

Quantitative Risk Assessment for DarkSide 50, a Nuclear Physics Experimental Apparatus Installed at Gran Sasso Nat'l Lab: Results and Technical Solutions Applied

Federico Gabriele^{a1}, Andrea Ianni^b, Augusto Goretti^b, Michele Montuschi^a, and Paolo Cavalcante^a on behalf of DarkSide Collaboration

^aGran Sasso National Laboratory, L'Aquila, Italy

^bPrinceton University, Princeton, USA

Abstract: DarkSide 50 (DS50) is a two phase argon Time Projection Chamber designed to search for dark matter at the Gran Sasso National Laboratory (LNGS). As in most rare event experiments hosted at the LNGS, the challenge of DS50 is to reduce the background due to natural radioactivity. To meet this challenge, DS50 has the unique feature of underground depleted argon and uses an active veto to account for neutrons, the most important source of background for WIMP searches.

In this paper we report the Quantitative Risk Analysis (QRA) of the whole apparatus that we implemented and developed in order to bring the failure rates in the range of the LNGS acceptable matrix.

Due to the complexity of the experimental apparatus the analysis takes a variety of accident scenarios into account.

Even though QRA is widely used internationally for many purposes, the peculiarity of this application makes the involved issues, interpretation and results extremely interesting for risk assessment in the application of low background experiments in a confined underground space.

Keywords: QRA, Low-background, Gran Sasso Nat'l Lab, Confined Space, Dark Matter.

1. INTRODUCTION

A wide range of astronomical evidence suggests the existence of dark matter, but as yet the nature of this major component of the Universe is completely unknown. A leading candidate explanation is that dark matter is composed of weakly interacting massive particles (WIMPs) formed in the early universe and gravitationally clustered together with the standard baryonic matter.

Such WIMPs could in principle be detected through their collisions with ordinary nuclei in a sensitive target, giving observable low-energy (<100 keV) nuclear recoils. The predicted collision rates are very low and require ultra-low background detectors with large (0.1–10 tonnes) target masses, located in deep underground sites to reduce the background produced by neutrons from cosmic ray muons [1].

Several technologies have been developed for direct detection of dark matter WIMPs. These detectors all share the common goal of achieving the low background and low threshold energy required to detect the nuclear recoils that are possibly produced by the extremely rare collisions of WIMPs with target nuclei.

Among the variety of detector technologies, noble liquid Time Projection Chambers (TPCs), which detect both the scintillation light and the ionization electrons produced by recoiling nuclei, are particularly promising.

DarkSide 50 is a Liquid Argon Time Projection Chamber (LAr-TPC) with a projected sensitivity of $2 \times 10^{-45} \text{ cm}^2$ for a WIMP mass of 100 GeV.

What makes this notable is that DS50 is designed to deliver this sensitivity via a long run with expected background well under 1 event, making a dark matter detection plausible.

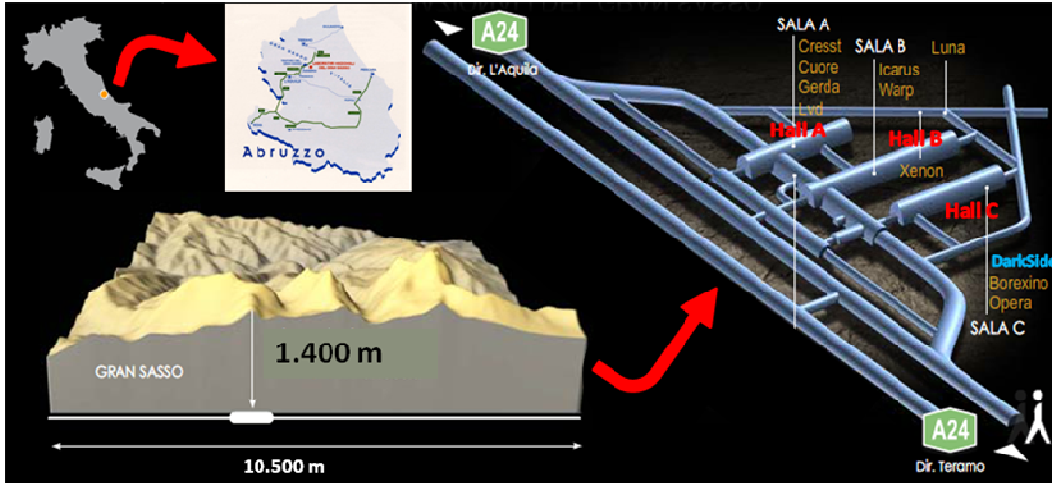
¹federico.gabriele@lngs.infn.it

2. GRAN SASSO NATIONAL LABORATORY

The Gran Sasso National Laboratory (LNGS), Figure 1, is one of the most important worldwide underground laboratories. The LNGS facility is part of the Italian National Institute of Nuclear Physics (INFN) and is made up of two main areas:

- the External Operations Centre (External Lab) in the town Assergi,
- and the Underground Laboratory.

Figure 1: The LNGS Location and a 3D Underground Lab Image



The whole experimental research centre is located in the heart of Gran Sasso and Monti della Laga National Park. The underground laboratory is located under a rock layer about 1,400 m thick, acting as a shield against cosmic radiation and currently housing about 20 experiments of different sizes. The underground cavity in the middle of a huge reservoir along the Gran Sasso highway tunnels (a double-tunnel 10,500 m long). The Underground Lab consists of three experiment halls: Hall A, Hall B and Hall C (about 100x20x20 m each), and a series of interconnecting smaller tunnels.

From the “safety point of view”, beyond health and safety regulation in the work place the LNGS is classified, according to the European Directive Seveso III (2003/105/CE), as a major accident hazard plant because of experiments using and storing a large amount of substances classified dangerous to the environment [2].

In this environment and in compliance with Seveso Law, the satisfactory demonstration of acceptable risk levels is a requirement for approval of an experimental apparatus at LNGS. For that reason, we performed a Safety Risk Analysis in order to evaluate the likelihood of occurrence of possible events and to improve the safety standards in a complex system such as the LNGS.

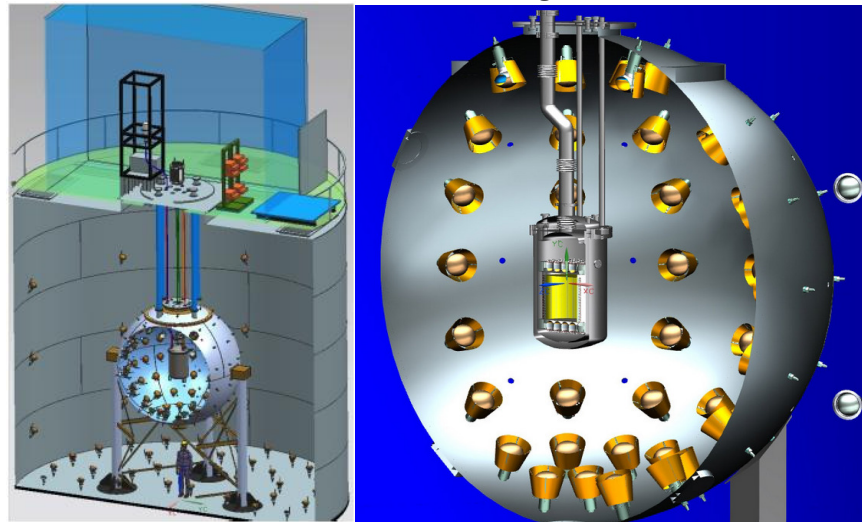
3. THE DARKSIDE 50 APPARATUS

The DarkSide 50 Detector apparatus consists of three nested detectors, as illustrated in the left panel of Figure 2.

From the center outward, the three detectors are:

- the DarkSide 50 Detector, (right panel of Figure 2),
- the Liquid Scintillator Detector Neutron Veto (right panel of Figure 2),
- the Water Čerenkov Detector Muon Veto (left panel of Figure 2).

Figure 2: On the right the Nested Detector System of DarkSide 50, on the left a 3D Image.



3.1. The Water Čerenkov Muon Veto

The outermost detector is an 11 m diameter, 10 m high cylindrical tank (variable thickness in height from 12 to 8 mm) filled with high purity and deionized water, 1000 tonnes, (this tank is known as the CTF). An array of 80 photomultiplier tubes (PMTs) is mounted on the side and bottom of the water tank to detect Čerenkov photons produced by muons traversing the water. The inside surface of the tank is covered with a laminated Tyvek-polyethylene-Tyvek reflector to enhance Čerenkov light detection efficiency. At the top of water surface a Gas Nitrogen (GN_2) blanketing with slight overpressure is present in order to prevent contamination by air inlet.

3.2. The Liquid Scintillator Neutron Veto

A 30 tonnes borated Liquid Scintillator Detector is contained in a 4 m diameter (6 mm thickness) stainless steel sphere (Liquid Scintillator Vessel, or LSV) inside the CTF water tank. The scintillator consists of a mixture of 2 hydrocarbons: Pseudocumene (PC) and Trimethylborate (TMB), in equal amounts, with the wavelength shifter Diphenyloxazole (PPO) at a concentration of 3 g/liter.

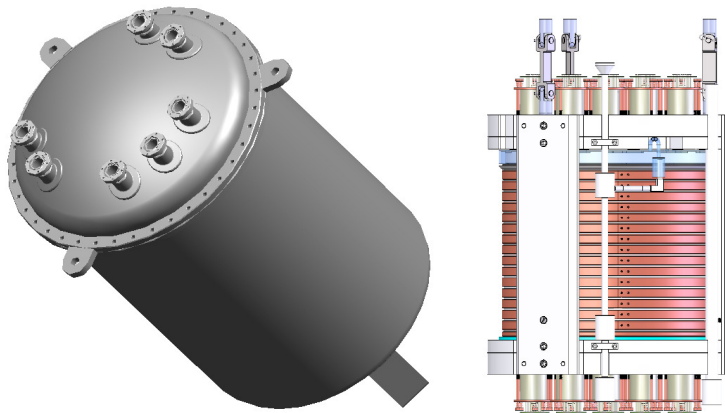
An array of 110 PMTs is used to detect the scintillated photons. The inside surface of the sphere is covered with a Lumirror reflecting foil. Each PMT is fixed to the external liquid scintillator vessel wall through 30 mm single o-ring welded supports. A mixture level indicator in scintillator expansion vessel is also provided. The Liquid Scintillator external walls have been tested with helium in order to detect leaks.

On the top of the LSV there are two flanges: a 2,000 mm flange used to seal the scintillator top dome and a 900 mm flange used to hold the seven tubes and the DS50 Detector. Finally, on the scintillator external wall there are three blind covered flanges, used for optical fibers inlet.

3.3. The DarkSide 50 Detector

The DarkSide 50 Detector is a two-phase Liquid Argon Time Projection Chamber (TPC), right panel of Figure 3, designed to be sensitive to nuclear recoils possibly associated to dark matter interactions.

Figure 3: On the right the Cryostat, on the left the TPC.



The Cryostat (or DAR) containing the TPC, as shown in the Figure 2 and in the left panel of Figure 3, is supported at the center of the LSV and operates at liquid argon (LAr) temperature immersed in the Liquid Scintillator Detector Neutron Veto. The total amount of LAr contained in the cryostat is about 150 kg.

The active volume of the TPC, 53.6 cm high and 47 cm wide, is contained laterally by a PTFE cylinder and at the top and bottom by fused silica windows. The volume is read out by 38 PMTs, nineteen each on the top and the bottom which view the active LAr.

The cylindrical surface (made of PTFE) is a reflector that is coated with tetra-phenyl-butadiene (TPB) wavelength shifter which is used to shift the UV scintillation photons to the visible spectrum for detection. The windows at the top and bottom of the cylinder are also coated with the wavelength shifter on the inner surfaces, and on both surfaces with transparent ITO conductive layers.

The Cryostat is a stainless steel, double walled, vacuum-insulated and super-insulated cylinder with two-to-one elliptical dished heads composed by two different vessels: the DAR vessel and the DAR vacuum jacket, both connected on the bottom of the top flange of the CTF and lowered inside the LSV through its north-side opening called the N2 Flange.

As shown in Figure 3, DAR has seven ports on top:

- LAr inlet port;
- vacuum port;
- 2 cable inlet/outlet ports (GAR outlet in normal conditions);
- GAR safety outlet port (GAR outlet in emergency conditions) [Blind Flange];
- 2 high voltage (HV) ports.

The LAr inlet, GAR safety outlet, cable inlet/outlet and HV ports are welded to the DAR inner vessel top dome and flanged with a ConFlat flange to the DAR vacuum jacket while the vacuum port, located in the center of cryostat top dome, is welded to the DAR vacuum jacket top dome.

The seven inlets listed above are provided through corrugated stainless steel-made tubes. The LAr inlet is vacuum insulated and the five others are with single wall (the Gar safety outlet port, vacuum port, the HV and cable inlet/outlet ports).

Both vessels are closed on top with two flanges:

- a 584 mm wire-seal type DAR vessel top flange,
- a 710 mm o-ring type DAR vacuum jacket top flange.

3.4. The DarkSide 50 Cryogenic System

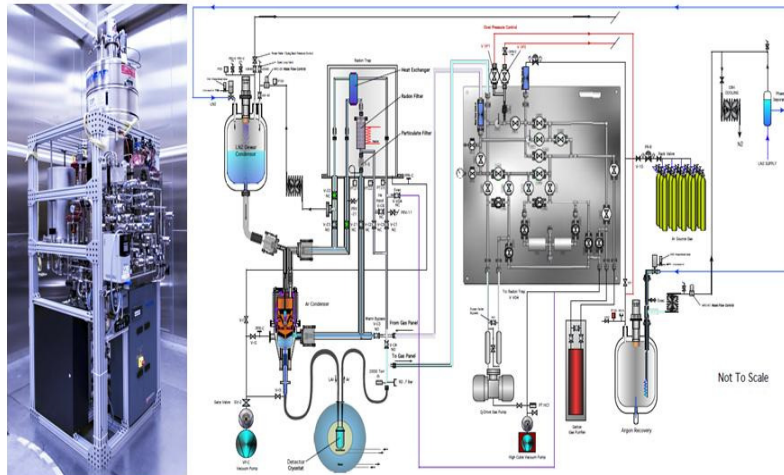
The DarkSide-50 Cryogenic System is designed to continuously recirculate GAR through the purification getter and re-condense it for return to the detector, while precisely maintaining the

working pressure of the argon in the cryostat under a range of heat loads during commissioning and operation. The design also insures that the system is safe in the case of loss of electric power.

The system (see Figure 4) can be divided in the following subsystems:

- Purification System,
 - Charcoal (Radon) Trap,
 - Ar Condenser,
 - Liquid Nitrogen Supply System
- and two closed-circulation cryogenic loops.

Figure 4: The DarkSide 50 Cryogenic System: on the left the System, on the right a Schematic Sketch



3.4.1. The Purification System

The Purification System (PS) is located in the so-called Hanoi Cleaning Room (CRH) placed on the top of the CFT tank, as illustrated in the Figure 2. The PS is directly connected to the Liquid Scintillator Detector and to the DS50 Detector through the N1 and N2 Flanges. The system is comprised of the Gas Panel, the Heated (SAES) Getter and the Circulation Pump (P-1). Its aim is to purify the GAR coming from the DAR and send it clean to the Radon Trap. All the above components are connected together through 0.5" DN tubes in which the GAR is circulated.

The gas panel itself is comprised of:

- Two filters (F-3, F-4) usually by-passed, except when the radioactive source connection between them is in use (only for calibration).
- Twelve pneumatic valves (VG01-12) which in case of emergency allow argon to bypass the gas panel itself, letting argon flow from the detector to the Ar condenser.

The Heated (SAES) Getter component is comprised of:

- the Getter, that is used to purify argon gas from H₂O and N₂ traces;
- the Heat Exchanger;
- the Filter (F-G).

The volumetric pump (P-1) is used to circulate GAR inside the purification system in order to overcome pressure drops in the purification loop. P-1 operates in resonance mode and the oscillation amplitude is related to input power, so it does not have a fixed compression ratio and it has a designed burst pressure of 27 bar, but the Maximum Allowable Working Pressure (MAWP) can be chosen according to particular needs and it will be dependent on input power and inlet delivery pressure (usually set equal to gas panel MAWP of 3 barg); the system is designed in order to allow only the set MAWP to be generated, even if the valves are blocked downstream.

P-1 is also set for a 100 sl/min maximum flow value but it normally operates at 50 sl/min. P-1 pressure and flow values are monitored by a Pressure Transmitter (PT P1), connected to a Pressure Relief Valve (PRV-P1) and a by-pass, activated by a pneumatic (V-G04) or a manual valve (V-S04).

3.4.2. Charcoal (Radon) Trap

The Charcoal (Radon) Trap is part of the gas circulation loop and its aim is to remove the radioactive contaminant Radon from the argon steam, using a vertical cold charcoal column: cold Nitrogen coming out from the Ar condenser head flows through a heat exchanger to cool down clean warm argon coming from the gas panel to a temperature just above the argon condensation temperature.

Cold argon gas then passes through the charcoal trap, it cools down and enters the Ar condenser, while warm Nitrogen coming out from the heat exchanger flows back to the liquid Nitrogen (LN₂) production dewar where it is condensed. A pump (P-20) is needed to overcome the pressure loss in the Mass Flow Control (MFC 20) and to force the Nitrogen back into the production dewar.

The vessel of the Charcoal Trap is a flat-headed vertical cylinder that includes the main filter, the heat exchanger and an additional filter (F-55) used to remove other gas traces. It is directly connected and located inside a stainless steel vacuum jacket, operating at temperature of 20 °C and a Maximum Allowable Working Pressure of 1.1 bar. Pressure values inside the Radon Trap are monitored by a pressure transmitter (PT 22) located on the Radon filter by-pass connection and a pressure indicator (PI 21) connected with the GAr outlet tube after control valve V-C2. Inside the Radon Trap, four temperature elements are also provided:

- TE N2-3, located on heat exchanger LN₂ inlet line;
- TE AR-1, located on heat exchanger GAr outlet line;
- TE RD-1/2, connected to the radon filter.

3.4.3. Argon Condenser

The argon condenser condenses clean cold Ar coming from the Radon trap and delivers the LAr to the cryostat through the above vacuum insulated transfer line. The cold head of the condenser condenses incoming gaseous argon using liquid N₂ through a copper-made exchanger.

The cold GN₂ generated during the argon condensation leaves the condenser through a vacuum insulated transfer line and feeds the Radon Trap heat exchanger that pre-cools the argon before entering the filter. The argon condenser is provided with stainless steel vacuum jacket, operating at a Temperature of 20 °C and a Maximum Allowable Working Pressure of 1.1 bar. Temperature inside the argon condenser is monitored by four temperature elements:

- TE N2-1, located on copper made exchanger LN₂ inlet line;
- TE N2-2, located on copper made exchanger LN₂ outlet line;
- TE AR-2/3, inside the argon condenser.

3.4.4. Liquid Nitrogen Supply System

The Liquid Nitrogen Supply System or Nitrogen Loop provides cooling for the liquefaction of argon. Starting at the LN₂ reservoir (a 160 l Dewar), a significant amount of LN₂ is stored as a buffer in the event of a power failure for an estimated time of about 24 hours. At the LAr condenser, LN₂ is used to liquefy the argon for the detector. This process of cooling the argon changes the phase of the LN₂ to N₂ cold gas. The cold gas return goes through a heat exchanger that is used to pre-cool the argon going to the radon trap and then to the condenser. The N₂ then travels to a room temperature heat exchanger that warms up the nitrogen gas before going through the MCF 20. Once the N₂ passes through the MFC 20 it returns back to the LN₂ Dewar where it is condensed to LN₂ completing the loop. The re-condensation of N₂ to LN₂ is done by the 300 W GM cryocooler mounted on the top of the LN₂ dewar. The above system allows high system stability and controllability during both normal and abnormal including emergency conditions.

Moreover the nitrogen system can be operated directly by a transfer line connected to the lab's large liquid nitrogen reservoir. There are the following control/monitoring devices connected to the LN₂ production dewar:

- the above MFC 20, on the Nitrogen gas line, which controls the cooling power: the MFC is also connected to the Distributed Control System (DCS), so that in the case of a malfunction, an alarm is sent from the control system;
- A pressure transmitter (PT 20) which measures the GN₂ line pressure value;
- 3 Pressure Relief Valves.

3.4.5. Argon Recovery System

The Argon Recovery System allows the recovery and storage of the Gas Underground Argon (GUA_r) coming from the DS50 Detector in case of evacuating of the LAr. It is connected directly to the above gas panel and composed of a 600 W GM cryocooler head-cold installed on the top of the LAr dewar. The system has two modes of operation, one by the local liquefaction of the 600 W GM cryocooler installed on top of the liquid argon dewar, and the other by the lab's liquid nitrogen reservoir. In the second mode, the Nitrogen return gas line provides another source of LN₂ System.

4. THE QUANTITATIVE RISK ANALYSIS

We began the analysis with a (PRA) Preliminary Risk Analysis (April 2012) [3, 5, 6, 7] in which we performed a FMECA for the above DS50 Apparatus. After this first evaluation and method application, we carried out a (QRA) Quantitative Risk Analysis [4, 5, 6, 7] (June 2013).

In the following table we report the Top Events (TE) and the Events (E) that emerged from the FMECA and then that were enhanced in the Fault Tree Analysis (FTA).

Table 1: Top Events and Events

Top Events	
A	Cryostat (DAr) overheating/overpressure
B	DarkSide 50 overheating/overpressure
Other Events	
C	Argon direct release
D	Water release in Hall C
E	Nitrogen direct release
F	Liquid Scintillator direct release in Hall C

We performed the FTA by the FTPlus software and we assessed the calculations assuming a DS50 life-time of 20 years. We consider component and safety system failures according to specifications and operating modes:

- Immediately revealed failures (Rate model);
- Dormant failures (Dormant model);
- Fixed model.

Safety system failures are typically detected when their availability is requested (dormant failures). In order to estimate unavailability when activation is requested ("No opening/working when requested") we apply the "dormant" model.

To assess non-time-dependant unavailability, failure rates, and probabilities (e.g. "human error" in normal operations) we shall use the "fixed" model, according to scientific literature. In this model, output value ω stands for the frequency of a human operating error based on the fact that the operation is done "n" times in a fixed time interval (e.g. 1 year).

4.1. Top Events A and B

In the assessment of Top Event A, we consider all initiator events which could lead to the condition of possible overheating/overpressure in DAr and consequent cryostat breakdown.

The Top Event A “Cryostat overheating/overpressure” main initiator events are:

- DAr vessel failures:
 - Hole or leak from DAr vessel external wall and top dome;
 - Hole or leak from n.10 DAr vessel welded points;
 - Hole or leak from n.7 DAr vessel top flanged ports for inlets/outlets;
 - Leak from DAr vessel top flange;
- Dar vacuum jacket failures:
 - Hole or leak from DAr vacuum jacket external wall and top dome;
 - Hole or leak from n.2 DAr vacuum welded points;
 - Hole or leak from n.7 DAr vacuum jacket top flanged ports for inlets/outlets;
 - Leak from DAr vacuum jacket top flange;
- Hole or leak from stainless-steel inlet/outlet tubes:
 - LAr inlet corrugated stainless steel tube;
 - DAr vacuum jacket vacuum line.
- Hole or leak from flex inlet/outlet lines:
 - n.2 cables flex lines;
 - DAr cryostat inner vessel vacuum line.
- Leak from gate valve GV-2.

The Top Event A main enablers are:

- DAr cryostat vacuum providing system unavailability;
- No Darkside-50 system rupture disks (RD-1, RD-3) opening when requested.

In the assessment of Top Event B, we consider all initiator events which could lead to the condition of possible overheating/overpressure in Darkside-50 system, including all auxiliaries (e.g. Argon condenser, LN2 production dewar, etc.) and also the “Purification with pump” configuration, that correspond to Darkside-50 normal operating conditions.

The Top Event B “Darkside-50 overheating/overpressure” initiator events are:

- Overpressure/vacuum loss in DAr cryostat (see Top Event A);
- Overpressure/vacuum loss in Argon condenser due to:
 - Vacuum gap failure;
 - Hole or leak from LN2 inlet tube;
 - Hole or leak from GAr inlet welded port;
 - Hole or leak from GN2 outlet welded port;
- Overpressure/vacuum loss in gas panel/Radon trap due to:
 - Vacuum gap failure;
 - Pneumatic valves (V-21, V-22) stuck closed;
 - Leak from filters (Radon filter, F-5, F-G);
 - Hole or leak from GAr inlet tube;
 - Leak from heat exchanger external shell;
 - n.8 pneumatic valves (V-G01, V-G05, V-G07, V-G08, V-G11, V-G12, V-C1 and V-C2) stuck closed.

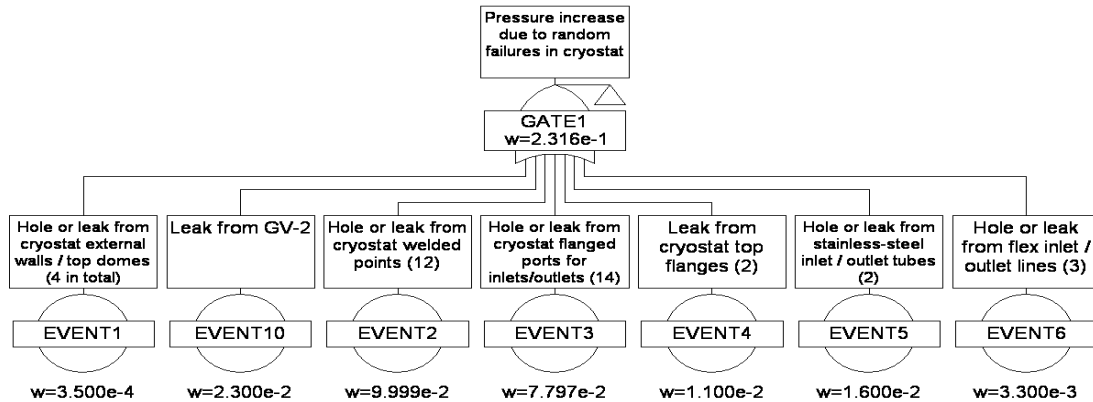
Top Event B main enablers are:

- All enablers considered in Top Event A simulation (see Top Event A);
- Radon trap/Argon condenser vacuum providing system unavailability;
- No pump P-1 by-pass/stop (e.g. PRV-P1/PT-PI unavailability, P-1 failure, etc.);
- No Pressure Relief Valves (PRV-2, PRV-4, PRV-21, PRV-11) opening when requested or failure;
- No LN2 production dewar Rupture Disk (RD-2) opening when requested.

In order to follow a conservative approach, holes/leaks considered in the analysis are micro-leaks due to operational error during welding, stainless-steel imperfections, etc. which have higher failure rates but also effects (e.g. Pressure increase, vacuum loss, etc.) that could be mitigated by vacuum providing system.

We also apply a high performance super insulation layer on the vacuum jacket internal walls in order to slow temperature/pressure increase down and help maintain the vacuum.

Figure 6: Top Event A: Gate 1



4.2. Events C, D, E and F

In the assessment of Event C, we consider all initiator events which could lead to the condition of possible Argon direct release which could be localized in the PS inside the CRH or directly in Hall C, depending on release of the starting point position.

The main initiator events in the PS inside the CRH are:

- Leak from pump P-1;
- Leak from n.2 sample valves (SVs);
- Leak from n.4 manual valves (V-Ss);
- Leak from n.4 vacuum valves (V-Vs and vacuum valve on P-1 line);
- Leak from manual valve V-PI3;
- Leak from n.14 pneumatic valves (V-Gs, PRV-1, PRV-3);
- Leak from filters (F-3, F-4, F-G).

The main initiator events with releases directly in Hall C are:

- Leak from gate valve GV-1;
- Leak from n.5 pneumatic valves (V-Cs);
- Pneumatic valve V-C6 stuck open/partially open;
- Leak from GAr outlet tube in Radon trap;
- Leak from GAr inlet port in Argon condenser;
- PRV-11 or Rupture Disks (RD-1, RD-3) undue openings.

The Event D does not lead to safety related consequences, but we have evaluated it regardless because it could lead to Hall C flood in case of relevant water release from Darkside-50 water tank.

The Event D "Water release in Hall C" initiator events are:

- Leak from water tank lateral manhole;
- Hole or leak from water inlet (water purification plant) or outlet (water drain) tubes;
- Hole or leak from n.8 blind covered flanges;
- Hole or leak from water tank external wall;
- Leak from manual valves (V-W1, V-W2).

In the assessment of Event E, we consider all initiator events which could lead to the condition of possible Nitrogen direct release.

The Event E “Nitrogen direct release” main initiator events are:

- Leak from n.6 pneumatic valves (V-21, V-22, V-23, V-24, V-25, V-26);
- Leak from n.3 manual/by-pass valves (V-BP1, V-BP2, Valve on PI 20 line);
- Manual valve V-25 stuck open/partially open;
- Hole or leak from Radon trap GN2 inlet/outlet tubes;
- Hole or leak from LN2 production dewar GN2 inlet tube;
- Pressure Relief Valves (PRV-21, PRV-2, PRV-4) and Rupture Disk (RD-2) undue opening;
- Hole or leak from Argon condenser GN2 outlet port;
- Hole or leak from LN2 production dewar outlet port;
- Leak from pump P-20.

In the assessment of Event F, we consider all initiator events which could lead to the condition of possible Liquid Scintillator directly in Hall C, depending on release starting point position.

The Event F initiator events are:

- Leak from the manual gate valves on the CTF pumping station, the draining lines and from the filter F-502;
- Leak from 3 solenoid valves on the CTF pumping station and draining lines;
- Leak from needle valve DS-514;
- Hole or leak due to buffer (HT 5302) failures;
- Hole or leak from scintillator inlet/outlet tubes;
- Hole or leak from CTF tank scintillator inlet/outlet ports;
- Leak from pumps in both CTF pumping station and draining lines;
- Leak from filter F-502;

It is important to underline that all component failure rates used for the analysis, and therefore the simulation performed, follow a conservative approach mainly because:

- All values derive from component failure rate records based on laboratory specific tests and previous experiences on each component: for that reason, all failure rates could be further specified, for example, considering more precise failure rates provided by component producers/suppliers.
- All component failure rates used in the analysis include all possible type of hole/leaks, from micro to relevant ones. For that reason, the above Events could lead to dangerous safety related consequences only if a relevant hole/leak occurred: these types of holes/leaks have a lower frequency of occurrence than small ones.

Following the same conservative approach, it is important to underline that no enablers can be considered in the analysis.

It is also important to note that, for the Events C and E, the Hall C ventilation system is provided, and for the Events D and F, the Hall C retaining basin is provided.

5. CONCLUSIONS

In this section we report remarkable technological solutions adopted, a summary of results, and the application of ALARP methodology.

First of all, it must be emphasized that a possible risk scenario leading to a Rapid Phase Transition (RPT) due to contact between LAr and liquid scintillator inside the LSV is not part of the analysis because of the high improbability of its occurrence due to the presence of a super-insulated layer which represents a further safety “containment” in case of a hole or leak in addition to the double-walled cryostat explained above.

That super-insulated layer represents also a significant reduction of heat exchange between two above liquids. The following technological solutions have been installed as results of analysis in order to reduce the likelihood of occurrence:

- Pressure Relief Valve (PRV) and Rupture Disc (RD) release points have been located in safe position and connected to the vent.
- A pressure regulator on gaseous Nitrogen line before LN₂ production dewar has been installed.
- A Slow Control System has been developed and installed in order to monitor and control the Cryogenic System and the Ar and N₂ flows.
- A specific maintenance/monitoring plan for pumps, filters, mass flow controllers, sensors, rupture disks and valves has been defined.
- A pressure comparison measuring system has been actuated between pressure transmitters and indicators.

In Table 2, we summarize the QRA results in term of probability.

Table 2: Summary of QRA Results

Top Events		Probability (ev/year)*
A	Cryostat (DAR) overheating/overpressure	$<10^{-7}$
B	DarkSide 50 overheating/overpressure	$<10^{-7}$
Other Events		Probability (ev/year)*
C	Argon direct release	$5.4e^{-1}$
D	Water release in Hall C	$8e^{-2}$
E	Nitrogen direct release	$3.7e^{-1}$
F	Liquid Scintillator direct release in Hall C	$3.4e^{-1}$

The events listed are evaluated and reported in the LNGS Acceptable Matrix, which defines the following categories: N=Unacceptable, T=Tolerable and A=Acceptable.

We created this matrix by taking into account the following 2 parameters:

- Frequency: in terms of event frequency of occurrence (ev/year or ev/hour).
- Consequence: in terms of effects on human health and safety. Consequences have been estimated on a quality level therefore a more precise consequence evaluations could be assessed in order to have more accurate results.

Table 3: Acceptable Matrix

Consequence ----- Frequency	Lethal / Irreversible Effects	Major Effects	Serious Effects	Minor Effects	No Relevant Effects
Frequent >1 ev/year < 1.1 e ⁻⁴ ev/hour					
Probable e ⁻¹ – 1 ev/year 1.1e ⁻⁴ – 5.7e ⁻⁶ ev/hour				Event C Event E Event F	
Occasional 3e ⁻² – e ⁻¹ ev/year 5.7e ⁻⁶ – 2.8e ⁻⁶ ev/hour					Event D
Remote 3e ⁻³ – 3e ⁻² ev/year 2.8e ⁻⁷ – 2.8e ⁻⁶ ev/hour					
Improbable 3e ⁻⁴ – 3e ⁻³ ev/year 2.8e ⁻⁷ – 2.8e ⁻⁶ ev/hour					
Extremely Improbable <3e ⁻⁴ ev/year <5.7e ⁻⁸ ev/hour	TE A TE B				

It is important to emphasize that we adopted the same conservative approach for all Top Events and for Events (C, E and F); we placed them in the Tolerable Area, the first one, for their frequency of occurrences which are much lower than credibility threshold (10^{-8} ev/year), and the second one, in terms of their potential effects on human safety which are much less dangerous, therefore the associated risks could be considered almost Acceptable (A).

In conclusion, the assessment altogether represents, from the point of view of the approach and modality to face the analysis, a relevant reference for the Risk Analysis in the application of the low background Experimental Apparatus of DarkSide 50 in the LNGS Underground Lab. Moreover, the results and the technological solutions emerged from the above analysis are extremely interesting and very useful for this application.

Acknowledgements

We would like to acknowledge all the personnel of the DarkSide 50 Collaboration. Thanks to those without whom the Experiment would be impossible, and in special way, to the DS50 Engineer Operative Group and to the Nier Ingegneria for the huge activities and efforts achieved during the 2 years it took in order to carry out the Risk Analysis on which this paper is based.

References

- [1] DarkSide 50 Collaboration. “*DS-50 NSF PNA Nov 2012*”, Proposal Experimental Collaboration (2012).
- [2] LNGS. “*Rapporto di Sicurezza*”, 2011.
- [3] DarkSide 50 Collaboration and Nier Ingegneria. “*FMECA DarkSide 50 rev.2 FINAL*”, Preliminary Risk Analysis (2012).
- [4] DarkSide 50 Collaboration and Nier Ingegneria. “*DarkSide 50 QRA rev.2*”, Quantitative Risk Analysis (2013).
- [5] RIAC. “*NPRD – Nonelectronic Parts Reliability Data*”, (2011).
- [6] D. Swain, H.E. Guttman, “*Handbook of human reliability analysis with emphasis on nuclear power plant applications*”, NUREG/CR-1278, U.S. Nuclear Regulatory Commission, Washington, DC (1983).
- [7] G. Mulé, “*Guida alla scelta e dimensionamento delle valvole di sicurezza e dei dischi di rottura*”, AIDIC Servizi S.r.l., ISBN 88-900775-6-5. First-edition 2005.