MFC forensic
investigation|simulation|consultancy

I metodi della ingegneria antincendio a supporto della ingegneria forense e della analisi degli incidenti occorsi: un ulteriore strumento di indagine

Relatori: L. Fiorentini (TECSA S.r.l.)*, B. Chiaia, L. Marmo (Politecnico di Torino), V. Puccia (Vigili del Fuoco)

* per SFPE: Research, Methods and Tools Committee // Fire protection magazine editorial board

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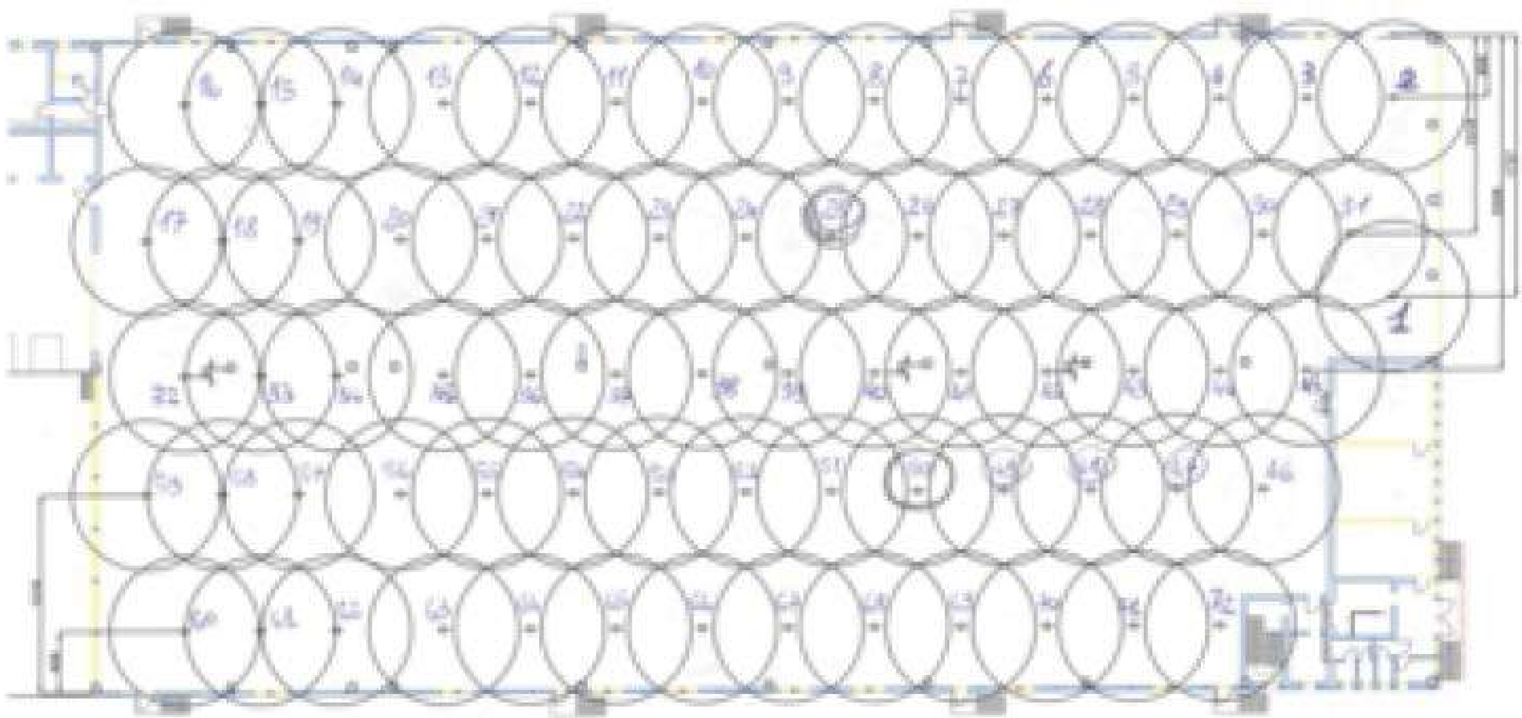
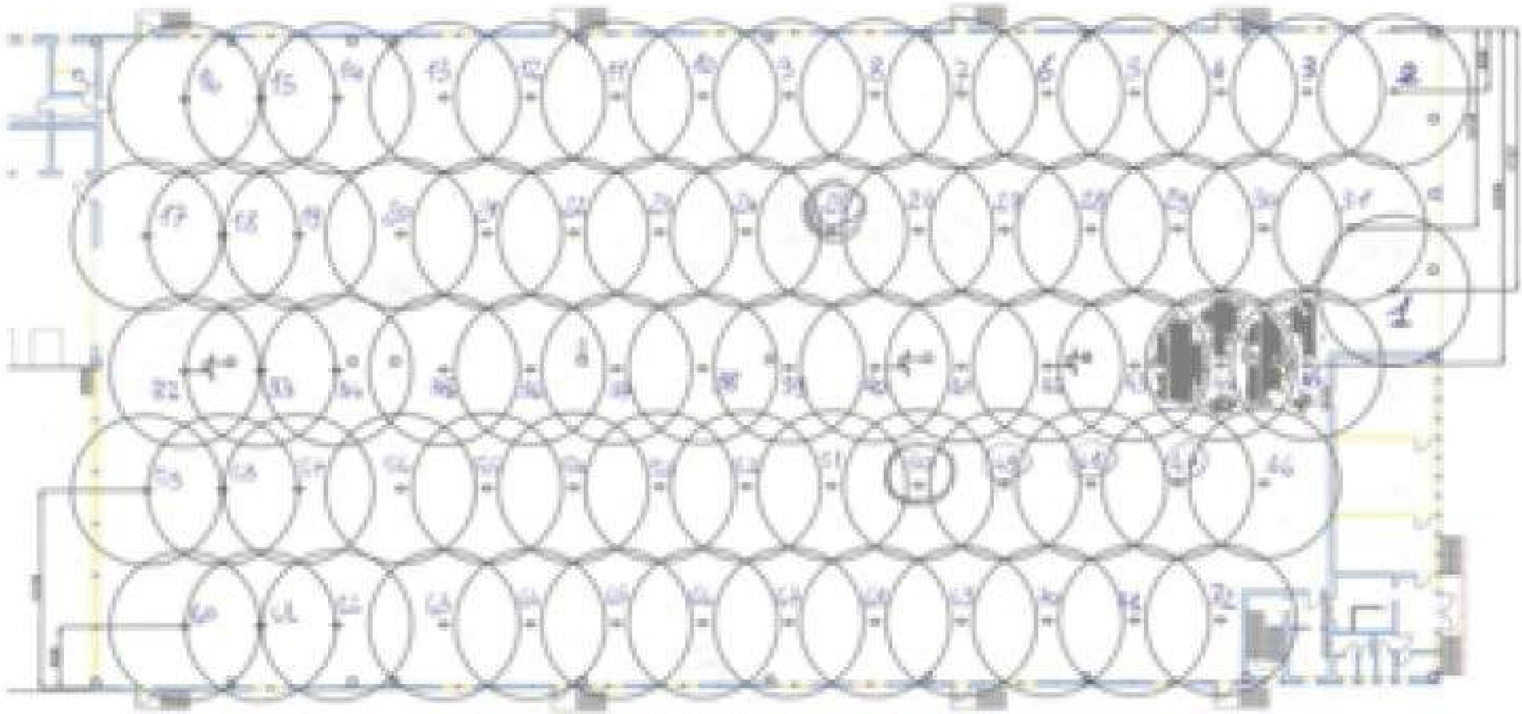
Un caso di studio…l’analisi della sequenza di allarme di un impianto di rilevazione fumi di tipo puntiforme per l’identificazione dello scenario di incendio:





Incendio	L1 A029 Z001		19:17
Incendio	L1 A030 Z001		19:17
Incendio	L1 A043 Z001		19:17
Incendio	L1 A046 Z001		19:17
Incendio	L1 A047 Z001		19:17
Uscita On	L1 A084 Z001		19:17
Incendio	L1 A042 Z001		19:17
Incendio	L1 A048 Z001		19:17
Incendio	L1 A031 Z001		19:17
Incendio	L1 A041 Z001		19:17
Incendio	L1 A049 Z001		19:17
Incendio	L1 A070 Z001		19:17
Incendio	L1 A071 Z001		19:17
Incendio	L1 A072 Z001		19:17
Incendio	L1 A001 Z001		19:17
Incendio	L1 A028 Z001		19:17

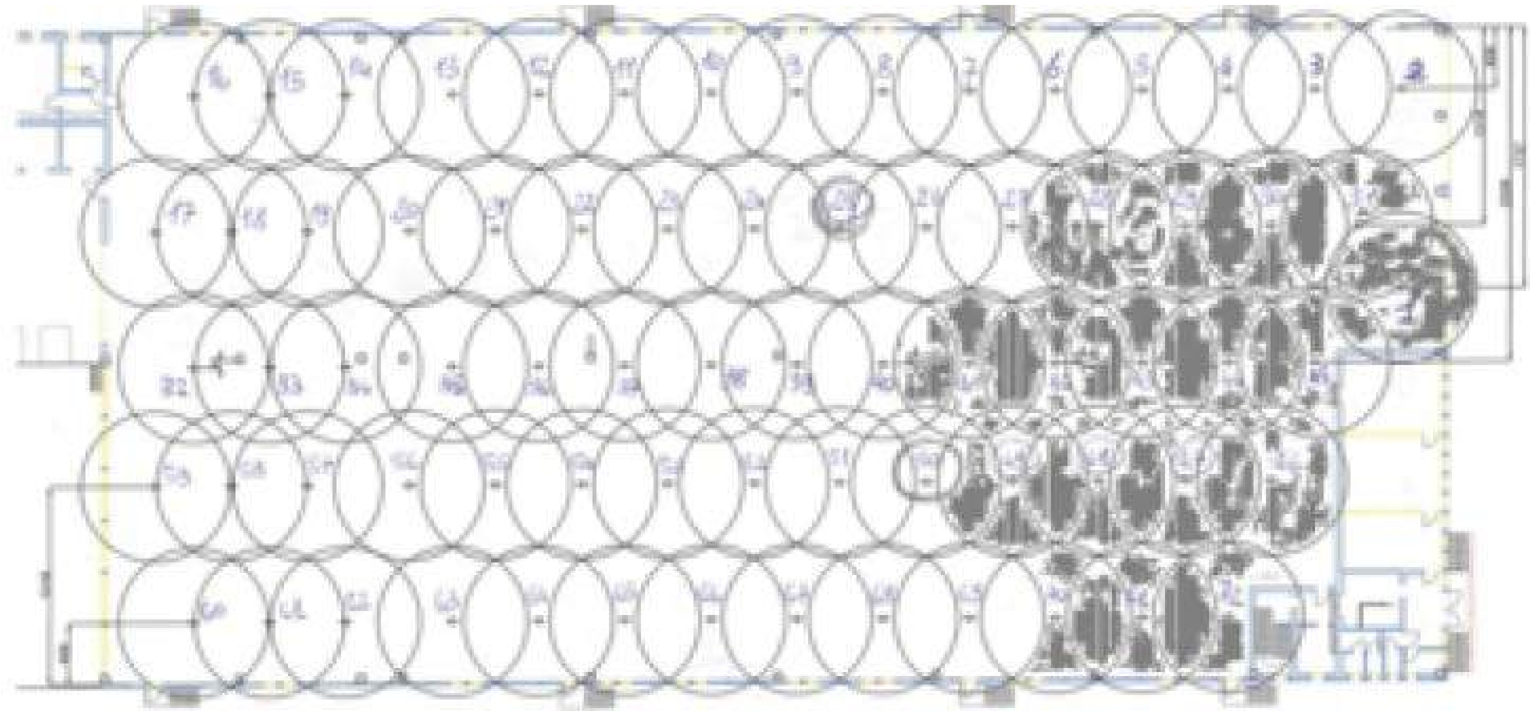


Fig 26 i sensori di rilevazione fumi attivatisi entro il primo minuto (17 sensori)

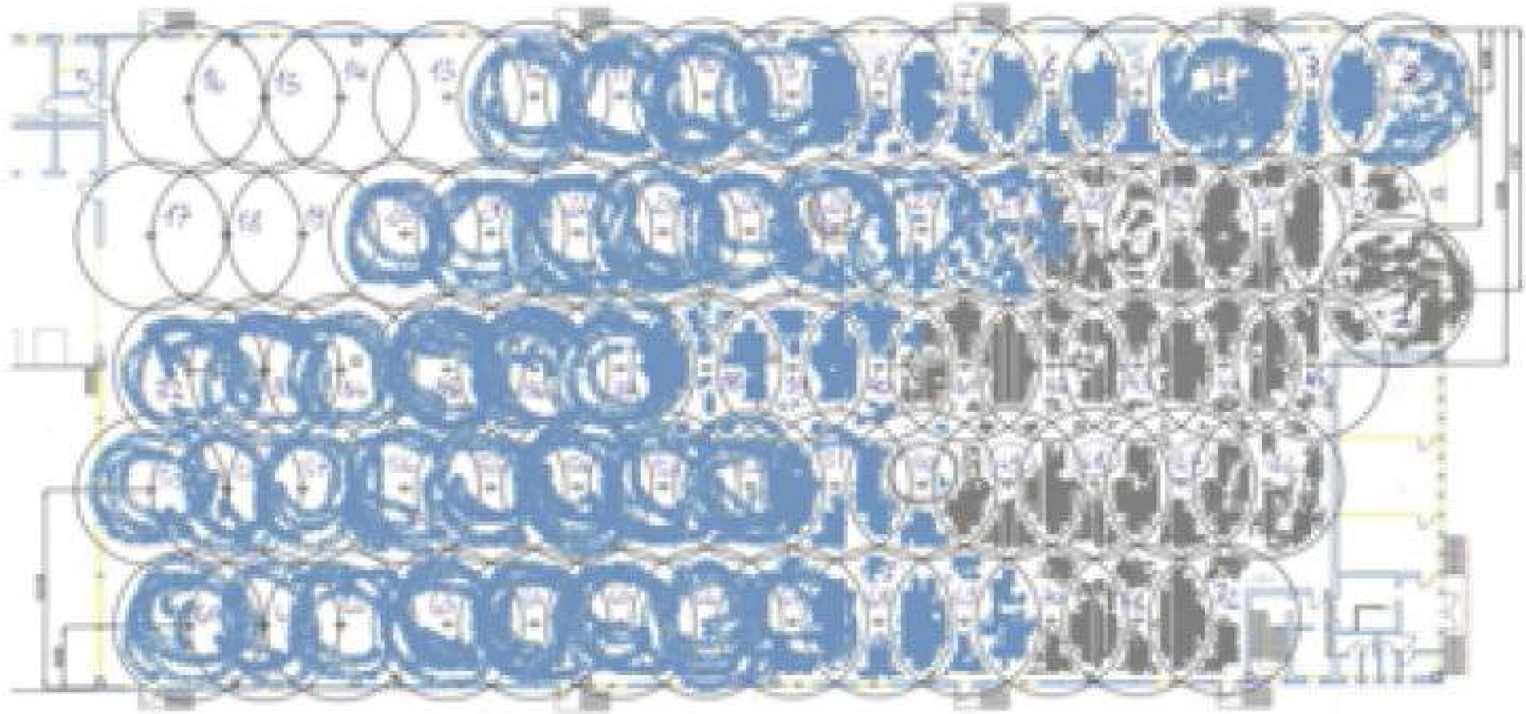


Fig.30 Schema dell' attivazione di sensori al termine del secondo minuto, orario stimato 19.41-19.42

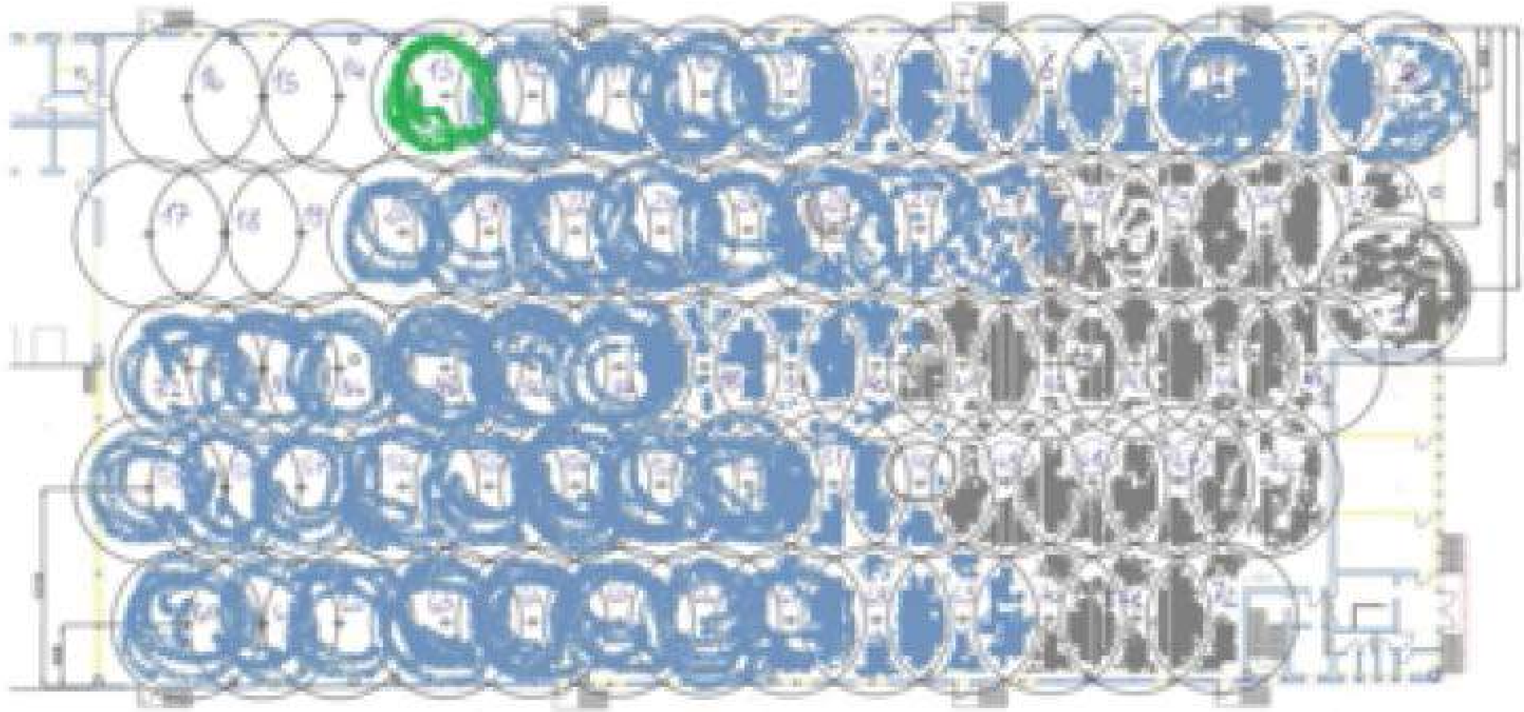


Fig.31 Schema dell' attivazione di sensori all'inizio del terzo minuto, orario stimato 19.42
a tale istante temporale deve riferirsi la prima chiamata di soccorso, che descrive già fiamme che protrudono dalla copertura, sviluppandosi per vari metri. Il circuito dell'impianto è ormai compromesso, in quanto la centrale segnale che il loop è aperto

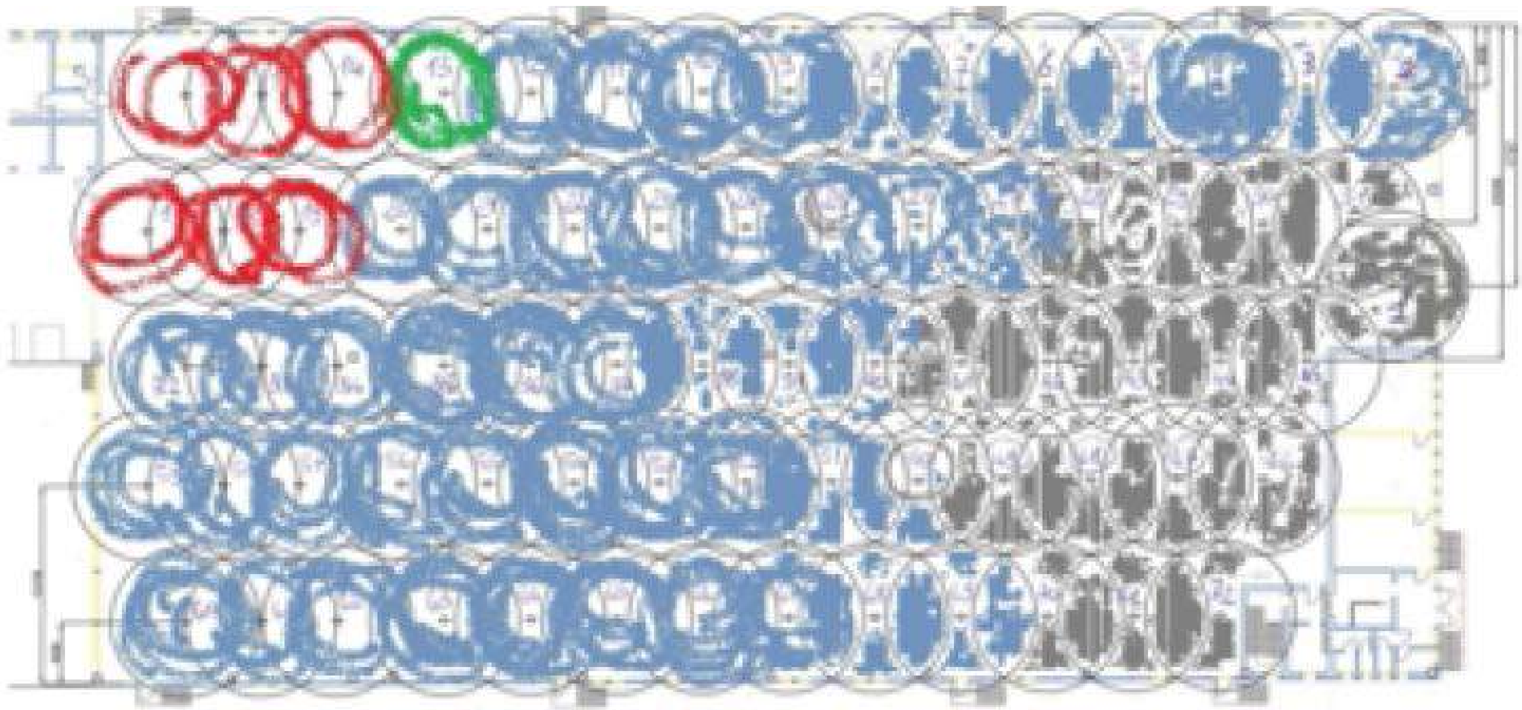


Fig.32 Schema dell' attivazione di sensori durante il terzo minuto, orario stimato 19.42, si è già verificata l'interruzione del circuito dell'impianto di rilevazione per fusione dei rilevatori o collasso parziale della copertura (controsoffitto e copertura) che ha trascinato con sé i cablaggi

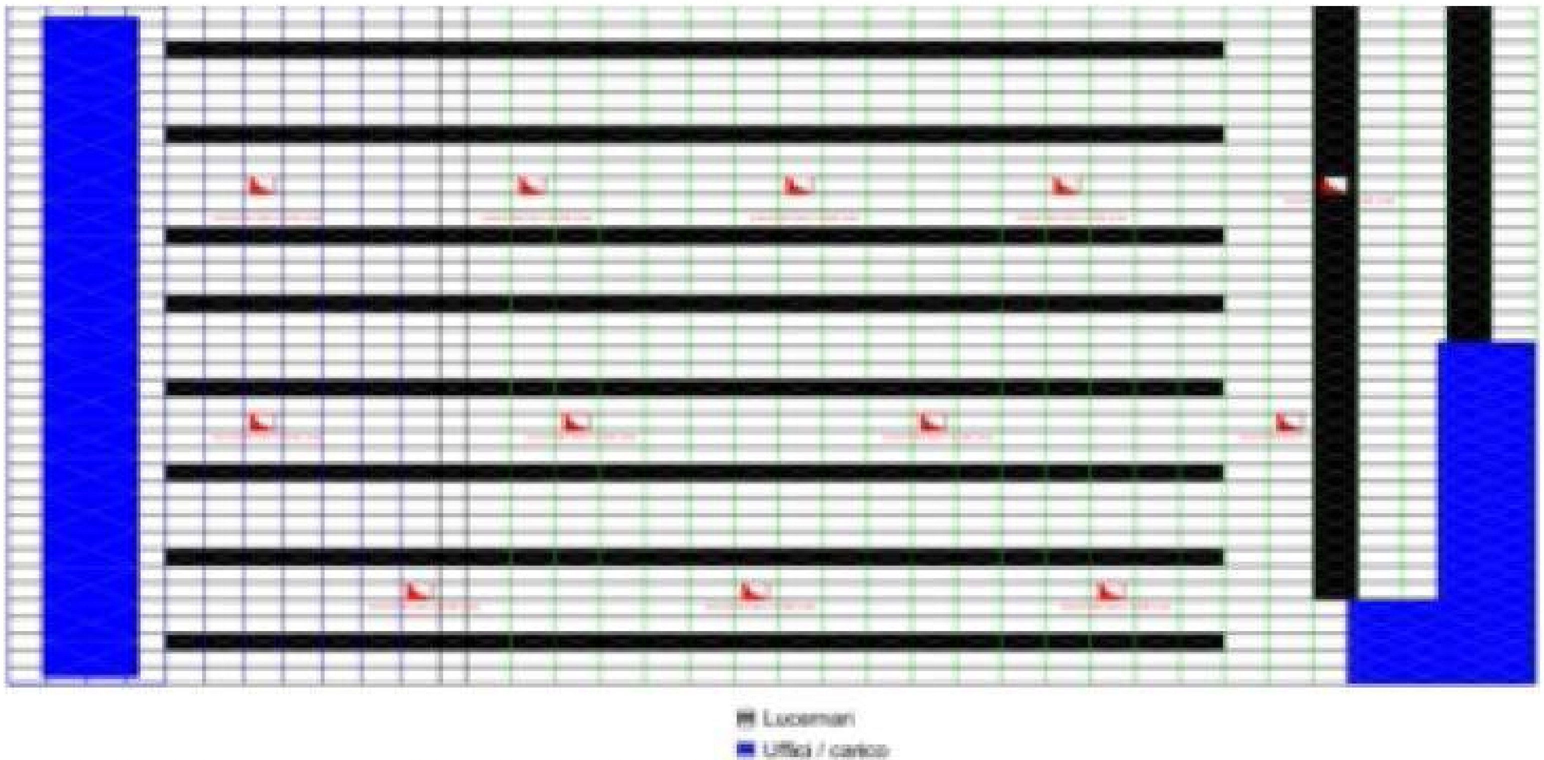


Fig.33 Planimetria con Evacuatori di Fumo e Calore e Lucernari

E' inoltre possibile applicare i modelli proposti dagli standard NFPA 92A/B per la portata volumetrica del plume, considerando che l'attivazione di tutti i sensori richiede un volume di fumi pari alla volumetria della copertura per uno spessore medio di almeno 50 cm (considerata la modalità di propagazione dei fumi a soffitto da una zona di maggior spessore ad una di minor spessore, nell'ipotesi di focolaio localizzato). Si tratta in tal caso di circa 1800 m^3 di fumi (3631m^2*0,5m) che dovrebbero venire generati da un unico focolaio e saturare la copertura in circa 2 minuti (120 secondi) ad una portata di 15 m^3 di fumi al secondo.

Il precedente calcolo risulta peraltro largamente approssimato per difetto, poiché il primo allarme avrebbe prodotto l'apertura degli evacuatori di fumo e calore, per cui una parte dei fumi prodotta sarebbe andata dispersa.
Appare evidente che tali valori non sono compatibili con un comune scenario accidentale.

La letteratura rende oggi disponibili svariati modelli matematici per scenari di incendio via via più complessi, al fine di stimare i parametri fondamentali che caratterizzano il rilascio di energia e la trasformazione della materia durante un incendio.

Poiché il materiale polimerico interessato dall'incendio è LDPE, un polimero termoplastico, è ragionevole, per una stima della potenza termica emessa, assimilarne la combustione ad una pozza equivalente di idrocarburo.

Il dato noto è che l'altezza di fiamma risulta superiore a quella del compartimento e può essere stimata, in proporzione alle dimensioni del fabbricato in 12 m, considerato che risultava visibile all'esterno.

Con il foglio di calcolo reso disponibile dal NUREG[17], applicando la correlazione di Herkestad[18] per il plume della pozza, per un'altezza di fiamma12m , si rilevano 55MW di potenza termica emessa, con una superficie di 27 m^2.

Poichè l'intera lunghezza del capannone era ormai interessato dalle fiamme, come si evince dal video e dalle immagini incluse, si devono supporre presenti più pozze, ciascuna del diametro di 6 metri circa, su una lunghezza di circa 90 metri si individuerebbero 15 pozze, per un totale di 825 MW di potenza termica.

In ogni caso la sola potenza termica emessa da ciascuna, modellata come stazionaria fino al consumo del combustibile, equivale a 55MW.In un'ora di combustione, (55MW * 3600 sec.) si otterrebbero 198'000 MJ.

Per un numero di 15 pozze, su un'ora, verrebbe liberata un'energia di 2'970'000 MJ, il triplo del valore integrale computando il carico di incendio prefigurato in progetto, su una sola ora di combustione.

Considerando un potere calorifico di 40 MJ/kg, trattasi di oltre 740 quintali di materiale, che verrebbero consumati in un'ora in tale regime di fiamma, sebbene il difetto di ossigeno, almeno prima del collasso catastrofico dei tamponamenti, limiterebbe tali valori in base al comburente disponibile.

Tale valore, riportato ad una superficie di 3631 m^2, genera u valore specifico di circa 818 MJ/m^2.

Ovviamente la durata dell'incendio è stata di svariate ore per cui, anche considerando un numero inferiori di pozze attive, la quantità di energia chimica liberata dalla combustione deve essere considerevole-

Le precedenti valutazioni cautelative, riferite ad una sola ora di combustione, pur con svariate approssimazioni riconducono alla considerazione che il carico di incendio stoccato all'interno doveva essere probabilmente almeno di un ordine di grandezza superiore a quanto previsto nel progetto del 2009 (87 quintali di polietilene e 267 di Polivinilcloruro).

Il metodo di Lawson e Quintiere[19] consente una semplice valutazione dell'irraggiamento da un focolaio ad un bersaglio posizionato

Per un focolaio di 1MW con diametro un metro, scaturito da un innesco accidentale, vi è un irraggiamento su modello emisferico di 1 kW/m^2 a 4 metri di distanza.

Si tenga conto che 1MW è un focolaio iniziale conservativamente elevato, specialmente come durata continua, e 1kW/m^2 rappresenta l'irraggiamento solare in una giornata limpida.

Quindi la possibilità di propagazione per irraggiamento da un focolaio accidentale isolato è legato ad una distanza prossima dello stesso, ove compete con a propagazione diretta delle fiamme, che da dati di letteratura noti ha ordini di grandezza del cm al secondo, o sue frazioni, su solidi[20].

Quindi in dieci minuti le fiamme, anche con una curva di crescita sostenuta, sarebbero avanzate di conservativamente dieci metri.

The Thyssen Krupp fire

- Location:
  - Thyssen Krupp plant, Turin, 12/06/2007
- Plant Involved:
  - Pickling and Annealing line N° 5, inlet (unrolling) section.
- Main features:
  - Small oil and paper fire which suddenly evolved into a jet fire
- Personnel directly involved:
  - 8
- Fatalities:
  - 7

Technical investigation activities

- Site survey:
  - Process and field variables,
  - Heat and flame damage extension,
  - State of the coils, position, scratching of a coil border against the carpentry,
  - Paper spread along the line. Residue of carbonized paper in the area of the fire.
- Witnesses:
  - Description of the event.
- Electronic data
  - PLC communications, time scale of the event.
- **Fire scenario modeling**
  - Temperature field, radiation intensity.

The plant and the process

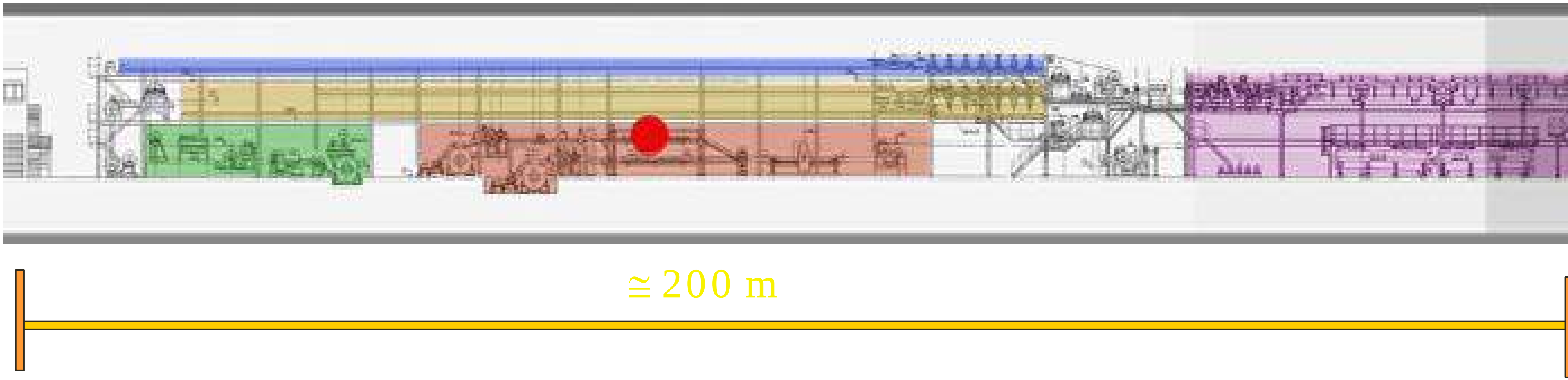
Pickling and annealing of stainless steel coils

- Unrolling
- Welding consecutive coils
- Annealing
- Pickling
- Cut
- Rolling up

Light green: discontinuous

Orange: continuous

The plant and the process



Red: inlet section

Yellow: inlet storage section

Violet: treatment section

Light blue: outlet storage section

Green: outlet section

Red dot: fire location

The plant and the process

The plant and the process

The plant and the process

- Process and field variables.

  Mandrel 1: Coil to process. 350 m of coils have been worked, (from welding position at the end of the chemical section),

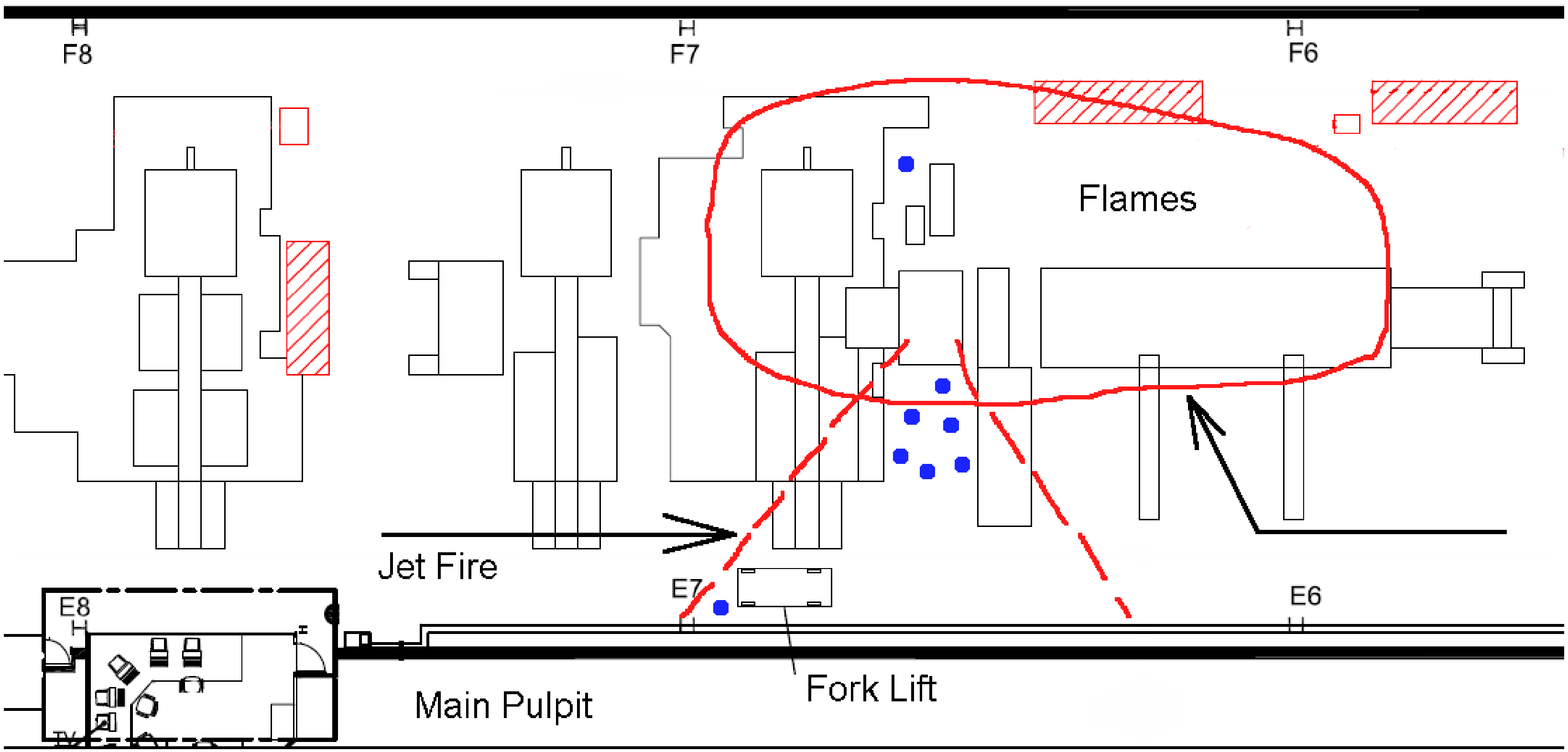
  Coil width 1500 mm

  Mandrel 2: Coil tip close to the welder

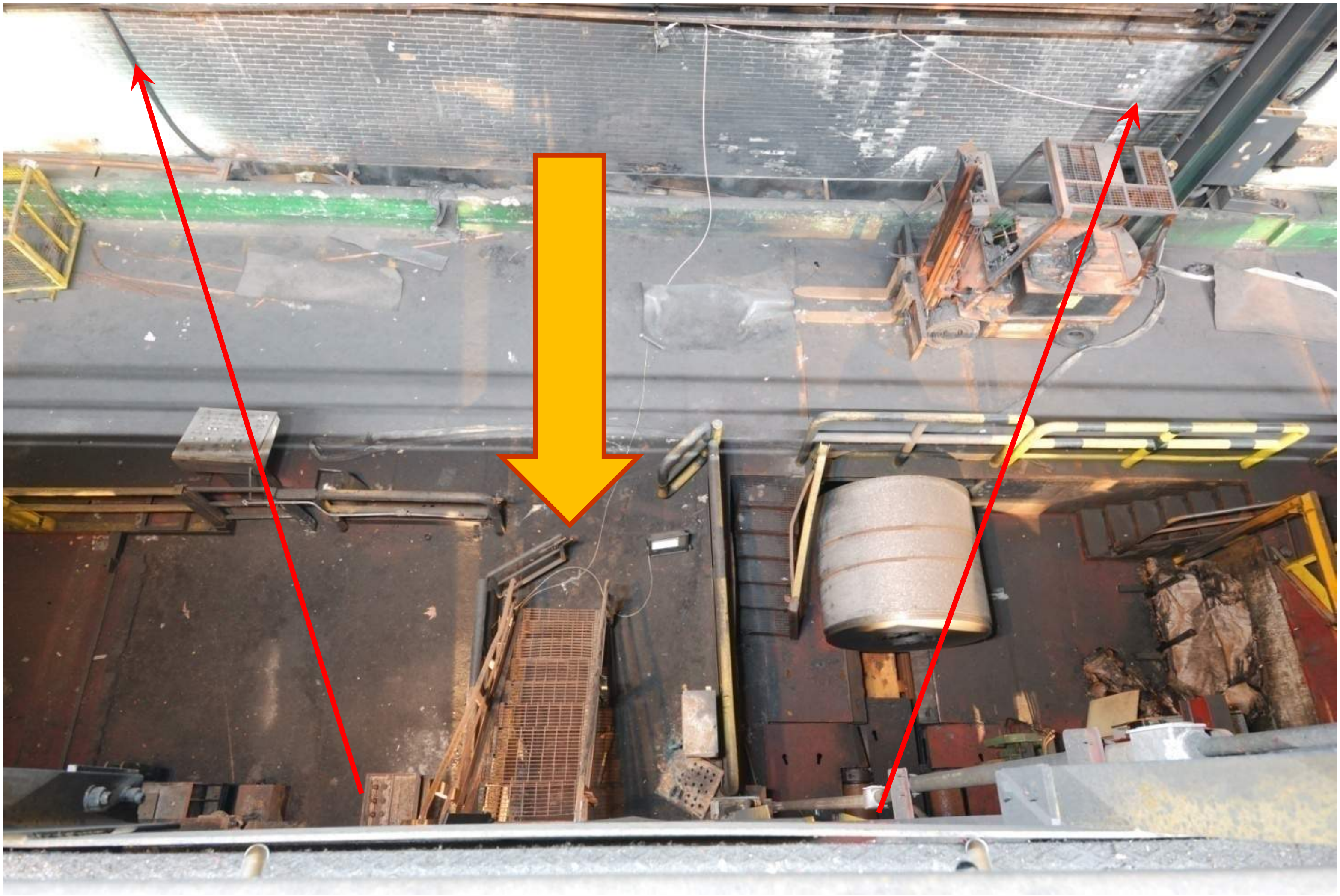
  Process speed: 21 m/min until decreased to 18 m/min,

  Unwind section velocity: +20 m/min

Heat and flame damages



Heat and flame damages



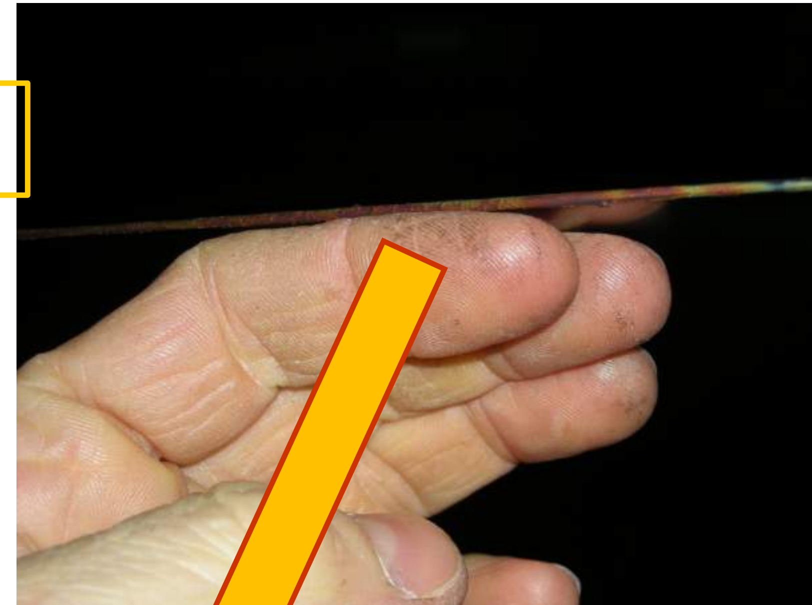
Heat and flame damages

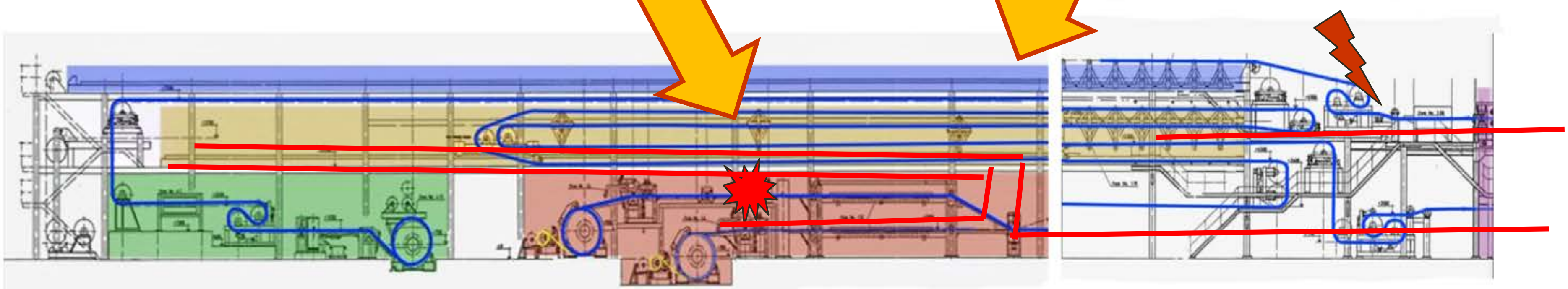
Heat and flame damages

Heat and flame damages

Heat and flame damages

Heat and flame damages





Witnesses

- 1 Worker on duty survived (A. Boccuzzi).

  Workers started the line at 00.35',

  7 were in the main control room, 1 was at the quality check point,

  A worker (coming from check point?) saw a small fire close to flattener N° 2,

  All the workers went out from the control room to extinguish the fire with CO_2 fire extinguishers without any success. Flame spread,

  Boccuzzi went to the closest fire hydrant,

  While he was there, he heard dumb blast and view a “fire wave” of a tenth of meters height coming towards his coworkers and him.

Electronic data collection and analysis

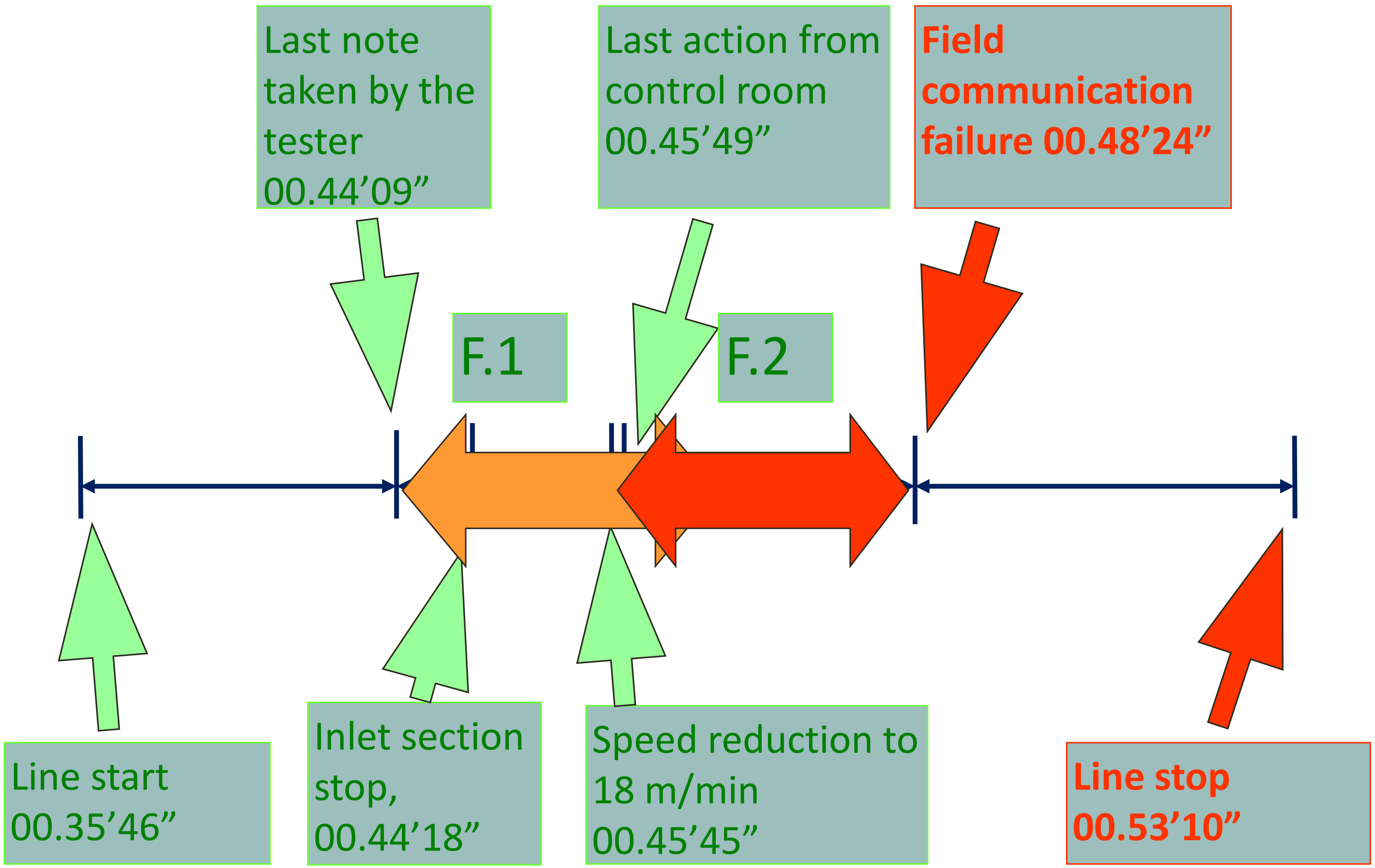
Forensic copies of the HD of the computer hosting the alarm database.

```
00.48.46.4 [L5SER   ] P5_R2462_9.F_CV set to    1.000 by LAF5T1::USER1
00.48.46.6 [L5SER   ] P5_R2462_9.F_CV set to    1.000 by LAF5T1::USER1
00.48.51.7 [L5SER   ] P5_R2463_1.F_CV set to    1.000 by LAF5T1::USER1
00.35.43.6 [L5SER   ] P4_OE_73                       CFN       CLOSE              M12 MAX PRESSIONE
00.35.43.6 [L5SER   ] P4_OE_76                       CFN       CLOSE              M11 MAX PRESSIONE
00.35.43.7 [L5SER   ] P2_R594_3                      OK        OPEN               PULSANTE ARR RAPIDO  DA PP  ARR. LINEA
00.35.43.8 [L5SER   ] P5_R2060_5                     CFN       CLOSE              FLAG MARCIA LINEA
00.35.46.8 [L5SER   ] P5_R2060_5                     OK        OPEN               FLAG MARCIA LINEA
00.35.48.6 [L5SER   ] P2_01_197                      CFN       CLOSE              MIN. PORTATA POMPE LAVAGGIO INTERMEDIO
00.49.36.2 [L5SER   ] P5_R2458_16.F_CV set to    1.000 by LAF5T1::USER1
```

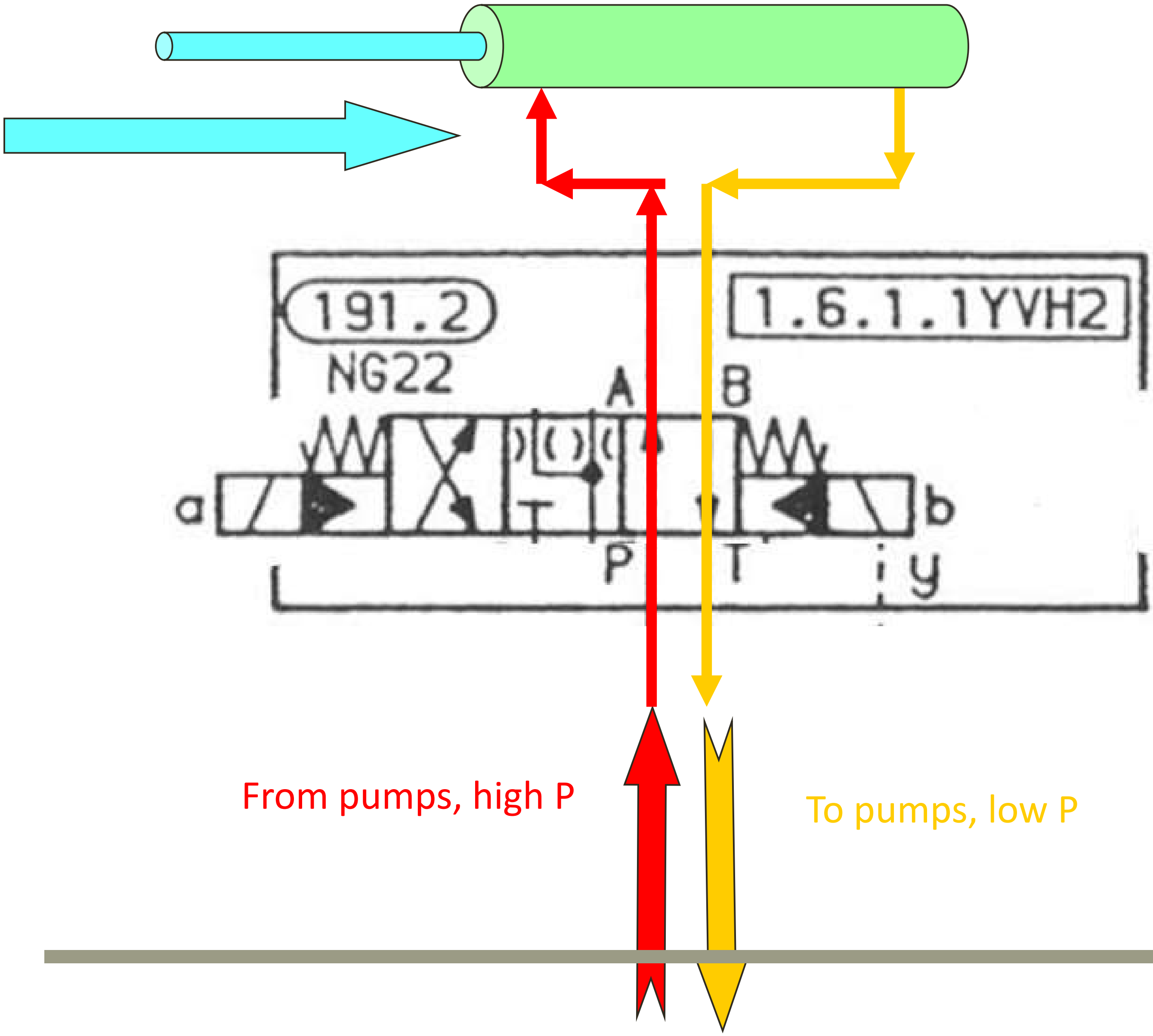
Raw data analysis and synchronization

Definition of coherent groups of events and of the time scale of the event

The time scale of the event

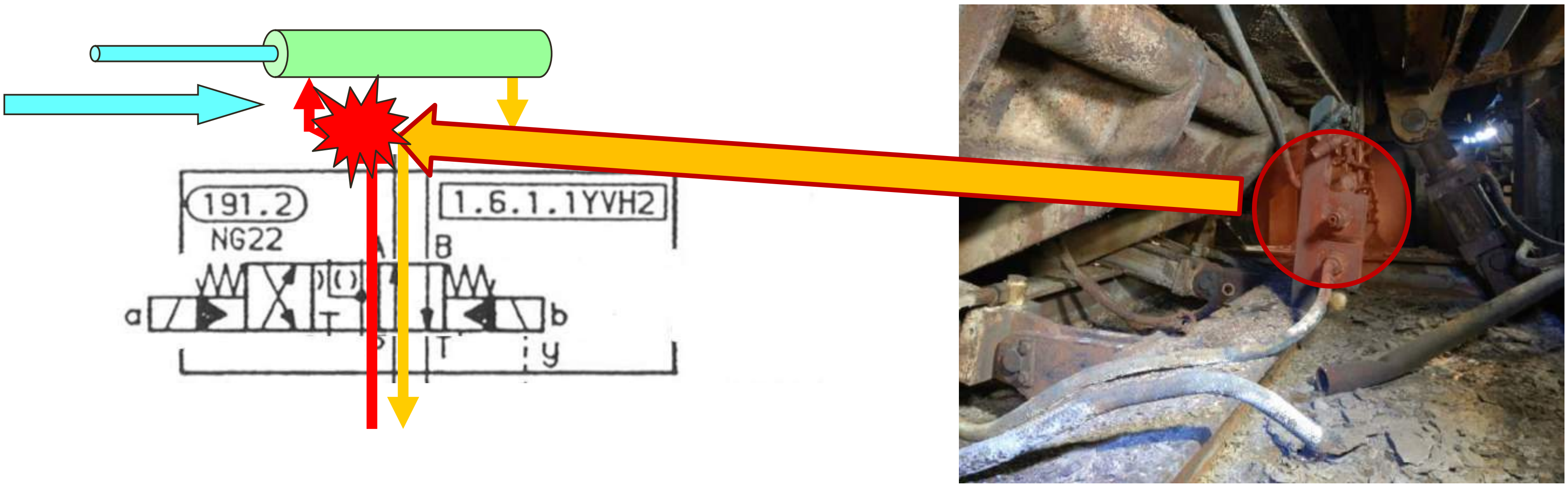


Jet fire causes



Jet fire causes

Sudden collapse of an hydraulic pipe which was fed by pump station (140 bar).



Ignition by the local fire

Hydraulic oil: Agip LH 46 (FP 220 °C), Fuchs Renolin HTF 46 (FP 202 °C)

CFD for forensic fire scene reconstruction

A specific analysis has been conducted in order to understand the consequences of the accident and the level of risk for the operators. The fire scenario was modeled by means of a specific CFD calculation tool (Fire Dynamics Simulator, generally known as ‘FDS’, which was developed by the Building and Fire Research Laboratory e BFRL e of the U.S. National Institute for Standards and Technology) on the basis of the evidence and information collected during the investigation.

The numerical simulation of the consequences of an accident is a useful and recognized methodology to estimate the consequences of accidental releases of hazardous chemicals in industrial premises in terms of thermal radiation, temperature rise, presence and extension of flames, smoke production, the dispersion of combustion products, and the movement of those species in the compartment/s under examination in order to verify what happened with a certain degree of certainty and to verify the modification of the consequences connected to the modification of the parameters that govern the accidental release.

The well-known NFPA n. 921 standard (2008) recognizes that fire behavior numeric codes play a fundamental role for in-depth analysis in the forensic framework: both simplified routines and zone and field models are explicitly quoted.

Fire scenario reconstruction

NIST, on behalf of the FEMA (Federal Emergency Management Agency) investigated (2002) the danger of the release of flammable liquids in the form of sprays and this danger was also assessed by conducting a number of real tests. Those tests were in fact similar to the activity that was later conducted by the U.S. Navy to test the consequences of the accidental release of hydraulic flammable oil at high pressure at a real

U.S. Navy: danger of hydraulic oil, even for releases of limited quantities of fuel, is described clearly.

The real, full-scale experiments conducted by the U.S. Navy are comparable with the data used by the authors for the simulation of the ThyssenKrupp accident, e.g. a pressure range from 69 bar to 103.4 bar, a released fluid with a combustion heat of 42.7 MJ/kg, and a similar viscosity.

First the authors validated FDS against the experimental results by the U.S. Navy. On this basis, FDS has been employed to reconstruct the accidental release and fire that actually occurred at the ThyssenKrupp plant in Turin.

Fire scenario reconstruction

CFD has been then used to best determine the hazard associated with such an accidental event for the workers that died during the activities adopted to govern the emergency.

The simulation activities helped the Authors to describe the consequences of the accident in order to define the real risk for the operators and, subsequently, to:

- **verify whether the calculated risk level corresponded to the level formally declared by the Owner (in the risk assessments required by law) to the AHJ;**
- **verify whether different scenarios could have exposed the operators to similar risks (e.g. with limited releases, with retarded ignition, etc.).**

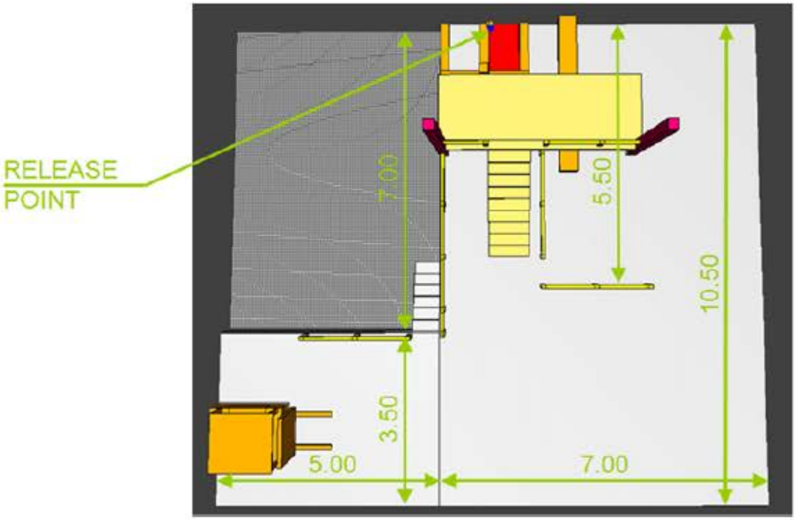


Fig. 7. The domain used in the FDS fire simulations.

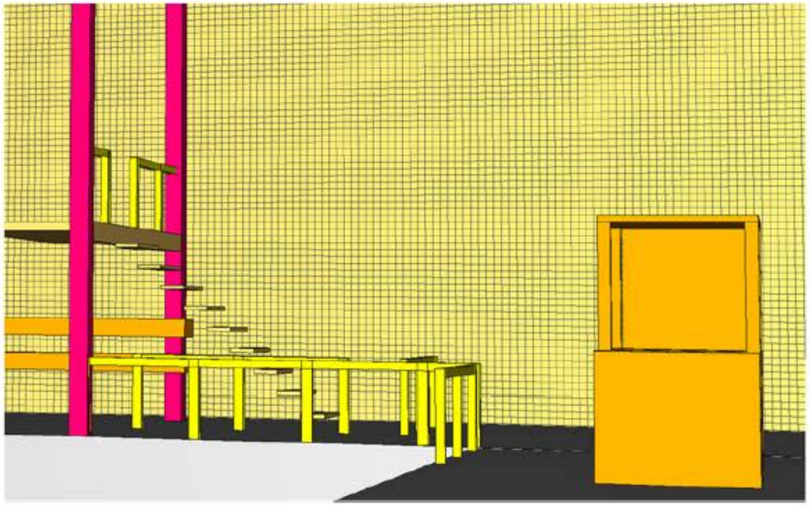
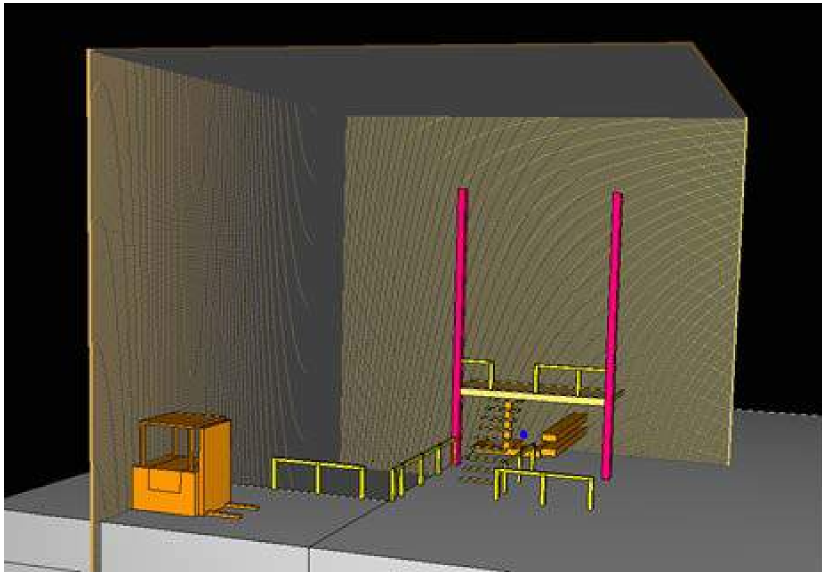
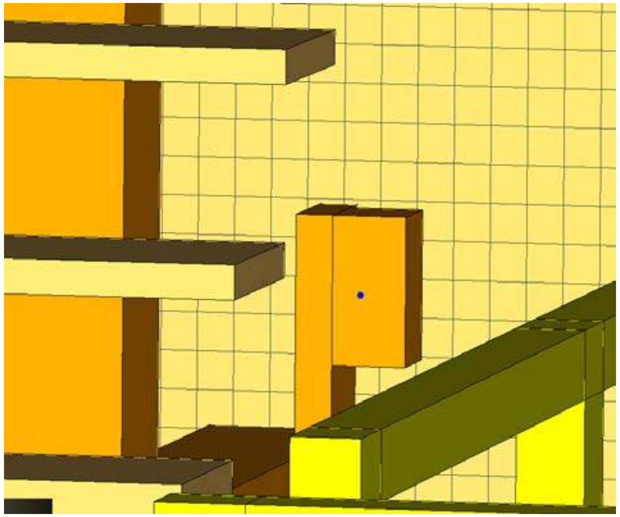


Fig. 8. Simulated area, elevation.





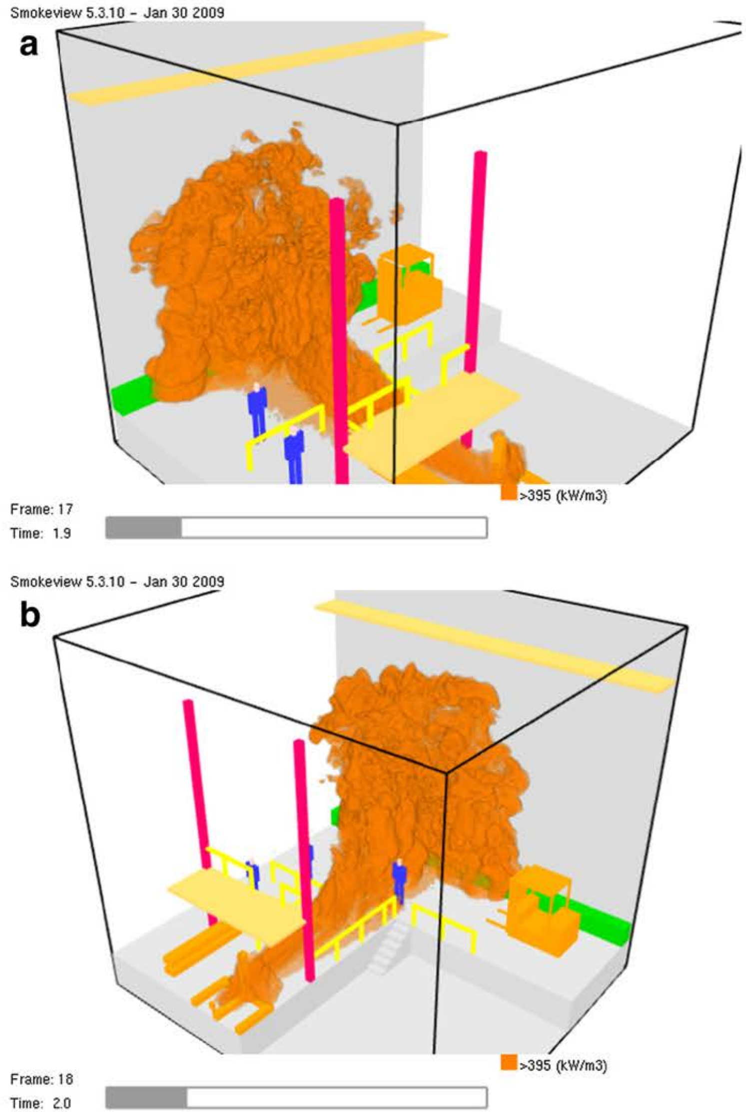


Fig. 10. a: Jet fire simulation results: Flames at 2 s from pipe collapse. b: Jet fire simulation results: Flames at 2 s from pipe collapse.

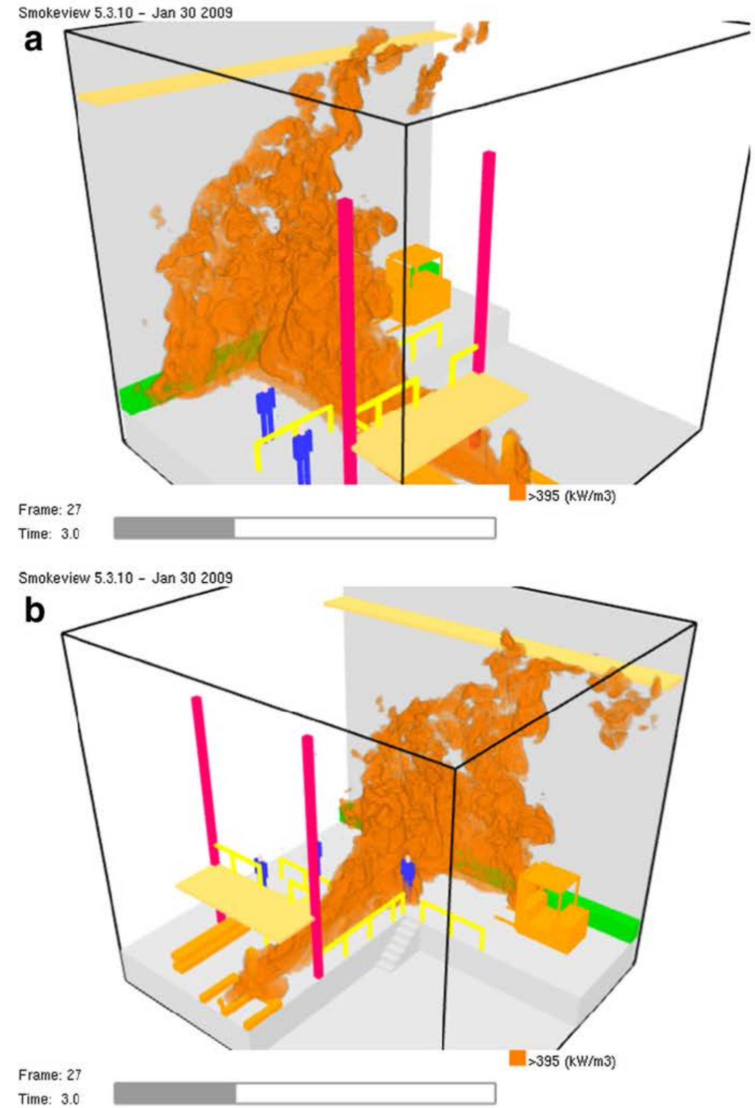


Fig. 11. a: Jet fire simulation results: Flames at 3 s from pipe collapse. b: Jet fire simulation results: Flames at 3 s from pipe collapse.

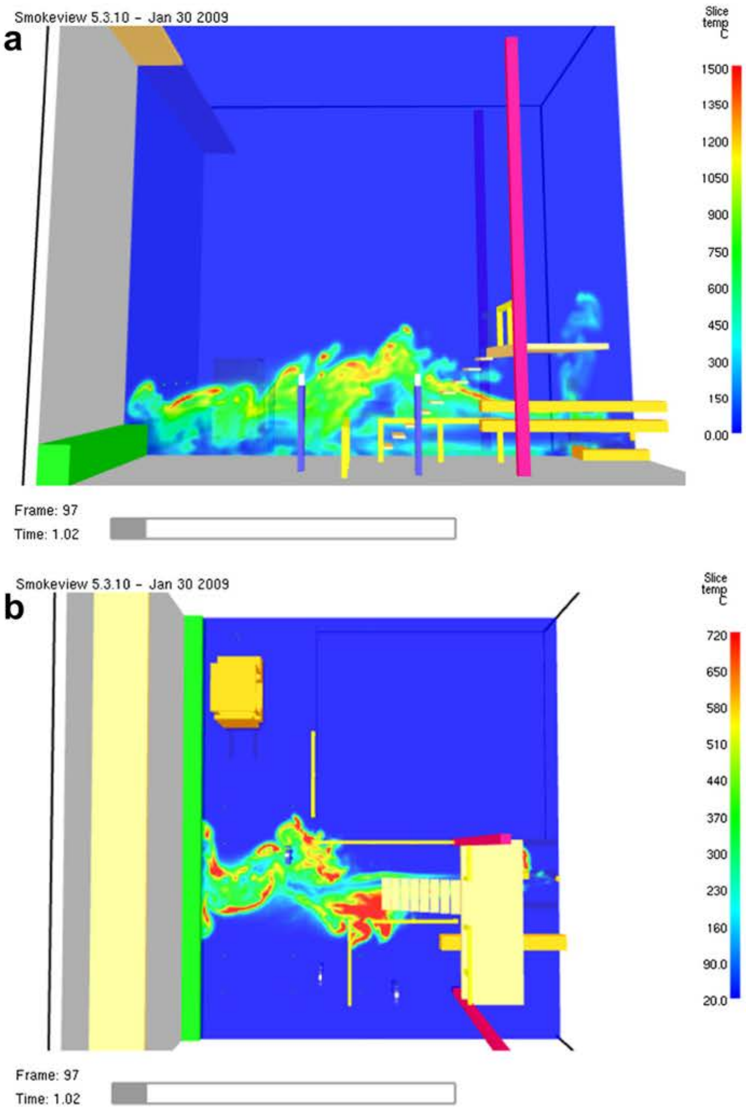


Fig. 12. a: Jet fire simulation results: Temperature at 1 s from pipe collapse. b: Jet fire simulation results: Temperature at 1 s from pipe collapse.

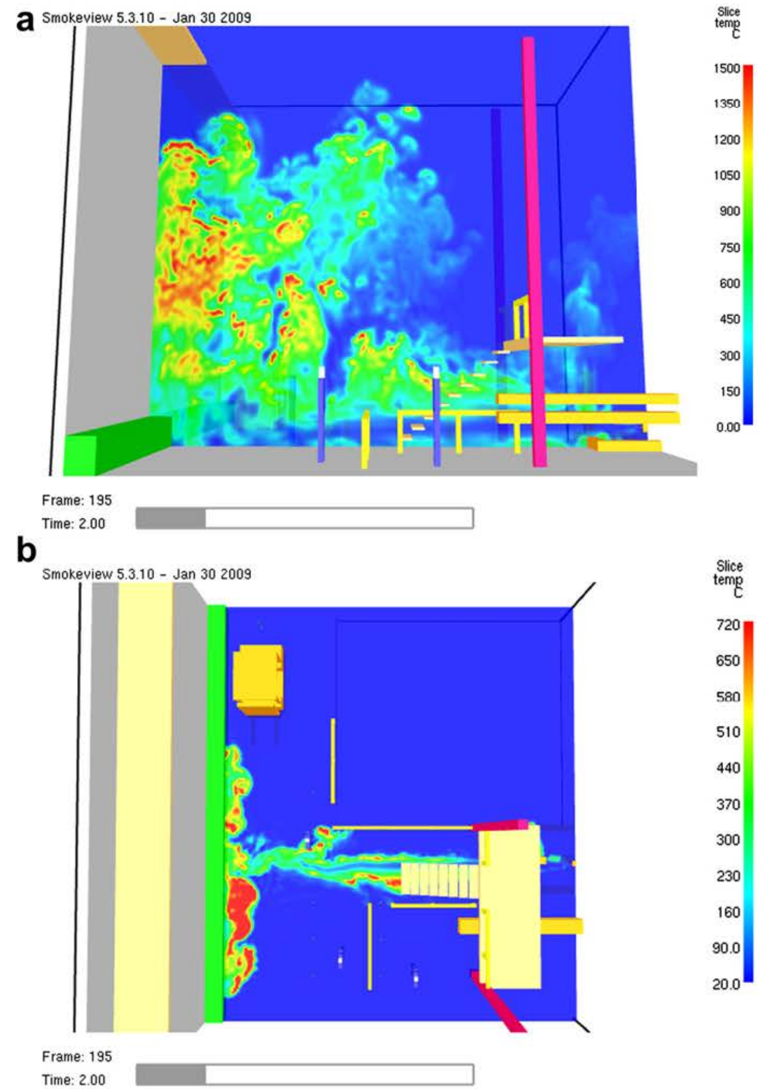


Fig. 13. a: Jet fire simulation results: Temperature at 2 s from pipe collapse. b: Jet fire simulation results: Temperature at 2 s from pipe collapse.

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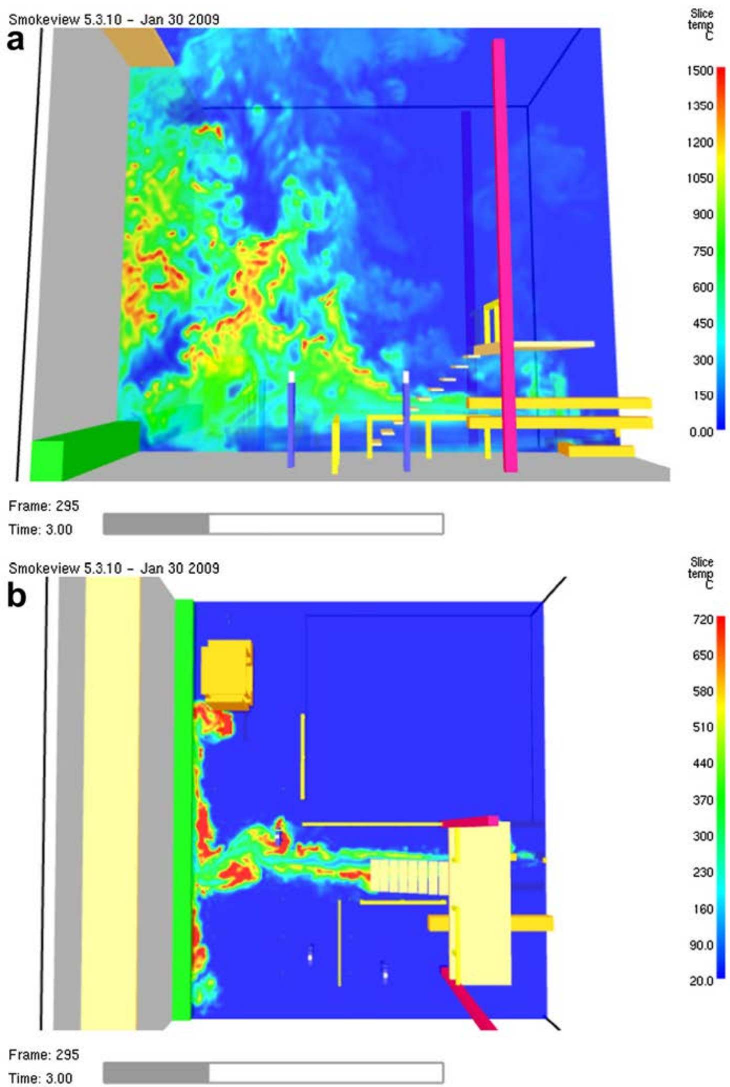
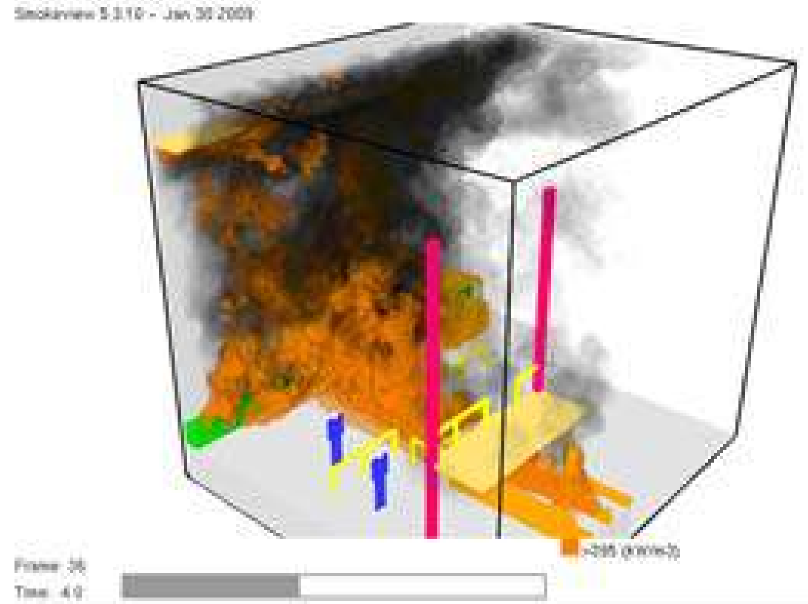


Fig. 14. a: Jet fire simulation results: Temperature at 3 s from pipe collapse. b: Jet fire simulation results: Temperature at 3 s from pipe collapse.



Summary of investigation

Activity	Evidences	Deductions
Site survey	Heat and fire damage, State of the coils, position, Scratching of coil against the carpentry (290 m), Paper spread along the line. Residue of carbonised paper in the area of the flattener.	Area reached by the jet fire, Area reached by the fire, Axial coil position not correct. Shift of coil N° 1 toward the side carpentry, Scratching lasted several minutes Scratching occurred above the flattener, Combustible material in the area.
Documents on Risk analysis	Fire risk evaluation. The area was considered at medium risk according to Italian regulation	No fire detection systems were provided.
Documents examination pertaining to technical description of plants	The complete inventory of the hydraulic circuits involved in the fire. Pipe state at the moment, Circuits working pressure were identified.	The pipe that collapse first one was identified, on the basis of position, direction, and because it was under pressure at normal conditions

Summary of investigation

Activity	Evidences	Deductions
Witnesses	The size and position of the initial fire. The size and shape of the jet fire Fire growth rate (roughly)	Small fire on the flattener at the beginning Fire grew in size after the first attempt to extinguish, Fire extinguishers unfit to control the fire, Sudden jet fire spreading "like a wave"
Electronic data	The time scale of the events	Line start at 00.35'46" Speed reduction by workers at 00.45'45" The PLC lost the sensors located close to the flattener at 00.48'24" Line emergency stop (automatic) at 00.53'10" due to low oil level

Considerations from CFD

- The jet fire involved the entire area opposite the release point in a direct manner and immediately created a serious risk for the workers that were in the area of interest;
- in fact conditions that could have lead to fatalities were recorded almost immediately;
- all the reference thresholds for fire thermal radiation were reached in the area (e.g. incident radiant heat, with a value of 200 kW/m^2, on the wall in front of the release point);
- a risk arose from both the direct and non-direct effects of the jet fire and it was also related to the flame extension, thermal radiation and temperature rise in the compartment area;
- the combustion of the hydraulic oil was characterized by a huge amount of smoke and soot which worsen the conditions in the area;
- the jet was vertically and horizontally fragmented as a result of the impact with the wall (and as a result of the impact with the main plant structures in the area). This fragmentation allowed a flame wall to build up that divided the compartments into two parts (thus creating problems for the emergency procedures) and it determined more serious conditions in the area than a similar jet without the presence of fixed obstacles. The amplitude and the dispersion of the jet was in line with the status of the compartment after the real fire;

- the fork-lift shielded a worker located behind it from the effects of the jet fire: this has been confirmed through an evaluation of the damage to the fork-lift itself, which presented different levels of damage on the two sides (the damage is coherent with the shape and effects of the simulated flames);

- HYPHOTESIS: the release of hypothetically smaller quantities of hydraulic oil could have exposed the workers who were possibly located at a distance of 15 m to a serious risk (with limited effects compared to the real jet-fire that occurred but which could have significant consequences on people);

- HYPHOTESIS: the same considerations were made for a hypothetical flash-fire considering that the reference thresholds were reached in the same area (a distance of 15 m for 0.5LFL from the release point in the case of the release of down to 500 cc of hydraulic oil);

- the real conditions could have been judged worse than then the simulated ones because the simulations only considered one single accidental release; it is very probable that the real evolution of the fire involved several subsequent collapses: the simulation of contemporary or slightly delayed releases from different sources would have led to a more significant impact, in terms of consequences for both accidental events (jet fire and flash-fire).

Lessons learned

- Coil position control.

The first automatic position control was located some tenths of meters downstream of the payoff mandrel.
Automatic position control is necessary.

- Housekeeping.

It was insufficient at the moment of the accident. The fire spread in the early phase is a direct consequence of the presence of paper and oil on site.

- **Fire load and fire detectors.**

No fire detectors in the area.
The reason was that the fire load, according to a "traditional" calculation approach, was negligible. This accident do demonstrate all the limits of such assumption.

Lessons learned

- **Automatic fire extinguishing systems.**

No automatic extinguishing system, which would have limited the worker exposure to the jet fire, was in place.
The presence of workers in the areas where hydraulic circuits are located should be limited as far as possible in the presence of fire.

- **Emergency stop.**

The emergency shutdown of the hydraulic units can lead to the loss of control of the actuators.
Despite this aspect, this episode demonstrate that hydraulic units should be properly shut down when involved in fires.

Lessons learned

- Emergency procedure

In the present case the procedure failed to prevent the accident because the fire was not evaluated as of “evident gravity” by the present personnel.

Procedures not involving or at least limiting as far as possible the personnel judgment should be set when huge hazard is detected.

- CFD simulation

Precise description of the magnitude of the consequences
Level of hazard posed by different accident scenarios

Thank You

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Missing safety measures led to the jet fire and seven deaths at a steel plant in Turin. Dynamics and lessons learned

Luca Marmo [a,*], Norberto Piccinini [a], Luca Fiorentini [b]

[a] *Politecnico di Torino, Dept. Applied Science and Technology, C.so Duca degli Abruzzi 24, 10129 Torino, Italy*
[b] *TECSA S.p.A., Via Figino, 101 Pero (MI), Italy*

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The Authors of this paper are the technical experts that were entrusted by the Public Prosecutor to conduct the technical inquiry into the accident that occurred in the ThyssenKrupp plant in Torino on December 6, 2007. The paper contains the results of the inquiry under the above mentioned point of view. The dynamics of the accident, the main causes and the consequences have been defined.

This was an unusual accident from which important lessons can be learned. On December 6, a modest fire developed in the entry section of a pickling and annealing line in the TK plant in Turin. The eight workers on duty seized the firefighting equipment and started to try to extinguish the fire. The workers had portable fire extinguishers and a fire hydrant, so they had to get close to the fire to fight it. Suddenly, a violent jet fire, caused by the rupture of a hydraulic circuit, occurred. The flame instantaneously struck the eight workers while they were still fighting the fire. Seven workers suffered very serious burns, one died instantaneously while the other six had over the following month. One of the workers, who was partly protected by an operating machine, suffered only minor burns and survived. The paper contains some important lessons that have been learned from the present case, which demonstrate that the fire risk at pickling and annealing lines has generally been underestimated by the steel industry. The fire risk due to hydraulic actuators is also evident and new fire fighting strategies are suggested.

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Tecsa S.r.l.
Via Figino, 101 - 20016 Pero (Milano) ITALY
Tel. +39 2 33910.484 - Fax +39 2 33910.737
PIVA: IT12396090156

info@mfcforensic.it
www.mfcforensic.it