

A Large Underground Liquid Argon Detector without a Cryostat?

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Introduction

The construction of a large liquid argon detector on the Earth's surface is advantageous because of the extensive experience of the liquefied natural gas industry in low-cost fabrication of cryogenic tanks of order of 100 kton. However, fabrication of this type of tank in an underground cavern is likely to be prohibitively expensive. Here, we note that the thermal conductivity of granite is low enough that a large, uninsulated cavity filled with liquid argon leads to thermal losses very similar to those of a cryogenic tank on the surface IF the granite at the cavity surface can be cooled to 87 K. However, it would take thousands of years to cool the surrounding rock, so we conclude that an underground liquid argon detector must have thermal insulation.

Heat Flow in a Large Cavity Filled with Liquid Argon

For simplicity, we consider a spherical cavity of radius r_0 that has been excavated out of granite, whose thermal conductivity is $\kappa = 2.2 \text{ W/m-K}$ and whose equilibrium temperature is $T_\infty \approx 300^\circ$. The cavity is filled with liquid argon whose temperature is $T_0 \approx 87^\circ$. The temperature difference $T_\infty - T_0$ results in a spherically symmetric temperature distribution $T(r)$ and a corresponding heat flow dQ/dt into the liquid argon.

The steady state temperature distribution obeys $\nabla^2 T = 0$, so for $r > r_0$ it has the form $T(r) = T_\infty - (T_\infty - T_0)r_0/r$. The rate of heat flow across a (vector) area element \mathbf{A} is $dQ/dt = -\kappa \nabla T \cdot \mathbf{A}$. Since $\nabla T = -(T_\infty - T_0)r_0 \hat{r}/r^2$, the total rate of heat flow into the sphere of radius r_0 is $dQ/dt = 4\pi\kappa(T_\infty - T_0)r_0$.

For example, if $r_0 = 20 \text{ m}$, then the mass of liquid argon in the cavity is 50 ktons, and $dQ/dt = 4\pi(2.2)(300 - 87)20 \approx 120 \text{ kW}$. As the heat of vaporization of argon is 160 kJ/kg, this heat flux will vaporize 0.75 kg/s, *i.e.*, 66 tons/day, or 0.13%/day of the detector mass. This rate is very similar to that quoted as the rate of vaporization of a surface cryogenic tank.

Hence, it appears that an uninsulated, underground granite cavity is as good a cryogenic vessel as a typical large surface tank of the liquefied natural gas industry.

Operational Issues

We comment briefly on issues that deserve further study as to the viability of operating an uninsulated, liquid-argon-filled cavity underground.

The heat load of 120 kW at 87° K must be compensated by a refrigerator operating between 87° K and $\approx 300^\circ$ K. If the efficiency of the refrigerator is, say, 12%, then 1 MW of wall power is required.

Outside a cavity with $r_0 = 20$ m, the temperature varies as $300^\circ - 4260^\circ/r$. The temperature reaches 0° K only at $r = 185$ m. Any tunnels closer than this to the cavity would have to be heated if/when they are to be used by people.

The heat capacity of granite is about 800 J/kg-K, and its specific gravity is about 2.7, so its heat capacity per volume is about 2.16 MJ/m³-K. The amount of energy required to cool a sphere of radius r of granite from 300° K to $300^\circ - 4260^\circ/r$ is roughly $6 \times 10^{16} r^2$ J for r measured in km. Perhaps we could afford 1 MW of cooling power, which implies a cooling capability of 3×10^{13} W/year. Thus, it would take several thousand years for the temperature distribution of the granite to approach the steady-state form $300^\circ - 4260^\circ/r$ for the case that the liquid argon volume is not surrounded by any thermal insulation.

Cold granite is, I believe, stronger than warm granite, so the rock surrounding the cold cavity is somewhat more robust against collapse than when warm. However, if the granite has enough water inside it, freezing the granite could lead to cracking upon formation of ice.

The cavity would, of course, have to be lined with some material that is impermeable to the flow of liquid argon.

Should the liner have a leak, some liquid argon would boil off into the surrounding environment, leading to an oxygen-deficiency hazard. If the cavity is designed so that the surrounding tunnels (whose walls are cold unless heated) form a trapped volume whose surface area is similar to that of the cavity (say 500 m of tunnels of 3-m diameter), the rate of vaporization of argon due to a leak would be less than or equal to that calculated above, namely 66 tons/day. In this case it would take over 2 years for the entire 50 ktons of liquid argon to vaporize. Of course, a boiloff of 66 tons/day would lead to $\approx 40,000$ m³ of argon gas at 300° K, which still constitutes a significant safety hazard unless properly ventilated.

Compatibility with a Large Magnet Coil

The simplicity of construction of a large liquid argon detector in an uninsulated, underground cavity is compatible with installation of a large magnet coil close to the surface of the cavity, inside the liquid argon. If this coil were superconducting, the liquid argon would serve as an intermediate temperature bath in place of the more typical use of liquid nitrogen. Furthermore, a giant magnet coil would require radial buttressing against the cavity wall to contain the expansive $\mathbf{I} \times \mathbf{B}$ forces, which buttressing could be readily accommodated in the design of an uninsulated cavity.