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The Thyssen Krupp Accident in Torino: Investigation Methods, Accident Dynamics and Lesson Learned

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The Authors of this paper were technical consultants of the Public Prosecutor in the trial for the accident occurred at the ThyssenKrupp(TK) plant in Turin on Dec. 6, 2007.
The accident has been recorded as one of the most serious and impressive work accidents happened in Italy in the last years. It caused seven fatalities.
On the early morning of December the 6th a modest fire started in the entry section of a pickling and annealing line in the TK plant in Turin. The eight workers that were then on duty started fighting the fire by using portable fire extinguishers and a fire hydrant, and got close to the fire. A violent jet fire, originated by the rupture of a hydraulic circuit, occurred. The flames instantaneously hit the eight workers while they were still trying to control the initial fire. Seven workers suffered very serious burst, one died instantaneously while the other six during the following month. One of them, that had been partially shielded by a fork lift, suffered only minor bursts and survived. The Authors conducted the investigation and followed the whole trial on charge by the Public Prosecutor Office. This paper summarizes the accident dynamics, the causes and the consequences and the forensic methods adopted by the Authors during their investigation.
This paper is based on the technical documents provided by the Authors to the Public Prosecutor and presents the Authors' perspective. Full content can be found in the official documents used in the trial.

1. Background

The TK plant in Turin produced stainless steel coils. The process phases, which are well known, are melting, casting, hot rolling, cold rolling, pickling and annealing. Only the rolling, pickling and annealing phases were active in the plant in Torino, at the time of the accident. The pickling and annealing process is conceptually very simple: it consists of a chemical-physical surface treatment involving liquid reactants and a thermal treatment. During this processsteel coils must be unrolled, then they should pass into a furnace and are guided through a series of basins where chemical and electrochemical treatments take place. At last, the coil is rolled up again. The main technical challenge of the process is that both the thermal and the electrochemical processes must run continuously, but the individual coils have a given length. Therefore, in order to keep the process going without interruption, several coils must be welded. However, this implies that, in input section of the line, where coils are initially unrolled, the process necessarily occurs in a discontinuous fashion. To deal with such constraints, the lines must be provided with tools able to temporary store the length of coil that must be supplied to the furnace and to the pickling section while the unrolling is suspended during welding. Further complications arise from the weight of the coils themselves (several tons, depending upon length and width), from the need

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to guarantee the correct traction on the coil in order to drive it along several hundred meters of process line providing adequate position control.
The coils are handled by hydraulic systems that use mineral oil. Generally this oil is not flammable but it is a combustible substance with flash point value of about 220 °C. Hydraulic circuits use high-pressure oil in the range of 70 and 140 bar.

2. Accident analysis process: gathering Evidences

Each relevant accident is usually the result of several interacting causes through logical sequences of events. Sometimes one or more causes derive from events in the distant past, such as design errors or errors in the maintenance procedures. The history of relevant industrial accidents is rich in examples (Mannan, 2005). While reconstructing accidental dynamics one should be able to identify all the initiating causes, the intermediate causes and the dynamics of the evolution of the phenomenon (Marmo et al., 2011). It is a very frequent mistake in the forensics field to focalise attention on a single episode, which perhaps provoked the dynamics of the accident, but this might also separate it and from the interaction with the other contributing factors.
Gathering evidences involves several activities. The collection phase of the evidence, apart from being conducted according to the provisions of the pertinent Code of Procedures enforced by Italian law, must guarantee the respect of a series of requirements:

- Safety: access to a site of an accident can present significant risks for the safety of the personnel.
- Timeliness: some probationary elements have a transitory nature and can result rapidly deteriorated or destroyed.
- Completeness: the investigation process should allow one to completely and objectively acquire all the information necessary to carry out the correct tests concerning the accidental dynamics in an exhaustive, complete and objective way.
- Non interfering: the evidence acquisition process should not disturb or alter the probationary elements.

The forensic inquiry of serious accidents involving fires and explosions is a complex task requiring a variety of skills. As a consequence team work is necessary. The team must be guided by a leader with considerable expertise and charisma. A systematic approach must be followed during the inquiry, in order to make sure that all the evidence is collected, fragility is controlled and site alterations do not affect the process. The security chain of each piece of evidence must be guaranteed through proper procedures for collection, conservation, identification and analysis. Technical standards, such as ISO, NFPA and ASME, usually provide a good framework for the majority of needs of forensic engineers.
An accident is often the ultimate consequence of a very complex sequence of events. This sequence can begin long before the accident, for example with design errors, maintenance defects and insufficient procedures, events which can be important to correctly attribute responsibility. The inquiry must identify these factors and include them in the primary causes of the accident.
During the investigation, the team identifies a set of evidence from which several deductions can usually be derived. It is important to recognize that some evidence could be misleading, and could suggest different accident processes. For this reason it is important to collect coherent evidence permitting to establish the accident dynamics exhaustively and unambiguously. During this process the team members must carefully analyze all the evidence, paying particular attention to studying those items leading to deductions which are not consistent with the accident process. An investigation cannot be considered concluded until each piece of evidence supports at least one deduction, according to a set of deductions that is coherent with a complete accident process.

3. The dynamics of the accident

On December 6th eight workers were on night duty on the annealing and pickling line of the Thyssen Krupp plant in Torino. Other three workers were on site for substitution or training. Short after midnight the line restarted after a 84 min stop for cleaning some paper lost by a previously treated coil. Being the inlet section missing of an automatic position control system, after some time the coil started to scrape against the line structure, which was made of iron carpentry. The scrapping lasted for several minutes, producing as a consequence sparks and local overheating. From these, a local fire started, which involved paper and the hydraulic oil released from previous spills occurred in the past. This initial fire could have possibly spread to an extent of some $5m^2$ involving one flattener and the hydraulic circuits therein. Roughly at 00:45 the workers realized the presence of a fire, and put in place some measures to fight it. First they halted the entry section of the line, they reduced the production line velocity, then they grab some portable fire extinguishers and went close to the fire to attack it from at least two sides. After a few seconds they decided to use also a fire hydrant: one of the workers walked to the fire hydrant and a second one handled the fire hose.

At that moment a hydraulic pipe (roughly 10 mm inner diameter)suddenly collapsed and released from the pipe fitting. The pipe was fed at the pressure of 70 bar by the main oil pump station, which was still running. As a consequence a spray of hydraulic oil was released into the existing fire. The ignition of the spray was immediate, resulting in a huge jet fire that hit almost directly all the eight workers. Figure 1 shows the site and Figure 2 shows a map of the site where the position of the workers and the extension of the area hit by the jet fire are indicated. The jet fire length was not determined precisely, since it hit the front wall that was located at a distance of more than 10 meters from the release point. The fire, due to the interaction of the fluid with the structures, spread also backwards with respect to the hose direction, in such a manner to include a significant wider area as indicated in Figure 2.

Figure 1: the area subject to the accident

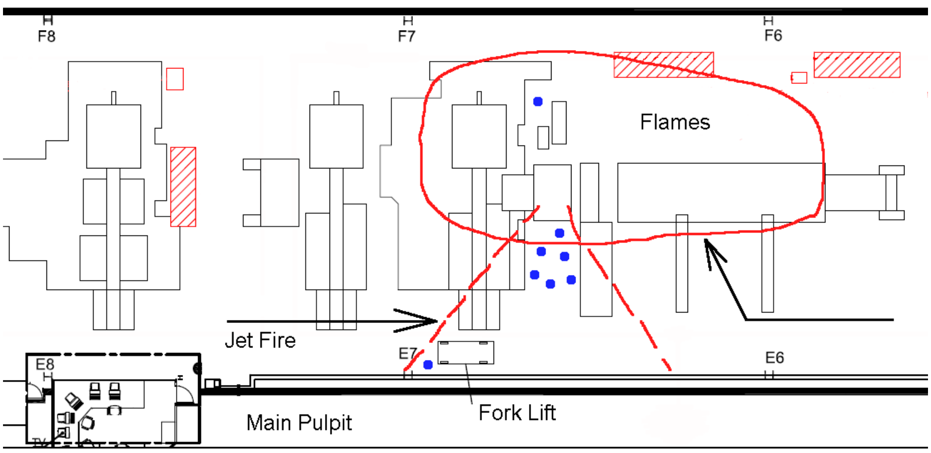

Figure 2: plot of the area interested by the flames, by the jet fire and position of the workers (blue dots).

The spreading fire engulfed many other hydraulic circuits and consequently 13 pipes collapsed in few minutes, determining a huge spread of oil and a significant increase of the flames. The pressure in the hydraulic circuit fell down due to the huge oil leak, thus the jet fire reduced his intensity quickly. The oil released by the collapsed pipes spread on the floor thus propagating the fire, as a consequence a quite violent fire developed.

From the analysis of the control system recording the time scale of the events resulted as indicated in Figure3. The first pipe collapsed in a time interval between 00:45'45" and 00:48'24", the pumps were stopped by the control system at 00:53'10" due to low level switch system based on the oil level in the main reservoir. In this time interval roughly escaped some 400 L of hydraulic oil.

The jet fire hit the eight workers that were fighting the first fire. Of them, the one that was close to the fire hydrant (see Figure 2), was shielded by a fork lift and could be able to suffer only minor bursts. Six were hit from the jet fire and suffered 3rd degree bursts ranging from the 60 % to the 90 % of their body. They died in the following month. One, which went to the back side of the plant to fight the fire, was trapped and died immediately. The fire spread to the machines and lasted for approximately two hours, before the fire brigade could extinguish it.

4. Technical investigation

The technical investigation was very complex because of its multidisciplinary characteristics. The enquiry was conducted by a team of more than 15 people including the Authors. The team included technicians such as engineers, work inspectors, firemen, public officers, informatics. This multidisciplinary team played a crucial role in order to individuate the dynamics and the main causes that led to the accident. The team activities began short after the accident with the first site survey. Beyond site surveys, the technical activity involved many other activities such as: Witnesses hearing, papery and, electronic data collection and examination, fire scenario modelling. These activities lead to collection of a bulk of evidence which was cross-compared in order to draw coherent deductions about the accident dynamics. Hereafter the main activities and deductions are presented; activities, deductions and evidences are summarised in Table 1.

4.1 Site examination and damages

Site examination began only three hours after the accident and continued for several weeks. Technical surveys were made together with the fire brigade and the police. Many surveys were dedicated to damages identification, which was obtained mainly by visual observation and fixed by photographs. Part of the surveys had more specific objectives such as the identification of all the hydraulic pipes collapsed, the coil position and damages, which were due to flames but also to striking against the carpentry structure.

An area roughly 20 m X 20 m X 6 m height presented evident heat damages (Figure 1) due to the presence of fire. The higher fire damages were evident in the area of the flattener (see Figure 1), where many hydraulic pipes collapsed. The coil under process presented damages due to striking against the iron carpentry on one border. Evident striking effects were detected up to some 290 m downstream the coil, till the bridle n. 3. Further 90 m of tape presented minor striking effects, which were present up to the chemical section entrance. Inside the chemical pool the coil presented evident corrosion occurred after the shutdown. As a consequence it was no longer possible to assess about coil scratching. The coil border up to the oven was coloured in blue-violet (Figure 4), indicating that the border reached a high temperature due to striking. A deep cut in the iron carpentry located roughly 60 cm above the flattener was recognised as the main striking location (see Figure 5).

4.2 Witnesses

Witnesses were heard by Public Officers together with the technical expert. Of the personnel present onsite, one, the unique survivor to the accident, eye-witnessed the accident. He reported firstly about a small fire of a fire in the area of the flattener with flames having a height of roughly 20 - 30 cm. The fire extended some 2-3 m width. The fire was spreading, slowly at first and then faster when also flame height began to grow faster. He reported that all the eight workers attempted to extinguish the fire with CO_2 fire extinguishers without any success. Then he moved to a fire hydrant. From that viewpoint, he heard a dumb blast and view a *"fire wave"* of a tenth of meters height coming towards him. Other witnesses which arrived later referred about the position of the injured.

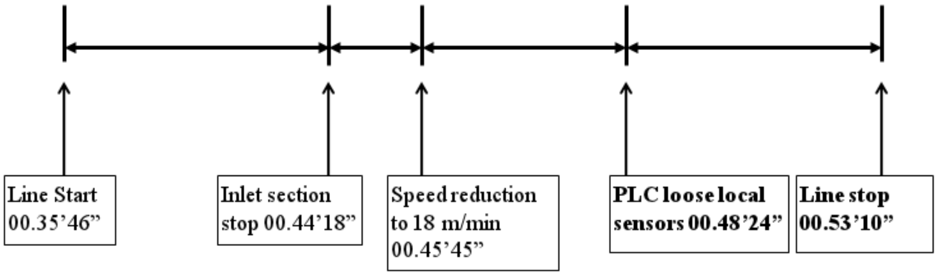

Figure 3: Time scale of the events(from the analysis of the control system records)

4.3 Electronic data collection and analysis
Electronic data were collected from the computers hosting the alarm databases. Forensic copies of the hard discs containing the data were extracted according to forensic procedure. Raw data were in the form of text files, made of strings.
The raw data required time synchronization since each string reported the time of the PLC that generated it. Time synchronization was obtained considering pairs of corresponding events generated by different PLC (example the onset of an alarm and the acknowledgment of the alarm from the system). The time of PLC 1was assumed conventionally as correct. This activity was instrumental in order to define some of the facts that occurred in the minutes before the accident. The time scale of Figure 3 would not be reconstructed without electronic data exam.

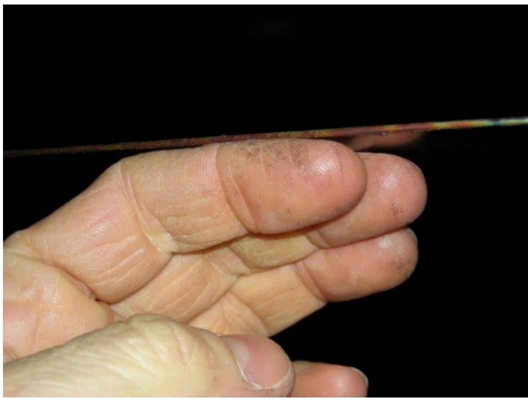

Figure 4: Consequences of coil striking *Figure 5: striking location*

4.4 Fire scenario modeling
A specific analysis has been conducted in order to simulate the effects of the accident and then quantifying the level of risk for the operators as well as verifying if the calculated risk level was in accordance to the level formally declared by the Owner (in the risk assessments required by law) to the AHJ as well as verifying if different scenarios could have exposed the operators to similar risks (e.g. with limited releases, with retarded ignition, etc.). Fire has been modeled with a specific CFD calculation tool 'FDS' on the basis of the evidences and information collected during the investigation and the approach has been validated against real scale experiments of similar conditions conducted by third parties (e.g. U.S. Navy). Simulation helped in identifying a number of key points of the real dynamic of the accident.

5. Conclusions

The enquiry about the TK accident can be considered an example of a very complex and articulated forensic case study. To make a complete technical enquiry, a team of more than 15 specialists was necessary to consider all the aspects. The dynamics of the accident was established after the exam of many source of evidences and cross correlations between witnesses formal declarations, data from the control system, design data, damages surveys. To this aim, a multidisciplinary approach involving engineers, informatics, public officers, firemen, work inspectors was followed. The enquiry showed how the jet fire that hit the eight workers killing seven of them originated by the rupture of an hydraulic circuit initially involved in a localized small pool fire. This case demonstrated how the fire risk associated with hydraulic circuits has been seriously underestimated.

Table 1: Summary of activities, evidences collected and deductions obtained

Activity	Evidences	Deductions
Site survey	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 carbonised paper in the area of the flattener	Area reached by the jet fire Area reached by the fire Axial coil position not correct. Axial shift of coil position toward the side carpentry Coil border presented scratching consequences to 290 m length Scratching occurred above the flattener.
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. Also exercise pressure were identified.	Among the collapsed pipe one was identified as the first to collapse such generating the jet fire, on the basis of position, direction, and because it was under pressure at normal conditions
Witnesses	The size and position of the initial fire. The size and shape of the jet fire	Small fire on the flattener at the beginning Fire extinguishers unfit to control the fire Fire grew in size after the first attempt to extinguish Sudden jet fire spreading “like a wave”
Electronic data	The time scale of the events	Line start at 00.35’46” Speed reduction by personnel at 00.45’45” The supervisor lost the signal of the sensors in the area on the flattener at 00.48’24” Line emergency stop (automatic) at 00.53’10” due to low oil level

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