Fermilab

Particle Physics Division
Mechanical Department Engineering Note

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Project: Long Baseline Neutrino Experiment

Title: LBNE Cavern Wall Temperature Profile

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Introduction / Abstract

Freezing of the rock against the membrane tank for LBNE at the Deep Underground Science and Engineering Laboratory (DUSEL) is a concern. Water could be present and thus freeze, causing rock breakage and damaging the tank liner. Understanding of the temperature gradient of the rock can show if this is a valid concern and if heaters along the walls are necessary.

Description

LBNE is a large-scale argon neutrino experiment that uses the cavern walls as the support for the tank liner. Therefore no vacuumed space is placed between the tank liner and rock surface. Water running through the rock can reach the lining and cause serious issues. If the results show minimal sub-freezing temperatures, then heaters may not be necessary to counteract the heat flux out of the rock wall.

Analysis

To begin understanding how the rock wall reacts with a low temperature body, material and property data must be obtained. Temperature-dependant equations for thermal diffusivity and conductivity are needed since temperature is the dominating factor. Data is sparse, but an article titled "Influence of temperature on thermal conductivity, thermal capacity and thermal diffusivity for different types of rock" was published in the Physics and Chemistry of the Earth, Vol 28 Issue 9-11 by Hans-Dieter Votleen and Ruediger Schellschmidt gave equations for different types of rock. Metamorphic rock is what is found in the caverns at DUSEL (http://homestake.sdsmt.edu/Geology/geology.htm). It states, "Homestake rocks comprise a variety of metamorphic rock types subdivided into three distinct units: Poorman, Homestake, and Ellison formations, listed from oldest to youngest."

Equations 1 and 2 were used to calculate the thermal conductivity, k (W/m-K), of metamorphic rock:

$$k(0C) = .53k(25C) + \frac{1}{2}\sqrt{1.13\left(k(25C)\right)^2 - .42k(25C)} \tag{1}$$

$$k(T) = \frac{k(0C)}{\left(.99 + T\left(.0030 - \frac{.0042}{k(0C)}\right)\right)} \tag{2}$$

For thermal diffusivity, α (m^2/s), a correlation between thermal conductivity and diffusivity was determined to make equation 3.

$$\alpha(k) = \frac{.53k(T) - 0.2}{1E6} \tag{3}$$

With these two properties, the thermal response of the rock walls can be estimated with the use of semi-infinite heat transfer equations. A surface heat flux boundary condition was used because the surface of the rock is not held at a constant temperature. Its heat flux will initially be 5 W/m^2 but since the rock surface cools, then the reduction in heat flux must be accounted for in the calculations.

From the Heat Transfer, 2nd edition book from A.F. Mills, the heat flux surface condition on a semi-infinite body equation is:

$$T(x) = T_o + \frac{q_s}{k}\left(\left(\frac{4\alpha t}{\pi}\right)^{\frac{1}{2}} e^{-x^2/4\alpha t} - x\,erfc\left(\frac{x}{(4\alpha t)^{1/2}}\right)\right) \tag{4}$$

Results

Due to the complimentary error function embedded in the solution and the changing thermophysical properties, Excel was utilized. It also allows a visual representation of the temperature profiles as time progresses and the gradient into the rock. With the initial 5 W/m^2 heat flux and initial temperature of ~300K, the table showed the surface of the rock freezing in as soon as 5 months.

Table 1: Rock temperature profile within a year

Time (Months)	k^b (W/mK)	α^b (m^2/s)	Surface heat flux (W/m^2)	Ts (K)	T(1m) (K)	T(2m) (K)	T(3m) (K)	T(4m) (K)	T(5m) (K)	T(10m) (K)	T(20m) (K)
0	2.49	1.12E-06	-5.00	300	300	300	300	300	300	300	300
1	2.49	1.12E-06	-4.91	296	298	299	300	300	300	300	300
2	2.49	1.12E-06	-4.78	291	294	297	298	299	300	300	300
3	2.50	1.13E-06	-4.64	285	290	293	296	298	299	300	300
4	2.51	1.13E-06	-4.47	278	284	289	293	296	297	300	300
5	2.52	1.14E-06	-4.29	270	279	285	290	293	295	300	300
6	2.53	1.14E-06	-4.11	263	272	280	286	290	293	299	300
7	2.55	1.15E-06	-3.92	255	266	275	282	287	291	299	300
8	2.56	1.16E-06	-3.73	246	259	269	277	283	288	298	300
9	2.58	1.17E-06	-3.53	238	252	264	272	279	285	297	300
10	2.59	1.17E-06	-3.34	230	245	258	268	275	282	296	300
11	2.61	1.18E-06	-3.15	222	239	252	263	271	278	295	300
12	2.62	1.19E-06	-2.96	214	232	246	258	267	275	294	300

This was startling since it was expected to take years for it to reach sub zero centigrade temperatures. Results of the Excel spreadsheet show that heaters may be necessary because after 3 years, 30 ft into the cavern surrounding the membrane tank becomes freezing with the surface at 107 K (-166 °C).