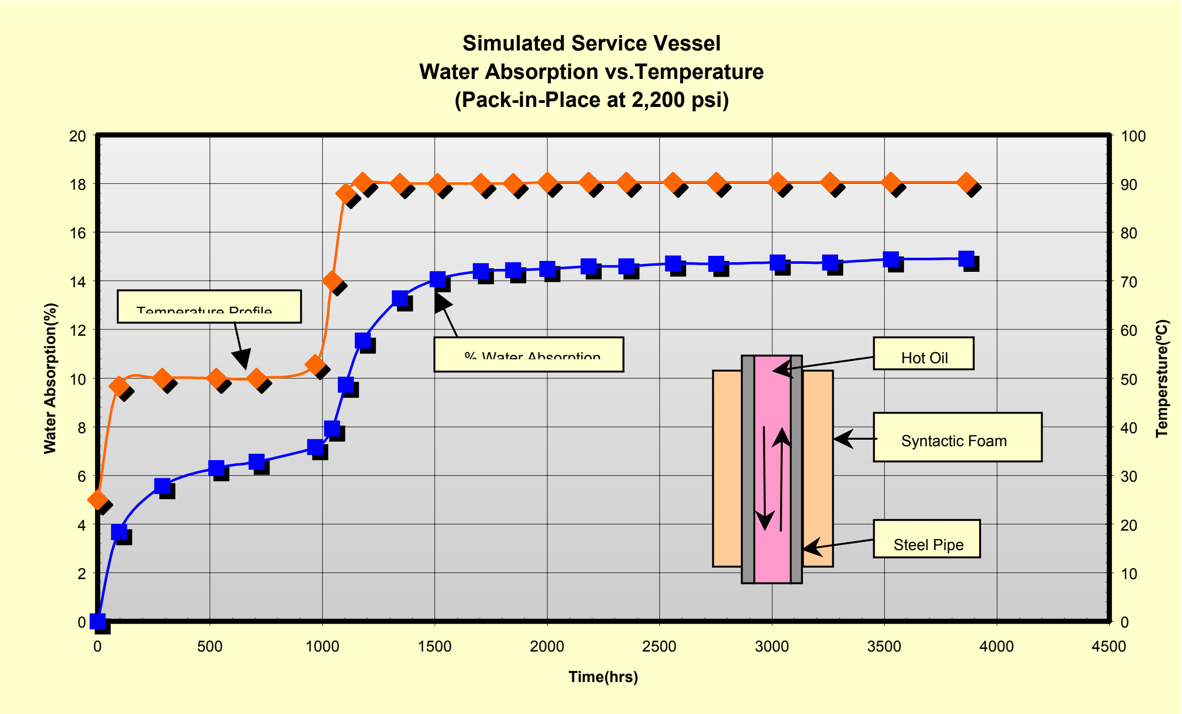

Figure 14. SSV Test of Pack-in-Place Insulation

4. Considering Point 3, the *Arrhenius* equation must be used with great caution in extrapolating water absorption from short-term data. The differing time constants of temperature and pressure effects must be taken into account.

5.The best way known for testing insulation material is the Simulated Service Vessel (SSV), but it is also the most expensive and inconvenient method. Further, SSV test duration is a topic requiring more study and discussion.

6. While it is every engineer’s goal to design a 100 % waterproof system, the possibility always exists for some leakage to occur during twenty or more years under high hydrostatic pressure. Therefore, it is advisable to design and test insulation materials under conservative “hot, wet” conditions.

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