Safety related issues of the unexpected Argon release into the tunnel

M Chorowski, Z M Malecha and J Polinski
Department of Cryogenic, Aeronautic and Process Engineering, Wroclaw University of Technology, Poland, ul. Wyb. Wyspianskiego 37, 50-370 Wroclaw, Poland
E-mail: ziemowit.malecha@pwr.edu.pl

Abstract. Modern physics laboratories require very large amounts of cryogenics fluids. Often the fluid must be transported along the tunnels or stored in the underground cavities. Currently, there are several ongoing projects where very large amounts of liquid (LAr) or gaseous Argon (GAr) will be used. One of them is a part of the LAGUNA-LBNO (Large Apparatus studying Grand Unification and Neutrino Astrophysics and Long Baseline Neutrino Oscillations) design study, where the GLACIER (Giant Liquid Argon Charge Imaging ExpeRiment) neutrino detector is considered. In order for it to properly operate, it requires the appropriate environment (it must be located in a deep, underground cavity) and approximately 150,000 tons of LAr. This huge amount of cryogen must be transported down the tunnel in cryogenic-tank trucks or by using pipelines. In both cases, there is a risk of uncontrolled LAr or GAr leakage into the tunnel, which can be dangerous for people, as well as during the installation itself. The presented work focuses on the risk analysis and consequences of unexpected Argon leakage into the tunnel. It shows the mathematical model and numerical tools which can serve to model the Argon cloud propagation, temperature distribution, and Oxygen deficiency. The results present a series of numerical experiments for Argon leakage into the tunnel with different external conditions (e.g. different ventilation regimes).

1. Introduction
The main goal of the LAGUNA-LBNO (Large Apparatus studying Grand Unification and Neutrino Astrophysics and Long Baseline Neutrino Oscillations) project is to evaluate the feasibility of a new pan-European research infrastructure which is able to host the next generation neutrino observatory. The total volume of the neutrino detector is estimated to be in the range of 100,000 to 1,000,000 m³ and must be located in a deep, underground cavity.

The future underground observatory is dedicated to the study of neutrinos from cosmic and atmospheric sources, as well as neutrinos from a future Super-Beam, in order to measure the neutrino mixing angle, Charge Parity (CP) violation, and mass hierarchy. It will provide key information on what has occurred elsewhere in the Universe and increase our understanding of neutrino properties [1]. The neutrino observatory is a very complex installation, but for the purposes of the present work, it can be seen as a huge tank filled with LAr. The LAGUNA-LBNO project assumes first, the construction of a smaller pilot installation and later, a much larger GLACIER (Giant Liquid Argon Charge Imaging ExpeRiment) installation.

The filling of the pilot installation and the two GLACIER tanks with LAr will require the transportation of large quantities of LAr down the Pyhasalmi mine (Finland). The pilot tank
and two GLACIER tanks will be filled with 3800 tons and 150,000 tons of LAr, respectively. For the pilot, the cryogen will be transported down the mine tunnel in cryogenic truck cisterns (vacuum jacketed tankers), each with a capacity of 20 m$^3$ (27.6 tons). Tank trucks filled with LAr will be driven down, along the 10.5 km long decline characterized by an irregular spiral shape with an average slope of 7.3 degrees. The incremental approach to the construction of the experimental installation requires firstly, the risk analysis of transportation by truck of the 3800 tons of LAr, which can be scalable to higher quantities of cryogen.

Assuming the average truck speed to be 20 km/h, it would take approx. 40 minutes to travel the full length of the mine tunnel. Such a low speed is a consequence of numerous bends and the tunnel slope. Other difficulties and potential sources of higher risk is one-way traffic. For the most part, the underground tunnel is limited to a height and width of 5 m.

The main principle of the present work is found in the risk analysis for personnel involved in the transportation process of LAr in underground tunnels. Due to limited access to the subterranean test facility and the large quantity of cryogen that was to be transported, a safety plan needed to be developed for precaution in the case of a truck accident. The flow conditions in the mine can be controlled by making changes to the air ventilation velocity. This is why the presented analysis focuses on the effects of the ventilation regime on the propagation of LAr in the tunnel.

2. Results

2.1. Calculation of the LAr mass flow through the rupture hole

In order to calculate the LAr mass flow from the hole of the ruptured tank into the mine tunnel, the following values were assumed: tank volume - 20 m$^3$, tank external diameter - 2.5 m, tank external length - 6 m, and tank maximum operational pressure $p_{op} = 2$ MPa. The initial pressure of LAr in the tank corresponded to LAr temperature 130 K.

For liquids, the escaping mass flow $q_m$ can be calculated from the equation:

$$q_m = CA\sqrt{2\rho(p_1 - p_2)}$$

where $p_1$ and $p_2$ are the pressures before and after flow constriction, respectively, $A$ is the area of the cross section of the constriction, $\rho$ is the density of the LAr, and $C$ is the dimensionless discharge coefficient. The coefficient $C$ depends on: constriction shape and the edge of the inlet to the constriction. For irregular holes, torn in the tanks, it is advised to assume $C = 0.6$ [2]. In [3], it can be found that in 90% of tank rupture cases, the equivalent area of the rupture is lower than the area of the 50 mm diameter hole.

From the equation (1), it can be deduced that the maximum LAr mass flow from the ruptured tank occurs just after tank failure, and its maximum is approximately 4.7 kg/s. The outflow itself lasts about 75 minutes.

2.2. Calculation of the substitute GAr area

The ground of the tunnel is characterized with high heat capacity. It can be assumed that during the spill accident, the temperature of the ground remains constant and equal to 300 K. After leaving the tank, the LAr comes into contact with the warm ground of the tunnel and quickly vaporizes.

Utilizing the fact that the LAr argon is thermodynamically similar to liquid nitrogen, the heat flux from the ground to the spilled LAr can be estimated using the data for liquid nitrogen [4]. It can be found that for 300 K, the heat flux for the liquid nitrogen is approximately $q = 40$ kW/m$^2$. The evaporation heat of liquid argon, at atmospheric pressure is, $r = 160$ kJ/kg. It can be calculated that the mass stream of evaporating argon, from the area of 1 m$^2$ is: $q_{ev} = 0.25$ kg/m$^2$s.
Assuming that the stream of LAr is 1 m wide, the length of the LAr stream will reach 20 m before it evaporates. Compared to the entire length of the tunnel, the LAr evaporation process can be considered a local event. For the purposes of numerical calculation, the evaporation process can be omitted and instead of the LAr inlet boundary conditions (BC), a substitute GAr inlet BC can be used.

The above assumptions do not have a crucial effect on the results. They just make the numerical model simpler. Even if the LAr would not evaporate completely at the vicinity of the spill point, it would evaporate during its movement down the tunnel (it would become a moving GAr source).

2.3. Numerical set-up of the Pyhasalmi mine tunnel

The simplified geometry of the mine tunnel is presented in figure 1. Similarly, as in the case of the real tunnel, its inclination angle \( \alpha = 7.3 \) deg. The area of the tunnel cross-section is \( A = 25 \text{ m}^2 \), with a height of \( H = 5 \text{ m} \) and a width of \( W = 5 \text{ m} \). For the sake of a simpler description, it will be assumed that \( x = 0 \text{ m} \) marks the middle of the tunnel and goes along it, whereas \( y = 0 \text{ m} \) marks the ground level of the tunnel and goes orthogonally to the floor. In the numerical model, two-dimensionality is assumed, and flow is invariant in the width (z) direction.

As mentioned above, the total length of the mine tunnel is 10500 m. From the perspective of numerical calculations, this would be prohibitively large and, more importantly, unnecessary to model the entire tunnel. For the purposes of numerical simulation, the length of the numerical geometry was assumed to be \( L = 400 \text{ m} \) and the spill accident occurred in the middle of the tunnel (for \( x = 0 \), see Figure 1).

The previous analysis showed that the pool of the liquid Argon should not exceed \( 20 \text{ m}^2 \). Following that analysis, it was assumed that the GAr, with a temperature of \( T = 87 \text{ K} \), enters the computational domain through the inlet with an area of \( 20 \text{ m}^2 \) and a mass flow of \( q_m = 4.7 \text{ kg/s} \). The inletting mass flow is assumed to be constant in the considered simulation time (up to 400 seconds). The inlet of GAr is located between \( -2 \leq x \leq 2 \).

Figure 1 also shows the collection of points where the detailed, time-dependent results were monitored. The symbol "\( x \)" ("+" ) marks the points which are located 0.5 m (1.75 m) above the ground and 0, ±10, ±50, ±100, ±150, ±195 m away from the middle of the GAr inlet (spill incident). The heights of 0.5 m and 1.75 m were chosen to reflect the average height of a person while kneeling and then standing, respectively.

![Figure 1](image_url)

**Figure 1.** Numerical geometry of the tunnel used in the calculations (not in scale). Length \( L = 400 \text{ m} \), height \( H = 5 \text{ m} \), inclination angle \( \alpha = 7.3 \) deg. The symbol "\( x \)" and "+" marks the locations where the detailed results were monitored.

The only control parameter which could have potentially influenced the dynamics of the cloud propagation, was the velocity of the ventilation air \( U_{air} \). It entered the tunnel from the right side. Numerical calculations were performed for different values of the \( |U_{air}| = (1, 2.5, 5, 6) \text{ m/s} \). These values spanned the possible range of the mine ventilation capabilities.
2.4. Mathematical model and numerical implementation

Numerical calculations were made using the reactingFOAM solver implemented in OpenFOAM (Open Source Field Operation and Manipulation) CFD toolbox [5]. OpenFOAM has been used effectively in diverse and challenging applications [6; 7]. For the present application, a finite volume discretization was employed in conjunction with the PISO (Pressure Implicit with Splitting of Operators) algorithm for compressible flows [8; 9]. PISO schemes belong to the family of pressure correction methods.

ReactingFOAM solves for flows with combustion and chemical reactions, but if some of its functions are disabled, it can also serve as a solver for mixing gases. For the sake of the present work, it is assumed that air is a mixture of two gases: Nitrogen (79%) and Oxygen (21%). The third gas is Argon with an initial temperature of 87 K. The mixing process is modeled by solving the diffusion-advection equation for each gas separately:

\[
\frac{\partial \rho Y_i}{\partial t} + \nabla \cdot (\rho \mathbf{u} Y_i) = \nabla \cdot (\mu \nabla Y_i)
\]  

(2)

where \( Y_i \) is \( i \)-th gas, \( \mathbf{u} = (u, v, w) \) is a velocity vector, \( \rho \) is the density of the mixture and \( \mu \) is the dynamic viscosity of the mixture. In the present work, \( i = 3 \) and \( \sum Y_i = 1 \). The velocity field is calculated by solving the compressible Navier-Stokes equations [10]:

\[
\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot (\mu \nabla \mathbf{u})
\]  

(3)

which, along with the continuity equation:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]  

(4)

constitute a closed system. The density and viscosity of the mixture is calculated assuming linearity: \( \mu = \sum Y_i \mu_i \) and \( \rho = \sum Y_i \rho_i \), whereas the density and viscosity of the individual gases are calculated using the ideal gas equation and the Sutherland approximation respectively [5]. Although the boiling point of oxygen is 90 K (which is higher than the temperature of Argon), the ideal gas approximation is justified. Numerical analysis showed that the temperature of the oxygen never drops below 200 K.

To calculate thermodynamic quantities such as \( C_p \) (heat capacity) and \( H \) (enthalpy), a polynomial temperature dependency is utilized. The temperature of the mixture is calculated from the enthalpy transport equation:

\[
\frac{\partial \rho h}{\partial t} + \nabla \cdot (\rho \mathbf{u} h) = \frac{D\rho}{Dt} + \nabla \cdot \left( \frac{k}{C_p} \nabla h \right)
\]  

(5)

where \( k \) is heat conductivity of the GAr.

3. Results of the numerical calculations

Table 1 summarizes the average propagation velocity \( U_{av} \) and direction of propagation of the GAr cloud for different ventilation regimes: \( |U_{air}| = (1, 2.5, 5, 6) \) m/s. Value 0 m/s means that the Argon cloud does not propagate in that direction.

For the \( |U_{air}| = 1 \) m/s ventilation regime, the entire GAr goes down the tunnel with an average speed of 3.7 m/s. A characteristic of this flow is the initial creation of the GAr "bubble", which later moves down the tunnel.

In the case of \( |U_{air}| = 2.5 \) m/s, still almost all of the Argon goes down the tunnel but with a lower average speed of 2.7 m/s. There is a nearly unnoticeable Argon mist going up
Table 1. Average propagation velocity $U_{av}$ and direction of propagation of the GAr cloud for different ventilation regimes.

| Ventilation speed | $U_{av}$ up the tunnel | $U_{av}$ down the tunnel |
|-------------------|------------------------|--------------------------|
| 1 m/s             | 0 m/s                  | 3.7 m/s                  |
| 2.5 m/s           | 0 m/s                  | 2.7 m/s                  |
| 5 m/s             | 4 m/s                  | 1.7 m/s                  |
| 6 m/s             | 5 m/s                  | 0 m/s                    |

the tunnel. Here, ventilation air slows down the Argon "bubble" while simultaneously making larger amounts of Argon rise away from the ground. This is why a lower concentration of oxygen for $y = 0.5$ m was noticed. Nevertheless, the general conclusion remains similar to that of the flow with $|U_{air}| = 1$ m/s. Oxygen concentration goes only slightly below 18% for $y = 1.75$ m at $x = 10$ m.

The first qualitative difference can be noticed for $|U_{air}| = 5$ m/s in figure 2. For this ventilation regime, the Argon "bubble" still goes down the tunnel with an average speed of 1.7 m/s, but contrary to the previous flows, a substantial amount of Argon is taken up the tunnel with an average speed of 4 m/s. A second significant change is in the blocking of the Argon "bubble" motion until time $t = 50$ s. Only after this time does it begin to go down the tunnel. For the lower ventilation speed, there was essentially no GAr taken up the tunnel. The "bubble" could rise faster. Consequently, the buoyancy force, related to gravity, could more easily overcome the opposite force related to ventilation. For the current case of $|U_{air}| = 5$ m/s, much more GAr was taken up the tunnel. Thus, more time was needed to build a critically sized "bubble", which could overcome the force related to ventilation.

Oxygen drops below 18% at height $y = 0.5$ m and at the Argon spill location ($x = 0$), but only occasionally for $y = 1.75$ m. Contrary to the previous ventilation regimes, in this case, large amounts of Argon can go up the tunnel and, e.g. for $x = -10$ m, the oxygen concentration can stay below 18% for longer periods of time. Further up the tunnel, oxygen concentration never goes below 18%. Figures 3 and 4 show detailed measurements of the O2 and temperature in the points shown in Figure 1.

The second qualitative difference can be noticed for $|U_{air}| = 6$ m/s. This ventilation regime is a limiting case. Contrary to the previous flows, the Argon "bubble" is smaller and blocked at the origin ($x = 0$). All of the Argon goes up the tunnel with an average speed of 5 m/s. Oxygen can drop substantially at the point of spillage, even below 12%, at $y = 0.5$ m, staying low for a majority of the time, but never going below 18% for $y = 1.75$ m. Since, in this case, all of the Argon goes up the tunnel, more oxygen deficiency can be observed, e.g. for $x = -10$ m, the oxygen can drop down to 18% for longer periods of time. Further up the tunnel, oxygen concentration never goes below 18% for both $y = 0.5$ m and $y = 1.75$ m.
Figure 2. Oxygen distribution in the tunnel. For $t = 50$ s the GAr reached the outlet of the tunnel, for $t = 165$ s, GAr reached the inlet to the tunnel (air inlet), $|U_{air}| = 5$ m/s. For the better visibility only three sections of the tunnel are shows and tunnel is straighten.
Figure 3. Oxygen content in the measuring points shown in Figure 1, as a function of time. Upper (lower) row shows results in locations 0.5 m (1.75 m) above the ground. Left (right) column shows results up (down) the tunnel from the Argon spill point. Results for $|U_{air}| = 5$ m/s.

Figure 4. The same as figure 3 but for temperature.
4. Conclusions
The likelihood in occurrence of the undesirable LAr spill incident during the filling of the pilot installation in the Pyhasalmi mine is very low. The results from the numerical simulations showed that the GAr cloud would tend to flow down the mine tunnel for small and moderate velocities of the ventilation air (1 – 3 m/s). The motion of the cloud would be relatively fast. In this case, the decreased temperature and oxygen deficiency hazard would be observed only at the tunnel ground level. Temperature and oxygen concentration, measured at 0.5 m and 1.75 m above the ground, would drop below the safety level only locally, and just for a short period of time. This suggests that this incident would not be critical for personnel located downwards from the incident location and at a distance farther than 10 m from the spill place.

In the case of air ventilation velocity larger than 5 m/s, the GAr clouds would stay in the vicinity of the incident or would even go slowly up the tunnel. In this case, the temperature and the oxygen concentration could drop in regions significantly above the tunnel ground. It could remain below the critical level for an extended period of time. This could be a serious hazard for personnel located in the vicinity of the Argon cloud.

This suggests that in the case of incidence, a different action can be taken regarding the situation. The tunnel ventilation can be set to its minimal or maximal operation velocity depending on the safer evacuation direction. For the lowest possible air velocity, personnel can be evacuated upwards from the incident location and for the maximum ventilation, evacuation can be directed downwards. Personnel, who can be affected by the GAr cloud (truck driver included), should be equipped with heavy shoes and protective clothing for protection against the very low temperature at the tunnel ground level and possible spewing of the LAr.

Acknowledgments
This project has received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement no 284518 [LAGUNA-LBNO]
The scientific work has been financed from the financial resources for science 2015 granted for an implementation of an international co-funded project
The work has also been supported by statutory funds from Polish Ministry for Science and Higher Education, Statutory Founding 2014/2015, S40104/K0901.
This research was supported in part by PL-Grid Infrastructure (http://www.plgrid.pl/en).

References
[1] Patzak T 2012 J. Phys.: Conf. Ser. 375 042
[2] Van den Bosh C and at al 1997 Methods for the calculation of physical effects due to releases of hazardous materials (liquids and gases) (Hague: Netherlands Committee for the Prevention of Disasters, Publicatieriek Sefarlijke Stoffen)
[3] OGP 2010 Risk Assessment Data Directory (London: International Association of Oil and Gas Producers)
[4] Merte H and Clark J 1962 Adv. Cryo Eng. 7 546
[5] OpenFOAM 2009 The open source CFD toolbox user guide (Free Software Foundation)
[6] Chini G, Malecha Z and Dreeben T 2014 J. Fluid Mech 744 327
[7] Malecha Z, Chorowksi M and Polinski J 2013 Cryogenics 57 181
[8] Ferziger J and Peric M 1999 Computational Methods for Fluid Dynamics (Germany: Springer)
[9] Issa R, Gosman A and Watkins A 1986 J. Comput. Phys. 62 66
[10] Batchelor G 1967 Introduction to fluid dynamics (Cambridge: Cambridge University Press)