A new fire compartment system in tunnel. – The case of the Gran Sasso National Laboratory.

A. Basti
INFN – National Laboratory of Gran Sasso (Operation and Maintenance Service)

D. Franciotti – G. Bucciarelli – G. Panella
INFN – National Laboratory of Gran Sasso (Operation and Maintenance Service)

ABSTRACT: The Gran Sasso National Laboratory (LNGS) of the National Institute for Nuclear Physics (INFN), is located in Abruzzo region (central Italy). It is the largest underground laboratory in the world for experiments in particle and nuclear astrophysics. It has been built under approximately 1400 meters rock. It is located between L'Aquila and Teramo. The underground facilities are located alongside the 10 km long highway tunnel (A24) crossing the Gran Sasso Mountain.
The following article aims at proving the effectiveness of the 'NIAGARA' fire fighting compartments system: Niagara system has been realized by LNGS staff to protect the three accesses of the Laboratory from the A24 tunnel (direction Teramo – L'Aquila).

1. GENERAL INFORMATION ON THE GRAN SASSO NATIONAL LABORATORY.

The Gran Sasso National Laboratory (LNGS) is an underground laboratory. It is located under the mountain of Gran Sasso (Italy), alongside one the 2 fornices constituting the Gran Sasso highway tunnel (Fig.1).

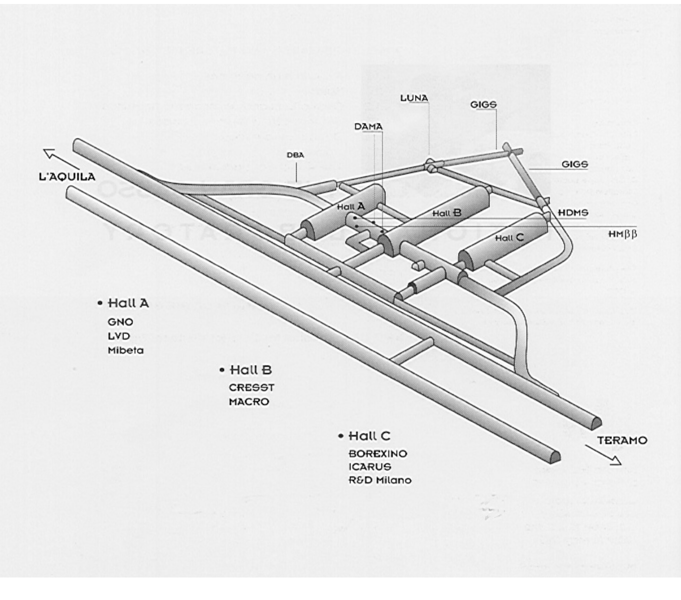

Fig 1: View of LNGS Laboratory

It consists of three experimental halls, simply (A, B, and C) and a series of connecting tunnels and service areas. The three experimental halls are more than 100 m long and about 18 m high and wide, enclosing a total volume that is about 25,000 m each. Moreover, around the Laboratory there is an aqueduct that feeds nearby towns.

The experiments inside the laboratory range over astrophysics of elementary particles and rare decays; over dark matter research and solar neutrino research. The reason why the laboratory was built inside a mountain is that 1400 meters of rock are a perfect filter to screen huge number of particles that hit the land surface; these particles are produced by the interaction of cosmic primary rays with the atmosphere's atoms. Muons (particles with positive charge and mass 200 times that of electrons) and neutrinos are the particles that are able to cross this filter. Solar and stellar neutrinos are studied in the Laboratory of Gran Sasso.

2. CRITICAL LOCATION OF LNGS INSIDE THE A24 HIGHWAY TUNNEL .

It is possible to access the Gran Sasso National Laboratory only from the A24 highway tunnel, through three connection tunnels (two of them – 30 meters long – are carriageable, one is 10 meters long and it is for pedestrians only). In these particular conditions, fire spread inside the highway tunnel could involve the Laboratory, diffusing combustion products and thermal irradiation.

In case of fire, the present solution, according to the Emergency Plan (approved by LNGS, Authority of highway tunnel - Strada dei Parchi S.p.a.-, Fire Brigades of L'Aquila and Governmental offices of Teramo and L'Aquila - Prefetture), provides for a separation between LNGS and highway tunnel by means of fire resistant compartments. On the existing fire proof doors, that separate highway from LNGS, a cooling plant is activated. The plant, named 'Niagara', should guarantee structural resistance (R), smoke seals (E) and heat insulation (I) of the door (REI), till fire is extinguished and all people evacuated.

The mentioned requirements are not easy to meet, considering high temperature and difficulty in removing hot smoke.

3. “NIAGARA” – GENERAL DESCRIPTION OF THE PLANT.

“Niagara” system, as already said, is placed by the three entrances. The following description is going to consider the plant placed close to the carriageable entrance of the underground laboratory, because, considering its position, this plant could be less efficient in case of fire in the highway tunnel. Cooling plant (“Niagara”) consists of a pipeline 1 cm thick and DN 100 diameter. The pipe is covered by heat insulator material 10 cm thick and contained in an aluminium sheet (Fig.2).

The plant is similar to the letter U upside down and it is located 3 m far from the door to be protected. Its dimensions are:

- Inner width: 5,10 m.
- Inner high 4,60 m.
- Total diameter (pipe + heat insulator material and aluminium sheet) 0,30 m.

On that pipeline, 7 nozzles have been placed:

- Three on the architrave.
- One at 1,6 m from the floor on each pier (total: 2 nozzles).
- One on the basement of each pier (total: 2 nozzles).

The above-mentioned nozzles have been oriented in order to distribute uniformly a film of water on the door of the laboratory. Even if, the door without Niagara, should resist fire for 120 minutes, according to the tests made simulating a ISO 834 fire curve, however, we have to consider that the ISO 834 fire curve is less conservative than the typical fire curve in a tunnel.

At the beginning, the nozzles installed on “Niagara” were:

- five (three on the architrave and two on piers at 1,6 m high from the floor) cone adjustable nozzles made of stainless steel AISI 316 diameter ¾” and 190 litres/min. flow rate at 4 bars (165 litres/min at 3 bars).
- Two fan nozzles at the base of the piers, made of stainless steel AISI 316 diameter ½” and 35 litres/min flow rate at 4 bars.

The two nozzles installed in the lower part, turned towards the highway, have the dual function of cooling the foundation and clearing the water column that tends to accumulate in the piers up to 1.6 meters in height and tends gradually, in case of fire, to warm bringing water at a temperature close to the transition state before the release on the door.

It is easy to understand that the above-mentioned water heating would reduce the effectiveness of the cooling system and it would lead to the structural collapse of "Niagara". Nozzles form, through the provision of water at a pressure of 4 bars, a film of water to protect the door, ensure scrubbing and cooling of hot fumes and prevent the passage of the fumes in the Laboratory. Moreover, nozzles are placed at a distance from the door to ensure, through the evaporation of water, an effective screen to radiation heat caused by fire.

Fig 2: “Niagara”

"Niagara" system uses water dripping on rock (100 litres/sec). The water adduction for the nozzles is via two pipes that pass through a reinforced concrete wall about 50 cm thick. Wall and door separate laboratory from the highway. In the Laboratory, water is pressurized to 8 bars, by a group of 4 fire pumps, 1,500 litres per minute each, using a 8" pipe. The four pumps can be operated manually or through the detection of 9 temperature sensors placed on the external face of the door. These sensors open the circuit when the temperature rises from about 14° C (constant temperature of the rock during the year) to 50 °C, or by the sudden temperature increase of 2 °C per minute.

The pumps that pressurize the system are electrically powered, in medium voltage by a redundant system and by a local and general diesel generator. On the water supply main circuit that serves "Niagara", a pressure reducer calibrated at 4 bars has been installed. The excess of water is collected by grids interposed between "Niagara" and highway. Collected water is discharged into the drain, to avoid, in case of accidental ignition of the system or during some tests, that water could flow into the highway causing sliding of cars.

4. SIMULATIONS WITH CFD SOFTWARE: DESCRIPTION OF THE MODEL.

Overview on the CFD calculation.

NIST's Fire Dynamics Simulator (McGrattan et al. 2001a, b) predicts smoke and/or air flow movement caused by fire, wind, ventilation systems and other sources of momentum. A post-processor called Smokeview can be used to visualize the predictions generated by NIST FDS (McGrattan & Forney 2001c).

FDS solves a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flows of smoke and hot gases generated in a fire. FDS was developed to specifically address fire-hazard scenarios.

Smokeview visualizes FDS computed data by animating time dependent particle flow, 2D slice contours and surface boundary contours. Data at a particular time may also be visualized using 2D or 3D contour plots or vector plots.

Modelling of the geometry in FDS.

The area that is relevant for the simulation of computational calculation on "Niagara" is limited to the tunnel access to the underground Laboratory and a stretch of highway tunnel of about 60 meters that forms a Y with the previous section. As already mentioned, fire is assumed in the Y area in the highway tunnel, while "Niagara" is placed at the end of the access tunnel to the Laboratory. Therefore, we have analyzed the volume with two different types of mesh. A larger type of mesh, consisting of cubic cells with side dimension of 100 cm, has been used in highway tunnel and access tunnel to the laboratory in order to simulate the fluid dynamic phenomena on a large scale omitting those located, not of interest for our purposes. Since, in the area where Niagara is, we are interested in localized fluid dynamic phenomena and also to determine the possible vaporization of the water that is made up of "droplets" of the average size of about 0.1 mm, we use a denser mesh that is compatible with the larger one. The program is not able to assess, without numerical instability, in a volume where there are two different types of mesh where the smaller size is less than 1/5 of the larger mesh. For this reason we have decided to use a mesh of side 20 cm, to simulate the localized effects on "Niagara". The value of the mesh size of 100 cm has been calculated as follows: the simulation was carried out on a three-dimensional domain of calculation. To implement a simulation, it is necessary to define the average size of the cell discretization (computational grid): that's why it is important to point out that this dimension is linked to an important parameter which indicates the correct resolution of the grid, that is, the characteristic diameter of fire, given by the following relation:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{\frac{2}{5}}$$

D* : characteristic diameter of fire;
Q : heat release total rate, kW;
ρ_∞ : density at room temperature, kg/m^3;
c_p : specific heat of gas, kJ/kg°K;
T_∞: room temperature, °K

Place T=283 °K , ρ_∞=1.2 kg/m^3 e c_p=1.0 kJ/kg°K e Q = 200.000 kW it results D* =8.12m.

Therefore, it is assumed an average size of the discretization at δ≅10% D*≅80cm.

What has been noticed, together with a contextual analysis of relationship with the densest grid on "Niagara", allow to assume an average size of the cell of discretization equal to 100cm, except for the use of smaller cells. This is considered a good compromise between computational resources and targets to be achieved.
Considering cells larger than 100 cm and cells smaller than 20cm, the total amount of cells that form the domain of simulation is equal to about 85,600 cells (Fig.3).

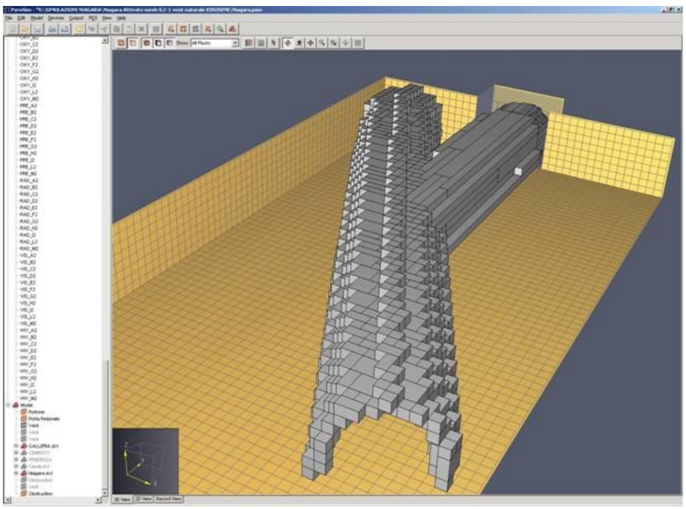

Fig 3: Model divided into cells

To model materials that form the tunnel, it was used a system consisting of completely adiabatic materials. This assumption is in favour of safety. In fact, inside the tunnel, temperature and speed of fumes will give a faster response, under the same conditions occurred during the fire, compared to a covering composed of materials that absorb heat and have a certain thermal inertia. Ventilation inside the tunnel is considered to be 2 m/s on the "VENT" input and to be an "OPEN VENT in output**.** Thus, we tried to simulate the natural ventilation inside the highway tunnel (natural ventilation caused by barometric depression that is created to the two opposites of the tunnel and by the highway traffic).
To simulate the fire, a radiating surface of 6m X 6m = 36 m^2 has been placed, in correspondence of the intersection between access and highway tunnel. The surface produces energy according to a curve HRR of a fire of HGV in a tunnel, inferred from data obtained in the literature and on experimental basis. The peak power of this curve is 220 MW (Fig.4).The maximum energy emitted by the surface unit in square meters is 6111 Kw/m^2 (HRRUA).

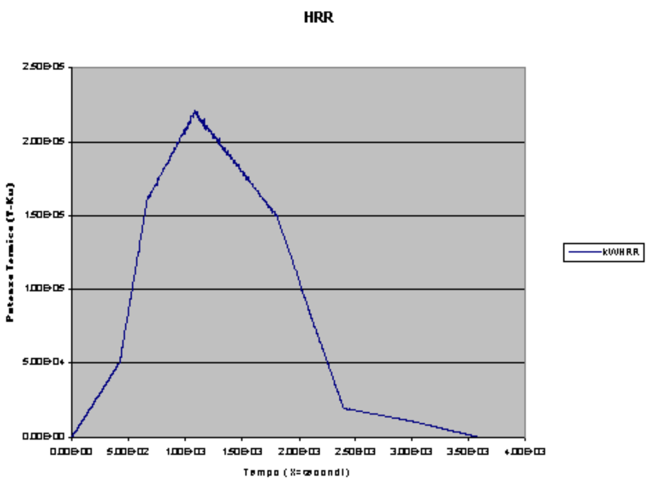

Fig 4: HRR fire curve of HGV in the tunnel

Combustion was simulated by imagining that the burnt material was made up of kerosene (material currently present in tunnel for example in the form of asphalt). In the model, inside the tunnel that access the laboratory, a row of probes has been inserted every 5 meters in plant, and for each row, a probe in every meter up to the keystone of the tunnel. The mentioned probes have provided data on the temperature of the gas, oxygen, carbon monoxide, carbon dioxide, nitrogen, hydrogen, pressure, water vapor and radiant energy, in order to monitor environmental conditions every moment. Two rows of the same probes have been inserted in the highway tunnel and, to be precise, before and after fire.

4.3 Analysis of results

The simulation of fire lasted for 3600 seconds, i.e. for the duration of the hypothetical fire. It produced good results with regard to the containment of the maximum temperature reached on the door: 227 °C 1190 seconds from the beginning of fire. (Fig.5).
Below, the diagrams of output produced by FDS.

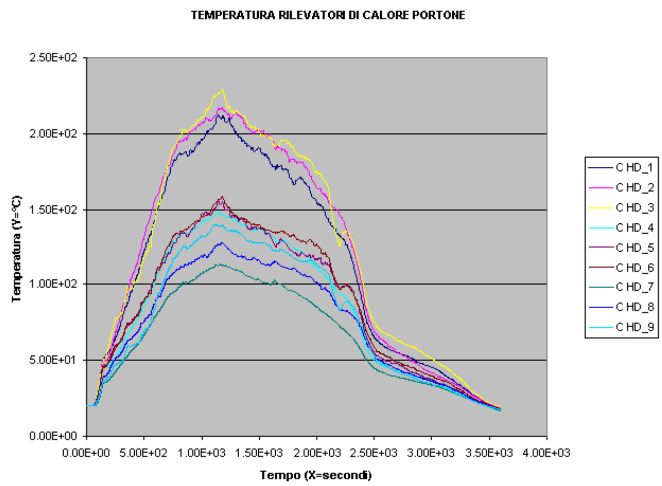

Fig 5: Temperature probes on the fire fighting door

5. SUGGESTED IMPROVEMENTS

After the first analysis of the model the authors have realized that the temperature on the fire door exceeded 100 °C (temperature of vaporization of water), since the film of water was not complete. In the parts of the door not covered by the film, temperature could have suffered sudden rise, loosing the REI requirements of the door.

In particular, from the water cooling diagram on the door, it was possible to notice that the cooling effect was lower in the central area than on the sides, even if temperature of the central part of the door was not higher than on the rest of the door.

This phenomenon has induced the authors to hypothesize a fumes flow from the central part of the door, directed towards the highway tunnel. Such smokes generated areas of overpressure on the door, so that water delivered by the nozzles with a speed of 13.5 m/s, a pressure of 4 bars and a flow rate of 233 litres/min could not have enough strength to reach the surface of the door. It could not overcome the overpressure and therefore it could not form a film of a few mm of water during the fire.

This problem has been solved by inserting, on the top of the door, two additional nozzles with an opening angle less than the others and with a greater efflux speed. Alternated to the three already installed, these two nozzles enabled to overcome the pressure

created on the door following the vaporization of water.
The system is now able to provide a film of water of a few mm on the door for the duration of the fire by ensuring a REI requirement as long as water is available. In the following simulation, all nozzles have been tilted 15° upward in order to optimize water delivered to the door. This solution is also easy to put in practice..
Added nozzles have been tilted 10° upward.
On the above mentioned door, the flow rates have been increased not to exceed 100 litres/s, considering also the flow rate required to cool the other two doors. Indeed, water available in the laboratory is water dripping on rock with a flow rate equal to that previously mentioned, not to exceed (100 litres/s). Below, the position in which the two nozzles will be installed (type BTF3195XX steel AISI 316 (Fig.6):

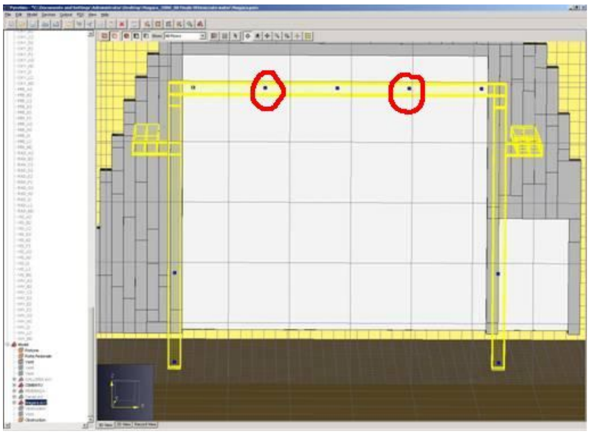

Fig 6: Position of the new nozzles

Based on the correlations between pressure and flow of the nozzles we have obtained the coefficient equal to:

$$\text{P=6 bar} \rightarrow Q = 272\ litres\ /\min$$

$$K = \frac{Q}{\sqrt{P}} \rightarrow 111 \frac{litres}{\min bar^{\frac{1}{2}}}$$

Knowing flow and section of the nozzle we easily get the water outflow speed:

$$V = \frac{Q}{S} = \frac{4.53*10^{-3}}{6.75*10^{-3}*6.75*10^{-3}*3.14} \rightarrow 32\frac{m}{s}$$

The simulation has been made again modelling and adding in FDS the two new nozzles. This time, the temperature of probes installed on the fire door did never exceed 100 °C (Fig.7), ensuring a persisting film of water on the fire door and an unlimited REI requirement.

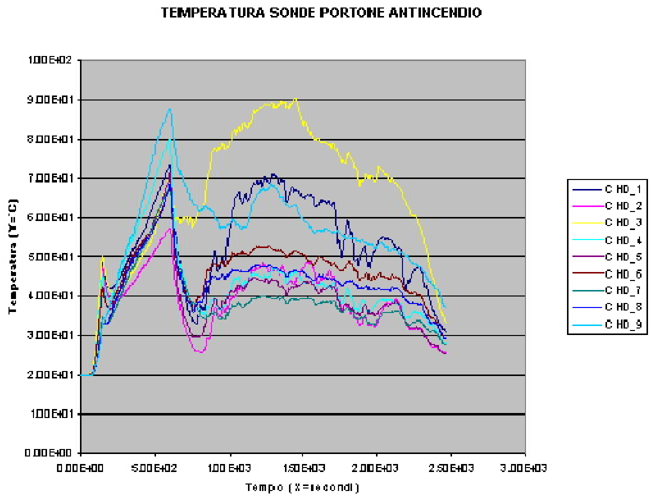

Fig 7: Temperature probes on the fire fighting door

6 COMPARISON BETWEEN THE SYSTEM WITH AND WITHOUT "NIAGARA".

In order to test again the efficiency of Niagara, another simulation with the plant switched off has been made. This is to compare the results with the ones obtained during the previous simulations.
In particular, the chart below shows how a fire can cause catastrophic effects (temperatures on the fire fighting door higher than 680 °C) without the activation of "Niagara". The system effectively reduces these effects, and most of all, it guarantees REI requirement of the door over time.

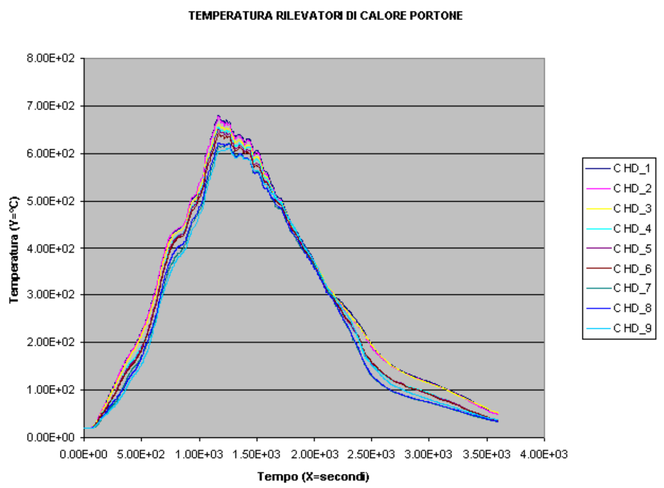

Fig 8: Temperature probes on the fire fighting door

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