EXPLOSION AND FIRE IN THE TAR EXTRACTOR OF A COKING PLANT

20/11/2020

Dunkerque (Nord)

France

Explosion
Metallurgy
Static electricity
Oxygen
Risk assessment
Property damage

THE FACILITY

Site:

The site is an integrated steel mill which produces steel from iron ore and coal. The plant was created in the early 1960s, covers an area of 450 ha, and employs approximately 3,100 people. It produces approximately 6.7 million tonnes of steel in the form of rolls and slabs.
The plant consists of four main production departments: the Coke Oven Department, the Casting Department (with the agglomeration of iron ore and the blast furnaces), the Steel Department (with the converters, ladle treatment and continuous casting) and the Rolling Mill Department.
The establishment is subject to authorisation and is classified as a SEVESO 'upper tier' site. The site is also subject to the Industrial Emissions Directive (IED) within the iron and steel production sector.

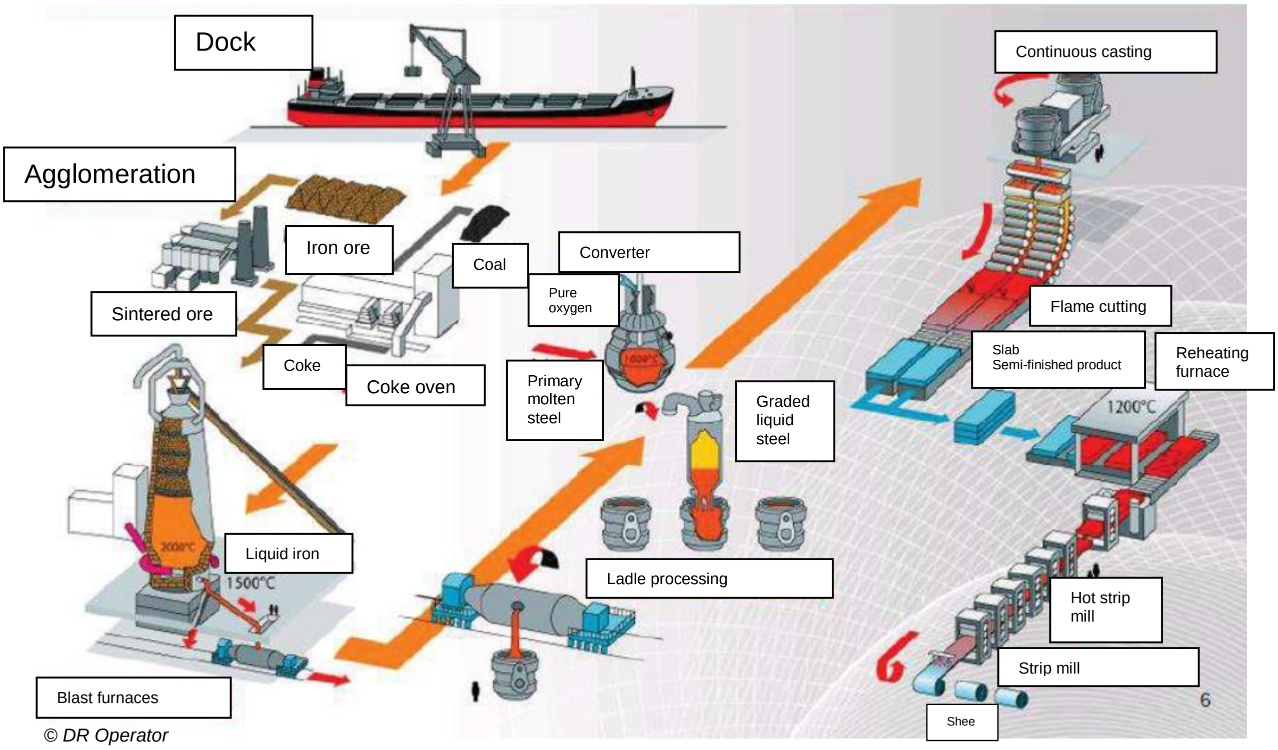


Figure 1: Descriptive diagram of the process

The unit and its operation:

On 20 November 2020 at 4:13 p.m., one of the two tar extractors (DE3) in the coke oven gas treatment plant exploded. A fire broke out at the time of the explosion. The tar extractor had just been washed. It was in the dewatering phase and not in operation.

A tar extractor is an electrostatic precipitator that captures dust and tar contained in the gas produced during the conversion of coal into coke.

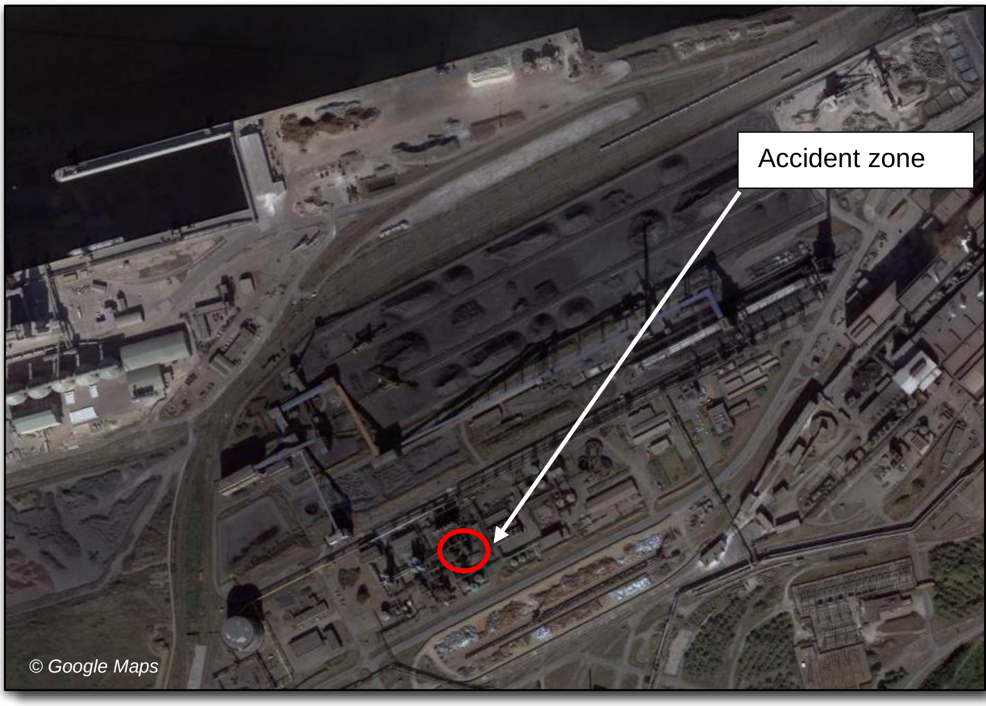


Figure 2: Aerial view of the unit involved

The coke oven gas treatment process:

The system for treating gases from the conversion of coal into coke operates in a vacuum. The cleaned gas is used as fuel in the site's other installations and a cogeneration plant near the site.

The coke oven gas is a mixture of several gases (in ascending order of importance):

- hydrogen (H_2);
- methane (CH_4);
- carbon monoxide (CO);
- carbon dioxide (CO_2);
- nitrogen (N_2).

Regarding the flammability range of the gas mixture, the lower flammability limit (LFL) is 4.6% gas in air, while the upper flammability limit (UFL) is 32% gas in air. The density of this coke gas is 0.35, which means that it is lighter than air.

Description of the tar extractor:

The site's two tar extractors operate in parallel with the same technology. They are parallel plate devices consisting of two stainless steel fields. Stainless steel deposition plates are associated with electrodes within the tar extractor chamber. An isolating goggle valve (VL) and a motorised valve (RM) are installed on the tar extractor's inlet and outlet.

The **high voltage** passes through several **porcelain insulators** enclosed in leaktight shells on the upper part of the tar extractor. These shells are maintained at temperature by heating resistors to avoid condensation on the porcelain. The shells are inerted with nitrogen to eliminate any risk of gas explosion in the event of damage to the porcelain caused by air entering the tar extractor.

An **optical oxygen analyser** is installed on the tar extractor's outlet. This analyser checks if the air is coming upstream from the tar extractor. The analyser is isolated from the tar extractor during the washing phase. The ambient temperature inside the tar extractor is also monitored.

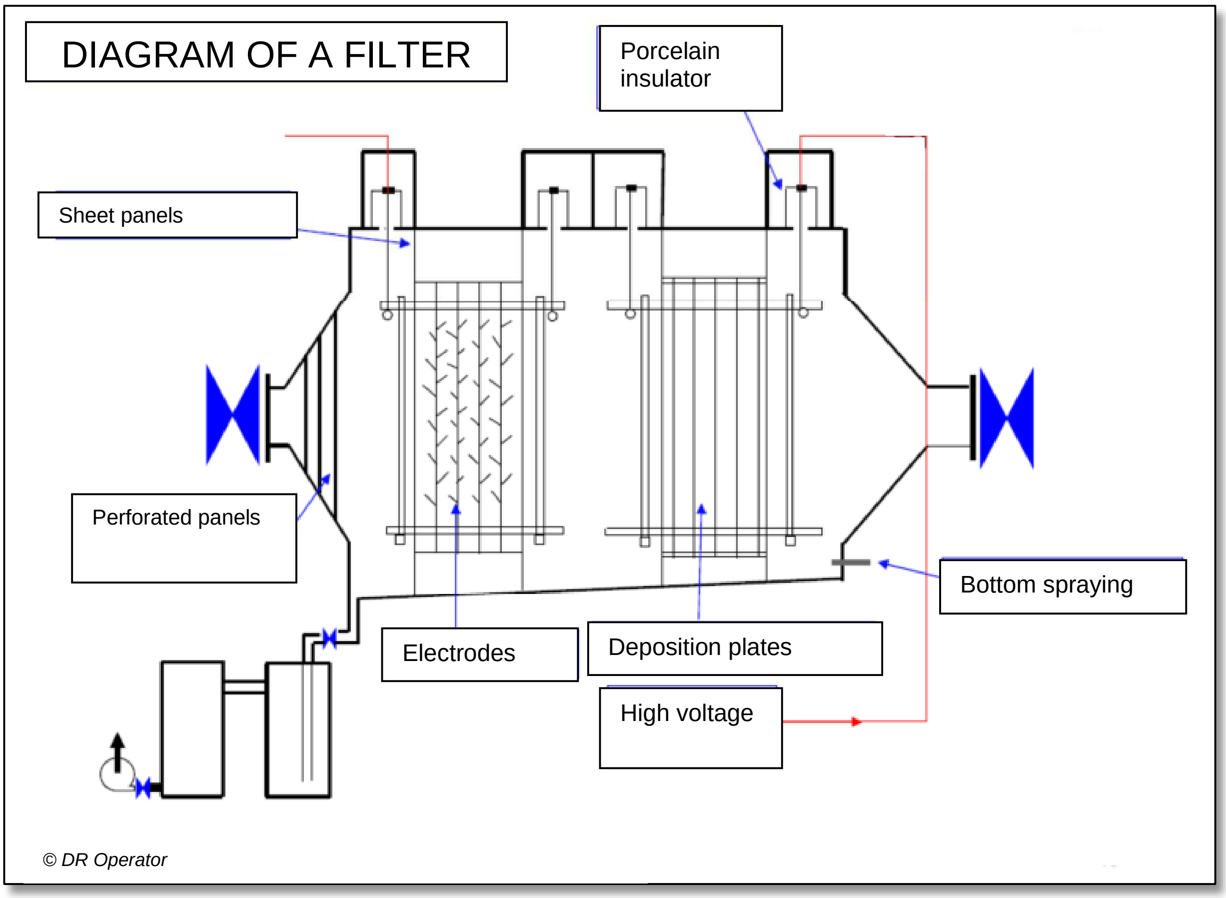


Figure 3: Inside a tax extractor chamber

Within the piping systems linking the various gas treatment equipment, **pyrophoric deposits** generated by the coke oven gas condensates may be present and give rise to slow **combustion**, releasing smoke (without flame) **in case of contact with air**. Interventions on these pipes must take this combustion risk into account. For example, phosphorus, cadmium, zinc/aluminium/magnesium powder or dust may be present.

The tar extractor's structure, stainless steel plates and anodes are earthed during washing operations. Before initiating any manoeuvre, the control room operator must secure the cabinets.
The operating personnel are trained by the site electricians to disconnect and earth the transformers. After the earthing switch has been actuated, a visual check is possible through an observation port.

The gas is loaded with dust and tar particles, and passes through perforated sheets to convey the gas over the entire filter section. The gas then circulates between the voids (rows of earthed vertical deposition plates). Emission electrodes are arranged between these plates and brought to a high negative DC voltage. Consequently, by the corona effect, the gas is ionised around the electrodes creating ions and electrons. These ions and electrons are then deposited on the plates by the electric field, are discharged there and flow along them. However, the particles do not always discharge on the plates, forming an adherent deposit that must be periodically cleaned.

Each tar extractor is washed every month. This operation requires that the electric fields be stopped.

Description of the tar extractor's washing operation:

The tar extractor washing operation consists of injecting steam into the lower part.

At the end of the washing process and after steam has been injected into the vents, the steam is cut off, and the tar extractor's **dewatering phase** is respected. The outlet valve is then opened. The dewatering time lasts several hours before restarting. During this phase, air can enter the tar extractor or through one of its associated systems.

To take into account the feedback from explosions that have already occurred in tar extractor restart events, a nitrogen inerting operation is carried out after the washing and dewatering phase to expel the air before the valves are opened and the return of the flow of coke oven gas. A vent collector was also installed on each tar extractor in 2005.

The tar extractor is isolated during the dewatering phase (the power supply is disconnected); nitrogen inerting is not performed. The washing phase is performed with coke oven gas inside the chamber. There is a risk of contact with air and, therefore, explosion.

Moreover, the oxygen level is not measured during the dewatering phase.

Once the tar extractor's dewatering phase is completed, it is purged with nitrogen, and the O2 analyser is put back into service.

THE ACCIDENT, ITS CHRONOLOGY, EFFECTS AND CONSEQUENCES

The accident:

The tar extractor DE3 exploded on Friday 20 November 2020, around 4:15 p.m, and was followed by a fire.

Context: the tar extractor DE3 had been in its dewatering phase since 12:25 p.m. (coke oven gas inlet valve closed / outlet valve open)

The chronology of the event is described below:

- around 4:15 p.m., an explosion occurred in the tar extractor, followed by a fire;
- following the explosion, the extractors were immediately actuated manually to limit the spread of fire;
- around 4:24 p.m., the site's firefighters headed toward the coking plant;
- around 4:30 p.m., heating of the coke oven batteries was stopped, and the coke oven gas pipes were isolated by a water seal;
- around 4:35 p.m., the power supply to the tar extractor substation, located between tar extractor DE1 and tar extractor DE3, was shut off;
- around 4:40 p.m., the firefighters began spraying down the burning shell of tar extractor DE3, which lasted until 8:15 p.m.;
- around 4:45 p.m., the departmental firefighting and emergency response service (SDIS) arrived on site; 36 firefighters were mobilised, with several water tenders (FPT);

- around 5:30 p.m., the output valves of the primary coolers were closed;
- around 5:50 p.m., SDIS reinforcements from the resource pooling centre (CRM, Centre de Regroupement des Moyens) arrived;
- around 6:45 p.m., spraying above the coke oven batteries was established;
- around 7:00 p.m., heating of the batteries was resumed;
- around 7:15 p.m., the extinguishing operations were stopped;
- around 7:30 p.m., the internal emergency plan (IEP) was lifted;
- around 8:15 p.m., a drone examination showed that there were no hot spots and that the risk of collapse by water accumulation (ponding) was reduced. The firefighters halted spraying operations at that time;
- around 8:30 p.m, a briefing was held to organise the following manoeuvres:
    - closure of the valves upstream and downstream from the tar extractors;
    - closure of the valves upstream and downstream from the H2S scrubbers;
    - return of the coke oven gas from the gasometer to the network, making sure that there was no return of the gas to the gas treatment system;
    - injection of nitrogen on the coke oven gas collector.
- around 11 p.m., the operator started injecting steam into the flare stacks to reduce the radiation.

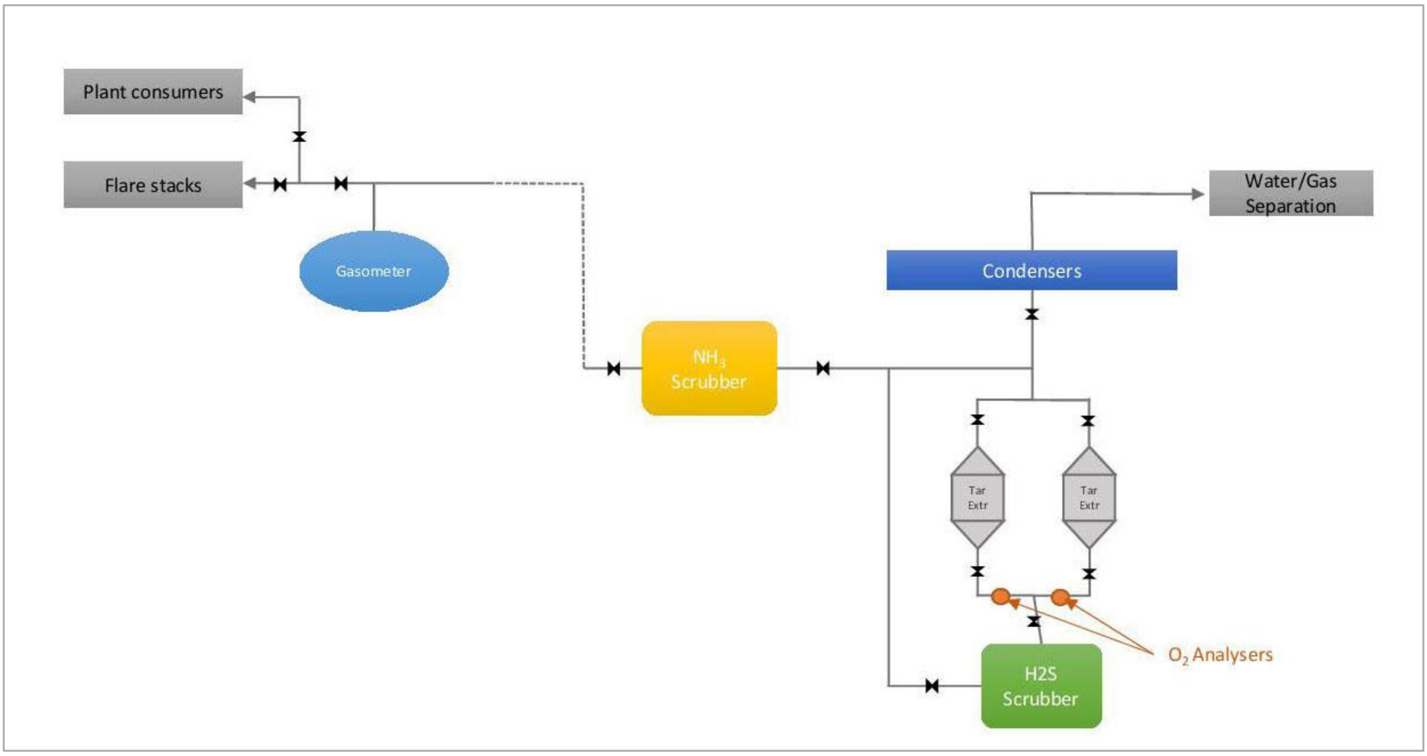


Figure 4: Layout of the gas treatment equipment

Consequences:

According to the operator, no dangerous or polluting material was released into the atmosphere, apart from smoke from the fire, which lasted about 3 hours.

The maximum quantity of material having reacted in the explosion of the tar extractor was evaluated at an equivalent of 170 kg of TNT. It was indicated that the raw coke gas from coal distillation was burned by the flare stacks (torches above the oven batteries) for nearly 5 days, the time required to put the gas treatment facility back into service (the destroyed tar extractor and the H2S scrubber were isolated from the coke oven gas treatment and remained unavailable for several months). An estimated 3,776,600 Nm³ of coke oven gas was sent to the flare stacks.

Flaring of the coke oven gas continued for 90 days until the tar extractor was replaced.

The operator estimates that 36,790 t of coke oven gas was sent to the flare stacks (or emergency torches).

A health assessment was conducted, and the SO2 emission was modelled. According to the operator, SO2 is the pollutant resulting from combustion, which has the most significant impact on the population and for which a regulatory emission threshold is defined. It was concluded that **the concentrations over the daily average limit value for protection of human health, the information and recommendation thresholds and the alert threshold were not exceeded**.

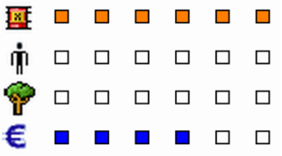
The reconstruction of the tar extractor took several months. **Property loss was estimated at €10M and production losses at €9M**.

Figure 5: Initial state of tar extractor DE3 before the explosion

Figure 6: Condition of the tar extractor DE3 after the accident

European scale of industrial accidents:

By applying the rating rules applicable to the 18 parameters of the scale officially adopted in February 1994 by the Member States' Competent Authority Committee for implementing the 'SEVESO' Directive and taking account of available information, the accident can be characterised by the following 4 indices:



Dangerous materials released
Human and social consequences
Environmental consequences
Economic consequences

The parameters comprising these indices and the rating method are available at this address: https://www.aria.developpement-durable.gouv.fr/in-case-of-accident/european-scale-of-industrial-accidents/?lang=en.

Dangerous materials released: the quantity of coke gas released to the torches and flares was estimated at **36,790 t**. This quantity represents 73,580% of the SEVESO threshold (50 t), which is the maximum level of the scale.

Human and social consequences: no injuries were reported, and no emergency measures outside the site were necessary (confinement of residents, safety perimeter), so level 0 of the scale was retained.

Environmental consequences: there were no environmental consequences. As such, level 0 of the scale was retained.

Economic consequences (€15 and €16): Loss of property was estimated at **€10M** and production losses at **€9M.** Level 4 of the scale was retained.

This characterisation led to the classification of this event on a SEVESO site as a **major accident** according to the SEVESO III Directive (2012/18/EU). France, therefore, shared the analysis of the feedback from this event in the EU Major Accident Reporting System (eMARS) database, which includes feedback from major European accidents.

THE ORIGIN, CAUSES, AND CIRCUMSTANCES SURROUNDING THE ACCIDENT

A third-party expert assessment was conducted at the operator's request. The report was finalised on 15 January, 2021 presenting the following findings.

Notable background elements:

- a 25-mm hole and a crack had been identified on the steam system 8 months before the accident. These defects could not be repaired without shutting down the tar extractor. As the oxygen measurement on the outlet of the tar extractor did not show any discrepancy, the repair was scheduled for the normal shutdown 3 days after the day of the accident;
- an anomaly had been detected on an isolating shell 2 days before the accident. A high-temperature alarm had been triggered, and a pressure of -15 mbar had been recorded instead of a nitrogen pressure of +30 mbar on the shell during regular operation. The porcelain of the insulator was very probably cracked. The nitrogen was most likely escaping from the shell through the insulator. If all the nitrogen was purged from this shell through the leak in the insulator, an air supply could have made it possible in the event of a loss of tightness defect in the walls of the shell housing this same insulator;
- on the day of the accident, brushing and painting work had been performed on the goggle valve on the outlet of the tar extractor DE3;

- the goggle valve's seal on the inlet of the tar extractor DE3 was replaced on the day of the accident;
- at 12:25 p.m., the washing phase was completed, the outlet valve on the tar extractor DE3 was opened, and the dewatering time started;
- the explosion occurred at 4:15 p.m.

Causes of the accident:

Three elements are required to generate an explosion within a tar extractor DE3:

- a fuel (flammable gas or finely-divided combustible solid);
- an oxidiser;
- a source of ignition.

Fuel:

Two types of fuel were present inside the tar extractor:

- **Dust and tar.** However, the tar extractor had undergone the washing phase, which suggests that the adhering deposit (dust and tar) on the plates and walls of the tar extractor was not very significant and could hardly be placed in suspension to generate a potential explosion. This type of fuel can be excluded;
- **The mixture of coke oven gas** consists primarily of hydrogen H_2 and methane CH_4. During the washing phase, a large volume of coke oven gas is present inside the tar extractor chamber.

The mixture of coke oven gas may be the fuel that caused the explosion.

The oxidiser:

Concerning the supply of oxidiser, it may have occurred because of a loss of tightness defect that allowed air to enter the tar extractor. A vacuum favours this influx of air into the tar extractor.

Several hypotheses have been put forward as to the origin of this loss of tightness defect:

- **The shells housing the insulators:** on 18 November 2020, a pressure defect was detected on one of the insulator shells (inerted with nitrogen). This defect suggests that the porcelain of the insulator was most likely cracked. An influx of air could have been made possible by an additional leak between the insulator and the tar extractor chamber. This is unlikely to be the case;

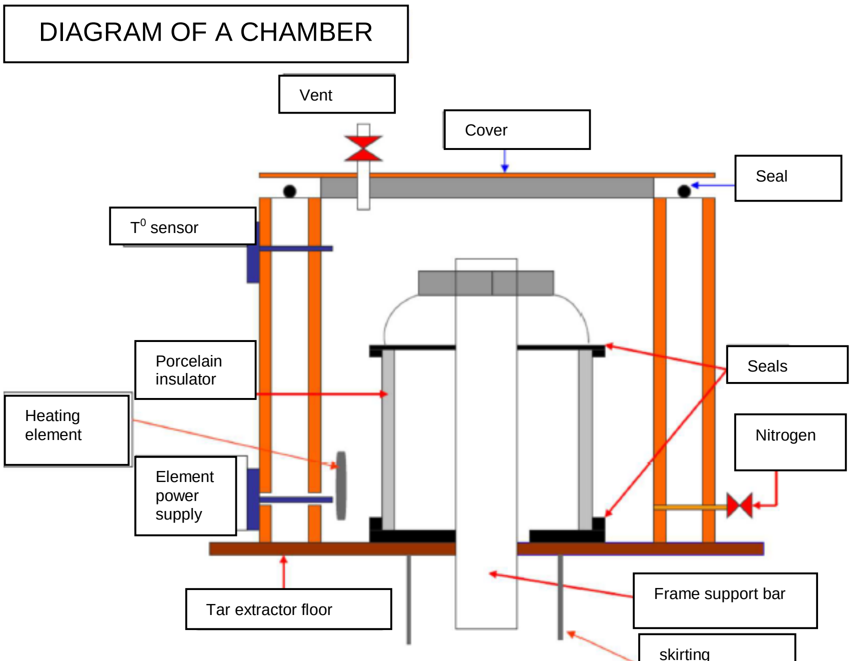


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Figure 7: Diagram of the shell receiving the insulators

- **Steam system**: According to the testimonies of the mechanics working on tar extractor DE3 before the accident, a hole (estimated to be approximately 26 mm in diameter) and a crack had been identified in the steam system of the tar extractor several months earlier. During the dewatering phase, the tar extractor was in a vacuum, so an influx of air may have been drawn into the chamber. This is likely to be the case;

- **The valves at the inlet and outlet of the tar extractor**: on the day of the incident, the seal of the goggle valve at the inlet of the tar extractor DE3 was being replaced between 7 a.m. and 12 p.m. If there had been a problem with the installation of the seal on the goggle valve leaking to a loss of tightness defect, an influx of air may have been created in the chamber. This is unlikely the case because when a seal is replaced, the position of the valves is not changed;

- **The chamber of the tar extractor**: there is an optical oxygen analyser at the exit of each tar extractor. This analyser checks if the air is coming upstream from the tar extractor and if there is an abnormal amount of oxygen in the piping. Consequently, a loss of tightness defect in the tar extractor chamber would have been detected beforehand by the oxygen analyser during regular operation of the tar extractor DE3. This hypothesis was excluded.

The most probable hypothesis that could explain the supply of oxidiser to ignite the coke oven gas is that of a leak in the steam system.

<u>The source of ignition</u>:

Several possibilities can be considered concerning the source of ignition of the oxidiser/fuel mixture:

- **Electrical energy**: during maintenance and washing operations, the tar extractor's structure, stainless steel plates and anodes are earthed. According to the testimonies, the earthing was checked visually during the accident. Even if there had been an earthing failure, the explosion would most likely have occurred before the dewatering phase, during the steam cleaning phase, due to the presence of a conductive fluid in this phase.

This source of ignition was thus excluded from the hypotheses.

- **Electrostatic energy:** An electrostatic discharge can be created when gas flows over a metal wall. When friction occurs, the metal wall will be charged by an increase in potential. If the increase in potential is sufficient, then an electric arc is created between two active elements through the gas. However, as they have the same earthing network, there cannot be a potential difference and, therefore, current flow. All exposed conductive parts must have the same potential, i.e. connected to the same earthing network. Electrostatic discharges can occur if there is a difference in potential between the earthing network of the tar extractor DE3 and the reference earth.

  Secondly, in the case of the tar extractor DE3, a cross-section reduction is located on the downstream part of the equipment. There is a venturi effect in this area, which can generate friction via pressure drops due to the phenomenon of depression within the tar extractor DE3 chamber during the dewatering phase.

  Finally, the possible presence of fouling on the tar extractor chamber walls may have also led to a variation in continuity within the same metal wall of the chamber. This phenomenon could have caused electrostatic discharges to occur.

  This source of ignition is probable.

- **Energy produced by a chemical reaction:** pyrophoric products are present in the pipes connecting the various equipment of the gas treatment process, which means there is a risk of a fire starting during an intervention on the pipes. These pyrophoric products (phosphorus, cadmium, etc.) are deposits generated by the coke oven gas.
  If pipe leaks near the tar extractor or on one of the inlet or outlet valves, the energy produced by the reaction between the air supply and the pyrophoric products could ignite the air/gas mixture in the tar extractor during the incident.
  This source of ignition was considered unlikely.

- **Mechanical energy:** given the small quantity of energy required (a few microjoules) to ignite an air/gas mixture, dropping an unidentified metal part (bolts, screws, etc.) inside the tar extractor is all that is required to create the activation energy required to ignite the gas mixture. It was impossible to verify this hypothesis, given the damage caused by the explosion on the tar extractor.
  This source of ignition cannot be excluded.

The most likely source of ignition is electrostatic energy.

The third-party expert report concludes that the explosion was caused by the contact of fuel (a mixture of coke oven gas), oxygen from the air (supplied by a leak in the steam system of the tar extractor DE3 – the most probable hypothesis) and energy (electrostatic energy – the most probable hypothesis).

An electrostatic tar extractor had already exploded at the site in July 2005 (DE1) and at the group's other sites abroad in November 2017 and in 2019. The explosions always occurred while the tar extractor was restarted while supplying the electric fields, but never during the washing and dewatering phases where the electric fields were not energised (no ignition source). **There was no feedback, and the operator had not identified this risk**.

The primary causes were identified through expert assessment.

The operator must also determine the root causes, i.e., the organisational causes that lead to the root causes to ensure that such an accident does not happen again.

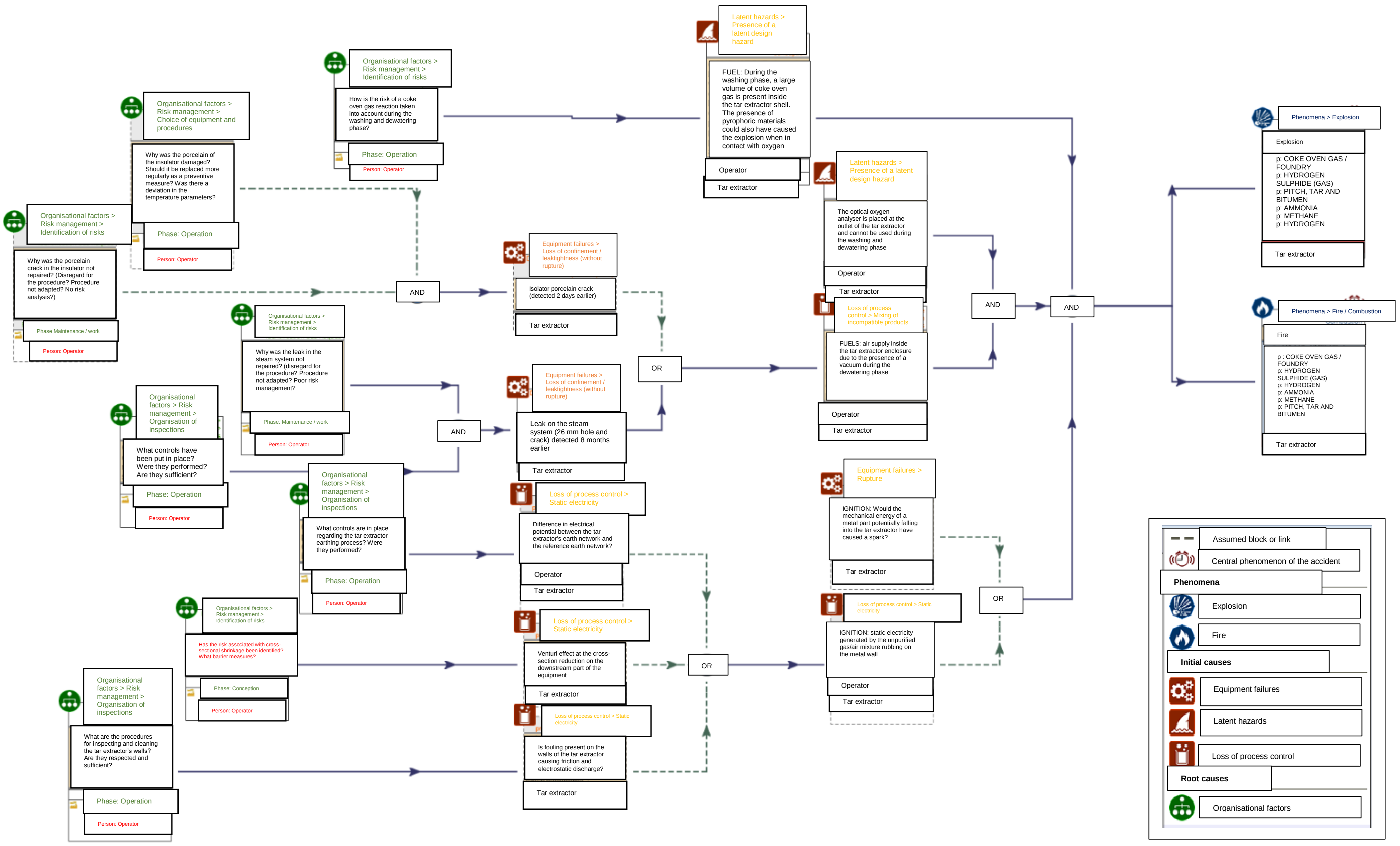
The BARPI model below represents the analysis approach.

The organisational causes to be addressed are:

- **Identification and management of risks** (insufficient responsiveness to repair the damaged equipment, which was not water leaktight, depression of the tar extractor's chamber, no inerting during the dewatering phase, venturi effect);

- **The choice of equipment and processes** (should a different technology be considered for certain elements involved?);

- **The organisation of inspections** (anomaly management to be reviewed, no control of the oxygen level during this stage, control of the cleanliness of the walls to avoid friction and pyrophoric aggregates).


Latent hazards > Presence of a latent design hazard
FUEL: During the washing phase, a large volume of coke oven gas is present inside the tar extractor shell. The presence of pyrophoric materials could also have caused the explosion when in contact with oxygen
Operator
Tar extractor
Organisational factors > Risk management > Identification of risks
How is the risk of a coke oven gas reaction taken into account during the washing and dewatering phase?
Phase: Operation
Person: Operator
Organisational factors > Risk management > Choice of equipment and procedures
Why was the porcelain of the insulator damaged? Should it be replaced more regularly as a preventive measure? Was there a deviation in the temperature parameters?
Phase: Operation
Person: Operator
Organisational factors > Risk management > Identification of risks
Why was the porcelain crack in the insulator not repaired? (Disregard for the procedure? Procedure not adapted? No risk analysis?)
Phase Maintenance / work
Person: Operator
AND
Equipment failures > Loss of confinement / leaktightness (without rupture)
Isolator porcelain crack (detected 2 days earlier)
Tar extractor
OR
Organisational factors > Risk management > Identification of risks
Why was the leak in the steam system not repaired? (disregard for the procedure? Procedure not adapted? Poor risk management?
Phase: Maintenance / work
Person: Operator
Equipment failures > Loss of confinement / leaktightness (without rupture)
Leak on the steam system (26 mm hole and crack) detected 8 months earlier
Tar extractor
AND
Organisational factors > Risk management > Organisation of inspections
What controls have been put in place? Were they performed? Are they sufficient?
Phase: Operation
Person: Operator
Organisational factors > Risk management > Organisation of inspections
What controls are in place regarding the tar extractor earthing process? Were they performed?
Phase: Operation
Person: Operator
Loss of process control > Static electricity
Difference in electrical potential between the tar extractor's earth network and the reference earth network?
Operator
Tar extractor
Organisational factors > Risk management > Identification of risks
Has the risk associated with cross-sectional shrinkage been identified? What barrier measures?
Phase: Conception
Person: Operator
Loss of process control > Static electricity
Venturi effect at the cross-section reduction on the downstream part of the equipment
Tar extractor
OR
Organisational factors > Risk management > Organisation of inspections
What are the procedures for inspecting and cleaning the tar extractor's walls? Are they respected and sufficient?
Phase: Operation
Person: Operator
Loss of process control > Static electricity
Is fouling present on the walls of the tar extractor causing friction and electrostatic discharge?
Tar extractor
Latent hazards > Presence of a latent design hazard
The optical oxygen analyser is placed at the outlet of the tar extractor enclosure and cannot be used during the washing and dewatering phase
Operator
Tar extractor
Loss of process control > Mixing of incompatible products
FUELS: air supply inside the tar extractor enclosure due to the presence of a vacuum during the dewatering phase
Operator
Tar extractor
AND
AND
Equipment failures > Rupture
IGNITION: Would the mechanical energy of a metal part potentially falling into the tar extractor have caused a spark?
Tar extractor
Loss of process control > Static electricity
IGNITION: static electricity generated by the unpurified gas/air mixture rubbing on the metal wall
Operator
Tar extractor
OR
Phenomena > Explosion
Explosion
p: COKE OVEN GAS / FOUNDRY
p: HYDROGEN SULPHIDE (GAS)
p: PITCH, TAR AND BITUMEN
p: AMMONIA
p: METHANE
p: HYDROGEN
Tar extractor
Phenomena > Fire / Combustion
Fire
p : COKE OVEN GAS / FOUNDRY
p: HYDROGEN SULPHIDE (GAS)
p: HYDROGEN
p: AMMONIA
p: METHANE
p: PITCH, TAR AND BITUMEN
Tar extractor
Assumed block or link
Central phenomenon of the accident
Phenomena
Explosion
Fire
Initial causes
Equipment failures
Latent hazards
Loss of process control
Root causes
Organisational factors

ACTIONS TAKEN

Following this accident, the operator reviewed the risk analysis, took additional measures to revise the tar extractor washing procedure and changed its maintenance plan.
This includes:

- Washing and dewatering operations are now performed under nitrogen pressure to expel the coke oven gas and to avoid any influx of air,
- Tar extractor maintenance includes an annual inspection of all the earthing systems and an annual inspection of the shell to ensure to check the fasteners of the various elements.

The operator has also been careful to share its experience with the group's other sites.

LESSONS LEARNT

This event was classified as a major accident according to the SEVESO III Directive, based on the failure to contain the hazardous materials used or produced (even if these materials were subsequently flared) and the very significant economic consequences, even though they were internal to the site.
The fire that followed the explosion was extinguished within 3 hours. The operator had mastered its IEP and immediately isolated the equipment, preventing the fire from spreading. The synergy of action between the site's internal emergency services and the departmental firefighting and emergency response service (SDIS) had proved effective.

However, this event reminds us that we must remain vigilant concerning alerts or so-called "weak" signals.
In this case, a 25-mm hole and a crack had been identified on the steam system 8 months earlier, and temperature and pressure alarms had highlighted an anomaly on an insulator chamber just 2 days before the accident. These anomalies, which could have endangered the airtightness of the tar extractor's chamber and caused an explosion during the washing phase, were not adequately addressed, despite the established safety culture at this SEVESO site.
A time for questioning and risk analysis must be systematically set aside to deal with all anomalies, including unusual ones.

Source of data:

Inspection report, Third-party expert report sent by the operator.