Thermal Insulation in Cryogenic Systems

Fulvio Ricci

Sapienza University of Rome and INFN Sezione di Roma

Types of insulation used in cryogenic equipment

- Expanded closed-cell foams,
- Gas-filled powders and fibrous materials,
- Aerogel insulation,
- Evacuated powders and fibrous materials,
- Opacified powders,
- Microsphere insulation,
- Multi layers Insulations - MLIs

Expanded closed-cell foams - I

A foam with a cellular structure produced by evolving gas during its formation

- Heat transfer contributions are due to the convection and radiation within the cells and the conduction through the solid structure.
- Thermal conductivity depends on the density and by the type of gas and the mean temperature used in the manufacturing process.

$$k_t = 0.4(1-\Phi)k_s + k_g + 4F_e d\sigma T_m^3$$

Φ porosity of the foam (volume of void per unit total volume)
k_s thermal conductivity of the solid foam material
k_g thermal conductivity of the gas within the cavities
d thickness of the foam
T_m mean insulation absolute temperature = $\frac{1}{2}(T_H + T_C)$
$\sigma = 0.1714 \times 10^{-8}$ Btu/h-ft^2-°R^4 = 5.669×10^{-8} W/m^2-K^4 (Stefan–Boltzmann constant)

Different Foam types made of
- polyurethane
- polystyrene
- glass foam

Main use: protect and insulate underground pipes

$$\frac{1}{F_e} = \frac{d}{d_c}\left(\frac{1+r-t}{1-r+t}\right)+1$$

F_e emissivity factor
r reflectivity of the foam material
t transmissivity of the foam material
d_c size of the foam cells

$$\rho_m = \rho_s(1-\Phi)+\rho_g\Phi$$

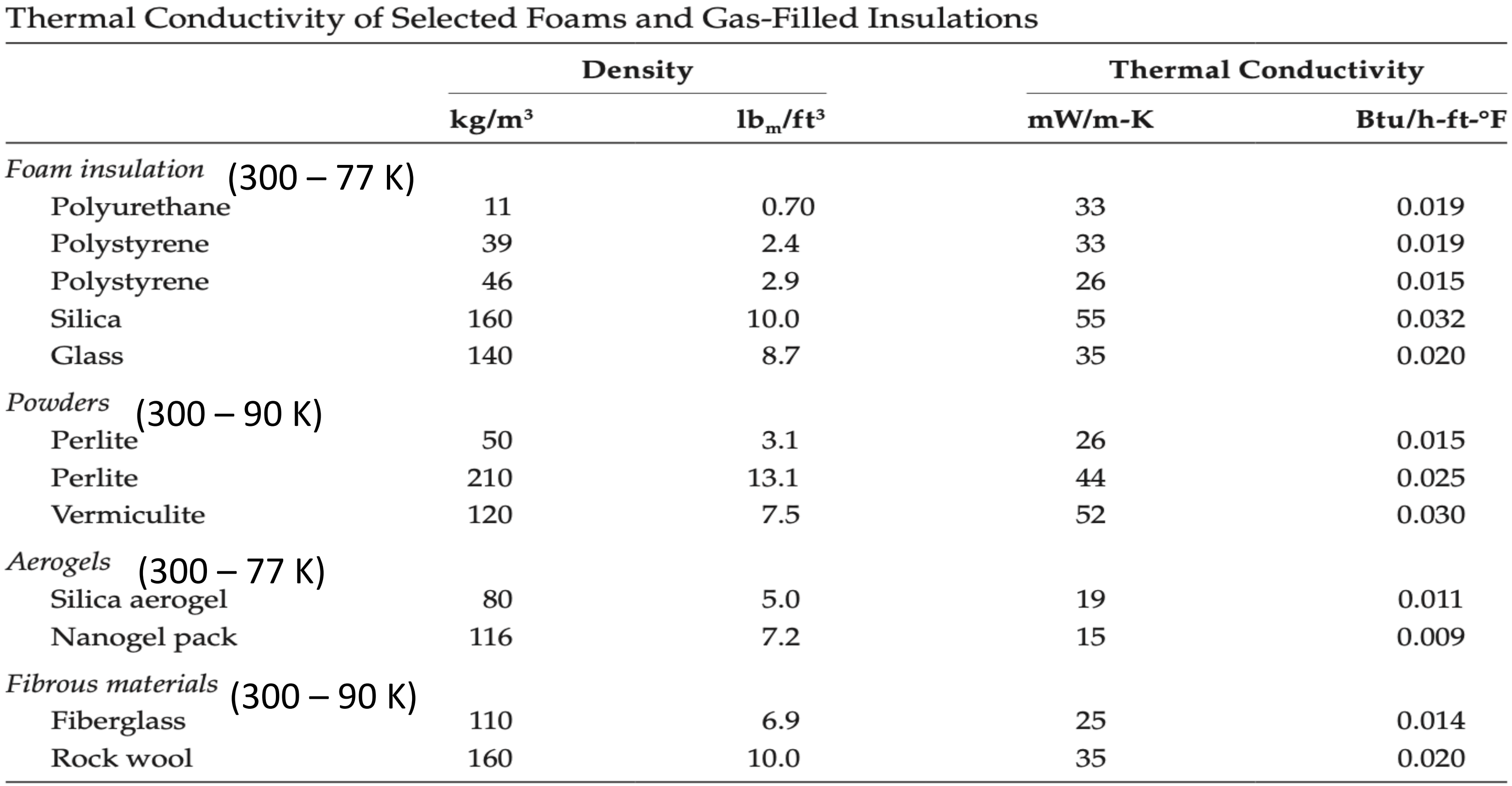
ρ_g = gas density
ρ_s = solid density

Expanded closed-cell foams - II

Insulation of liquid natural gas pipes (higher tolerance of thermal input)

Advantage: low cost solution

Disadvantage: large thermal contraction in the case rigid foam insulations .



Thermal Conductivity of Selected Foams and Gas-Filled Insulations

	Density		**Thermal Conductivity**	
	kg/m^3	**lb$_m$/ft^3**	**mW/m-K**	**Btu/h-ft-°F**
Foam insulation (300 – 77 K)				
Polyurethane	11	0.70	33	0.019
Polystyrene	39	2.4	33	0.019
Polystyrene	46	2.9	26	0.015
Silica	160	10.0	55	0.032
Glass	140	8.7	35	0.020
Powders (300 – 90 K)				
Perlite	50	3.1	26	0.015
Perlite	210	13.1	44	0.025
Vermiculite	120	7.5	52	0.030
Aerogels (300 – 77 K)				
Silica aerogel	80	5.0	19	0.011
Nanogel pack	116	7.2	15	0.009
Fibrous materials (300 – 90 K)				
Fiberglass	110	6.9	25	0.014
Rock wool	160	10.0	35	0.020

Example:

Thermal exp. coeff.

7.2×10^{-5} K^{-1} glass foam

1.5×10^{-5} K^{-1} carb. steel

$\Delta T = 100$ K, $L = 6$ m

$\Delta L = 3.6$ cm

A cover is needed to prevent diffusion of water vapor and air into the foam. It will reduced also the replacement of the foaming agent with hydrogen and helium gases, which deteriorate the the thermal insulation.

Expanded closed-cell foams - III

Typical values for polyurethane foam

$r = 0.034$ → reflectivity
$t = 0.493$ → transmittivity
$d_c = 0.25 – 0.50$ mm → cell dimensions
$\Phi \simeq 1$ → porosity

Typical budget of thermal input in the case of polyurethane foam

Conduction via solid ~ 20 %
Conduction via gas ~ 70 %
Radiation ~ 10 %

The problem of differential themal contraction: an example:

Thermal exp. coeff.
7.2×10^{-5} K^{-1} glass foam
1.5×10^{-5} K^{-1} carb. steel
$\Delta T = 100$ K, $L = 6$ m

$\Delta L = 3.6$ cm

A cover is needed to prevent diffusion of water vapor and air into the foam. It will reduced also the replacement of the foaming agent with hydrogen and helium gases, which deteriorate the the thermal insulation.

Gas-filled powders and fibrous materials - I

- fiberglass,
- perlite (a silica powder),
- silica aerogel (Santocel, Cab-O-Sil),
- rock wool
- vermiculite.

$$\frac{1}{k_t} = \frac{1-\Phi}{k_s} + \left[\frac{k_g}{\Phi} + \frac{4\sigma d_s T_m^3}{(1-\Phi)}\right]^{-1}$$

At cryogenic temperatures

$$k_t = \frac{k_g}{1-(1-\Phi)\left(1-\frac{k_g}{k_s}\right)}$$

d_s is the size of the particles or fibers
Φ is the porosity
k_s = thermal conductivity of solid
k_g = thermal conductivity of gas

Thermal conductivity: main differenece to the respect of the expanded closed celles foama
Suppression of gaseous convection due to the small size of the voids within the material.

Gas-filled powders and fibrous materials - II

If $k_s >> k_g$ for example

Silica glass $k_s = 0.95$ W/m-K , N_2 $k_g = 0.017$ W/m-K

$$k_t = \frac{k_g}{1-(1-\Phi)\left(1-\frac{k_g}{k_s}\right)} \Longrightarrow k_t = \frac{k_g}{\Phi}$$

The case of fine powder.

k_g depends on the free path of the gas molecules which is reduced if we use fine powder.

However, this decrease in thermal conductivity is also influenced by the increase in overall contact resistance because more contacts exist in series for small powder particles than for larger particles.

Aerogel insulation - I

AerogeL➔ synthetic material produced from liquid gels by replacing the liquid with a gas through a drying process.

Density 1/10 of H_2O ➔ 80 – 130 kg/m^3

Structure: chains of spherical particles (~ 2- 5 mm diameter) fused in cluster and pores of 0.1 mm diameter

Typical trapped gas : air

Thermal conductivuty at 200 K ➔ 18 mW/m-K

Transparent to infrared radiation ➔ radiant heat transfer is the most significant contribution

$$k_t = k_0 + \frac{k_g}{1+1.6(\lambda/d_1)}$$

k_0 thermal conductivity at low gas pressure (p → 0)

k_g ithermal conductivity of the gas at themean temperature

λ mean free path of the gas at the mean temperature,

d_1 mean diameter of the micropores

k_0 is the sum of the solid conduction and the radiation contributions.

The case of silica aerogel

k_0 = 1.2 mW/m-K

d_1 = 9 µm

Aerogel insulation - II

Advantages:

Low density (lightweight) and low thermal conductivity.
Flexible aerogel blankets can withstand a load pressure of about 35 kPa for a 10% deformation.

Disadvantages:

It must be protected from moisture in the atmosphere: it will form a gel after prolonged contact with moist air.
Therefore, a vapor barrier must be used around the insulation.

Evacuated powders and fibrous materials - I

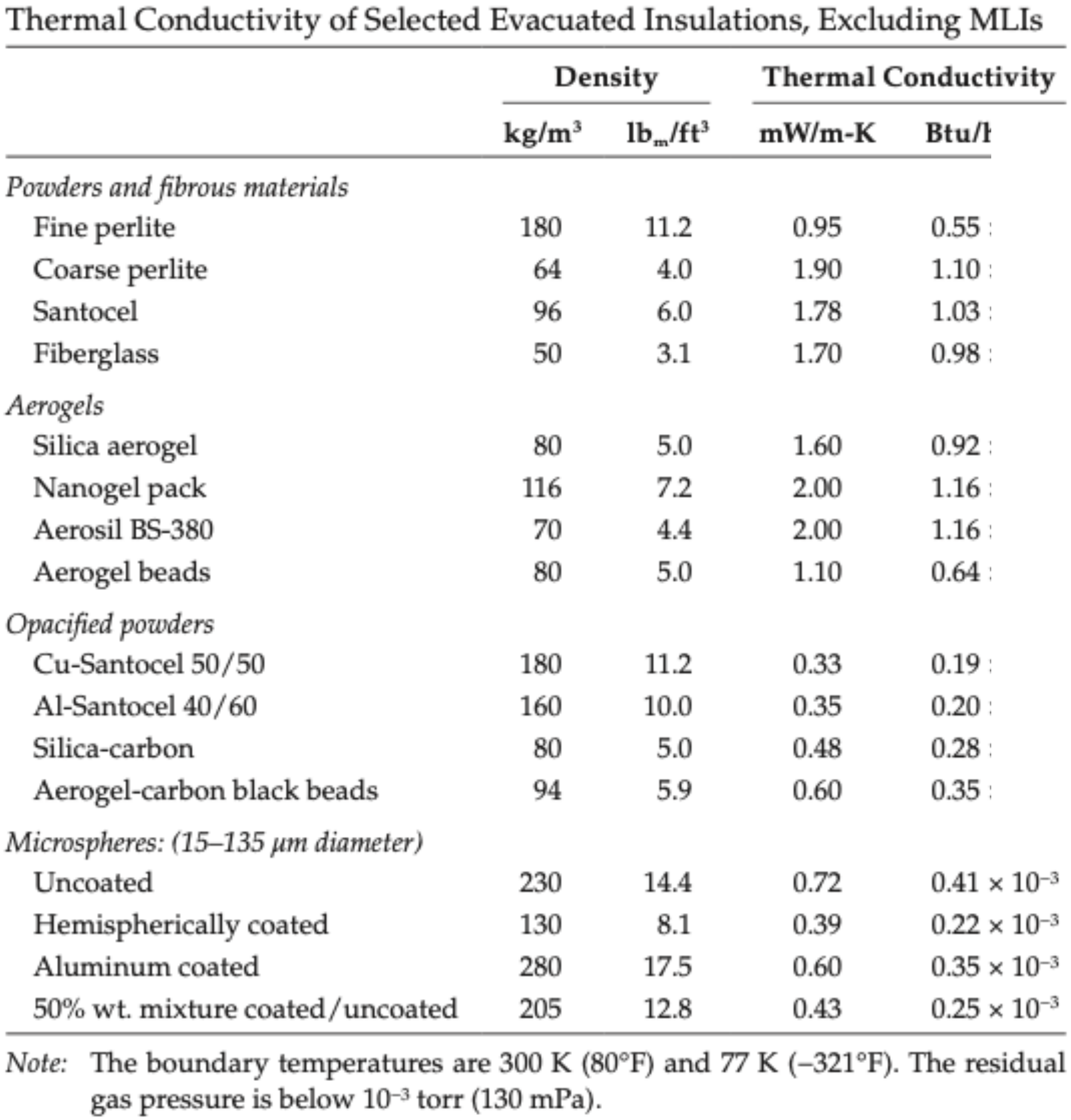
Obvious method of reducing the heat transfer rate through these insulations is to evacuate the gas from the insulation.

Typical residual pressure 100 mBar range where the thermal conductivity of the gas is practically independent of pressure

Typical gas residual below 10 mbar , thermal conductivity is almost directly proportional to the gas pressure (free path of N_2 at 300 K ~ 5 μm). With gaps between particles of 15 μm, the heat transfer via molecular conductions decreases with the pressure

At ~10^{-3} mbar the only contributions to the heat transfer are due to radiation and solid conduction

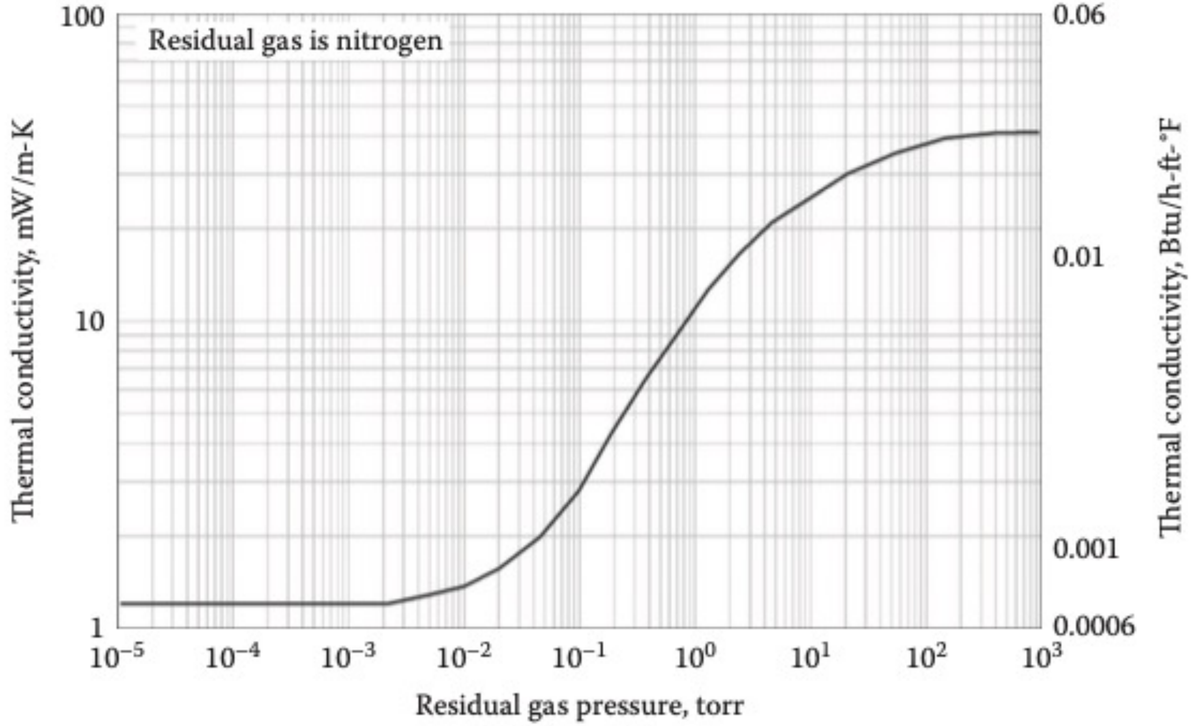
Evacuated powders and fibrous materials - II



Thermal Conductivity of Selected Evacuated Insulations, Excluding MLIs

	Density		Thermal Conductivity	
	kg/m³	lb$_m$/ft³	mW/m-K	Btu/
Powders and fibrous materials				
Fine perlite	180	11.2	0.95	0.55
Coarse perlite	64	4.0	1.90	1.10
Santocel	96	6.0	1.78	1.03
Fiberglass	50	3.1	1.70	0.98
Aerogels				
Silica aerogel	80	5.0	1.60	0.92
Nanogel pack	116	7.2	2.00	1.16
Aerosil BS-380	70	4.4	2.00	1.16
Aerogel beads	80	5.0	1.10	0.64
Opacified powders				
Cu-Santocel 50/50	180	11.2	0.33	0.19
Al-Santocel 40/60	160	10.0	0.35	0.20
Silica-carbon	80	5.0	0.48	0.28
Aerogel-carbon black beads	94	5.9	0.60	0.35
Microspheres: (15–135 μm diameter)				
Uncoated	230	14.4	0.72	0.41×10^{-3}
Hemispherically coated	130	8.1	0.39	0.22×10^{-3}
Aluminum coated	280	17.5	0.60	0.35×10^{-3}
50% wt. mixture coated/uncoated	205	12.8	0.43	0.25×10^{-3}

Note: The boundary temperatures are 300 K (80°F) and 77 K (–321°F). The residual gas pressure is below 10^{-3} torr (130 mPa).



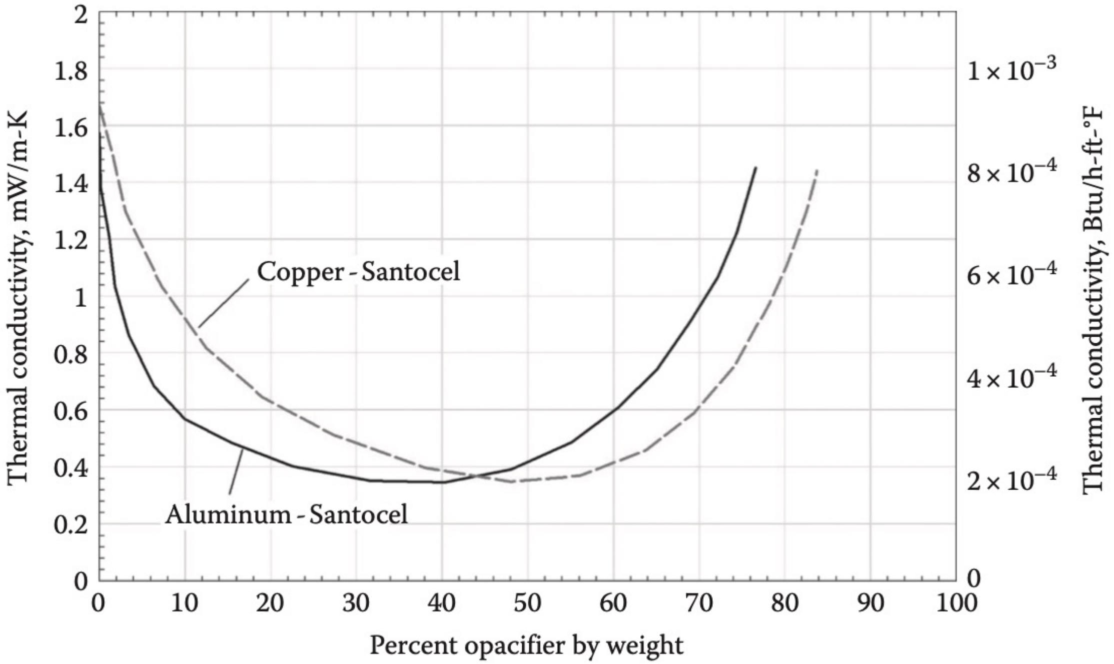
Variation of thermal conductivity vs residual nitrogen pressure (powder 30–80 mesh perlite). Boundary temperatures 300 - 78 K

Opacified powders

A technique for reducing the radiant heat transfer through the powder insulation is to add opaque, highly reflecting metal flakes

Example of Thermal conductivity Gain in the case of both perlite and copper flakes loaded by 40 % of opacifier (mass fraction)

1.9 mW/m-K ➔ *1.2 mW/m-K*



Disadvantage:
Degradation of ethe performance in the insulation zones where the metallic flakes are concentrated

Microsphere insulation

The microsphere insulation:

- packed, hollow glass spheres, size 15 - 150 µm diameter,
- coated on the outer surface with a highly reflective film.

Heat flux (under a vacuum $>10^{-4}$ mbar) limited by

- the resistance to conduction between spheres
- radiation attenuation due to the metal coating and scattering between spheres.

$$k_t = k_s + \left(\frac{4}{3b}\right)\sigma(T_H^2 + T_C^2)(T_H + T_C)$$

k_s ➔ thermal conductivity associated with conduction through the solid material
b ➔ extinction (absorption) coefficient for radiant heat transfer through the insulation
σ =➔ Stefan–Boltzmann constant (5.669×10^{-8} W/m^2-K^4)
T_H and T_C hot and cold boundary absolute temperatures respectively

Examples:
aluminized microspheres with a 20–80 nm coating thickness, $k_s = 1.84 \times 10^{-4}$ *W/m-K ,* $b = 13750$ m^{-1}
fully aluminized microspheres $k_s = 5.17 \times 10^{-4}$ *W/m-K ,* $b = 34000$ m^{-1}

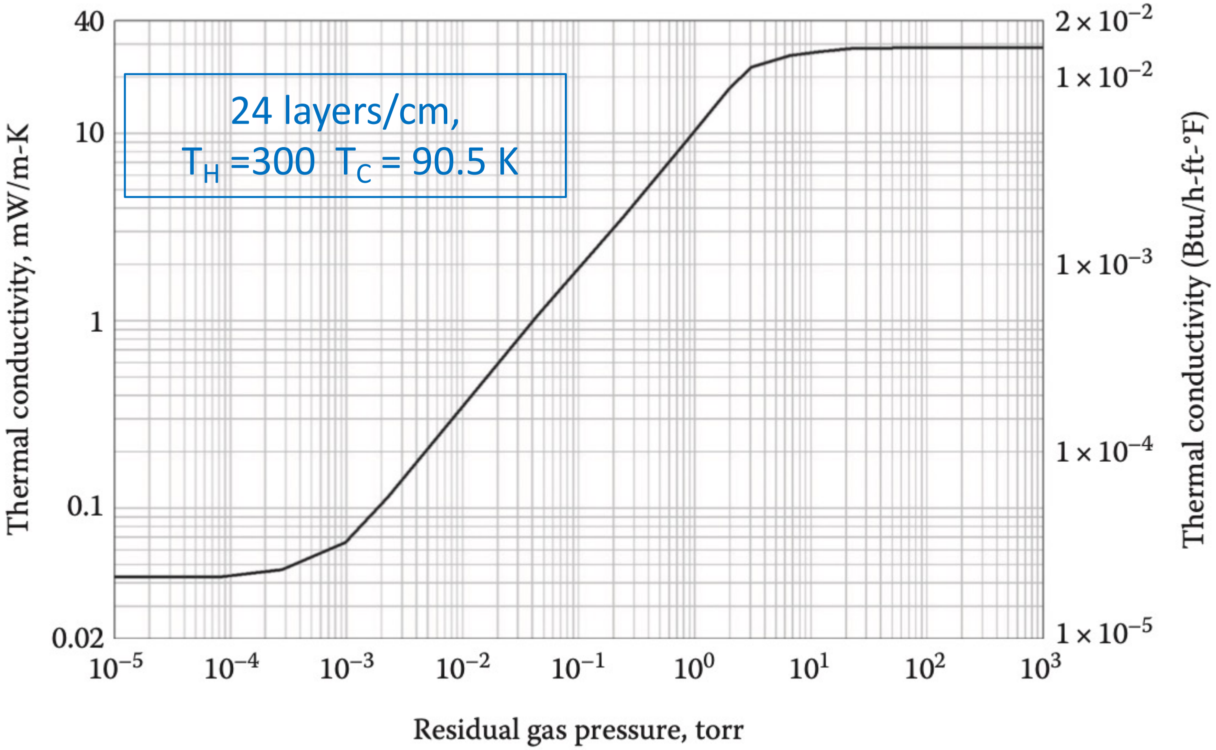
MLIs – Multi Layers Insulation - I

Alternating layers of highly reflecting foil, such as aluminum or copper foil, and a low-conductivity spacer, such as fiberglass paper, Dacron fabric, or silk net.

Foil material are fragile and develops pin holes when crinkled, ➔ replaced by aluminized Mylar,

Mylar plastic thickness ~ 6 - 10 μm , Aluminum layer 40 - 60 nm

Operation in Vacuum $>8 \times 10^{-5}$ mbar (10 mPa)



24 layers/cm,

$T_H = 300$ $T_C = 90.5$ K

Variation of the mean apparent thermal conductivity with residual gas pressure for a typical MLI.

MLIs – Multi Layers Insulation - II

Heat flux reductions:

- Solid conduction minimized by the low-conductivity spacers (contacts just in few points).
- Gaseous conduction killed by reducing the residual gas pressure below 10^{-5} mbar .
- Radiation heat transfer is minimized by using many layers of highly reflective metal foil

$$k_t = \frac{1}{(N/\Delta x)}\left[h_c + \left(\frac{e}{2-e}\right)\sigma\left(T_H^2 + T_C^2\right)\left(T_H + T_C\right)\right]$$

h_c ➔solid conductance of the spacer material

σ ➔Stefan–Boltzmann constant (5.669×10^{-8} W/m^2-K^4)

e ➔ the emissivity of the radiation shields

T_H and T_C ➔ boundary temperatures of the insulation in Kelvin

$N/\Delta x$ ➔ layer density (1 layer = 1 sheet foil + 1 sheet of spacer)

The case of MLI made of double-aluminized Mylar shields and a double layer of silk net as separator. Empirical formula for h_c

$$\boxed{h_c = C_s (N/\Delta x)^{2.56} (T_H + T_C)}$$

with

$C_s = 2.24 \times 10^{-8}$ W-cm$^{2.56}$/m^2-K^2

MLIs – Multi Layers Insulation - III

MLI Optimum insulation :

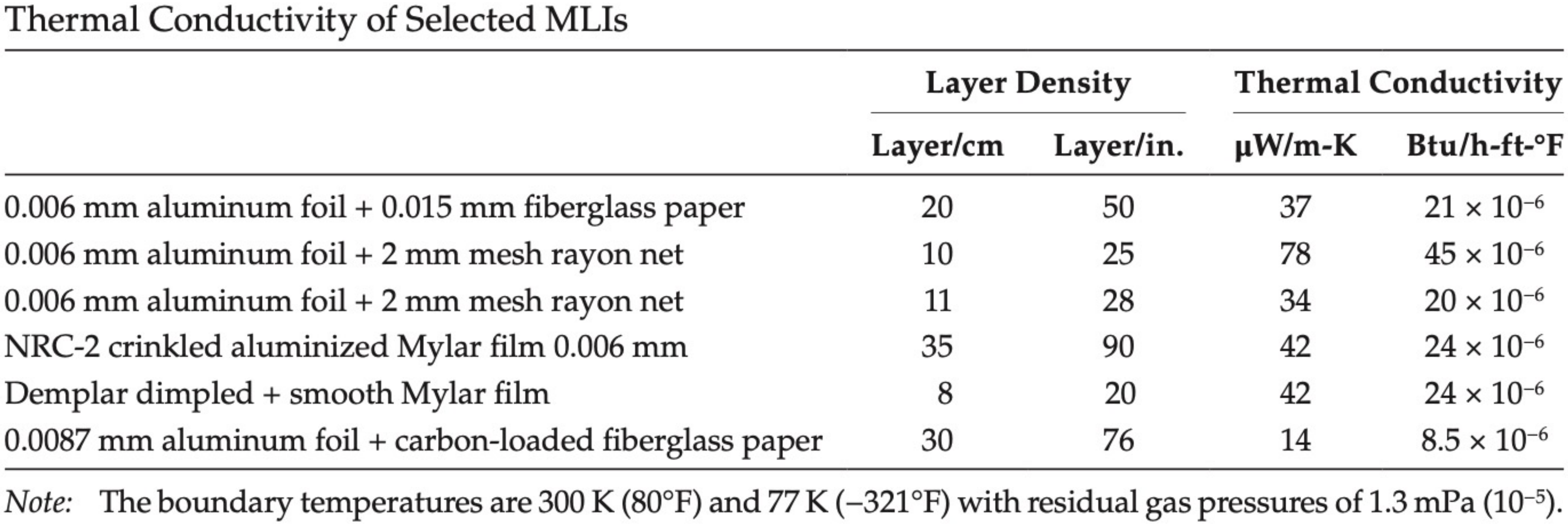
- Solid conduction minimized by the low-conductivity spacers (contacts just in few points).
- Gaseous conduction killed by reducing the residual gas pressure below 10^{-5} mbar .
- Radiation heat transfer is minimized by using more layers of highly reflective metal foil
- Optimization of the Layer Density $\rho_m = (S_s + \rho_r t_r)(N/\Delta x)$

S_s ➔ mass of spacer material per unit area

ρ_r ➔ density of the shield material

t_r ➔ thickness of the radiation shields

$N/\Delta x$ ➔ layer density (1 layer = 1 sheet foil + 1 sheet of spacer)

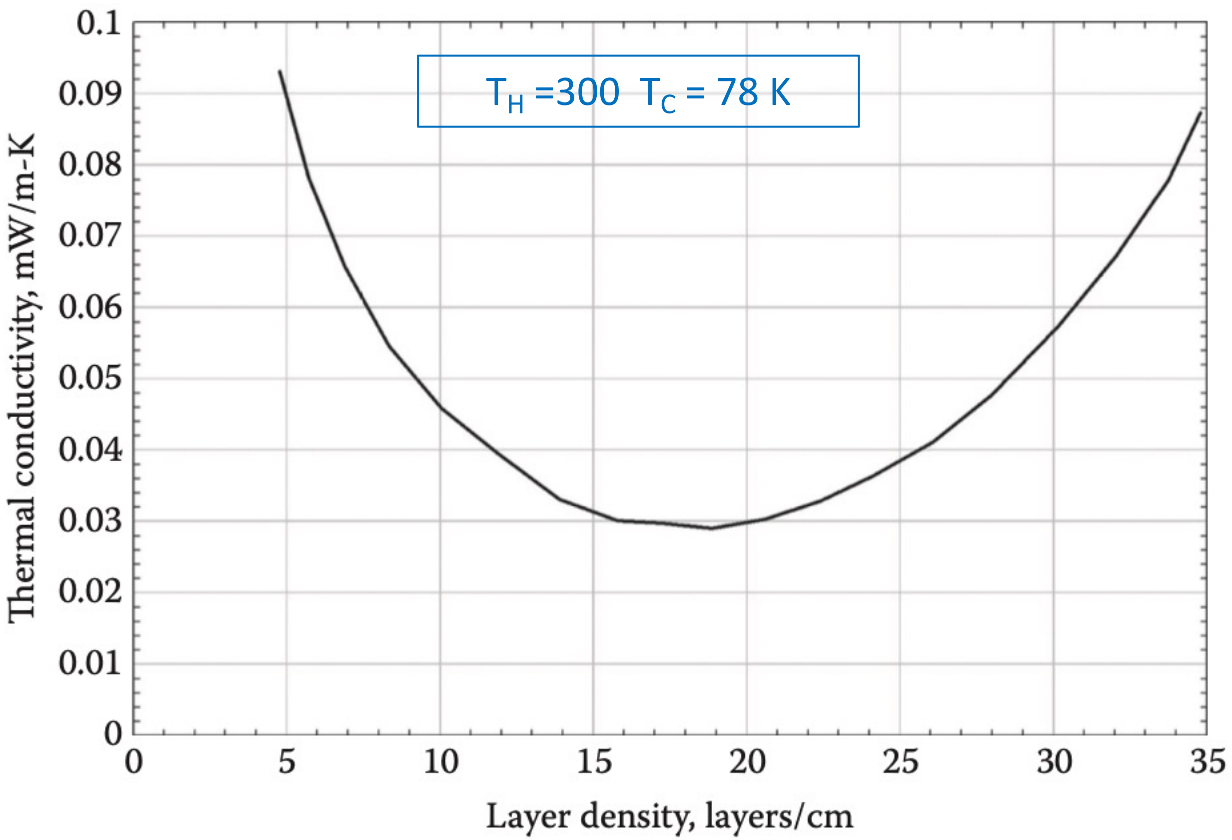


Thermal Conductivity of Selected MLIs

	Layer Density		Thermal Conductivity	
	Layer/cm	Layer/in.	μW/m-K	Btu/h-ft-°F
0.006 mm aluminum foil + 0.015 mm fiberglass paper	20	50	37	21×10^{-6}
0.006 mm aluminum foil + 2 mm mesh rayon net	10	25	78	45×10^{-6}
0.006 mm aluminum foil + 2 mm mesh rayon net	11	28	34	20×10^{-6}
NRC-2 crinkled aluminized Mylar film 0.006 mm	35	90	42	24×10^{-6}
Demplar dimpled + smooth Mylar film	8	20	42	24×10^{-6}
0.0087 mm aluminum foil + carbon-loaded fiberglass paper	30	76	14	8.5×10^{-6}

Note: The boundary temperatures are 300 K (80°F) and 77 K (–321°F) with residual gas pressures of 1.3 mPa (10^{-5}).

MLIs – Multi Layers Insulation - IV



Optimisation of the layer density:

If N/Δx increase, <u>radiant</u> thermal input decrease

If N/Δx increase (higher compressed pack of MLI) <u>solid conduction</u> increase

MLIs – Multi Layers Insulation – V

Thermal conductivity of MLI in the direction parallel to the shields

$$k_{||} = \left(\frac{N}{\Delta x}\right)\left\{k_r t_r + \left(\frac{2t_p}{N/\Delta x}\right)\left[2\ln\left(\frac{L_p}{2t_p}\right)-1\right]\sigma\left(T_H^2+T_C^2\right)(T_H+T_C)\right\}$$

k_r ➔ thermal conductivity of the reflective radiation shield
t_r ➔ shield thickness
L_p ➔ length of the shield parallel to the shield layers
t_p ➔ space between the shields, given by ➔ ➔ ➔ ➔ ➔ $t_p = \dfrac{1-(N/\Delta x)t_r}{(N/\Delta x)}$

*Thermal conductivity of MLI in the **direction parallel to the shields** may be as much as **three orders of magnitude larger** **than the** **thermal conductivity normal to the radiation shields***

Insulation performance degraded if the radiation shields edges contact another surface!!!!

MLIs – Multi Layers Insulation - VI

Residual pressure among the various layers

- Effective evacuation of the residual gas from within the insulation blanket is difficult: Mylar is and hydrophilic material!!

- Pressure within the insulation may be 2 orders of magnitude higher than the pressure outside the insulation

- Outgassing of the shields can also introduce significant quantities of gas within the insulation

Improvements:

- Small holes are present in the foil layers to improve the gas removal in the blanket (holes can be made by means of an ordinary sewing needle)

- MLI using carbon-filled glass-fiber paper for the spacer material. Carbon acts as “getter” to adsorb the outgassing load at cryo temperatures.
  Results: Effective Thermal conductivity down to 14 µW/m-K

MLIs – Multi Layers Insulation ➔Conclusion

Complex system involving three heat transfer processes

$Q_{MLI} = Q_{rad} + Q_{sol} + Q_{res}$

– With n reflective layers of equal emissivity,

$Q_{rad} \sim 1/(N+1)$

– Due to parasitic contacts between layers, Q_{sol} increases with layer density

– Q_{res} due to residual gas trapped between layers, scales as $1/N$ in molecular regime

– Non-linear behaviour requires layer-to-layer modelling

In practice

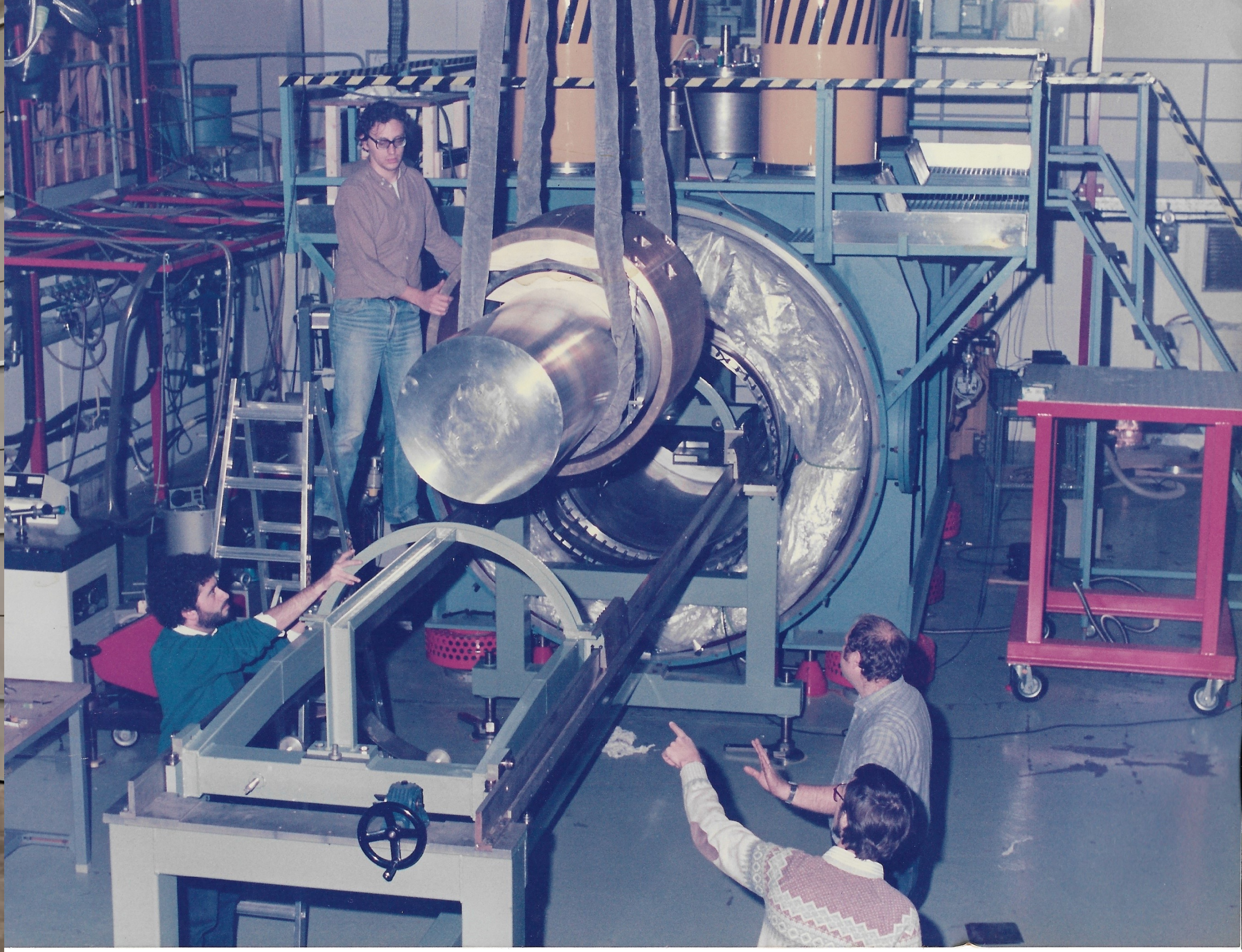
– Typical data available from (abundant) literature

– Measure performance on test samples

My personal experience:

Minimal cover 30 layers at least

MLI on the 77 K
Archimedes_2 cryostat



Installation of the resonant GW Antenna in the He-II cryostat
The MLI blacket was wrapped around the N_2 shield of the cryostat;the spacer was made by fiber glass foils