SIMULATIONS OF LIQUID ARGON ACCIDENTS IN THE ATLAS CAVERN

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ABSTRACT

ATLAS is a high energy physics detector for the Large Hadron Collider (LHC) at CERN. It is located in a cavern 100m underground and uses Liquid Argon in one of its sub-detectors. We simulated accidental spillage scenarios with a Finite-Volume Element code, Star-CD, in order to evaluate the consequences. We used a 2D model using 100% of flash-evaporation to carry out a sensitivity analysis on the main parameters, which revealed the most critical factors regarding temperature and argon distributions. A series of Liquid Argon tests were performed in a 250m^3 enclosed space. Experimental and simulation results corroborated each other with regards to Argon concentration but not for temperature. The latent heat of liquid evaporation had to be taken into account. After carrying out a computing time consuming droplet simulation, we implemented a model with energy sinks extracting the latent heat of evaporation, which gave good results with a flash-evaporation of 82%. We eventually renormalized the full ATLAS model and could confidently evaluate the critical leak rates vs. evacuation time.

THE ATLAS EXPERIMENT

ATLAS will be one of the four high energy physics detectors for the new Large Hadron Collider (LHC) at CERN. It is located in a cavern 100m underground and uses a Liquid Argon calorimeter: 45m^3 of argon will be stored in the barrel and 19m^3 in each of the two end-caps. These baths will be cooled via liquid nitrogen heat exchangers to balance the heat leaks.The general layout is shown in figure 1.

The cavern will be air conditioned using a low velocity air displacement system. Supply air will be blown by 12 large diffusers located at floor level and a bypass coming from the technical cavern. It will be returned via a ceiling plenum and a pit extraction system designed to avoid the creation of a confined space under the detector. The flow rate of the ventilation can be doubled in exceptional conditions such as an accident.

The heat load dissipated in the cavern will reach 180kW, mainly released by the electronics in the detectors, the associated acquisition racks and cables.

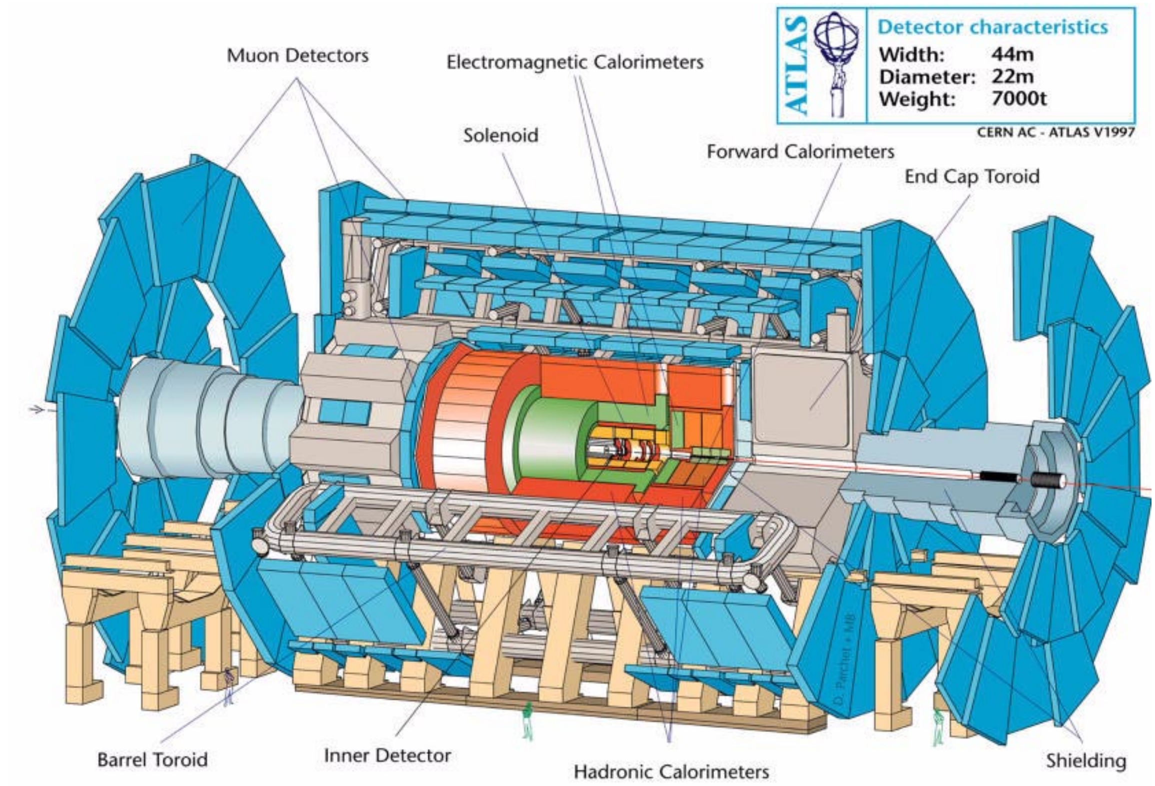

Figure 1. View of the ATLAS Cavern

The main goal of this study was to estimate the evacuation time vs. the argon leak rate and its consequences using an iterative process. First, the dispersion of argon during a leak was estimated using a finite element computer code. Secondly, an experiment was carried out and the measurements where compared with the simulation. Finally, renormalization factors where calculated and eventually introduced in the ATLAS model to perform the final simulations.

SIMULATIONS

Modelling using StarCD

StarCD uses a finite volume method which is a well-established, thoroughly validated general purpose technique. It supports turbulence and laminar models, steady state and transient regimes, buoyancy, lagrangian and newtonian models, and combines conduction, convection, radiation.

Due to the complexity of the geometry of the cavern and the limited computational power it was decided to implement a two dimensional model representing the most critical cross-section of the cavern. All boundary parameters were averaged over the cavern s length. The supply air rate is 60000 m^3/h from the diffusers and 16000 m^3/h from the technical cavern bypass. Exhaust rate is 60000 m^3/h from the plenum and 16000 m^3/h from the argon retention pit. The total heat load is 180 kW, the walls of the cavern are modelled isothermal.

A PISO algorithm in transient regime was used [1]. The temporal discretisation was Fully Implicit to get a stable scheme. A low-order spatial scheme, Upwind differencing

(UD) was used for all magnitudes except for density, which was using a high-order scheme, Central Differencing (CD) with a blending factor to avoid numerical dispersion. An under-relaxation factor of 0,8 for pressure was used to help convergence, which could only be obtained with very small time steps (~0.01s) due to a large temperature gradient near the spill point and a compressible turbulent fluid modelization.The number of PISO correctors, the maximum and mean Courant numbers and the total heat balance in the cavern (HDIFF) were always kept into the recommended limits.

Sensitivity analysis on the flow rate and on the main parameters of the model

A maximum evacuation time of 2.5 minutes was calculated taking into account walking distances from any part of the cavern to the nearest safe zone. By performing a sensitivity study, the associated argon flow was found to be around 18 l LAr/s. Larger spills would quickly create dangerous conditions, preventing people from escaping safely. On the other hand, flows below 4 l LAr/s are completely absorbed by the pit extraction.

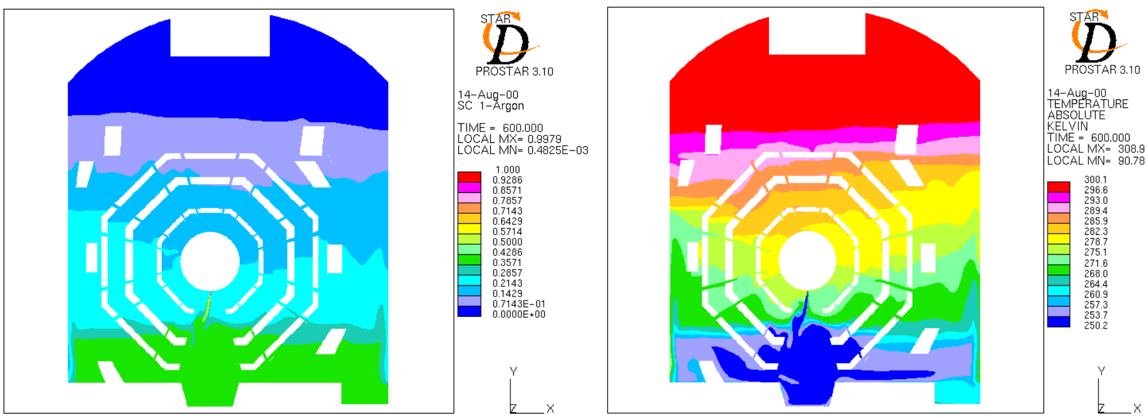

Figure 2. Argon Concentration in Mass and Temperature after 5 min. of 18l/s Leak

The sensitivity study on the main parameters of the model showed that neither the variation of the ventilation flow rate nor the heat load were influencing significantly the temperature or argon concentration distribution. The hypothesis of isothermal wall is not critical. This study also demonstrated that a High-Reynolds model is suitable, even though the mesh is so refined near some walls that we should have implemented in these regions a Low-Reynolds model. The UD spatial differencing for speed, temperature and turbulence parameters is an appropriate and stable scheme.

The comparison between simulations of an open detector where the bottom muon chambers are removed for maintenance and a closed detector scenario demonstrate that the pit extraction is favoured in the first configuration. In an open detector scenario the argon pit plays an important role in avoiding the argon to spread, specially for small leaks.

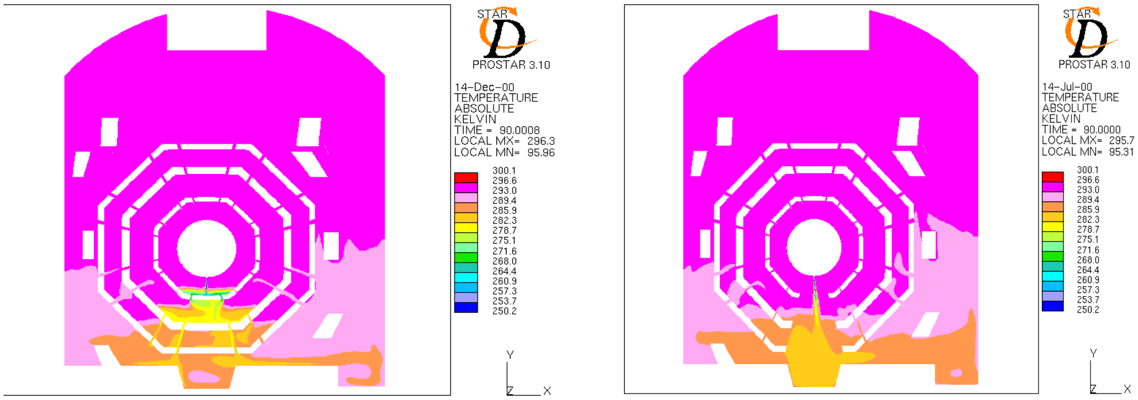

Figure 3. Small Leak Comparison in Open and Closed Detector Scenarios

ARGON SPILL TESTS

Experiment setup

In order to validate or renormalize the ATLAS model, a series of liquid argon spill tests were conducted in a zone specially set up at CERN (building 180) during the summer of 2000. The spills of argon, ranging from 4 l LAr/min. to 50 l LAr/min. took place in an area delimited by concrete blocks of 9,6 x 4,8 x 4,8 m as seen in the following photographs.

Figure 4. General layout of the experiment and spill point during a 50 l LAr/min. leak

The experiment reproduces the main characteristics found in ATLAS: the ventilation was supplied via two lateral fans (3.200 m^3/h) fitted with low air velocity diffusers, and a pit extraction fan (1.000 m^3/h). The heat load due to the electronic racks and muon chambers in ATLAS was simulated by two electric heaters (1.200 W each).

Twelve zirconia oxygen sensors and sixteen thermocouples type J were distributed within the volume to monitor temperature and oxygen concentration, while the data acquisition was done with LabVIEW.

Observations

These tests provided us with a lot of valuable data and allowed us to gain insight into the behavior of liquid argon when released from a pressurized dewar into the ambience. Since we tested a wide range of flows, we had the physical appreciation for both catastrophic and very small leaks. Several tests were also carried out without ventilation to put into evidence stratification.

For large leaks, a small pool of liquid argon formed in the pit. This pointed out the existence of a two-phase flow, even though a large amount of liquid is evaporated in the dewar valve (flash-evaporation), and the insulated line.

In all tests we observed that the air temperature dropped rapidly below the dew point generating a dense fog in the room, even though the ventilation was playing an important role in its evacuation.

Modeling of the experiment

The experiment was modeled using StarCD with the same set of hypothesis as for the ATLAS cavern. In order to evaluate the importance of the 3D effect of the fluid motion along the pit, both a 2D and a 3D model were implemented, showing slight differences.

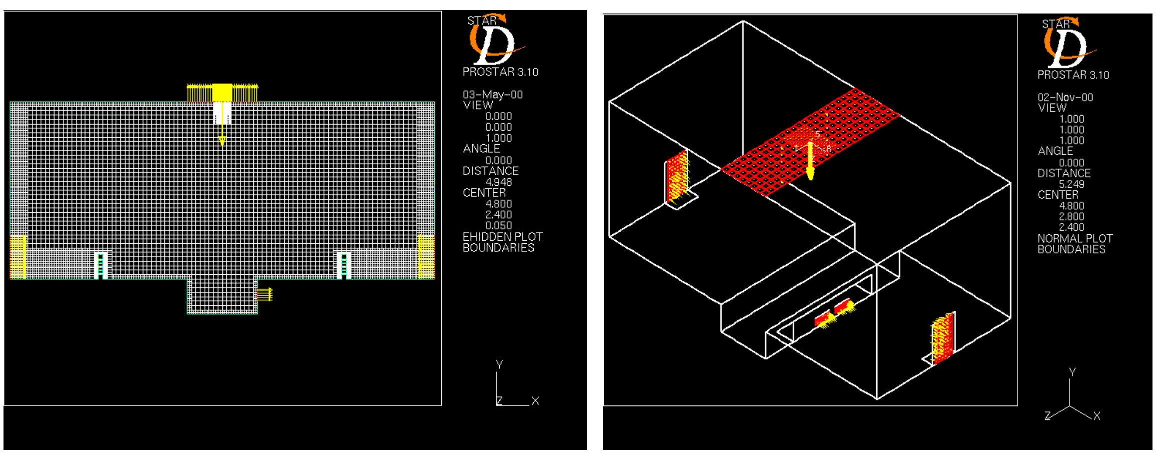

Figure 5. Two-dimensional and three dimensional experiment models

Comparison between simulations and experimental results

The results pointed out that the simulated and experimental argon concentration distributions do not differ significantly as shown in the following graphs. Deviations from experimental results were within the error of sensor (– 1% O_2 in volume) except near the pit where they reached 2,7% O_2. Therefore we can conclude that the model is predicting accurately the argon concentration distributions.

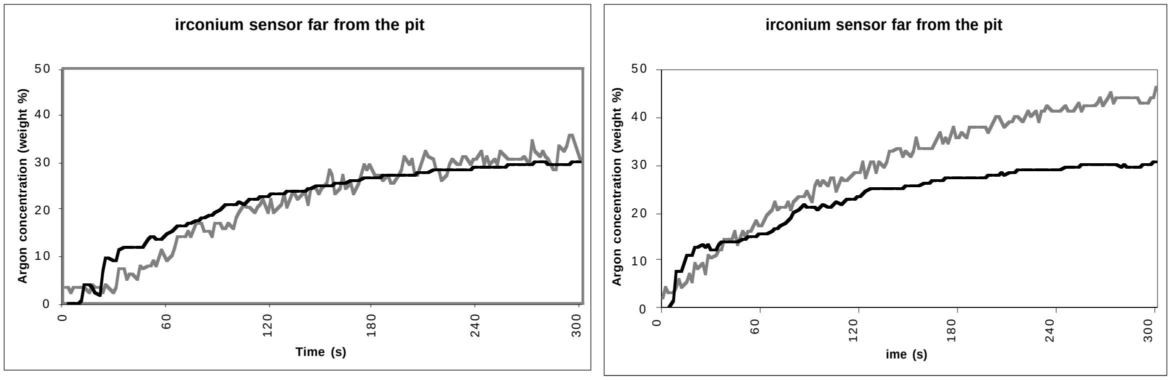

Figure 6. Argon Concentration Evolution for Zirconia Sensors Close and Far from the pit

However, the temperatures for the experiment and simulation were not in good agreement. For small leaks the differences were ranging from 5 ¡C near the walls to 20 ¡C close to the pit reaching for large leaks 10 ¡C and 60 ¡C respectively. The measured temperatures were always lower than the estimated ones. These large differences near the pit combined with the experimental evidence of a LAr pool, lead us to think that we should modify our hypothesis of a one-phase flow (100% of flash evaporation at the outlet) and implement a two-phase flow model where the effects of the change of phase were taken into account.

New models

Since evaporation in free surfaces is not supported by StarCD, a dynamic model with a disperse phase of droplets of liquid argon within a continuous phase of argon gas (consequence of flash evaporation due to the pressure difference between the dewar and ambience) was the best modeling approach [2]. The implementation of this Lagrangian model within StarCD was very complex (droplet diameter, speed of liquid and gas phases, wall impingement, etc.) and computing-time consuming due to the small time steps needed for convergence of the coupled equations (heat, mass and momentum transfer). A sensitivity study on the diameter of the droplet, the key parameter of this model, was impossible to envisage.

We therefore decided to implement a one-phase flow model with distributed energy sinks, extracting the equivalent latent heat of evaporation of the liquid phase entering the domain. The energy sinks were distributed along a cone with its vertex on the spill point and its basis on the pit. This way we were assuming that more liquid is evaporated near the pit, which was in agreement with our experiment. This approximated model predicted very well both the temperature and argon concentration distributions. However, the flash-evaporation ratio of 85% had to be adjusted by doing a sensitivity analysis. We used for this purpose a simplified model with a constant negative flux boundary along the symmetry axis. By reducing the number of elements by half we tuned the flash-evaporation ratio very quickly. A value of 85% gave good results for the whole range of flows that had been tested (4 l LAr/min. to 50 l LAr/min.).

The benefits of the new model are clearly shown on the graphs below. The temperature plot vs. time for the two locations show a significant improvement of the one-phase flow model with distributed sinks of energy (grey) compared to the one-phase flow model with 100% of flash evaporation (black). For sensors located far from the pit curves are superimposed, and there is a significant improvement near the pit.

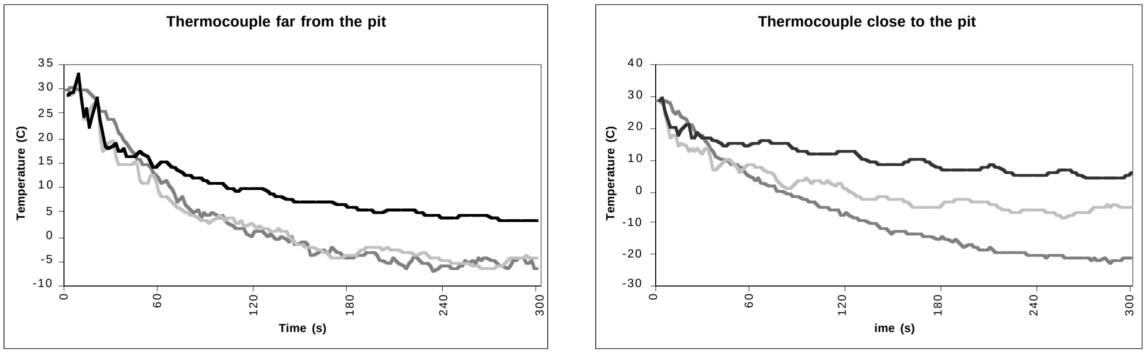

Figure 7. Temperature evolution for new model compared to old one and measured data

This new evaporation model was implemented on the full ATLAS cavern, keeping in mind that temperature in the retention pit might be lower in reality.

Renormalisation of the ATLAS model

Since we could not perform all simulations again, we chose to implement the model for a limited number of leak rates: the largest flow of the real test, a similar flow (proportional to the section of the cavern vs. the experiment, ratio of 20), the critical flow (evacuation time of 2.5 min.), and finally a catastrophic situation (extrapolated).

As expected, the renormalization of the ATLAS model has a significant influence on the temperature distribution. Even though these temperatures should be very accurate in most locations, we still have to be careful when it comes to interpreting the results in the retention pit. The argon concentration do not differ from the One-Phase flow model which gave good predictions.

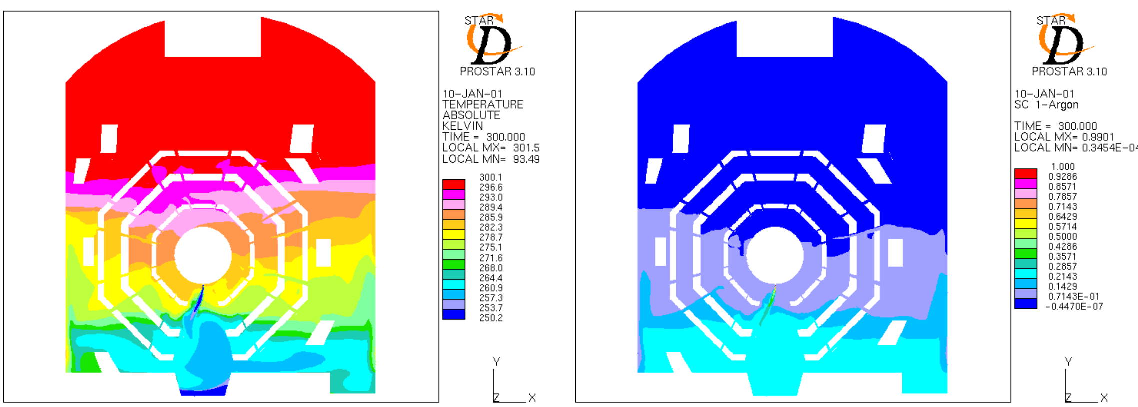

Figure 8. Temperature and Argon Concentration Renormalized for a 18l/s Argon Leak

These last simulations showed that a catastrophic leak in the test room has almost no consequences in the ATLAS cavern. Five minutes after the accident, temperatures in most locations are above the dew point meaning that fog presence would be limited to the vicinity of the leak.

A leak of 10 l LAr/s which would be *similar* to an intermediate flow in the experiment would not be catastrophic. People could escape easily providing a good evacuation plan is implemented.

During the experiment, we intuitively acquired the certitude that a catastrophic flow in the ATLAS cavern such as the full rupture of a double wall feedthrough (13 cm diameter) is not realistic.

CONCLUSIONS

The main result of this study was the validation of the ventilation scheme and the evaluation of the argon leak rate vs. the evacuation time. The experts estimate that two and a half minutes is the maximum evacuation time to reach the safe zones, which according to our simulations corresponds to a LAr leak rate of 18 l/s. Spills of less than 4 l/s are completely absorbed by the pit extraction fan.

The simulation confirmed that the phenomenon is driven essentially by strong buoyancy forces due to the nature of the gases: warm air and very cold argon gas. The ventilation system was designed from the beginning to enhance natural convection by helping heat removal and evacuating cold argon gas from a pit located directly under the detector.

One of the great benefits of the argon leak test was to provide us with a large amounts of valuable data and to give us a better feeling of what could happen in the event of a leak. It validated the model for argon concentration but raised the problem of temperature discrepancies in the pit. The implementation of an evaporation model using droplets being too computer intensive, we used the energy sinks method which proved to be simple and accurate. It corrected the temperature distribution perfectly in the whole domain except in some zones of the pit. The renormalisation of the full ATLAS model allowed us to perform the final simulations with good confidence in the results.

These simulations put into a new perspective the problem of an accident in the ATLAS cavern. Asphyxiation which was intuitively considered as the main problem was found to be less problematic than low temperatures and the formation of mist. The experiment let us observe that after just a few second the visibility was impaired, that the temperatures were dropping very quickly, and that the air/argon mixture would not drop as fast as expected while the ventilation was on.

This study also demonstrated that computer fluid dynamic codes need experience, a good intuition in order to guaranty the results and computing power.

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REFERENCES

1. F. Balda, M. Vadon, *Simulation of accident scenarios in the ATLAS experimental cavern, a safety analysis*, CERN-TIS/2000-009/GS, (June 2000).
2. B. Perea Solano, M. Vadon, *Simulations of Liquid Argon Spills in the ATLAS Cavern,* CERN - TIS/2001 - 03/GS
3. *Star-CD, Methodology and User Guide*, Computational Dynamics (1999).
4. M.A. Aamir, A.P. Watkins, UMIST, Manchester, *Numerical analysis of depressurisation of highly pressurised liquid propane,* International Journal of Heat and Fluid Flow, 21 (2000).