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# Syntactic Foam Thermal Insulation for Ultra-Deepwater Oil and Gas Pipelines

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## Abstract

Syntactic foam has been used successfully for over thirty years in the offshore industry, primarily as a buoyancy material for supporting marine riser pipe, and in floats and buoys of various kinds. Now its use is growing as a thermal insulating material for subsea equipment and pipelines, ensuring continued flow of hydrocarbons under adverse conditions. Experience to date shows that syntactic foam can in many cases offer significant engineering and economic advantages compared to more conventional insulation. However, realizing the full benefit of these new materials requires careful selection of ingredients and optimization of all relevant properties using a systems approach to the manufacture, assembly, and installation of the equipment.

## Introduction

Syntactic foam is a composite material made from tiny hollow glass microspheres embedded in a polymeric binder, as shown in **Figure 1**. In some cases other fillers are added as required to modify the composite properties. High compressive strength and low density are the properties that make syntactic foam an efficient buoyancy material, and low thermal conductivity is a byproduct of its construction. Given its thermal efficiency and water resistance, syntactic foam is a natural choice for insulating subsea equipment. However, syntactics for thermal insulation are designed differently than are materials intended solely for buoyancy purposes. Density of the material is of less interest, while long-term thermal stability becomes critical. As long as service is limited to cold water, a wide range of polymer binders is available, and the spherical fillers are strongly reinforced by the surrounding matrix. At elevated temperature, on the other hand, materials choices are limited and the strength of the composite may be affected in ways that are difficult to predict. Such are the challenges that are continuing to shape the development of syntactic foam insulation.

## History and Applications

It has long been known that subsea production of hydrocarbons is prone to blockage by paraffins or hydrates that can form when the fluid temperature falls below some critical level. One aim of flow assurance technology, therefore, is to conserve the heat of the fluid and prevent excessive cooling, even during shutdown periods. This has become an increasingly important concern as production has moved into deeper water and longer flowlines have been required, and a variety of different insulation methods have evolved. The following components have received attention to date:

**Wet trees and valves** are routinely insulated. Key issues include high temperature, differential thermal expansion and contraction, and the necessity of some parts to move or to be serviced or replaced while in service.

**Jumpers** are also frequently insulated. These pipes are often of complex curvature and usually require insulation materials with a great deal of flexibility. Speed and ease of installation is an important objective.

**Sleds and PLEM's** often require not only thermal insulation, but also buoyancy to aid in installing the subsea system. Syntactic foam can be designed to combine the buoyancy and insulation functions. See **Figure 2** for a typical PLEM application.

**Risers and flowlines** often need a high degree of insulation as well, as illustrated in **Figure 3**. The insulation system must be compatible with the desired lay method and fabrication technique, and buoyancy may be an issue. Long service life, of course, is always a major objective.

## Materials Selection

The uniquely characteristic component of syntactic foam is the fine-grained glass microsphere filler that imparts much of its thermal and physical behavior. Glass microspheres, typically 100 to 200 microns in diameter, are preferred over plastic microspheres because they retain much of their strength at elevated temperature. The choice of glass chemistry is also important, with borosilicates preferred over more common high-sodium glasses which may exhibit solubility problems. Certain types of ceramic microspheres have excellent resistance to hot water, but their density and thermal conductivity are not acceptable for many applications.

Larger fiberglass macrospheres, 6.0 to 12.0 mm in diameter, are often used in buoyancy applications to lower density and improve the cost effectiveness of syntactic foam castings. Unfortunately, the fiberglass walls of conventional macrospheres are adversely affected by high temperature, and so-called “composite” insulation materials (containing macrospheres) are usually limited to temperatures of about 100º C or less. However, research is continuing to develop new, high-temperature-tolerant macrospheres for insulation purposes.

The binder resin, a polymerized plastic material, forms the matrix that “glues” the various filler ingredients together. Choices include various rigid and semi-rigid types of epoxy, and elastomeric plastics such as polyurethane. The more rigid the binder, the better it reinforces the hollow spherical fillers and retains its strength at elevated temperature. A flexible binder, on the other hand, will resist cracking and permit the pipe to be bent, or in some cases, reeled. The degree of adhesion to the pipe or substrate is often important, as is resistance to impact and abrasion. The selection of the binder resin is strongly influenced by its ability to withstand the long-term effects of hot water, which can be very serious. Many plastics exhibit thermal degredation that can only be revealed by testing for long periods of time.

## Testing

Thorough testing of syntactic foam insulation is critical to achieving a successful application. The challenge here is that little long-term data are available, and the established standards and specifications are not always applicable. A list of those standards commonly applied to insulation materials is given in **Table 1**. A typical thermal conductivity measuring device is shown in **Figure 4**. The following is a brief summary of the “testing hierarchy” that is now slowly emerging among users and suppliers in the industry:

**Initial Screening.** Immersion of small samples (typically 3mm x 25mm x 50mm) in hot water at atmospheric pressure to detect any signs of swelling, warpage, embrittlement, or hydrolysis. Accelerated aging is possible by raising the water temperature, but just under 100º C is the practical limit for open water baths. The equipment is simple and inexpensive, but interpretation of results is often difficult.

**Pressurized Thermal Testing.** Testing of larger samples (typically 50mm cubes) under hydrostatic pressure and temperature. Orders of merit include low levels of water absorption, retention of insulating value, and absence of deterioration. Temperatures above 100º C are possible. Interpretation of results is highly dependent upon area-to-volume ratios and other effects that cannot be fully appreciated without larger scale tests.

**Full-scale Proof Testing.** Testing of a full-scale section of insulation under pressure and temperature, preferably mounted on pipe or other substrate simulating the actual application. Properly administered, such tests yield realistic results. However, the specialized equipment required is expensive and often not readily available, severely limiting the extent and duration of testing that can be performed.

## Density vs. Depth

As its required service depth increases, the design density of the syntactic foam must be increased accordingly to provide additional strength. This is done primarily by increasing the wall thickness of its spherical fillers. A similar effect occurs as the service temperature rises. Because heat lowers the modulus or stiffness of the reinforcing binder, the spheres must necessarily be made heavier and stronger to resist hydrostatic pressure. As a result, syntactic foam insulation is usually heavier than buoyancy materials rated for the same depth. Although density itself is seldom a critical factor in specifying insulation, it is of importance in determining thermal efficiency, since the conductivity of syntactic foam tends to be proportional to density. Achieving an optimal combination of thermal conductivity and hydrothermal resistance requires careful selection of both binder and fillers. The chart in **Table 2** compares typical densities of syntactic foam buoyancy materials and equivalent syntactic foam insulation, while the chart in **Table 3** lists expected thermal properties.

## Special Challenges

The use of syntactic foam as an insulation material has encountered a number of hurdles, many of which have been met successfully, while others require further development, especially as projects go deeper and hotter. The following three items are probably the greatest technical challenges facing the use of syntactic insulation today in ultra-deepwater applications.

**Hydrothermal Aging**. All plastics exhibit some degradation when exposed to hot, high-pressure water, an effect which must be taken into account if the insulation is to perform for its design service life. Hydrolysis is the gradual breakdown of the plastic’s polymeric chain, resulting in loss of properties. Binder materials vary widely in their resistance to hydrolysis, depending on formulation and processing, and behavior is very dependent on specific conditions. Several industry-wide programs are presently under way to promote long-term testing and broaden our understanding of these phenomena.

**Filler Stability.** Glass microspheres also suffer to some extent from hydrothermal effects. If the glass used to form the microspheres contains too much free sodium or some other water-soluble ion, it will exhibit much the same behavior as described above: gradual loss of properties, breakage, and dissolution. Special high performance microspheres, coatings, and coupling agents are available which ensure stability under extreme conditions, and suppliers of glass microspheres are working to create further improvements. At the same time, the same industry groups cited above are addressing the issue as part of their materials studies.

**Flexibility and Cracking.** A certain amount of flexibility is desirable in an insulation material, to accept bending and differential expansion under thermal cycling. Materials that are too rigid will crack in service, raising the possibility of convective heat losses. The extent to which such cracks actually affect the overall insulating value of the system is a complex question requiring analysis. Flexibility becomes even more important in the cases of flexible risers, or of reel laying of rigid flowlines. The only practical solution for highly flexible applications at this time is to employ an elastomeric resin binder in place of more rigid materials.

## Advantages

Syntactic foam has been used successfully as an offshore buoyancy material for over thirty years, and today is in service at depths of 3,000 meters or more. Syntactic foam's use as a deepwater insulation system is growing because it offers a number of advantages over more conventional materials, based largely on its unique fine-celled structure and high strength-to-weight ratio. The following are among the important advantages offered by syntactic foam:

**Low Density.** In most cases, syntactic foam provides the lowest density solution to any buoyancy or insulation requirement, at any depth. This is often a big advantage, particularly in deep water, where the weight of the pipe string can become excessive.

**Low Thermal Conductivity.** Again, in most cases, syntactic foam offers the lowest thermal conductivity at any depth, as compared to alternative materials. This means smaller profile, less hydrodynamic drag, and more available space on the lay barge.

**Virtually Zero Creep.** Other insulation materials, especially those based on thermoplastic foam, exhibit long-term creep, or volumetric deformation, that significantly degrades performance. Syntactic foam is inherently stable and does not show such behavior.

**Integral Buoyancy.** The low density of syntactic foam permits buoyant lift to be designed into the insulation system, if desired. This eliminates the need for separate buoys and flotation hardware, greatly simplifying the pipeline package and laying process.

**Ruggedness and Durability.** Its great compressive strength makes syntactic foam resistant to crushing and mechanical damage during storage, handling, and laying. Tests have confirmed that syntactics are compatible with tensioners, stinger rollers, and other conventional laying equipment.

**Adaptability.** Because syntactic foam can be manufactured by any of a number of methods and in many forms, it can be adapted to any insulation requirement: cast-on-pipe, half-shells, tapes, cast-in-place, precast custom shapes, and pack-in-place kits are available.

**Compatibility.** Syntactic foam insulation systems are fully compatible with conventional flowline, riser, and subsea equipment technology. Syntactic insulating collars for bulkheads and field joints have been used many times with good success.

**Cost-Effectiveness.** In many cases, syntactic foam has proven to be the lowest cost solution to insulating flowlines and subsea equipment, often saving users hundreds of thousands of dollars per project. This advantage is discussed in more detail below.

## Economics

Aside from its technical performance advantages, syntactic foam is selected because it is often the least-cost solution to complex subsea problems. For example, no other material can successfully provide both buoyancy and insulation in a compact, volumetrically-efficient package. To realize its full economies, however, the syntactic foam must be engineered with a systems approach that integrates materials science, processing, and mechanical design. The cast-on-pipe process can apply syntactic buoyancy to a riser at lower overall installed cost than the traditional method of molding half-shells and strapping them onto the pipe. Similarly, pipe supplied with integral buoyancy and insulation is much less expensive and time-consuming to deploy than the conventional way of attaching clamps and assembling annular buoys onto the pipe at sea. The chart in **Table 4** compares the economics of various approaches to insulation and buoyancy.

## Track Record

The following is a list of "highlights" of syntactic foam insulation applied to ultra-deepwater production risers or flowlines, either already installed or in process, which are known to the authors at this time. It should be noted that this is only a small sampling of the total number of related projects at all depths, and does not include syntactic insulation applied to and in service on flexible risers, or a large number of miscellaneous subsea devices and equipment.

Shell *King* Flowlines
    Installation: 1999
    Location: Gulf of Mexico
    Length: 10 kilometers
    Temperature: 75º C
    Water Depth: 1,000 meters

BP Amoco *King* Flowlines
    Installation: 2001
    Location: Gulf of Mexico
    Length: 50 kilometers
    Temperature: 85º C
    Water Depth: 1,600 meters

TotalFina/Elf *Girassol* Risers and Flowlines
    Installation: 2001
    Location: Offshore Angola
    Length: 30 kilometers
    Temperature: 95º C
    Water Depth: 1,500 meters

## The Future

Syntactic foam thermal insulation is still in its infancy. As the above list indicates, much more experience will be gained over the next two or three years with syntactic foam on deepwater risers and flowlines. In addition, numerous projects are in the planning stages that will take this exciting new technology into deeper water and higher temperatures. Several industry groups are at work, compiling information and drafting testing standards for the design and construction of these new systems. Suppliers are aggressively developing and testing new products for more demanding service. The production industry has targeted 3,000 meters as its next depth benchmark, and temperatures as high as 150º C are being suggested. Only time will tell how well these ambitious objectives are met, but it seems certain that the growing need for offshore oil and gas will continue to demand dramatic improvements in ultra-deepwater thermal insulation.

## Bibliography

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## Tables

**Table 1**. Testing Standards.

**Table 2**. Comparisons of Densities

**Table 3**. Ultra-Deepwater Syntactic Foam Insulation Materials.

**Table 4**. Relative Economics

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**Figure 1**. Cross Section of Syntactic Foam.

**Figure 2**. Shell *King* PLEM.

**Figure 3**. Shell *King* Quad Joints.

**Figure 4.** Holometrix Thermal Cell.

Table 1
**TESTING STANDARDS**

| Testing Method | Physical Property |
|---|---|
| ASTM D 792 | Density |
| ASTM D 518 | Thermal Conductivity |
| ASTM D 351 | Specific Heat Capacity |
| ASTM D 2240 | Hardness |
| ASTM D 695 | Compressive Strength |
| ASTM D 1623 | Tensile Strength |
| ASTM D 2736 | Hydrostatic Strength |
| ASTM D 570 | Water Absorption |

Table 2
**COMPARISON OF DENSITIES**
(Numbers are approximate)
Nominal kg/m$^3$ (lbs/ft$^3$) vs. Operating Temperature

| Max Depth, m (ft) | Syntactic Foam Buoyancy Mtls at 4º C (40º F) | Syntactic Foam Insulation Mtls at 80º C (175º F) |
|---|---|---|
| 1200<br>(4,000) | 450<br>(28.0) | 513<br>(32.0) |
| 1500<br>(5,000) | 480<br>(30.0) | 545<br>(34.0) |
| 1800<br>(6,000) | 513<br>(32.0) | 577<br>(36.0) |
| 2300<br>(7,500) | 545<br>(34.0) | 641<br>(40.0) |

Table 3
**ULTRA-DEEPWATER SYNTACTIC FOAM INSULATION MATERIALS**
(Numbers are approximate)

| Type of Syntactic Construction | Maximum Service Depth Rating, m (ft) | Maximum Temperature, ºC (ºF) | Thermal Conductivity, W/m ºK (Btu/ft ºF hr) | Specific Heat Capacity, J/g ºC (Btu/lb ºF) |
|---|---|---|---|---|
| **Rigid** | 1200 (4,000) to 2300 (7,500) | 80 (175) to 100 (212) | 0.08 (0.04) to 0.12 (0.07) | 1.28 (0.30) |
| **Semi-Rigid** | 1200 (4,000) to 2300 (7,500) | 80 (175) to 100 (212) | 0.09 (0.05) to 0.13 (0.08) | 1.28 (0.30) |
| **Flexible** | 1200 (4,000) to 2300 (7,500) | 80 (175) to 100 (212) | 0.10 (0.06) to 0.15 (0.09) | 1.28 (0.30) |

Table 4
**RELATIVE ECONOMICS**
(Numbers are approximate)

| Insulation Method | Service Limitations | Application Notes | Relative Cost **1** = Least Costly |
|---|---|---|---|
| Unfilled Polyolefin | Unlimited Depth<br>100º C Max. Temp. | Limited Insulation Only | **1** |
| Polyolefin Foam | 1000 m Max. Depth<br>100º C Max. Temp. | Insulation Only | **2** |
| Flexible Syntactic | 2000 m Max. Depth<br>100º C Max. Temp. | Insulation Only | **3** |
| Rigid/Semi-Rigid Syntactic | 3000 m Max. Depth<br>100º+ C Max. Temp. | Insulation and Buoyancy | **3** |
| Steel Pipe In Pipe | 3000 m Max. Depth<br>100º+ C Max. Temp. | Insulation Only | **5** |

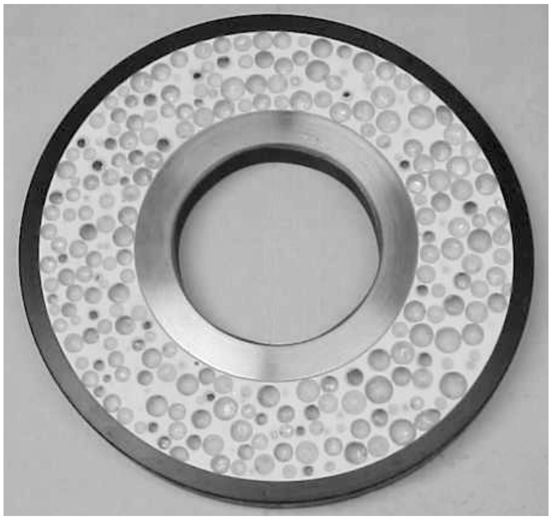

**Figure 1: Cross Section of Syntactic Foam**

**Figure 3: Shell *King* Quad Joints**

**Figure 2: Shell *King* PLEM**

**Figure 4: Holometrix Thermal Cell**