FOREST FIRE NET 2008

The Accident of Kornati (Croatia)

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ABSTRACT

Croatia belongs to countries with high forest fire risk and lot of open space fires, particularly in summertime, along the coast and on numerous Croatian islands. Damages caused by fires are not very height because the fire fighting service in Croatia is organized quite well, having both professional and voluntary fire fighting organizations. The history of organized fire fighting in Croatia is 144 years and during this long history, until 2007, no one fire fighting accident with lot of causalities has been recorded. Since 1980 not more then 15 fire fighters and civilians have lost their lifes as a direct consequence of the open space fires. The accident of Kornati which happened on August 30, 2007 is the biggest fire fighting accident ever recorded in Croatia. Twelve fire fighters, both professional and voluntary, lost their lives and one was badly injured in a small canyon near Sipante bay on island Kornat in National park Kornati. In order to explain what had happened in Sipnate canyon and why experienced fire fighters lost their life during quite simple intervention, the Office for National Security of Croatian Parliament and law-court in Sibenik have engaged more than 50 researchers and experts from various fields. One year after the accident we will present in this paper the main results of this investigation with emphasize on physical aspect of accident, primarily meteorology, vegetation, fire spread, aerodynamics and thermodynamics. Our aim in studying this accident was not to find who is guilty or to blame anyone, but rather to find what happened and to extract lessons, to avoid future accidents. Kornati victims will never been forgotten and they will live in our memory, but we hope that lessons learned from the accident could help to further prevent such accidences. The accident of Kornati was the fist accident in Croatia with lot of causalities, but we hope that it will be also the last one, too.

INTRODUCTION

Croatia belongs to countries with high forest fire risk. In summer seasons seven coastal counties in Croatia and in particular the Adriatic islands are permanently exposed from high to very high fire risks, due to densely-spaced conifer forests, very warm climate with low level of humidity and lot of tourists visiting various costal and islands regions. Because of that Croatia has a long history of organized fire fighting in both, professional and voluntary services. The first voluntary fire fighting organization in Croatia was established in 1864. in Varazdin. During this long history of fire fighting in Croatia, the fire fighting accidents with such huge causalities have never been recorded until the accident of Kornati in 2007.

According to official data, the fire season 2007 belongs to most severe fire seasons, but the reason why it will be forever remembered in Croatia is because on August 30th, 2007, the routine fire fighting operation on island Kornat in National Park Kornati islands ended with 12 dead and one badly injured fire fighters.

Short after the accident, in September 2007, in order to understand what could happened during the Kornati accident the Office for National Security of Croatian Parliament and Ministry of Interior Affairs formed the voluntary research team conceived of researchers from various Croatian Universities and institutions. The experienced research team from Forest Fire Laboratory of the University of Coimbra Portugal has also been included and independent scientific investigation was performed. The accident was primarily analyzed from meteorological, vegetation, fire spread, thermodynamics and aerodynamic points of view, but also the fire fighters injuries, equipment, communication and fire fighting and rescue operation organization was analyzed too. The main task of this research was not to find who is guilty. That is the task of official law-court investigation which is, at the end of August 2008, still in progress. The law-court in Sibenik has appointed its own independent team of court experts having the same task as our team – to analyze the fire spread and possible accidents causes. Until the end of the official law-court investigation, the integral report of court experts will not bet available. Publicly, only its short summary was presented at the end of August 2008. Although this paper describes primarily the research of our independent scientific commission we will mention main conclusions of official court experts too.

After the accident there were a lot of speculations about its possible cause. Most of them were connected with human artifacts. Let us mention few of them with additional comments why they have been officially declined:

- The airplane bomb from the Second World War. (Comment - Around accident place there was no one evidence of explosion, but also pathological analyses has not found any injury which could be caused by explosion.).
- The gasoline reservoirs explosion. (Comment - The firefighters have carried two gasoline tanks, each one of 20 l, but both of them has not exploded, the gasoline has burned as a torche.)
- The helicopter accident. This theory said that the helicopter was damaged so the gasoline sprayed fire fighters. (Comment – Official investigation of helicopter said that its only damage was the broken tie.)
- The mistake of helicopter pilot. This theory said that the pilot made a mistake activating the fuel bleeding procedure used when there is a danger of crash, so that the fire fighters were sprayed by fuel. (Comment - Official investigation of helicopter declined this theory.)
- Experimentation with the new NATO techniques for fire fighting which includes explosive devices in pipes used for generation of water steam. The accident was caused by explosion because of bad equipment handling. (Comment - Stupid theory by itself, but also there were no evidences of any kind of explosion, both on terrain and on victims bodies)
- Experimentation with new explosive technique for fire fighting based on small napalm bomb. (Comment – The same as before.)
- Again explosion, but this time caused by military weapons and bombs. Ten years ago NATO had a military exercise close to Kornati islands, so one theory said that they have forget some of their weapons or bombs (Comment – The same as before.)
- The last theory of explosion. It said that before Natonal park period the army used Kornati for disposal of unused weapons so that the soil was polluted by explosive liquids or white phosphor. (Comment - Kornati islands are national park for 40 years, but also official investigation have not found any unusual material on the soil.)

Investigation and accident evidence analysis have declined all this, men made caused reasons of accident. In spite of that, not only ordinary people, but also some professionals still did not believe that the grass vegetation and natural phenomena could cause such a terrible accident.

Because of that the main task of our research was primarily to analyze is it possible that the accident was caused by natural phenomena only. Our report ended with lessons learned from Kornati accident and 37 recommendations for further improvement of fire fighting organization, education and research in Croatia. We hope that the Croatian fire fighting services will be further improved and that the Kornati accident will be the first and the last such terrible accident in Croatia.

The research team has visited the accident place twice, on September 25th 2007, when the weather conditions were similar to those on the day of accident and on February 5th 2008. Terrain configuration, local weather conditions and vegetation samples were collected and analyzed. In the rest of this paper we will shortly described our research conclusions.

THE ACCIDENT PLACE DESCRIPTION

The island of Kornat is the largest of 365 islands in Croatia's Kornati National Park, a popular tourist resort. . The fire ignition point was in Vrulje bay and the accident happened in the small canyon on the north side of Sipnate bay (Sipnate canyon). The canyon shown in fig.1 is opened only from the south and on other three sides surrounded by hills Glavica (135 m – west), Meja (150 m – north) and Veli vrh (212 m – east).

Injured fire-fighters were found on three places, marked with A, B and C in fig.2. Six were found dead and seven injured. The injuries were very severe, so 17 days after the accident six badly injured fire-fighters passed away. Only one fire-fighter recovered completely.

During our first visit to accident place in September 2007, when the weather conditions were quite similar to those during the accident, we have noticed that in addition to the strong S-E wind, several aspects relating to the enclosed location played important roles in the accident, as described in detail in [1] and briefly in [2]. The most important facts about accident place are:

- The location has stone terrain with no pathways and a complex topography. It is a small canyon about 500 m long, closed from three sides, from east by Veli vrh hill (212 m), from north by Meja hill (150 m) and from west by Glavica hill (135 m) and open only from the south side (fig.1).
- The canyon's main axis is directed to the north, with 15% (9^o) average slope, and 29% (16^o) and 45% (24^o) maximum slopes on the left and right sides of canyon, respectively (fig.3).
- The total burned area located on the canyon bottom was 99 887 m^2 (ca. 10 ha).
- The location has low and rare vegetation, mostly grass, which in fitogeographic sense belong to eumediterain vegetation zone, with 35%–45% woody vegetation and total cover between 45%–55%. There are only a few small isolated trees and bushes [1 , 3].
- The fuel load ranged from 0.561 kg/m^2 – 0.837 kg/m^2, and the average vegetation heat content was estimated to be 18,000 kJ/kg [1 , 3].
- Vegetation was extremely flammable, with ignition delay less than 2 s, and the average burning time of grass vegetation was 12 s [1 , 3].

Figure 1. Ignition point and the place of accident – the Sipnate canyon

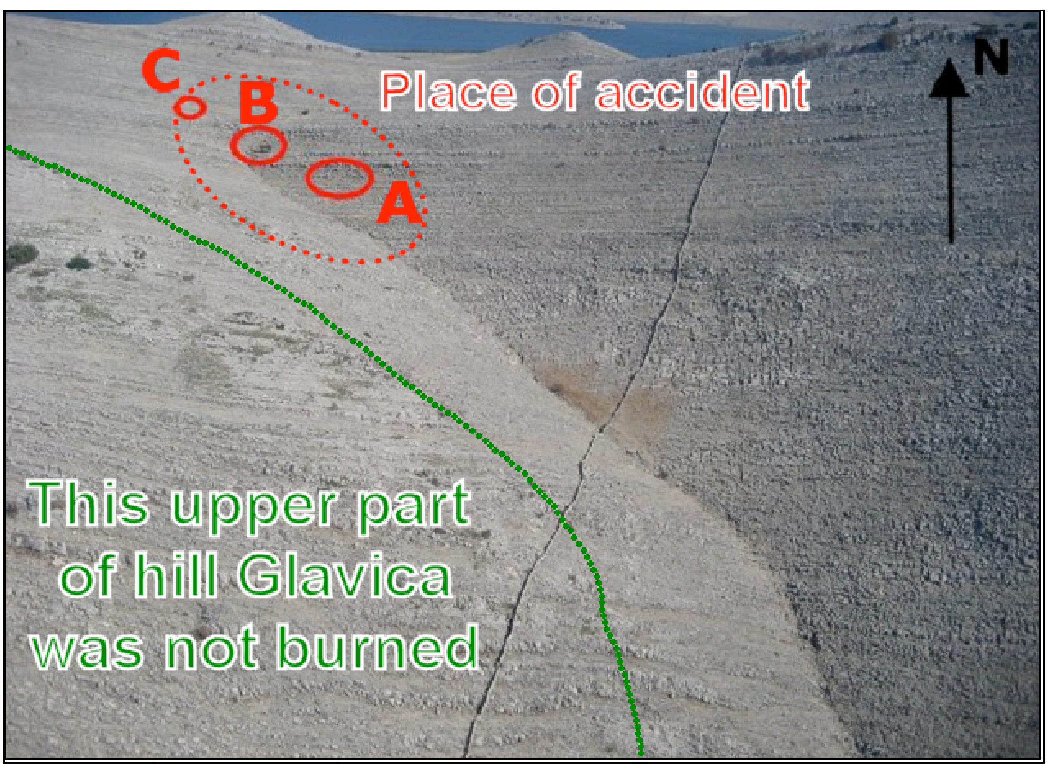

Figure 2. Air photo of Sipnate canyon with marked places where fire-fighters were found. Upper part of hill Glavica was not burned (see fig.5).

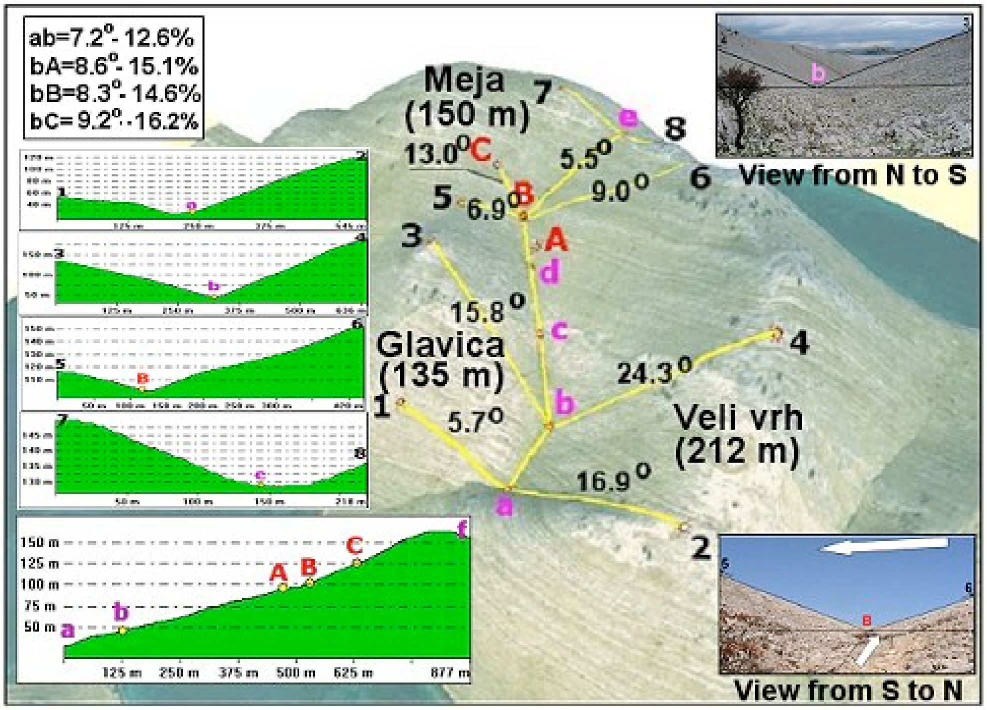

Figure 3. Sipnate canyon configuration with slope angles and canyon photos from north to south and vice versa

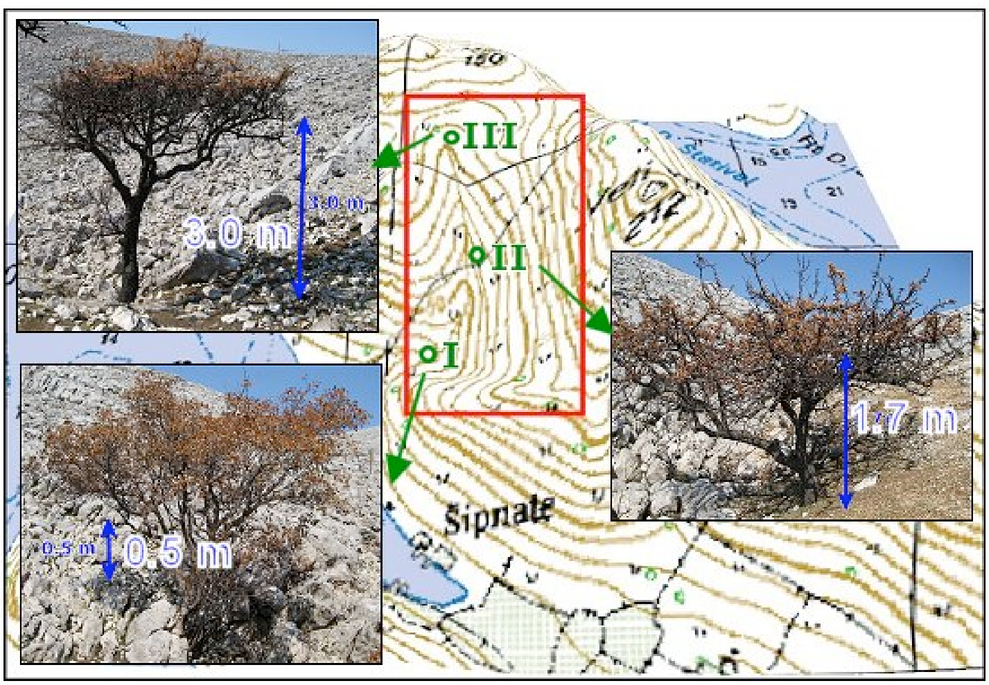

Figure 4. Unburned trees found on the line of canyon axis.

- The humidity content of the grass vegetation ranged from 12% to 14% [1 , 3].
- Dehydrated leaves on several trees showed the direction of the hot air flow from south to north (fig.4).

- Visible layers of burned and dehydrated bark, branches and leaves were present on several trees following the thermal boundary layer composition with heights from 0.5 m on the south side to 3.0 m on the north side of the canyon (fig.4).
- Glavica hill, settled on the west side, was unburned in its upper part (fig.2), giving us the possibility to collect appropriate vegetation samples and analyzed them in laboratory (fig.5).

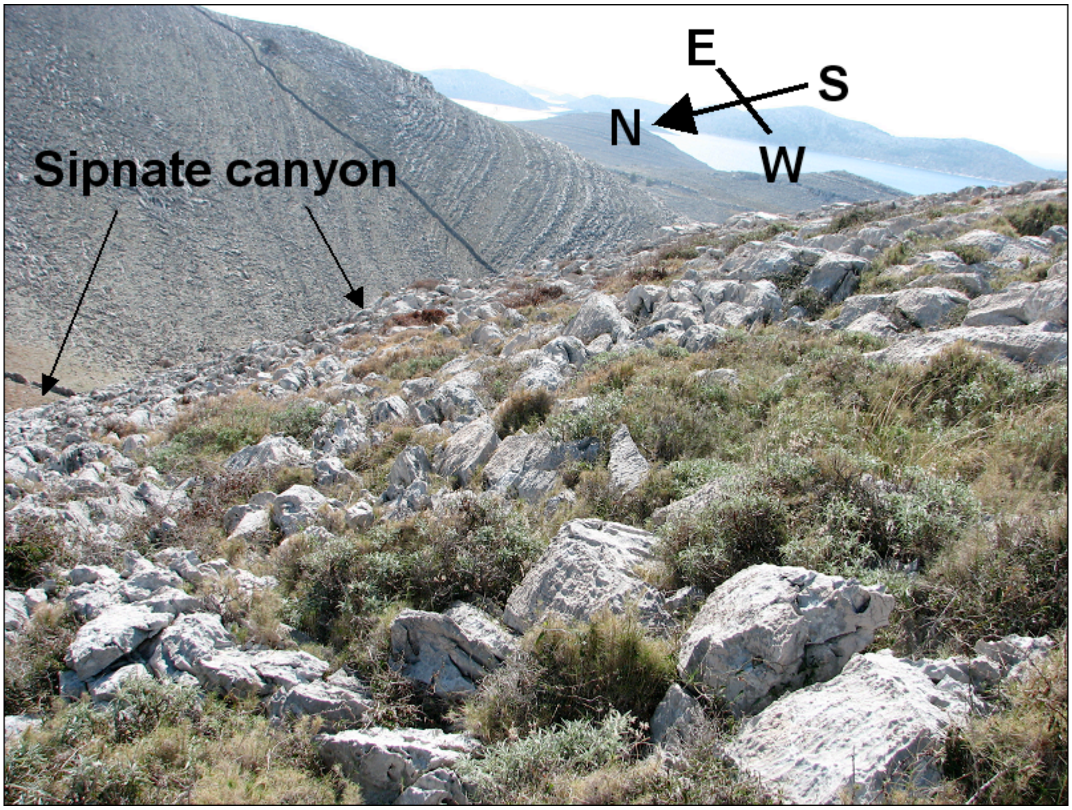

Figure 5. Unburned vegetation on the slopes of Glavice hill located on the west side of canyon.

DESCRIPTION OF THE ACCIDENT

The official scenario of the accident was as follows:

- 11:00 – 11:30 - The fire begins in Vrulje bay 6.6 km south-east from Sipnate canyon, quite close to official building of National park Kornati. The official investigation said that the fire was probably initiated by cigarette-stub thrown through the window by seasonal employer of National park Kornati.
- 11:48 – The first information about fire was received in Fire fighting operation centre in Sibenik. They sent the official request for helicopter.
- 11:50 – Fire fighters from professional brigade Sibenik, and voluntary organisations in Vodice, Tisno and Zablace start to prepare for helicopter departure.
- 12:00 – The helicopter was admitted.
- 13:00 – The helicopter take off from Sibenik with 23 fire fighters.
- 13:15 – The helicopter landed of on island Kornat near Kravljacice bay. Fire fighters were split in two groups. The first one composed of 6 fire fighters leave the helicopter here. They were not injured.

- 13:34 – The helicopter landed the second time between Lucice bay and Sipnate bay. The second fire fighters group composed of 17 fire fighters embarked here.
- 13:40 – The commander of the terrain fire fighters group Dino Klaric contacted the professional brigade in Sibenik and said that they are waiting for water reservoir.
- 13:44 – Communication between Dino Klaric and Drazen Slavica – the county fire fighters commander. Mr. Klaric said that the situation is not simple, fire front is very big, the grass is burning and the fire spread speed is huge.
- 13:50 – The Canader airplane start to fight the fire on island Kornat.
- about 14:00 – The water container took off from Sibenik and 15 minutes latter the reservoir was left on the south slopes of hill Veli vrh (see fig. 6).
- 14:30 – 14:45 – 13 fire fighters from the second group were brought by the helicopter from Sipnate bay to the new location. The helicopter has tried to embarked them close to water reservoir couple of times without success because of the strong wind from SE direction. The group commander Dino Klaric and pilot have decided to embark fire fighters on the new location and that was the top of Meja hill.
- 14:40 - The Canader airplane was sent from Kornati to another location.
- 14:58 -The fire fighters were embarked on the new location – the top of the Meja hill.
- 15:26 – The last communication with 13 fire fighters. Mirko Juricev Mikulin from Vodice has contacted the professional brigade in Sibenik with information that he had a contact with his son Ante who said to him that the group of 13 fire fighters was surrounded by the fire.
- 16:25 – Josko Knezevic contacted Operation centre in Sibenik and asked urgently for helicopter. He had a contacted Marko Knezevic who said to him that there were burned and injured fire fighters.
- 16:50 – The first rescue helicopter leave Divulje. He has located injured fire fighters but it was not equipped for air rescue.
- 17:35 – Fire fighters from the first group reached the Sipnate canyon.
- 18:00 – The voluntary Mountain rescue service from Split started the rescue operation.
- 19:40 – The last fire fighter was took of from Kornat island.

The professional fire fighters from Sibenik brigade made a reconstruction of the accident in Sipnate canyon using photos from camera found on the accident place belonging to Tomislav Crvelin. The reconstruction is schematically shown in fig. 6. The group of 13 firefigters was landed on the top of Meja hill and the water container was left on the south slopes of the Veli vrh hill. The straight line air distance between the embarkation point and water reservoir location is 928 m, but as the terrain is not flat, the right pedestrian distance is almost doubled. All equipment was embarked. They have carried some motor pumps, back-pack hand pumps, fuel containers and other tools but they did not have water. The fire fighters started to walk on the very difficult terrain of the island in the direction of the water container to start attacking the fire using the shortest path. In that moment the fire was not still visible from their location.

On their way they found that the fire line was along the crest of the ridge of the Veli vrh hill. This fire line is clearly visible on photo taken by Tomislav Crvelin before the accident and shown in fig.7. Probably the fire fighters have decided to turn from the fire to go around it. In the process of surrounding the fire line, the group started to descend along the eastern slope of Sipnate canyon and to actually place them near point A at the water line of this canyon shown in fig.3. Certainly unknown to them the southernmost edge of the fire line had probably entered the base of the canyon much below their position. Given the configuration of the canyon and the curvature of its water line from the position A the group could not see the bottom of the canyon. Therefore they must have realized that the fire was below them quite late to have a chance to escape collectively. Most of the equipment was dropped by the fire fighters near point A. It was also near this point that the majority of the victims were found. The only survivor was a fire fighter that remained slightly behind the group and escaped from the very intense and quick fire updraft along the canyon. A small group of fire fighters managed to reach point B but were found dead there. Remarkably a fire fighter was able to run until point C in spite of the extremely difficult terrain conditions but he was overwhelmed by the hot gases produced by the fire.

This reconstruction coincides with the interview with Frane Lucic, the only one firefighter from this group who has survived the accident of Kornati [4]. In one part of this interview Frane Lucic said: *"The grass was up to our knees. But the important fact was the very strong wind. In the canyon where we were found, the wind has changed its direction and formed the fire front in crescent moon shape reaching us with very high speed – maybe six, seven m/s. The grass was dry as gunpowder. We saw that flames and very thick smoke are going in our direction with high speed. We have been shorted of the breading air. We have stared to run. We have through away our equipment to run faster. I was responsible for rucksack with food, so I through it away. I run as fast as possible. Me and fire, but the fire was quicker. In a moment I was hip by the fire but I had enough time to put down the shield on my hamlet and that has saved my face. Then my legs were overtaken. I have been burned but in a fragment of second I have jump into the burned grass behind me. The heat has violently burned my fists but that has saved my life. Practically I stop running from the fire, turned myself toward the fire direction and went through the fire. After five to six steps I found myself on burned land, .out of hell. But my friends were not so lucky."*

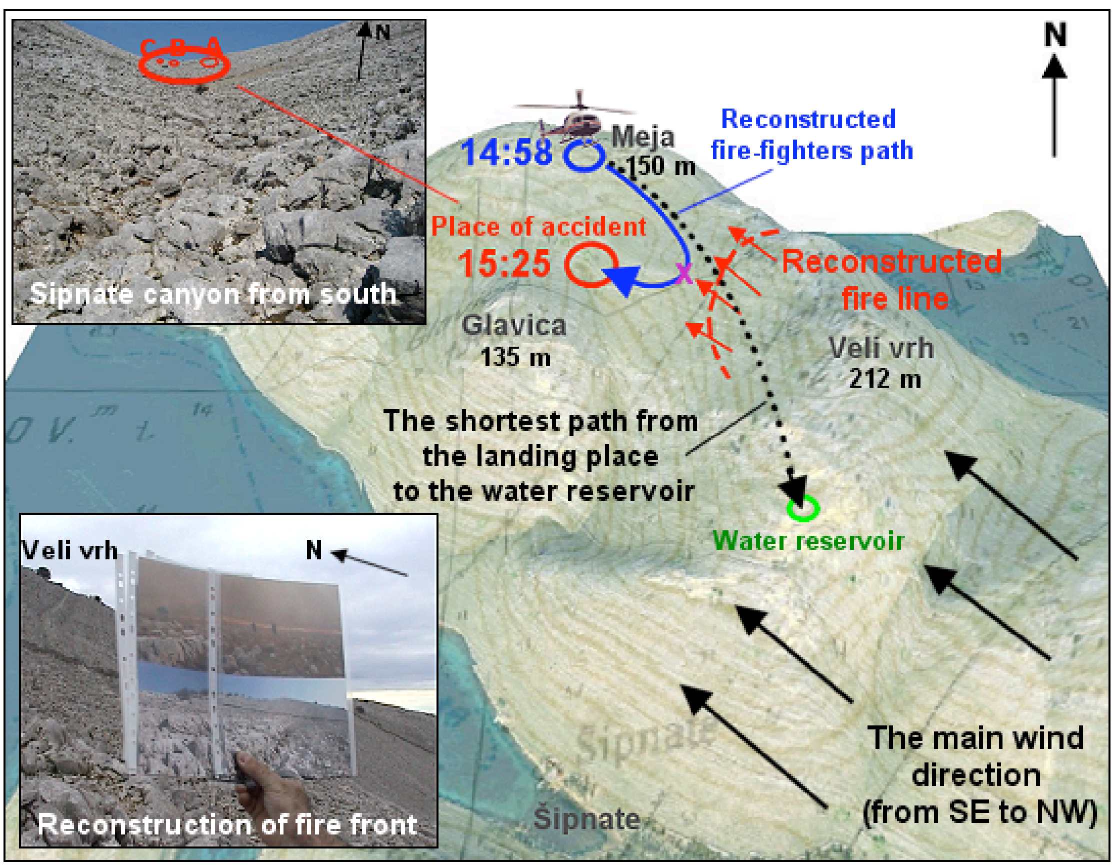

Figure 6. The location of the accident and important facts about the accident, including fire front reconstruction from photos taken by fire fighters half an hour before the accident

Figure 7. Photo from the camera of Tomislav Crvelin found on the accident place. According to reconstruction the photo was taken on the west slopes of Veli vrh hill. The fire front came from the east and it blocked the fire fighter path to water reservoir.

METEOROLOGY SITUATION DURING THE ACCIDENT

The researchers from the Meteorological and Hydrological Service of Croatia have analyzed the meteorological situation during the accident in details [1, 5, 6]. Here only a short their summary important for further accident analysis is presented.

- On August 30th 2007 there was a shallow meso-cyclone over the Zadar area (cca. 30 km straight line aerial distance) which produced sultry, partly cloudy and windy weather, with moderate to strong *jugo* (SE wind) and visibility limited to 10 km.
- The temperature in Zadar was 26°C, with maximum of 29°C in afternoon. The relative air humidity was between 55% and 70%. Because of cloudy sky the sun radiation has varied between 5 kJ/m^2 and 55 kJ/m^2.
- Gusts of *jugo* exceeding 10 m/s (36 km/h) at 10 m height were recorded in Zadar between 10 and 16 hrs. The maximal wind gust was 15.9 m/s (57 km/h) recorded at 13.20. The maximal 10-minutes avarage wind speed value was 11.6 m/s (42 km/h) recorded soon after the maximal wind gust.
- There are no wind measurements from the accident place, but the wind speed and direction in accident area was simulated using two models: ALADIN/HR and MM5. According to them, at 10 m height in accident area the wind was from SE direction and wind speed varied between 5.5 m/s and 10.8 m/s (19.8 km/h and 39 km/h).
- The MM5 model simulations of the vertical structure of the atmosphere showed that the weather in the lower layers of the troposphere was favorable for the development and spread of the fire.
- The MM5 model simulations also shown a sudden increase in wind speed to 12–14 m/s in the first 100–200 m height above the mean sea level, indicating the low-level jet stream with a very strong vertical wind shear in this layer, whereas very high values of turbulent kinetic energy

point at strong turbulence. Above this layer, a layer of temperature inversion was formed, about 300 m thick, preventing further updraft movements in the lower layer. In the inversion layer, wind speed rapidly decreased and the direction turned to S.

- As the largest amount of humid air penetrated only up at 500 m, strong convective cloud development did not took place on August 30th 2007.
- The Canadian Forest Fire Weather Index System for the Zadar station has shown that FWI *(Fire Weather Index)* and ISI *(Initial Spread Index)* reached their maximum precisely on August 30th 2007. Their values were 66.6 and 31.8, respectively. The FFMC (*Fine Fuel Moisture Code)* value on August 30th 2007 was 88.5, which would indicate a moisture content equal to 10–12% of the fine fuel mass.

FIRE PROPAGATION SIMULATION BEFORE AND DURING THE ACCIDENT

The fire began between 11:00 and 11:30 at Vrulje bay, located 6.6 km SE of the Sipnate canyon. The accident happened between 15:20 and 15:30, so the average fire Rate of Spread (ROS) was therefore of the order of 0.46 m/s (1.66 km/h, 46 cm/s).

At the University of Split, we have developed a fire propagation simulator iForestFire® [7,8], based on Rothermel equations and cellular automata, particularly adapted for the Croatian coast and islands, so we have used it to simulate Kornat island fire the spread. During data preparation for simulation the biggest problem was how to derive the appropriate vegetation map, because Croatian vegetation has never been analyzed according to fire spread characteristics. Our approach was to use standard Kornat island vegetation maps and Kornat CORINE 2000 land cover-land use classification and replace their vegetation categories with fuel models proposed by Albini-Anderson [9] and Scott-Burgan [10]. During our research, many simulations were performed to find appropriate input parameters that would best fit the observed data, particularly the fire's time of arrival at the accident location and average ROS of 0.46 m/s. For the main fuel category defined by Albini-Anderson as fuel model type 1 (short grass 1 foot) and dead fuel humidity 12% the best fit was obtained for mid-flame wind speed 2.29 m/s (fig.8).

The most important conclusion derived from all our simulations was that the fire front propagate faster on the north side of island Kornat. Witnesses have mentioned this as well, and this fact was used in the reconstruction of the firefighters' path, shown in fig. 6. According to simulation, the south part of fire has propagated slower, entering to the south part of Sipnate canyon after the fire front has reached the top of the hill Veli vrh.

The second part of our fire propagation analysis was the fire propagation inside the Sipnate canyon. In Sipnate canyon, the dominant vegetation type was very dry grass. Fuel load estimation, based on vegetation sampling was 0.561 kg/m^2 – 0.837 kg/m^2 [1,3]. The most similar standard grass vegetation categories close to this fuel load are Albini-Anderson fuel model type 3 (A-A M3) with a fuel load of 0.744 kg/m^2 [9], and the Scott-Burgan fuel model GR4 (S-B GR4) with a fuel load of 0.531 kg/m^2 [10]. In Sipnate canyon, the mid-flame wind direction was parallel to the main canyon axis and mid-flame speed was 1.8 m/s – 4 m/s (6.4 km/h – 14.4 km/h). These values were calculated using Anderson methods from 10 m wind speed obtained by meteorological simulation models. Fine Fuel Moisture Content (FFMC) was 12% – 14% and moisture in live grass fuel was 30%. The Dead Fuel Moisture of Extinction (ME) was estimated to be 40% because the original ME values for A-A M3 (25%) and S-B GR4 (15%) fuel models were not appropriate. The same problem for Mediterranean vegetation was also noted by Yebra et al [11]. Their ME estimation for grass vegetation of 40% corresponds to our experience too. The average slope of Sipnate canyon's main axis is 14%.

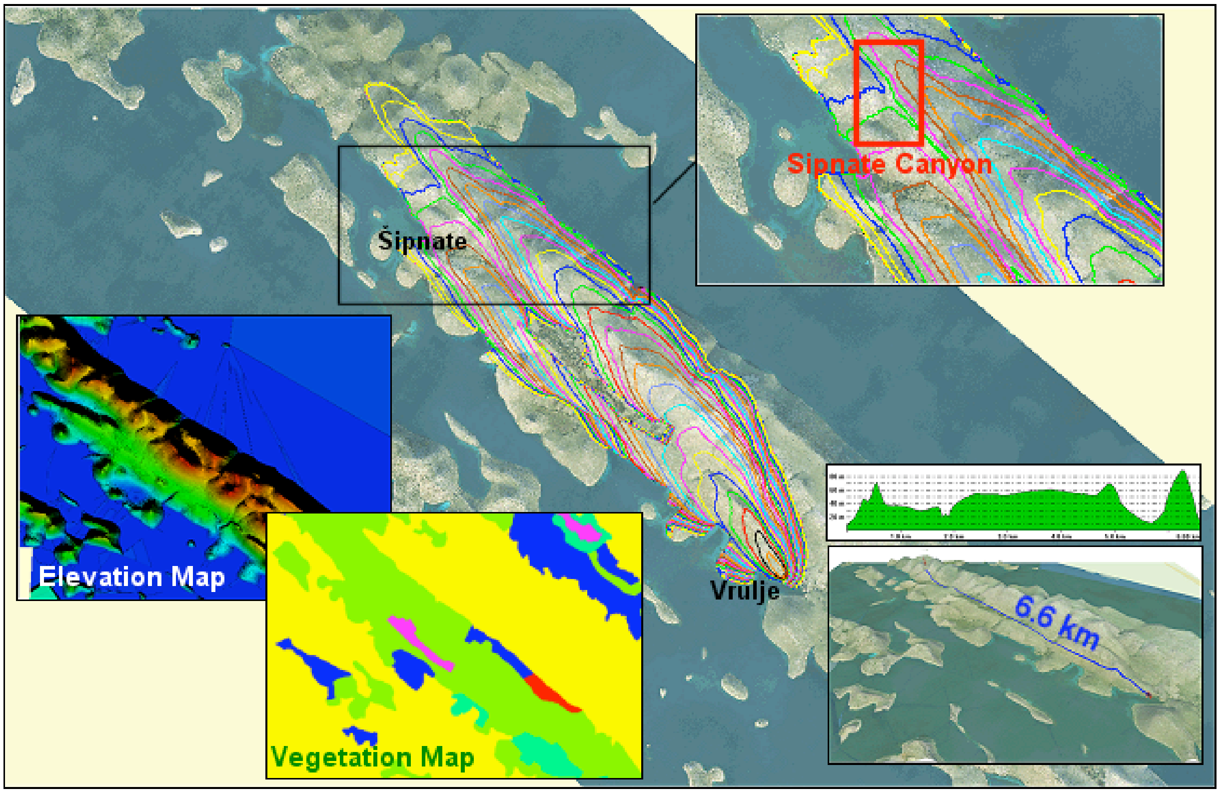

Figure 8. Fire spread simulation from the ignition point at Vrulje bay to the location of accident at Sipnate canyon based on Rothermel equations and adapted for Croatia at the University of Split. The dominant vegetation (light green) was modeled by Albini-Anderson category 1 (short grass), dead fuel humidity was 12% and average mid-flame wind speed 2.29 m/s.

Fire propagation parameters were calculated using the BehavePlus3 simulation program, and results for A-A M3 and S-B GR4 fuel models and FFMC 12% are given in fig. 9. The burned area at the bottom of the canyon was about 10 ha, so the total released heat energy caused by vegetation burning could be estimated to 550 GJ – 750 GJ. The Rothermel equations and the BehavePlus3 program suppose a constant rate of spread for the fire, and according to them, arrival time from the point visible from the accident to the location of the accident (distance 350 m) is between 5.21 min to 15.91 min, which is not realistic.

The firefighters were quite experienced, so if the arrival time of the fire front in Sipnate canyon was between 5 to 15 minutes, they would have had enough time to escape. Thus, our conclusion was that the Rothermel model with constant fire rate of spread was not appropriate for simulation the fire behavior in Sipnate canyon. Another possibility was eruptive fire model. At University of Coimbra Forest Fire laboratory simulation of Sipnate fire was performed and results were applied in eruptive fire mathematical model.

A-A M.3

Midflame Wind Speed km/h	Rate of Spread m/min	Heat per Unit Area kJ/m2	Fireline Intensity kW/m	Flame Length m	Reaction Intensity kW/m2	Spread Distance m
6.4	23.9	7963	3168	3.2	518	1432.4
9.6	39.2	7963	5205	4.0	518	2353.1
14.4	65.3	7963	8670	5.0	518	3919.6

S-B GR4

Midflame Wind Speed km/h	Rate of Spread m/min	Heat per Unit Area kJ/m2	Fireline Intensity kW/m	Flame Length m	Reaction Intensity kW/m2	Spread Distance m
6.4	22.0	5123	1877	2.5	406	1319.2
9.6	38.1	5123	3252	3.2	406	2285.4
14.4	67.2	5123	5735	4.1	406	4030.1

Figure 9. Fire propagation parameters in the canyon for Albini-Anderson type 3 and Scott-Burgan GR4 fuel categories and various mid-flame wind speed

LABORATORY SIMULATION OF FIRE AND ERUPTIVE FIRE MATHEMATICAL MODEL

A laboratory simulation of the fire evolution in Sipnate canyon was performed at the Forest Fire Laboratory of the University of Coimbra at its large canyon table DE4. Only few details of the experimental conditions are given here. The Table has two faces that were set at the inclination angles given in fig. 10 in order to represent the basic shape of the lower part of the canyon. The fuel that was used in the tests was straw that replicated well the combustibility properties of the herbaceous fuel that existed largely in the area. An ignition line was set at the position shown in the same figure.

Video and infra-red cameras were used to register the experiments. Several experiments were carried out with slight differences in the pattern of ignition. The evolution of the fire front along the three main directions S1, S2 and S3 was analyzed from the IR images and the results are shown in figure 6. As can be seen in this figure the linear fire front propagated relatively slowly down slope towards the water line (direction S3) but when it reached this line and the bottom of the eastern slope of the canyon it spread very rapidly along it (line S2) and along the water line (S1). Given the differences in scale and configuration we do not claim that these experiments replicate with great precision the fire spread conditions before and during the accident but they do show some very important qualitative features of the fire in this process.

We can see that the spread along S2 exhibits an acceleration that is characteristic of eruptive fire behavior. In our opinion this was most likely to have occurred in Sipnate canyon before the accident. One other point that we can see in that figure is that the fire spread along the water line (line S1) was also very quick and it happened almost at the same time as the other eruption. This is consistent with the facts that the group of fire fighters was caught near the water line and on the West side of it.

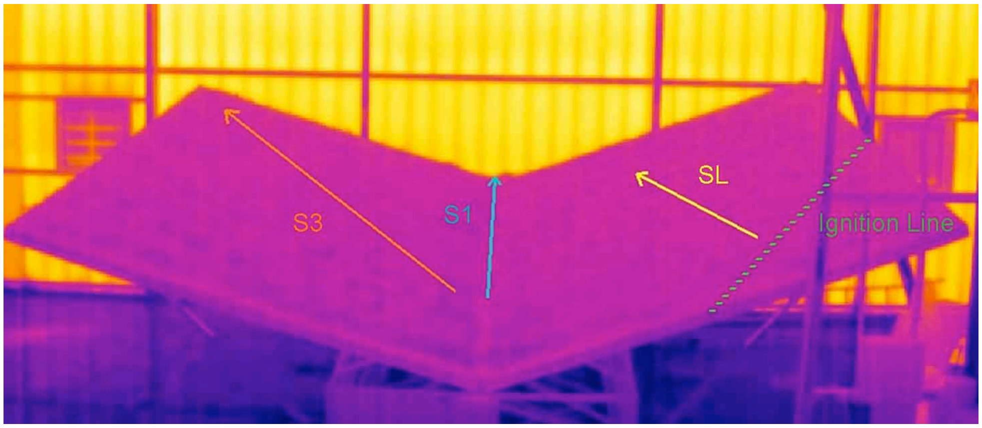

Figure 10. Schematic view of the Canyon Table of the Forest Fire Laboratory of the University of Coimbra indicating the position of the ignition line and the three directions S1, S2, and S3 along which the fire spread was analyzed.

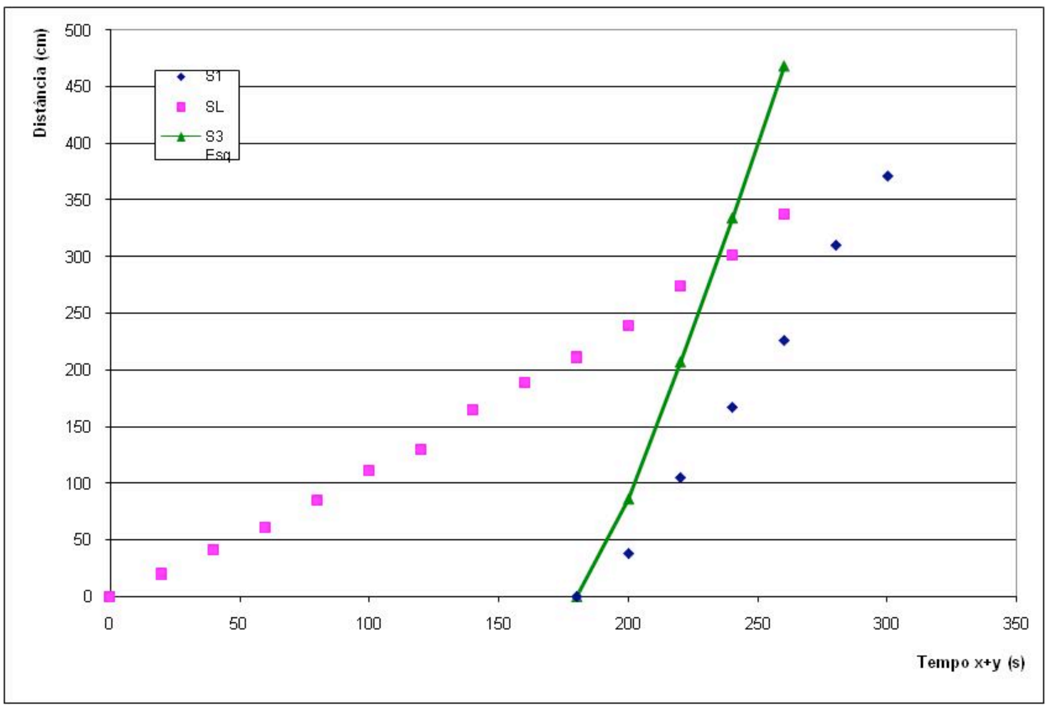

Figure 11. Distance traveled by the fire along the three main directions indicated in figure 10.

We remark that in this test no wind was used over the test area. Comparing with the actual situation of the accident we know that the presence of a relatively strong wind aligned with Sipnate canyon would make these conditions even worse.

Given the evidence of the very likely existence of an eruptive propagation of the fire in Sipnate canyon we shall apply the mathematical model [12] to predict the rate of spread of the head fire in this case. In spite of the simplicity of the mathematical model it is necessary to know the adequate parameters and initial conditions in order to apply it. As the properties of the fuel bed that existed in Kornat Island are not yet well known we can only apply the parameters that were measured for similar fuels assuming that they are analogous to the conditions in Sipnate canyon. We shall use the following set of parameters in order to apply the mathematical model to estimate the advance of the head fire along the water line of the canyon and along the left (East) slope of the canyon.

Table 2. Parameters used in eruptive fire mathematical model

R_o (cm/s)	R'$_i$	t_o (s)	b_1	b_2	a'_1	a'_2
0.61	1.5	50	1.8	1.0	0.2	0.2

Using the above mentioned values the differential equation of the rate of spread was integrated twice to determine the distance of advance of the head fire since its arrival at the water line of the canyon (at point *a* of fig. 3) and the result is shown in fig. 13. The relevant points of the trajectory of the head fire along the water line of the canyon are indicated on the curve.

If the prediction that is indicated in this figure is correct we can see that since the fire entered the base of the canyon it may have taken some minutes to reach point *b*, but from this point onwards it must have taken less than two minutes to reach the main group at positions A and B. In less than three minutes it must have reached position C. These time intervals are consistent with the distances and displacement times that would be required to travel from A to b and to C. If we assume a displacement velocity of 2m/s for the escaping fire fighters they would require between one and three minutes to reach from A to B or to C respectively, taking into account the difficulties of the terrain.

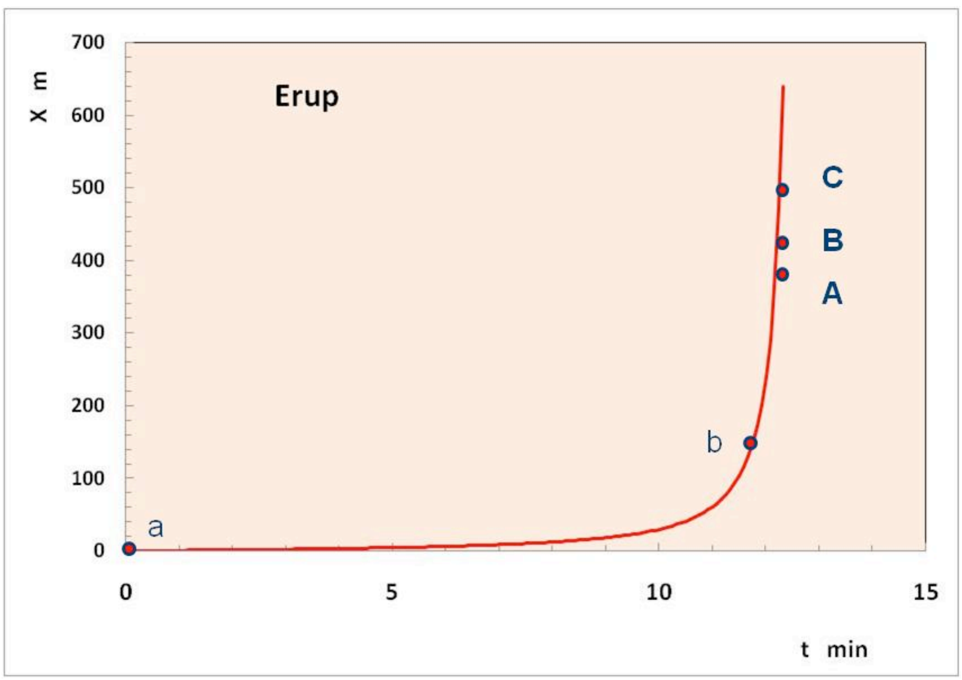

Figure 12. Predicted distance of advance of the fire along the water line of Sipnate canyon with time since its entrance at the base of the canyon at point *a*.

We remark that the presence of flames at the bottom of the canyon could only be perceived when they reached point *b*, although we can assume that the presence of smoke could have been perceived a bit earlier and might have triggered the alarm one or two minutes before. Even so it was probably too late for the group to reach a safe zone.

In this simulation we also did not consider the effect of the wind on the fire eruption. Based on our previous observations we assume that the presence of wind might anticipate the moment of eruption but would not otherwise change the sequence of events. The eruption would have occurred with the support of the wind giving even less time for the group to escape from the fire.

AERODYNAMIC AND THERMODYNAMIC ASPECTS OF ACCIDENT

The basic aerodynamic and thermodynamic analyses was also performed [1,13,14] based on a number of assumptions [15]. The most important one is that if we use only the standard assumptions of fire development, including the eruptive fire propagation effect, there is not enough energy flow and expansion in a grassy landscape fire development that could result in this violent accident and so severe injuries. Other assumptions based on accident place analysis are as follows:

- Stones on the terrain are large, with high grass in between. No one can walk or run on this terrain, especially not heavily loaded and equipped fire fighters. Only short jumps are possible as a means to move around. Natural stone walls up to 5 m high serve as obstacles; therefore, fire fighters must follow the directions of these stone walls.
- Veli Vrh hill is the main terrain obstacle for air flow above the canyon. Its side line is almost perpendicular to Kornati Island's main axis. It could be expected that the main air flow bypasses the peak. Because of the relative canyon depth, large eddies can be produced over the canyon. This means there is local backward flow.
- The canyon over Sipnata Bay has its main axis in the north-south direction. The canyon begins at sea level with the main part just below Veli Vrh hill side. The canyon end is on the north side, just below the maximum jet stream layer. On this side is a small plateau located between Veli Vrh and Meja. On the east side of the canyon lies a flat skew plain, which was the location of the accident. The main thermal boundary layer was developed here.
- The surface jet stream layer over the complex terrain caused tunnelling of the hot air flow and renders analysis very complex. Therefore, some reasonable assumptions have to be made in order to achieve satisfactory results.
- There are two factors that aid the analysis. The first is the presence of dehydrated leaves on several trees in the path of the hot air flow. The hot air speed does not allow for burning, but only for heat transfer, which dries up leaves. Few other places in surrounding locations are visible with dry leaves in different paths.
- Another aiding fact is the visible layers on several small trees, composed of burned and dehydrated bark, branches and leaves, following the thermal boundary layer development from the bottom of the canyon (0.5 m) up to the middle part (1.7 m) and the plateau at the end (3.0 m). These heights provide iterative backward analysis of the thermal boundary layer.
- Half of Glavica hill was unburned due to backward flow caused by a large eddy, and the peak of Veli Vrh was partly unburned, probably due to a strong wind in the surface jet stream.
- The first canyon section is not visible from the location of the accident.
- During our first visit to the accident place at the end of September 2007, the wind conditions were similar to those during the accident. We have noticed two wind streams. The first one was dominant from the SE direction, blowing over the edges of Veli vrh hill. The second one was following the water line of the canyon blowing from S to N. The first dominant wind stream was much stronger on the N side of the canyon Top side). At the bottom of the

canyon, close to its south entrance, the wind stream from SE was not presented. Only the second wind stream which followed the canyon water line could be noticed.

Two possible thermodynamic explanations of accident were given:

a) The theory of Fast Heat Shock (FHS) derived during accident investigation by voluntary scientific research team established by Office for National Security of Croatian Parliament and Ministry of Interior Affairs [1, 14, 15].
b) The theory of "burning of no-homogenous gas mixture", derived by court expert team. Their theory has not been yet published with all details, because the court experts report is the integral part of court investigation which is still not finished, but its summary was given [16].

Fast Heat Shock Theory

This thermodynamic analysis was based on the assumption that the downwind terrain section was quickly burned. However, a fast inflammation effect is not sufficient to explain the accident, particularly the firefighters' severe injuries. Therefore, after analyzing all the evidence, Ninic and Nizetic derived one possible explanation, called the **Fast Heat Shock (FHS)** explain in details in [1, 14, 15].

According to their theory, the fire fighters may have been surrounded by the flames or in the enclosure of the rapidly shifted fire front. In any case, at the moment of inflammation of section at the bottom of Sipnate canyon, this modeling of the accident includes fast heat input along the whole canyon section. This heat input caused temperature-turbulent boundary layer formation. Its thickness at location of accident was 2.5 m, known as the height of the dehydrated leaves on small trees in the area. As the primarily research goal was to estimate only the possibility of an accident due to natural causes, relatively unfavorable circumstances were assumed, as for example a relatively low air excess factor λ=1.5, local air speed at 2.5 m above the ground was estimated to be 10 m/s, and dry grassy fuel was estimated to be 0.6 kg/m^2. With the assumed effective flame temperature and inflammated section length, this input data provided iterative estimation of the mean temperature in a boundary layer at accident location.

Energy balance for flow through a rectangular space of length 300 – 350 m and height 2.5 m, was calculated. For typical accident input data, the calculated average hot wind temperature was at least 420 K (150° C) and the duration was 2-3 minutes. Results show that this mechanism, called 'FHS - Fast Heat Shock', could explain the unusually violent consequences from apparently harmless circumstances. This explanation is independent of the fast inflammation mechanism.

Burning of no-homogenous gas mixture

As we don't know all details we can not discuss this theory in deep, so we will shortly present official report summary given to press by judge investigator Branko Ivic on August 22, 2008 [16]:

"The Kornati accident was caused by natural phenomenon known as 'burning of no homogenous gas mixture'. Gas mixture was created as a result of few hours burning of Kornati grass vegetation from the fire ignition point (Vrulje bay) to accident place (Sipnate canyon). The

distance between them is more then 6.5 km. As a result of vegetation burning, gasses and vapor composed of hydrogen, methane, ethane, CO, methanol and others were produced. They have been carried by wind over the top of hill Veli vrh and started to concentrated and accumulated Sipnate canyon. One fire front has entered the Sipnate canyon from its south part. Fire propagation through canyon probably had the eruptive fire behavior, so the fire front has reached the accumulated gas mixture in Sipnate canyon rather quickly and burned it.

The characteristic of natural phenomenon known as 'burning of no-homogenous gas mixture' is high temperature burning, sometimes more than 1200 ^{o}C. Also its consequences is very fast expansion of hot gasses. During this expansion their volume could be increased five to eight times in relation with the initial volume. The firefighters were first exposed to hot gases and after that to flames of burning vegetation, equipment and cloths. 'No-homogenous gas burning' was the primarily cause of fire fighters injuries. It is very rare natural process but not unknown. Similar think happened in Australia January 18, 2008 close to Canaberre and September 17th 2000 near Palasca at Corsica.

The experts also found that the helicopter has no connection with accident and that there were no any other kind of explosive devices – mines, bombs or phosphor as was speculated before.“

The members of the court expert group were *M.Drakulic, M.Carevic, B.Grisogono, S.Kocian, V.Mastruko, D.Zecevic and others*. In the future, when their integral report, will be publicly available, we could discuss this theory in more details. Here, let us only mention that we have considered the accumulated gas theory described by Peuch [17] in our original report [1]. After analysis we have throw it away, particularly because during our first visit to the accident place we have noticed two wind streams – the dominant one from SE, and local one in canyon which followed the canyon water line. Our conclusion was that the accumulation was not possible in canyon, but we will reconsider this theory again when details of court expertise will be available.

LESSONS LEARNED AND CONCLUSIONS

What we have learned from this accident? The most important conclusion is that there any fire fighting intervention could be potentially dangerous, so it is necessary to apply all measures of precautions. The Kornati fire looked at the first site quite simple fire because fuel was mostly short grass. The fire fighters said that the fire front on its way from Vrulje to Sipnat was not severe, so they have crossed the fire line couple of times. But the vegetation fire is so complex phenomenon that usually it is not so easy to predict its further development. Good fire fighters education and preparation, but also maximal concentration during intervention is vital for successful and safe fire fighting operations.

In this paper our interest was primarily in technical explanation of accident, but during investigation some organizational and procedural mistakes in fire prevention and fire fighting procedures were recorded. For example:

- The fire protection in National park Kornati was not appropriately organized according to existing plans.
- The fire fighters radio communication was not adequate.

- Part of fire fighters equipment was not appropriate.
- Lot of organizational problems were reported, for example two fire fighters were youngsters (less then 18 years), although according to Croatian low youngsters could not participate in fire fighting intervention.
- In summer 2007 Croatia had only 4 Canader airplanes for attacking forest fires. At the end of August, two of them were out of order for repairmen and one was sent to Greece as a help, although the summer 2007 was very dry and at the end of August the fire danger index was very height. Only one airplane was in operation in Croatia. On August 30, 2007, two other big fires were in Croatia, so in 14:40 the airplane was sent from Kornati to another location.
- The rescue operation was not organized appropriately, because the system was not prepared for such disaster.

Also lot of questions has been raised about decision where to attack the Kornat fire. For lot of people, particularly families of victims, but also some professionals, it is still not clear why the decision was to attack the fire front instead of protecting rare houses and rare fields of olive trees. For centuries Kornat islands were used for sheep pasture, so it was well known that shepherds used to burn the island to recuperate the grass. Houses are located only at isolated bays close to the see and it was quite easy to protect them from the fire. Couple of months after the fire, the grass vegetation on Kornat islands has been regenerated almost completely.

After detail analyze of all aspects of Kornati accident we have concluded our report with 37 recommendations concerning fire fighting education, fire fighting intervention organization and forest fire research, but also a number of recommendations concerning fire fighters equipment, communication and global organization were given too. Until 2007, in almost century and half long history of fire fighting in Croatia, they have never been recorded any accident with such causalities. We hope that our recommendation will be accepted by authorities in order to further improve fire fighting in Croatia. The accident of Kornati was the fist one such accident in Croatia, but we hope that it will be also the last one.

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