Underground LNG storage – insulation

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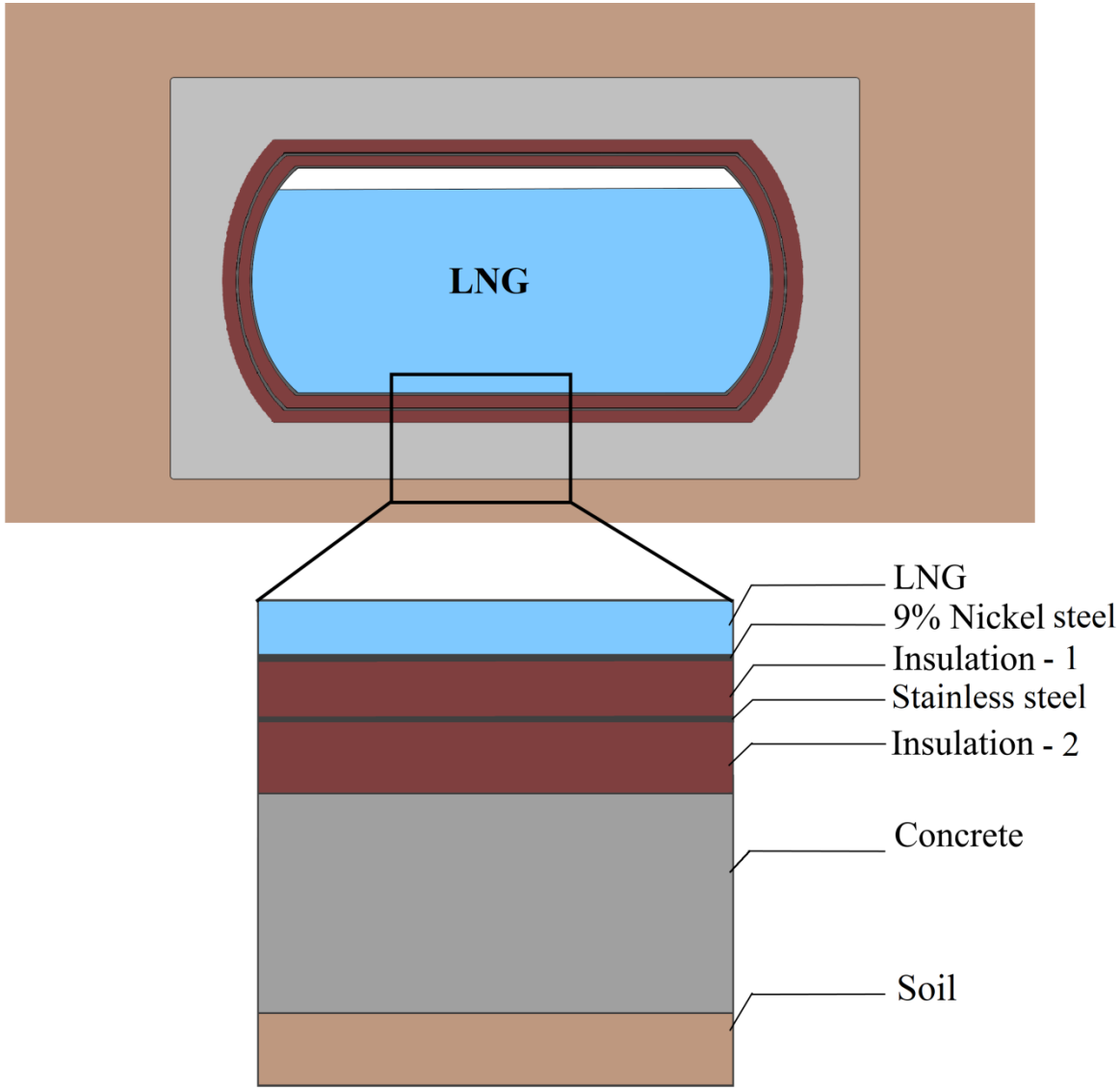
Thermal insulation of the underground LNG tank

Materials/layers of the underground LNG storage

1. **Primary metal layer** – direct contact with LNG (-162 ^{0}C)
   - Cryogenic steel: *mostly 9% nickel steel since it remains ductile even when extremely cold*

2. **Insulation layer 1 –** low conductive material
   - Can be perlite, polyurethane, mineral wool, etc.

3. **Secondary metal layer –** 100% redundancy in case of leakage



Thermal insulation materials

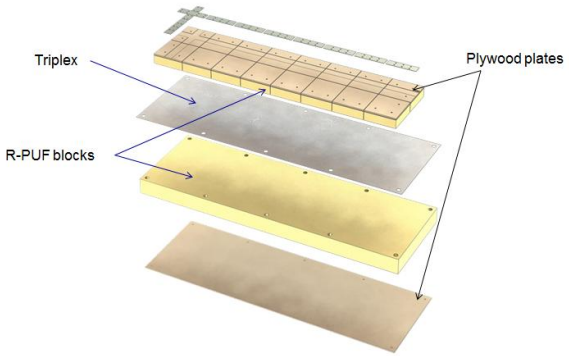
Insulation materials listed by their thermal Conductivity

Not all of them can be used for cryogenic applications due to:

- Price
- Technical difficulties (i.e. not bendable for bullet tanks, etc.)
- Relatively high conductive

Common insulation materials for cryogenic applications:

- ***Polyurethane***
- ***Cellular glass***
- ***Perlite***
- ***Mineral wool***
- ***Foam glass***



Thermal insulation of the underground LNG tank

Boil-off rate

- As we discussed during the last meeting (SJ-NTU), the target is **0.04% per day**

$$BOR = \frac{q}{\rho V h_{fg}} \times 24 \times 3600 \times 100\%$$

- q – the total heat leaking through the insulation to the cargo(J/sec)
- h_{fg} – latent heat of vaporization (511kJ/kg)
- rho – density (424 kg/m^3)
- V – volume of the LNG inside the tank
  (assume LNG occupies 90% of 100 m^3 volume)

$$q = \frac{BOR \cdot \rho V h_{fg}}{24 \times 3600 \times 100\%} = \frac{0.04\% \cdot 424\,(\frac{kg}{m^3}) \cdot 90(m^3) \cdot 511000\left(\frac{J}{kg}\right)}{24 \times 3600\ (\text{sec}) \times 100\%} = 90.28\,(\frac{J}{sec})$$

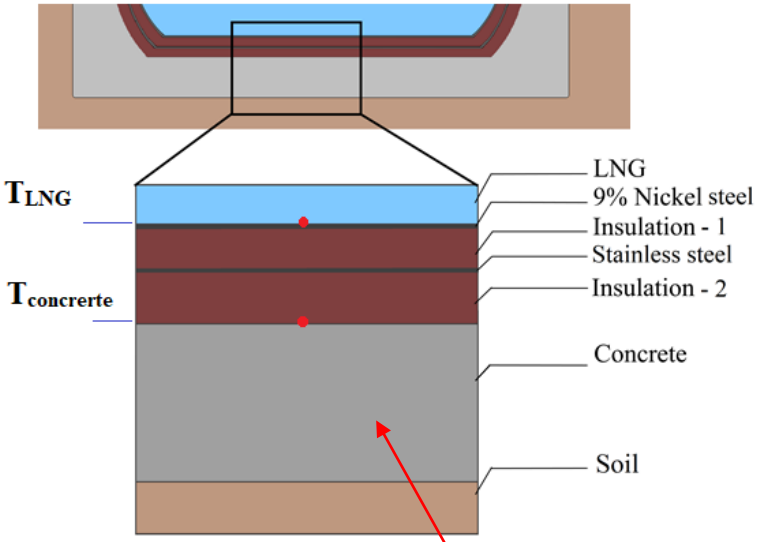
This is the maximum allowed heat ingress to achieve 0.04% BOR!

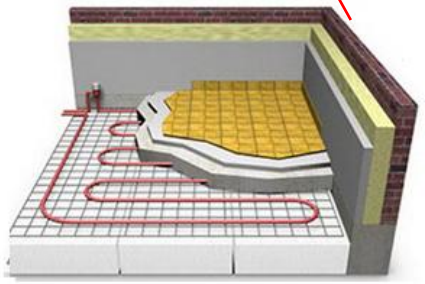
$$q = \frac{T_{concrete} - T_{LNG}}{R_{total}} = 90.28$$

$$T_{concrete}\ (0\ ^\circ\text{C}) - T_{LNG} = 162\ ^\circ\text{C}$$

$$T_{concrete}\ (-10\ ^\circ\text{C}) - T_{LNG} = 152\ ^\circ\text{C}$$

$$T_{concrete}\ (-20\ ^\circ\text{C}) - T_{LNG} = 142\ ^\circ\text{C}$$

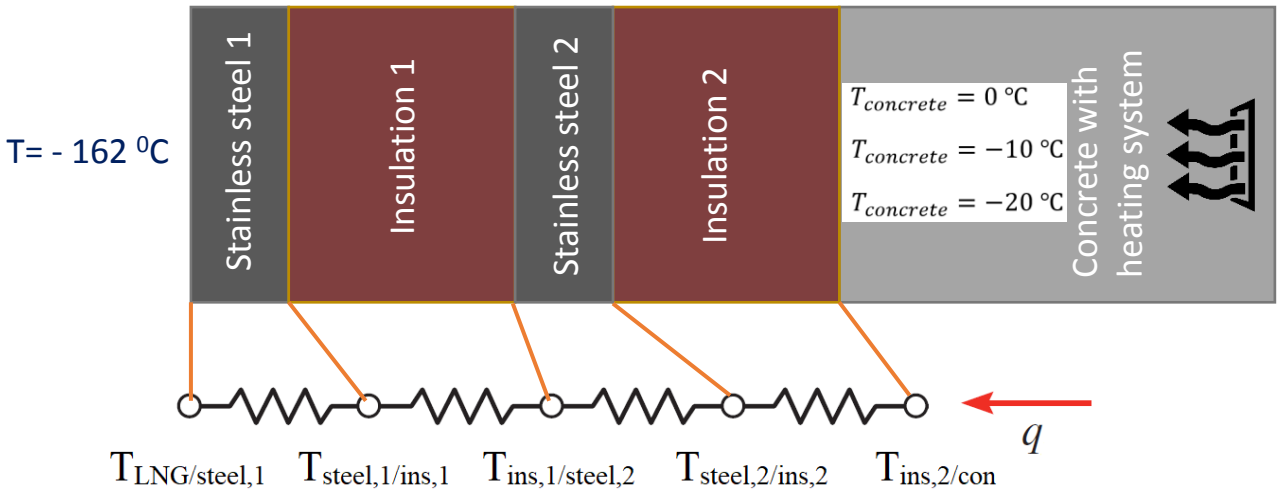


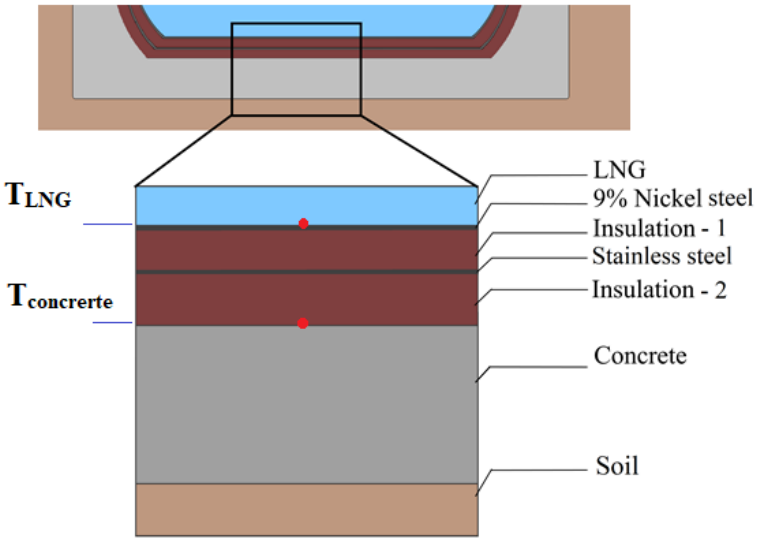


Heating system to avoid ice formation in the soil

Thickness of the thermal insulation

$$q = \frac{T_{concrete} - T_{LNG}}{R_{total}} = 90.28 \longrightarrow R_{total} = \frac{\Delta T}{90.28}$$





Surface area ***A*** must be minimized to avoid heat ingress:

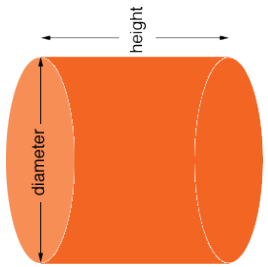
The cylinder has the least surface area when Height = Diameter

$$R_{total} = \frac{\Delta T}{90.28} \longrightarrow \frac{L_{steel,1}}{k_{steel,1}A} + \frac{L_{ins,1}}{k_{ins,1}A} + \frac{L_{steel,2}}{k_{steel,2}A} + \frac{L_{ins,2}}{k_{ins,2}A} = \frac{\Delta T}{90.28}$$

~10^{-4} ~10^{-4}

In case, same material is used in both layers:

$$L_{ins} = L_{ins,1} + L_{ins,2} \longrightarrow L_{ins} = \boxed{\frac{k_{ins} A \Delta T}{90.28}}$$



V = 100 m^3
H = 5.1 m
D = 5 m
A = 119.3 m^2

Thermal insulation of the underground LNG tank

$$L_{ins} = \frac{k_{ins} A \Delta T}{90.28}$$

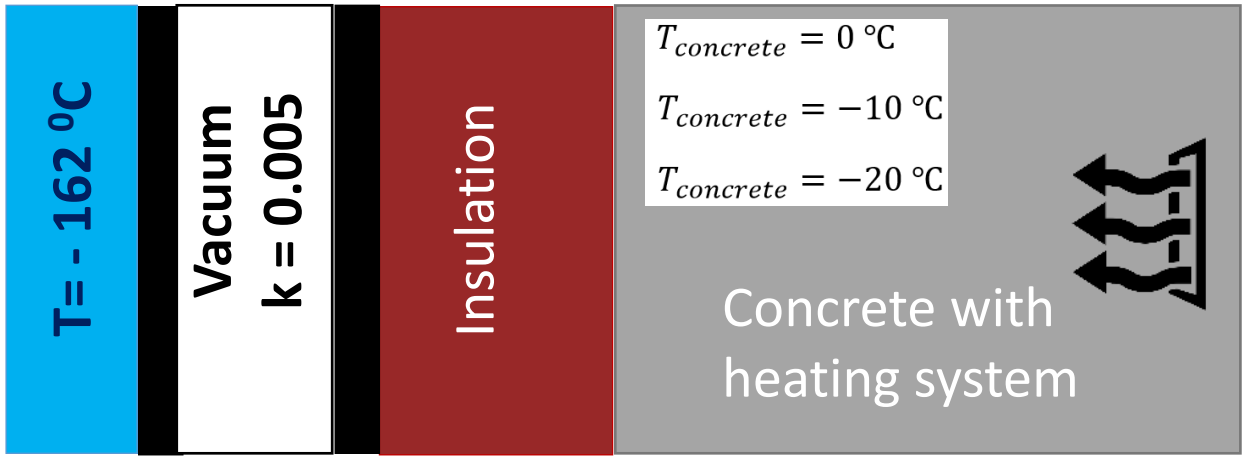
Insulation Materials	Thermal conductivity	Thickness		
		Concrete T = 0C	Concrete T = -10C	Concrete T = -20 C
Polyurethane	0.02	4.27	4.00	3.74
Polyisocyanurate Foam	0.021	4.48	4.20	3.93
Perlite	0.027	5.76	5.41	5.05
Cellular Glass	0.036	7.68	7.21	6.73
Mineral wool	0.039	8.32	7.81	7.29
Polystyrene	0.042	8.96	8.41	7.85
Plywood	0.06	12.80	12.01	11.22

This is due to BOG, which is **0.04% per day**

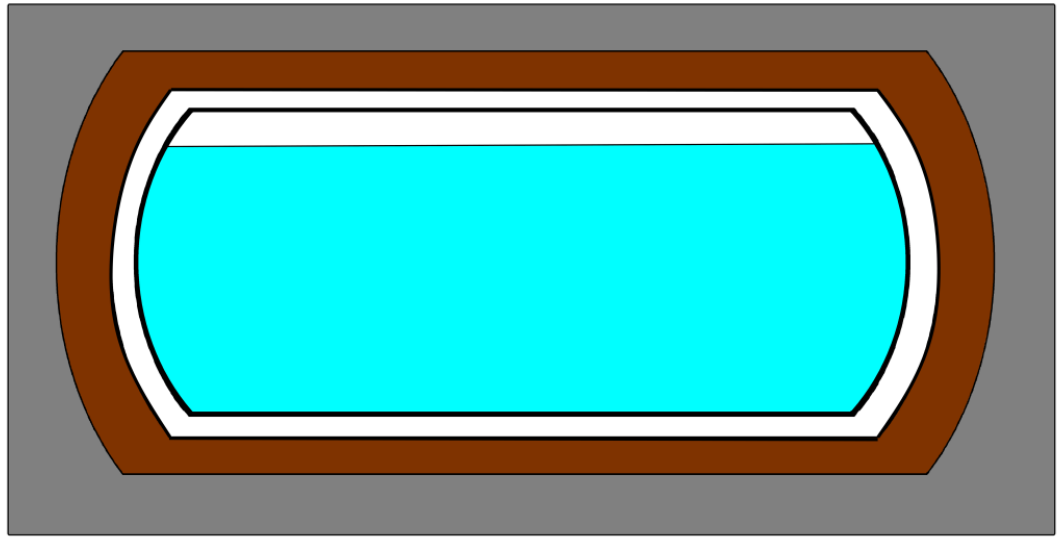
If BOG is **0.1%**

Insulation Materials	Thermal conductivity	Thickness		
		Concrete T = 0C	Concrete T = -10C	Concrete T = -20 C
Polyurethane	0.02	1.71	1.60	1.50
Polyisocyanurate Foam	0.021	1.79	1.68	1.57
Perlite	0.027	2.30	2.16	2.02
Cellular Glass	0.036	3.07	2.88	2.69
Mineral wool	0.039	3.33	3.12	2.92
Polystyrene	0.042	3.58	3.36	3.14
Plywood	0.06	5.12	4.80	4.49

Thermal insulation with vacuum of the underground LNG tank



Thickness 0.1 m



Thermal insulation with vacuum of the underground LNG tank

$$L_{ins} = \frac{\boxed{k_{ins}} A \Delta T}{90.28}$$

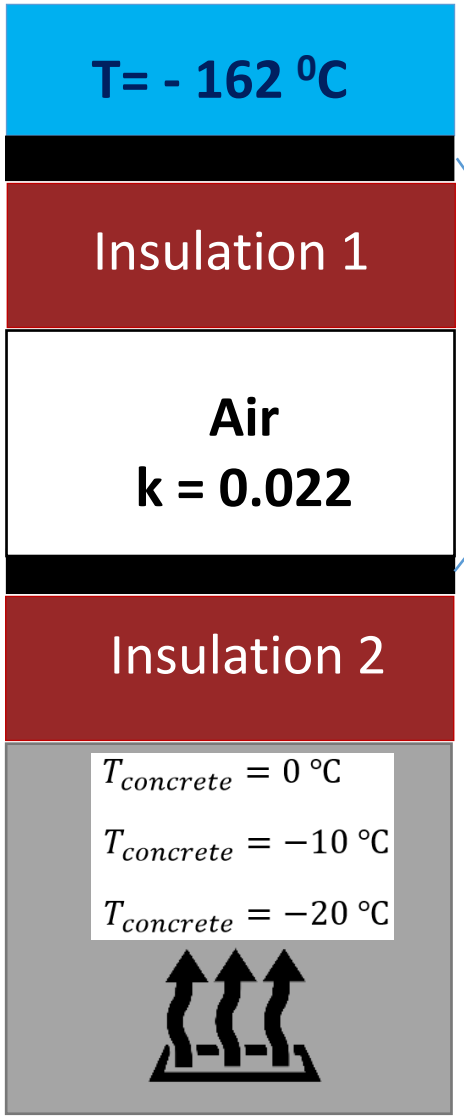
Insulation Materials	Thermal conductivity	Thickness		
		Concrete T = 0C	Concrete T = -10C	Concrete T = -20C
Polyurethane (PUF)	0.02	3.95	3.69	3.43
Polyisocyanurate Foam	0.021	4.15	3.87	3.60
Perlite	0.027	5.34	4.98	4.63
Cellular Glass	0.036	7.12	6.64	6.17
Mineral wool	0.039	7.71	7.19	6.68
Polystyrene	0.042	8.30	7.75	7.19
Plywood	0.06	11.86	11.07	10.28

This is due to BOG, which is **0.04% per day**

If BOG is **0.1%**

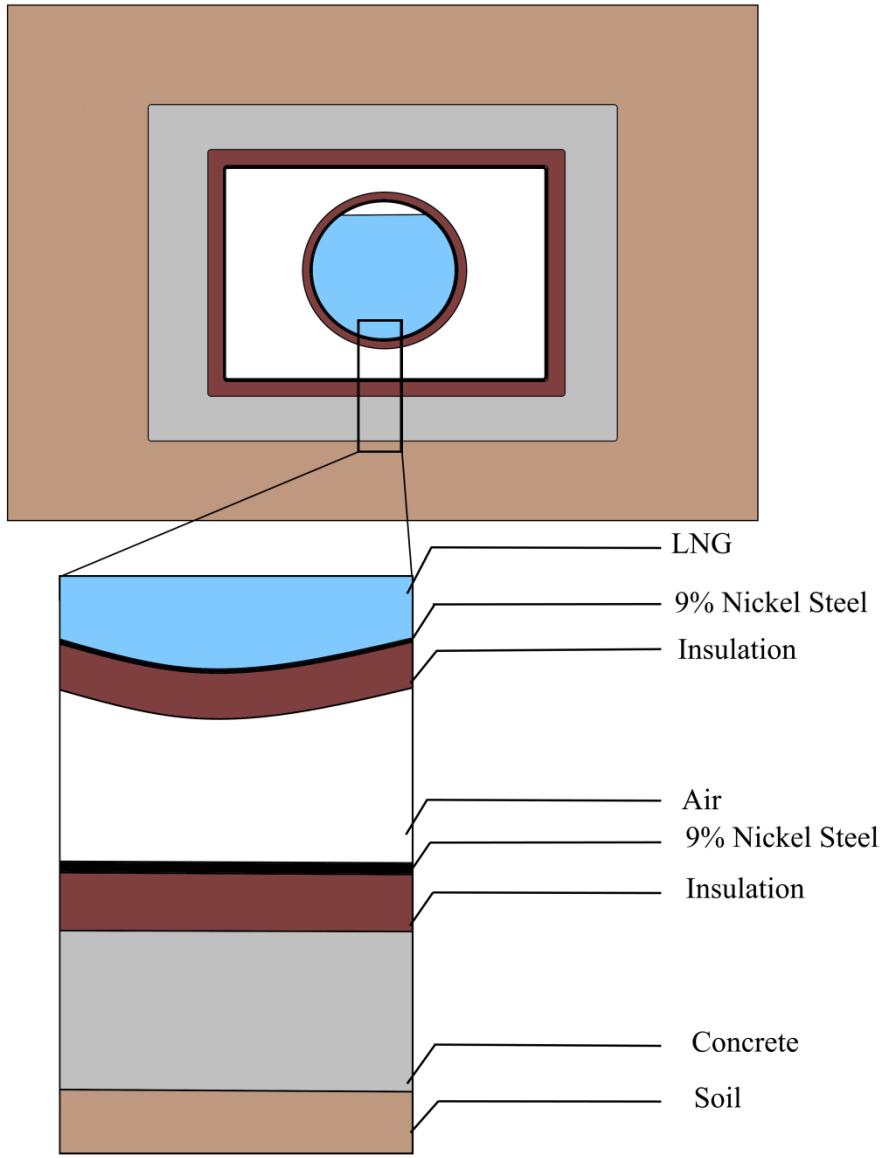
Insulation Materials	Thermal conductivity	Thickness		
		Concrete T = 0C	Concrete T = -10C	Concrete T = -20C
Polyurethane (PUF)	0.02	1.39	1.29	1.18
Polyisocyanurate Foam	0.021	1.46	1.35	1.24
Perlite	0.027	1.88	1.74	1.60
Cellular Glass	0.036	2.51	2.32	2.13
Mineral wool	0.039	2.72	2.51	2.30
Polystyrene	0.042	2.92	2.70	2.48
Plywood	0.06	4.18	3.86	3.55

Thermal insulation with air of the underground LNG tank



Stainless steel 1,2

Concrete with heating system



Thermal insulation with flow of the underground LNG tank

$$L_{ins} = \frac{k_{ins} A \Delta T}{90.28}$$

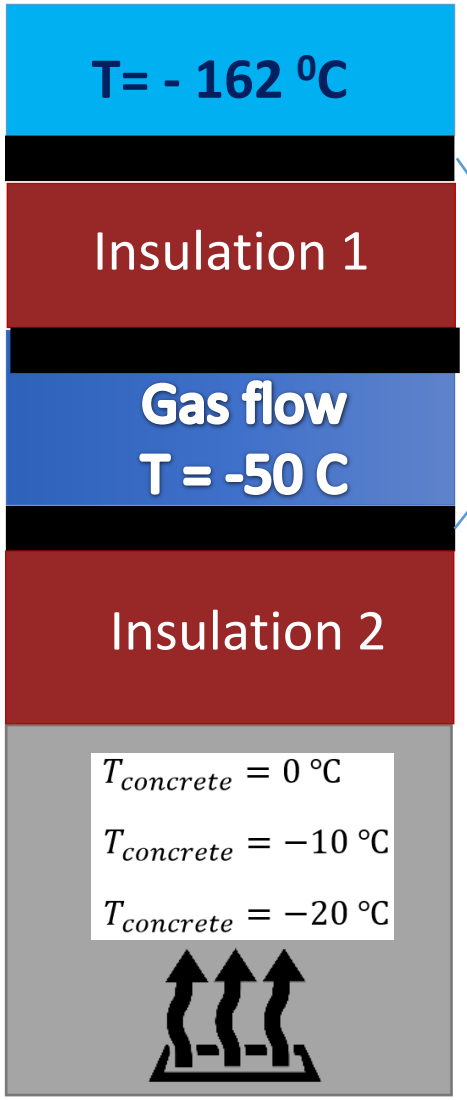
Insulation Materials	Thermal conductivity	Thickness		
		Concrete T = 0C	Concrete T = -10C	Concrete T = -20C
Polyurethane (PUF)	0.02	3.36	3.09	2.83
Polyisocyanurate Foam	0.021	3.53	3.25	2.97
Perlite	0.027	4.53	4.18	3.82
Cellular Glass	0.036	6.04	5.57	5.10
Mineral wool	0.039	6.55	6.03	5.52
Polystyrene	0.042	7.05	6.50	5.95
Plywood	0.06	10.07	9.28	8.49

This is due to BOG, which is **0.04% per day**

If BOG is **0.1%**

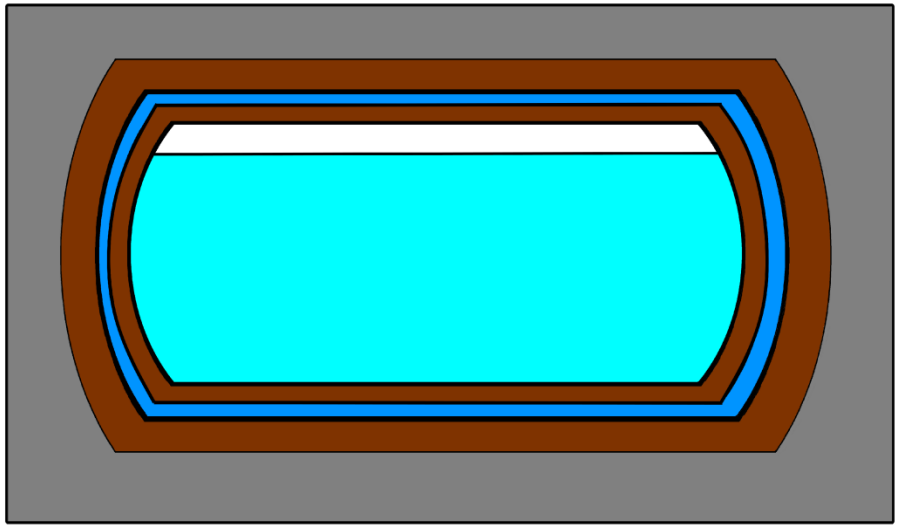
Insulation Materials	Thermal conductivity	Thickness		
		Concrete T = 0C	Concrete T = -10C	Concrete T = -20C
Polyurethane (PUF)	0.02	0.80	0.69	0.59
Polyisocyanurate Foam	0.021	0.84	0.73	0.62
Perlite	0.027	1.08	0.93	0.79
Cellular Glass	0.036	1.44	1.25	1.06
Mineral wool	0.039	1.56	1.35	1.14
Polystyrene	0.042	1.68	1.45	1.23
Plywood	0.06	2.39	2.08	1.76

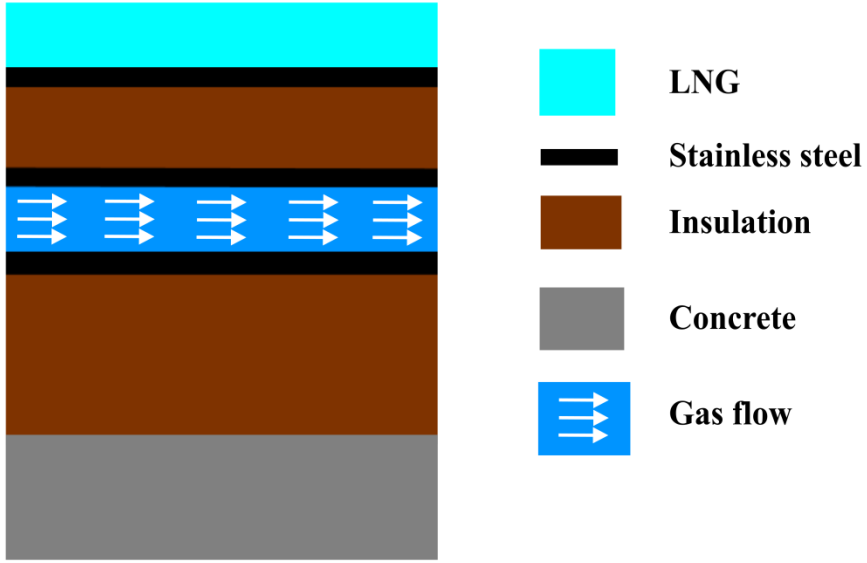
Thermal insulation with vacuum of the underground LNG tank



Stainless steel 1,2

Concrete with heating system





Thermal insulation with flow of the underground LNG tank

BOG = **0.04% per day**

$T_{concrete} = 0\ ℃$

$T_{concrete} = -10\ ℃$

$T_{concrete} = -20\ ℃$

Insulation Materials	Thermal conductivity	Thickness		Summa
Polyurethane (PUF)	0.02	2.95	1.32	4.27
Polyisocyanurate Foam	0.021	3.10	1.38	4.48
Perlite	0.027	3.98	1.78	5.76
Cellular Glass	0.036	5.31	2.37	7.68
Mineral wool	0.039	5.75	2.57	8.32
Polystyrene	0.042	6.20	2.77	8.96
Plywood	0.06	8.85	3.95	12.80

Insulation Materials	Thermal conductivity	Thickness		Summa
Polyurethane (PUF)	0.02	2.95	1.05	4.00
Polyisocyanurate Foam	0.021	3.10	1.11	4.20
Perlite	0.027	3.98	1.42	5.41
Cellular Glass	0.036	5.31	1.90	7.21
Mineral wool	0.039	5.75	2.05	7.81
Polystyrene	0.042	6.20	2.21	8.41
Plywood	0.06	8.85	3.16	12.01

Insulation Materials	Thermal conductivity	Thickness		Summa
Polyurethane (PUF)	0.02	2.95	0.79	3.74
Polyisocyanurate Foam	0.021	3.10	0.83	3.93
Perlite	0.027	3.98	1.07	5.05
Cellular Glass	0.036	5.31	1.42	6.73
Mineral wool	0.039	5.75	1.54	7.29
Polystyrene	0.042	6.20	1.66	7.85
Plywood	0.06	8.85	2.37	11.22

Thermal insulation with flow of the underground LNG tank

BOG = **0.1% per day**

$T_{concrete} = 0\ ℃$

$T_{concrete} = -10\ ℃$

$T_{concrete} = -20\ ℃$

Insulation Materials	Thermal conductivity	Thickness		Summa
Polyurethane (PUF)	0.02	1.18	0.53	1.71
Polyisocyanurate Foam	0.021	1.24	0.55	1.79
Perlite	0.027	1.59	0.71	2.30
Cellular Glass	0.036	2.12	0.95	3.07
Mineral wool	0.039	2.30	1.03	3.33
Polystyrene	0.042	2.48	1.11	3.58
Plywood	0.06	3.54	1.58	5.12

Insulation Materials	Thermal conductivity	Thickness		Summa
Polyurethane (PUF)	0.02	1.18	0.42	1.60
Polyisocyanurate Foam	0.021	1.24	0.44	1.68
Perlite	0.027	1.59	0.57	2.16
Cellular Glass	0.036	2.12	0.76	2.88
Mineral wool	0.039	2.30	0.82	3.12
Polystyrene	0.042	2.48	0.89	3.36
Plywood	0.06	3.54	1.26	4.80

Insulation Materials	Thermal conductivity	Thickness		Summa
Polyurethane (PUF)	0.02	1.18	0.32	1.50
Polyisocyanurate Foam	0.021	1.24	0.33	1.57
Perlite	0.027	1.59	0.43	2.02
Cellular Glass	0.036	2.12	0.57	2.69
Mineral wool	0.039	2.30	0.62	2.92
Polystyrene	0.042	2.48	0.66	3.14
Plywood	0.06	3.54	0.95	4.49

	Thickness (PUF)	Volume of concrete m3	Concrete mass(tonn)
Single	1.71	508.19	863.923
Air	0.8	520.13	884.221
Gas flow	1.71	522.01	887.417
Vaccum	1.39	464.5	789.65