HELLENIC TRAIN- RAILWAY COMPANY SOCIETE ANONYME

INVESTIGATION

on Accident dynamics, explosion, and fire

Collision between Intercity train 62 and freight train 63503

on 28 February 2023

Document: YC23-010

Revision: _Final _Released

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2023 July 25th

1. Introduction

The accident on 28 February 2023 around 11:15pm on the line Athens - Thessaloniki, between Larissa and Leptokaria, at km 371+000 involved a passenger train and a freight train, both operated by Hellenic Train on which 57 people lost their lives.

Passenger train IC 62 composed of a Hellas Sprinter locomotive 120.023 , one first class, one bar coach and six second class coaches (B2-B7) was on service between Athens and Thessaloniki with 342 passengers on board (estimated from tickets), freight train 63503 with two Hellas Sprinter locomotives 120.022 and 120.012, consisting of 13 flat freight wagons, first 3 wagons with steel plates, rest with closed containers, was on the Thessaloniki-Athens route.

Regarding the dynamics of the accident, the Intercity involved in the collision (IC 62) was routed by the station manager in Larissa on the opposite track to the one normally used (the one on the left-hand side of the direction of travel/the illegal), on which freight train 63503 was also running, but in the opposite direction (legal for the freight train).

2. Subject

The below report is focusing on the accident dynamics at the crash and right after with regards to the rolling stock behavior, with investigation on the root cause of the explosion and fire on the passenger locomotive and first coaches right after the crash. It also provides an analysis if any technical improvements on the rolling stock or maintenance processes could reduce the risk or impact of such disaster.

It does not analysis nor conclude on any aspects on the initial question, why the 2 trains were running at full speed on the same track.

3. References & Information Sources

- Investigation report 15/05/2023 and revision 25/04/2023 Investigation committee Hellenic train
- Photos and videos made available by HT (Hellenic Train One drive)
- Information gathered during site visit and interviews.
- Video1: News site: Camera motorway https://www.youtube.com/watch?v=On5_Fn_NfpQ taken from the camera on the motorway southwards the accident place.
- Video2: Open News: Camera position unknown but most probably north-westwards the accident place. https://www.youtube.com/watch?v=gfUBN_6CJ9A
- Video2_a: video 2 with the time before and after the explosion in slow motion: made available on Hellenic Train OneDrive
- Siemens Transformer : document TWN/WNR/3517112ff/BA rev. 1.0
- Bayer Baysilone Fluids M https://dcproducts.com.au/wp-content/uploads/2020/12/BayerBaysiloneFluidsBrochure.pdf
- 3M Fluorinert^{TM} Electronic Liquid FC-3284 datasheet https://www.3m.com/3M/en_US/p/d/b10144228/
- Hoppecke FNC rail battery datasheet (Locomotives)

- Saft SRM battery datasheet (Coaches)
- R134a Safety data sheet (air-conditioning refrigerant)
- Drawings locomotive Siemens Hellenic Sprinter (lay-out, HV schematics, pneumatic schematics)
- Finally, many thanks to Mr. Antonios Moschopoulos for the pictures, videos and train data and testimony being at the location of the wreckage shortly after the accident.

No reports or information from official investigation committee were available at the time of this report. The investigation and conclusions are only based on evidence and own finding from pictures, videos and vehicle data and knowledge. New information or evidence can perhaps re-open some assumptions or conclusions.

4. Passenger train coach references

1. Loco 120023,
2. First Admz 8496019, compartments
3. Bar Wrmz 8896734, bar
4. B2 Bmz 2196003, compartments
5. B3 Bmpz 2096503, central corridor
6. B4 Bmpz 2096569, central corridor
7. B5 Bmpz 2096567, central corridor
8. B6 Bmpz 2096563, central corridor
9. B7 Bmpz 2096507, central corridor

5. Investigation on the collision dynamics

4.1 Positioning of the vehicles before and after

Positioning of the different locomotives, wagons, and coaches before and after the collision related to the infrastructure around.

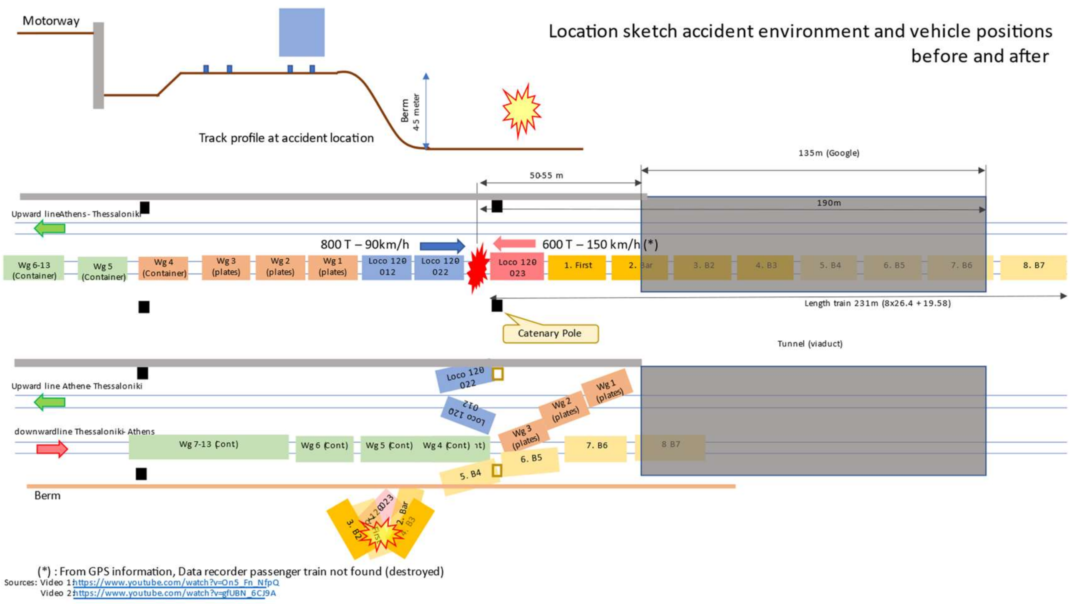


Figure 1: Location sketch infrastructure and vehicles before and after the crash

The infrastructure dimensions are based on Google Earth data (from before the accident). The pictures are available but cannot be published as no authorisation has been asked (yet) from Google to use publicly the data.

4.2 Short description on the most probably hypothesis of the dynamics during the crash

Although no real video recording of the collision exists (was night) and the information of the data recorders / “black box” (freight) is not in our possession or lost (passenger train), we can assume from the positioning, kinematic energies and deformations observed the following:

From the surveillance video[1] on the motorway south of the accident we can see that the freight train and passenger train drivers did not expect a collision as we cannot observe that an emergency brake has been applied. The location of the crash itself is hidden from the camera by the motorway viaduct. As it was night and the track is slightly curved in that area, with the tunnel/viaduct in between, the head-on collision could not be seen until the very last moment and not at all possible to apply the brakes with any effect.

- We can consider that the trains collide with full-service speed (Freight 90km/h, passenger train 150km/h) to each other.

[1] Videolink: https://www.youtube.com/watch?v=On5_Fn_NfpQ

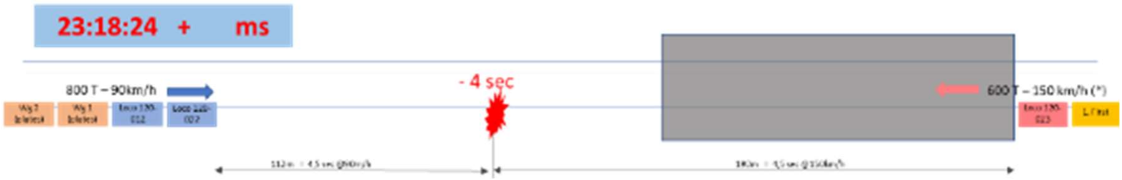


Figure 2: Overview with timing as per video camera from the motorway (for simplicity the tracks are shown straight)

Given the different loading and speeds the kinematic energy of the freight train, despite a heavier loading, is much lower than the passenger train (250 MJ versus 592 MJ). Also taking in consideration the fact that the freight train did have 2 locomotives in front, each of 80 tons, which have a more solid/stronger structure and a higher axle load, and the fact of the flat steel wagons went under the locomotives, the absorption of the collision energy on the freight train took mainly place on the 2 locomotives.

- The freight wagons except for the 2 locomotives did remain mainly on the track and did not crumble much together.
- The collision energy was mainly taken by the first and then the second locomotive also considering the special load and trajectory of the following freight wagons (see below).

The first freight locomotives 120-022 was catapulted over the upward line track (driving direction leftwards) and heavily smashed against the motorway wall with equipment going over the wall (Figure 9). The locomotive most likely jumped up (headstock bended downwards) and took the overhead pole and catenary line with it in the crash trajectory as the catenary and catenary pole can be found under the locomotives (see Figure 11 and Figure 12).
This led to a rather hard short-circuit of the upward overhead line with limited flashes (they are not visible, or the line was not powered due to earlier problems). The second freight locomotive 120-012 crushed in the first and while most likely stay coupled together till the last moment, turned around and becoming in opposite direction against the first to standstill (electrical coupler were still connected see Figure 13).

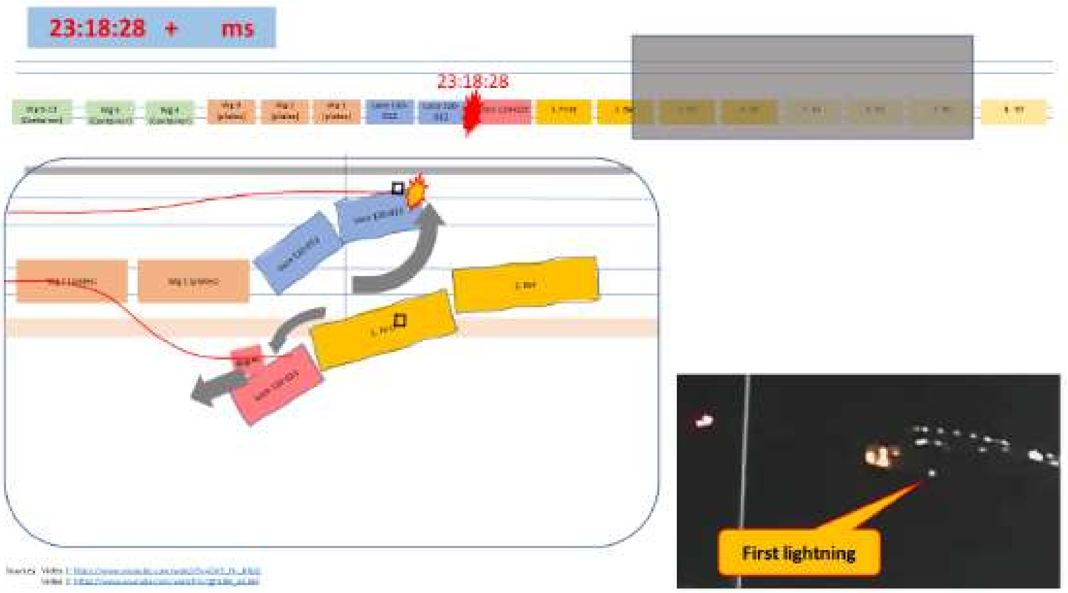


Figure 3: First lightning

The absorption of the much higher collision energy of the passenger train was taken by many vehicles starting from the locomotive, first, and bar coach and being more destructive as little identifiable parts can be found in the wreckage. The passenger locomotive 120-023 crashed in the first freight locomotive and flow (opposite) leftwards circa 30 meters further along the driving direction into the lower berm (4 to 5 meter lower).
During that 'flight' the locomotive lost the bogies, and these went rather straight forwards. Then most likely the locomotive carbody dive a bit further into the ground and ripped off the cabine and machine room, all crumbled together. The middle part of the frame with the transformer, the most solid and heaviest part (circa 10 ton) with most inertia, sheared off (bolster with pivot pin bended into the frame/transformer) and overturned to come down another few meters further any. The top roof panel most likely detached at the first impact flow through the air and came down partly on the carbody base.

Important to mention is that the catenary poles at the time of the accident (seems now be placed a bit further down to the tunnel) were standing at the accident location (about 50 meters from the tunnel as can be seen from the Google Earth view from before the crash). The passenger train locomotive took during the crash trajectory the catenary pole down and most probably carried the overhead wire till the landing of the locomotive parts in the berm. The catenary wire can be found in several locations in the debris of the remaining locomotive frame with the transformer as shown in Figure 14 and Figure 15.

The first-class coach and bar coach are the next cars in the passenger train consist that had to take the collision energy and were very much mangled and fragmented with parts such as seats, interiors, buffers, door leaves, bogie, side walls and carbody frame parts but also luggage found in a large perimeter (> 200 meter) around the accident area. Given the heavy destructive forces and very high accelerations no passenger had a chance to survive in these coaches.
Little major parts from these 2 coaches are recognizable and can be found in the debris, but based on the locations where the bodies were identified by the fire brigade, we can conclude with high probability that both 'coaches' landed fragmented in the lower berm between the locomotive bogie and locomotive frame parts a bit away from where the explosion and fire took place (see further). The high accelerations means also that all the interiors, including passengers and luggage were initially smashed to the front.

During that event the B2 coach was catapulted on top of the locomotive, first and cab coach debris with the B3 coach still connected and angled with the rear end towards the track where the remaining coaches were coming to a standstill. The B2 coach is the first recognizable on the debris but burned completely out while the B3 was showing limited areas of fire/heat impact (see further analysis).

The event also unrolls on the other side with the freight train. The 3 freight wagons with steel plates behave a bit differently than the other vehicles in the collision. As can been observed from the position of the wagons and the locomotives, the flat wagons and heavy steel plates (different size from 10-25mm – 2 to 5 ton/plate) glided underneath the locomotives and continue their trajectory along the track till standstill in front of the locomotives (Figure 10).
During that route some plates hit different parts of the passengers' trains of which most visible are the cuts on the sidewalls on B4 and B5. Apart from the material damage no passengers were reported injured by this. From the remaining of the freight train was only the first container wagon damaged, the other 9 container wagons were intact with only the first 2 containers pushed together and little damaged.

From the passenger train, the coaches B5, B6 and B7 came also to a standstill little crushed together and not or little derailed.

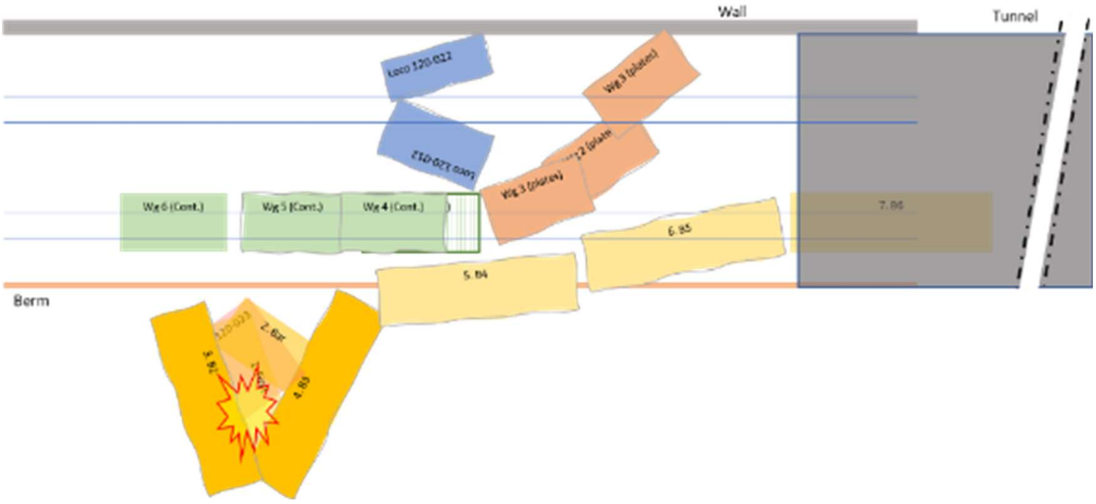


Figure 4: sketch position vehicles after the crash

6. Hypotheses on the Explosion and fire

Element 1 in hypothesis: 25kv overhead line arcing and short-circuit on transformer.

An important incident which will determine the further course of the accident is the arcing and short circuit of the overhead line (downward-line) and the big flashes seen on the video's especially on video 2 indicating that several arching took place before the line was finally short-circuited. It is not clear where exactly this happened during the above-described accident dynamics, but as noted above the catenary pole for the downward line was standing in the 'fly zone' of the locomotive and/or first coach.

From the pictures, Figure 14 and Figure 15 we can see that the broken overhead wire has been carried away with the locomotive and can be found in the debris of the locomotive frame and transformer which was laying upside down with one end dig into the ground.

Since the locomotive was catapulted in the air for circa 30 meters to the 5-meter lower berm, the overhead line came only to a short circuit the moment the locomotive hits the ground. From the video 2, we can be see that it took 2 to 3 flashes (blue light) in the same location with the last one the biggest before the overhead line (25kV) was switched off[2] (see Figure 5 and Figure 6).

The arc flashes happen for about 100 to 200msec and can create temperatures over 5000°C [3] and create a blue light due to ionization of the air, the last lightning with more yellow/orange is the start of the explosion.

Element 2 in hypothesis: location of the short circuit

From the transformer picture, Figure 17, we can recognize a possible spot (blue marked) near the explosion hole where the short circuit on the transformer could have taken place. More detailed analysis is necessary to confirm this, but as this location was in the core of the subsequential explosion and fire /heat (see further) most evidence of the short circuit burned/melded away.

Element 3 in hypothesis: The location of the transformer corresponds with the pictures of the explosion and fire on the video.

[2] The overhead line was at the moment of the accident feeding at least 3 locomotives of 6.2MVA each. Before the line get switched off the power station usually try to automatically re-energy the line one, two times before completely switching off the power (to be confirmed by the power grid-manager).

[3] Arc flash occurs when electrical current becomes uncontrolled, and passes through an air gap between conductors in an attempt to "jump" from one conductor to another or earth. This results in a release of electrical energy that ionizes the surrounding air, generating an enormous amount of light, heat, and sound. Temperatures of an arc flash can reach as much as 2,800 (low Voltage) to 19,000 °C (very high voltage). (https://www.electricityforum.com/iep/arc-flash/arc-flash-temperature and others)

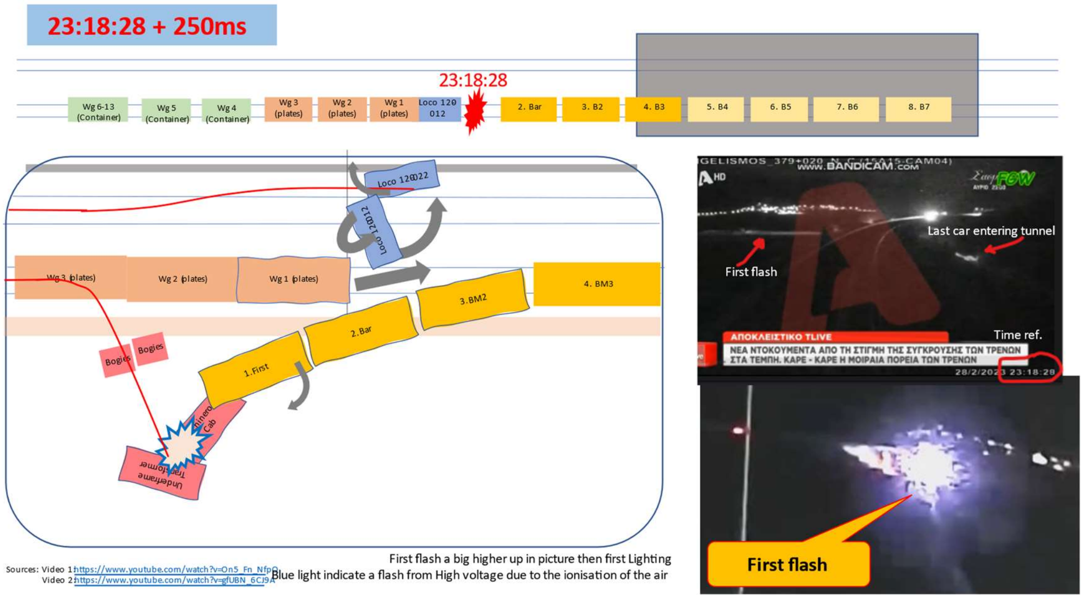


Figure 5: first arc flash overhead line

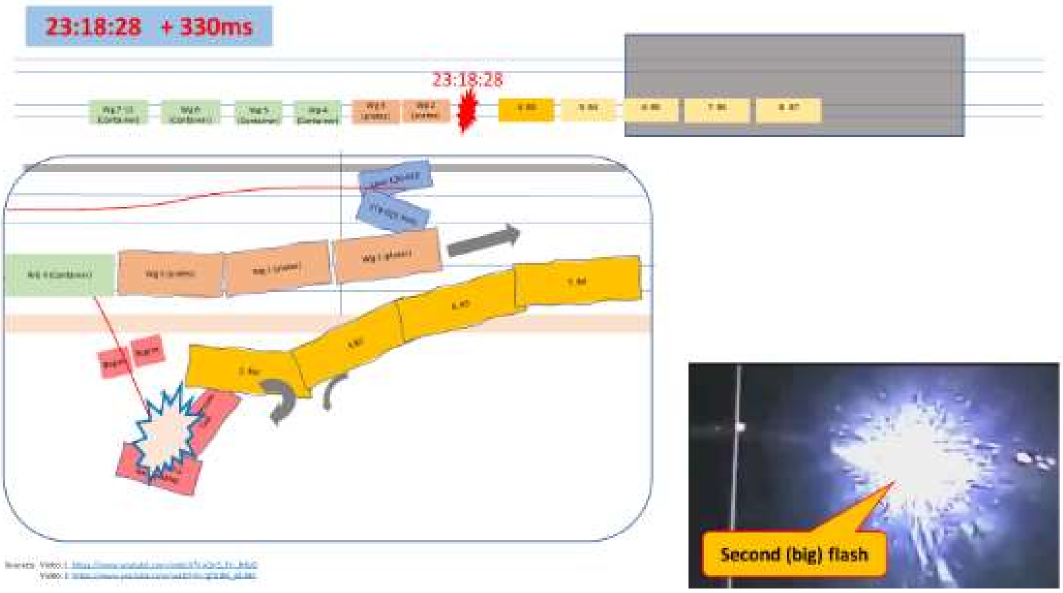


Figure 6: Second arc flash overhead line

The 2-3 arc flashes from the High voltage short-circuit seen on the video 2 are all happening at the same location and immediately right after the last and biggest short-circuit flash the explosion happened. Looking into the video in slow motion, we can see that the last glow of the short-circuit flash raising and fade away while from below the light of the explosion become visible.
Interesting to notice is that the light become visible from behind an object, depending on the position of the camera (exact location unknown at this time), this should most likely be coach B2. This is the location where the transformer is laying on the ground in the corner between coach B2 and coach B3. Both are laying about 3 meters higher on the debris of the locomotive and the first cars.

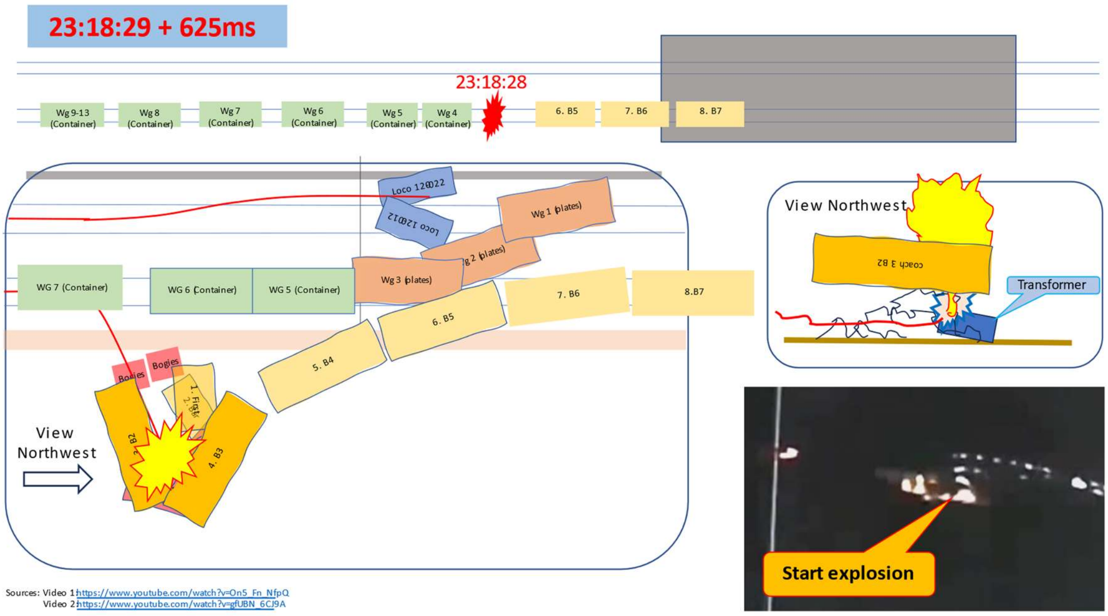


Figure 7: Sketch Start explosion

Element 4 in hypothesis: Several indications show that the transformer more precisely the refrigerant fluid is the main source of the explosion and fire.

Investigating the transformer container in more detail, we can find more evidence on the root cause of the explosion and fire to support further the hypothesis;

- On the transformer container, we can see in the picture Figure 16 a hole with the steel plates bended to the outside indicating a burst in the transformer container from an explosion inside. Giving the steel thickness (5 mm) of the container the hole should be caused by a rather big explosion.

- The transformer container (manufacture Siemens) is containing ca. 2.4-ton refrigerant liquid, a polydimethyl silicone product which has a flash point at temperatures > 300 °C and a fire point > 350°C. With the catenary arc flashes and short circuit on the transformer container or if not being close to the transformer with already fluid leaked out, the 2.4-ton fluid would quickly hit the flash and fire point leading to an explosion (Arc flashes of High voltage systems reach easily 5000°C). See datasheet in reference: Bayer Baysilone Fluids M 50 EL. In addition, the capacitors at the transformer, damaged due to the crash, could also create additional short-circuits an explosion (see further).

- At the explosion location on the transformer container, we can see on the color tint the different temperature the steel has had around the hole. One plate is bended downward indicating a very high temperature (> 600 °C). The different color tint also indicating that the fire had his source from this opening and the fire burned like a kind of 'Bunsen burner'. Also, soot is visible at that location indicating a longer fireplace as can be seen in the red marked area on picture Figure 17.

- The cover of the net filter capacitors in that same explosion location seems also to be blow away as no screw nor cover part can be found despite bolted with 26 bolts of M10 and the capacitor itself nor the capacitor fixation is much mechanical destroyed (white box on Figure 19).

- The other site of the same transformer box / locomotive frame is heavy mechanical destroyed, even the carbody-bogie pivot point is bended inside this area, but it does show far less heavy fire marks, basically blackened by root and even some paint color is still visible (see Figure 22). It should be also noted that this part of the transformer was laying partly dig onto the ground while the other end (site explosion hole) was slightly up in the air.

- Despite the very heavy explosion and long fire, the debris around the transformer and in a wider area on the ground do not show fire marks as the color of some vehicle parts is still visible. Only the parts right on top of the fireplace are burned (Figure 9 and Figure 21Figure 20). This confirms that the fire was very heavy but very local and fueled from the transformer refrigerant fluid out of the container through the explosion hole in a type of "Bunsen burner" fire. The lower level of the debris was providing air/oxygen to the fire from below.

- The fact that the coach B2, laying about 3 meters on top of the other debris, was complete burned out is because some part of the coach was right above the fire zone of the transformer. The fire was then horizontal spread throughout the whole coach via the materials (interiors, seats, ...) of the coach itself and eventually fueled by other flammable fluids from batteries and air conditioner refrigerants (see further). Coach B3 although also not far from the origin fireplace is showing some fire and head marks close to the transformer location but did not catch fire.

- The transformer container bottom plate, after the crash laying on top, is showing on the whole surface heavy heat deformations and different color tints indicating the location of the fire source and the high temperatures during a longer period (see picture Figure 20Figure 18).

Other possible source for main and secondary explosion and fire:

A second possibility of ignition beside the overhead line short-circuit could be the short circuit of the line-filter capacitors and traction convertor capacitors, the first once installed on the transformer, the other in the machine room. During the crash and collapsing of the locomotive frame we can assume with high probability that these components also got damaged and generating short-circuits with explosions and flashes. The energy stored in these components is more temporary (seconds) and not of the same magnitude of that of the overhead line but sufficient to generate explosion and or fuel existing fires.

Assuming for one moment that the high voltage short-circuit visible on the videos was not happening on the transformer itself or later, then the explosion of the line capacitor and the damaged transformer box could lead with the refrigerant fluid to an internal bigger explosion and creating the hole from where the fire was burning as described above. As we can see from the video 2, it is most likely that the explosion from these components fueled the already existing explosion and fire or were happening more or less at the same time.

Considering the same equipment is installed on both freight locomotives also heavily damaged a similar explosion or fire did not happen.

Other components on the locomotive and coaches do also contain flammable or explosive fluids when exposed to high temperatures. Most important to mention related to this subject are;

Locomotive:

- Ni-Cd batteries: Hoppecke - type FNC142LR - 142 Ah – 110V, 72 cells split in 2 boxes per locomotive – 66,24 liter (18-30% potassium hydroxide (KOH)) as electrolyte with an addition of lithium hydroxide (LiOH). – when overheated, generate explosive and flammable hydrogen gas. The 2 battery boxes are installed just beside the transformer. It is not clear if the battery boxes were still assembled on the underframe and the transformer or already been ripped off before the landing due to the high weight and accelerations. In the first case they would also add explosion and fire load. In the wreckage they are not visible anymore.

- Traction convertor: The traction convertor installed in the locomotive machine room is cooled with 720-liter 3M Fluorinert™ Electronic Liquid FC-3284. The liquid is classified as not hazardous (not classified as hazardous according to OSHA standard 29 CFR 1910.1200). It has no flash or fire point (flammability) but under extreme conditions of heat toxic decomposition products such as hydrogen fluoride and perfluoroisobutylene can be generated. Hydrogen fluoride reacts with metals such as steel to produce flammable and explosive Hydrogen gas. Since the traction converter is completely fragmented, we are not sure where the coolant leaked around, but most likely not at the transformer location, but this cooling fluid fire could be secondary to the main fire.

Coaches

- Ni-Cd batteries: Saft type SRM - 24 volt - one box per coach on the underframe – 104,4 liters of electrolyte with the same characteristics and behavior as explained above for the Ni-Cd batteries of the locomotive. Most probably the battery cells of the first, bar and B2 coach are in the debris of the coaches where no or limited fire happened, away from the fire hot spot.
- The electrolyte is dangerous in contact with skin and can cause severe injury and in eye contact even to lead to permanent damage. Rescue and fire brigade people were mentioning aggressive liquids dropping in one of the coaches (B3?), this is most likely coming from the battery electrolyte spilt whether mixed with fire extinguishing water (battery box is installed in the underframe overturned in the debris).

- Air conditioner refrigerant (1 HVAC group - 22.4 liter per coach in the underframe); The refrigerant normally operates under high pressure in ventilation and air-conditioning systems (HVAC). The used refrigerant R-134a (Tetrafluoroethane) is not flammable at ambient temperatures and atmospheric pressure. However, this material will become combustible when mixed with air under pressure and exposed to strong ignition source.
  Contact with certain reactive metals may result in formation of explosive or exothermic reactions under specific conditions (e.g., very high temperatures and/or appropriate pressures). (Ref: R134a safety data sheet)
  They mix readily with air and vaporizes to lower concentrations but in first instances could have developed a secondary fire from ignition source in the vicinity of a leak of the refrigerant. Since the air-conditioning units from the first coaches were not found in the debris, it is not sure if they contribute to a secondary fire.

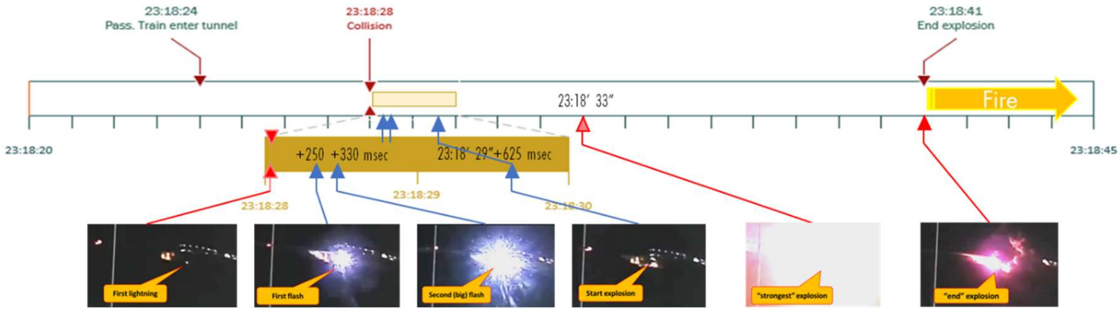
Beside the flammable materials also the compressed air tanks for the pneumatic / brake systems can contribute to the explosion and fire by providing under high pressure air/oxygen to the fire. There are several smaller and bigger air tanks of compressed air in each locomotive, most important to mention here are 2 air tanks of 150 liter, one of 800 liters and one of 80 liters. They were not found in the debris of the passenger locomotive so we cannot be sure if and how much this contributed to the fire propagation.

We can see in the video that after the first big explosion during more than 10 seconds several bigger and smaller explosion, re-ignitions took place, most likely from sources mentioned above.

Figure 8: Mid and end of explosion on video

7. Conclusion

Analyzing the video of the 2 surveillance cameras (night pictures) we can deduce the timing of the most important events, and matching them with the pictures of the accident place and wreckage.



The conclusion is supported by the following evidence and indications described :

- the location of the overhead wire in the debris.
- the overhead line short-circuits flashes, very visible in video 2, happened all in a very short time and on the same spot where the explosion and fire took immediately right after place.
- Arc flashes in High voltage systems can reach temperature as much as 5000 °C.
- the explosion hole in the transformer container, and soot at that location indicating a heavy and longer fireplace.
- the transformer container has the biggest fire load in the locomotive with 2.4-ton refrigerant fluid with flash & fire point between 300 and 400°C;
- the color tints and heat deformation of the transformer container indicate that this is the fire origin with very high temperatures and lasted till the refrigerant fluid was burned out.
- the surrounding of the wreckage indicate that the transformer container (laying upside down on the ground) was the local/single main fire origin, a type of 'Bunsen burner' fire getting the oxygen from below with a subsequential extension to the coach B2 on top of the debris.

With reasonable high probability we can conclude that the explosion was due to the arc flashes and short circuit of the catenary happened very close to or on the transformer, with eventually additional short circuits of the capacitors, creating an ignition and explosion of the refrigerant fluid which then burned out (2.4 ton) till the end.

The coach B2 complete burned out, because a portion of the coach was right above the fire zone of the transformer. The fire was then horizontal spread throughout the whole coach via the materials (interiors, seats, …) of the coach itself and eventually fueled by other flammable fluids from batteries and air conditioner refrigerants.

The explosion and fire are an unfortunate coincidence with the fact that the catenary got short-circuited on or near the transformer.

8. Learnings and recommendations related to the rolling stock.

Considering all above facts and evidence from the disaster, there is little or no vehicle architectural element, construction, or technical improvement nor activity related to maintenance or train operation onboard that could reduce the risk of repetition or element that could reduce the impact under the same conditions and circumstances. The necessary train control systems (ERTMS/ETCS) are onboard since some years but waiting for the infrastructure to be retested and switched on.

The forces at the collision were such that no design solution can withstand or avoid the disintegration of the locomotives and coaches. Also, the explosion and fire were and are not avoidable under the given conditions and circumstances nor can be limited with existing technical solution (e.g., fire detection and extinguishing systems).

More recent international rolling stock standards (TSI) are improving the crashworthiness of trains and reduce fire and smoke hazards, but these cannot reasonable be implemented retrospectively and would not or very limited reduce the human and material impact in the given collision circumstances.

The main root cause is clearly outside the scope of this report and related to the infrastructure and train control management system and procedures allowing two trains running for a long time on the same track.

Without any judgment and again clearly outside the scope of this report, a temporary recommendation could be to reduce the operational speed of a train re-routed on an opposite track as long as no fully functional train management system (ETCS / ERTMS) is operational and by this reducing the kinematic energy and destructive forces at an eventually collision (kinematic energy = square of the speed).

9. Pictures

Pictures used in the report

(Ctrl + click on reference in the text to automatically select the relevant picture below)

Figure 9: Drome view Freight locomotives and Passenger locomotives (screenshot video ABCNL news)

Figure 10: Overview vehicle positions after the crash

Figure 11: Catenary pole downward line under freight locomotive (2023-03-01 16.46.00.jpg)

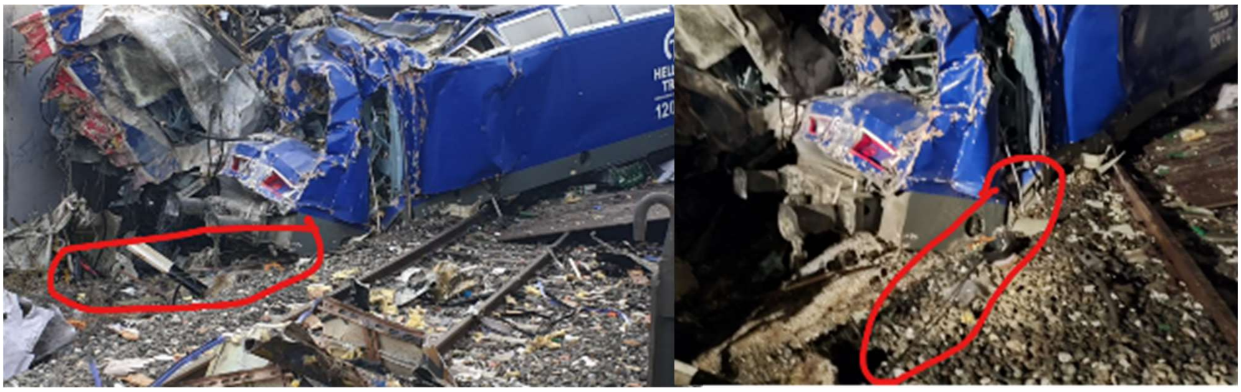


Figure 12: Catenary line under freight locomotive (20230301-105223.jpg & 20230301-034238.jpg)

Figure 13: Freight locomotives - Still electrical connected (UIC-plugs) (20230301-071311.jpg)

Figure 14: Transformer Loc 120 023 showing catenary line on transformer - file: 20230305_184147.jpg

Figure 15: Transformer 120-023 with catenary line assembled Extract from file 230307_123525.jpg

Figure 16: Transformer 120023 with explosion hole - file: 230307_123509.jpg

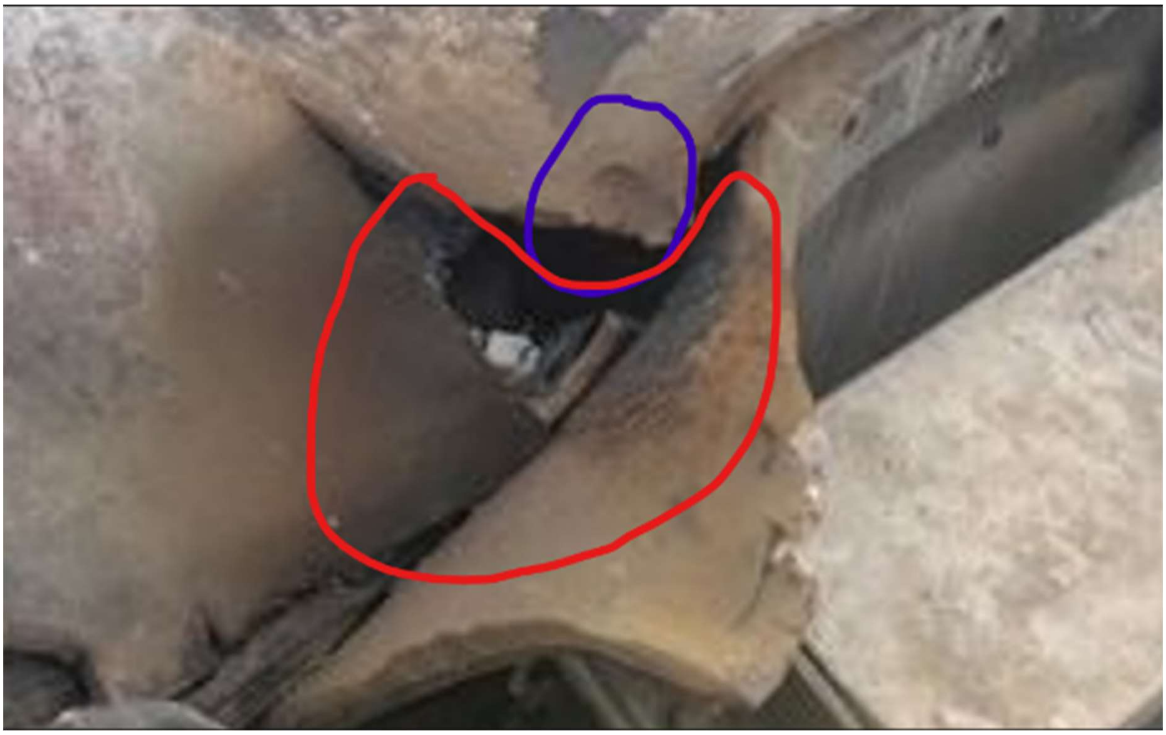


Figure 17: Detail explosion hole - file : 230307_123509.jpg

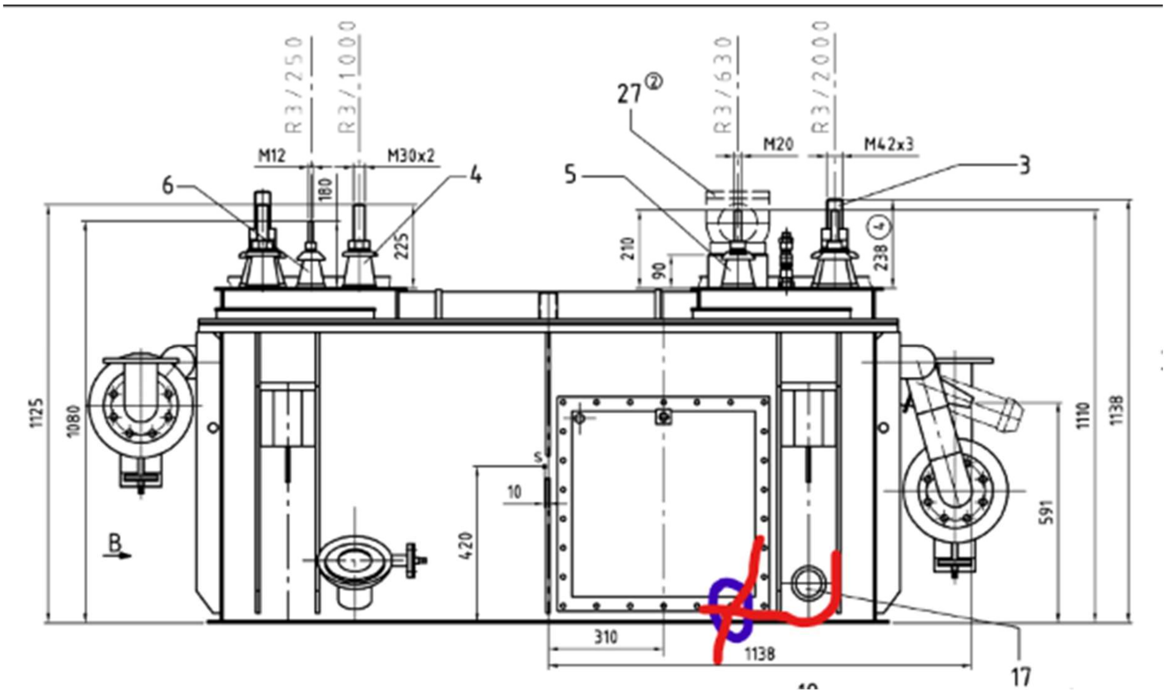


Figure 18: Drawing Siemens Transformer with indication of possible flash point (blue) and torn open sheets (red)

Figure 19: transformer from same view as drawing (here upside down in debris)

Figure 20: Transformer bottom view (on top in wreckage) file: 230303_104150.jpg

Figure 21: wreckage around transformer and fireplace - file: 230301_073502.jpg

Figure 22: Transformer opposite site explosion & fire hole (extract file : 20230307_124.106.jpg)

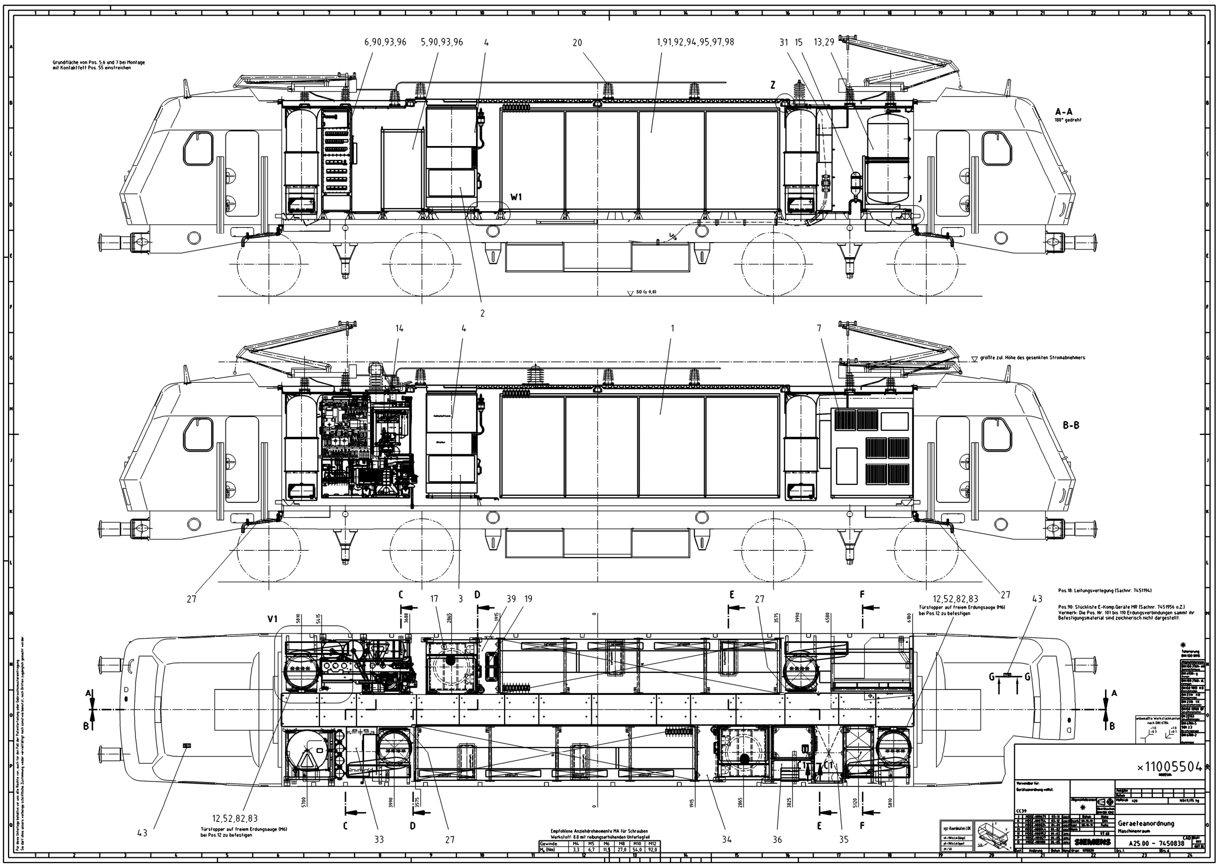


Figure 23: Overview drawing Siemens locomotive - Hellenic sprinter series 120-0xx

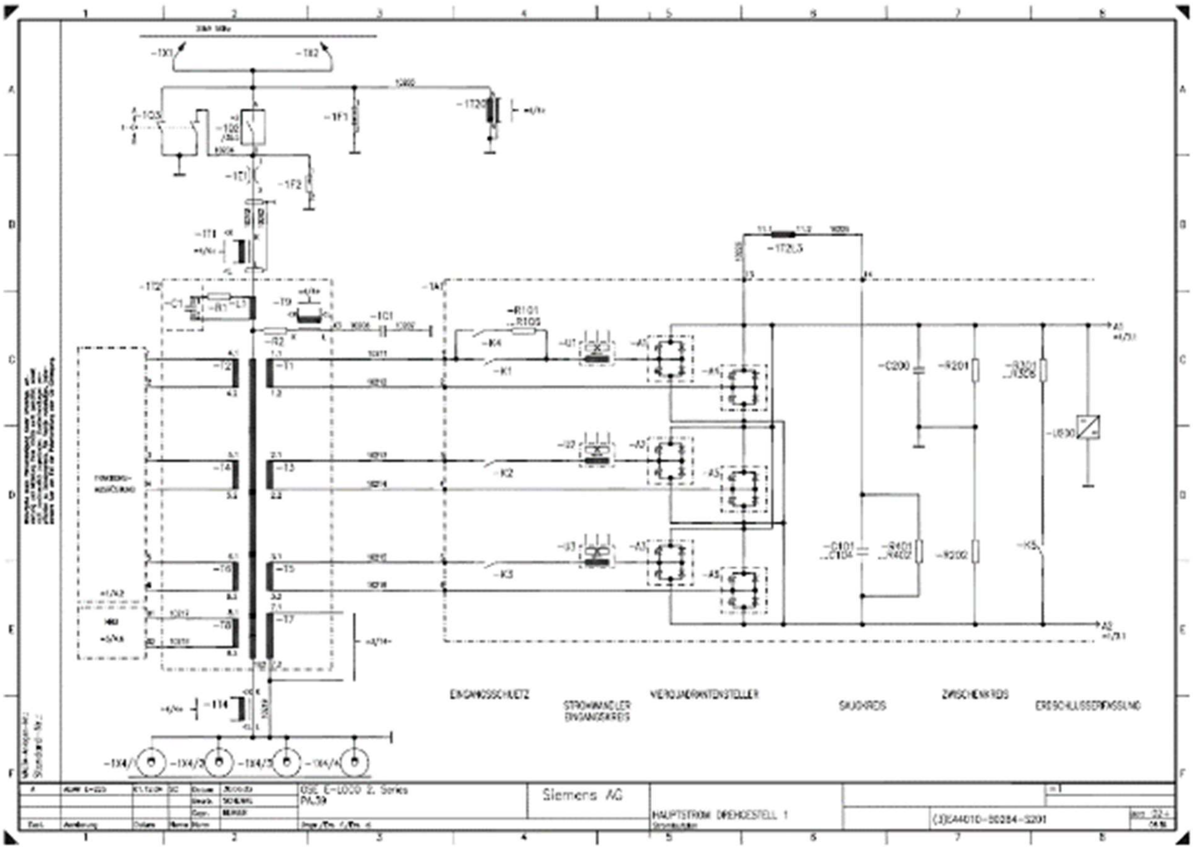


Figure 24: Siemens Locomotive Hellenic Sprinter - Main High Voltage Power Circuit