Safety analysis and quantitative risk assessment of a deep underground large scale cryogenic installation

Effie Marcoulaki[*] **and Ioannis Papazoglou**
National Centre for Scientific Research “Demokritos”, Athens, Greece

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Abstract: This work considers the safety analysis and quantitative risk assessment of a deep underground cryogenic installation intended for neutrino physics. The neutrino detector equipment will be submerged in 50ktons fiducial mass of purified liquid argon, stored in a specially designed heat insulated tank located inside a deep underground cavern. The conditions inside the tank and the cavern, and the purity of argon will be maintained using appropriate systems for cooling, heating, pressurization and filtration. Smaller adjacent caverns will host the process unit equipment (process unit caverns). The caverns for the tank and the process units are planned to be excavated inside a mine at about 1400 meters underground. The quantitative results presented here provide incentives for improvements on the current process design of the installation that can reduce significantly the expected frequencies of accidental argon release due to tank overpressure.

Keywords: safety assessment, cryogenic argon, loss of containment, underground installation, tank overpressure, neutrino detectors

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1. INTRODUCTION

Advances in neutrino physics, low energy neutrino astronomy and direct investigation of Grand Unification require the construction of very large volume underground observatories. Many European national underground laboratories with high technical expertise are currently operated with forefront smaller-scale underground experiments, and there is currently a lot of activity worldwide on the construction of a large-scale facility. The heart of these neutrino observatories is a detector consisting of specialized sensitive detection devices submerged into a detector medium. The detector medium on which the neutrino interact can be purified water, organic scintillators or in the present case liquid argon. The measurements of the particles produced are analyzed to establish the characteristics of the neutrinos that generated the interactions. There is significant evidence that large-scale observatories will enable fundamental discoveries in the field of particle and astroparticle physics [1].

The safety analysis presented here is part of an excessive multiyear design study elaborated by a large consortium of neutrino physicists and European construction companies, within the projects LAGUNA (2008-2011) and LAGUNA-LBNO[†] (2011-2014) funded by the European Commission. Among other issues, the study considered (a) the selection of an appropriate location and the conduction of geomechanical investigations, (b) the design and costing of the excavation of underground caverns and tunnels, (c) the design and costing of a tank and its construction plan to host the liquid argon, (e) the design, construction and costing of the detector equipment, (f) the design and costing of on ground and underground processes to fill the tank with argon and (g) to maintain argon at the desired conditions etc. Safety issues have been granted significant attention from the beginning of this study. Several types of risks have been identified and registered, and specific measures were proposed to prevent and mitigate them. The authors were responsible for assessing the safety of the underground installation at normal operation and quantifying the risks of cryogenic argon releases.

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[*] Contact person: Dr. Effie Marcoulaki, email: emarcoulaki@ipta.demokritos.gr, tel.: +302106503743

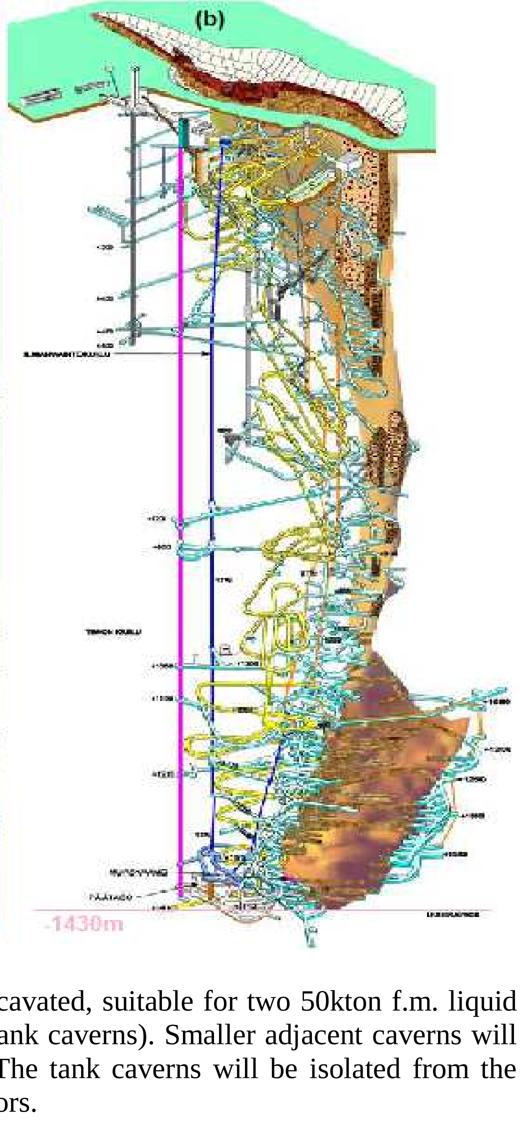
[†] LAGUNA is the abbreviation for Large Apparatus for Grand Unification and Neutrino Astrophysics. LBNO stands for Long Baseline Neutrino Observations

2. GENERAL DESCRIPTION OF THE INSTALLATION

In the present work, the neutrino detector is a tank with gross capacity 52,300 m^3 filled with cryogenic argon at 87K. The argon tank and associate processes considered here will be located in specially excavated caverns 1400m underground (see Figure 1a). The location considered is a copper and zinc mine at Pyhäsalmi in central Finland (see Figure 1b). The location selection was based on various criteria, including the excellent rock characteristics, the absence of nearby nuclear plants and hence of neutrons, the depth of the mine, the low seismicity and the distance from CERN. The latter is ideal for the study of accelerated neutrinos generated at CERN and aimed towards a detector at Pyhäsalmi. Information on the site selection and characteristics is publicly available in the LAGUNA project deliverables [1].

Figure 1a: Pyhäsalmi mine, Central Finland

Figure 1b: Present mine layout [1]



At -1400m (see Figure 1b) three large caverns will be excavated, suitable for two 50kton f.m. liquid argon tanks and one 50kton f.m. liquid scintillator tank (tank caverns). Smaller adjacent caverns will host the process unit equipment (process unit caverns). The tank caverns will be isolated from the process unit caverns and the rest of the mine using lock doors.

The LAGUNA-LBNO project team has provided detailed designs on the location, sizing, cost and equipment types of the on ground facilities and the shafts used for technical infrastructure (like piping, electricity wires). This information is published at [1] in strict confidence. The process flow sheet, the argon tank and process unit sizes, the temperature and pressure conditions etc used in the present analysis are also found in [1]. In particular, the present QRA is based on the geotechnical designs and rock mechanical analysis conducted by Kalliosuunnittelu Oy Rockplan Ltd, the tank design and calculations elaborated by Technodyne International Ltd and Rhyal Engineering Ltd, and the liquid handling process design proposed by Sofregaz SA.

The detector medium is argon, kept at cryogenic conditions and vapour-liquid equilibrium at 87K and 1265mbar in specially designed and heat insulated tank. A detector network and appropriate instrumentation to measure neutrino interactions with argon atoms will be immersed in the argon liquid inside the tank. A ventilation system (pressurizer) and a cavern heating system will work in parallel to maintain the conditions in the tank cavern at 22°C and 1250mbar.

The neutrino experiments require argon liquid of particularly high purity, so argon liquid will be taken from the tank and processed in a set of filtration units. The argon boil-off produced inside the tank due to heat influx in the tank will be re-condensed in heat exchanger units that use nitrogen as coolant. The argon cooling system will also include expansion and compression units arranged in loops that aim to cool down, re-condensate and reuse the nitrogen coolant, and a nitrogen storage vessel.

The ventilation and heating system units, the pumps, motors and turbines for fluid transmission and processing, and the filtration units will be located in the processes cavern, next to the tank cavern. The heat generated by the instrumentation in the tank cavern and all the equipment located in the process cavern will be rejected finally into the surface atmosphere through a specially built Cooling Water System. Presently the design of this system comprises a motor driven cooling tower using cooling water from the nearby Lake Pyhäjärvi, and a pipeline running several hundred meters through the rock to transmit the water underground. In case of overpressure in the argon tank, the water cooling system is able to transmit the released argon gas to the mine surface atmosphere. Note that, the pipes transmitting argon between the surface and -1400m are empty during normal operation.

A safety analysis along with a Quantitative Risk Analysis (QRA) has been performed based on the existing design details. The QRA includes: (a) an assessment of the various accident sequences leading to Ar release; (b) an estimation of their frequencies; and (c) a calculation of the consequences for three types of Ar release using CFD tools. This paper presents only the accident sequences that lead to Ar release owning to overpressure in the LAr tank. The release can be either inside the tank cavern, or in the process units cavern, or at the surface of the mine.

3. HAZARD IDENTIFICATION

The main concern of storing such a large quantity of liquefied Argon stems from the possibility that Liquid Argon (LAr) may be released from its containment, evaporate and (a) reach concentrations in a particular confined space that can expel oxygen from the air and/or (b) result to extremely low temperatures in the confined space. Two main areas exist where argon is contained and there is a possibility of a Loss of Containment (LOC) and a subsequent release of argon:

a. Tank cavern: Main cavern with the cryogenic argon tank
b. Process unit cavern: Process area where argon is cooled / condensed (if it is in gas phase), filtrated and returned to the argon tank.

A LOC and hence an argon release may occur as a result of a number of immediate causes. A number of safety measures either engineered features or procedural are employed to prevent the occurrence of each of the immediate causes of LOC. This section presents the immediate causes for LOC due to overpressure and the associated safety measures.

All different type of containment failure may be divided in two major categories:

a. Structural Failures
b. Containment Bypassing

A structural failure of the containment occurs if the stress employed on the containment by the various operating conditions is larger than the stress of the containment. This inequality may happen when the strength of the containment is as designed but the stress exceeds the design limits. Alternatively, an inequality may also occur if the strength of the containment becomes lower than the normally expected stresses.

Containment Bypassing occurs whenever an engineered opening in the containment (like a valve) opens inadvertently when it is supposed to be closed. Such failures are mainly caused by human actions either during normal operation or during test and maintenance activities. Assessment of causes of containment bypass requires a detailed final design, and the detailed relevant operating, test and maintenance procedures. At this stage of the system design these details are not available, hence the corresponding potential causes of argon release are not included. Immediate causes of structural failure of the liquid argon containment are determined with the help of the Master Logic Diagram [2].

4. OVERPRESSURE AND ASSOCIATE SAFETY MEASURES

Increase of the internal pressure can cause an increase of the stress on the containment exceeding its design limits and resulting in LOC. In the present installation the critical design feature that might cause a LOC owing to overpressure, is the roof of the tank. Its design requires that the overpressure inside the tank with respect to the pressure in the cavern does not exceed the 25mbarg. It is assumed that, causes that result in a gauge pressure greater than 25mbarg will result in LOC and in particular in a small break at the gaseous phase of the argon. Furthermore, if the pressure increase is relieved through the pressure relief valves of the tank, Ar is transferred outside the tank in the Ar-processes cavity, from where it is transferred to the mine surface through an appropriate system.

This section presents the safety functions and the safety measures incorporated in the design to prevent pressure difference beyond the design limit, and the mitigating measures to relieve overpressure and preserve the containment integrity. Systems that directly serve a safety function are called *Primary Safety Systems* (PSS). For successful operations, the Primary Safety Systems sometimes depend on other systems that provide support services to them, called *Support Safety Systems* (SSS). Their operation is also safety significant, but only through the impact they have on the operation of the PSS.

Argon is kept at vapor-liquid equilibrium (VLE) at cryogenic conditions using a cooling system, to remove the heat influx from the cavern air to the argon contained in the tank. Any heat imbalance can cause an increase in the tank internal pressure, leading to LOC and argon release. The heat imbalance may be caused by either an increase in the heat influx or a decrease in the heat removal capacity. Heat flux into the cryogen from the environment will vaporize the liquid and potentially cause pressure build-up in cryogenic containment vessels and transfer lines. Cryogenic fluids have small latent heats and expand 700 to 800 times to room temperature, so even small heat inputs can cause significant pressure increase.

4.1. Safety Function F1: Maintain Heat influx into LAr within design limits

To maintain the heat influx down to acceptable levels, the tank is equipped with an appropriate insulation. Provided that the cavern air conditions are at the required levels, the insulation is designed to maintain the heat influx rate from the cavern air at 43kW.

Safety system PS1: Tank Insulation

Additional support systems to maintain the integrity of the insulation are systems to detect loss of insulation, and the design considerations allowing insulation replacement [1]. Given the preliminary stage of the design, in section 5 it is simply assumed that given a loss of insulation it will take approximately one month to detect the loss and repair it to the design specifications.

4.2. Safety Function F2: Maintain pressure within Tank below the maximum acceptable level

Heat influx into the tank must be removed, to keep the pressure inside the tank below the acceptable level. There are two sources of heat influx: (a) 43kW from the cavern air (through the insulation); and (b) 84kW from the detector instrumentation.

System PS2: The re-condensation system

This system removes the Ar boil-off generated by the heat influx, maintaining the tank pressure at 1265mbara. The boil-off circulates with the help of a motor driven pump through a Heat Exchanger where it is re-condensed. The process uses liquid N_2 converted to N_2 gas. Heat is removed through the N_2 cycle and eventually is rejected into the surface atmosphere through the Service Water Cooling system (section 4.5/SS1). There are two N_2 loops to convert N_2 gas back to liquid N_2. One loop is sufficient to remove the 127kW produced during normal operation of the LAr tank The success criteria for the re-condensation system depend on the size of the extra heat load generated by the loss of insulation and on whether the instrumentation has been turned off (as presented later in Table 5).

System PS3: Operator's action to switch off Instrumentation

Operators must diagnose the increased heat flux and switch off the instrumentation and other heat producing loads. Two possible states are considered: (a) Instrumentation loads are switched off (success); and (b) Instrumentation loads are not switched off (failure).

4.3. Safety Function F3: Maintain Cavern Conditions

Cavern air pressure should be maintained at 1250mbar or higher, given that the Tank pressure is increasing and the tank gauge pressure should remain lower than 25mbarg. Furthermore, the cavern air temperature should be maintained at 22^{o}C.

System PS4: Ventilator system

This system takes air from the tank cavern exterior and injects it into the tank cavern to maintain the required ambient pressure of 1250mbar. There are two loops, and each one is capable to maintain the cavern pressure at the required level even if the Cavern Heating system (PS5) has failed.

System PS5: Cavern Heating System

This system is heating the cavern to maintain the air temperature at the required 22^{o}C. If the cavern-air temperature decreases, this system can heat it up to the required 22^{o}C. Therefore, this system alone can maintain the temperature of the cavern air and hence the air pressure at its required levels. If the heating system is not available, the cavern temperature will decrease, thus reducing the air pressure, unless PS4 is available. Based on design information available at the time of the analysis it is assumed that, if PS5 is available then it can maintain the cavern air at the required temperature. Systems PS4 and PS5 are thus completely redundant.

4.4. Safety Function F4: Relieve Extra Pressure

If the gauge pressure in the tank exceeds 25mbarg, argon gas must be relieved from the tank and released into the surface atmosphere via the Service Water Cooling system (section 4.5/SS1).

System PS6: Set of Tank Relief Valves

The argon tank is equipped with a set of safety relief valves. The pressure relief system typically comprises at least 4 valves in operation. The same applies for vacuum relief valves [1]. The released argon is then lead to the surface by the Service Water Cooling system (section 4.5/SS1).

4.5. Support safety systems

System SS1: Service Water Cooling System

Heat generated in the cavern and the associated process systems is removed by SS1 and transferred to the surface atmosphere through a cooling tower-type process. Hot water carrying the heat from all systems in the installation (including heat generated by motors and turbines) is fed into an evaporating system where the heat is deposed into water ultimately coming from the surface and the nearby lake. This water is evaporated and sent to the surface through forced circulation powered by a ventilator.

The safety significance of this system is extremely high. Lack of cooling signals inability of heat transfer from the tank, and failure of all motors, pumps and turbines in the process equipment. Given the current level of information, it has been assumed that failure of this system (as a whole) will result in failure of all PSSs and SSSs that need cooling for their continuing function. In case of SWCS failure, success of the pressure relief (PS6) results in Ar release in the area of the SWCS. If PS6 fails then tank overpressure occurs and Ar is released in the tank cavern.

System SS2: Electric Power

Electric power is another essential service needed by almost all PSSs and SSSs systems for successful operation. Loss of AC and/or DC power for prolonged period of time would result in failure of all PSSs, as well as SS1. Consequently, the safety significance of the electricity supply system is extremely high. At this stage of the design there is no detailed information on the design of the electricity supply system. This analysis assumes two sources of electric power: an offsite source (from the grid) and an Emergency Diesel Generator (DG). Loss of both these sources for more than certain time periods (to be determined for each initiating event) will cause a total blackout, which in turn will cause failure of all equipment depending on electricity.

5. DELINEATION OF ACCIDENT SEQUENCES

Accident sequences are sequences of events that lead to LOC integrity and hence to argon release. An accident sequence consists of an initiating event that challenges the safety functions/systems of the installation, and of additional events representing either hardware failures and/or human actions that collectively result in a LOC. For the safety systems described above, accident sequences are obtained using Functional Block Diagrams and the associated Event Trees [3]. All systems are operating during normal operation. Failure of any major component of the safety systems constitutes an initiating event.

5.1. Loss of Offsite Power

With the exception of the Ar-N_2 Heat Exchanger, some turbine driven pumps in the Re-condensation system PS2 and the relief system PS6, all safety related systems depend on electric power to operate. Consequently, following Loss of Offsite Electric Power (LOOP), if the DG does not start, the installation gets into blackout conditions. Unless power is restored on time, over-pressurization occurs. Then, if the relief valves open we have release of Ar gas in the processes cavern, otherwise we have release of Ar gas in the tank cavern.

During blackout, the SWCS, the systems maintaining cavern pressure and the Ar re-condescension system do not operate. Instrumentation is turned off since there is no power, and the heat influx towards the Ar tank is equal to the 43kW from the cavern air. Since boil off is not re-condensed, the pressure inside the Tank increases at a rate of 0.25mbar/hr [1]. Furthermore, since there is no cabin air pressurization or heating, the predicted cavern pressure drop is 4.3mbar/hr. As a result, the gauge pressure in the Tank will reach the tank design limit of 25mbarg within 2.2 hours. Consequently there is a time period of about 2.2 hours within which either the offsite power or the DG ought to be repaired to avoid argon release in the cavern. The events considered in this Event Tree are given in Table 1. The calculations of component availabilities and failure/repair probabilities within a given time period are based on classical reliability techniques.

A reduced Event tree depicting the accident sequences following a LOOP is given in Figure 2.

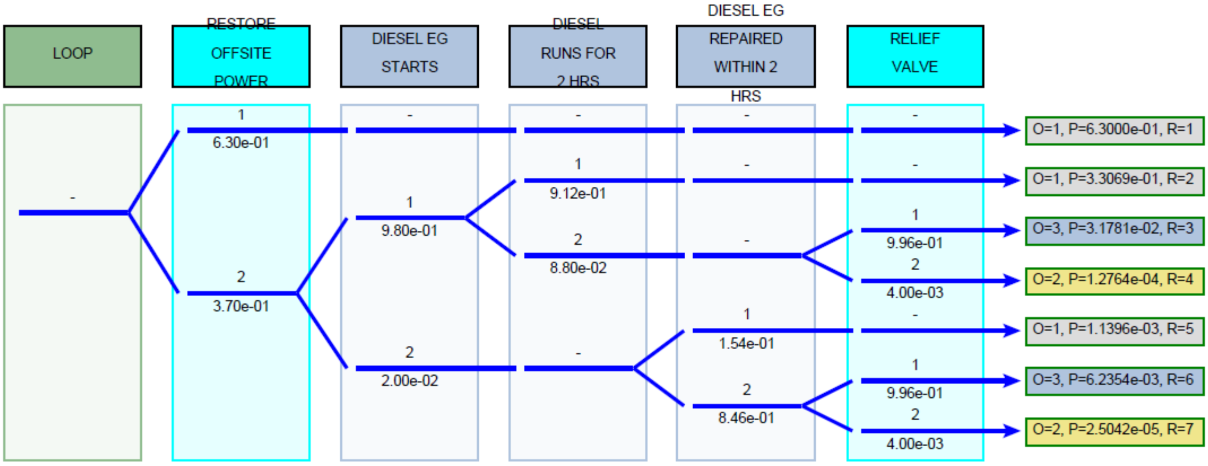
- Accident sequence #1 is a successful sequence since following the initiation of LOOP, offsite power is restored within 2.2hrs. The state of the DG and its repair is indifferent in this sequence.

- Accident sequence #2 is also successful since although offsite power is not restored within 2.2 hours, the DG starts and it runs for more than 2.2 hours.
- Accident sequences #3 & #4 result in an overpressure because offsite power is not restored within 2.2 hours, the DG starts but it fails to run for 2.2 hours. In sequence #3 the relief valves open releasing Ar in the Ar-processes cavern. Sequence #4 results in Ar release in the tank cavern since the relief valve system fails.
- In sequences #5, #6 & #7 the offsite power is not restored within 2.2 hours and the DG does not start. Sequence #5 is successful since the DG is repaired and started within 2.2 hours.
- In sequences #6 & #7 the DG is not is repaired and started within the 2.2 hour window. Then, if the relief valve system operates there is Ar release in the Ar-processes cavern (#6). If the relief valve system fails there is Ar release in the tank cavern due to overpressure (#7).

Table 1: Events considered in Loss of Offsite Power Event Tree

EVENT	PROBABILITY
Loss of offsite Power	10^{-5}/hr (Frequency) [4]
Mission Duration	2.2 hours
Failure to recover Offsite Power within 2.2 hours (MTTR=2hours)	0.37
Emergency Diesel Generator starts on Demand	0.98
Emergency Diesel Generator is repaired within 2.2 hours	1.54×10^{-1}
Given that Emergency Diesel Generator starts, mean availability over 2.2 hours	9.11×10^{-1}
Pressure Relief System failure (on demand)	4×10^{-3}

Figure 2: Loss of Offsite Power Event Tree



5.2. Loss of Service Water Cooling System

The initiating event here is a failure of the Service Water Cooling System (SWCS) for reasons other than lack of electric power. Without cooling, all safety systems except the human action switching off the instrumentation (PS3) will fail. If instrumentation is switched off, then the situation is exactly as in the station blackout (section 5.1), so there is a period of 2.2 hours before argon release due to overpressure. If the instrumentation is ON then the heat input rate at the Ar in the tank is 126.6kW resulting at an internal pressure increase rate of 0.74mbar/hr [1]. The cavern pressure still drops at a rate of 4.3mbar/hr, but in this case the differential pressure limit will be exceeded in just 2 hours. Consequently, quantification of this event should include the probability of not recovering the system within 2 hours.

There are two general ways for losing the SWCS: either by failure of one of the motor drive pump or by failure of the motor driven fan. The events considered in this Event Tree are given in Table 2. An additional failure mode consists in loss of cooling water transported from the nearby lake. This failure mode has not been considered since the design of this part system did not exist at the time of the analysis.

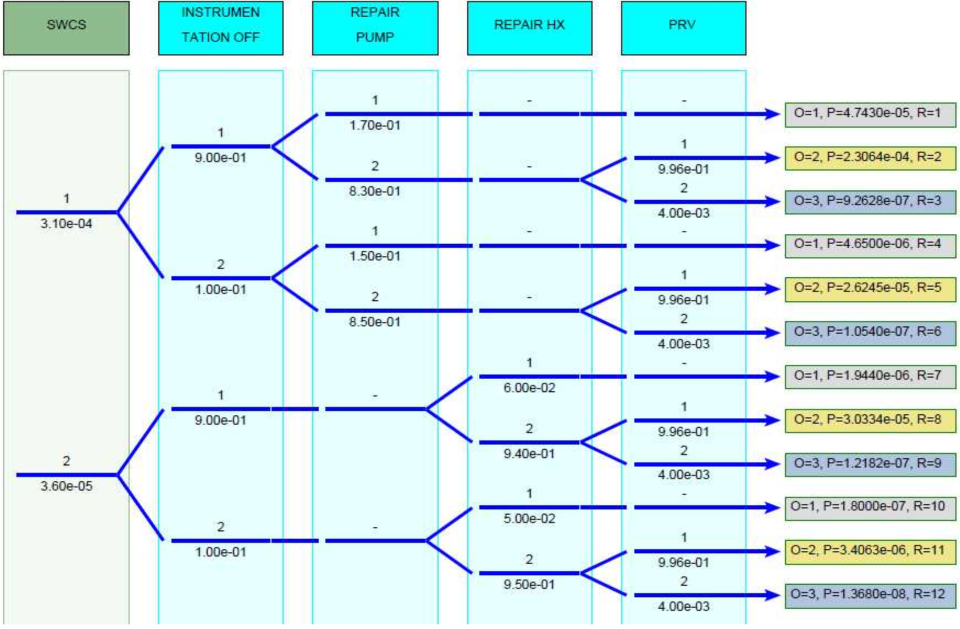
A reduced Event Tree for the loss of SWCS is depicted in Figure 3. Two initiating events have been considered, corresponding to: (a) the loss of a pump and (b) a loss of a Heat exchanger. The logic is simple resulting in success if the failed component is repaired within 2.2 hours (if instrumentation is turned off) and in 2 hours (if instrumentation is not turned off). If the failed component is not repaired within the available grace period the sequences result in failure due to overpressure.

Sequences #2 & #5 are accident sequences, as they involve failure of the SWCS pump with failure to recover it within the available time. PS6 is successful and Ar is released in the SWCS area, Sequences #3 & #6 involve Ar release in the tank cavern since PS6 has failed. Similar accident sequences #8 & #11 and #9 & #12 are calculated for shorter grace period since the Instrumentation is left ON.

Table 2: Events considered in Loss of Service Water Cooling System Event Tree

EVENT	PROBABILITY
Loss of the operating fan	3.1×10^{-4}/hr (Frequency)
Loss of the Heat exchanger (ventilator)	3.6×10^{-5}/hr (Frequency)
Failure to recover pump within 2 hours (MTTR=12hours)	0.85
Failure to recover pump within 2.2 hours (MTTR=12hours)	0.83
Failure to recover Heat Exchanger within 2 hours (MTTR=36hours)	0.95
Failure to recover Heat Exchanger within 2.2 hours (MTTR=36hours)	0.94
Failure to switch Instrumentation OFF	0.1

Figure 3: Event Tree for Loss of Service Water Cooling System (SWCS)



5.3. Loss of Cavern Heating System

Loss of the cavern heating system, for causes other than a station blackout or loss of service water cooling system, does not create an immediate problem provided that the cavern ventilator (pressurizer) is available. This is because it has been assumed that the cavern ventilator is capable to maintain the cavern pressure at the required levels. The analysis is similar to subsections 5.1 and 5.2 and the results are given in Table 7.

5.4. Loss of one Cavern Ventilator (Pressurizer) Train

Cavern air is maintained at a constant pressure of 1250mbar through the Ventilator system which is continually operating during the operational phase of the LAGUNA LAr detector. The system has two trains each capable of pressurizing the cavern. Failure of the operating train constitutes the initiating event. The standby train has to start and continue operation. However, even if the second train does not start, the Cavern heating system is capable to maintain the cavern air at the required pressure. The analysis here is similar to subsections 5.1 and 5.2 and the results are given in Table 7.

5.6. Loss of Ar boil off re-condensation pump

Loss of the argon boil-off re-condensation pump results in loss of the boil-off re-condensation system. Depending on whether instrumentation has been turned off or not the available grace period is 10 hours and 40 hours, respectively. The analysis is similar to subsections 5.1 and 5.2 and the results are given in Table 7.

5.7. Loss of Operating Re-condensation Train Event Tree

Loss of the Operating Re-condensation Train results in a challenge to the boil off re-condensation system. For this system to fail, the standby train or the Ar pump must fail before restoring the online failed N_2 train. Depending on whether instrumentation has been turned off or not the available grace period is 10 hours or 40 hours, respectively. The analysis is similar to subsections 5.1 and 5.2 and the results are given in Table 7.

Table 5: Success criteria for Re-condensation system given Loss of insulation

Extra Heat load (H) due to Loss of Insulation	**Instrumentation and other loads turned off**	**Total heat load to Re-condensation system (H)**	**Re-condensation requirement**	**Time window before Tank – Cavern overpressure exceeds 25mbarg**		
				2 N_2 trains	1 N_2 train	0 N_2 trains
LI1: $H \leq 87$kW	YES	$H \leq 130$kW	1/2 N_2 trains	∞	∞	> 13 hrs
LI2: 87kW < $H \leq$ 130kW	YES	$130 < H \leq 173$ kW	Both N_2 trains	∞	>40 hrs	10 < t < 13 hrs
LI3: 130kW < H $\leq$ 217kW	YES	$173 < H \leq 260$ kW	Both N_2 trains	∞	13 < t < 40 hrs	6.6 < t < 10 hrs
LI4: 217kW < H	YES	260kW < H	System inadequate	Depends on size of LI	t < 13hrs	t < 6.6 hrs
LI1: $H \leq 87$kW	NO	$H \leq 217$kW	Both N_2 LOOPs	∞	t > 20 hrs	t >8 hrs
LI2: 87kW < $H \leq$ 130kW	NO	$217 < H \leq 260$ kW	Both N_2 LOOPs	∞	13 < t < 20 hrs	6.6 < t < 8 hrs
LI3: 130kW < H $\leq$ 217	NO	$260 < H \leq 347$ kW	System inadequate	t > 20 hrs	8 < t < 13.6 hrs	5 < t < 6.6 hrs
LI4: 220kW < H	NO	347kW < H	System inadequate	t < 20 hrs	t < 8 hrs	t < 5hrs

5.8. Loss of Tank Insulation

Loss of insulation (LI) results in higher heat influx to the tank, increasing the Ar boil off rate and hence the required re-condensation rate. Under normal operating conditions (with insulation intact) the heat load that must be removed through the re-condensation of the boil-off is about 127 kW. If there is an abnormal situation it is possible to switch off the instrumentation and other heat producing functions, thus reducing the necessary heat removal rate to 43kW.

In order to include all possible combinations of insulation loss and whether instrumentation is switched off, the following four different types of insulation loss are considered:

- LI1: the additional resulting heat influx to the LAr Tank is $H \leq 87$kW
- LI2: the additional resulting heat influx to the LAr Tank is 87kW < $H \leq 130$kW
- LI3: the additional resulting heat influx to the LAr Tank is 130kW < $H \leq 217$kW
- LI4: the additional resulting heat influx to the LAr Tank is H > 217kW

Since each train of the N_2 cooling system can remove up to 130kW, the requirements for the N_2 cooling system are given in Table 5. Loss of insulation is an event that occurs randomly in time. It is assumed that it will take, on the average, one month or 720 hours to completely repair the insulation. Since all the safety systems are online (continuously operating), the probability of failing given a loss of insulation event (and within the time that this event has not been recovered) is a second order effect, can therefore be neglected. In other words, the failure of the various safety systems has been taken into consideration when their failure has been considered as an initiating event. This is true for the all safety systems with the exception of the LAr boil-off-re-condensation system. Successful operation of this system depends on the amount of heat that it has to remove from the tank and hence it is directly affected by the occurrence of reduction in the insulation. For this reason, in calculating the conditional probability of argon release due to overpressure given a Loss of Insulation initiating event, only the LAr-re-condensation system is considered. All other systems are assumed to operate successfully. The frequency for loss of insulation is taken equal to $1x10^{-2}$/yr. The conditional probabilities that, given a loss of insulation, the loss will be according to LI1, LI2, LI3 and LI4, are suggested equal to 0.8, 0.1, 0.07 and 0.03, respectively.

Loss of insulation resulting in a Heat Influx less than 87kW

The calculation for the frequency of Loss of insulation resulting in a Heat Influx less than 87kW take into account the state of operation of the N_2 cooling system. If this system is completely failed then with the instrumentation OFF there is a heat input equal to 43kW + 87kW = 130kW (maximum) hence the pressure inside the tank will increase by 25mbar within 13 hours (for 130kW). If the instrumentation is ON then the maximum heat input is about 217kW and the available time is 8 hours. If one N_2 train is operating, then with the instrumentation OFF it can remove the net heat input of 130kW. If the instrumentation is ON then net heat input is about 217kW the operating train removes 130kW, hence the second train is needed and it has to be available within 20 hours. The events included in the Event Tree are given in Table 6.

Loss of insulation resulting in a Heat Influx between 87kW & 130kW

With the added heat influx due to LI, the available time for recovering failed parts of the LAr re-condensation system changes. If this system is completely failed then with the instrumentation OFF there is a heat input between 130kW and 173kW (maximum) hence the pressure inside the tank will increase by 25mbar within 10 to 13 hours. If the instrumentation is ON then the heat input is between 217kW and 260kW and the available time is between 6.6 hours and 8 hours. If one N_2 train is operating, then with the instrumentation OFF there is an extra heat input between 0 and 43kW (maximum) hence the pressure inside the tank will increase by 25mbar in more than 40 hours. If the instrumentation is ON then the extra heat input is between 87kW and 130kW and the available time for the second train to be recovered is between 13 hours and 20 hours. Similarly to LI1, the frequency for Loss of insulation resulting in a Heat Influx between 90kW & 130kW is set at $1.14x10^{-7}$/hr.

Table 6: Events considered in the for LI resulting in a Heat Influx less than 87kW

EVENT	PROBABILITY
Loss of insulation resulting in a Heat Influx less than 90kW	$9.12x10^{-7}$/hr (Frequency)
Failure of Ar Pump (mean failure probability for 720 hours)	0.1
Ar Pump not recovered within 13 hours (Instrumentation OFF)	0.338
Ar Pump not recovered within 8 hours (Instrumentation ON)	0.513
Failure of the Operating Re-condensation N_2-Train (ORTr) (mean failure probability for 720 hours)	0.16
Standby Re-condensation N_2-Train fails to start	$2x10^{-2}$
Probability of not recovering failed ORTr within 20 hours (MTTR=12hours) (Instrumentation ON and one train operating)	0.189
Probability of not recovering failed ORTr within 8 hours (MTTR=12hours) (Instrumentation ON and no train operating)	0.513
Probability of not recovering failed ORTr within 13 hours (MTTR=12hours) (Instrumentation OFF and no train operating)	0.338

Loss of insulation resulting in a Heat Influx between 130kW & 217kW

With the added heat influx, the available time for recovering failed parts of the LAr re-condensation system changes. If this system is completely failed then with the instrumentation OFF there is a heat input between 173kW and 260kW (maximum) hence the pressure inside the tank will increase by 25mbar within 6.6 to 10 hours. If the instrumentation is ON then the heat input is between 260kW and 347kW and the available time is between 5 hours and 6.6 hours. If one N_2 train is operating, then with the instrumentation OFF there is an extra heat input between 43 and 130kW (maximum) hence the pressure inside the tank will increase by 25mbar within 13 hours and 40 hours. If the instrumentation is ON then the extra heat input is between 130kW and 217kW and the available time for the second train to be recovered is between 8 hours and 13 hours. Similarly to LI1, the frequency for Loss of insulation resulting in a Heat Influx between 130kW & 220kW is set at $7.98\text{x}10^{-8}$/hr.

Loss of insulation resulting in a Heat Influx Higher than 217kW

If insulation is lost to such an extent that the extra heat input exceeds 217kW, then the total heat input with the instrumentation OFF exceeds 260kW. Since the existing Ar re-condensation system (even if both N_2 trains are available) is able to remove only 260kW, the extra heat will eventually lead to Tank overpressure. The time until tank over-pressurization depends on the extent of the heat input in excess of 260kW. The conditional probability of this happening is therefore equal to unity and whether there will be Ar release into the surface atmosphere or inside the tank cavern depends on the successful operation of the pressure relief system. The estimated frequency of this event occurring is $3.42\text{x}10^{-8}$/hr.

5.8. Summary of argon release owning to overpressure and recommendations

The results of the event tree analysis are summarized in Table 7. In the case of overpressure in the argon tank, argon gas can be released to the mine surface atmosphere through the PSVs and the SWCS. The frequency of such an event has been estimated at $5.74\text{x}10^{-1}$/year or once every 21 months. This mainly comprises the frequencies of loss of the argon pump in the re-condensation system (by 99%), and the loss of the operating nitrogen loop (about 0.4%), and finally the loss of insulation (0.6%). Increasing the reliability of the argon gas pumping system can reduce significantly the expected frequency of this type of release.

Perusal of Table 7 indicates that the frequency of argon release inside the tank cavern owing to overpressure, is almost once every seven months. This frequency is notably high, but only 17% of this value is attributed to initiating events other than the failure of the SWCS. If the SWCS is not considered, the main failure cause is the loss of the argon pump in the re-condensation system (99%). This is due to the complete lack of redundancy in this system. It is recommended that the final design incorporates redundancy in the SWCS, as well as in the Ar side of the re-condensation system. This could reduce the expected frequency of LOC due to overpressure by two to three orders of magnitude. It is noteworthy that, the literature for double walled refrigerated LNG containments suggests a frequency for failure of the roof and vapor release in the order of $3.5\text{x}10^{-9}$/hr [5]. This is the order of magnitude for the contribution of those systems that contain redundancy, like the cavern atmosphere regulating systems, the N_2 side of the re-condensation system and the loss of insulation events.

7. CONCLUSIONS

This work quantifies the risk for loss of containment in a deep underground installation involving large quantities of a cryogenic substance. The work is part of a very extensive study to select the site, design the excavation, construction and deployment phases, design of the process units etc, undertaken by a pan-European team of highly specialized and experienced engineers. The engineers collaborated closely with distinguished scientists, so that the proposed installation meets the requirements for next generation particle and astroparticle physics experiments.

Table 7: Frequencies for Loss of Containment owning to overpressure

INITIATOR = LOSS OF:	**Frequency (hr^{-1})**	**Conditional Probability of Argon Release in**			**Frequency (hr^{-1}) of Argon Release in**		
		Tank Cavern	**Process Area**	**Surface of Mine**	**Tank Cavern**	**Process Area**	**Surface of Mine**
LOOP	1.00x10^{-5}	1.5x10^{-4}	3.8x10^{-2}	--	1.50x10^{-9}	3.80x10^{-7}	--
SWCS Pump	3.10x10^{-4}	3.65x10^{-3}	8.3x10^{-1}	--	1.13x10^{-6}	2.57x10^{-4}	--
SWCS HX	3.60x10^{-5}	3.76x10^{-3}	9.4x10^{-1}	--	1.35x10^{-7}	3.38x10^{-5}	--
Operating Pressurizer Train	1.00x10^{-5}	2.00x10^{-8}		5.00x10^{-6}	2.00x10^{-13}		5.00x10^{-11}
Cavern Heating System	3.10x10^{-4}	6.80x10^{-10}		1.70x10^{-7}	2.11x10^{-13}		5.27x10^{-11}
Ar Pump	3.10x10^{-4}	8.60x10^{-4}		2.10x10^{-1}	2.67x10^{-7}		6.51x10^{-5}
Operating N_2 train	5.00x10^{-5}	2.60x10^{-5}		6.40x10^{-3}	1.30x10^{-9}		3.20x10^{-7}
Insulation: LI1	9.12x10^{-7}	2.60x10^{-5}		3.90x10^{-2}	2.37x10^{-11}		3.56x10^{-8}
Insulation: LI2	1.14x10^{-7}	2.30x10^{-4}		5.70x10^{-2}	2.62x10^{-11}		6.50x10^{-9}
Insulation: LI3	7.98x10^{-8}	4.50x10^{-4}		1.10x10^{-1}	3.59x10^{-11}		8.78x10^{-9}
Insulation: LI4	3.42x10^{-8}	4.00x10^{-3}		9.96x10^{-1}	1.37x10^{-10}		3.41x10^{-8}
TOTAL					**1.54x10^{-6}**	**2.92x10^{-4}**	**6.55x10^{-5}**

The analysis presented here generates and investigates accident sequences leading to overpressure in the cryogen (argon) containment and estimates their frequencies of occurrence. The results based on the present state of the design identify weak spots. Incorporating design with higher reliability for these parts of the system would greatly decrease the associated risks.

Note that, the present study is a summary of a detailed analysis, including CFD dispersion simulations, and assessment of adverse consequences on personnel health and the cavern structural integrity following a potential argon release in the experimental facility. The analysis concluded that there is no risk for personnel present in the tank cavern when the release occurs or the tank cavern integrity [1].

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