FIRE SIMULATION, EVACUATION ANALYSIS AND PROPOSAL OF FIRE PROTECTION SYSTEMS INSIDE AN UNDERGROUND CAVERN

BY

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THESIS

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Dedicated to everybody who helped me in my educational and personal development.

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LIST OF ABBREVIATIONS

CERN = European Center for Nuclear Research

LEP = Large Electron Positron collider

LHC = Large Hadron Collider

CMS = Compact Muon Solenoid

ATLAS = A Toroidal LHC Apparatus

ALICE = A Large Ion Collider Experiment

CFD = Computational Fluid Dynamics

CZ = Control Zone

SZ = Service Zone

ST = Service Room

HFC = HydroFluoroCarbons

SUMMARY

The intent of this thesis is to perform, with the program FDS, a fire simulation inside the CERN USC55 underground cavern in order to evaluate the fire development in time. The data obtained from this analysis are used as input in an evacuation program, called BuildingEXODUS, to determine if the cavern exits are sufficient to guarantee the evacuation of the whole personnel. The combined results of the fire simulation and evacuation analysis are then analyzed in order to determine if, and where, specific fire extinguishing systems are needed.

1. INTRODUCTION

1.1 CERN

CERN is the European Laboratory for particle physics, the world's largest particle physics research centre. Founded in 1954, the Laboratory was one of Europe's first joint ventures, and has become an example of successful international collaboration. From the original 12 signatories of the CERN convention, membership has grown to the present 20 Member States[1] which provide the budget in proportion to their national revenues. The Laboratory sits astride the Franco-Swiss border west of Geneva at the foot of the Jura Mountains. Some 6500 scientists, half of the world's particle physicists, use CERN's facilities representing 500 universities and over 80 nationalities.

CERN's purpose is fundamental research in Nature's tiniest buildings blocks, the elementary particles, to find out how our world and universe work. The energy densities reached in head-on collisions of particles accelerated in special machines, called accelerators, approach those which may have prevailed immediately after the Big Bang, and are sufficient to create the elementary particles which populated the early universe. Detectors, built around the collision points, record the brief existence of these particles, re-enacting moments in the evolution of the early universe. Although CERN is dedicated to the fundamental research in particle physics, a wide range of different research areas and engineering tasks are inevitably in the construction of these installations.

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[1] Austria, Belgium, Bulgaria, Czech Republic, Denmark, Hungary, Germany, France, Finland, Greece, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland, and the United Kingdom

CERN's accelerator complex (see Figure 1) is the most versatile in the world and represents a considerable investment.

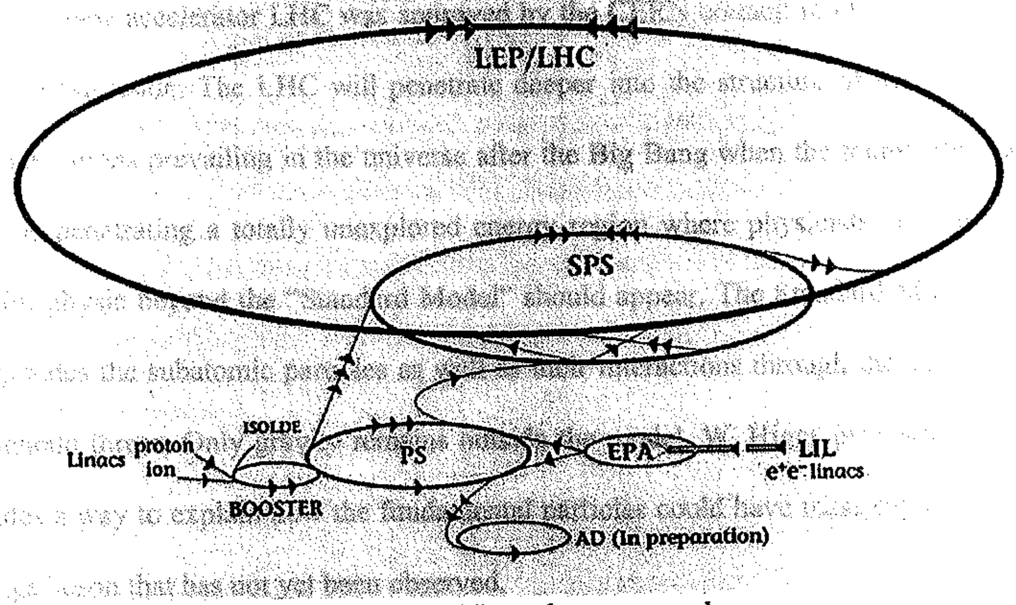

Figure 1. Schematic representation of the CERN accelerator complex.

It includes particle accelerators and colliders, which can handle beams of electrons, positrons, protons, antiprotons, and "heavy ions." Each type of particle is produced in a different way, but then passes trough a similar succession of acceleration stages, moving from one machine to another. The first steps are usually provided by linear accelerators, followed by larger circular machines. CERN has 10 accelerators altogether, the biggest was the Large Electron Positron collider (LEP) that is going to be replaced by a new one called Large Hadron Collider (LHC).

1.2 LHC

The new accelerator LHC was approved by the CERN council in December 1994 and is now under construction. The LHC will penetrate deeper into the structure of matter and will re-create the conditions prevailing in the universe after the Big Bang when the temperature was $10^{\wedge 32}$ K. It will be penetrating a totally unexplored energy region where physicists are convinced that evidence for physic beyond the "Standard Model" should appear. The Standard Model is a theory that incorporates the subatomic particles as well as their interactions through the strong, weak and electromagnetic forces. Only gravity remains outside the model. W. Higgs proposed a mechanism that provides a way to explain how the fundamental particles could have mass supposing a particle called Higgs boson that has not yet been observed.

LHC will accelerate particles close to the light speed that hit, in the collision points, other particles traveling in opposite direction. It will use powerful electromagnetic fields to push energy into the beam, to keep it tightly focused, and to steer the particles around the ring.

It will replace LEP using the same tunnel, which will minimize the construction work and costs. Like the LEP, the LHC will have eight long straight sections symmetrically distributed around the ring, available for experimental insertions or utilities (see Figure 2).

There are only four points where the beams pass from one ring to the other (particles bunches are running into two parallel beam pipes) and there will be placed the LHC experiments.

The two high-luminosity collision points are located at diametrically opposite straight sections, point 1 (ATLAS) and point 5 (CMS). Two more experimental collision points are located at point 2 (ALICE) and point 8 (LHC-B). These latter straight sections also contain the injection systems.

CMS, the Compact Muon Solenoid experiment, is an omni purpose experiment that will search for the origin of mass. It will help us to understand why some elementary particles have mass and others do not. ATLAS, A Toroidal LHC Apparatus experiment, is an omni purpose experiment that will compete with CMS, and the common main aim is to provide proof of the Higgs' particle existence which will complete the prediction of the Standard Model. ALICE, A Large Ion Collider Experiment, is a detector for heavy ion collision. Its main goal is to study matter as it would have been less than a millionth of second after the universe was born. LHC-B is a detector designed to study especially B-mesons.

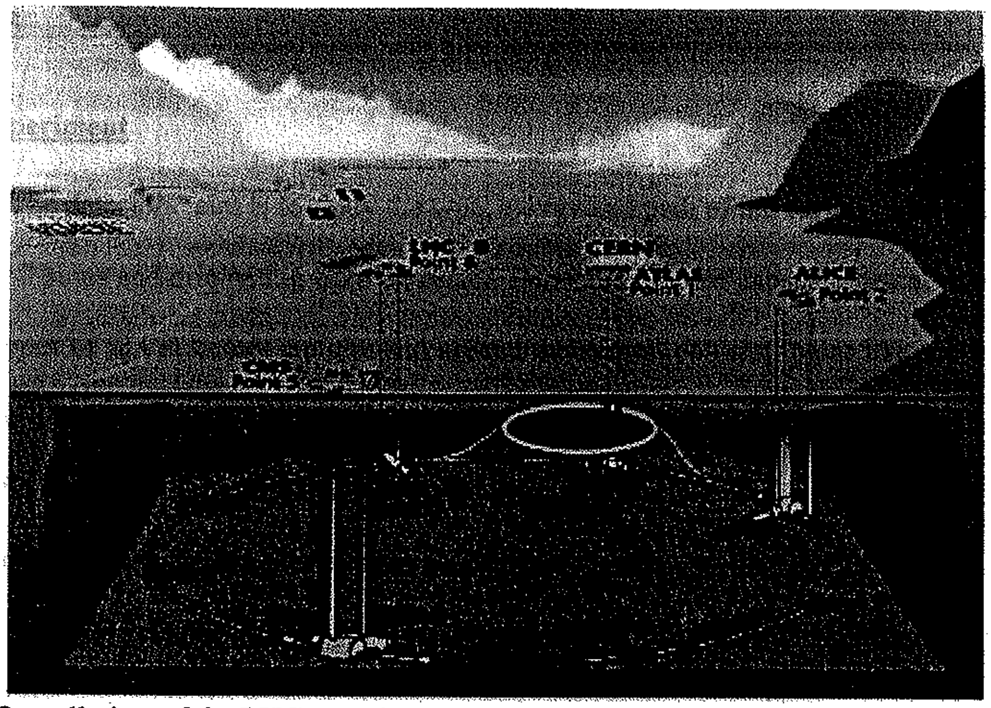

Figure 2. Overall view of the LHC experiments.

Insertions 3 and 7 each contain two beam collimation systems using only classical magnets. These insertions are designed to be robust against the inevitable beam loss on the primary collimators, and to keep the amount of new infrastructure needed to an absolute minimum.

The LHC experiments are being designed to look for theoretically predicted phenomena, however they must also be prepared as far as possible for unexpected events.

1.3 CMS

1.3.1 Experiment

The detectors' aim is to study the type, energy and path of the various particles generated by these collisions and originating from its center. Depending on the expected cascades of reactions different types of sub detectors are grouped around the central collision point like the layers of an onion. The detector machine can also simply be described as a solenoid that generates a strong magnetic field coaxial to the colliding beam, and by a great number of channels and sensors capable of transducing the passage of a particle into an electrical signal.

A single detector usually can't make measures of all the particle characteristics, but it is build up to measure, with the highest precision allowed by materials and technology, one or more of the revealed particle characteristics. This is the reason why many times the word detector is used referring to a number of sub-detectors assembled all together to form a machine capable of recording in only one sequence a huge number of information.

Different names are given to detectors that measure different characteristics: for example the ones establishing the initial particle tracks after collision are usually called trackers while those called calorimeter are designed to measure particles' energy.

The most important aspect of an overall detector design is the configuration and parameters of the magnetic field. The momentum measurement of charged particles in the detector is based on the bending of their trajectories. High momentum resolution is achievable either through a large bending power or through a very high precision on the spatial resolution and alignment of the detectors; CMS has both of these. For a similar bending power, the overall size of a solenoidal system is smaller than that of a toroid. Within the space available the powerful superconducting CMS solenoid provides a very high magnetic field of four Tesla at an electrical current of 20000 Amperes. The stored energy is 2.6 Giga Joules, equivalent to the energy which is needed to melt 18 tons of gold. The CMS experimental machine has a total weight of about 14,500 tons a total length of 21.6 meters and a diameter of 14.6 meters; the particles collide exactly at the center of the machine.

1.3.2 Underground caverns

The underground area at Point 5 of the LHC ring is composed of an experimental cavern called UXC55 and of a service cavern called USC55 with their relative shafts. The caverns are placed at a depth of 90 m with respect to the ground level of the French village Cessy.

The detector will be installed in the UXC55 cavern, subjected to high radioactive and magnetic fields during the LHC running periods. No access to this area will be allowed during the operation mode and any kind of maintenance will be possible only during shutdowns. The proposed scheme in which all detector units and the magnet are fully assembled and tested on the surface and brought into the experimental cavern with a minimum of further assembly work, has resulted in reduced dimensions of the underground cavern that are 26 m in diameter and 53 m long.

The main access shaft (PX56), 23 m in diameter, provides a 16 m per 16 m opening for the installation of the magnet and the detector units.

Aside the experimental cavern there is a service cavern (see Figure 3), called USC55, 18 m large, 84 m long and 13.5 m high, shielded by a 4 to 7 meters concrete wall from the radioactive environment of the experimental area.

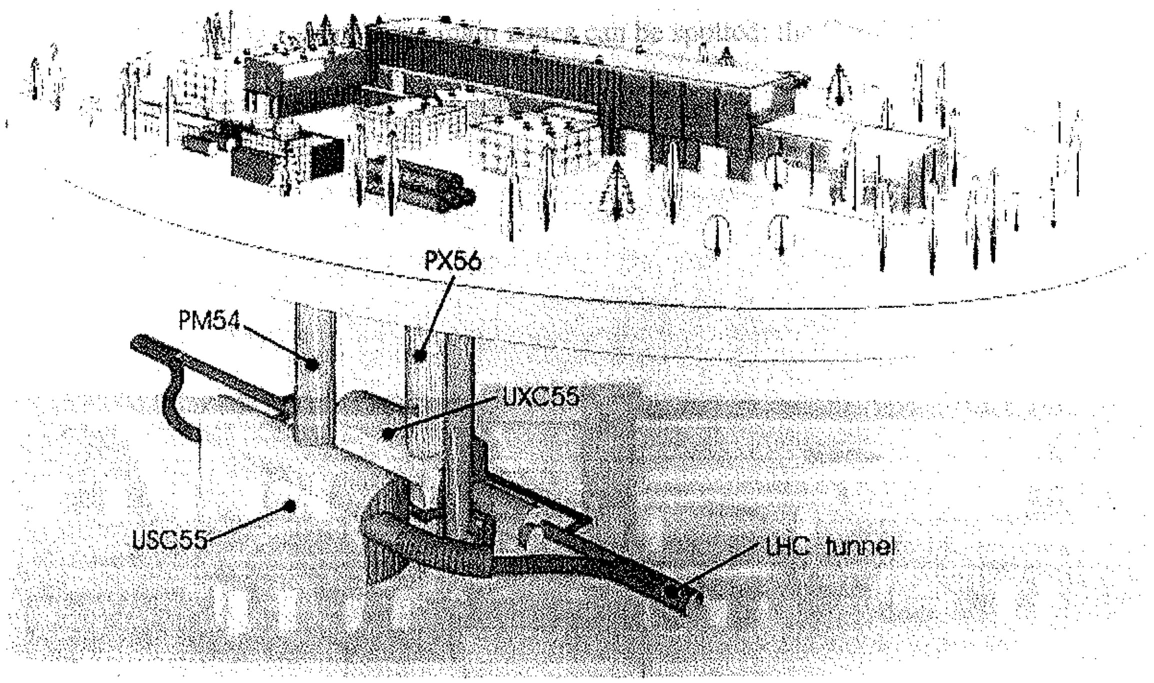

Figure 3. Point 5 underground caverns

A dedicated 12 m diameter shaft will provide access to this cavern and it will be equipped with a fire protected lift and staircase system.

1.4 USC55 cavern

Most of the detectors' controls and services as well as the components that cannot resist to magnetic or radioactive fields are located inside this service cavern. All these equipments have to be accessible to the personnel during LHC running, consequently safety measures had to be provided to ensure that the cavern was a safe working place.

In the USC55 cavern three main zones can be spotted: the Control Zone, the Pit Zone and the Service Zone (see Figure 4).

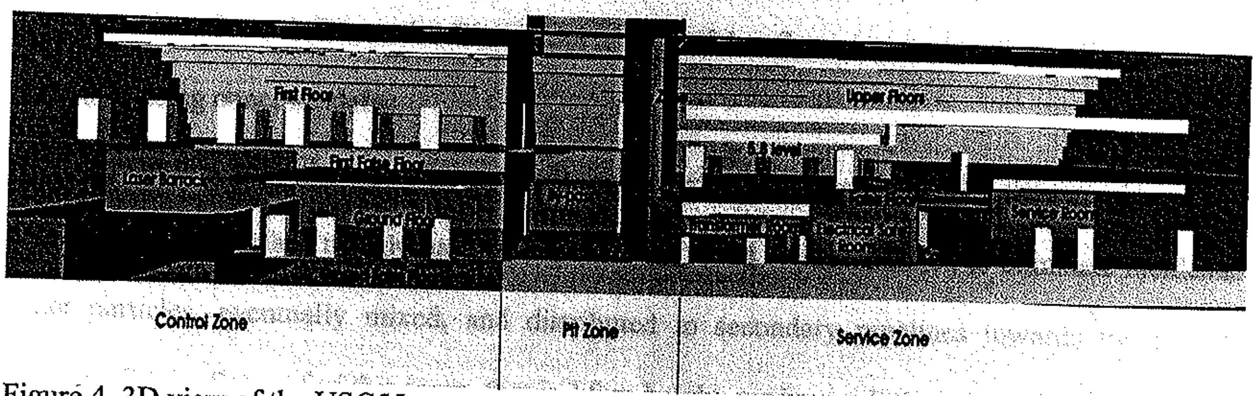

Figure 4. 3D view of the USC55 cavern.

1.4.1 Control Zone

This zone occupies about half cavern (see Figure 5, Figure 6, Figure 7) and it contains the most part of the electronic material. On the two main floors, one at 2 meters and the other one at 7.5 meters of height, will be installed, inside racks, the electronic units controlling::

- the different subdetectors running parameters
- the detectors gases composition
- the pre-processement of the data obtained from the experiment

Each floor has got a false floor underneath to collect wires from and to the racks. These are not common electrical wires, but optical fibers. The path from the detector to the rack has to be as short as possible to reduce signal transfer time to the minimum.

The Ground Floor, the First Floor and its false floor are made of metallic structures instead of using concrete slabs.

In this zone there is also a Gas Room where the gasses needed by the experiment and coming from the surface trough main pipelines in the PM54 are conditioned to eliminate incidental water particles, eventually mixed, and distributed to secondary pipelines towards the particle detector. On the flat roof of this room, that is 3.9 m height, we have a little construction called Laser Barrack which will be full of laser instrumentations. The same roof is used as middle landing for the staircase that goes from the Ground Floor to the first one. This area is completely separated from the next one, the Pit Zone, by a fireproof wall that has got just one fireproof door every main floor.

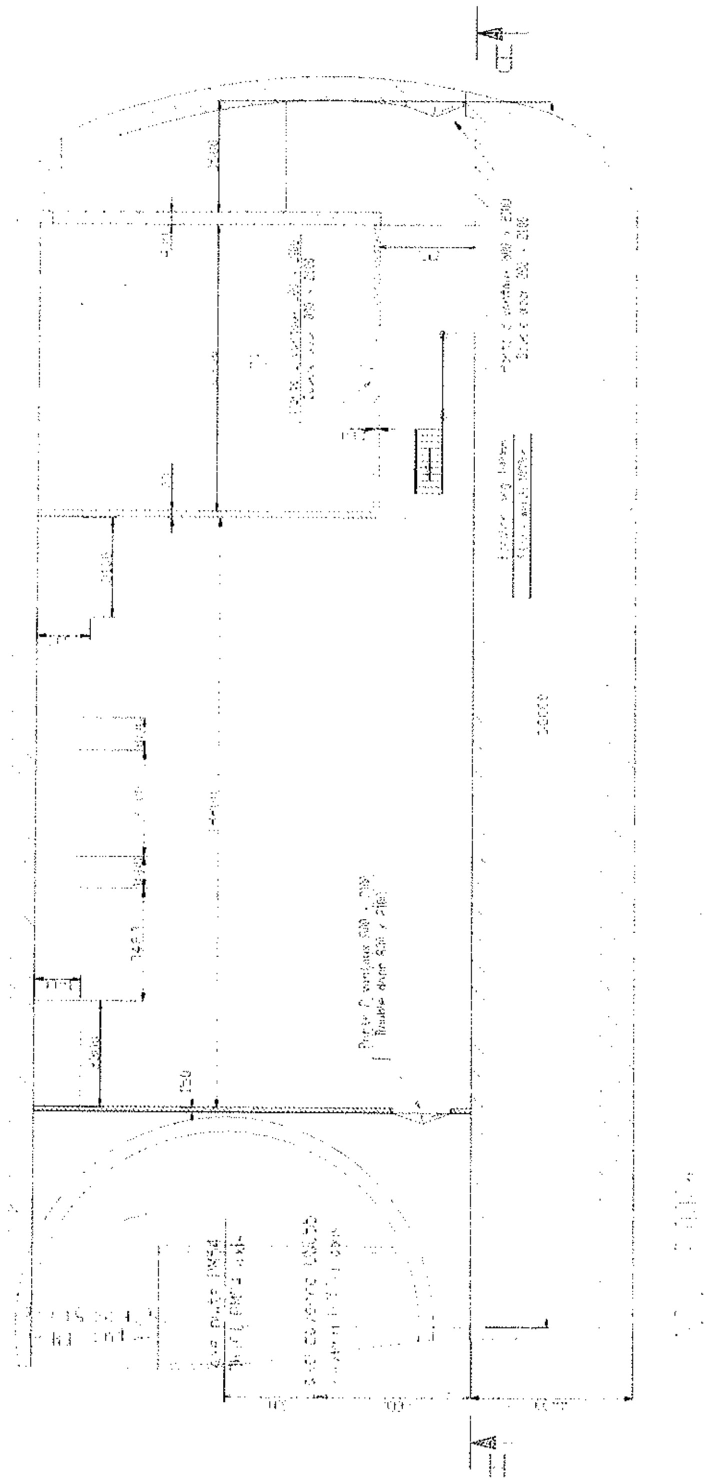

Figure 5. Ground floor control zone.

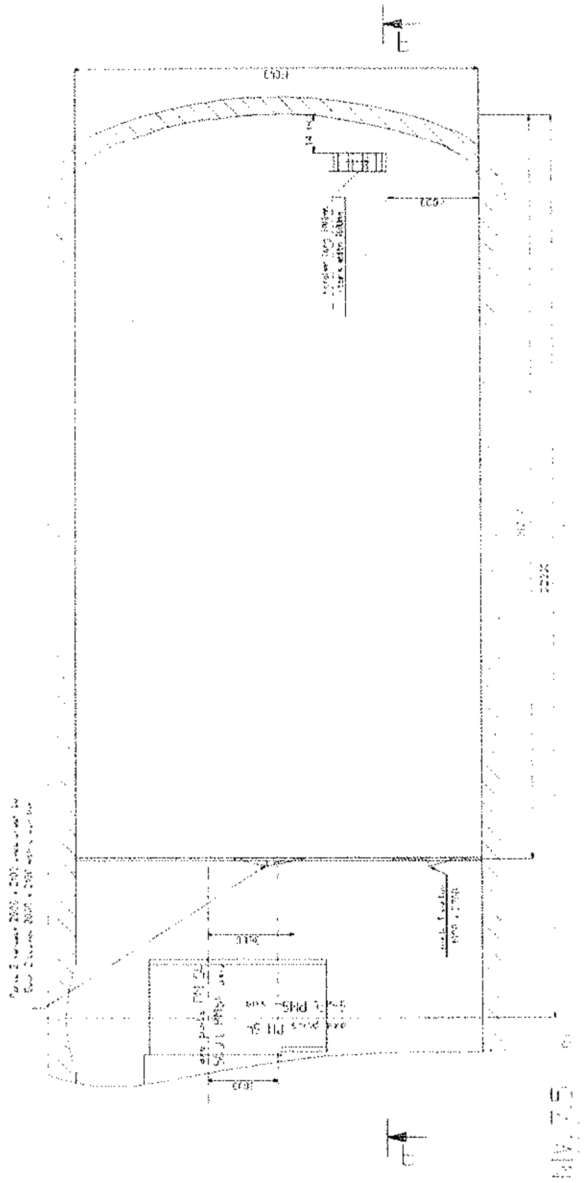

Figure 6. First floor control zone.

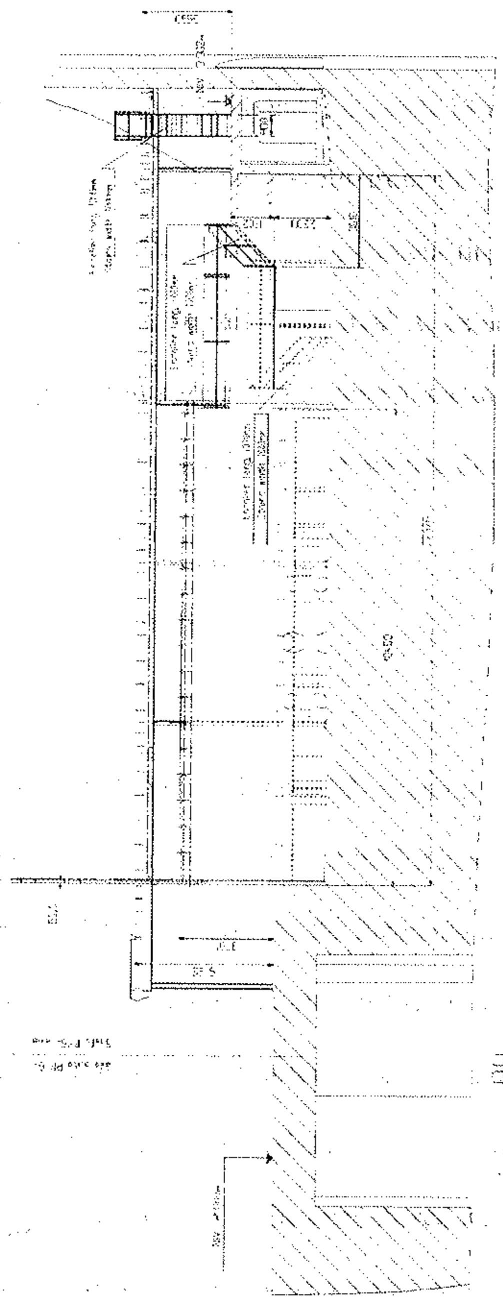

Figure 7. Control zone section.

1.4.2 Pit Zone

This is the zone under the pit PM54 and it is about 13 m x 13 m. In this area there is the elevator shaft that provides the access to the cavern from the surface. To guarantee fire safety measures the shaft is installed in a pressurized compartment that prevents smokes incoming and allows us to consider cavern exit doors to this “safe area” as external exits even if they are 100 m underground. The remaining part of this zone is dedicated to the material movement from and to the outside. The Pit zone is completely separated from the Service Zone at the ground floor, whereas at the upper level there is a communication between them.

1.4.3 Service Zone

This zone (see Figure 8, Figure 9, Figure 10) is composed at the ground floor from two main sub zones. The first one, that is the closest one to the Pit Zone, is called Transformer Zone and there are placed the transformers battery to convert the incoming medium voltage in a low one both at 50 Hz and 400 Hz and a fireproof building to protect the electrical commands. The second sub zone that we encounter going towards the end of the cavern, passing an intermediate corridor with an exit to the by-pass, is the Service Room. Here will be placed the cooling and ventilation equipments needed from the USC55 and part of the ones shared with the UXC55.

The upper level is composed by a unique volume which longitudinal boundaries are the Control Zone fireproof wall and the end wall of the cavern. It will be filled of racks placed at two different levels: one determined by the Service room roof and the other one, with a false floor underneath, built with metallic beams and plates.

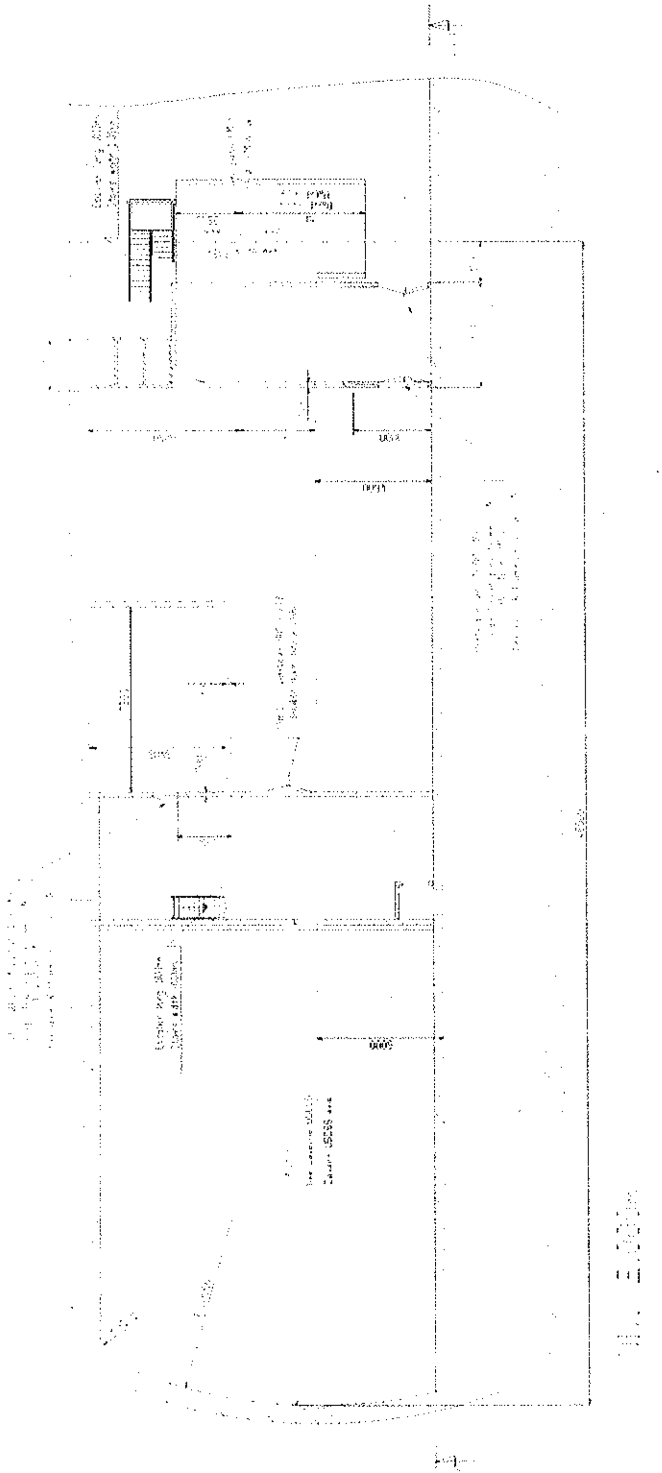

Figure 8. Ground floor service zone.

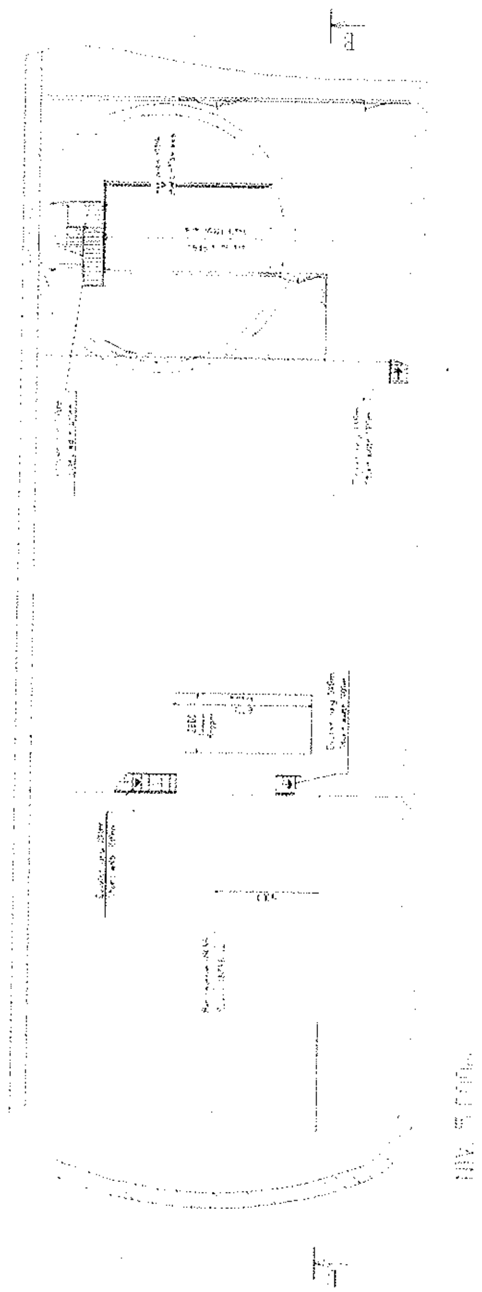

Figure 9. Upper floors service zone.

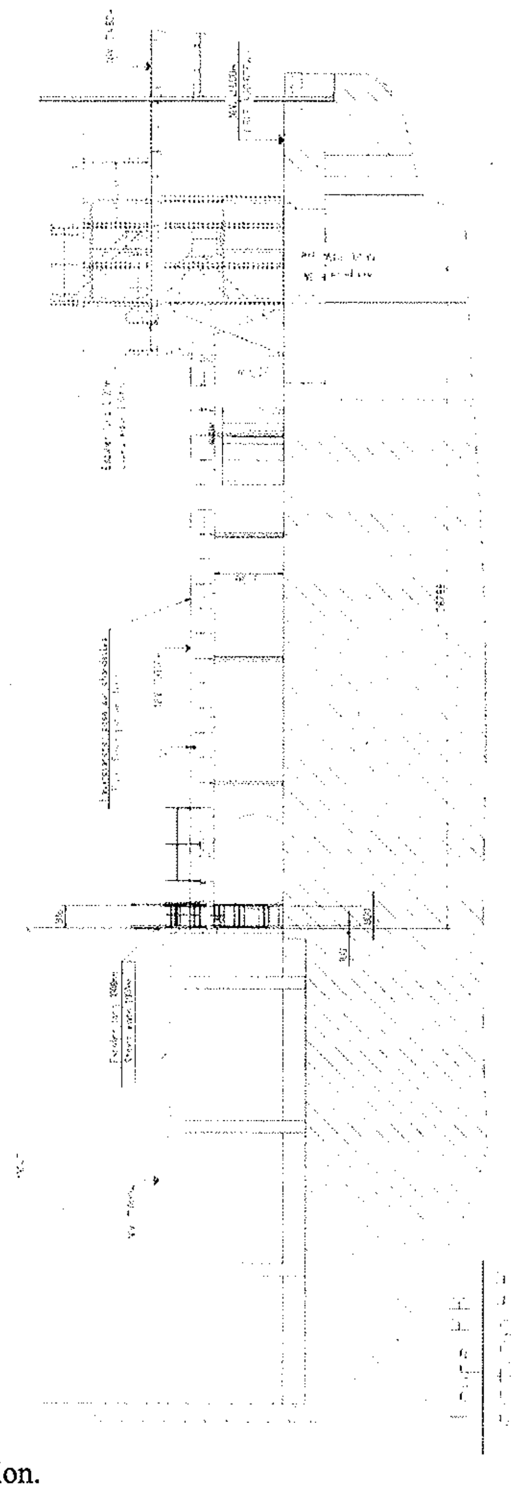

Figure 10. Service zone section.

1.5 Ventilation

The cooling and ventilation system of the service cavern is quite complex. It has a primary fresh air flow rate from the surface of 12000 m^3/h only against a total needed of 80000 m^3/h. This huge amount will be obtained treating the used air present in the cavern to cover the remaining 68000 m^3/h.

The USC55 cavern shall be maintained at overpressure with respect to the UXC55 cavern by introducing of pre-treated fresh air trough the post-treatment units located in the cavern. Used air shall be extracted mechanically by the continuous gas extraction system and statically by expansion towards experimental cavern UXC55 through gaps in the sealing.

1.6 Exits

In spite of its dimensions the cavern presents 5 exits, 3 to the Safe Zones and 2 to the By-pass, 1.6 m large and 2.1 m high. They are placed as shown in Figure 11 and Figure 12: 4 at the Ground Floor and 1 at the Upper Floor. Not being verified everywhere the standard prescription of a maximum path from the exits of 30 m an accurate analysis of the evacuation would be performed. All the stairs inside the cavern are made of steel, 1 m large and equipped with handrails.

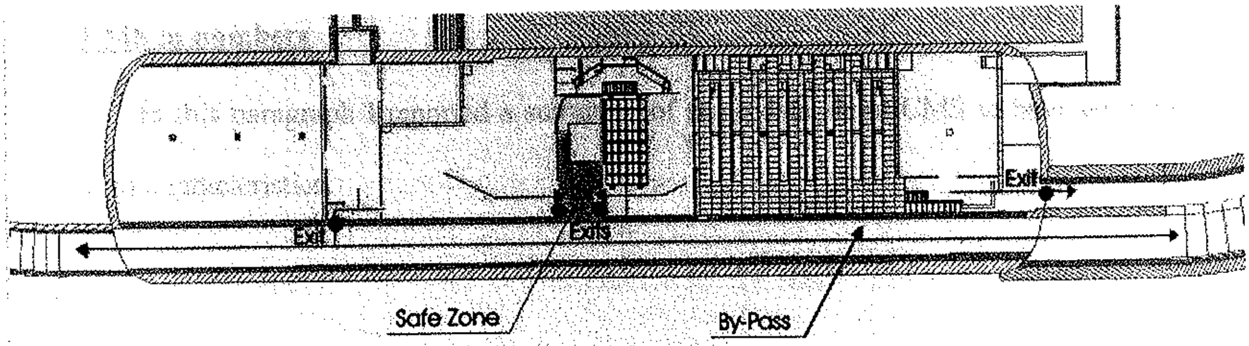

Figure 11. Ground floor exits

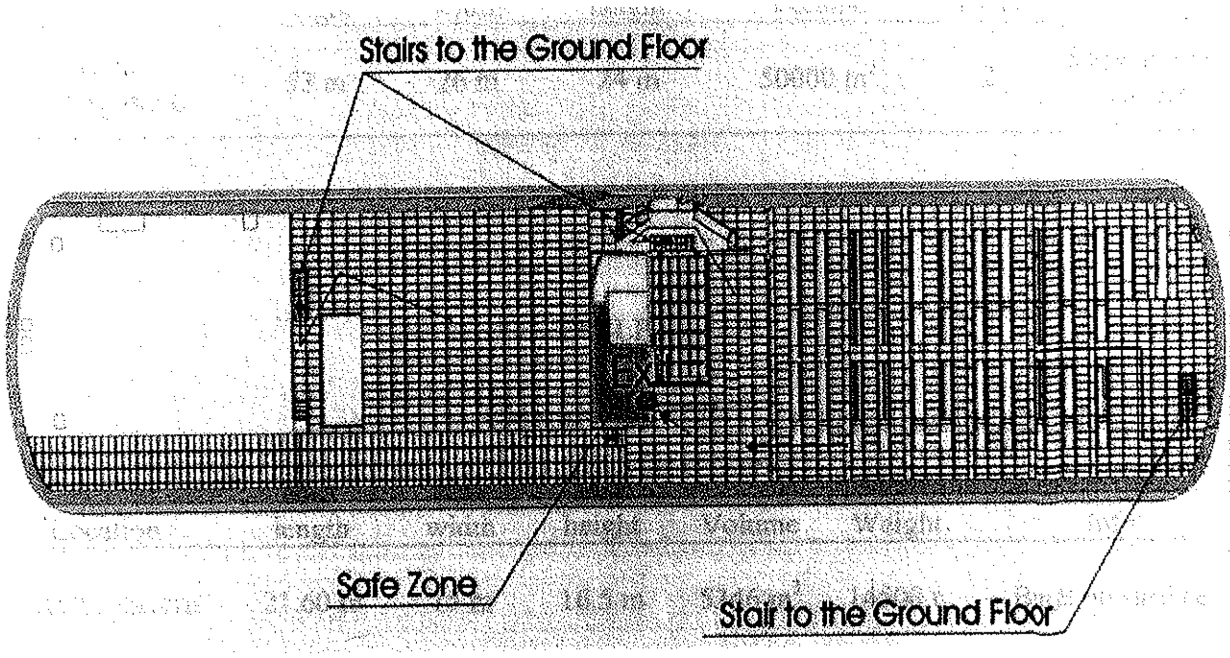

Figure 12. Upper floors exits.

1.7 CMS in numbers

In this paragraph I reported a summary of same data about CMS to have an immediate look on its characteristics.

TABLE I

CAVERN UXC 55

Location	Max length	Max width	Max height	Volume	Exits	Info
90 m underground	53 m	26 m	24 m	50000 m^3	2	Experimental cavern

TABLE II

CMS EXPERIMENT

Location	Max length	Max width	Max height	Volume	Weight	Info
UXC55 cavern	21.60 m	15 m	16.5 m	5346 m^3	14500 t.	Built on surface

TABLE III

PIT PX 56

Location	Diameter	Main use
UXC55	23 m	To descend the experiment in the cavern.

TABLE IV

CAVERN USC 55

Location	Max length	Max width	Max height	Volume	Exits	Ventilation	Info
90 m underground	84 m	18 m	13.5 m	28180 m^3	5	80000 m^3/h	Service cavern

TABLE V

PIT PM 54

Location	Diameter	Main use
USC55	12 m	Give access to the USC55 to the personnel

2. FIRE SIMULATION

2.1 Introduction

To date, distinct approaches to the simulation of fires have emerged. Each of these treats the fire as an inherently three dimensional process evolving in time. The first to reach maturity, the "zone" models, describe compartment fires. Each compartment is divided into two spatially homogeneous volumes, a hot upper layer and a cooler lower layer. Mass and energy balances are enforced for each layer, with additional models describing other physical processes appended as differential or algebraic equations as appropriate. Examples of such phenomena include fire plumes, flows through doors, windows and other vents, radiative and convective heat transfer, and solid fuel pyrolysis.

The relative physical and computational simplicity of the zone models has led to their widespread use in the analysis of fire scenarios. So long as detailed spatial distributions of physical properties are not required, and the two layer description reasonably approximates reality, these models are quite reliable. However, by their very nature, there is no way to systematically improve them. The rapid growth of computing power and the corresponding maturing of computational fluid dynamics (CFD), has led to the development of CFD based "field" models applied to fire research problems. The use of CFD models has allowed the description of fires in complex geometries, and the incorporation of a wide variety of physical phenomena.

2.2 Fire simulation program (FDS)

FDS is a Computational Fluid Dynamics (CFD) model of fire-driven fluid flow. The model solves numerically a form of the Navier-Stokes equations appropriate for low-speed flow with an emphasis on smoke and heat transport from fires. The partial derivatives of the conservation equations of mass, momentum and energy are approximated as finite differences, and the solution is updated in time on a three-dimensional, rectilinear grid. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver. Lagrangian particles are used to simulate smoke movement and sprinkler discharge.

FDS was chosen among a variety of different CFD programs because of its stability, the continuity in software development and assistance.

Although FDS can address most fire scenarios, here are limitations in all of its various algorithms. Some of the more prominent limitations of the model are listed here.

- Low Speed Flow Assumption: the use of FDS is limited to low-speed flow with an emphasis on smoke and heat transport from fires. This assumption rules out using the model for any scenario involving flow speeds approaching the speed of sound, such as explosions, choke flow at nozzles, and detonations.
- Rectilinear Geometry: the efficiency of FDS is due to the simplicity of its rectilinear numerical grid. This can be a limitation in some situations where certain geometric features do not conform to the rectangular grid, although most building components do.

- Fire Growth and Spread: because the model was originally designed to analyze industrial-scale fires, it can be used reliably when the heat release rate (HRR) of the fire is specified and the transport of heat and exhaust products is the principal aim of the simulation. However, for fire scenarios where the heat release rate is predicted rather than prescribed, the uncertainty of the model is higher. There are several reasons for this: (1) properties of real materials and real fuels are often unknown or difficult to obtain, (2) the physical processes of combustion, radiation and solid phase heat transfer are more complicated than their mathematical representations in FDS, (3) the results of calculations are sensitive to both the numerical and physical parameters. Current research is aimed at improving this situation.
- Combustion: for most applications, FDS uses a mixture fraction combustion model. The mixture fraction is a conserved scalar quantity that is defined as the fraction of gas at a given point in the flow field that originated as fuel. The model assumes that combustion is mixing-controlled, and that the reaction of fuel and oxygen is infinitely fast, regardless of the temperature. For large-scale, well-ventilated fires, this is a good assumption.
- Radiation: radiative heat transfer is included in the model via the solution of the radiation transport equation for a non-scattering gray gas. The equation is solved using a technique similar to finite volume methods for convective transport, thus the name given to it is the Finite Volume Method (FVM). There are several

limitations of the model. First, the absorption coefficient for the smoke-laden gas is a complex function of its composition and temperature. Because of the simplified combustion model, the chemical composition of the smoky gases, especially the soot content, can affect both the absorption and emission of thermal radiation. Second, the radiation transport is discretized via approximately 100 solid angles. For targets far away from a localized source of radiation, like a growing fire, the discretization can lead to a non-uniform distribution of the radiant energy.

2.3 Cavern Model

The first thing that had to be done was to analyze carefully all the limitations in the previous paragraph to be sure that we were not in one of those. The low speed flow assumption was verified because considering the equipments and materials inside the cavern we did not find anything that could bring to explosion or detonation events. The rectilinear geometry condition was not a big problem, as everything in the cavern was linear except the vault that could be approximated with a saw tooth without loosing accuracy in relation to the volume involved. Prescribing the heat release rate of the fire we pass over the third point. The use of a mixture fraction combustion model was good in this case being the cavern well ventilated. About the last limitation it is not so important in my simulation being the attention focused on smoke more than on heat.

Without big problems from this previous step I started to define the size of the physical domain. To minimize the number of cells involved in the calculation I decided to use a multiple mesh option defining two rectangular meshes. The one of the cavern was 84 meters long 18 large and 13.5 high while that one of the pit was 10.7 x 10.7 x 80 meters. The size of each cell was to be defined trough the number of cells in the three directions x, y, and z where x is the longer horizontal direction and z the vertical one. To specify this numbers I analyzed the cavern to set the minimum dimension that could be of interest in the simulation looking to program and hardware limitations. Due to the fact that an accurate ventilation representation was requested to have more precise results and being its smallest part of the order of magnitude of half a meter I decided to set this as the smaller unit of my domain. To maximize the program performance cells has to be as close as possible to a cube so I chose as numbers of cells of the cavern 162 in x direction, 36 in y and 24 in z while 10, 10 and 80 for the pit.

The geometry within the flow domain was made using simple rectangular solids which had material properties and, where necessary, particular surface conditions as was the case of ventilation components. In fact, to model the ventilation system I had to create surface attributes on solid blocks with temperature and flow values of the incoming or outgoing fluid.

2.4 Fires

The main flammable materials we can have in the USC55 cavern are: cables, plastic, electronic material, paper and eventually cleaning materials.

The status of the art of the computer fire simulation does not yet allow calculating the complex interaction between the flame and the combustible. What is normally done is to superimpose in the geometrical model a predetermined source of heat and smoke having a heat release rate profile that makes sense, given the quantity of combustible present and the condition of ventilation. The fire that was used for the simulations was a medium growth rate parabolic fire reaching a peak power of 4 MW. This is the standard fire that the CERN Safety Commission uses in underground cavern fire simulations and it corresponds to the heat release rate of almost 20 kg of polyurethane fully burning. This can be a good approximation, at least in the first 10 minutes, of a possible fire burning the fuel available in the vicinity of the origin spot. The surface of the fire was one meter squared. The growth is shown in Figure 13. Larger fires or time horizons were not simulated because of time-machine limits in the PC hardware used, and because this was a sufficient interesting period for the evacuation simulation.

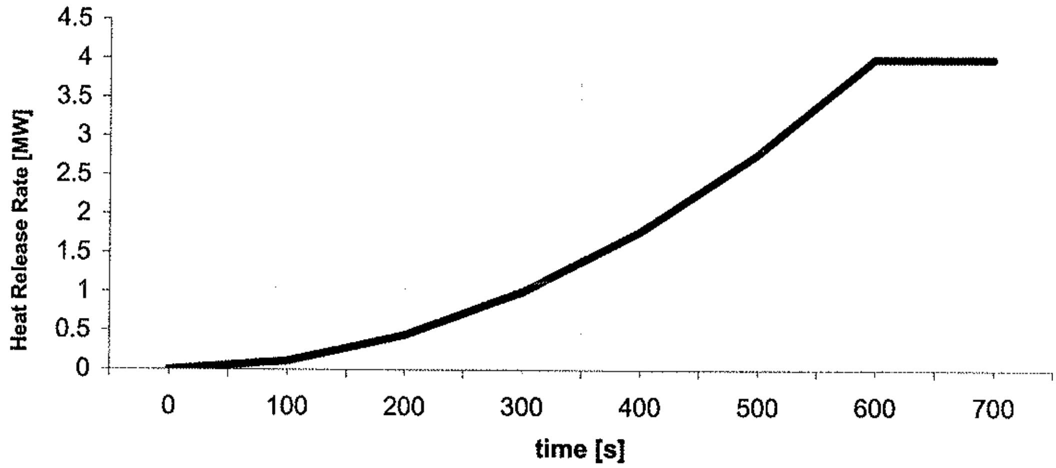

Figure 13. Fire curve assuming 20 kg. of polyurethane fully burning. This will be the standard curve for all the fire simulations.

2.5 Scenarios

Due to the fact that the cavern has got many compartments six different fire locations were individuated.

The first location was underneath the Ground Floor of the Gas Zone (see Figure 14). The presence of a huge number of wires and the difficulty in detecting an eventual fire make this an interesting place to study.

The second location was at the First Floor of the Gas Zone just in proximity of the exit door to the Safe Zone (see Figure 15). This eliminated one possibility of evacuation to the personnel.

The third one was in the Transformer Room (see Figure 16). The presence of big step down transformers on the imaginary line connecting the two room doors individuated the place where to put the fire hazard.

The fourth one, placed in the corridor between the Service Room and the Transformer Room (see Figure 17), could interest the exit to the By-pass and the staircases to the first floor forcing people in that floor to evacuate entirely to the Safe Zone.

The fifth scenario represented a fire in the First False Floor of the Control Zone (see Figure 18). Here again we had presence of wires and the fact that the fire here can grow a lot before being visible. Besides it can block the staircases from the First Floor and that one to the Ground Floor.

The last scenario was created placing the fire at the level 5.8 meters of the Service Zone (see Figure 19) and, as in case two, in a way that the evacuation was only possible using the staircase towards downstairs.

You can find the FDS ASCII commands for the first case in Appendix A. I did not report all the files because the difference between them was only in the fire position.

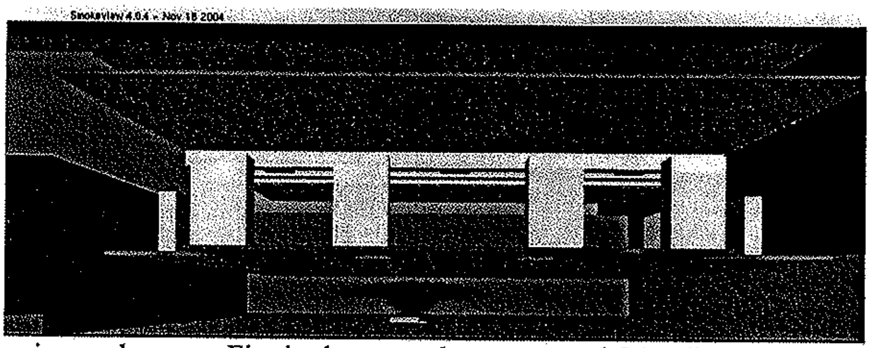

Figure 14. Scenario number one. Fire in the control zone ground false floor.

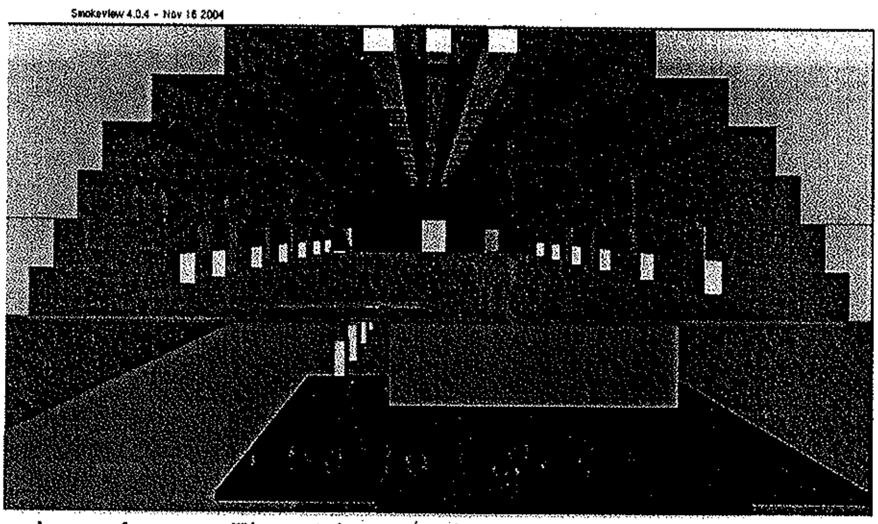

Figure 15. Scenario number two. Fire on the control zone first floor.

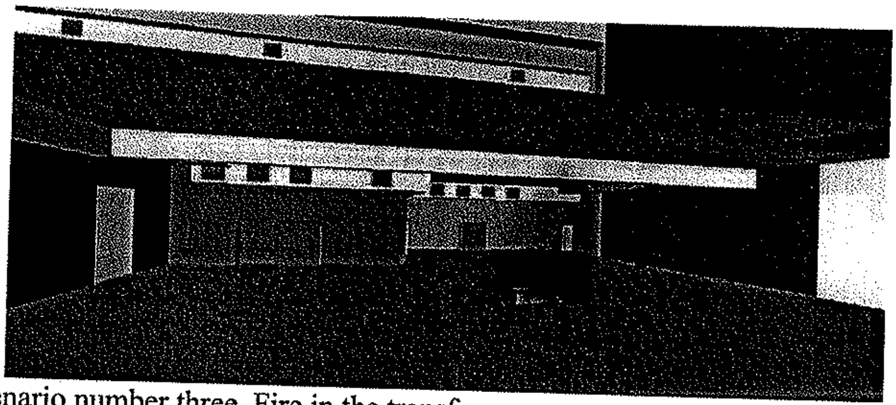

Figure 16. Scenario number three. Fire in the transformer room.

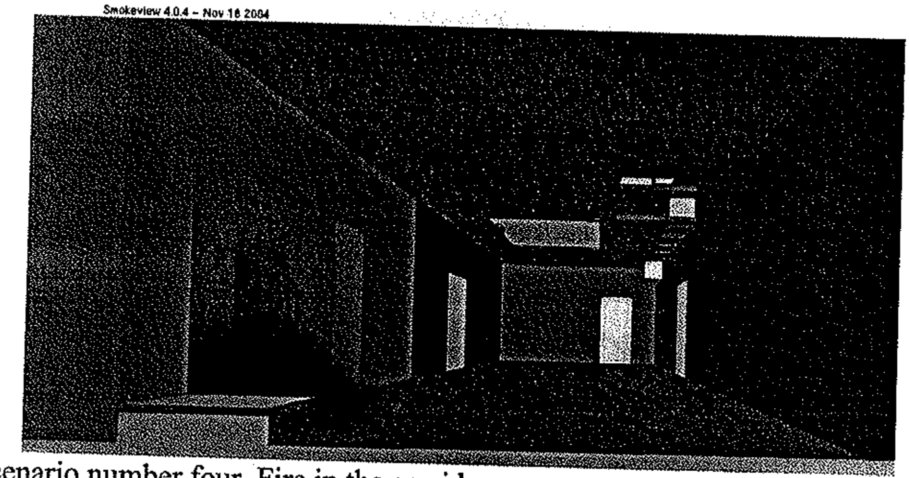

Figure 17. Scenario number four. Fire in the corridor.

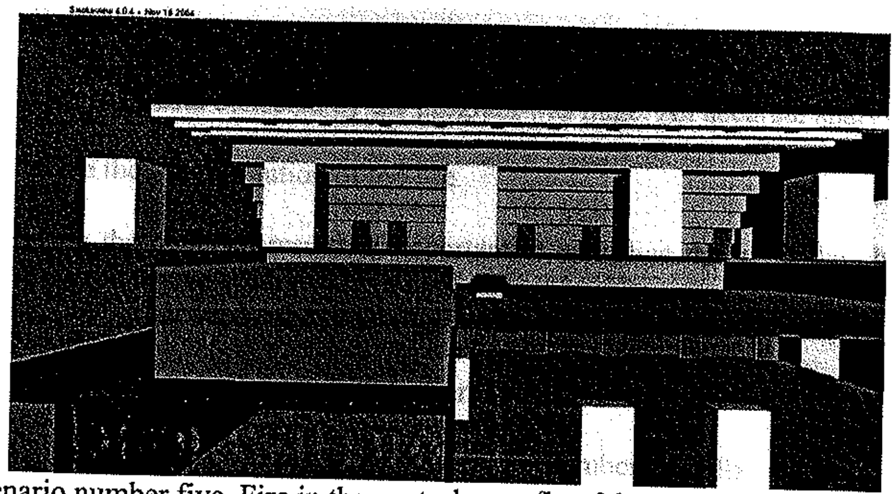

Figure 18. Scenario number five. Fire in the control zone first false floor.

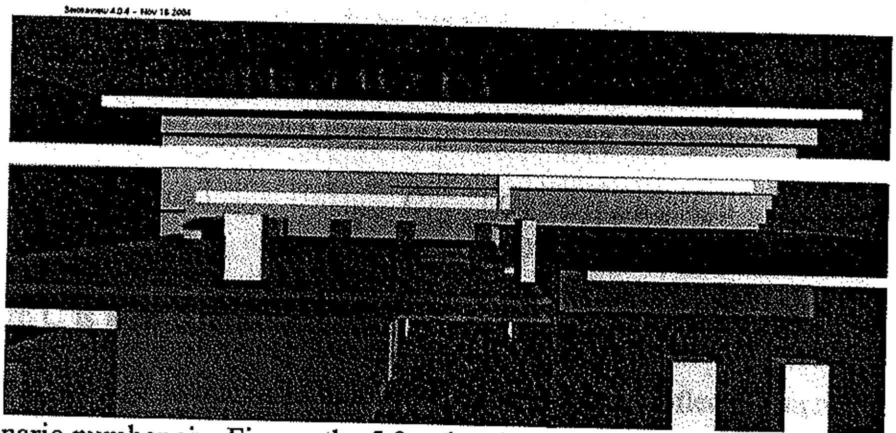

Figure 19. Scenario number six. Fire on the 5.8 m level of the service zone.

2.6 Analysis Results

The amount of data collected by the program was huge. An accurate analysis of them was performed to analyze the time evolution of the fire.

Analyzing the obtained results is important to underline that with the chosen mesh the smoke evolution and afterwards the visibility are well evaluated, whereas temperatures are indicative of the analyzed phenomena. Whereas an accurate temperature analysis was requested a finer mesh would have to be used either increasing the number of cells or reducing the physical domain.

Each case will be explained in the following sub-paragraphs. At the end of each case will be reported a short table with the temperatures and the visibility registered where evacuation path is supposed to be performed with respect to exits and fire location of the analyzed scenario. The visibility through smoke was estimated from the program using the equation

$$S = \frac{C}{K} = \frac{C}{K_m \rho Y_s}$$

where C is a no dimensional constant characteristic of the type of object being viewed trough the smoke (set to 2 in our cases that is the value of a light-reflecting signal) and K, the light extinction coefficient, is a product of the density of smoke particulate, ρY_S, and a mass specific extinction coefficient that is fuel dependent (7600 m^2/kg for the polyurethane).

2.6.1 Case One

The fire was originated in the Ground False Floor. The false floor is not closed, but communicates with the room above it with four openings in the ceiling and with a frontal opening determined from the fact that what is usually called ground floor is at 2 meters with respect to the Gas Room floor level.

After 150 seconds evacuation from the Ground False Floor could be difficult and the smoke began to fill the above room. After 177 second the exit to the by pass near the Gas Room was no more visible and a smoke layer was forming at the ceiling and slowly descending towards the ground floor (see Figure 20). At about 200 seconds half room is full of smoke and just the part with the exit door is still available for evacuation (see Figure 21).

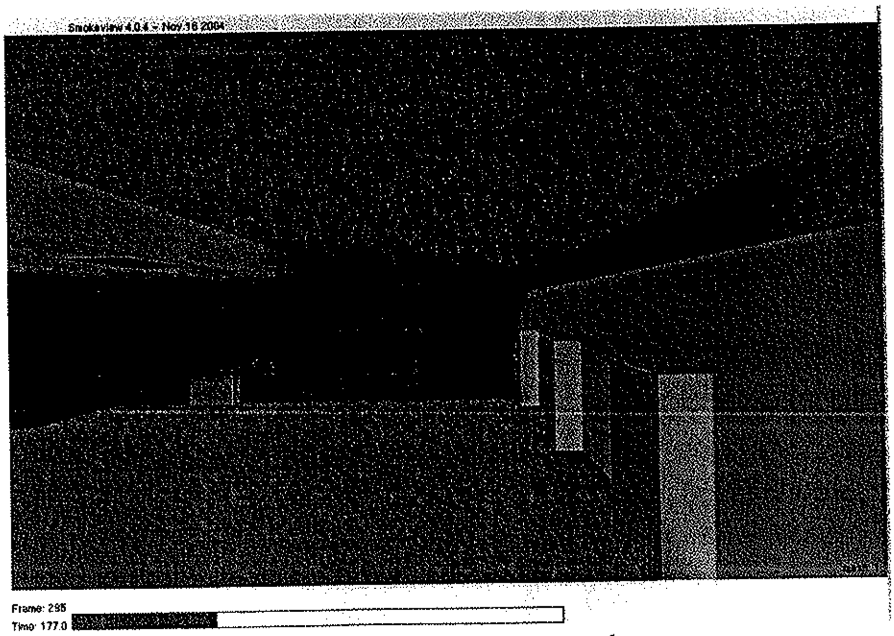

Figure 20. Control zone ground floor situation after 177 seconds

At 227 seconds the visibility in the whole room is compromised and the scenario went rather quickly (see Figure 22). At 267 seconds the room was completely filled of smoke and the visibility in the laser barrack zone was critical.

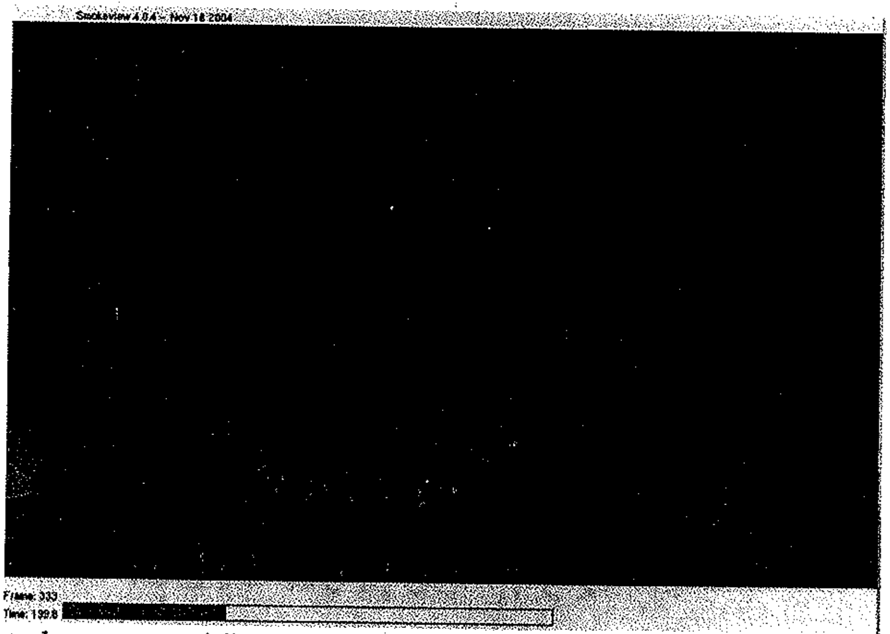

Figure 21. Control zone ground floor situation after 200 seconds.

At the First Floor the evacuation continued to be possible only using the door in the fireproof wall to access the Safe Zone in the Pit Zone.

In this upper floor a smoke layer formed at 570 seconds, but at the end of the simulation it had not yet caused visibility problems (see Figure 23).

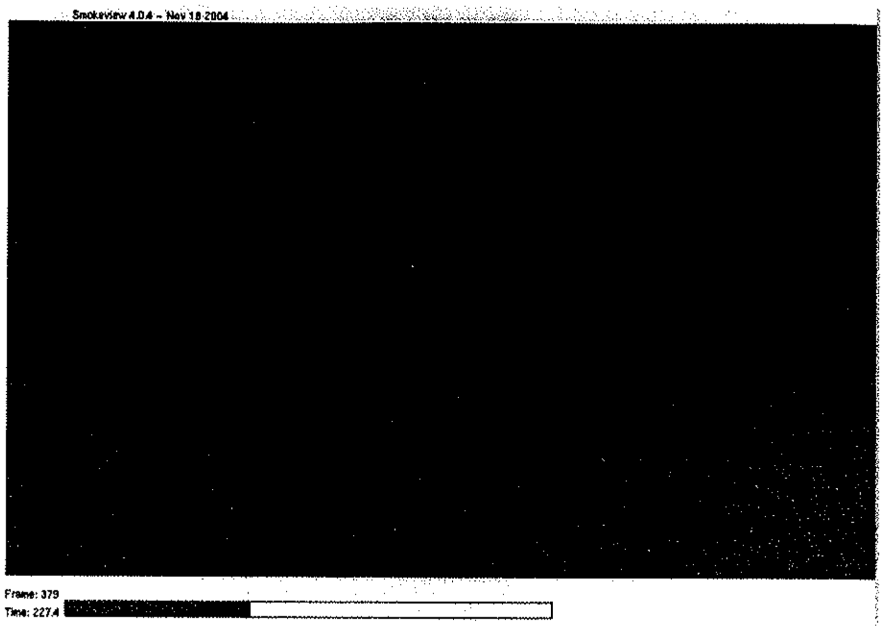

Figure 22. Control zone ground floor situation after 227 seconds.

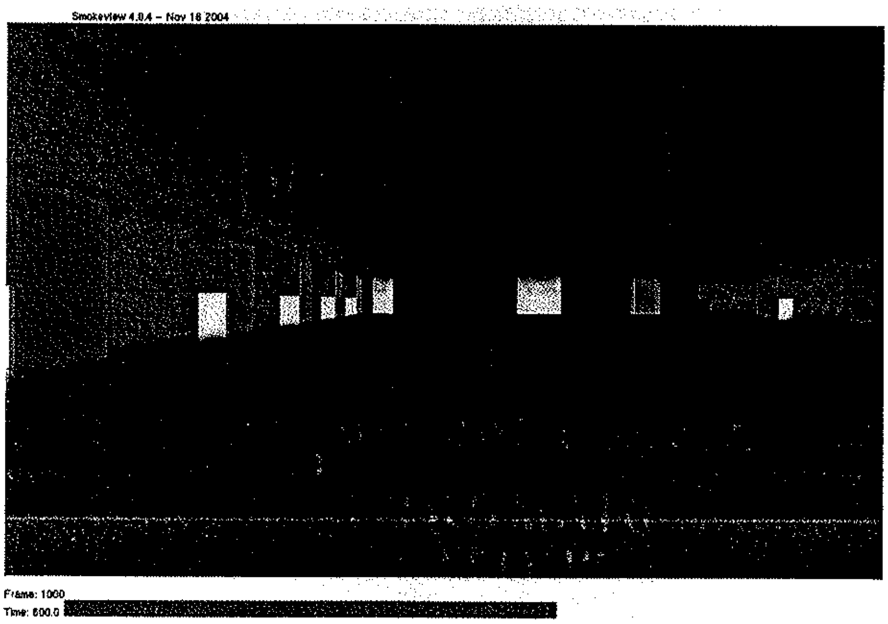

Figure 23. Control zone first floor situation after 600 seconds.

TABLE VI

SCENARIO ONE RESULTS

t	T 5 m from the door	T floor room center	T 4 m from the fire	S at the room center	S 5 m from the door	S 4 m from the fire
~ 2.5 min.	293 K	303 K	313 K	> 30 m	> 30 m	2 m
~ 3 min.	293 K	311 K	328 K	21 m	> 30 m	1 m
~ 3.5 min.	298 K	322 k	343 K	4 m	12 m	< 1 m
~ 5 min.	302 K	336 K	363 K	< 1 m	< 1 m	< 1 m

2.6.2 Case Two

This is the fire location that blocked the Control Zone First Floor evacuation door to the pit. This will cause some problems in the evacuation. At about 195 seconds (see Figure 24) the division between the smoke layer and the air was evident and the interface started to descend.

The visibility decrease rather quickly and at about 273 seconds it is possible to evacuate only by crawling (see Figure 25). After 380 seconds evacuation is no more possible as visible in Figure 26.

Figure 24. Control zone first floor situation after 195 seconds

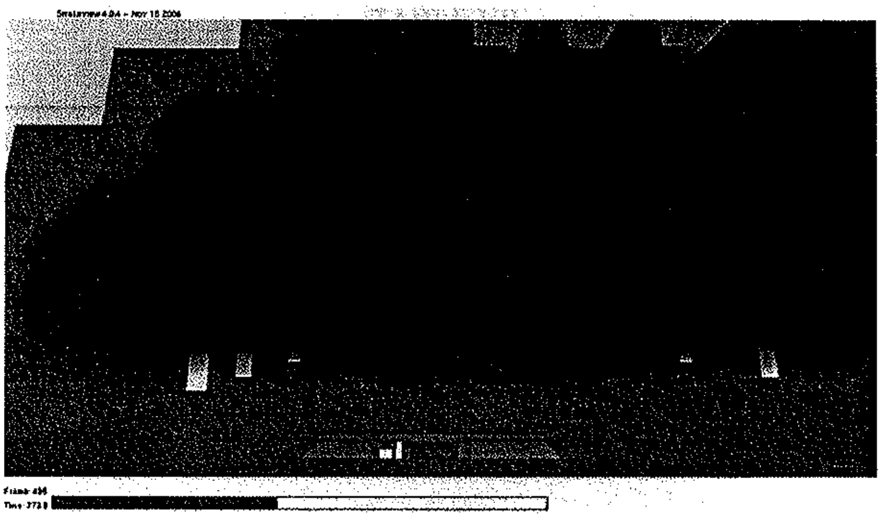

Figure 25. Control zone first floor situation after 273 seconds

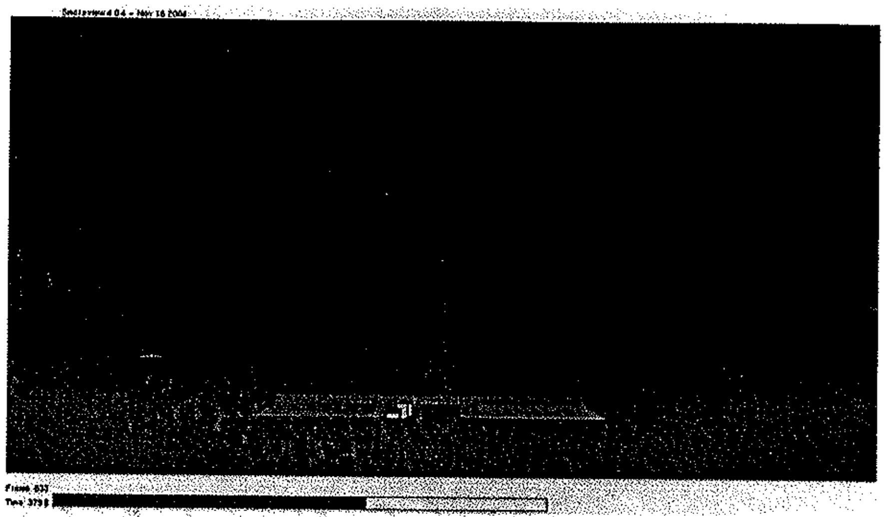

Figure 26. Control zone first floor situation after 380 seconds

TABLE VII

SCENARIO TWO RESULTS

t	T 7 m from the fire	T 15 m from the stair	T 5 m from the stair	S 15 m from the stair	S 5 m from the stair
~ 3 min.	293 K	293 K	293 K	21 m	>30 m
~ 4.5 min.	302 K	298 K	298 K	4 m	12 m
~ 6 min.	323 K	315 K	313 K	<1 m	<1 m

2.6.3 Case Three

This was the case of a fire in the Transformer Room. At about 135 seconds smoke started to create evacuation problems at the Safe Zone exit door as shown in Figure 27.

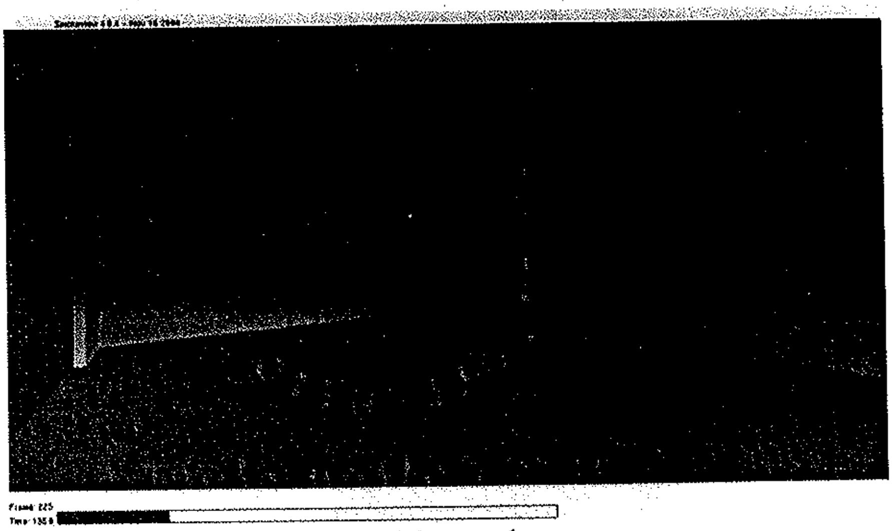

Figure 27. Transformer room situation after 135 seconds.

After 189 seconds evacuation was only possible crawling to exits (see Figure 28) and the room was completely filled with smoke at about 237 seconds.

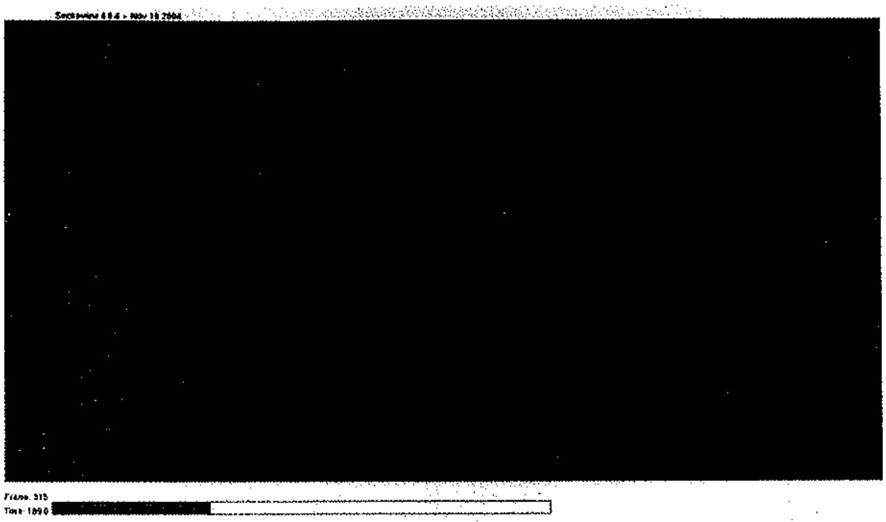

Figure 28. Transformer room situation at 189 seconds.

TABLE VIII

SCENARIO THREE RESULTS

t	T 3 m from fire	T 7 m from fire	S at the Safe Zone door	S at the door to the Corridor
~2 min.	298 K	295 K	4 m	12 m
~3 min.	305 K	306 K	2 m	4 m
~4 min.	310 K	315 K	<1 m	<1 m

2.6.4 Case Four

This is the simulation of a fire in the Corridor. This is a critical zone because in it there is the access to the Electrical, Transformer and Service rooms, the exit to the by-pass and the stair to the Upper Floors.

After 102 seconds the evacuation from the electrical safe room becomes difficult (see Figure 29) as the use of the staircase. This means that people upstairs are obliged to evacuate to the only exit placed at that floor. At about 126 seconds the smoke blocked the other doors and evacuation became more difficult. Forty seconds later that area is completely filled with smoke and it begins to form a ceiling layer at the first floor. 273 seconds are sufficient to cause evacuation problems at the first floor and after 351 seconds the access to Safe Zone Exit was hardly accessible (see Figure 30)

Figure 29. View from the exit to the by-pass of the corridor at 102 seconds.

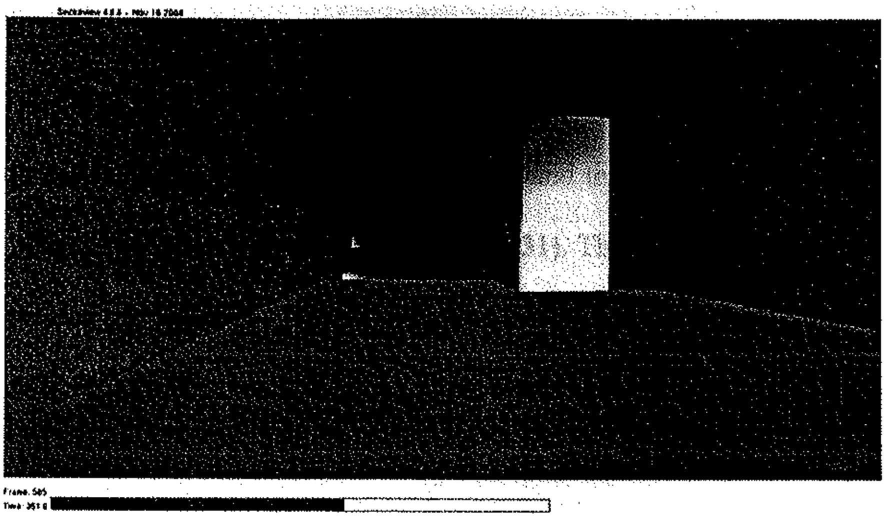

Figure 30. View from the safe zone exit of the service zone first floor after 351 seconds.

TABLE IX

SCENARIO FOUR RESULTS

t	T 2 m from the fire	T 7 m from the stair	T upper floor	S at the exit to by-pass	S at the Upper Floors exit
~1.5 min.	294 K	295 K	293 K	9 m	>30 m
~2.5 min.	303 K	313 K	293 K	1 m	>30 m
~4.5 min.	333 K	353 K	293 K	<1 m	7 m
~6 min.	348 K	383 K	293 K	<1 m	2 m

2.6.5 Case Five

The fire was placed in the False Floor underneath the First Floor of the Control Zone. After 183 seconds the smoke formed a consistent layer and the visibility at the Laser barrack level was no more sufficient to evacuate walking (see Figure 31). The stair to the upper level was blocked by the smoke column forcing here again people at the First Floor to evacuate using the door towards the Safe Zone exit. After 447 seconds evacuation problems became evident also at the First Floor as shown in Figure 32.

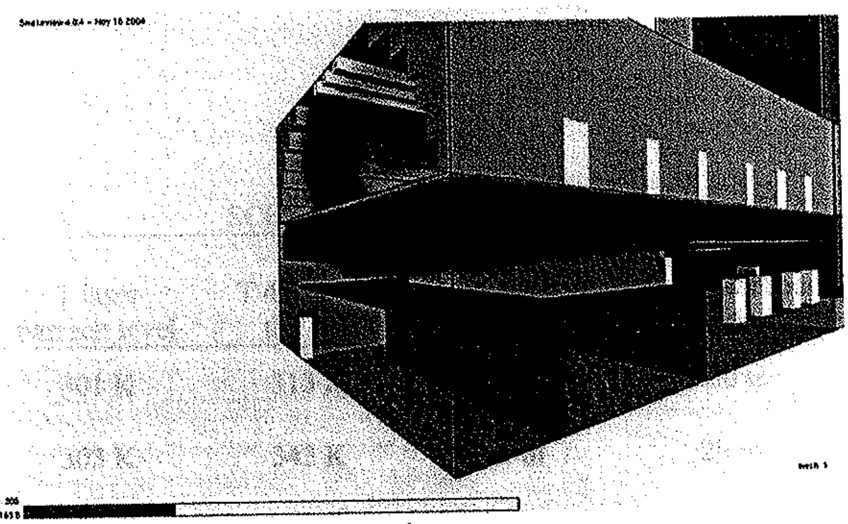

Figure 31. Control zone situation after 183 seconds.

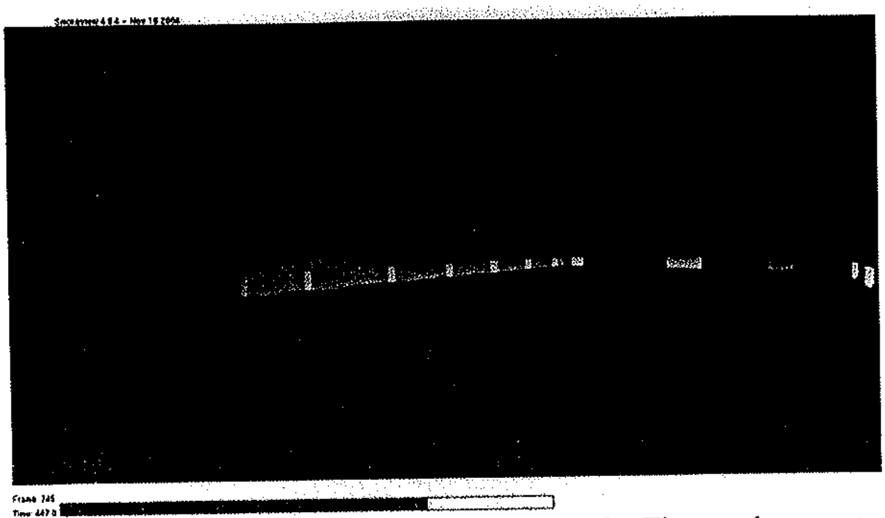

Figure 32. Control zone first floor situation after 447 seconds. The smoke structure on the floor level is an artefact of the mesh.

TABLE X

SCENARIO FIVE RESULTS

t	T laser barrack level	T 4 m from the fire	S at the laser barrack level	S at 3 m from the First Floor exit	S at 4 m from the fire
~3 min.	301 K	313 K	15 m	>30 m	3 m
~5 min.	303 K	343 K	1 m	29 m	<1 m
~7.5 min.	333 K	363 K	<1 m	9 m	<1 m
~10 min.	348 K	383 K	<1 m	1 m	<1 m

2.6.6 Case Six

This last scenario was introduced to analyze if evacuation was possible in case of Safe Zone access blocked and staircase as only way out from the Upper Floors of the Service Zone.

After 390 seconds the area formed by the Service Room ceiling was filled of smoke, but evacuation continued to be possible at level 5.8 (see Figure 33). At the end of the simulation the situation started to be critical there too as shown in Figure 34.

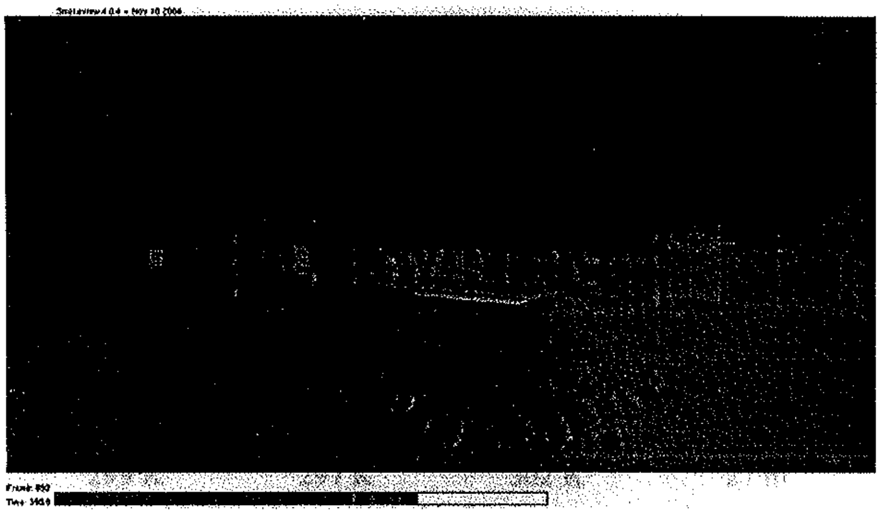

Figure 33. Service zone upper floors after 390 seconds.

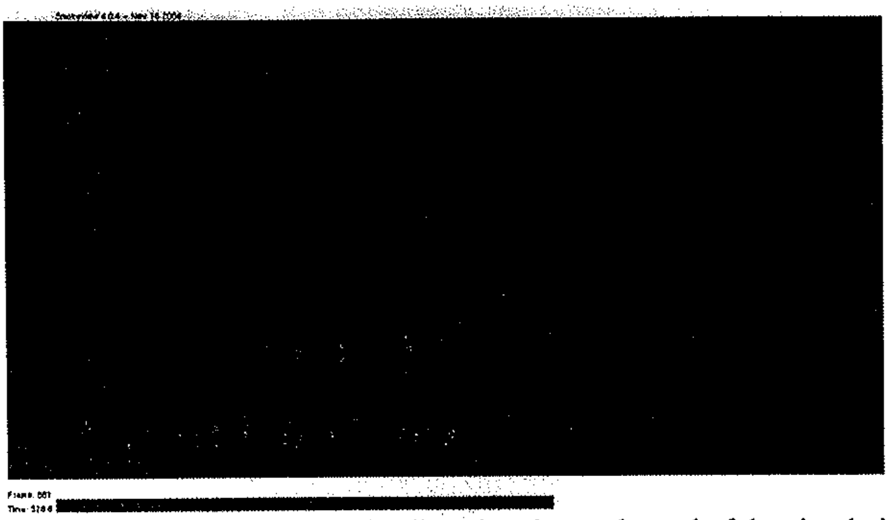

Figure 34. Service zone first floor staircase landing situation at the end of the simulation.

TABLE XI

SCENARIO SIX RESULTS

t	T 5 m from the fire	T 1 m from the stair	T at the ST roof area	S at 2 m from the stair	S at the ST roof area
~5 min.	296 K	293 K	298 K	29 m	10 m
~6.5 min.	299 K	297 K	302 K	27 m	4 m
~10 min.	303 K	301 K	313 K	3 m	1 m

2.7 Fire Analysis Conclusions

The cavern has been modeled with the program FDS in order to evaluate the fire development due to a medium growth rate parabolic fire reaching a peak power of 4 MW in 600 seconds. This is the standard fire that the CERN Safety Commission uses in underground cavern fire simulations. Six cases, where the fire has been put in different locations, have been analyzed considering the geometry of the cavern and the risks present in it.

The data obtained from this simulation have been introduced in BuildingExodus, an evacuation dedicated software, described in the following chapter, which was chosen by CERN to perform all the evacuation simulations of its underground caverns.

3. PERSONNEL EVACUATION SIMULATION

3.1 Evacuation Simulation Program (Building Exodus)

EXODUS is a suite of software tools designed to simulate the evacuation and movement of large numbers of individuals within complex structures. BuildingEXODUS is designed for applications in the built environment and can be used to demonstrate compliance with building codes, evaluate the evacuation capabilities of all types of structures and investigate population movement efficiencies within structures.

The EXODUS software takes into consideration people-people, people-fire and people-structure interactions. The model tracks the trajectory of each individual as they make their way out of the enclosure, or are overcome by fire hazards such as heat, smoke and toxic gases. It has been written in C++ using Object Orientated techniques and rule-base concepts to control the simulation. Thus, the behavior and movement of each individual is determined by a set of heuristics or rules. For additional flexibility these rules have been categorized into five interacting sub-models, the occupant, movement, behavior, toxicity and hazard sub-models. These sub-models operate on a region of space defined by the geometry of the enclosure. Each of these components will be briefly described in turn in this paragraph and more accurately in the followings.

The entire space of the geometry is covered in a mesh of nodes that are typically spaced at 0.5m intervals. The nodes are then linked by a system of arcs. Each node represents a region of space typically occupied by a single occupant.

The movement sub-model controls the physical movement of individual occupants from their current position to the most suitable neighbouring location, or supervises the waiting period if one does not exist. The movement may involve such behavior as overtaking, sidestepping, or other evasive actions.

The behavior sub-model determines an individual's response to the current prevailing situation on the basis of his/her personal attributes, and passes its decision on to the movement sub-model. The behavior sub-model functions on two levels: global and local. The local behavior determines an individual's response to his/her local situation while the global behavior represents the overall strategy employed by the individual.

The occupant sub-model describes an individual as a collection of defining attributes and variables such as gender, age, fast walking speed, walking speed, response time, agility, etc… Some of the attributes are fixed throughout the simulation while others are dynamic, changing as a result of inputs from the other sub-models.

The hazard sub-model controls the atmospheric and physical environment. It distributes pre-determined fire hazards such as heat, smoke and toxic products throughout the atmosphere.

The toxicity sub-model determines the effects on an individual exposed to toxic products distributed by the hazard sub-model. These effects are communicated to the behavior sub-model which, in turn, feeds through to the movement of the individual.

To aid in the interpretation of the results produced by buildingEXODUS the vrEXODUS has been developed. This tool is a post-processor virtual-reality graphics environment enabling an animated three-dimensional representation of the evacuation simulation to be produced.

3.2 Cavern Geometry

The cavern geometry was defined in the GEOMETRY MODE of EXODUS operation. Geometries within EXODUS are represented as two-dimensional grids manually constructed using the interactive tools provided. Each location on a grid is called a node, and each node may be linked to its nearest neighbours by a number of arcs. Occupants travel from node to node along arcs. Associated with each node is a set of attribute that are used to define the nodes terrain type, environmental state and location. The attributes associated with a node are important as they may exert an influence over the person traversing the node. In the next table I reported the nodes types I used with a short description.

Associated with each arc are two attributes. The first attribute is the length attribute. This represents the actual physical distance between nodes. The second attribute is known as the Obstacle. The Obstacle attribute is an integer measure of the degree of difficulty in passing over the node. Obstacle values can be used to differentiate node types and I set this value to two for the False Floors where people are forced to walk on cables in a non totally upright position while it is one everywhere else.

Multi-level geometries, as the USC55 is, have to be constructed in more than one geometry window, usually one per floor and each level should be considered a separate entity until the levels require joining. In TABLE XIII I reported the name attributed to the different levels with the relative areas modelled in them.

TABLE XII

NODE TYPES USED

Node type	Description of use and influence on behaviour
Free-Space	Allows unhindered movement and represents unobstructed horizontal terrain.
Boundary	Occupants attempt to avoid if possible, if not possible to avoid, occupants traverse at reduced speed (WALK SPEED). Used in proximity of every kind of obstruction like walls, racks, stairs, transformers, …and in the False Floors.
Stair	Used to represent staircase and forces the occupant speed to be reduced, according to the direction of travel. Occupant forced to adhere to a range of behaviour rules associated with stairs.
Landing	Replicates the behavioural impact of the Free-Space nodes, however is specifically designed to connect staircases. It also reduces the travel speed of the individual to Walk Rate.
External Exit	Represents final exit point for the occupant population. Once an occupant has reached this point, they are assumed to have completed the evacuation. It may be manipulated to control the flow capabilities, attractiveness and availability of the particular exit point.
Internal Exit	Used to represent an exit within the building, i.e. that does not immediately lead to the outside of the structure.

Joins between levels are made by floor links that are 'portals' between the floors between which the evacuees move. Therefore no explicit connection is made between the windows representing the floors to be connected. This is a simple way to built multi-level buildings, but introduces some problems in the 3d visualization. Stairs, that are used to connect floors, cannot be placed exactly inside the geometry where they are, but outside the boundaries setting the arc length to the nodes of the lower floor to zero and associating those ones to the upper floor trough a link. The result is that people attempting to use stairs disappear from the level in which they are to appear on the stair aside the room and in the same way they disappear from the stair to appear in the other level.

TABLE XIII

LEVELS NAME AND CONTENT

Name	Content
Gas Room Level	Gas Room, Ground False Floor and the corridor to the By-Pass Exit of the Control Zone
Ground Floor	Ground Floor, Transformer Room, Corridor and the Service Room
Laser Barrack	Laser Barrack area
5.8 Level	First False Floor and the 5.8 Level of the Upper Floors
ST roof	The area formed by the Service Room roof
First Floor CZ	First Floor

In Figure 35 is shown the 3d representation of the cavern model created in the Geometry mode.

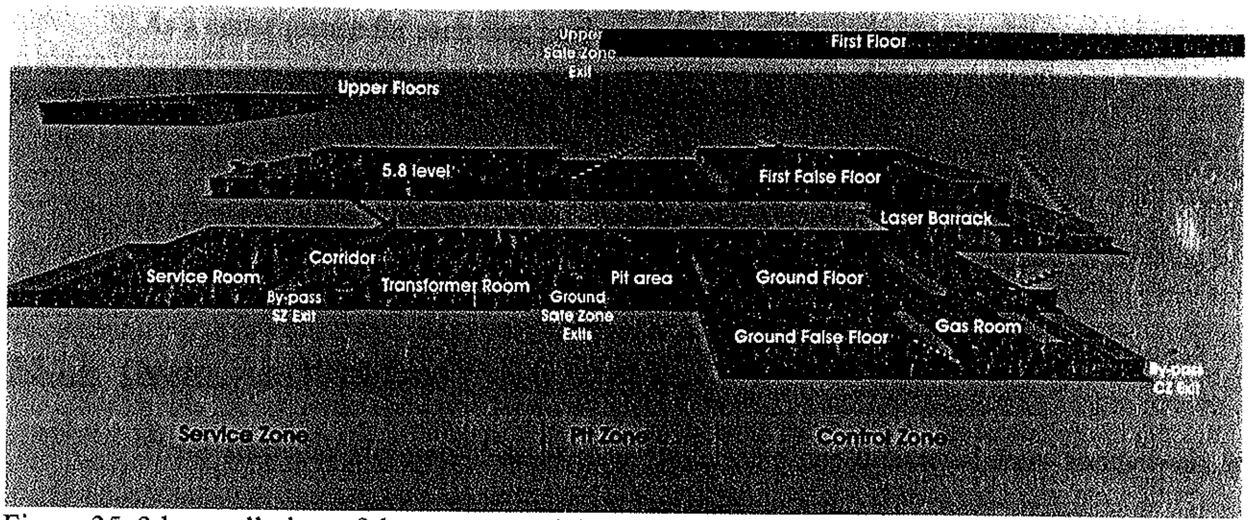

Figure 35. 3d overall view of the cavern modeled with buildingExodus.

3.3 Occupant Sub-Model

The OCCUPANT sub-model defines each individual as a collection of attributes which broadly fall into four categories, physical (such as Age, Gender, Agility, etc…), psychological (such as patience, drive, etc…), experiential (such as Distance, PET, etc…) and hazard effects. These attributes have the dual purpose of defining all occupants as individuals while allowing their progress through the enclosure to be tracked. Some of the attributes are fixed throughout the simulation while others are dynamic, changing as a result of inputs from the other sub-models.

Considering that CERN decided that only 100 people can be underground at the same time at Point 5 and that less than 40 has to be in the UXC55 cavern I decided to perform the simulations with all the people in the USC55. Furthermore I considered that all them were in the hazard zone considered.

As a consequence for each case I created a block of 100 individuals whose parameters are randomly distributed between defined upper and lower bounds.

3.3.1 Physical Attributes

3.3.1.1 Gender, Age, Height and Weight Attributes.

These attributes are used to assist in distinguishing one individual from another and in providing a rationale for assigning various attributes. This type of distinction is necessary because, on average, values for the defining characteristics are dependent on age, gender and weight.

Attribute	: Gender.
Range	: Male or Female.
Value	: Random.
Influenced by	: None.
Influences	: Agility, Drive, Travel Speed, Height and Weight.
Note	: Used to represent the gender of each occupant.

Attribute	: Age.
Range	: 21 - 65 years.
Value	: Random.
Influenced by	: None.
Influences	: Travel Speed, Height and Weight.
Note	: Used to represent the age of each occupant.

Attribute	: Weight.
Range	: 50 -90 Kgs.
Value	: Random.
Influenced by	: None.
Influences	: None.
Note	: Used to represent the weight of each occupant.

Attribute : Height.
Range : 1.54 – 2.0 m.
Value : Random.
Influenced by : Age and Gender.
Influences : None.
Note : Used to represent the height of each occupant.

3.3.1.2 Mobility Attribute.

It is a multiplicative factor used in conjunction with the Travel Speed and Agility attributes. It has two functions: initially, it is intended to allow the introduction of physical disability into the occupant description. An occupant not suffering from any disability will have an initial Mobility of one, while an occupant with a minor disability, such as an arm in plaster, will have a slightly reduced Mobility value of for example 0.9. The second function of the Mobility attribute is to reduce the occupants' Travel Speed and Agility in response to their growing exposure to the narcotic agents and smoke concentration. The Mobility may vary from its initial value (no detrimental effects), to zero (individual has expired). So the Mobility is multiplied by the occupant's initial mobility level to form a dynamically calculated mobility, dependent upon the surroundings conditions, reflected in:

Occupant Mobility = Initial Mobility * Mobility

Smoke has the effect of obscuring vision and irritating the eyes thus impairing the ability of an individual to escape. Several studies like that one from Jin [4,5] have suggested that a victim's movement rate decreases as the smoke concentration increases. This effect is thought to be concentration related and does not increase with prolonged exposure. Within EXODUS, the smoke density is linked to the Mobility attribute and it may also exert an influence on the occupant's navigation efficiency.

The impact of smoke upon the individual's Mobility is related to the representation of irritants within the simulation. The Jin 'irritant' data-set is used to describe the complete impact of the smoke and irritant gases on the movement rates of exposed individuals. This does not require the specification of irritant gas concentrations. The applied relationship is intended to approximate the reduction in the individuals travel speed due to the impact of irritant smoke (including the obscuration effect of smoke). However, it does not directly impact the well-being of the exposed individuals.

The Mobility attribute is kept constant up to smoke concentrations of 0.1 /m after which point it is calculated according to the following function,

$$\text{Mobility} = -2.08\,K^2 - 0.38\,K + 1.06$$

where K represents the extinction coefficient (/m) of the smoke (see Figure 36). For a smoke concentration of 0.45 /m, the above formulation decreases the mobility to approximately half of its original value. For smoke concentrations above 0.5 /m (i.e. Mobility less than 0.36) occupant escape abilities are severely limited and the model assumes a maximum Travel Speed equivalent to the Crawl Rate, that is set to 20% of the occupant's Fast Walk speed, rather than establishing the Travel Speed according to the occupant Mobility.

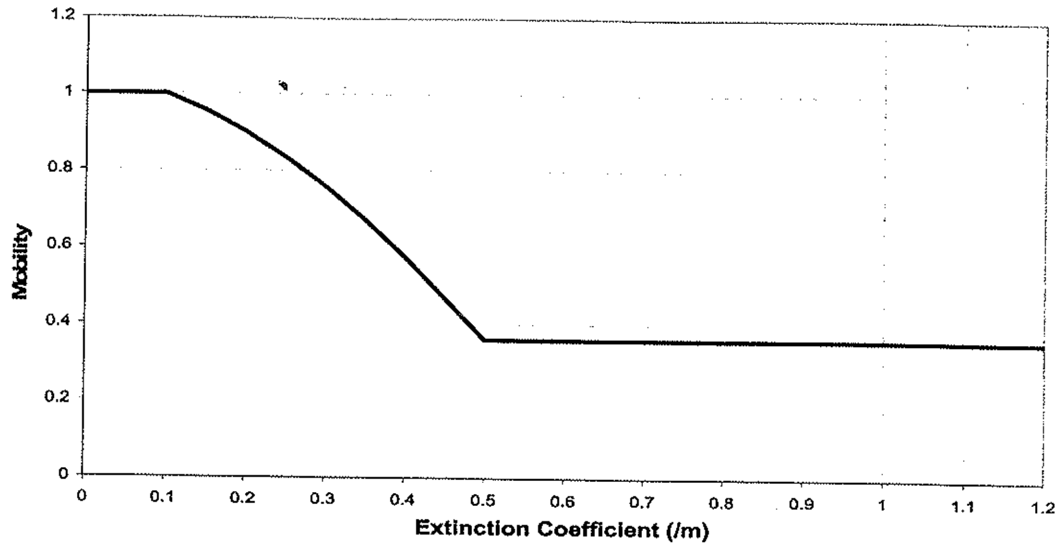

Figure 36. The impact of smoke upon occupant mobility.

Attribute	: Mobility.
Range	: 0.0 – 1.0.
Initial Value	: 1.0.
Influenced by	: Smoke Concentration.
Influences	: Agility, Travel Speed.
Note	: Used to represent movement impairing disability and the impact of fire hazards.

3.3.1.3 Travel Speed Attribute.

It reflects the occupant current travel speed. This is dependent on the occupant's initial maximum Travel Speed, their Mobility and the nodes being traveled over. I set five levels of travel speeds identified as Fast Walk, Walk, Crawl, Stairs-Up and Stairs-Down. These represent the maximum unhindered speed the occupant can attain under a variety of conditions. Initially each occupant is assigned a maximum Fast Walk speed and the Walk and Crawl rates are automatically determined as a percentage of this speed as shown in TABLE XIV. The Stairs-Up and Stairs-Down rates are dependant on age and gender and are determined from data generated by Fruin [6] (see TABLE XV).

The nodes attributes govern which one of the six travel speed rates is appropriate according to TABLE XVI

TABLE XIV

FAST WALK, WALK AND CRAWL TRAVEL SPEEDS

Travel Speed Type	Speed m/s
Fast Walk (Initial Travel Speed)	0.8 - 1.5
Walk	Fast Walk * 90%
Crawl	Fast Walk * 20%

TABLE XV

DEFAULT STAIR TRAVEL RATE

Gender	Age (years)	Down average (m/s)	Up average (m/s)
Male	< 30	1.01	0.67
Female	< 30	0.755	0.635
Male	30 – 50	0.86	0.63
Female	30 – 50	0.665	0.59
Male	> 50	0.67	0.51
Female	> 50	0.569	0.485

TABLE XVI

NODE – TRAVEL SPEED DEPENDANCE

Node Type	Travel Speed
Free-Space ⇔ Free Space	Fast Walk
X ⇔ Boundary	Walk
X ⇔ Landing	Walk
X ⇔ External Exit	Walk
Stair	Stairs-Up / Stairs Down
Free-Space ⇔ Internal Exit	Fast Walk

The final contribution to the travel speed is derived from the occupant's mobility attribute. Reductions in Mobility cause a reduction in Travel Speed. An occupant's Travel Speed at any point in time is determined by the relation:

Travel Speed = initial Travel Speed * Mobility

When caught in a crowd or queue, EXODUS regulates an individual's Travel Speed through the Conflict Resolution procedure in which a time penalty is added to each occupant involved in a conflict. Thus, even if an individual is assigned a high Fast Walk rate, if the individual is caught in a slowly moving crowd or exit queue, he will automatically move with a reduced speed. The reduced speed is intended to represent the speed of the crowd or queue resulting from the congestion.

Attribute	: Travel Speed.
Range	: 0.0 – 1.5 m/s.
Value	: Calculated.
Influenced by	: Mobility, Terrain, Atmospheric conditions.
Influences	: Performance and Behavior.
Note	: Used to represent the maximum travel speed of an occupant.

3.3.1.4 Agility

Agility is intended to represent the physical prowess of the individual in tackling obstacles. An occupant's Agility at any point in time is determined by the relation,

Agility = Initial Agility * Mobility

Attribute	: Agility.
Range	: 1.0 – 7.0.
Value	: Calculated.
Influenced by	: None.
Influences	: Performance and Behavior.
Note	: Used to represent movement impairing disability and impact of fire hazards on exposed occupants.

Attribute	: Initial Agility.
Range	: 3.0 – 7.0.
Value	: Random.
Influenced by	: None.
Influences	: Performance and Behavior.
Note	: Used to represent initial movement impairing disability.

3.3.2 Psychological Attributes

3.3.2.1 Drive Attribute

The Drive attribute is a measure of the assertiveness of an occupant. It is used as a basis for conflict resolution. In situations where occupants compete to occupy a node, the occupant's Drive will resolve possible conflicts. The Drive attribute is assigned values from 1 (low drive) to 15 (high drive). There is some evidence to support the belief that young males generally have the highest drive while older females tend to have the lowest drive. This is suggested from competitive evacuation trials involving financial payments to evacuees who are amongst the first few to successfully evacuate [7].

Attribute	: Drive.
Range	: 1 – 10 female 5 – 15 male.
Value	: Random.
Influenced by	: None.
Influences	: Conflict resolution, Performance and Behavior.
Note	: Used in conflict resolution by BEHAVIOUR Sub-model

3.3.2.2 Patience Attribute

During a simulation, various occupants will be forced to remain stationary while in a queue or while attempting to join a flow of moving people. The Patience attribute is a measure of the amount of time (in seconds) that an occupant is prepared to wait before considering or attempting an alternative action. Compliant occupants will have a long Patience while less compliant occupants will have a relatively short Patience attribute.

Attribute : Patience.
Range : 0 – 1000 seconds.
Value : Random.
Influenced by : None.
Influences : Performance and Behavior.
Note : Used by BEHAVIOUR Sub-model

3.3.2.3 Response Time Attribute

The Response Time is intended to be a measure of the pre-evacuation movement time incurred by the occupant. It represents the difference in time between the time the occupant begins to actively evacuate and the time at which the call to evacuate was issued. With the current version of Exodus this time is counted from the beginning of the simulation for all the people, but due to the fact that our geometry is quite complex and so in certain zone people becomes aware of the hazard after a certain period Response Zones had to be set. This zones guarantee that the personnel starts to evacuate after user defined times (see TABLE XVII) which is the worst condition, in fact it does not take in consideration the presence of a fire alarm system.

TABLE XVII

RESPONSE ZONE TIMES

Scenario	Zone	Time (seconds)
One	Ground Floor Control Zone	90
	Laser Barrack	150
	First False Floor	150
	First Floor	540
Four	Upper Floors Service Zone	190
Five	First Floor Control Zone	100

3.3.3 Experiential Attributes

3.3.3.1 Personal Elapsed Time (PET) Attribute

The PET (Personal Elapsed Time) is a dynamic attribute that is calculated continuously by EXODUS for each occupant. It is a measure of the time spent by the occupant in the evacuation. At the end of the simulation, it measures the time to exit or incapacitation. PET is initially set to zero.

Attribute	: PET.
Range	: 0 – indefinite seconds.
Initial Value	: 0 seconds.
Influenced by	: None.
Influences	: None.
Note	: The PET is a measure of time. At the end of the simulation it indicates the time to evacuate or to incapacitation.

3.3.3.2 Distance Traveled Attribute

Distance Traveled is a dynamic attribute that is calculated continuously by EXODUS for each occupant. It is a measure of the total distance (measured in meters) traveled by the occupant at any point in time. At the end of the simulation, it measures the distance traveled to an exit point, or the point of incapacitation. The Distance Traveled attribute is initially set to zero.

Attribute	: Distance Traveled.
Range	: 0 – indefinite seconds.
Initial Value	: 0 seconds.
Influenced by	: None.
Influences	: None.
Note	: The Distance Traveled attribute is a measure of the distance traveled.

3.3.3.3 Distance Remaining Attribute

The Distance Remaining is a dynamic attribute that is calculated continuously by EXODUS for each occupant. It represents the remaining distance (measured in meters) that the occupant must travel in order to reach their exit point. If the occupant successfully evacuates from the enclosure, at the end of the simulation, it is zero. If the occupant is incapacitated the Distance Remaining attribute specifies how close to an exit point he/she was at the time of incapacitation. The Distance Remaining attribute is initially set to zero.

Attribute	: Distance Remaining.
Range	: 0 – indefinite meters.
Initial Value	: 0 meters.
Influenced by	: None.
Influences	: None.
Note	: The Distance Remaining attribute is a measure of the remaining distance (measured in meters) that the occupant must travel in order to reach an exit.

3.3.3.4 Cumulative Wait Time (CWT) Attribute

The CWT attribute is a dynamic attribute that is calculated by EXODUS for each occupant. The CWT is a measure of the total time (in seconds) that an occupant remains stationary after he/she has started to evacuate The CWT attribute is initially set to zero

Attribute	: CWT.
Range	: 0 – indefinite seconds.
Initial Value	: 0 seconds.
Influenced by	: None.
Influences	: None.
Note	: The CWT measures the total time an occupant remains stationary.

3.3.4 Hazard Effect Attributes

The link between the degradation in occupant attributes and increasing exposure to narcotic gases and the influence of thermal radiation and elevated temperatures on human behavior during evacuation have not been researched thoroughly and as a result no attempt has been made to model directly this influence on the decision making process.

3.4 Movement Sub-Model

It is primarily concerned with the physical movement of the occupants through the different terrain types. It consists of a number of rules, the main function of which is to determine the appropriate travel speed for the current terrain type. In addition, the MOVEMENT sub-model ensures that the occupant has the capability of performing the requested action, for example it checks if the occupant Agility is sufficient to allow travel over nodes with particular Obstacle values. While the MOVEMENT sub-model is responsible for moving the occupant, it is the BEHAVIOUR submodel that selects the direction of travel. If a suitable move is not available to the occupant, the MOVEMENT sub-model will supervise a Wait period. During the Wait period the occupant remains stationary until a suitable move becomes available.

In the current version of EXODUS there is no provision for occupant's to push past each other while in queues. In these circumstances, the person can wait for his/her turn to move, or if their Patience has expired, take a detour round the obstruction.

3.5 Hazard Sub-Model

In this sub-model the hazard zones, parameters and evolution were to be defined. It would be too long to report here all the zones and parameters I putted in the program I reported all the data in Appendix B remembering that the hazard evolution is described by the following equation:

$$\text{Hazard} = \text{Initial hazard} + m\, t^p$$

Being the heat release rate of the parabolic type it would be reasonable to assume that the parameter K, which is the inverse of the visibility, rose with the same trend. Unfortunately given an exponent p=2 and the initial and final value of the parameter K in the previous equation, the constant m was of the order of magnitude of 10^-4 or less. The disponible digits in the program were only sufficient to display values of 10^-3. An exponent p=1 was then chosen that is moreover a conservative assumption.

The program could assign different hazard values to the walking layer (placed at 1.7 m with respect to the floor) and to the crawling one (placed at 1 m), but having in FDS a grid dimension of half a meter it was not possible for me to distinguish them. Afterwards I decided to assume for the lower layer the same values of the upper one that is a conservative assumption being these values lower than those assumed.

3.6 Toxicity Sub-Model

In this sub-model is calculated the Mobility in function of the local visibility as I already explained in the Mobility Attribute paragraph.

3.7 Behavior Sub-Model

3.7.1 Global Behavior

Occupants move under the influence of the nodal potential, which is a measure of the distance from the node to the most attractive exit point, attempting to move in a manner that lowers their potential. However, situations arise where this may not always be possible. In these circumstances the best move will be selected in this way: the top priority is to move to a node with a lower potential, thus reducing the distance to the nearest exit point. If more than one node is available that reduces the potential, the node reducing it by the largest amount will be selected. If a node of lower potential is unavailable, nodes of equal potential may be considered. Where no nodes of lower or equal potential are available, an occupant will wait. Nodes with higher potentials are normally not considered until the occupant Wait Counter attribute exceeds the corresponding Patience attribute (Extreme Behavior). An occupant will revert to the Normal Behavior once a move has occurred that lowers their potential. Using this approach, occupants will generally move to their nearest serviceable exit.

3.7.2 Local Behavior

It includes people – people interactions, people – fire (environmental) interactions and people – structure (terrain) interactions.

3.7.2.1 Response Time

As already said I decided to utilize Response Zones instead of the individual response Time. Prior to the commencement of evacuation the occupants are allowed to mill around. This movement will not allow them to accidentally evacuate and will not be recorded as part of the evacuation process.

3.7.2.2 Conflict Resolution

If the occupants are determined to arrive at a node during the same tick of the simulation clock they are deemed to be in conflict. The resolution of such a conflict is then attempted through an evaluation of the drive attribute for each of the occupants. The Drive for each occupant involved in the conflict is compared. If one of the occupants has a Drive significantly higher than the others, this occupant becomes the winner. However, if the Drives are sufficiently close, the winner is randomly selected. All occupants involved in conflicts attract a time penalty that is randomly selected between predetermined limits. The time penalty represents the time lost in the interaction. There are two levels of time penalty. The first level (0.5 – 0.7 seconds) is associated with conflicts that are resolved on clear differences in Drive. If the conflict is resolved in a random manner, the second level time penalty (0.8 – 1.5 seconds) is used. Conflict losers may continue to wait in the same location until another opportunity to occupy the node arises, or perform another action such as change direction.

3.7.2.3 Inefficient Movement within Smoke

Under experimental conditions Jin found that when encountering smoke, in addition to a reduction in travel speed the evacuee movement became increasingly inefficient, with evacuee's 'staggering' along a smoke-filled corridor. This was due to the visual obscuration caused by the dense, irritant environmental conditions. An additional behaviour noticed by Jin was that in smoke conditions, occupants tended to use the walls to assist them in navigation. Both these behaviours have been considered in the simulation.

As the extinction coefficient of the smoke increases, so the likelihood of inefficient movement increases; the possibility of the occupant straying from his optimal path is directly linked to the environmental conditions. Instead of the nodal attractiveness being entirely dependent upon its distance from a particular destination or the nodal potential differences, the extinction coefficient of the smoke also has an impact upon the attractiveness of the node, allowing non-optimal decisions to be made.

The occupant initially prioritises the nodal options according to their attractiveness in relation to their target. Once completed the attractiveness of the node is biased in relation to the environmental conditions. This biasing is weighted according to the severity of the conditions and is then multiplied by a random value (between 0 and 1.0), to incorporate stochastic processes. Therefore, as the occupant passes through a smoke filled environment his identification of nodes as viable options becomes inaccurate, forcing him to adopt node off his optimal line of egress, and causing a stagger. The probability of this movement occurring is bounded, with smoke levels influencing occupant behaviour between extinction coefficients of 0.1/m and 0.5/m.

The Stagger Behaviour may also cause the occupants to temporarily avoid nodes that have a relatively high smoke concentration. If an alternative node exists, which satisfies the rules of movement according to the behavioural regime and that has a lower smoke concentration, it will appear more attractive than an otherwise equivalent node of higher smoke concentration.

3.7.2.4 Occupant Redirection in Response to Smoke

For the behaviour to be activated, the occupant has to be located in a relatively clear environment. This is determined as being when the occupant is located on a node with an extinction coefficient less than 0.1/m. If this is not the case then the occupant is assumed to be 'engulfed' in smoke, which may trigger other environmental behaviours. If the occupant satisfies this condition, it is determined whether the occupant is confronted with a smoke barrier. For any analysis of this type to occur the occupant must be adjacent to the smoke hazard. The smoke barrier is only influential if it lies closer to the occupant's target than the occupant's present position. Therefore if all of the nodes that are situated sufficiently closer to the occupant's target have an extinction coefficient greater than 0.1/m, then it is assumed that a barrier has been formed and redirection is performed.

Given that the barrier is perceived, the visibility afforded by the environment is calculated according to $S = C / K$ where S is the visibility (m), K is the extinction coefficient (m^{-1}) and C represent a dimensionless constant assumed to be equal to 2 that is the most conservative estimate of the occupant's visual ability. If the visibility afforded by the smoke barrier is greater than his expected travel distance to his target exit, then the occupant automatically maintains the current egress route. This prevents occupants redirecting once they are close to their exit or when they are 'in sight' of their exit. If the occupant is not within the calculated visible range of his exit, the occupant must decide his next course of action. Only two options are available to the occupant, either continuing through the smoke barrier or re-directing away from it.

3.8 Evacuation Results

I run 5 simulations for each Case to be sure that results where quite similar. In the following you can find the worst simulation I got for each one of the simulated scenarios. A table summarizes the most important random attribute assigned with the minimum value, the maximum value and the average one. There are also indicated the amount of people out and the time at which the first and the last person evacuated. In the last part of each table you can find the number of people starting from a level and the time at which the level was completely empty.

Moreover for each Case I produced a graph reporting the people out with respect to time both for each exit involved in the simulation and the cumulative one.

TABLE XVIII

SIMULATION OF CASE ONE WITH 100 PEOPLE.

Attribute	Average	Min	Max
Males	46	46	46
Female	54	54	54
Age	40.14	20	59
Agility	5.11	3.02	6.94
Drive	7.44	1.33	14.87
Fast Walk(m/s)	1.16	0.81	1.5
Walk (m/s)	1.04	0.73	1.35
Crawl (m/s)	0.23	0.16	0.3
Leap (m/s)	0.93	0.65	1.2
Mobility	1	1	1
Patience (s)	1000	1000	1000
Response (s)	325.07	90.58	540
Weight	60.89	49	74
Height	1.69	1.54	1.83

100 out	first out (s)	100.52	last out (s)	601.78

People Starting	on Gas_Room_level	4	last exit (s)	222.56
	on Ground_Floor	30	last exit (s)	206.68
	on Laser_Barrack	14	last exit (s)	171.2
	on Level_5.8	2	last exit (s)	174.43
	on First_Floor_CZ	50	last exit (s)	601.78

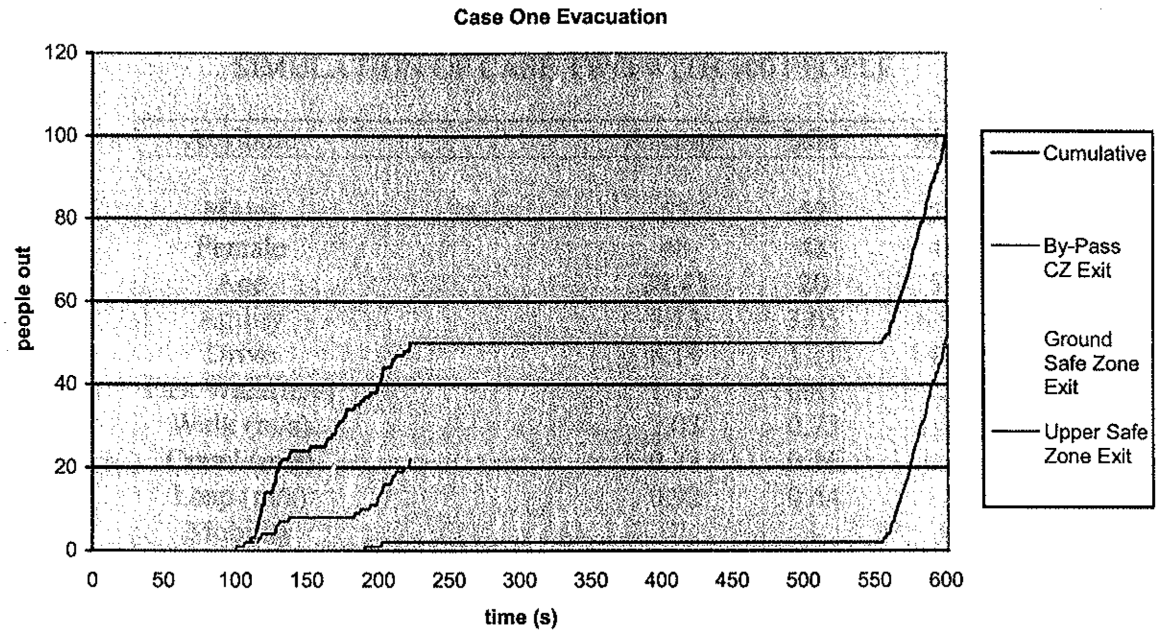

Figure 37. Evacuation trend for case one. Assuming people are not alerted by a fire alarm system. Evacuation for individuals is triggered by direct encounter to smoke (smoke is visible at the upper level only after about 550 seconds).

TABLE XIX

SIMULATION OF CASE TWO WITH 100 PEOPLE

Attribute		Average	Min	Max
Males		52	52	52
Female		48	48	48
Age		39.43	20	59
Agility		5.13	3.05	6.94
Drive		8.14	1.11	14.71
Fast Walk(m/s)		1.15	0.81	1.5
Walk (m/s)		1.03	0.73	1.35
Crawl (m/s)		0.23	0.16	0.3
Leap (m/s)		0.92	0.64	1.2
Mobility		1	1	1
Patience (s)		1000	1000	1000
Response (s)		13.47	0.17	29.83
Weight		61.11	49	74
Height		1.69	1.55	1.83
100 out	first out (s)	36.61	last out (s)	154.18
People Starting	on Gas_Room_level	0	last exit (s)	154.18
	on Ground_Floor	0	last exit (s)	133.66
	on Laser_Barrack	0	last exit (s)	109.4
	on Level_5.8	5	last exit (s)	56.39
	on First_Floor_CZ	95	last exit (s)	89.43

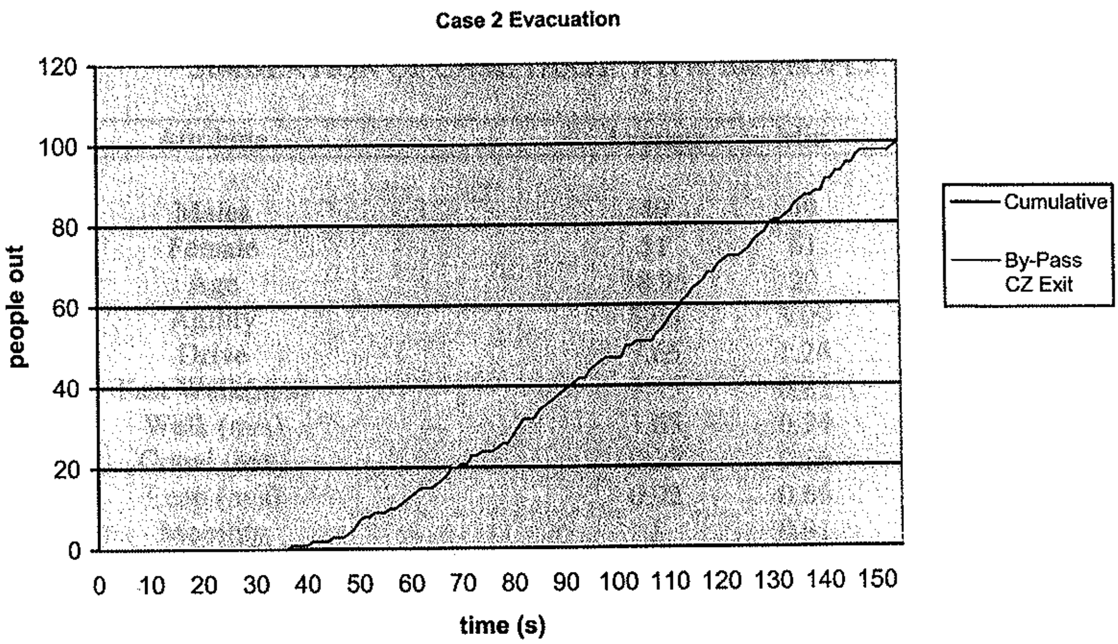

Figure 38. Evacuation trend for case two

TABLE XX

SIMULATION OF CASE THREE WITH 100 PEOPLE

Attribute		Average	Min	Max
Males		49	49	49
Female		51	51	51
Age		38.95	20	59
Agility		5.08	3.09	6.93
Drive		7.65	1.26	14.94
Fast Walk(m/s)		1.15	0.82	1.48
Walk (m/s)		1.03	0.74	1.33
Crawl (m/s)		0.23	0.16	0.3
Leap (m/s)		0.92	0.66	1.18
Mobility		1	0.91	1
Patience (s)		1000	1000	1000
Response (s)		14.2	0.01	29.08
Weight		60.96	49	74
Height		1.68	1.54	1.83
100 out	first out (s)	6.95	last out (s)	54.21
People Starting	on Ground_Floor	100	last exit (s)	54.21

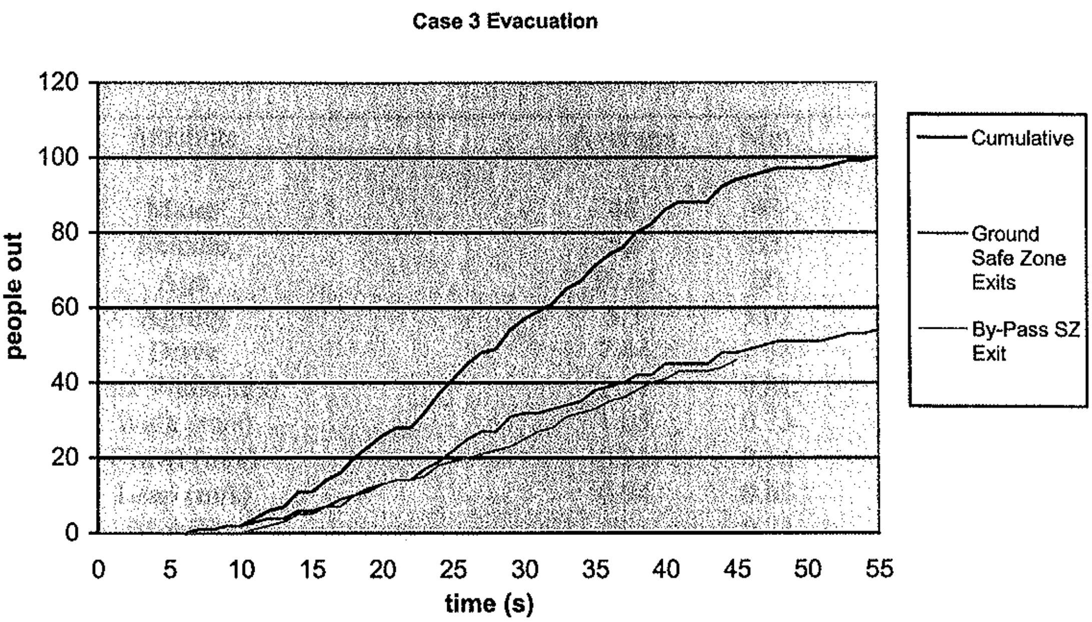

Figure 39. Evacuation trend for case three

TABLE XXI

SIMULATION OF CASE FOUR WITH 100 PEOPLE

Attribute		Average	Min	Max
Males		48	48	48
Female		52	52	52
Age		38.64	20	59
Agility		5.3	3.02	7
Drive		7.44	1.38	14.81
Fast Walk(m/s)		1.17	0.81	1.49
Walk (m/s)		1.05	0.73	1.34
Crawl (m/s)		0.23	0.16	0.3
Leap (m/s)		0.94	0.65	1.19
Mobility		1	0.71	1
Patience (s)		1000	1000	1000
Response (s)		154.65	1.7	186.25
Weight		60.46	49	74
Height		1.68	1.54	1.82
100 out	first out (s)	13.46	last out (s)	538.78
People Starting	on Ground_Floor	15	last exit (s)	538.78
	on Level_5.8	70	last exit (s)	471.37
	on ST_roof	15	last exit (s)	253.64
	on First_Floor_CZ	0	last exit (s)	382.98

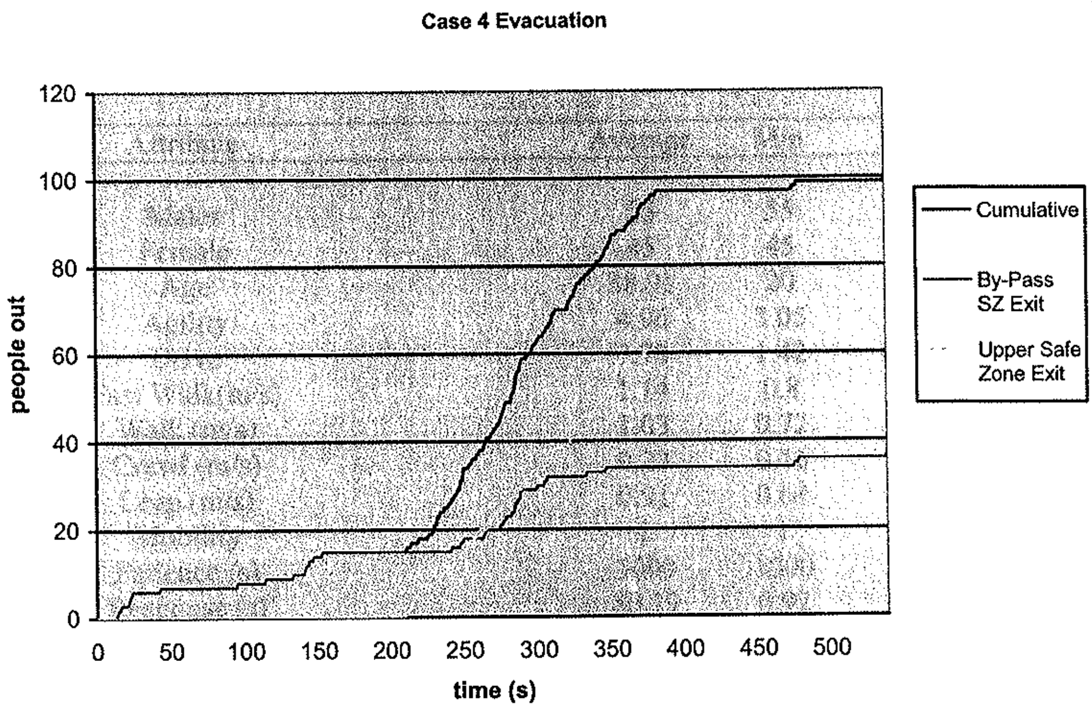

Figure 40. Evacuation trend for case four

TABLE XXII

SIMULATION OF CASE FIVE WITH 100 PEOPLE

Attribute	Average	Min	Max
Males	55	55	55
Female	45	45	45
Age	38.91	20	59
Agility	4.96	3.05	6.99
Drive	7.78	1.42	14.19
Fast Walk(m/s)	1.14	0.8	1.49
Walk (m/s)	1.03	0.72	1.34
Crawl (m/s)	0.23	0.16	0.3
Leap (m/s)	0.91	0.64	1.19
Mobility	1	1	1
Patience (s)	1000	1000	1000
Response (s)	80.19	0.92	100
Weight	61.42	49	74
Height	1.69	1.54	1.82

100 out	first out (s)	23.14	last out (s)	168.25

People Starting	on Gas_Room_level	0	last exit (s)	104.82
	on Ground_Floor	0	last exit (s)	89.47
	on Laser_Barrack	15	last exit (s)	82.39
	on Level_5.8	5	last exit (s)	69.59
	on First_Floor_CZ	80	last exit (s)	168.25

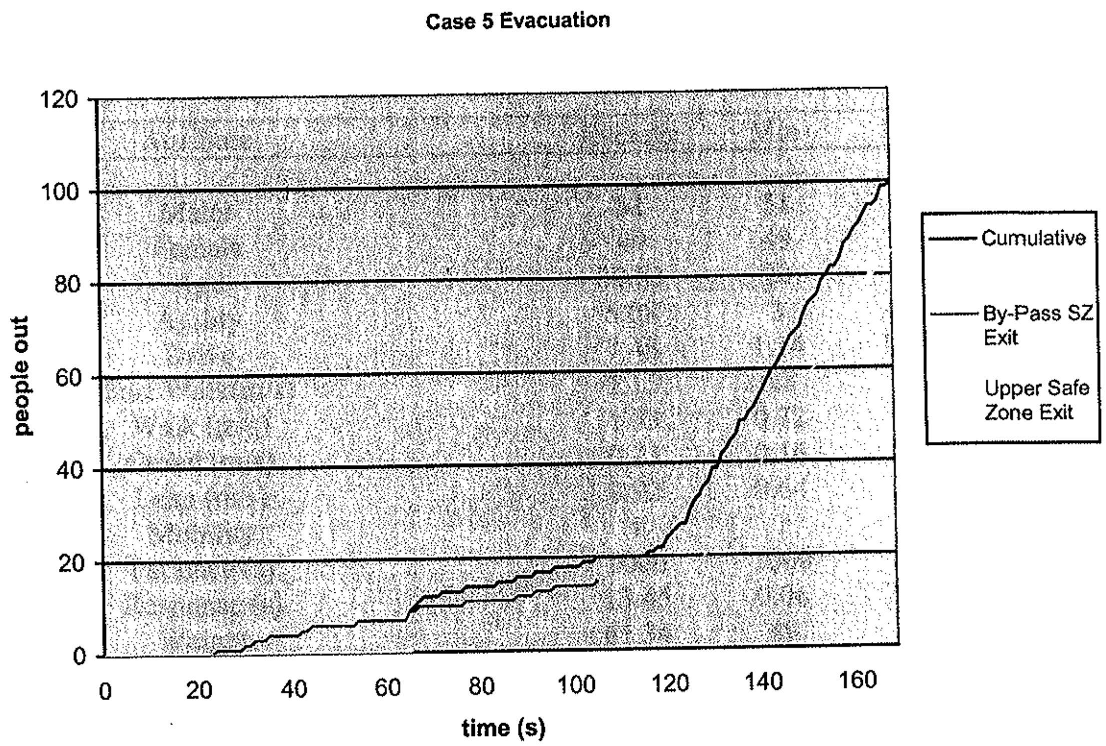

Figure 41. Evacuation trend for case five.

TABLE XXIII

SIMULATION OF CASE SIX WITH 100 PEOPLE

Attribute	Average	Min	Max
Males	51	51	51
Female	49	49	49
Age	39.83	20	59
Agility	5.08	3	6.77
Drive	7.48	1.14	14.94
Fast Walk(m/s)	1.15	0.8	1.5
Walk (m/s)	1.03	0.72	1.35
Crawl (m/s)	0.23	0.16	0.3
Leap (m/s)	0.92	0.64	1.2
Mobility	1	1	1
Patience (s)	1000	1000	1000
Response (s)	13.45	0.06	29.88
Weight	61.34	49	74
Height	1.68	1.54	1.83

100 out	first out (s)	24.64	last out (s)	123.27

People Starting	on Ground_Floor	0	last exit (s)	123.27
	on Level_5.8	70	last exit (s)	103.01
	on SR_roof	30	last exit (s)	39.68

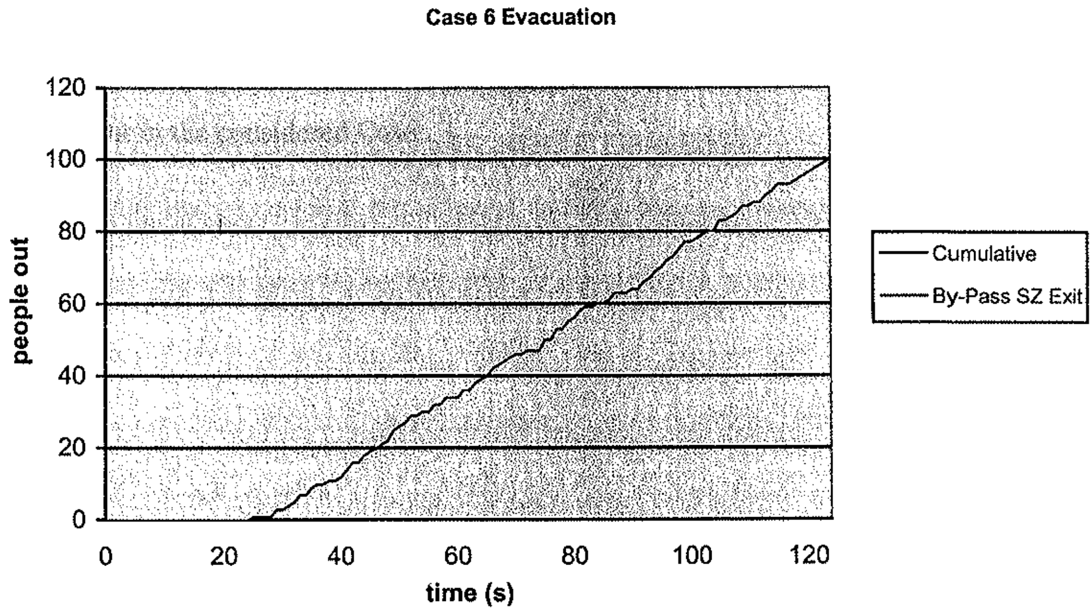

Figure 42. Evacuation trend for case six.

3.9 Conclusions on Evacuation

No problems arose from the simulations, but some considerations have to be done at least for the Safe Zone Exits. In fact in the EXODUS program they were considered as external exits, but they are not, so I have to verify that the Safe Zone is sufficient to host the incoming people and that the lift is suitably dimensioned.

The dimension of the two Safe Zones is of 19 square meters for the one at the ground level and of 19.5 for the one placed at the upper level. Considering a maximum population density of 3 person per square meter I get that the Ground Floor Safe Zone can store 57 people while the other one 58. The only Case that has an amount of people evacuating to a Safe Zone higher than 58 was Case Five where 78 people evacuated to the Upper Safe Zone Exit in 50 seconds. The elevator can transport 40 people at a speed of 1.6 m/s that means 40 people out almost every 2 minutes which is sufficient in the considered Case.

4. EXTINGUISHING SYSTEMS PROPOSED

4.1 Introduction

Due to the presence of racks on the main floors an automatic water extinguishing system can not be installed there and being the involved volume very big neither a gas system is feasible. Some of the racks are equipped with high cost mission-critical electronics designed for the CMS detector. The money invested and the long waiting time for replacement are sufficient to impose a fast fire protection system which does not cause collateral damages. The solution proposed is to provide each critical rack with an internal fire detection system connected to a fire extinguishing system. No automatic fire protections other than this will be provided at the main floors and so personnel will have to be trained in fire fighting.

The manual fire fighting is almost impossible in the Control Zone false floors because of the height and of the presence of cables that transform these zones in a very intricate maze. So I proposed to install there an automatic system.

The halon replacement clean agent systems were not took into consideration because of the volume of the considered zones. It was not possible to isolate these areas from the other part of the cavern and neither from the UXC55 cavern with which they communicate trough the holes hosting the wires.

The presence of a cooling tower in each LHC experimental point used both to cool water of the cooling systems and to store water pumped up from the tunnel to guarantee that if the main LHC circulating pump fail a water supply is still available, represents a very good opportunity to get a water reserve without building a new tank. The total amount of water stored in the cooling tower is 350 m^3 of which 150 m^3 are available for only the cooling system. The UXC55 foam system needs 100 m^3 to be always disposable, finally we have a water supply of 50 m^3. Therefore the goal is to identify an automatic system with a total water requirement less than 50 m^3.

The only requirement given by CERN about an automatic extinguishing system was that it shall have both automatic and manual activation.

4.2 Racks Extinguishing System

Being the installed rack a confined space 0.6 m large, 0.9 m long and 2.57 m high it is possible to install a gas extinguishing system there. After the Montreal Protocol signed in September, 16, 1987 halon can not be used anymore as extinguishant. Among the variety of halon replacement clean agents, like Inergen, Argonite, Argon, ..., I focused my attention on the FM-200® because:

- It is proven safe for people through extensive toxicology testing and real-world experience
- It is non-conducting and non-corrosive, and leaves behind no oily residue, particulate, or water. After a system discharge, the agent can be cleared from the room by simple ventilation, minimizing downtime.
- It does not deplete stratospheric ozone and it has the shortest atmospheric lifetime of all of the HFC alternatives to Halon 1301 (31-42 years), assuring minimal atmospheric impact.

- It takes up less storage space than most other fire suppressants. Moreover the excellent storage efficiency of FM-200® agent minimizes the number of steel storage containers required, an often-overlooked indirect contributor to global warming.
- Availability on the market of pre-engineered systems for applications in electronic racks.

FM-200® has both physical and chemical extinguishing mechanisms but the physical mechanism in the form of energy absorption predominates over the chemical mechanism. The chemical mechanism involves reacting with the transient combustion products stopping flame propagation. Most ordinary combustible fires are quickly extinguished with concentrations of only 7% of the gas, by volume.

The standard for this application is the NFPA 2001: Standard on Clean Agent Fire Extinguishing Systems, 2000 Edition.

4.3 False Floors Extinguishing System

The first system analyzed for these areas was the sprinkler one that is the most used and cheap available in the market.

4.3.1 Sprinkler System

Automatic sprinkler systems are considered to be the most effective and economical way to apply water to suppress a fire. There are four basic types of sprinkler systems:

- A wet pipe system is by far the most common type of sprinkler system. It consist of a network of piping containing water under pressure. Automatic sprinklers are connected to the piping such that each sprinkler protects an assigned building area. The application of heat to any sprinkler will cause that single sprinkler to operate, permitting water to discharge over its area of protection.
- A dry pipe system is similar to a wet system, except that water is held back from the piping network by a special dry pipe valve. The valve is kept closed by air or nitrogen pressure maintained in the piping. The operation of one or more sprinkler will allow the air pressure to escape, causing operation of the dry valve, which then permits water to flow into the piping to suppress the fire. Dry systems are used where the water in the piping would be subject to freezing.
- A deluge system is one that does not use automatic sprinklers. A special deluge valve holds back the water from the piping, and is activated by a separate fire detection system. When activated, the deluge valve admits water to the piping network, and water flows simultaneously from all of the open sprinklers. Deluge systems are used for protection against rapidly spreading, high hazards fire.
- A preaction system is similar to a deluge system except that automatic sprinklers are used, and a small air pressure is usually maintained in the piping network to

ensure that the system is air tight. As with a deluge system, a separate detection system is used to activate a deluge valve, admitting water to the piping. Because automatic sprinklers are used, however, the water is usually stopped from flowing unless heat from the fire has also activated one or more sprinklers. Preaction systems are generally used where there is a special concern for accidental discharge of water.

The applicable standard for the sprinkler systems is the NFPA 13 [9] that is a design and installation standard which can refers to other NFPA standards for details. Most of the NFPA 13 protection criteria are the result of evolution and application of experienced judgment. In the following I will perform, following the NFPA 13, some simple calculation commonly performed in determining water supply requirements.

Occupancy hazard classification is the most critical aspect of the sprinkler system design process. If the hazard is underestimated, it is possible for fire to overpower the sprinklers.

I assumed to have an Ordinary Hazards Group 2 which correspond to definition: occupancies shall be occupancies or portions of other occupancies where the quantity and combustibility of contents is moderate to high, stockpiles of combustibles do not exceed 12 ft (3.7 m), and fires with moderate to high rates of heat release are expected.

Between different types of sprinkler I decided to use standard pendent sprinklers and following NFPA Table 5-6.2.2(b) I got for them that the protection area and maximum spacing for Ordinary Hazards were respectively 12.1 m^2 (130 ft^2) and 4.6 m (15 ft). For a sprinkler spacing of 4 m and a distance between the branches of the pipeline of 3m the Coverage Area is of 12 m^2. The design area is 243 m^2 for the Ground False Floor and 322 m^2 for the First False Floor. Consequently to obtain the number of sprinklers to be installed in each zone NFPA13 requires that each design area be divided by the maximum sprinkler spacing used, and that any fractional result be rounded up to the next whole sprinkler.

$$\text{Ground False Floor} \quad \frac{243}{12} = 20.25 \rightarrow 21$$

$$\text{First False Floor} \quad \frac{322}{12} = 26.83 \rightarrow 27$$

The water supply for sprinklers must be determinate from the area/density curves shown in Figure 43 where you enter the diagram with the design area and you get the minimum required density for every sprinkler. In the case of the entering value 243 I got 0.0073 m/min while in the case of 322 I got 0.0066 m/min. The minimum flow from a sprinkler must be the product of the area of coverage multiplied by the minimum required density; multiplying this value for the number of sprinklers operating in that design area we have the minimum flow for the considered area.

$$Q \text{ Ground False Floor} = 12 \times 0.0073 \times 21 = 1.84 \text{ m}^3/\text{min}$$

$$Q \text{ First False Floor} = 12 \times 0.0066 \times 27 = 2.14 \text{ m}^3/\text{min}$$

The standard imposes (see Table 7-2.2.1 of the NFPA13) for Ordinary Hazards a minimum flow duration of 60 minutes. The specification that the extinction system has to give the possibility to be manually activated imposes the use of a deluge sprinkler system with a separate detection system.

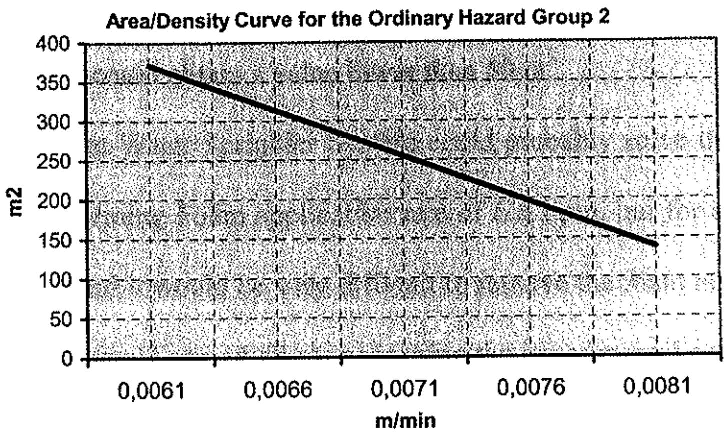

Figure 43. Area/density curve for the ordinary hazard group 2.

Although heat detectors have the lowest false alarm rate of all automatic fire detector devices, they also are the slowest in fire detecting. Because flame detectors must be able to 'see' the fire, they must not be blocked by objects placed in front of them consequently they were not at all useful in our case. A smoke detection system is then required and a VESDA one is preferable because of its widest sensitivity range and low false alarms. Using a smoke detection system the First False Floor can be activated by a fire placed in the Ground False Floor, so the water supply has to be designed to feed both the False Floor sprinkler systems at the same time for at least 60 minutes. The minimum amount of water to be stocked to guarantee the correct working of the extinguishing system is obtained adding the two flows obtained above and multiplying them for 60 minutes.

$$\text{Water supply} = (1.84 + 2.14) * 60 = 238.8 \text{ m}^3$$

This is more than 4 times the supply available in the cooling tower. Neither considering only one system operating I could obtain a value lower than 50 m^3.

The use of a Foam-Water Sprinkler System could probably solve the problem needing a minimum Aqueous Film-Forming Foam application rate of 6.6 Lpm, but for a duration reduced to 10 minutes. On the other hand it would be very difficult to remove the foam and, not being possible to seal the zones, the foam would spread all over reaching the experimental cavern trough the holes hosting cables.

4.3.2 Water Mist System

A water mist system is a fire protection system using very fine water sprays. The very small water droplets allow the water mist to control or extinguish fires by cooling of the flame and fire plume, oxygen displacement by water vapor, and radiation heat attenuation.

The idea is to install a Low Pressure Water Mist System with open nozzles activated by a separate fire detection system. This to achieve the CERN requirement of manual activation option already exposed. The standard to be followed was the NFPA750.

Currently, no generic design method is recognized for water mist protection systems. The relationship between flux density or nozzle spacing and performance in controlling fires is not consistent between systems designed by different manufactures. The system features, such as nozzle spacing, flow rate, drop size distribution, cone angle, and other characteristics, need to be determined for each manufacturer's system through full-scale fire testing to obtain a listing for each application.

It is by the way useful to make a preliminary calculation to verify if it is possible to install a low pressure water system in which the pressure is only given by the difference in height between the water tank, placed at the surface, and the system location (90 m underground). This could bring a reduction of both construction and maintenance costs as well as a relevant increase in reliability of the system not using any kind of active water displacement.

Contacting the main water mist companies I got, for the given zone and hazard, a minimum flow rate value of 0.0021 m^3/min, required to protect with one nozzle an area of 9 m^2. A minimum pressure of about 0.8 MPa (8 bar) had to be guaranteed at the remotest nozzle.

Dividing the design areas for the coverage area, and rounding up any fractional result to the next whole nozzle:

Ground False Floor $\frac{243}{9} = 27 \rightarrow 27$ nozzle

First False Floor $\frac{322}{9} = 35.78 \rightarrow 36$ nozzles

Multiplying the minimum flow rate of 0.0021 m^3/min for the number of nozzles present in that area I obtained the minimum flow for each False Floor:

Q Ground False Floor = 0.0021 x 27 = 0.057m^3/min

Q First False Floor = 0.0021 x 36 = 0.075 m^3/min

The total flow in case both the systems are contemporarily working is of 0.132 m^3/min that, with the 50 m^3 water supply, gives a duration of more than 6 hours while the minimum requested duration is of 30 minutes. It is therefore possible to use the water reserve available in the cooling tower. It remained to verify the pressure requirement.

The pressure drop calculation was done using the Hazen-Williams calculation method, proposed by the NFPA750 standard, valuable for water mist systems with working pressure not exceeding 0.12 MPa (12 bar) and having no additives.

The equations used are:

Bernoulli's Equation

$$p + \frac{1}{2}\rho u^2 + \rho g h = \cos t$$

where:

p = pressure (Newton/m^2)

u = particle velocity (m/s)

ρ = volume density of water (Kg/m^3) assumed to be 998 Kg/m^3

g = Newton's gravitational constant (m/s^2) assume to be constant and equal to 9.81 m/s^2

h = height of center of mass axis (m)

assuming water as a non viscous, incompressible fluid.

Hazen-Williams Friction Loss Formula

$$P_m = 6.05 \frac{Q_m^{1.85}}{C^{1.85} d_m^{4.87}} \times 10^5$$

where:

P_m = frictional resistance (bar/m of pipe)

Q_m = flow (L/min)

d_m = actual internal diameter of the pipe (mm)

C = friction loss coefficient (equal to 150 for stainless steel pipes)

To get the pressure drop, taking into account the local friction resistances, the frictional resistance has to be multiplied by the Total Pipe Length which is defined as follow:

Total Pipe Length = Pipe Length + $\sum$ N. of fittings/valves * Equivalent Length

Where the pipe length is the effective length of the pipe, while the equivalent length is added to take into account the presence of different fittings or valves. The values of this equivalent lengths for different kind of pipes are reported in TABLE XXIV.

TABLE XXIV

EQUIVALENT LENGTH OF PIPE FOR C=150

Nominal or Standard Size		Fittings				Valve
		Standard Ell		90° Tee		Butterfly
		90°	45°	Side branch	Straight run	
mm	In.	m	m	m	m	m
9.53	⅜	0.15	-	0.46	-	-
12.7	½	0.31	0.15	0.61	-	-
15.88	⅝	0.46	0.15	0.61	-	-
19.05	¾	0.61	0.15	0.91	-	-
25.4	1	0.76	0.31	1.37	-	-
31.75	1 ¼	0.91	0.31	1.68	0.15	-
38.1	1 ½	1.22	0.46	2.13	0.15	-
50.8	2	1.68	0.61	2.74	0.15	2.29
63.5	2 ½	2.13	0.76	3.66	0.15	3.05
76.2	3	2.74	1.07	4.57	0.31	4.72
88.9	3 ½	2.74	1.07	4.27	0.31	-
101.6	4	3.81	1.52	6.40	0.31	4.88

Due to the configuration of the False Floors it is evident that the remotest nozzle will be the one placed at the First False Floor ceiling at the opposite side of the cavern with respect to the main pipeline as shown in Figure 44.

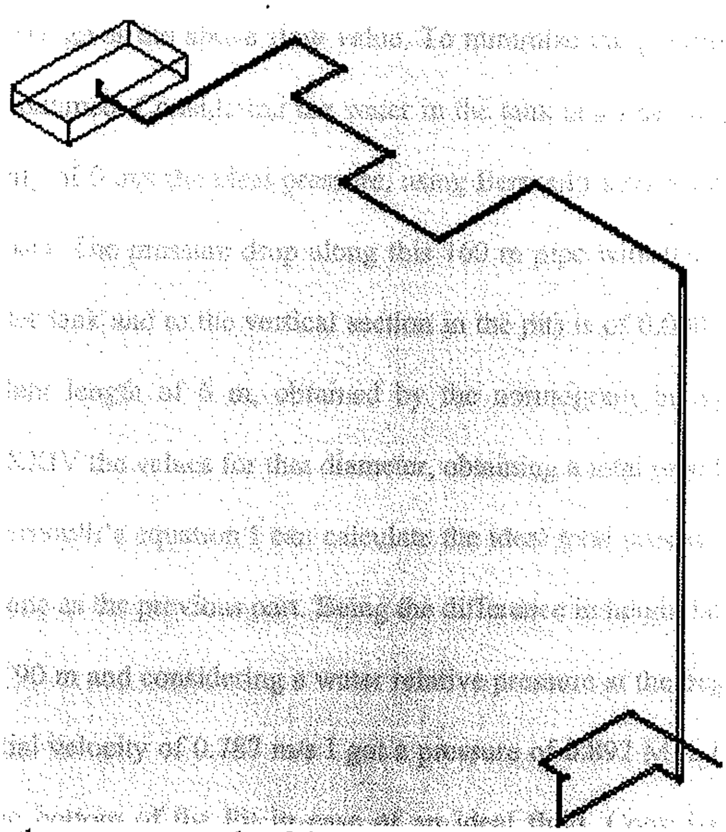

Figure 44. Pipeline to the remotest nozzle of the water mist system.

The water reserve in the cooling tower is 2 m higher than the pit entrance. A tunnel to host all the pipes from the cooling tower to the entrance of the pit already exists. It does not connect these two points in a straight way, but with eight 90° turns with a total pipe length of 160 m. The design of this part of the pipe will be performed considering a flow of 0.0139 m^3/s (834 L/min) which will empty the reserve in one hour. This value was assumed considering that the Fire Brigade estimated, following the standards, that a flow of 0.0069 m^3/s (417 L/min) was needed by the hydrants system. A safety factor of 1.5 was then introduced by the CMS group that added to the Water Mist requirement gives the above flow value. To minimize the pressure drop a pipe of 150 mm (6 in.) has been assumed. Considering the water in the tank at a relative pressure of 0 MPa (0 bar) and with a velocity of 0 m/s the ideal pressure, using Bernoulli's equation, at the top of the Pit is 0.019 MPa (0.19 bar). The pressure drop along this 160 m pipe with ten turns (considering the connection to the water tank and to the vertical section in the pit) is of 0.008 MPa (0.08 bar). Each turns has an equivalent length of 6 m, obtained by the normogram in Appendix C not being available in TABLE XXIV the values for that diameter, obtaining a total pipe length of 220 m. Now applying again the Bernoulli's equation I can calculate the ideal total pressure at the bottom of the Pit. The flow is the same as the previous part. Being the difference in height between the top and the bottom of the pipe of 90 m and considering a water relative pressure at the beginning of 0.011 MPa (0.11 bar) and an initial velocity of 0.787 m/s I got a pressure of 0.892 MPa (8.92bar). This would be the pressure at the bottom of the Pit in case of an ideal fluid. Considering that water is not frictionless, I subtracted from the value calculated with the Bernoulli's equation the frictional resistance multiplied by the length of the pipe.

The total pressure at the bottom of the Pit, p_2, is then equal to:

$$p_2 = 8.92 - 0.00036 \times 90 = 8.89 \text{ bar}$$

At this point I have a tee that splits the Water Mist flow from the hydrant system flow. The pipe diameter becomes now of 50.8 mm (2 in.). The Water Mist pipe crosses the cavern to the by-pass and runs along it to a rack placed in front of the Gas Room. The fire brigade will have there the possibility, trough a butterfly valve, of manually stopping the water mist in case of necessity.. The length of the tube is 25 m with 2 straight turns, a butterfly valve at its end and a 90° side branch tee at the beginning. The equivalent length for 90° ells is 1.68 m, the one for the 90° tee is 2.74 m and the one for the butterfly valve is 2.29 m. The total length is therefore 33.39 m and it gives a pressure drop of 0.08 bar. At the rack the pressure is 0.88 MPa (8.80 bar). In the rack the flow is split in two main branches, the Ground False Floor and the First False Floor ones. The calculation proceeds along the second branch that presents a flow of 0.00125 m^3/s (75 L/min) and for which I selected a 38.1 (1 ½ in.) pipe. It is now necessary to rise up to 7.8 m that is the height of the First False Floor ceiling. In doing this the pressure drop is equivalent to ρgh, 0.077MPa (0.77 bar). The frictional resistance multiplied for 7.8 m gives a pressure drop of 0.003 MPa (0.03 bar). The pressure at the beginning of the First False Floor main pipe is of 0.8 MPa (8 bar). This pipe provides the water to six branches each one equipped with six nozzles that means five 90° straight run tee and one 90° ell. There are also two other 90° ells. The length of the pipe is 24 meters at which I have to add the equivalent lengths of the fittings from TABLE XXIV.

$$\text{Total length} = 24 + 5 \times 0.15 + 3 \times 1.22 = 25.97 \text{ m}$$

The frictional resistance for the given flow and internal diameter is 0.0033 bar/m so at the end of the pipe the loss in pressure is of 0.009 MPa (0.09 bar). The flow in each nozzle branch is one sixth of the flow in the First False Floor pipe that means a flow of $2.08*10^{\wedge-4}$ m^3/s (12.5 L/min).

I chose for these pipes a diameter of 19.05 mm (¾ in). The frictional resistance in this pipe is 0.0036 bar/m. The length of the pipe is 18 m with five 90° straight run tees and 1 90° ells.

$$\text{Total length} = 18 + 5 \times 0.91 + 1 \times 0.61 = 23.16 \text{ m}$$

The pressure drop in this pipe is of 0.008 MPa (0.08 bar). Finally the pressure at the remotest nozzle is 0.783 MPa (7.83 bar). Therefore it is verified the minimum pressure of about 8 bar at the remotest nozzle.

TABLE XXV

WATER MIST PRESSURE CALCULATION SUMMARY

Pressure at the bottom of the Pit using Bernoulli's Equation	9 bar
Pressure drop up to here	0.11 bar
Relative pressure at the bottom of the Pit	8.89 bar
Pressure drop along the pipeline to the remotest nozzle	1.05 bar
Relative pressure at the remotest nozzle	7.83 bar

5. WATER MIST TECHNICAL SPECIFICATION

CERN accepted the Water Mist proposal, however, it was not possible to design the system with the NFPA750. In order to buy it from a specialized company, I wrote a technical specification for the supply and installation of a low pressure water mist system. The absence in the standard of a complete regulation makes water mist technical specifications less accurate than others.

Following the CERN purchasing rules this technical specification has been integrated in the CERN official invitation to tender.

5.1 Low Pressure Water Mist requirements

NFPA 750 [10] code sets the basic requirements to be fulfilled by this water mist system. In addition to the specification of the NFPA 750 code the following special requirements shall be also fulfilled:

- The system shall be designed in order to extinguish a well developed fire involving an area of 565 m^2 of cables and optic fibers, and considering the possibility of having deep-seated fires. The areas to be protected are respectively the Ground False Floor and the First False Floor of the USC55 cavern. Their dimensions are 13.5 m wide x 18 m long x 2 m high and 18 m wide x 18 m long x 2 m high respectively.
- Extinguishing mean shall be only water, no additional bottles or extinguishing means shall be used.
- The system shall use the existing water reserve of 50 m^3

- The pressure in the system shall be obtained only by the difference in height between the water tank on the surface and the system in the underground cavern. No bottles or pumps shall be installed.The system shall be of the dry type with a separate smoke detection systems. It shall be divided into zones in order to reduce the water consumption. Each zones activation shall be done by the opening of a single valve.
- Nozzle shall be of the open type.
- The Low Pressure System proposed shall be certified by a national or international third party body for the extinguishing of a typical computer room fire without preventive shout-down of the electronic.
- Possibility of stopping the discharge sequence via a purely mechanical device (valves). These valves shall be located at the entry of the Ground False Floor protected area.
- Possibility of an automatic stop of the discharge sequence after an adjustable time.
- Hardwire input for automatic activation from a VESDA system and output on the operation state of the water mist system.
- All activation valves shall be installed in convenient and easily accessible locations.
- The tubing shall be of corrosion resistant stainless steel in order to ensure a long lifetime and clean water.

5.2

Scope of the Supply

The contractor's offer shall include the following:

- The design, procurement, manufacture, delivery, installation, testing and commissioning of the Low Pressure Water Mist systems with all pipes and accessories such as nozzles, valves, regulators, connectors, flow restrictors, pipe support and fittings needed to connect the different components in the system.
- The hydraulic and pneumatic calculations for the dimensions of the pipelines, the water flow needed considering that the available water reserve amount is of 50 m^3.
- Detailed characteristics of each component used.
- All kind of filter or other device needed to match the water quality requested by the system.
- An acoustic and optical alarm for each zone in case the water mist system is activated.
- Safe electrical source to assure the functioning of any electrical equipment installed on the water mist system.
- The design, procurement, manufacture, delivery, installation and testing of special supports, fixed-point anchors, and special accessories or tools.
- Complete technical documentation of the supplied system with layout drawings, designs, execution drawings, installation drawings and detailed drawings of important components, part lists, connection procedures and installation procedures in the "as built" configuration.
- All specified tests at the premises of the Contractor or his Subcontractor.
- Inspections by an official inspection authority and the test certificates.

- Safe transport to CERN of any material, pre-fabricated sections if applicable, the equipment required for their installation and testing on the CERN site, and the cost of packing, insurance, shipping and other related costs.
- 5% spare nozzles, but at least 10 for every nozzle type.
- Establishment of a safety plan for the work to be performed at CERN, in accordance with the safety rules of CERN and the CERN host member states.
- All necessary insurances, especially against damage and theft of material until the completion of the installation.
- All expenses involved due to restoring working areas at CERN to thei original conditions.
- Maintenance, testing and training.
- All other costs necessary to ensure compliance with the requirements.

CITED LITERATURE

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2. User's Guide for Smokeview Version 4 – A Tool for Visualizing Fire Dynamic Simulation Data, NIST Special Publication 1017, August 2004.

3. BuildingExodus User Guide and Technical Manual revision 4.00, University of Greenwich, 2004.

4. Jin, T. Visibility through fire smoke, J of Fire and Flammability, 9, 135-155, 1978.

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6. J. Fruin. Pedestrian planning and design, Metropolitan Association of Urban Designers and Enviromental Planners, New York, 1971.

7. D.A. Purser, Modelling time to incapacitation and death from toxic and physical hazards in aircraft fires. AGARD No 467, pp 41-1 – 41-12, 1989.

8. NFPA 2001: Standard on Clean Agent Fire Extinguishing Systems, NFPA, 2000.

9. NFPA 13: Standards for the Installation of Sprinkler Systems, NFPA, 2000.

10. NFPA 750: Standard on Water Mist Fire Protection Systems, NFPA, 2003.

11. L. Corbo, Prevenzione incendi: Corso di sicurezza nelle costruzioni, ETASLIBRI, 1992.

12. The SFPE Handbook of Fire Protection Engineering Second Edition, NFPA, 1995.

APPENDICES

APPENDIX A

&HEAD CHID='USC55',TITLE='Medium growth fire in the Control Zone Ground Floor' /

&PDIM XBAR0=0,YBAR0=-9,ZBAR0=0,XBAR=84.0,YBAR=9.0,ZBAR=13.5 / Cavern domain dimensions.
&GRID IBAR=162,JBAR=36,KBAR=24 / Cavern grid dimensions.

&PDIM XBAR0=32.65,YBAR0=-8.35,ZBAR0=13.5,XBAR=43.35,YBAR=2.35,ZBAR=93.0 / Pit domain dimensions.
&GRID IBAR=10,JBAR=10,KBAR=80 / Pit grid dimensions.

&TIME TWFIN=600. / Total simulation time.

' MATERIAL DEFINITIONS /

```
&SURF ID    = 'CONCRETE'
    FYI    = 'Quintiere, Fire Behavior'
    RGB    = 0.66,0.66,0.66
    C_P    = 0.88 / Specific heat [kJ/kg/K]
    DENSITY = 2100.
    KS     = 1.0 / Thermal conductivity [W/m/K]
    DELTA  = 0.1 / Wall thickness [m]

&SURF ID        = 'SHEET METAL'
    FYI        = '18 guage sheet metal'
    RGB        = 0.80,0.80,0.80
    C_DELTA_RHO = 4.7 / Specific heat x thickness x density [m]
    DELTA      = 0.0013 / Wall thickness [m]

&SURF ID        = 'METAL'
    RGB        = 0.0,0.9,0.0
    C_DELTA_RHO = 20. / Specific heat x thickness x density [m]
    DELTA      = 0.005 / Wall thickness [m]

&SURF ID        = 'DOORS'
    RGB        = 1.0,1.0,1.0
    C_DELTA_RHO = 20. / Specific heat x thickness x density [m]
    DELTA      = 0.005 / Wall thickness [m]
```

APPENDIX A (CONTINUED)

```
&REAC ID='POLYURETHANE'
   FYI='C_6.3 H_7.1 N O_2.1, NFPA Handbook, Babrauskas'
   SOOT_YIELD = 0.10 / Fraction of soot from fuel
   MW_FUEL    = 130.3 / Molecular weight of fuel [g/mol]
   FUEL_N2    = 0.5 / Number of N2 molecules in fuel
   NU_CO2     = 6.3 / Stoich. Coefficient for CO2
   NU_H2O     = 3.55 / Stoich. Coefficient for Water
   NU_O2      = 7.025 / Stoich. Coefficient for Oxygen

&MISC          SURF_DEFAULT='CONCRETE',          REACTION='POLYURETHANE',
BNDF_DEFAULT=.FALSE /


'OBSTRUCTIONS /

' CAVERN VAULT /

&OBST XB= 0, 84, 8.5, 9, 7.5, 8.5 /
&OBST XB= 0, 84, 8, 9, 8.5, 9.5 /
&OBST XB= 0, 84, 7.5, 9, 9.5, 10.5 /
&OBST XB= 0, 84, 7, 9, 10.5, 11.5 /
&OBST XB= 0, 84, 6, 9, 11.5, 12.5 /
&OBST XB= 0, 84, 4.5, 9, 12.5, 13.5 /

&OBST XB= 0, 32.65, -9, -8.5, 7.5, 8.5 / Control Zone Pit side
&OBST XB= 0, 32.65, -9, -8, 8.5, 9.5 / Control Zone Pit side
&OBST XB= 0, 32.65, -9, -7.5, 9.5, 10.5 / Control Zone Pit side
&OBST XB= 0, 32.65, -9, -7, 10.5, 11.5 / Control Zone Pit side
&OBST XB= 0, 32.65, -9, -6, 11.5, 12.5 / Control Zone Pit side
&OBST XB= 0, 32.65, -9, -4.5, 12.5, 13.5 / Control Zone Pit side
&OBST XB= 43.35, 84, -9, -8.5, 7.5, 8.5 / Service Zone Pit side
&OBST XB= 43.35, 84, -9, -8, 8.5, 9.5 / Service Zone Pit side
&OBST XB= 43.35, 84, -9, -7.5, 9.5, 10.5 / Service Zone Pit side
&OBST XB= 43.35, 84, -9, -7, 10.5, 11.5 / Service Zone Pit side
&OBST XB= 43.35, 84, -9, -6, 11.5, 12.5 / Service Zone Pit side
&OBST XB= 43.35, 84, -9, -4.5, 12.5, 13.5 / Service Zone Pit side


' BY-PASS /

&OBST XB= -1, 85, 4.6, 10, -4, 5.1, COLOR='CYAN'/ By-pass x-direction
```

APPENDIX A (CONTINUED)

' CONTROL ZONE /

&OBST XB= 0, 0.5, 4, 4.6, 0, 2.1, SURF_ID='DOORS', BNDF_BLOCK=.TRUE / Exit Door to By-pass

&OBST XB= 3.7, 4.1, -10, 1.6, 0, 3.9, COLOR='BLUE'/ Gas Room wall
&OBST XB= 13, 13.2, -10, 1.6, 0, 3.9, COLOR='BLUE'/ Gas Room wall
&OBST XB= 3.7, 8, 1.4, 1.6, 0, 3.9, COLOR='BLUE'/ Gas Room door wall
&OBST XB= 8.9, 13.2, 1.4, 1.6, 0, 3.9, COLOR='BLUE'/ Gas Room door wall
&OBST XB= 3.7, 13.2, 1.4, 1.6, 2.1, 3.9, COLOR='BLUE'/ Gas Room door wall
&OBST XB= 0, 13.2, -9, 1.6, 3.7, 3.9, COLOR='BLUE'/ Gas Room ceiling
&OBST XB= 0, 4.1, 1.6, 4.6, 3.7, 3.9, COLOR='BLUE'/ Gas Room ceiling
&OBST XB= 4.1, 8, 1.6, 4.6, 3.7, 3.9, COLOR='BLUE'/ Gas Room ceiling
&OBST XB= 8, 8.9, 1.4, 1.6, 0, 2.1, SURF_ID='DOORS', BNDF_BLOCK=.TRUE / Gas Room door

&OBST XB= 13.2, 31.4, -9, 5, 1.9, 2, SURF_ID='METAL', BNDF_BLOCK=.TRUE / Ground Floor Control Zone
&HOLE XB= 13.2, 16, -9, -7.4, 1.7, 2.1 / Ground Floor Hole: right
&HOLE XB= 28.1, 31.4, -9, -7.6, 1.7, 2.1 / Ground Floor Hole: left
&HOLE XB= 23.7, 24.7, -7.8, -6.8, 1.7, 2.1 / Ground Floor Hole: center left
&HOLE XB= 19.4, 20.4, -7.8, -6.8, 1.7, 2.1 / Ground Floor Hole: center right

&OBST XB= 13.2, 31.4, -10, 4.6, 5.7, 5.8, SURF_ID='METAL' / Control Zone First False Floor

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&OBST XB= 1.3, 2.4, -10, 0.4, 7.4, 7.5, SURF_ID='METAL', BNDF_BLOCK=.TRUE / First Floor Control Zone
&OBST XB= 1.3, 2.4, 4, 10, 7.4, 7.5, SURF_ID='METAL', BNDF_BLOCK=.TRUE / First Floor Control Zone

&OBST XB= 5, 13, 1.4, -7.6, 3.9, 6.9, COLOR='CYAN'/ Laser Barak

&OBST XB= 31.4, 31.6, -10, 10, 4.7, 7.5, COLOR='BLACK'/ Fire Proof Wall to First Floor

APPENDIX A (CONTINUED)

&OBST XB= 31.4, 31.6, -10, 0.8, 2, 4.7, COLOR='BLACK'/ Fire Proof Wall to First Floor
&OBST XB= 31.4, 31.6, 2.9, 10, 2, 4.7, COLOR='BLACK'/ Fire Proof Wall to First Floor
&OBST XB= 31.4, 31.6, 0.8, 2.9, 2, 4.7, SURF_ID='DOORS', BNDF_BLOCK=.TRUE / Fire Proof Wall DOOR Ground Floor

&OBST XB= 31.4, 31.6, -10, -1.5, 7.5, 13.5, COLOR='BLACK'/ Fire Proof Wall to Vault
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&OBST XB= 31.4, 31.6, 7.5, 10, 7.5, 13.5, COLOR='BLACK'/ Fire Proof Wall to Vault
&OBST XB= 31.4, 31.6, -1.5, 0.6, 10.2, 13.5, COLOR='BLACK'/ Fire Proof Wall to Vault
&OBST XB= 31.4, 31.6, 6.5, 7.5, 9.5, 13.5, COLOR='BLACK'/ Fire Proof Wall to Vault
&OBST XB= 31.4, 31.6, -1.5, 0.6, 7.5, 10.2, SURF_ID='DOORS', BNDF_BLOCK=.TRUE / Fire Proof Wall DOOR First Floor
&OBST XB= 31.4, 31.6, 6.5, 7.5, 7.5, 9.5, SURF_ID='DOORS', BNDF_BLOCK=.TRUE / Fire Proof Wall DOOR First Floor

' SERVICE ZONE /

&OBST XB= 31.4, 85, -10, 4.6, 0, 2 / Niv. 2.0

&OBST XB= 64.8, 85, -10, 4.6, 6.6, 7, COLOR='RED'/ Service Room ceiling
&OBST XB= 64.8, 65, -10, -1.4, 2, 7, COLOR='RED'/ Service Room front wall
&OBST XB= 64.8, 65, 0.2, 5, 2, 7, COLOR='RED'/ Service Room front wall
&OBST XB= 64.8, 65, -10, 5, 4.1, 7, COLOR='RED'/ Service Room front wall
&OBST XB= 64.8, 84, 4.6, 5, 5.1, 7, COLOR='RED'/ Service Room
&OBST XB= 64.8, 65, -1.4, 0.2, 2, 4.1, SURF_ID='DOORS', BNDF_BLOCK=.TRUE / Service Room door

&OBST XB= 43.35, 60, -10, 4.6, 5.1, 5.2, SURF_ID='METAL' / Service Zone False Floor
&OBST XB= 60, 63.2, -10, -2.3, 5.1, 5.2, SURF_ID='METAL' / Service Zone False Floor
&OBST XB= 63.2, 64.8, -10, -5, 5.1, 5.2, SURF_ID='METAL' / Service Zone False Floor
'&OBST XB= 63.2, 64.8, -5, -2.3, 5.1, 5.2, COLOR='YELLOW' / Service Zone False Floor Stair PIT side
'&OBST XB= 60, 62.9, -2.3, 4.6, 5.1, 5.2, COLOR='YELLOW' / Service Zone False Floor Hopper
&OBST XB= 62.9, 64.8, -2.3, 4.6, 5.1, 5.2, SURF_ID='METAL' / Service Zone False Floor

&OBST XB= 43.35, 60, -10, 5, 5.7, 5.8, SURF_ID='METAL' / Service Zone 5.8 level
&OBST XB= 60, 63.2, -10, -2.3, 5.7, 5.8, SURF_ID='METAL' / Service Zone 5.8 level
&OBST XB= 63.2, 64.8, -10, -5, 5.7, 5.8, SURF_ID='METAL' / Service Zone 5.8 level
&OBST XB= 62.9, 64.8, -2.3, 5, 5.7, 5.8, SURF_ID='METAL' / Service Zone 5.8 level

APPENDIX A (CONTINUED)

&OBST XB= 41.9, 64.8, 5, 10, 5.7, 5.8, SURF_ID='METAL' / Service Zone 5.8 level corridor By-pass side
&OBST XB= 41.9, 43.35, 4.6, 5, 5.7, 5.8, SURF_ID='METAL' / Service Zone 5.8 level corridor By-pass side

&OBST XB= 41.9, 43.9, -9, -5.9, 5.7, 5.8, SURF_ID='METAL' / Service Zone 5.8 level corridor Pit side
&OBST XB= 41.9, 43.9, -9, -5.9, 5.1, 5.2, SURF_ID='METAL' / Service Zone False Floor corridor Pit side
&OBST XB= 64.8, 85, 5, 10, 6.9, 7, SURF_ID='METAL' / Service Room roof level corridor

&OBST XB= 52.4, 59.7, -9, -3.4, 2, 5.1, COLOR='CYAN' / Electrical Safe Room
&VENT XB= 59.7, 59.7, -6.3, -5.5, 2, 4.1, COLOR='YELLOW' / Electrical Safe Room
&OBST XB= 59.5, 59.7, -3.4, -1.4, 2, 5.1, COLOR='BLACK' / Transformer Room wall
&OBST XB= 59.5, 59.7, 0.2, 5, 2, 5.1, COLOR='BLACK' / Transformer Room wall
&OBST XB= 59.5, 59.7, -1.4, 0.2, 4.1, 5.1, COLOR='BLACK' / Transformer Room wall
&OBST XB= 59.5, 59.7, -1.4, 0.2, 2, 4.1, SURF_ID='DOORS', BNDF_BLOCK=.TRUE / Transformer Room door

&OBST XB= 63, 64, 4.4, 4.6, 2, 4.1, SURF_ID='DOORS', BNDF_BLOCK=.TRUE / Exit door to By-pass

' PIT ZONE /

&OBST XB= 41.35, 43.35, -9, -5.9, 2, 5.1, COLOR='CYAN'/ WC
&OBST XB= 41.35, 41.9, -9, -5.9, 5.1, 13.5, COLOR='CYAN'/ WC wall to the wall

&OBST XB= 39.7, 43.35, -5.9, 4.6, 2, 13.5, COLOR='MAGENTA'/ ELEVATOR Shaft
&OBST XB= 39.5, 39.7, 3, 4.6, 2, 5.1, SURF_ID='DOORS', BNDF_BLOCK=.TRUE / Ground door
&OBST XB= 43.35, 43.5, 3, 4.6, 2, 5.1, SURF_ID='DOORS', BNDF_BLOCK=.TRUE / Ground door

&OBST XB= 31.4, 35.4, -10, 10, 7.4, 7.5, SURF_ID='METAL' / First Floor
&OBST XB= 35.4, 39.7, 2, 10, 7.4, 7.5, SURF_ID='METAL' / First Floor
&OBST XB= 39.7, 41.9, 4.6, 10, 7.4, 7.5, SURF_ID='METAL' / First Floor
&OBST XB= 39.5, 39.7, 3, 4.6, 7.5, 10.6, SURF_ID='DOORS', BNDF_BLOCK=.TRUE / First Floor door

APPENDIX A (CONTINUED)

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' PIT /

&OBST XB= 39.7, 43.35, -5.9, 2.35, 13.5, 93, COLOR='MAGENTA'/ ELEVATOR Shaft

'VENTILATION /

' CONTROL ZONE UPPER FLOOR AIR SUPPLY /

&SURF ID='BLOWER', VOLUME_FLUX=-0.445, TMPWAL=17., RGB=1.0,0.5,0.0 / with 0.445
tot 40050 m3/h vs 40000

&OBST XB= 31.4, 30.9, -6, -4.8, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 30.9, 30.9, -6, -4.8, 7.5, 9.5, SURF_ID='BLOWER' /
&OBST XB= 25.8, 27, -9, -8, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 25.8, 27, -8, -8, 7.5, 9.5, SURF_ID='BLOWER' /
&OBST XB= 21.5, 22.7, -9, -8, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 21.5, 22.7, -8, -8, 7.5, 9.5, SURF_ID='BLOWER' /
&OBST XB= 17.2, 18.4, -9, -8, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 17.2, 18.4, -8, -8, 7.5, 9.5, SURF_ID='BLOWER' /
&OBST XB= 12.9, 14.1, -9, -8, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 12.9, 14.1, -8, -8, 7.5, 9.5, SURF_ID='BLOWER' /
&OBST XB= 8.6, 9.8, -9, -8, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 8.6, 9.8, -8, -8, 7.5, 9.5, SURF_ID='BLOWER' /
&OBST XB= 4.3, 5.5, -9, -8, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 4.3, 5.5, -8, -8, 7.5, 9.5, SURF_ID='BLOWER' /

&OBST XB= 30, 31.2, 8, 9, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 30, 31.2, 8, 8, 7.5, 9.5, SURF_ID='BLOWER' /
&OBST XB= 25.8, 27, 8, 9, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 25.8, 27, 8, 8, 7.5, 9.5, SURF_ID='BLOWER' /
&OBST XB= 21.5, 22.7, 8, 9, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 21.5, 22.7, 8, 8, 7.5, 9.5, SURF_ID='BLOWER' /
&OBST XB= 17.2, 18.4, 8, 9, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 17.2, 18.4, 8, 8, 7.5, 9.5, SURF_ID='BLOWER' /
&OBST XB= 12.9, 14.1, 8, 9, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 12.9, 14.1, 8, 8, 7.5, 9.5, SURF_ID='BLOWER' /
&OBST XB= 8.6, 9.8, 8, 9, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 8.6, 9.8, 8, 8, 7.5, 9.5, SURF_ID='BLOWER' /
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APPENDIX A (CONTINUED)

&OBST XB= 6.2, 7.4, 8, 9, 7.5, 9.5, SURF_ID='SHEET METAL' /
&VENT XB= 6.2, 7.4, 8, 8, 7.5, 9.5, SURF_ID='BLOWER' /

' CONTROL ZONE GROUND FLOOR AIR SUPPLY /

&OBST XB= 31.4, 30.9, -5.1, -3.9, 2, 4, SURF_ID='SHEET METAL' /
&VENT XB= 30.9, 30.9, -5.1, -3.9, 2, 4, SURF_ID='BLOWER' /
&OBST XB= 13.2, 13.7, -5.1, -3.9, 2, 4, SURF_ID='SHEET METAL' /
&VENT XB= 13.7, 13.7, -5.1, -3.9, 2, 4, SURF_ID='BLOWER' /
&OBST XB= 26.7, 27.9, -9, -8.5, 2, 4, SURF_ID='SHEET METAL' /
&VENT XB= 26.7, 27.9, -8.5, -8.5, 2, 4, SURF_ID='BLOWER' /
&OBST XB= 23.6, 24.8, -9, -8.5, 2, 4, SURF_ID='SHEET METAL' /
&VENT XB= 23.6, 24.8, -8.5, -8.5, 2, 4, SURF_ID='BLOWER' /
&OBST XB= 19.3, 20.5, -9, -8.5, 2, 4, SURF_ID='SHEET METAL' /
&VENT XB= 19.3, 20.5, -8.5, -8.5, 2, 4, SURF_ID='BLOWER' /
&OBST XB= 16.2, 17.4, -9, -8.5, 2, 4, SURF_ID='SHEET METAL' /
&VENT XB= 16.2, 17.4, -8.5, -8.5, 2, 4, SURF_ID='BLOWER' /

&OBST XB= 30, 31.2, 4.1, 4.6, 2, 4, SURF_ID='SHEET METAL' /
&VENT XB= 30, 31.2, 4.1, 4.1, 2, 4, SURF_ID='BLOWER' /
&OBST XB= 25.8, 27, 4.1, 4.6, 2, 4, SURF_ID='SHEET METAL' /
&VENT XB= 25.8, 27, 4.1, 4.1, 2, 4, SURF_ID='BLOWER' /
&OBST XB= 21.5, 22.7, 4.1, 4.6, 2, 4, SURF_ID='SHEET METAL' /
&VENT XB= 21.5, 22.7, 4.1, 4.1, 2, 4, SURF_ID='BLOWER' /
&OBST XB= 17.2, 18.4, 4.1, 4.6, 2, 4, SURF_ID='SHEET METAL' /
&VENT XB= 17.2, 18.4, 4.1, 4.1, 2, 4, SURF_ID='BLOWER' /
&OBST XB= 13.2, 14.4, 4.1, 4.6, 2, 4, SURF_ID='SHEET METAL' /
&VENT XB= 13.2, 14.4, 4.1, 4.1, 2, 4, SURF_ID='BLOWER' /

' CONTROL ZONE FIRST FLOOR RETURN AIR /

&SURF ID='ASPIRATOR', VOLUME_FLUX=0.278, RGB=0.0,0.0,0.0 / 40 blowers with 0.278 tot 40032 m3/h vs 40000

&OBST XB= 0, 31.2, -1.6, -1, 13, 13.5, SURF_ID='SHEET METAL' / Duct
&OBST XB= 0, 31.2, 1, 1.6, 13, 13.5, SURF_ID='SHEET METAL' / Duct

&VENT XB= 4.6, 5.1, -1.6, -1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 7.1, 7.6, -1.6, -1, 13, 13, SURF_ID='ASPIRATOR' /

APPENDIX A (CONTINUED)

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&VENT XB= 9.7, 10.2, -1.6, -1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 12.1, 12.6, -1.6, -1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 14.6, 15.1, -1.6, -1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 17.1, 17.6, -1.6, -1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 19.6, 20.1, -1.6, -1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 22.1, 22.6, -1.6, -1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 24.6, 25.1, -1.6, -1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 27.1, 27.6, -1.6, -1, 13, 13, SURF_ID='ASPIRATOR' /

&VENT XB= 4.6, 5.1, 1.6, 1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 7.1, 7.6, 1.6, 1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 9.7, 10.2, 1.6, 1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 12.1, 12.6, 1.6, 1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 14.6, 15.1, 1.6, 1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 17.1, 17.6, 1.6, 1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 19.6, 20.1, 1.6, 1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 22.1, 22.6, 1.6, 1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 24.6, 25.1, 1.6, 1, 13, 13, SURF_ID='ASPIRATOR' /
&VENT XB= 27.1, 27.6, 1.6, 1, 13, 13, SURF_ID='ASPIRATOR' /


' CONTROL ZONE GROUND FLOOR RETURN AIR /

&OBST XB= 13.2, 31.2, -3.6, -3, 5.2, 5.7, SURF_ID='SHEET METAL' / Duct
&OBST XB= 13.2, 31.2, -0.8, -1.4, 5.2, 5.7, SURF_ID='SHEET METAL' / Duct

&VENT XB= 15.7, 16.2, -0.8, -1.4, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 16.2, 16.7, -0.8, -1.4, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 18.7, 19.2, -0.8, -1.4, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 19.2, 19.7, -0.8, -1.4, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 21.7, 22.2, -0.8, -1.4, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 22.2, 22.7, -0.8, -1.4, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 24.7, 25.2, -0.8, -1.4, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 25.2, 25.7, -0.8, -1.4, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 27.7, 28.2, -0.8, -1.4, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 28.2, 28.7, -0.8, -1.4, 5.2, 5.2, SURF_ID='ASPIRATOR' /

&VENT XB= 15.7, 16.2, -3.6, -3, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 16.2, 16.7, -3.6, -3, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 18.7, 19.2, -3.6, -3, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 19.2, 19.7, -3.6, -3, 5.2, 5.2, SURF_ID='ASPIRATOR' /
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APPENDIX A (CONTINUED)

&VENT XB= 21.7, 22.2, -3.6, -3, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 22.2, 22.7, -3.6, -3, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 24.7, 25.2, -3.6, -3, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 25.2, 25.7, -3.6, -3, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 27.7, 28.2, -3.6, -3, 5.2, 5.2, SURF_ID='ASPIRATOR' /
&VENT XB= 28.2, 28.7, -3.6, -3, 5.2, 5.2, SURF_ID='ASPIRATOR' /

' CONTROL ZONE FIRST FLOOR SMOKE EXTRACTION /

&SURF ID='ASPIRATORSMOKE', VOLUME_FLUX=0.278, RGB=0.0,0.0,0.0 / 10 with 0.278 tot 10008 m3/h vs 10000

&OBST XB= 0, 31.2, -0.2, 0.3, 13, 13.5, SURF_ID='SHEET METAL' / Duct
&VENT XB= 0.6, 1.4, -0.2, 0.3, 13, 13, SURF_ID='ASPIRATORSMOKE' /

' CONTROL ZONE GROUND FLOOR SMOKE EXTRACTION / finished

&OBST XB= 13.2, 31.2, -2.4, -1.9, 5.2, 5.7, SURF_ID='SHEET METAL' / Duct
&VENT XB= 13.2, 14, -2.4, -1.9, 5.2, 5.2, SURF_ID='ASPIRATORSMOKE' /

' SERVICE ZONE UPPER FLOORs AIR SUPPLY / tot 20000 m3/h vs 20000

&SURF ID='BIGBLOWER', VOLUME_FLUX=-0.555, TMPWAL=17., RGB=1.0,0.5,0.0 / 8 big blowers with 0.555 tot 15984 m3/h vs 16000

&OBST XB= 63.4, 64.6, 8, 9, 5.8, 7.1, SURF_ID='SHEET METAL' /
&VENT XB= 63.4, 64.6, 8, 8, 5.8, 7.1, SURF_ID='BIGBLOWER' /
&OBST XB= 57.8, 59, 8, 9, 5.8, 7.1, SURF_ID='SHEET METAL' /
&VENT XB= 57.8, 59, 8, 8, 5.8, 7.1, SURF_ID='BIGBLOWER' /
&OBST XB= 53.1, 54.3, 8, 9, 5.8, 7.1, SURF_ID='SHEET METAL' /
&VENT XB= 53.1, 54.3, 8, 8, 5.8, 7.1, SURF_ID='BIGBLOWER' /
&OBST XB= 48.4, 49.6, 8, 9, 5.8, 7.1, SURF_ID='SHEET METAL' /
&VENT XB= 48.4, 49.6, 8, 8, 5.8, 7.1, SURF_ID='BIGBLOWER' /
&OBST XB= 43.7, 44.9, 8, 9, 5.8, 7.1, SURF_ID='SHEET METAL' /
&VENT XB= 43.7, 44.9, 8, 8, 5.8, 7.1, SURF_ID='BIGBLOWER' /

APPENDIX A (CONTINUED)

&OBST XB= 64.3, 64.8, -6.6, -5.4, 5.8, 7.9, SURF_ID='SHEET METAL' /
&VENT XB= 64.3, 64.3, -6.6, -5.4, 5.8, 7.9, SURF_ID='BIGBLOWER' /
&OBST XB= 54.6, 55.8, -7.6, -7.1, 5.8, 7.9, SURF_ID='SHEET METAL' /
&VENT XB= 54.6, 55.8, -7.1, -7.1, 5.8, 7.9, SURF_ID='BIGBLOWER' /
&OBST XB= 43.8, 45, -7.6, -7.1, 5.8, 7.9, SURF_ID='SHEET METAL' /
&VENT XB= 43.8, 45, -7.1, -7.1, 5.8, 7.9, SURF_ID='BIGBLOWER' /

&SURF ID='SMALLBLOWER', VOLUME_FLUX=-0.278, TMPWAL=17., RGB=1.0,0.5,0.0 / 4 supply grilles with 0.278 tot 4003.2 m3/h vs 4000

&OBST XB= 43.8, 81, -7.2, -6.5, 9.4, 10.1, SURF_ID='SHEET METAL' /

&OBST XB= 43.8, 64.8, 8.1, 7.4, 8.2, 8.9, SURF_ID='SHEET METAL' /
&OBST XB= 64.8, 81, 5.7, 6.4, 9.6, 10.3, SURF_ID='SHEET METAL' /
&OBST XB= 64.8, 65.5, 5.7, 6.4, 8.2, 9.6, SURF_ID='SHEET METAL' /
&OBST XB= 64.8, 65.5, 5.7, 7.5, 8.2, 8.9, SURF_ID='SHEET METAL' /

&VENT XB= 68, 68.6, -6.5, -6.5, 9.5, 10, SURF_ID='SMALLBLOWER' /
&VENT XB= 63.5, 64.1, -6.5, -6.5, 9.5, 10, SURF_ID='SMALLBLOWER' /
&VENT XB= 57, 57.6, -6.5, -6.5, 9.5, 10, SURF_ID='SMALLBLOWER' /
&VENT XB= 47, 47.6, -6.5, -6.5, 9.5, 10, SURF_ID='SMALLBLOWER' /

' SERVICE ZONE UPPER FLOORS SMOKE EXTRACTION /

&OBST XB= 43.8, 82, -0.2, 0.3, 13, 13.5, SURF_ID='SHEET METAL' /
&VENT XB= 75.4, 76.2, -0.2, 0.3, 13, 13, SURF_ID='ASPIRATORSMOKE' /
&VENT XB= 60.4, 61.2, -0.2, 0.3, 13, 13, SURF_ID='ASPIRATORSMOKE' /
&VENT XB= 45.4, 46.2, -0.2, 0.3, 13, 13, SURF_ID='ASPIRATORSMOKE' /

' SERVICE ZONE SERVICE ROOM AIR SUPPLY /

&SURF ID='BIGBLOWERST', VOLUME_FLUX=-0.556, TMPWAL=17., RGB=1.0,0.5,0.0 / 5 big blowers with 0.556 tot 10008 m3/h vs 10000

&OBST XB= 67, 81, 3.9, 4.6, 6, 6.6, SURF_ID='SHEET METAL' /
&OBST XB= 68.9, 70.1, 4.3, 4.6, 2, 4.1, SURF_ID='SHEET METAL' /
&VENT XB= 68.9, 70.1, 4.3, 4.3, 2, 4.1, SURF_ID='BIGBLOWERST' /
&OBST XB= 77.9, 79.1, 4.3, 4.6, 2, 4.1, SURF_ID='SHEET METAL' /
&VENT XB= 77.9, 79.1, 4.3, 4.3, 2, 4.1, SURF_ID='BIGBLOWERST' /

APPENDIX A (CONTINUED)

&OBST XB= 66.4, 81, -7.1, -6.4, 6, 6.6, SURF_ID='SHEET METAL' /
&OBST XB= 68.2, 69.4, -9, -8.5, 2, 4.1, SURF_ID='SHEET METAL' /
&VENT XB= 68.2, 69.4, -8.5, -8.5, 2, 4.1, SURF_ID='BIGBLOWERST' /
&OBST XB= 71.3, 72.5, -9, -8.5, 2, 4.1, SURF_ID='SHEET METAL' /
&VENT XB= 71.3, 72.5, -8.5, -8.5, 2, 4.1, SURF_ID='BIGBLOWERST' /
&OBST XB= 78.6, 79.8, -9, -8.5, 2, 4.1, SURF_ID='SHEET METAL' /
&VENT XB= 78.6, 79.8, -8.5, -8.5, 2, 4.1, SURF_ID='BIGBLOWERST' /

&SURF ID='SMALLBLOWERST1', VOLUME_FLUX=-0.208, RGB=1.0,0.5,0.0 / 4 supply grilles with 0.208 tot 2995.2 m3/h vs 3000

&VENT XB= 78.3, 78.8, 3.9, 3.9, 6, 6.6, SURF_ID='SMALLBLOWERST1' /
&VENT XB= 76.8, 77.3, 3.9, 3.9, 6, 6.6, SURF_ID='SMALLBLOWERST1' /
&VENT XB= 71.9, 72.4, 3.9, 3.9, 6, 6.6, SURF_ID='SMALLBLOWERST1' /
&VENT XB= 70.4, 70.9, 3.9, 3.9, 6, 6.6, SURF_ID='SMALLBLOWERST1' /

&SURF ID='SMALLBLOWERST2', VOLUME_FLUX=-0.243, RGB=1.0,0.5,0.0 / 4 supply grilles with 0.243 tot 3499.2 m3/h vs 3500

&VENT XB= 67.1, 67.6, -6.4, -6.4, 6, 6.6, SURF_ID='SMALLBLOWERST2' /
&VENT XB= 69.9, 70.4, -6.4, -6.4, 6, 6.6, SURF_ID='SMALLBLOWERST2' /
&VENT XB= 74.4, 74.9, -6.4, -6.4, 6, 6.6, SURF_ID='SMALLBLOWERST2' /
&VENT XB= 77.4, 77.9, -6.4, -6.4, 6, 6.6, SURF_ID='SMALLBLOWERST2' /

' SERVICE ZONE SERVICE ROOM RETURN AIR /

&SURF ID='ASPIRATORST', VOLUME_FLUX=0.278, RGB=0.0,0.0,0.0 / 20 grilles with 0.278 tot 20016 m3/h vs 20000

'&HOLE XB= 64.7, 65.1, -3.8, -2.8, 6, 6.6 /
&OBST XB= 65, 84, -3.8, -2.8, 6, 6.6, SURF_ID='SHEET METAL' /
&VENT XB= 64.8, 64.8, -3.6, -3, 6.1, 6.6, SURF_ID='ASPIRATORST' /
&VENT XB= 65.8, 66.3, -3.8, -2.8, 6, 6, SURF_ID='ASPIRATORST' /double
&VENT XB= 66.8, 67.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple
&VENT XB= 67.8, 68.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple
&VENT XB= 68.8, 69.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple
&VENT XB= 69.8, 70.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple
&VENT XB= 70.8, 71.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple
&VENT XB= 71.8, 72.3, -3.8, -2.8, 6, 6, SURF_ID='ASPIRATORST' /double

APPENDIX A (CONTINUED)

```
&VENT XB= 72.8, 73.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple
&VENT XB= 73.8, 74.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple
&VENT XB= 74.8, 75.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple
&VENT XB= 75.8, 76.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple
&VENT XB= 76.8, 77.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple
&VENT XB= 77.8, 78.3, -3.8, -2.8, 6, 6, SURF_ID='ASPIRATORST' /double
&VENT XB= 78.8, 79.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple
&VENT XB= 79.8, 80.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple
&VENT XB= 80.8, 81.3, -3.5, -3, 6, 6, SURF_ID='ASPIRATORST' /simple

' SERVICE ZONE SERVICE ROOM SMOKE EXTRACTION /

&OBST XB= 81, 83.5, -4.3, -3.8, 6.1, 6.6, SURF_ID='SHEET METAL' /
&VENT XB= 82.9, 82.1, -4.3, -4.3, 6.1, 6.6, SURF_ID='ASPIRATORSMOKE' /
&VENT XB= 81, 81.8, -4.3, -3.8, 6.1, 6.1, SURF_ID='ASPIRATORSMOKE' /

&OBST XB= 65, 66.8, 4.1, 4.6, 6.1, 6.6, SURF_ID='SHEET METAL' /
&VENT XB= 66, 66.8, 4.1, 4.6, 6.1, 6.1, SURF_ID='ASPIRATORSMOKE' /

' SERVICE ZONE CORRIDOR AIR SUPPLY /

&SURF ID='BLOWERIB', VOLUME_FLUX=-0.208, TMPWAL=17., RGB=1.0,0.5,0.0 / 4 grilles
with 0.208 tot 2995.2 m3/h vs 3000

&HOLE XB= 64.3, 64.8, -2.1, 3.1, 5.0, 5.2 /
&OBST XB= 64.3, 64.8, -2.1, 3.1, 5.1, 5.6, SURF_ID='SHEET METAL' /
&OBST XB= 64.3, 64.8, 3.1, 4.6, 4.6, 5.1, SURF_ID='SHEET METAL' /
&VENT XB= 64.3, 64.8, -2, -1.4, 5.1, 5.1, SURF_ID='BLOWERIB' /
&VENT XB= 64.3, 64.8, -0.9, -0.3, 5.1, 5.1, SURF_ID='BLOWERIB' /
&VENT XB= 64.3, 64.8, 0.2, 0.8, 5.1, 5.1, SURF_ID='BLOWERIB' /
&VENT XB= 64.3, 64.8, 1.3, 1.8, 5.1, 5.1, SURF_ID='BLOWERIB' /

' TRANSFORMER ROOM AIR SUPPLY /

&OBST XB= 51.7, 58.7, -3.4, -2.7, 4.4, 5.1, SURF_ID='SHEET METAL' / 0.7*0.7
&OBST XB= 51.7, 52.4, -3.4, -8.4, 4.4, 5.1, SURF_ID='SHEET METAL' / 0.7*0.7
&OBST XB= 43.35, 51.7, -8.4, -7.7, 4.4, 5.1, SURF_ID='SHEET METAL' / 0.7*0.7
```

APPENDIX A (CONTINUED)

&SURF ID='SMALLBLOWERTR', VOLUME_FLUX=-0.204, TMPWAL=17., RGB=1.0,0.5,0.0 /
9+6 grilles with 0.204 tot 11016 m3/h vs 10995

&VENT XB= 57.8, 58.4, -2.7, -2.7, 4.5, 5, SURF_ID='SMALLBLOWERTR' / duct side
&VENT XB= 56.6, 57.2, -2.7, -2.7, 4.5, 5, SURF_ID='SMALLBLOWERTR' / duct side
&VENT XB= 55.4, 56, -2.7, -2.7, 4.5, 5, SURF_ID='SMALLBLOWERTR' / duct side
&VENT XB= 53, 53.6, -2.7, -2.7, 4.5, 5, SURF_ID='SMALLBLOWERTR' / duct side
&VENT XB= 51.7, 51.7, -7.4, -6.8, 4.5, 5, SURF_ID='SMALLBLOWERTR' / duct side
&VENT XB= 50.2, 50.8, -7.7, -7.7, 4.5, 5, SURF_ID='SMALLBLOWERTR' / duct side
&VENT XB= 49, 49.6, -7.7, -7.7, 4.5, 5, SURF_ID='SMALLBLOWERTR' / duct side
&VENT XB= 47.8, 48.4, -7.7, -7.7, 4.5, 5, SURF_ID='SMALLBLOWERTR' / duct side
&VENT XB= 46.6, 47.2, -7.7, -7.7, 4.5, 5, SURF_ID='SMALLBLOWERTR' / duct side

&VENT XB= 56.6, 57.2, -3.3, -2.8, 4.4, 4.4, SURF_ID='SMALLBLOWERTR' / duct bottom
&VENT XB= 54.2, 54.8, -3.3, -2.8, 4.4, 4.4, SURF_ID='SMALLBLOWERTR' / duct bottom
&VENT XB= 51.8, 52.3, -6.4, -5.8, 4.4, 4.4, SURF_ID='SMALLBLOWERTR' / duct bottom
&VENT XB= 51.8, 52.3, -5.4, -4.8, 4.4, 4.4, SURF_ID='SMALLBLOWERTR' / duct bottom
&VENT XB= 49, 49.6, -8.3, -7.8, 4.4, 4.4, SURF_ID='SMALLBLOWERTR' / duct bottom
&VENT XB= 46.6, 47.2, -8.3, -7.8, 4.4, 4.4, SURF_ID='SMALLBLOWERTR' / duct bottom

&SURF ID='BIGBLOWERTR', VOLUME_FLUX=-0.694, TMPWAL=17., RGB=1.0,0.5,0.0 /
blowers with 0.694 tot 14990.4 m3/h vs 15000

&OBST XB= 57.5, 58.7, -3.4, -2.9, 2, 3.3, SURF_ID='SHEET METAL' /
&VENT XB= 57.5, 58.7, -2.9, -2.9, 2, 3.3, SURF_ID='BIGBLOWERTR' /
&OBST XB= 55.1, 56.3, -3.4, -2.9, 2, 3.3, SURF_ID='SHEET METAL' /
&VENT XB= 55.1, 56.3, -2.9, -2.9, 2, 3.3, SURF_ID='BIGBLOWERTR' /
&OBST XB= 52.7, 53.9, -3.4, -2.9, 2, 3.3, SURF_ID='SHEET METAL' /
&VENT XB= 52.7, 53.9, -2.9, -2.9, 2, 3.3, SURF_ID='BIGBLOWERTR' /
&OBST XB= 52.4, 51.9, -7.8, -6.6, 2, 3.3, SURF_ID='SHEET METAL' /
&VENT XB= 51.9, 51.9, -7.8, -6.6, 2, 3.3, SURF_ID='BIGBLOWERTR' /
&OBST XB= 47.9, 49.1, -9, -8.5, 2, 3.3, SURF_ID='SHEET METAL' /
&VENT XB= 47.9, 49.1, -8.5, -8.5, 2, 3.3, SURF_ID='BIGBLOWERTR' /
&OBST XB= 43.35, 43.9, -9, -8.5, 2, 3.3, SURF_ID='SHEET METAL' /
&VENT XB= 43.9, 43.9, -8.3, -7.7, 2, 3.3, SURF_ID='BIGBLOWERTR' /

' TRANSFORMER ROOM RETURN AIR /

&OBST XB= 43.8, 58.8, 0.2, 1, 4.8, 5.1, SURF_ID='SHEET METAL' / lxh 0.8*0.3
&OBST XB= 43.8, 44.6, 0.2, -7.8, 4.8, 5.1, SURF_ID='SHEET METAL' / lxh 0.6*0.5

APPENDIX A (CONTINUED)

```
&SURF ID='ASPIRATORTR', VOLUME_FLUX=0.444, RGB=0.0,0.0,0.0 / 14 grilles with 0.444
tot 22377.6 m3/h vs 22400

&VENT XB= 58, 58.8, 0.4, 0.8, 4.8, 4.8, SURF_ID='ASPIRATORTR' /
&VENT XB= 57, 57.8, 0.4, 0.8, 4.8, 4.8, SURF_ID='ASPIRATORTR' /
&VENT XB= 56, 56.8, 0.4, 0.8, 4.8, 4.8, SURF_ID='ASPIRATORTR' /
&VENT XB= 55, 55.8, 0.4, 0.8, 4.8, 4.8, SURF_ID='ASPIRATORTR' /
&VENT XB= 53, 53.8, 0.4, 0.8, 4.8, 4.8, SURF_ID='ASPIRATORTR' /
&VENT XB= 52, 52.8, 0.4, 0.8, 4.8, 4.8, SURF_ID='ASPIRATORTR' /
&VENT XB= 51, 51.8, 0.4, 0.8, 4.8, 4.8, SURF_ID='ASPIRATORTR' /
&VENT XB= 50, 50.8, 0.4, 0.8, 4.8, 4.8, SURF_ID='ASPIRATORTR' /
&VENT XB= 48, 48.8, 0.4, 0.8, 4.8, 4.8, SURF_ID='ASPIRATORTR' /
&VENT XB= 47, 47.8, 0.4, 0.8, 4.8, 4.8, SURF_ID='ASPIRATORTR' /
&VENT XB= 46, 46.8, 0.4, 0.8, 4.8, 4.8, SURF_ID='ASPIRATORTR' /
&VENT XB= 45, 45.8, 0.4, 0.8, 4.8, 4.8, SURF_ID='ASPIRATORTR' /

&VENT XB= 44, 44.4, -3.9, -4.7, 4.8, 4.8, SURF_ID='ASPIRATORTR' /
&VENT XB= 44, 44.4, -4.9, -5.7, 4.8, 4.8, SURF_ID='ASPIRATORTR' /


' TRANSFORMER ROOM SMOKE EXTRACTION /

&OBST XB= 43.8, 59, 1.2, 1.7, 4.6, 5.1, SURF_ID='SHEET METAL' / lxh 0.5*0.5
&OBST XB= 58.5, 59, 1.7, 4.6, 4.6, 5.1, SURF_ID='SHEET METAL' / lxh 0.5*0.5

&VENT XB= 56.6, 57.4, 1.2, 1.7, 4.6, 4.6, SURF_ID='ASPIRATORSMOKE' /
&VENT XB= 46, 46.8, 1.2, 1.7, 4.6, 4.6, SURF_ID='ASPIRATORSMOKE' /


' FIRE /

&PART ID='smoke', MASSLESS=.TRUE.,  /

&SURF     ID='BURNER',PART_ID='smoke',HRRPUA=4000.,TMPWAL=500.,TAU_Q=-600     /
Ignition source definition

&OBST XB= 20, 21 -3, -2, 0, 0.2, /
&VENT XB= 20, 21, -3, -2, 0.2, 0.2, SURF_ID='BURNER' /  fire source

' MONITORIZED QUANTITIES /
```

APPENDIX A (CONTINUED)

```
&BNDF QUANTITY='WALL_TEMPERATURE' /
&SLCF PBY=0, QUANTITY='TEMPERATURE' /
&SLCF PBX=22, QUANTITY='TEMPERATURE' /
&SLCF PBX=50, QUANTITY='TEMPERATURE' /
&SLCF PBX=62, QUANTITY='TEMPERATURE' /
&SLCF PBX=74, QUANTITY='TEMPERATURE' /
&ISOF QUANTITY='TEMPERATURE', VALUE(1)=50., VALUE(2)=200., VALUE(3)=500. /
&SLCF PBY=3, QUANTITY='visibility' /
&SLCF PBZ=3.7, QUANTITY='visibility' /
&SLCF PBZ=9.2, QUANTITY='visibility' /
&PL3D QUANTITIES(5)='visibility' /
```

APPENDIX B

CASE ONE Fire in the Ground False Floor of the Control Zone

Ground False Floor			0	-	150	s		
			p	1				
Final Visibility			2	m	Kf	1.00	/m	
Initial Visibility			1000	m	K0	0.002	/m	
dt	2.5	min	dt	150	s			
			m	0.006653333				
Ground False Floor			150	-	600	s		
			p	1				
Final Visibility			0.1	m	Kf	20.00	/m	
Initial Visibility			2	m	K0	1	/m	
dt	7.5	min	dt	450	s			
			m	0.042222222				
4 m round the fire			0	-	60	s		
			p	1				
Final Visibility			0.1	m	Kf	20	/m	
Initial Visibility			1000	m	K0	0.002	/m	
dt	1	min	dt	60	s			
			m	0.3333				
Stair to Gas Room			90	-	210	s		
			p	1				
Final Visibility			2	m	Kf	1	/m	
Initial Visibility			1000	m	K0	0.002	/m	
dt	2	min	dt	120	s			
			m	0.008316667				
Stair to Gas Room			210	-	600	s		
			p	1				
Final Visibility			0.1	m	Kf	20	/m	
Initial Visibility			2	m	K0	1	/m	
dt	6.5	min	dt	390	s			
			m	0.048717949				

APPENDIX B (CONTINUED)

Ground Floor holes half			90	-	210	s
			p	1		
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			2	m	K0	1	/m
dt	2	min	dt	120	s	
			m	0.158333333		

Ground Floor holes half			210	-	600	s	
			p	1			
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			2	m	K0	1	/m
dt	6.5	min	dt	390	s		
			m	0.048717949			

Ground Floor By-pass half			120	-	600	s	
			p	1			
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			1000	m	K0	0.002	/m
dt	8	min	dt	480	s		
			m	0.0416625			

Laser Barrack		150	-	270	s		
			p	1			
Final Visibility			2	m	Kf	1	/m
Initial Visibility			1000	m	K0	0.002	/m
dt	2	min	dt	120	s		
			m	0.008316667			

Laser Barrack		270	-	600	s		
			p	1			
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			2	m	K0	1	/m
dt	5.5	min	dt	330	s		
			m	0.057575758			

First Floor		150	-	270	s		
			p	1			
Final Visibility			2	m	Kf	1	/m

APPENDIX B (CONTINUED)

Initial Visibility			1000	m	K0	0.002	/m
dt	2	min	dt	120	s		
			m	0.008316667			
First Floor		270	-	600	s		
			p	1			
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			2	m	K0	1	/m
dt	5.5	min	dt	330	s		
			m	0.057575758			

CASE TWO Fire in the First Floor of the Control Zone

Near the fire		0	-	270	s		
			p	1			
Final Visibility			2	m	Kf	1	/m
Initial Visibility			1000	m	K0	0.002	/m
dt	4.5	min	dt	270	s		
			m	0.003696296			
Near the fire		270	-	600	s		
			p	1			
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			2	m	K0	1	/m
dt	5.5	min	dt	330	s		
			m	0.057575758			
Near the Stair		0	-	270	s		
			p	1			
Final Visibility			4	m	Kf	0.5	/m
Initial Visibility			1000	m	K0	0.002	/m
dt	4.5	min	dt	270	s		
			m	0.001844444			
Near the Stair		270	-	600	s		
			p	1			
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			2	m	K0	1	/m
dt	5.5	min	dt	330	s		

APPENDIX B (CONTINUED)

m 0.057575758

CASE THREE Fire in the Transformer Room

To Safe Zone 0	-	180	s		
	p	1			
Final Visibility	2	m	Kf	1	/m
Initial Visibility	1000	m	K0	0.002	/m
dt 3 min	dt	180	s		
	m	0.005544444			

To Safe Zone 180	-	240	s		
	p	1			
Final Visibility	0.1	m	Kf	20	/m
Initial Visibility	2	m	K0	1	/m
dt 1 min	dt	60	s		
	m	0.316666667			

To Corridor 0	-	180	s		
	p	1			
Final Visibility	4	m	Kf	0.5	/m
Initial Visibility	1000	m	K0	0.002	/m
dt 3 min	dt	180	s		
	m	0.002766667			

To Corridor 180	-	240	s		
	p	1			
Final Visibility	0.1	m	Kf	20	/m
Initial Visibility	4	m	K0	0.5	/m
dt 1 min	dt	60	s		
	m	0.325			

CASE FOUR Fire in the Corridor

Corridor Stair area 0-120	0	-	102	s	
	p	1			
Final Visibility	2	m	Kf	1	/m
Initial Visibility	1000	m	K0	0.002	/m

APPENDIX B (CONTINUED)

dt	1.7	min	dt	102	s		
			m	0.009784314			
Corridor Stair area 120-600				102	-	600	s
			p	1			
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			2	m	K0	1	/m
dt	8.3	min	dt	498	s		
			m	0.03815261			
Corridor Exit area 0-120				0	-	120	s
			p	1			
Final Visibility			2	m	Kf	1	/m
Initial Visibility			1000	m	K0	0.002	/m
dt	2	min	dt	120	s		
			m	0.008316667			
Corridor Exit area 120-600				120	-	600	s
			p	1			
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			2	m	K0	1	/m
dt	8	min	dt	480	s		
			m	0.039583333			
First Floor 180-360			180	-	360	s	
			p	1			
Final Visibility			2	m	Kf	1	/m
Initial Visibility			1000	m	K0	0.002	/m
dt	3	min	dt	180	s		
			m	0.005544444			
First Floor 360-600			360	-	600	s	
			p	1			
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			2	m	K0	1	/m
dt	4	min	dt	240	s		
			m	0.079166667			

APPENDIX B (CONTINUED)

Exit Upper 180	-	360	s		
	p	1			
Final Visibility	0.1	m	Kf	20	/m
Initial Visibility	1000	m	K0	0.002	/m
dt 3 min	dt	180	s		
	m	0.1111			

CASE FIVE Fire in the First False Floor of the Control Zone

First False Floor	0	-	180	s	
	p	1			
Final Visibility	0.1	m	Kf	20	/m
Initial Visibility	1000	m	K0	0.002	/m
dt 3 min	dt	180	s		
	m	0.1111			

Laser Barrack 0	-	180	s		
	p	1			
Final Visibility	0.1	m	Kf	20	/m
Initial Visibility	1000	m	K0	0.002	/m
dt 3 min	dt	180	s		
	m	0.1111			

Stair 100 -	180	s			
	p	1			
Final Visibility	0.1	m	Kf	20	/m
Initial Visibility	1000	m	K0	0.002	/m
dt 1.333333333	min	dt	80	s	
	m	0.249975			

First Floor 100	-	450	s		
	p	1			
Final Visibility	9	m	Kf	0.222222222	/m
Initial Visibility	1000	m	K0	0.002	/m
dt 5.833333333	min	dt	350	s	
	m	0.000629206			

First Floor	450	-	600	s

APPENDIX B (CONTINUED)

			p	1			
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			9	m	K0	0.222222222	/m
dt	2.5	min	dt	150	s		
			m	0.131851852			

CASE SIX Fire at 5.8 level of the Service Zone

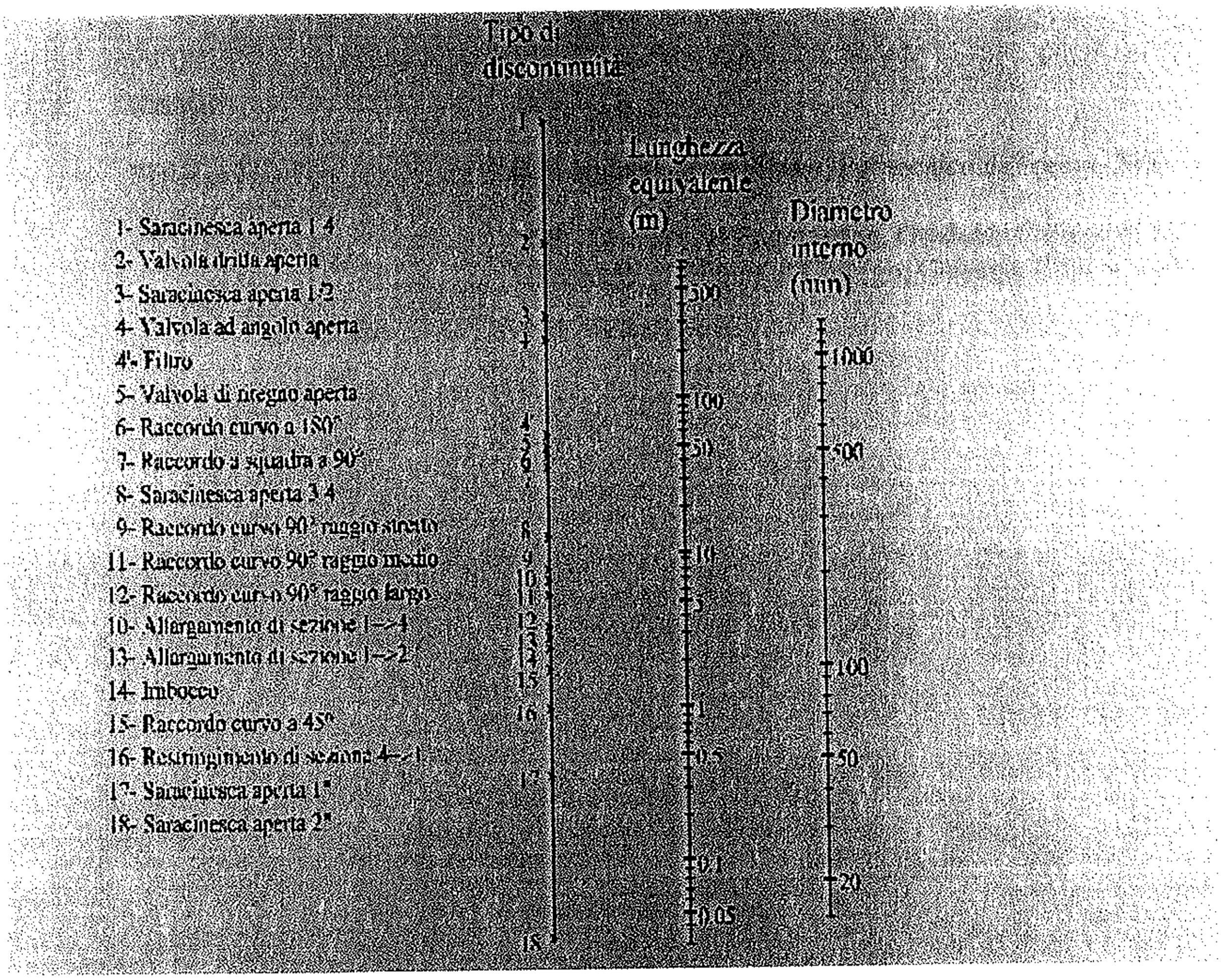
Near the Fire	0		-	60	s		
			p	1			
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			1000	m	K0	0.002	/m
dt	1	min	dt	60	s		
			m	0.3333			
ST ceiling	0		-	390	s		
			p	1			
Final Visibility			4	m	Kf	0.5	/m
Initial Visibility			1000	m	K0	0.002	/m
dt	6.5	min	dt	390	s		
			m	0.001276923			
ST ceiling	390		-	600	s		
			p	1			
Final Visibility			0.1	m	Kf	20	/m
Initial Visibility			4	m	K0	0.5	/m
dt	3.5	min	dt	210	s		
			m	0.092857143			
5.8 level	0		-	390	s		
			p	1			
Final Visibility			27	m	Kf	0.074074074	/m
Initial Visibility			1000	m	K0	0.002	/m
dt	6.5	min	dt	390	s		
			m	0.000184805			
5.8 level	390		-	600	s		
			p	1			

APPENDIX B (CONTINUED)

Final Visibility	3	m	Kf	0.666666667	/m
Initial Visibility	27	m	K0	0.074074074	/m

dt	3.5	min	dt	210	s
			m	0.002821869	

APPENDIX C


Tipo di discontinuità
Lunghezza equivalente (m)
Diametro interno (mm)
1- Saracinesca aperta 1/4
2- Valvola dritta aperta
3- Saracinesca aperta 1/2
4- Valvola ad angolo aperta
4'- Filtro
5- Valvola di ritegno aperta
6- Raccordo curvo a 180°
7- Raccordo a squadra a 90°
8- Saracinesca aperta 3/4
9- Raccordo curvo 90° raggio stretto
11- Raccordo curvo 90° raggio medio
12- Raccordo curvo 90° raggio largo
10- Allargamento di sezione 1-->4
13- Allargamento di sezione 1-->2
14- Imbocco
15- Raccordo curvo a 45°
16- Restringimento di sezione 4-->1
17- Saracinesca aperta 1"
18- Saracinesca aperta 2"
500
100
50
10
5
1
0.5
0.1
0.05
1000
500
100
50
20

VITA

NAME: Carlo Stella

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