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Quantitative safety analysis of cryogenic liquid releases in a deep underground large scale installation

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ABSTRACT

The present work considers the quantitative risk assessment of a heat insulated Tank designed to host over 65 kt of cryogenic argon. A specially built detector grid will be submerged in the cryogenic medium to allow the detection of subatomic particles (neutrinos). The Tank and associated equipment for cooling, heating, pressurization and filtration, are located in appropriately constructed caverns 1400 m underground. Previous work on this infrastructure focused on pressure control failures leading eventually to minor argon gas leaks (Marcoulaki et al., 2016 [7]). This work identifies possible initiators for direct loss of containment and release of liquid argon in the underground premises, discusses the proposed safety measures, and presents results for two release category types involving medium and major liquid argon spills. Assessment of consequences aims at identifying the risks of human casualties and/or collapse of the underground caverns. Detailed thermodynamic predictions and CFD dispersion simulations are performed to support the phenomenology analysis.

1. Introduction

The present work is part of an excessive multiyear study elaborated by a large consortium of neutrino physicists and European construction companies, for the design of very large volume underground observatories for fundamental research in particle and astroparticle physics. The underground infrastructure considered here employs specially built devices for the detection of neutrinos, submerged into high purity cryogenic argon at 87 K.

The study was funded by the European Commission under the projects [5] and LAGUNA-LBNO (2011–2014), and 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. More information can be found at the LAGUNA and LAGUNA-LBNO projects websites [5,6].

The presence of several ktons of cryogenic argon in confined space conditions presents a significant safety concern. Uncontrolled argon release may create conditions that pose a risk of significant adverse health consequences for exposed personnel and jeopardize the structural integrity of the underground caverns. Marcoulaki et al. [7] considered the cryogenic release of the gaseous argon in the underground premises owning to pressure control failure under normal operating conditions. Their analysis included: (a) identification of the accident sequences leading to argon gas release; (b) estimation of their frequencies; (c) identification of Plant Damage States and the associated argon gas Release Categories; and (d) assessment of the consequences of argon gas release in the Tank cavern using CFD simulations.

The present work identifies possible initiators for direct loss of containment and release of liquid argon in the installation premises, reports the proposed safety measures, and conducts a detailed assessment of two release categories. The paper is organized as follows. Section 2 presents briefly the installation and discusses the risk sources. Section 3 identifies the immediate causes for loss of containment, and describes the associated safety measures applied. Section 4 discusses the plant damage states assumed in phenomenology analysis of Section 5. The phenomenology analysis involves CFD simulations of liquid argon dispersion and predictions of the cavern rock temperature, complemented with analytical thermodynamic predictions and qualitative analyses. Section 6 concludes this work.

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2. Description of the installation – associated risks

2.1. General description of the installation

The neutrino detector proposed during the LAGUNA and LAGUNA-LBNO projects (2011, 2014) is a custom designed and heat insulated Tank with gross capacity 52,300 m^3 filled with 65 kt of cryogenic argon at 87 K and 1265 mbar. The argon Tank and associate processes will be located in specially excavated caverns 1400 m underground, in the Pyhäsalmi mine in central Finland. The present analysis is based on the design details proposed during the LAGUNA-LBNO project. In particular, the project consortium included industrial partners who elaborated the geotechnical designs and rock mechanical analysis (Kalliosuunnittelu Oy Rockplan Ltd, Finland); the Tank design and calculations (Technodyne International Ltd and Rhyal Engineering Ltd, UK); and the liquid handling process design (Sofregaz SA, France). The delivered technical reports are available at the LAGUNA-LBNO website (2014) in strict confidence.

Fig. 2-1 provides a simple illustration of the underground infrastructure. Equipment is located in two caverns, the argon Tank cavern and an auxiliary cavern for the liquid handling processes. The processes include units to re-condense the argon boil-off, to purify liquid argon, to control the air temperature and pressure conditions in the Tank cavern, and to transmit argon gas to the surface in case of Tank overpressure requiring operation of the Tank safety valves. A specially designed Service Water Cooling System (SWCS): (a) removes the heat generated by the instrumentation in the Tank cavern and all the equipment located in the process cavern, and (b) transmits argon gas to the mine surface atmosphere in case of Tank overpressure. Marcoulaki et al. [7] provide more details on the underground installation.

2.2. Nature and sources of risk

The main concerns of storing such a large quantity of liquefied Argon stems from the possibility that cryogenic argon may be released from its containment, 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. The former can occur if the released substance is in vapor phase, or after evaporation of released liquid. If there are personnel in this particular area, significant health effects as severe as death from asphyxiation or cold are possible. The normal oxygen concentration lies between 20.8% and 21.0%, while oxygen deficiency and oxygen enrichment occur when the concentration is below 19.5% or above 22%, respectively (OSHA) [9]. Exposure to atmospheres containing oxygen in concentrations less than 10% can rapidly overcome a person and bring about unconsciousness without warning. Lack of sufficient oxygen can cause serious injury or death (APC) [1]. In terms of human hazards associated with low temperatures, cryogenic liquids can cause thermal burn injuries. Brief exposure can damage delicate tissues and lungs, while prolonged contact of the skin with cold surfaces will cause frostbite, and prolonged exposure to a very cold atmosphere can reduce the body core temperature and cause hypothermia (OEHS, BOC) [2,8]. In addition, the extremely low temperatures of the cavern flour and walls resulting from leaks of cryogenic fluids may affect the rock stress and lead to the occurrence of cracks. These could jeopardize the structural integrity of the cavern and damage the foundations of the Tank.

Two main critical 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.

An argon release in either of these two critical areas may occur during: filling the Tank with the liquid argon, normal operation, or emptying the Tank to perform maintenance on the detector instruments. The present Quantitative Risk Assessment (QRA) considers only the normal operating phase, that is when the experiment is performed and the argon remains inside the Tank.

3. Direct causes for loss of containment

A LOC and hence an argon release may occur as a result of various immediate causes. A number of safety measures, either engineered

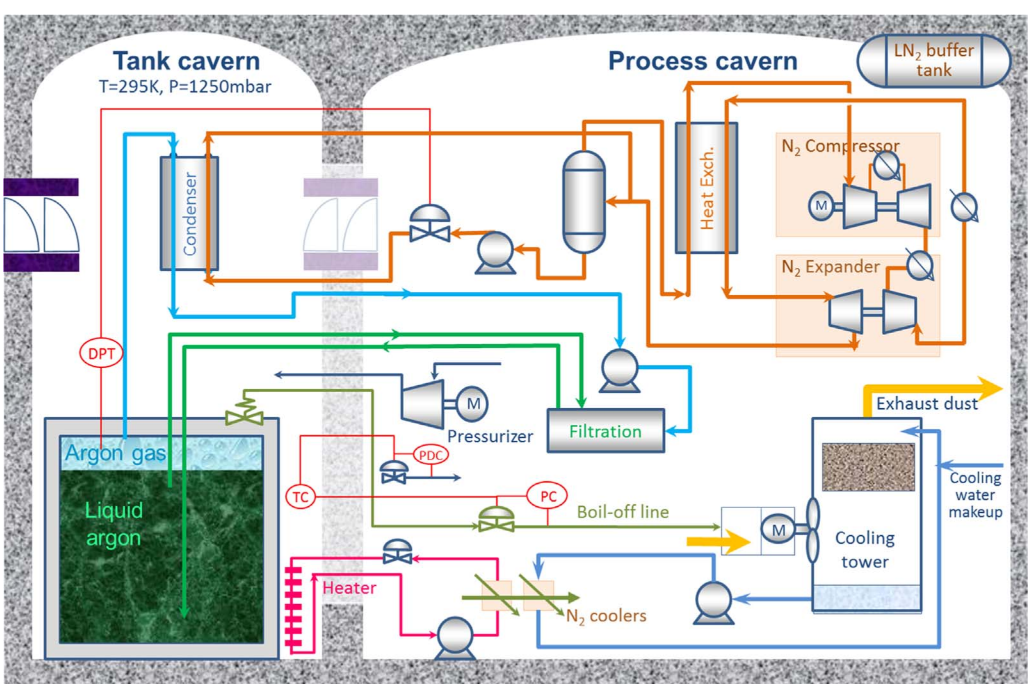

Fig. 2-1. Flowsheet of the underground installation.