Technical Note 600-4

NOTES ON THERMAL PROPERTIES AND HEAT TRANSFER OF SYNTACTIC FOAM SUBSEA INSULATION

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1. The properties that make syntactic foam an efficient buoyancy material also make it a good subsea thermal insulator: low density, high strength, and resistance to water penetration. The hollow spherical fillers in the foam contain air and prevent its compres-sion by hydrostatic force. The air in turn acts as a very effective insulator, slowing heat transfer as long as structural integrity is maintained.

2. Heat transfer textbooks list three modes of heat transfer: *conduction*, *convection*, and *radiation*. Radiation is seldom a factor in “wet” subsea insulation, and convection plays a role only when water is free to circulate, a condition normally avoided. Therefore, this paper focuses on *conduction* as the principal way in which heat travels through syntactic foam insulation.

3. A glossary of heat transfer properties is given on Page 4. The following definitions apply to the terms we will be using most frequently:

<u>Density:</u> Mass per unit volume is symbolized by the Greek letter *rho* (_); it is usually numerically equivalent to *weight* per unit volume, but caution is required to make sure the correct values are always used.

<u>Thermal Conductivity:</u> The rate at which heat is conducted through the material in question. The higher the conductivity (**k**-value), the more easily heat will be transmitted from the “hot” to the “cold” side of the material.

<u>Specific Heat:</u> A measure of how much heat is stored per unit mass of the material in question. The higher the specific heat (**c**), the more heat will be absorbed (or given up) as the material heats (or cools). This term must be distinguished from *heat capacity* (**C**), the total amount of heat energy stored in a given mass of material.

<u>Thermal Diffusivity:</u> An indicator of how rapidly heat diffuses through the material, based on the numerical relationship among the above three properties. The lower the diffusivity (_), the more slowly heat will spread.

<u>Heat Transfer Coefficient:</u> The **U**-value, or relative rate at which heat will be lost from an insulated system, based on the **k**-value of the insulating layer and the specific dimensions and geometry of the system. The **U**-value is also often referred to as the Overall Heat Transfer Coefficient, or “OHTC.”

4. Syntactic foam is a lightweight material with inherently low thermal conductivity and low heat capacity. Conductivity is generally proportional to density, as is strength, so heavier, deeper-rated materials exhibit greater conductivity than do lighter, shallow-rated materials. Also, because they are exposed to the effects of hot water, (see Reference 1), insulation materials are usually formulated to be somewhat heavier (i.e., more dense) than similarly rated buoyancy materials that are exposed only to cold water.

5. The specific heat of a material does not always increase in proportion to its density in the same way that conductivity usually does. However, the actual heat capacity, or energy stored, always rises as density increases, due to the greater mass involved. Efficient design of syntactic foam insulation calls for careful tradeoffs among density, strength, long-term rate of water absorption, thermal conductivity, and specific heat.

6. Calculating steady-state heat transfer through a flat, homogeneous insulating panel of thickness **t** is simple, knowing the thermal conductivity **k** of the material:

U = **k**/**t**

Example: A subsea tree block has been insulated with a 3.00” thick layer of *C-THERM* syntactic foam, **k** = 0.08 Btu/hr-ft-oF. What is **U**, the heat transfer coefficient?

U = 0.08/(3.00/12) = 0.32 Btu/hr-ft2-oF

7. Making the same calculation for insulation wrapped around a pipe requires correction to be made for curvature and differing surface areas of the OD and ID:

where:
D1 = pipe OD, in. **U** with respect to pipe OD = **UOD** = (24**k**)/(**D1**(Ln(**D2**/**D1**)))
D2 = insulation OD, in.
D3 = pipe ID, in. **U** with respect to pipe ID = **UID** = (24**k**)/(**D3**(Ln(**D2**/**D1**)))

Example: A pipe 10.75” OD x 9.75” ID is coated with a layer 3.00” thick of *C-THERM* syntactic foam, k = 0.08 Btu/hr-ft- oF. What is **UID**, the heat transfer coefficient with respect to the pipe inner diameter?

UID = ((24)(0.08))/(9.75(Ln(16.75/10.75))) = 0.44 Btu/hr-ft2-oF (Note: **UOD** = 0.40)

8. Diffusivity _ is a good overall measure of insulation effectiveness, since it takes all of the principal thermal characteristics into account:

_ = [**k**/(**c** x **_**)]

Example: Two candidate insulation materials have the following properties:

	k	**c**	**_**
Material **A**	0.080	0.38	44.0
Material **B**	0.090	0.30	44.0

_A = [0.080 / (0.38 x 44.0)] = .005 ft2 /hr
_B = [0.090 / (0.30 x 44.0)] = .007 ft2 /hr

Note: If applied in equal thickness, Material **A** will provide approx. 30% longer cool-down time than Material **B**.

9. In the building trades, insulation is often characterized by **R**-Value:

R = Thickness/Conductivity = **t**/**k** = (hr-ft2- oF) / Btu

Example: 3.5” thick fiberglass batting has conductivity **k** = 0.035 Btu/hr-ft- oF. What is its **R**-value?

R = (3.5/0.035) x (1/12) = 8.3 (hr-ft2- oF) / Btu

Note: Sometimes expressed in **R**/inch, in this case = 2.4.

10. The above “building industry” definition of “**R**-Value” should not be confused with that of *thermal resistance* **Rt**, which has the area term removed, as shown below. **Rt** is used in **U**-value and cool-down calculations, as explained in Section 11.

$$\mathbf{Rt} = \text{Thickness}/(\text{area} \times \mathbf{k}) = (\text{hr-oF}) / \text{Btu}$$

11. Subsea insulation can have many purposes, but often the most important one is to increase the system’s *cool-down time*, the time required for an offshore oil or gas pipe to cool from its operating temperature to some lower threshold at which harmful precipi-tates may form, thereby extending the opportunity for corrective intervention.

$$\boldsymbol{T}\text{hours} = \overset{\text{Scaled Ratio of}}{(\text{Temperatures})} \times \overset{\text{Total } \mathbf{Rt} \text{ of}}{(\text{Pipe and Coatings})} \times \left[\overset{\mathbf{C} \text{ of}}{(\text{ Pipe })} + \overset{\mathbf{C} \text{ of}}{(\text{ Fluid })} + \overset{\mathbf{C} \text{ of}}{(\text{ Coatings })} \right]$$

Example: *C-THERM* syntactic foam with the properties of Material **A** in Section 8 is cast onto a 12.75” OD steel pipe to form insulation 2.75” thick. The pipe carries natural gas at a temperature of 181o F. Sea water temperature is 39o F. If the line is shut in, how long will it take for the gas to cool to its threshold temperature of 61o F? An intervention time of at least 24 hours is desired.

$$\boldsymbol{T}\text{hours} = 1.882 \times 0.715 \times 18.946 = 25.5 \text{ hours}$$

12. Epoxy-based syntactic foam insulation materials do not degrade under long-term exposure to high-pressure seawater, nor do they exhibit appreciable creep. Therefore, it is possible to extrapolate performance out to very long service periods. Syntactic foam does, however, absorb small amounts of water, which will have an impact on its thermal properties. See Reference 2 for a discussion of this behavior.

References

1. Technical Note 600-3, “Notes on the Mechanical Properties of Syntactic Foam Flotation and Insulation.”

2. Technical Note 600-2, “Notes on the Design and Construction of Syntactic Foam Products.”

3. DeRuntz, J. A.: “Micromechanics and Macromechanics of Syntactic Foam,” Proceedings of the 1969 Southampton Conference.

4. Watkins, Lou: “Syntactic Foam Buoyancy for Production Risers,” Offshore Mechanics Conference Technical Paper, 1988.

5. Kreith, Frank, and Bohn, Mark S., “Principles of Heat Transfer,” Brooks / Cole, 2001.

GLOSSARY OF THERMAL TERMS AND PROPERTIES

Property
Symbol
Units, English/SIEnergy
(Heat)
Q1 Btu = 1055.1 J
1 cal = 4.186 JPower
(Heat Transfer Rate)
P1 Btu/hr = 0.2931 W
2545 Btu/hr = 1.0 hpHeat Flux
(Heat Transfer Rate per Unit Area)
q”
1 Btu/hr-ft2 = 3.154 W/m2Heat Transfer Coefficient
(Rate of Heat Loss per Unit Area)
U
1 Btu/hr-ft2- oF = 5.678 W/m2-KSpecific Heat
(Heat Stored per Unit Mass)
c
1 Btu/lbm- oF = 4187 J/kg- KThermal Conductivity
(Heat Transmission per Thickness)
k
1 Btu/hr-ft- oF = 1.731 W/m-KThermal Resistance
(Resistance to Heat Transmission)
Rt
(1 hr- oF)/Btu = 1.896 K/WThermal Diffusivity
(Rate of Heat Diffusion)
_
1 ft2/hr = 0.093 m2/hr

TYPICAL PROPERTIES OF MATERIALS

MaterialDensity **_**,
lbm/ft3 (kg/m3)Conductivity **k**,
Btu/hr-ft-oF(W/m-K)Specific Heat **c**,
Btu/lbm-oF(J/kg-K)CTE **_**,
1/R (1/K) x10-4
Aluminum
168 (2700)
96 (167)
0.21 (896)
0.13 (0.24)
Concrete
131 (2100)
0.78 (1.35)
0.24 (1000)
0.06 (0.11)
Crude Oil @ 68o F
44 (700)

0.076 (0.13)
0.47 (1968)
——Natural Gas,
1 atm @ 68o F
0.04 (0.67)
0.019 (0.03)
0.53 (2221)
——
Polyethylene
58 (925)
0.17 (0.30)
0.52 (2200)
1.17 (2.10)
Steel
490 (7801)
25 (43)
0.11 (473)
0.06 (0.11)
Syntactic Foam 1
38 (610)
0.08 (0.14)
0.30 (1260)
0.60 (1.00)
Syntactic Foam 2
44 (705)
0.07 (0.12)
0.36 (1508)
0.50 (0.83)
Water, Fresh
62 (1000)
0.34 (0.58)
1.00 (4188)
0.38 (0.69)
Water, Sea
64 (1026)
0.33 (0.58)
0.93 (3911)
0.36 (0.65)
Wood, Dry
26 (425)
0.087 (0.15)
0.65 (2720)
0.03 (0.05)