ΕΛΛΗΝΙΚΗ ΔΗΜΟΚΡΑΤΙΑ
Υπουργείο Υποδομών & Μεταφορών
Εθνικός **Ο**ργανισμός **Δ**ιερεύνησης
Αεροπορικών & **Σ**ιδηροδρομικών **Α**τυχημάτων
& **Α**σφάλειας **Μ**εταφορών (ΕΟΔΑΣΑΑΜ)
Σιδηροδρομικός Τομέας

Ταχ/κή Δ/νση: Βυτίνης 14-18
Νέα Φιλαδέλφεια, 143 42
Αττική
Τηλέφωνο: 210-9608080
Πληροφορίες: Κ. Καπετανίδης
Email: kkapetanidis@harsia.gr

Ν. Φιλαδέλφεια, 27/3/2025
Αρ. Πρωτ.: ΕΟΔΑΣΑΑΜ/Β529

Προς : **Εφετείο Λάρισας**
Εφέτης Ανακριτής
Δικαστικό Μέγαρο Λάρισας
Μεγάλου Αλεξάνδρου & Κούμα
41442 Λάρισα
Τηλ. : 2410531693
Δ/νση Ηλ. Ταχ. :
efetisanakritis@gmail.com

Θέμα : Παροχή στοιχείων προς το Εφετείο Λάρισας
Σχετ. : Το υπ. αριθμ. πρωτ. 112/5-3-2025 έγγραφό σας.

Αξιότιμε κύριε Πρόεδρε,

Σε συνέχεια του σχετικού ως άνω έγγραφό σας, σας ενημερώνουμε ότι η επίσημη μετάφραση των στοιχείων (1) και (2.α) έως (2.ε), είναι σε εξέλιξη και προβλέπεται να ολοκληρωθεί σε περίπου 15 ημέρες, οπότε και θα σας αποσταλεί συμπληρωματικά στο παρόν έγγραφο.

Σε αναμονή των ανωτέρω, σας υποβάλλουμε τα στοιχεία στην αγγλική, και σας ενημερώνουμε για τα κάτωθι, σχετικά με την ενότητα 4.4.3 της Έκθεσης Διερεύνησης (Πιθανές αιτίες της πυρόσφαιρας και των φωτιών) :

Σημείωση : Στο ακόλουθο κείμενο οι αριθμοί σε παρενθέσεις είναι παραπομπές στις αντίστοιχες παραγράφους της Έκθεσης Διερεύνησης και το κείμενο με πλάγια γραφή παραπέμπει στα αντίστοιχα χωρία, χωρίς όμως να αποτελεί πιστή μετάφραση των αντίστοιχων κεφαλαίων της Έκθεσης. Επιπλέον διευκρινιστικά στοιχεία παρέχονται με κανονική *γραφή.*

1. **Παρατηρήσεις (Ενότητα 4.4.3.1)**

Το φαινόμενο της πυρόσφαιρας προσεγγίστηκε αρχικά μέσω των διαθέσιμων βίντεο (δύο βίντεο από κάμερες από τον Αυτοκινητόδρομο Αιγαίου, ένα βίντεο από κάμερα από τον αυτοκινητόδρομο Μαλιακός - Κλειδί και τέσσερα μικρά βίντεο που τράβηξαν επιβάτες του τρένου). Επίσης χρησιμοποιήθηκαν οι διαθέσιμες φωτογραφίες, συμπεριλαμβανομένων αυτών που περιλαμβάνονται στη δικογραφία, από το αρχείο του Εφέτη Ανακριτή Λάρισας (περίπου χίλες φωτογραφίες).

Η διαδικασία και οι παρατηρήσεις αυτές αναλύονται στην Έκθεση, ενότητα 4.4.3.1 (Observations/Παρατηρήσεις), παρ. (453) έως (480). Το συμπέρασμα των παρατηρήσεων συνοψίζεται στην παρ. (480):

(480) Δεδομένων των τεχνικών τους χαρακτηριστικών και των ποσοτήτων των υλικών στα τρένα που θεωρητικά θα μπορούσαν να έχουν συμβάλει (π.χ. μπαταρίες υγρών στους ηλεκτροκινητήρες και βαγόνια επιβατών, υγρό ψύξης στα ηλεκτρονικά κυκλώματα ισχύος, ψυκτικό μέσο στα κλιματιστικά σε κάθε επιβατικό βαγόνι, δεξαμενές πεπιεσμένου αέρα σε κάθε ηλεκτροκινητήρα), αυτά δεν παρέχουν αρκετή ποσότητα καυσίμου για να εξηγήσουν τη δημιουργία και την ανάπτυξη της παρατηρούμενης πυρόσφαιρας (80μ διάμετρο και διάρκειας 10 δευτερόλεπτων). Επιπλέον, η τεχνική περιγραφή του βαγονιού του εστιατορίου (πούλμαν WRMZ) δεν αναφέρεται σε οποιαδήποτε εγκατάσταση κάποιου τύπου υγροποιημένου αερίου και από τις πληροφορίες μας δεν πραγματοποιείται κανονικό μαγείρεμα επί του βαγονιού. Χρησιμοποιούνται μόνο ηλεκτρικές τοστιέρες για σάντουιτς και φούρνοι μικροκυμάτων για να ζεστάνουν τα προμαγειρεμένα φαγητά. Επομένως, αποκλείοντας οποιοδήποτε άλλο εύφλεκτο υλικό από το βαγόνι του εστιατορίου και εξαλείφοντας κάθε άλλη πιθανότητα, η πιο πιθανή εξήγηση για τα παραπάνω ευρήματα φαίνεται να είναι ένας άγνωστος όγκος υγρού καυσίμου ο οποίος πιάστηκε στο πλαίσιο του βαγονιού του εστιατορίου (το οποίο παραμορφώθηκε σε σχήμα S κατά τη δεύτερη σύγκρουση μεταξύ του βαγονιού του εστιατορίου και της πρώτης φορτάμαξας του εμπορευματικού τρένου 63503 και παρασύρθηκε στην τελική θέση των συντριμμιών).

2. <u>Γνωμοδοτήσεις Ειδικών και Προσομοιώσεις (Ενότητα 4.4.3.2)</u>

(481) Έχοντας ως δεδομένα τις πληροφορίες από τα βίντεο από τις 3 διαφορετικές κάμερες έγιναν προσπάθειες υπολογισμού και/ή προσομοίωσης των πιθανών αιτιών της πυρόσφαιρας και των πυρκαγιών, μέσω αντίστροφης μηχανικής.

Η Επιτροπή Διερεύνησης του ΕΟΔΑΣΑΑΜ συναντήθηκε με τον κ. Α. Μιχόπουλο, Χημικό Μηχανικό MSc ΑΠΘ/UMASS, τεχνικό σύμβουλο οικογενειών, ύστερα από δική του επικοινωνία, με σκοπό την ανταλλαγή πληροφοριών για το φαινόμενο της πυρόσφαιρας. Κατά τη συνάντηση παρουσιάστηκε από τον κ. Μιχόπουλο η «ΑΝΑΛΥΣΗ ΤΩΝ ΔΕΔΟΜΕΝΩΝ – ΔΙΕΡΕΥΝΗΣΗ ΑΙΤΙΩΝ ΔΗΜΙΟΥΡΓΙΑΣ ΠΥΡΟΣΦΑΙΡΑΣ (FIREBALL) ΣΤΟ ΣΙΔΗΡΟΔΡΟΜΙΚΟ ΔΥΣΤΥΧΗΜΑ ΤΩΝ ΤΕΜΠΩΝ, 28/2/2023» (περιλαμβάνεται στη δικογραφία) και στη συνέχεια προσκομίστηκαν επόμενες εκδόσεις αυτής. Τα στοιχεία αυτά (και ειδικότερα η ενότητα "Συμπεράσματα από τη μελέτη των δεδομένων αναφλεξιμότητας") έχουν ληφθεί υπόψη κατά τη σύνταξη της Έκθεσης.

(48) Επιπλέον, έγινε μεταξύ του Ευρωπαϊκού Οργανισμού Σιδηροδρόμων (ERA) και του κ. Κ. Λακαφώση, Μηχανολόγου-Αεροναυπηγού Μηχανικού MEng, και μέλους της

Επιτροπής Διερεύνησης Ανεξάρτητων Πραγματογνωμόνων Οικογενειών (ΕΔΑΠΟ), σύμβαση παροχής υπηρεσιών, με βασικό αντικείμενο την παροχή στοιχείων (για την τεκμηριωμένη καταγραφή και περιγραφή γεγονότων σχετικά με τη σύγκρουση, τη χαρτογράφηση των βαγονιών, την φωτιά και την πυρόσφαιρα και το χρονολόγιο συμβάντων μετά τη σύγκρουση).

(483) Πρώτα επικοινωνήσαμε με το κρατικό ινστιτούτο RI.SE το οποίο συνεργάζεται με τον ακαδημαϊκό χώρο, τη βιομηχανία και την κοινωνία ως κεντρικό κομμάτι του σουηδικού συστήματος καινοτομίας. Στο ινστιτούτο RI.SE ανατέθηκε ένα έργο γνωμοδότησης διάρκειας 2 εβδομάδων σχετικά με τη δυνατότητα ανάφλεξης από τα ήδη γνωστά υλικά και ουσίες στο τρένο.

Το ερώτημα ήταν ποιοι μηχανισμοί και ποια υλικά θα μπορούσαν να έχουν δημιουργήσει την πυρόσφαιρα κατά τη διάρκεια του ατυχήματος, λαμβάνοντας ως δεδομένα μόνο τα γνωστά και καταγεγραμμένα καύσιμα επί των αμαξοστοιχιών. Αναλύοντας τα δεδομένα και τις πληροφορίες, διερευνήθηκαν δύο πιθανά σενάρια, η καύση αερολύματος υγρών σταγονιδίων και η έκρηξη της δεξαμενής λαδιού μετασχηματιστή (φαινόμενο έκρηξης αναβράζοντος υγρού – διαστελλόμενου αερίου - BLEVE). Η πιθανότητα έκρηξης της δεξαμενής λαδιού μετασχηματιστή προέκυψε από την ανάλυση ότι είναι πολύ μικρή.

(484) Ως αποτέλεσμα, το RI.SE παρείχε μια έκθεση με γνωμάτευση σχετικά με την πιθανότητα διάσπασης υγρού ελαίου σιλικόνης σε σταγονίδια μεγεθών που κυμαίνονται από 0,5 έως 4 mm σε διάμετρο και την διασπορά αυτών σε μια περιοχή που θα ήταν σύμφωνη με τις υφιστάμενες παρατηρήσεις για το μέγεθος της πυρόσφαιρας και τα ευρήματα στον τόπο του ατυχήματος. Σύμφωνα με αυτή την υπόθεση, είναι δυνατό (από ρευστοδυναμικής άποψης) να διασπαστεί το λάδι σιλικόνης με τέτοιο τρόπο ώστε να δημιουργούνται σταγονίδια των αναφερόμενων μεγεθών και να διασκορπιστούν στην περιοχή (ώστε να καλυφθεί η περιοχή με νέφος σταγονιδίων). Έτσι, έγινε η υπόθεση ότι θεωρητικά θα μπορούσε ένα τέτοιο νέφος να αναφλεγεί και να δημιουργήσει πυρόσφαιρα είναι, σύμφωνα με αναφορές στη βιβλιογραφία.

Αναλυτικά **(2.α της παραγγελίας σας)** :

REPORT

Contact person
Ying Zhen Li
Division Safety and Transport
+46 10 516 58 29
yingzhen.li@ri.se

Date
2024-11-22

Reference
18533801

Dr. Christos Papadimitriou
National Aviation and Railway Accidents
Investigation and Transport Safety Authority,
Vitinis 14-18, N.Filadelfeia, Attica, Greece ,
POST CODE 14342

Investigation of fireball in Tempi railway accident on 28 Feb 2023

This work was conducted based on the request from the National Aviation and Railway Accidents Investigation and Transport Safety Authority (HARSIA), Greece. It was related to the train accident that occurred in Tempi on 28 Feb 2023. The purpose of this work was to identify the most probable and realistic cause(s) of the fireball in this accident based on the existing information and state-of-the-art knowledge.

RISE Research Institutes of Sweden AB

Postal address
Box 857
501 15 BORÅS
SWEDEN

Office location
Brinellgatan 4
504 62 Borås
SWEDEN

Phone / Fax / E-mail
+46 10-516 50 00
+46 33-13 55 02
info@ri.se

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1. Background

This accident was related to a collision of a passenger train and a freight train, which produced a large fireball with a subsequent fire. HARSIA noticed that the fuels available were limited, and it was difficult to identify which was the fuel resulting in the fireball and what mechanism was behind it. One probable reason could be the locomotive's transformer oil, but HARSIA supposed this oil was difficult to ignite and the holes in the transformers were probably too small to create such a large fireball so quickly.

The focus of this investigation is therefore to answer the questions. Specifically, the purpose of this work is to identify the most probable and realistic cause(s) of the fireball in this accident based on the existing confirmed information and state-of-the-art knowledge.

In the following sections, observations and facts are presented at first to form the basis for this investigation. Thereafter, two possible scenarios are investigated, based on the observations and facts. In this work, the words "transformer oil tank" and "tank" are equivalent to "transformer container".

2. Observations and facts

For clarity, a snapshot of the map is given in Figure 1, showing the surroundings and the approximate location of the collision. Note that the marked point is made by the investigator for information and may not be the real collision point. The collision point was close to the bridge. The passenger train ran north and the freight train ran south.

Figure 1. A photo of the site. The marked point is only for information and may not be the real collision point.

Key observations and facts are listed below:

(1) From the observations, it is certain that a large amount of fuel was released into the surrounding air and burnt within a short period, forming the fireball.

(2) Different to a common fireball from a pressurized tank rupture or BLEVE, The observed fireball seems to have a certain direction, upwards and tilted towards the bridge side (the east). From existing information, HARSIA believes that one large fireball moves towards the bridges or the south (following the freight train movement) and a smaller one follows the movement of the restaurant car of the passenger train (towards the north).

(3) The fireball starts immediately after the collision, and lasts for about 6-8 seconds.

(4) The fireball starts from a location close to the ground, as observed from the videos.

(5) From the videos, it is found that there are some flying objects on flames. They may be large liquid droplets or volumes that continue to burn after leaving the fireball or after the fireball has ended. Some flying objects may be pieces of shiny metal sheets that were found in the surrounding fields after the accident.

(6) The passenger train was running at 148 km/h at the moment of collision, corresponding to 41.1 m/s. After the collision, this train's locomotive was totally destroyed and become fragmented. The transformer was found not a part of the main locomotive wreckage. It was found among the debris leaking silicone oil towards the restaurant car. Several cracks were found around the transformer container (or tank).

(7) The speed of the freight train was about 90 km/h at the moment of collision, corresponding to 25 m/s. Cracks were also found on the two transformers but much smaller in size.

(8) From one of the videos, it can be found that there was a very bright light after collision (cold colour), probably a strong electric arc. After the bright light, the fire started (warm colour). HARSIA believes that the blue flashes (3 of them in quick succession) were caused by the locomotives hitting against the catenary line and creating a short circuit. The fire started about 0.3 seconds later.

(9) There were three transformers involved in this accident, one from the passenger train locomotive and one from each of the two freight train locomotives. Cracks were found in all three transformer containers. However, the most damaged one is the transformer container of the passenger train locomotive, which indicates large impact of the collision on it.

Dimensions of cracks on the transformer of the passenger train locomotive:

- **Four cracks**: 50cm x 10cm, 30cm x 20cm, 15cm x 2cm, 12cm x 4cm
- **One hole**: diameter 4cm
- **Broken Oil recirculation tubes:** unknown for the investigator, not considered in flow calculations but the influence is considered small due to the existence of other large racks.

Dimensions of cracks on the transformer of the 1st locomotive of the freight train:

- **1 triangular crack**: approximate dimensions of 22 cm × 25 cm
- **Broken Oil recirculation tubes:** the sample applies here.

Dimensions of cracks on the transformer of the 2nd locomotive of the freight train,

- **1 crack**: approximate dimensions of 10 cm × 15 cm and
- **A hole:** a diameter of 7 cm
- **Broken Oil recirculation tubes:** the sample applies here.

(10) According to the interviews of the survivors after the accident, there was no sign of explosion.

(11) The meteorological measurements close to the site indicates that the average wind velocity is low. However, the site is next to short tunnels under the bridge. The passenger train just drove out of it and then hit the freight train. The piston effect may affect the external windy conditions slightly although some openings on the tunnel wall tend to reduce this effect. The influence compared to the wind existing beside the train bodies is considered small.

(12) The temperature of the silicon oil under normal condition is about 90 °C. The properties at this temperature are used in the analysis presented in Section 3.1.

(13) The only fuel that has been confirmed to be onboard the train sets and found to be a possible contributor to a large fireball is the silicon oil used in the locomotive transformers (See Figure 2). It was about 2.4 tons in each of the three locomotives. The silicone oil used is Baysilone M 50 EL. According to the manufacturer, its properties are:

- Density: 960 kg/m^3 at 25 °C, 900 kg/m^3 at 100 °C and 840 kg/m^3 at 175 °C
- Viscosity: 50 mm^2/s at 25 °C, 16 mm^2/s at 100 °C and 10 mm^2/s at 140 °C
- Flash point: ~ 300 °C
- Boiling temperature: ~ 400 °C
- Surface tension: 19-21 mN/m

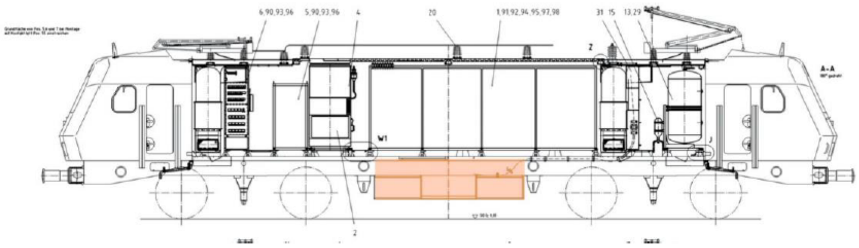


Figure 2. Location of the transformer with silicon oil inside it under normal conditions.

3. Possible scenarios

For the fireball observed in this accident, the possible fuels are combustible gases (vapor form), liquid fuels, and dusts. As neither large amount of fine dusts nor combustible gases in pressurized tanks that may produce such large fireballs (tons of fuels) were found on board, they are excluded in the following analysis. The remaining one is the liquid fuels.

The only known and verified liquid fuel with a significant amount on aboard the train sets is the silicon oil in the transformers of the three locomotives.

This work is conducted based on the assumption that except the silicon oil in the transformers, no significant amounts (> 1000 kg) of dangerous goods (especially in liquid or gas form) were found onboard the train sets.

Two possible scenarios are investigated on the observations and facts. They are called Scenario 1 and Scenario 2. In Scenario 1, the fireball is considered as a result of burning of atomized liquid fuel droplets discharged through cracks of the transformer containers. In Scenario 2, the fireball is considered as a result of a BLEVE of transformer container. They are described below in sequence.

3.1 Scenario 1: Burning of atomized liquid droplets

In this scenario, it is considered that the liquid temperature is lower than the flash point and boiling temperature. If they slowly spilled out of the container, only pools will be on the ground.

The ignition of mist formed from flammable liquids at temperatures below their flash points is a well-known phenomenon [1]. If we spray liquid droplets and mists, the flash point becomes insignificant [2]. When finely sprayed with, e.g. a rotary atomizer, even heavy fuels or cleaning oils with a flash point above 300°C may ignite producing an astonishingly heavy explosion [2]. In fact, the flash point of a liquid does not predict whether or not a liquid spray is ignitable [2].

3.1.1 Energy of the silicone oil

The silicone oils in transformers were moving together with the trains. At the moment of collision, the speed of the passenger train was 41.1 m/s and it was about 25 m/s for the freight train. It has been found that the damages to the train bodies and to the transformer containers by the collision are much serious for the passenger train, as explained in Section 2. The following analysis will thus focus on this transformer.

After the train was forced to stop (closely stop, velocity decreased from 41 m/s to a small value), the silicone oil still contains the momentum and energy. If there was no rupture of the transformer container, this energy would have been dissipated within a certain period, assuming the transformer container can withstand its integrity in the accident. However, if the container of silicone oil (transformer tank) ruptured immediately in the collision due to mechanical forces (probably the case in this accident), the liquid fuel will be splashed or sprayed out of the container. This phenomenon can occur regardless of the location of the cracks (front or rear side of the container). This is mainly due to the fact that the dynamic energy of the silicone oil cannot be dissipated instantaneously. There would have been some loss of energy on the way out, e.g., by the shear stress at the interface between the liquid and the walls of the container or by possible pressure waves and vortexes inside the tank. However, the main energy of the sprayed liquid is expected to remain. In such case, much of the liquid would spray out with a high initial velocity.

Besides the liquid splashed and sprayed out, a certain amount of gaseous silicone oil that was produced under normal operation conditions is expected to have also escaped from the container. Note that this amount of gaseous fuel is combustible and easier to ignite than the fuel in liquid form, and may play a key role at the ignition stage.

3.1.2 Flow rate of liquid silicone oil possibly sprayed out of the transformer

As described above, much of the liquid silicon oil in ruptured tanks will be sprayed out. The amount of the flow rate is difficult to accurately estimate. An approximate estimate of the initial discharge rate is given first, assuming the initial discharge velocity of 41.1 m/s for the passenger train (i.e., assuming no energy loss on the way). This results in a spray rate of 4.9 m^3/s through the cracks and 4.4 tons of fuel per second. This indicates for a duration of one second, the fuel that may be discharged is 4.4 tons, much larger than the amount of fuel inside the container, i.e., about 2.4 tons. The actual amount of fuel spilled may vary, but this estimate suggests that 1 to 2 tons of silicone oil spilled from the tank is highly plausible.

It is found from some simple tests by the investigator (author) that there is usually a small amount of liquid remain in such a container, i.e., not all the liquid succeed in escaping from the liquid container. This is in accordance with the observations during the accident, i.e., some liquid remained and contributed to subsequent fires.

For the freight train locomotives, the cracks are smaller. For the 1st locomotive of the freight train, a triangular crack was found (approximate dimensions of 22 cm × 25 cm) and the oil recirculation tubes were broken. For the 2nd locomotive of the freight train, a crack with approximate dimensions of 10 cm × 15 cm and a hole with a diameter of 7 cm were found and the oil recirculation tubes were broken. The speed of the freight train was about 90 km/h at the moment of collision, corresponding to 25 m/s. At the moment of collision, it is possible that the transformer container cracked and spill the fuel out. The corresponding flow rate is 1.38 m^3/s and 0.47 m^3/s, or 1.2 ton/s and 428 kg/s for the 1st and the 2nd locomotive of the freight train, respectively. Note that these values are much lower than that for the passenger train. Their contributions to the fireball are also expected to be less significant. Despite this, the gaseous silicone released from the tank may play a key role at the ignition stage, as explained above. Note that from one video, it is clear that the ignition point is close to the collision point and where the strong arc was observed.

3.1.3 Atomization of the liquid fuel

There are two types of fluid atomization: primary atomization and secondary atomization. The primary atomization refers to that bulk fluid, typically in the form of a sheet or jet, breaks up for the first time and forms drops [3]. The manner in which this sheet disintegrates into drops depends upon the operating conditions. However, the principal cause of instability is due to the interaction of the sheet with the surrounding atmosphere whereby rapidly growing waves are imposed on the sheet. Disintegration occurs when the wave amplitude reaches a critical value and fragments of sheet are torn off. The fragments rapidly contract into unstable ligaments under the action of surface tension and drops are produced as the latter subsequently break down [4]. In spray formation, primary atomization occurs near the exit of sprays.

Primary atomization is usually followed by secondary atomization, which typically occurs further downstream [3]. The secondary atomization is the process of breakup of drops or ligament structures into smaller droplets. It usually involves in complex phenomena, such as, single droplet deformation and breakup, droplet collision, droplet impact on surface [5]. The secondary atomization is found to be mainly a function of Weber number and Ohnesorge number. Breakup was found for a wide range of Weber number and Ohnesorge number, and they are mainly in a range of 1-1000 for Weber number and 10^{-3} – 300 for Ohnesorge number [3]. The new data in ref. [5] provide further support for Weber number in a range of 1-1000 and the Ohnesorge number in a range of 10^{-3} – 2.

This accident involves high speed fuels released from small cracks of irregular shapes into the surroundings. The fuels may probably be highly turbulent due to the collision and movements before they were released. The release conditions are similar to nozzles used for fire protection and agriculture to a large extent. The fuels may even impinge onto some surfaces before they were released into the air, e.g. some train body panels or even the other train carriages that continue their movements towards the release points close to the collision point. Especially for the passenger train which became fragmented after the collision, its transformer may probably hit something on the way and may even rotate before it rested on the ground. Furthermore, the released droplets were highly influenced by the strong winds in front of and nearby the train locomotives and carriages. It is quite clear that there exist a large velocity gradient (indicating a large shear stress) between the movement paths of the two trains after the collision.

Note that both the impingement onto solid surfaces and the strong winds usually result in much finer droplets [6], and they are also two typical ways of producing fine droplets from relatively low speed sprays. We have examined the Weber number and the Ohnesorge number, both of which fall in the region where secondary atomization could occur.

It is expected that a significant number of liquid droplets were released into the surroundings. They have various droplet sizes. For a given crack, the droplet size distribution is expected to be characterized by a log-normal distribution similar to water spray nozzles. The volumetric median droplet size may be approximately estimated using the correlation in the references [7-9]. This correlation shows that the droplet size is mainly a function of outlet size, initial velocity, liquid density and surface tension of the liquid. For nozzles, the nozzle diameter is usually used as the characteristic length. For the cracks in this accident, the width of the cracks (shorter side length for a rectangular crack) is considered as the characteristic length. The calculations show that the median droplet size is mainly in a range of 0.5 mm and 2.7 mm for the cracks identified after the accident. Note that some droplet sizes can be much smaller than 0.5 mm, e.g., 0.1 mm, and some droplets can be much larger than 2.7 mm, as the droplet sizes usually follow a certain distribution function as mentioned above. However, the volume proportion of extremely small droplets and extremely large droplets are considered low. These values refer to the sizes of initial spray. It is highly possible that the droplets undergo further secondary atomization and become much finer droplets, especially when high turbulent winds or even vortexes are expected to exist at the site due to the collision of two trains with high speeds and the further movement in two different directions. There may also be some droplets merging to form larger drops after they were discharged. Note also that the cracks identified after the incidents are approximately estimates, and in fact they are in irregular shape and smaller cracks exist at some parts of the cracks. If the liquid was discharged through such smaller and narrower cracks, the droplet size will also be smaller. Therefore, the droplets discharged should cover a wide range of sizes.

The above analysis of the atomization of liquid fuel is for the passenger train. For the freight train, the transformer container may also release some fuels through the cracks. The volumetric median droplet size is estimated to be about 4 mm for the 1st locomotive, and about 1.9 mm for the 2nd locomotive. Therefore, relatively larger droplet sizes may be produced from the freight trains. These droplets may also contribute to the fireball.

Note that for atomization of liquid, surface tension and viscosity are two important parameters. The surface tension of the silicon oil used in the transformer is about 20 mN/m, which is much lower than that of water which is about 71 mN/m. For liquid, a lower surface tension indicates less inherent force and thus easier break up. Moreover, at room temperature (i.e., 25 °C), the viscosity of the silicone oil is much higher than that of water. However, when the temperature increases to 90 °C, which is the normal operating temperature of the silicon oil in the transformer, the viscosity decreases significantly from 50 mm^2/s to 18 mm^2/s. This significantly reduces the Ohnesorge number, increasing the strength and probability of secondary atomization.

3.1.4 Spatial distribution of the fuel in the surroundings

In this scenario, the combustibles are millions of liquid droplets spraying out of the transformer container with a high initial velocity. The initial discharge velocity can be as high as 41.1 m/s. Initially, they may be distributed along a certain direction in accordance with the initial spray direction, e.g., towards the sky. But afterwards they could hit some objects and were forced to change directions. They mix with the surrounding turbulent air and form combustible mixture. Note that the direction is not a necessity for this incident as fine droplets will be carried away by the flows, i.e., the vertical flow caused by combustion expansion (towards surroundings) and buoyancy forces (vertical), the flow towards the south induced by the freight train, and the flow towards the north induced by the passenger train. However, the direction may affect the dimension of the fireball assuming the contribution from the large droplets is significant. It is worth noting that if the initial sprays and droplets from the tanks hit some objects, the influence of direction will become very insignificant, as after impingement, these droplets usually become smaller and can be more easily carried away by the flows mentioned above, and most of which probably contribute to the fireball. The influence of flows on the movement of fine droplets will be explained in the following subsections on trajectories of spray with air drag.

Trajectories of droplets without air drag

Without air drag, the trajectories can be simply calculated using the initial velocity and discharge angle. The vertical discharge with an initial velocity of 41.1 m/s gives a highest distance of 86 m above the discharge point, and the longest duration of 4.2 seconds sustaining in the air. The longest horizontal spray distance of 172 m is achieved when the discharge angle is 45°. Under this angle, when the object reaches the highest point of 43 m, the horizontal distance is 86 m.

Trajectories of droplets with air drag in quiescent environments

With air drag, the trajectories are different to some extent. The drag reduces the duration in the rising period and increases the duration in the dropping period. The drag is highly dependent on the droplet size.

Calculations of droplet trajectories in quiescent environments by solving the controlling equations for the silicon droplets discharged into the air are carried out to find out possible locations of droplets and durations. Here droplets of various diameters are discharged vertically to the air. The results for the heights of the droplets as a function of time are shown in Figure 3. Clearly, the droplet size has a strong influence on the trajectories. The larger the droplet size, the longer the duration, and the higher it can reach, although at the end all droplets fell to the ground. Note that the height is much lower than 86 m which refer to the scenario without air drag. By increasing the droplet size, the air drag effect diminishes and a value close to 86 m can be obtained. In other words, the air drag plays a key role in the trajectory for fine droplets.

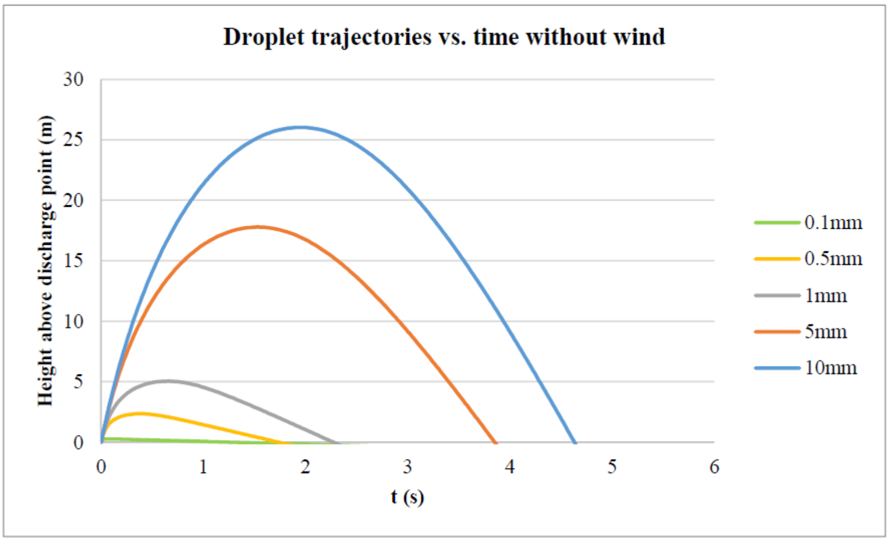


Figure 3. Trajectories of droplets with air drag in quiescent environments

Trajectories of droplets with air drag in case of a vertical flow caused by combustion

Fine droplets can be carried away by the wind. In this case, there exist strong and complex winds surrounding the site. It is especially of interest to know the influence of the vertical flow caused by combustion expansion and buoyancy forces. Here a gentle vertical flow of 10 m/s is assumed to understand the influence of such a vertical flow on the droplet trajectories. Note that a 10 m/s flow is typically found in flames at about 10 m high. The results are shown in Figure 4. They are very different to the results presented in Figure 3. For large droplets (5mm and 10mm), the trend is similar to that shown in Figure 3, but both the heights and durations are significantly increased. The large differences can be found for the fine droplets with a diameter of 1 mm, 0.5 mm and 0.1 mm. The height continues to increase with time under the vertical flow. In theory, it can go to any height if the wind exists on the way and the earth atmosphere's effect can be ignored. The rising velocity, however, is greater for finer droplets. Under a vertical velocity of 10 m/s, the locations of the droplets at 8 seconds are approximately 60 m, 70 m and 80 m for a diameter of 1 mm, 0.5 mm and 0.1 mm, respectively. The reason for the continuous rising is due to the fact that the droplet has a balanced force between gravity and air drag, after which the droplet moves forward (higher) at the equilibrium speed. The transition point has been checked and it was found that the equilibrium droplet size under a vertical flow of 10m/s is between 3 mm and 4 mm. See the results in Figure 5.

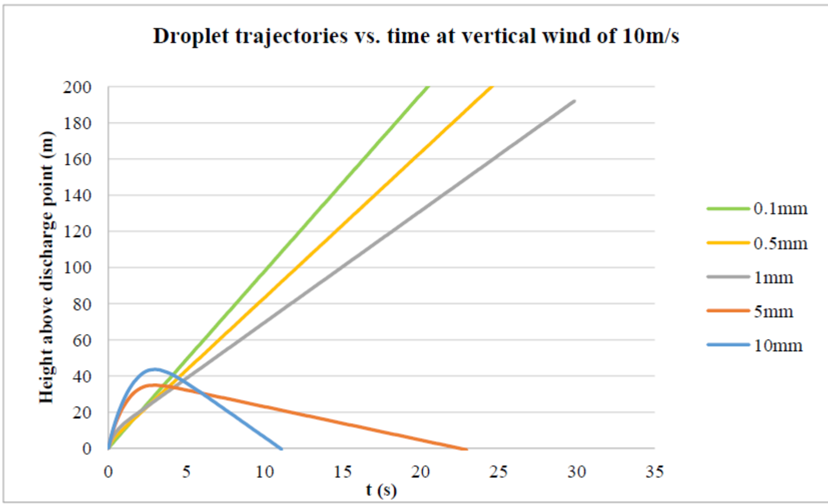


Figure 4. Trajectories of droplets with air drag in a vertical flow of 10 m/s.

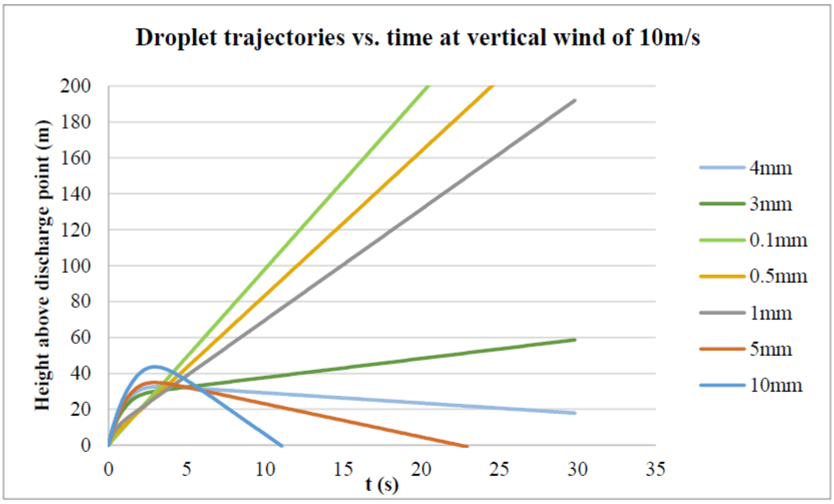
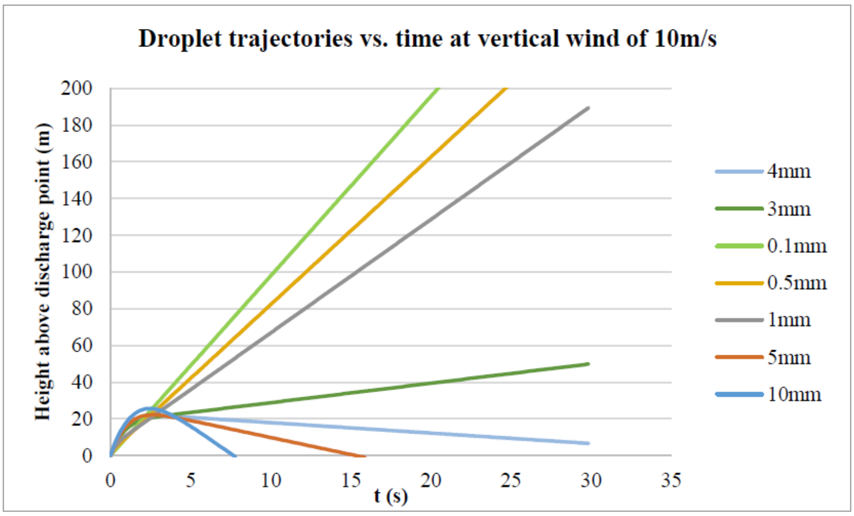


Figure 5. Trajectories of droplets with air drag in a vertical flow of 10 m/s. See the transition when the droplet size varies from 3 mm to 4 mm.

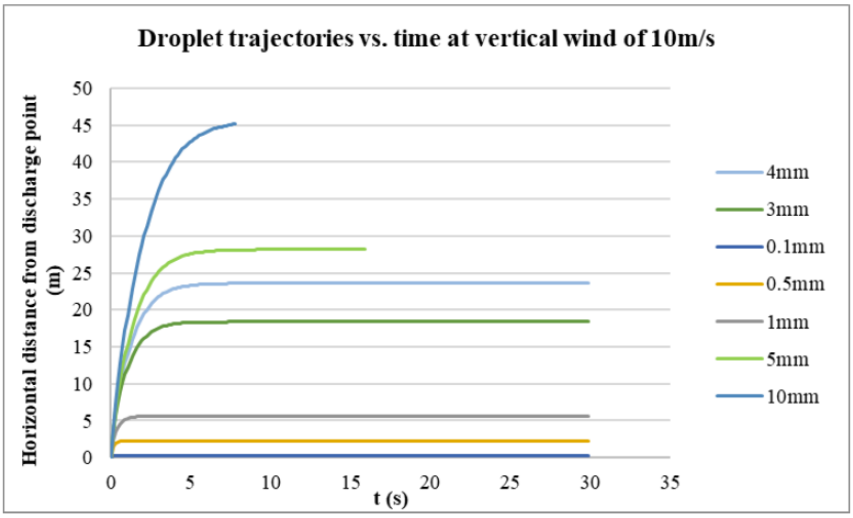
Note that if the velocity of vertical flow caused by combustion and buoyancy force is higher than 10 m/s (probably true at a higher location and at a later moment), the rising height and the duration can be much greater.

Trajectories of droplets – Spray angle

If the droplets are discharged at an angle of 45° from the ground, the results for heights are similar but the droplets also travel horizontally. See Figure 6. Large droplets will be thrown far horizontally but lower at height and finally they will fall. Small droplets are carried away by the wind, so mainly following the path of wind.



(a) Height above discharge point



(b) Horizontal distance from discharge point

Figure 6. Trajectories of droplets with air drag in a vertical flow of 10 m/s. The droplets are discharged into the air flow at an angle of 45° from the ground.

Trajectories of liquid fuels in this accident

Comparing the cracks of the three transformer oil tanks and the severity of the train locomotives, it is very probable that the main discharge of liquid fuel comes from the transformer oil tank of the locomotive of the passenger train.

The above analyses indicate that if droplet sizes are smaller than 4 mm, the trajectories are strongly influenced by the flows, e.g., the horizontal flows and the vertical flow. Note that in this accident, most of droplets are probably smaller than 4 mm, as described in Section 3.1.3.

After the collision, the freight train derailed but continued to move towards the bridge/tunnel (south) and the passenger train crashed, derailed but continued to move towards the north. Some of the droplets discharged into the air close to the collision point will probably be forced to move to the south by the freight train and some will be forced to move to the north by the passenger train carriages. As the fuel was ignited immediately after the collision and the arc, the combustion of the droplets can thus be observed as moving towards two horizontal directions, besides the vertical movement. This is consistent with the observations from the videos and the existing findings.

3.1.5 Combustion of the fuel dispersed in the surroundings

There could be many ignition sources existing at the site. Note that the electric trains use high voltage electricity (25 kV). From one of the videos, it can be found that there was a very bright light after collision (cold colour), probably a strong electric arc. After the bright light, the combustion certainly started (warm colour). The observed ignition occurred immediately after the collision, about 3/10 seconds, which however can be earlier as the ignition of a small volume of combustible mixture may not be well observed from the videos that we have. There are probably some arcs existing at the moment of ignition. The mechanical force and friction may also produce sparks sufficient for ignition. Moreover, it should be noted that in the surroundings, not only liquid droplets but probably also some gaseous silicon oil exist, which facilitates the ignition. For combustible gases, which could be released from ruptured transformer tanks, small ignition energy is required to ignite it. Afterwards, the combustion can further develop if proper fuels are nearby.

The origin of the fireball comes from a location close to the ground, as observed from the videos. In this scenario, the combustibles are millions of liquid droplets sprayed out of the transformer container with a high initial velocity. They may probably be distributed along a certain direction in accordance with the initial spray direction, but may also hit some objects and thus be distributed evenly around. They mix with the surrounding turbulent air and form combustible mixture. They are highly influenced by the wind prior to ignition.

At the beginning, the combustion of vapor and fine droplets probably dominated. The combustion heat contributed to heat up the liquid droplets further and more vapor would be produced, contributing to further combustion.

The fireball will sustain when there is fuel and oxygen mixture. It disappears after the fuel burns out or some large liquid drops or volumes leave the fire cloud. In the mixture cloud, the fireball continues to develop outward and push unburnt droplets further away (fine droplets will be carried away by flows, as shown above), thus increasing the size of the fireball.

There could be two methods to estimate the dimensions of the fireball.

The first method is the possible droplet trajectories. From the analysis of the spray trajectories, it is known that the fine droplets are carried away by the winds while the large droplets (larger than 4 mm) are more influenced by its initial conditions. It should, however, be noted that during the combustion, large droplets will probably become small droplets due to vaporization, and thus becomes easier to be carried away by the flows. The ignition took place right after the collision (estimated to be 3/10 seconds after the collision indicated by the strong arc). At the ignition moment, the radius of the cloud (spray length of the droplets) is about 7 m (Figure 3). Within it, the vapors released from the tanks are expected to also exist. However, three transformer tanks ruptured in this accident and the directions of sprays may probably vary although unknown. In other words, an hemisphere larger than 7 m in radius is expected to exist at the ignition moment. As a comparison, at 1 second, the cloud full of droplets of various sizes is probably about 20 m (Figure 3 and Figure 4), for one transformer tank. Note that after ignition, the combustion or deflagration will push flows outward, acting similar to a wind for those unburnt droplets. This area continues to increase and the fireball expands until the fuel burns out or some large liquid drops or volumes leave the fire cloud. These large drops or volumes may still be burning after they leave the fireball. This is partly confirmed by the videos where flying burning objects can be found although some of them are considered to be solid objects.

The second method is to find some hints from the location and dimensions of the fireball, while this only shows the trajectories of the fuels where they have ever been during the combustion, different to where they could have travelled in case of no combustion. See information in Section 3.1.5.

3.1.6 Fireball

The fireball was registered by cameras. The height was estimated to be around 79 m. It needs to be pointed out that the fireball was recorded by cameras in the evening. Under such conditions, the boundaries of the fireball are usually overestimated, especially at the early stage with bright flames (not sooty flames as observed at the last stage).

The fireball diameter is usually calculated based on the flame volume assuming stoichiometric combustion of the fuel. This method is widely used in estimation of diameter of fireballs caused by pressurized tank rupture and BLEVE [10]. The scenario considered here is neither a pressurized tank rupture or BLEVE. However, this could give a rough estimate of the possible fireball dimension. A check on the fire chemistry of the silicone oil shows that their stochiometric mixing ratio is similar to common hydrocarbons. A rough estimation gives a fireball dimeter of 73 m with a duration of about 6 seconds for 2 tons of typical hydrocarbon fuels. If the fuel is 1 ton, the estimated fireball diameter is 58 m and the duration is 4.5 seconds. However, it should be noted that the estimated fireball diameter is based on the assumption of stoichiometric mixing of fuel and air [11]. For a fuel rich scenario such as a tank rupture or a BLEVE, this is usually a good assumption. However, in this accident, the cloud is probably not stoichiometric, and a more probable case could be fuel lean. If so, the fireball dimension in this accident is expected to be much larger than the calculated fire diameter or volume based on the assumption of stoichiometric mixing of fuel and air, and the actual duration of fireball will also be longer. It is believed that even if the fuel is 1 ton, it is possible to produce such a large fireball in case of a fuel lean combustion. Therefore, the calculation results are consistent with the observations.

3.1.7 Consequences of possible blast waves

In this scenario, as the tank pressure is considered low, there will be no strong blast waves at the moment of tank rupture.

The combustion within the fireball may result in a blast wave. The strength is related to the flame speed. From the videos, the flame speed appears to be low, and it is therefore not expected to be affiliated with a strong blast wave. The low flame speed is probably because the combustion was fuel lean, at least at the early stage.

In other words, the blast wave strength is weak and not expected to cause significant damage or harm to the surrounding train carriages and personnel. This is consistent with the observations that no awareness of explosion was registered from the interviews after the accident.

Therefore, the consequences of Scenario 1 are consistent with the observations, both in terms of the fireball and the possible blast waves.

3.2 Scenario 2: BLEVE of the transformer oil tank

In this scenario, it is assumed that the liquid temperature is higher than the flash point and boiling temperature. Rupture of a tank containing such fuel, i.e., a crack formed on the container, results in a BLEVE. A BLEVE is characterized as the rupture of tank containing hot liquids, followed by a fireball.

There is no information about the boiling temperature of the silicon oil used in the transformer. There is also no information about latent heat of vaporization of the silicon oil used in the transformer. The manufacturer's product sheet shows various types of silicon oil which refer to a flash point within a large range. It is probably unreliable to use data from other literature for this calculation. There is also no information about the actual liquid temperature of the silicon oil in the transformer at the moment of collision. It is therefore not possible to give any accurate estimate of the consequence in this scenario. In the following part, we make some assumptions to give a rough estimate of the blast wave strength using Prugh's method [12, 13].

The assumptions for the calculations:

- Different amounts of liquid fuels are vaporized after the rupture of the container, i.e., a flash fraction of 25%, 50% or 100%. Note that 100% tends to be conservative, as some fuels remained in liquid form and sustain its burning on the ground after the fireball according to the observations of the accident.
- The tank rupture pressure is assumed to be 20 bar. This value is chosen based on the values for other fuel tanks.
- The liquid temperature is 450 °C, i.e., about 50 °C above the boiling temperature.
- Molecular weight of density of silicon oil vapor is assumed to be 74.15 kg/kmol [14]. This is used to estimate the vapor density, which is about 2.6 times that for air.
- Blockages of train carriages and winds are not considered.

The blast pressures are shown in Figure 7. The blast pressure decay rapidly with distance within the first 10 m – 20 m. At 10 m from the tank, the blast pressure is 50 kPa, 70 kPa and 100 kPa, respectively.

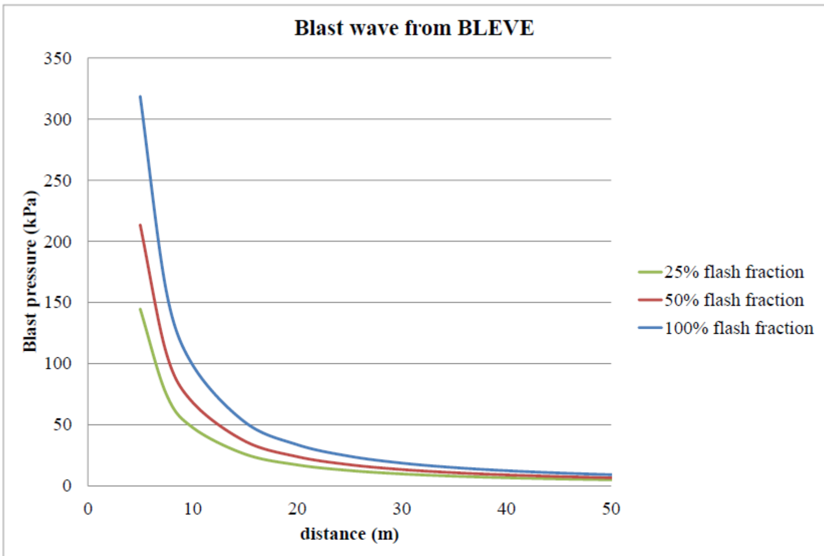


Figure 7. Blast pressures from BLEVE of the transformer container based on the assumptions mentioned above.

In case that one transformer container underwent a BLEVE, the resulting maximum fireball diameter is estimated to be about 78 m, with a duration of 6 seconds, assuming stoichiometric mixing. This correlates reasonably well with the observation. This, however, is not the only evidence to consider, as a BLEVE results in not only a fireball but also an explosion when the tank ruptures.

Note that modern train windows usually resist a blast wave of about 50 kPa or more. This means if the train carriage is more than 15 m away from the site, the windows will probably remain their integrity.

The incidents with blast pressures shown in Figure 7, should have produced loud sounds. However, according to the interviews of the survivors after the accident, there was no sign of explosion.

More importantly, the precondition for a BLEVE is that the liquid should have a very high temperature, i.e., certainly higher than the boiling temperature of the silicon oil, which is about 400 °C. By contrast, the operating pressure is supposed to be about 90 °C. This indicates for a BLEVE to occur, the transformer must have had a serious failure prior to the accident. This may probably cause malfunction of the transformer as one key function of these oil is to remove the heat generated during the operation of the transformer. Note that it is considered almost impossible that all the transformers contain very hot liquid inside and underwent a BLEVE. So while calculating the blast pressures form BLEVE, only one tank was considered.

In summary, in this scenario, the estimated fireball diameter correlates reasonably well with the observations, but there was no sign of explosion from the interviews of survivors, which is inconsistent with the blast wave analysis. More importantly, the precondition for a BLEVE is that the liquid must have a very high temperature, i.e., higher than the boiling temperature of the silicon oil of about 400 °C. If the evidence "no sign of explosion" is reliable, this scenario can probably be excluded.

4. Summary

This report presents results from an investigation of the Tempi accident with a focus on the fireball. Different scenarios are considered and the most probable scenario has been identified and verified using the existing most reliable information.

The most probable scenario refers to the combustion of atomized silicon oil droplets rapidly discharged from the transformer containers of the train locomotives through cracks after the collision. The atomization of droplets, i.e., the process of a volume of liquid becoming a large number of liquid droplets, is due to the high momentum of the liquid fuels in the tank at the moment of collision. After the passenger train was forced to stop or closely stop and its velocity suddenly decreases from 41 m/s to a small value close to 0, the silicone oil still contained the initial momentum and energy. If there was no rupture of the transformer container, this energy would have been dissipated within a certain period, assuming the transformer container can withstand its integrity in the accident. However, if the container of silicone oil (transformer tank) ruptured immediately after the collision due to mechanical forces (probably the case in this accident), the liquid fuel will be splashed or sprayed out of the container. This is mainly due to the fact that the dynamic energy of the silicone oil cannot be dissipated instantaneously. In such case, much of the liquid would spray out with a high initial velocity. Besides the liquid splashed and sprayed out, a certain amount of gaseous silicone oil that was produced under normal operation conditions is expected to have also escaped from the container. This amount of gaseous fuel is combustible and easier to ignite than the fuel in liquid form, and may probably play a key role at the ignition stage. The silicon oil discharged from the small cracks with high initial velocities will undergo atomization and become fine droplets within a short distance from the cracks. These droplets were exposed to strong wind at the site, and they may probably hit some objects after they were discharged, both of which usually make the droplet size become much smaller. Note that this also applies to the silicon oil discharged from the two transformers of the freight train, but the contribution from the freight train is considered to be lower due to the lower velocity and the less cracks. It is believed that large amounts of fine droplets were distributed at the site within a very short period of time after collision. The ignition of the fuel occurred immediately after the collision, probably due to the strong arc, arcs remaining after the strong arc, or sparks or heat due to the collisions. The combustion spread within the combustible cloud and the key direction of flame movement is vertical due to both combustion expansion and buoyancy force. The vertical flow pushes the unburnt liquid droplets further up (increase the size of cloud), and results in faster flame spread within the cloud. The combustion is also highly influenced by the horizontal flows towards the south induced by the freight train and the horizontal flows towards the north induced by the passenger train. Both flows carry liquid fuel droplets away, ignition of which shows the flames are moving as observed in videos. This scenario does not result in a severe explosion, consistent with the information collected from the accident. Therefore, the consequences of Scenario 1 are consistent with the observations, both in terms of the fireball and the possible blast waves.

The possibility of a BLEVE of transformer oil tank is very low. If the evidence “no sign of explosion” is reliable, this scenario can probably be excluded. A BLEVE results in both a fireball, and an explosion due to the tank rupture. The estimated fireball diameter correlates reasonably well with the observations, but there was no sign of explosion from the interviews of survivors. More importantly, the precondition for a BLEVE is that the liquid must have a very high temperature, i.e., higher than the boiling temperature of the silicon oil, which is about 400 °C. By contrast, the operating pressure is supposed to be about 90 °C. This indicates for a BLEVE to occur, the transformer must have a serious failure.

To sum up, from the current evidence, the most probable scenario for creating the observed fireball is the combustion of atomized silicon oil droplets rapidly discharged from the transformer containers of the train locomotives through cracks after the collision.

Key limitations and possible future work are listed in the Appendix.

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Appendix – Limitations and possible future work

The following issues may need further considerations:

- Investigation of ignition and combustion of silicone oil clouds with different droplet sizes at various temperatures using different ignition sources helps to improve the understanding of the phenomena.
- The amounts of fuel that sprayed out of the transformers are not clearly known. It was considered that a significant amount of fuel sprayed out of the transformer of the passenger train and a less amount sprayed out from the transformers of the freight train. The trajectories of the transformer of the passenger train may also have influences on this parameter.
- Quantification of droplet sizes from the atomization processes improves the understanding of the phenomena (primary atomization and secondary atomization).

RISE Research Institutes of Sweden AB
Fire and safety - Societal Safety

Performed by

Ying Zhen Li

Examined by

Tove Mallin

Verifikat

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Signerare

Ying Zhen Li (YZL)
RISE Research Institutes of Sweden AB
Org. nr 556464-6874
yingzhen.li@ri.se
+46 10 516 58 29

Signerade 2024-12-10 13:36:25 CET (+0100)

Tove Malin (TM)
RISE Research Institutes of Sweden
tove.mallin@ri.se
+46 10 516 55 67

Signerade 2024-12-10 13:44:46 CET (+0100)

Όπως αναφέρεται στο Παράρτημα της έκθεσης (Appendix – Limitations and possible future work), απαιτείται περαιτέρω διερεύνηση της συμπεριφοράς της εκνέφωσης με διαφορετικά μεγέθη σταγονιδίων, σε διαφορετικές θερμοκρασίες και με διαφορετικές πηγές αρχικής ανάφλεξης ώστε να εκτιμηθούν καλύτερα οι πιθανότητες για κάθε διαφορετική περίπτωση. Επιπλέον, αναφέρεται ότι η ποσότητα του καυσίμου (ελαίου σιλικόνης) που συμμετείχε στο φαινόμενο της δημιουργίας νέφους δεν είναι γνωστή και γι' αυτό έγινε μια εκτίμηση ότι "σημαντική" ποσότητα από τον μετασχηματιστή της επιβατικής και "μικρότερη" ποσότητα από τους μετασχηματιστές της εμπορικής συμμετείχαν στην εκνέφωση. Επίσης, η επιβεβαίωση των διαμέτρων των σταγονιδίων (μέσω περαιτέρω διερεύνησης) θα βοηθούσε στην καλύτερη κατανόηση των φαινομένων.

Από τις παραπάνω εκπεφρασμένες επιφυλάξεις της τεχνικής έκθεσης και σε συνδυασμό με την αδυναμία της έκθεσης να δώσει συγκεκριμένες εξηγήσεις σε παρατηρηθέντα φαινόμενα (μηχανισμό τροφοδοσίας της πυρόσφαιρας μετά τα πρώτα 2 δευτερόλεπτα, ποσοτικοποίηση συνολικών μαζών, διαπίστωση αρχικής αιτίας έναυσης του αερολύματος, μετεωρολογικές συνθήκες διαφορετικές από τις επικρατούσες κλπ), θεωρήθηκε σκόπιμο να γίνει προσπάθεια περαιτέρω διερεύνησης των ανοικτών ζητημάτων στα οποία δεν είχε δοθεί κατηγορηματική απάντηση.

(485) Επιπροσθέτως των ανωτέρω, ο ΕΟΔΑΣΑΑΜ επικοινώνησε με τον κ. Κωνσταντόπουλο, Καθηγητή Χημικών Μηχανικών (Νέες Προηγμένες Καθαρές Τεχνολογίες Καύσης) του Αριστοτελείου Πανεπιστημίου Θεσσαλονίκης, με ερωτήσεις σχετικές με την πιθανότητα σχηματισμού εύφλεκτου μίγματος αερολύματος από λάδι σιλικόνης ως άμεση συνέπεια της σύγκρουσης. Ο καθ. Κωνσταντόπουλος προσέφερε μια σύντομη τεχνική έκθεση για τα επίμαχα ζητήματα. Σύμφωνα με αυτή, δεδομένου του κατά προσέγγιση χρόνου 0,4 δευτερολέπτων για την αρχική ανάφλεξη και ανάπτυξη της πυρόσφαιρας, δεν υπάρχει ρεαλιστικός τρόπος για μια τέτοια μεταφορά ενέργειας και ανάφλεξη και καύση λαδιού σιλικόνης να συμβούν, στο δεδομένο χρονικό πλαίσιο και με το δεδομένο ρυθμό ανάπτυξης της πυρόσφαιρας. Περαιτέρω, ο καθ. Κωνσταντόπουλος υπολόγισε την ποσότητα της λευκής σκόνης (διοξείδιο σιλικόνης, $SiO2$) που θα είχε σχηματιστεί μετά την καύση 2,4 μετρικών τόνων ελαίων σιλικόνης, σε 1,94 μετρικούς τόνους, οι οποίοι δεν παρατηρήθηκαν στο σημείο του ατυχήματος.

Αναλυτικά **(2.ε της παραγγελίας σας)** :

ARISTOTLE UNIVERSITY OF THESSALONIKI
School of Engineering – Department of Chemical Engineering
Aerosol and Particle Technology Laboratory
Building D, School of Engineering, University Campus, 54124 Thessaloniki, Greece
Tel.: +306956200018 e-mail: agk@auth.gr

Athanasios G. Konstandopoulos, PhD, KLH
Professor

February 24, 2025

To
Dr. Christos Papadimitriou
National Aviation and Railway Accidents
Investigation and Transport Safety Authority,
Vitinis 14-18, N.Filadelfeia, 14342, Athens

Subject: Your Feb 19, 2025 request for opinion on questions regarding the Feb 28, 2023 Tempi Railway Accident Fireball

Dear Dr. Papadimitriou,

Please find attached a short document with my answer on the question you posed i.e. whether the transformer silicone oils could be the cause of the observed fireball along with a number of additional remarks. You may consider the document as DRAFT due to the short time available to prepare it and I am available to address any of your comments and include them in a future revision.

In short, my answer to your question as explained in detail in the document is:
Although the employed silicone oil can be combusted at appropriately high temperature (as stipulated in its specification brochure) its ignition and combustion could not possibly occur within the given timeframe of the fireball generation, due to insufficient time for the required reaction kinetics. Furthermore, the absence of white dust (Silicon dioxide, SiO_2) at the scene of the accident, in quantities that would justify the combustion of a large quantity of silicone oil and the resulting combustion aerosol generation, is another clear indication that such an occurrence did not take place. Hence, the origin of the fireball consistent with a few tons of a flammable volatile compound needs to be searched elsewhere.

Sincerely

Athanasios G. Konstandopoulos, *PhD, KLH*

EXPERT OPINION ON THE TEMPI RAILWAY ACCIDENT:
Transformer Oil and Fireball

Athanasios G. Konstandopoulos, *PhD, KLH*
Professor of Chemical Engineering – Aristotle University, Thessaloniki, Greece
agk@auth.gr

1. Background

On Feb 28, 2023 a collision of a passenger train and a freight train occurred near Tempi, producing within fractions of a sec (~0.4 sec) a large fireball (~20 m in diameter) in the external to the trains free space (of environmental temperature 8-10 C) from an unknown volatile flammable substance, which upon further growth (in two additional stages after the first ignition, moving and feeding on the unknown volatile flammable substance) reached its maximum size (~80 m) and consumed its fuel within ~10 sec from inception. The fireball induced subsequent fires in the wagons of the trains, claiming the lives of 57 passengers and resulting in 180 injuries.

HARSIA based on its own search for experts, has requested on Feb 19, 2025 my opinion on the question whether silicone transformer oils (Bayer Baysilone M50 EL Flash point: > 300 °C /Fire point: > 350 °C) existing in all trains involved in the collision, could create the observed fireball (recorded by 3 independent video cameras) as well as any other information I deemed relevant along with a scientific explanation.

I am a Professor of Chemical Engineering at Aristotle University of Thessaloniki (AUTH) with 40 years of professional and research experience in combustion and aerosol processes. The opinions expressed in the present document are of my own and do not reflect in any way the views of Aristotle University.

Given the short time available to me from the initial HARSIA request to the requested day of submission of the present documetn (Feb 24, 2025) I will not include here known facts about the Tempi accident that have become publicly available and I have used them in preparing the present document. I remain available to refer to them explicitly should a relevant request arise.

2. Silicone Oil Fate – Transformer Cracks

All 3 transformers (1 on the passenger train and 2 on the freight train) after the collision exhibited fractures, attributable to impact of the transformer on external bodies, based on the shape and direction of metal sheet deformations and fractures. The transformer of the passenger train (PT1) exhibited the larger damage with several large cracks of large aspect ratio (50cm x 10cm, 30cm x 20cm, 15cm x 2cm, 12cm x 4cm) and a hole of 4 cm. The transformer of the 1st locomotive of the freight train (FT1) exhibited a crack of 22 x 25 cm, while the transformer of the 2nd locomotive of the freight train (FT2) exhibited a crack of 10 x 15 cm and a hole of 7 cm. All transformers were recovered from the accident and exhibited no signs of melt-down or other exposure to ultra-high temperatures. Some residues of ash (white powder) and soot (black powder) were seen around some cracks/holes, apparently due to the localized combustion of the silicone oil spilling out.

As mentioned, the PT1 transformer had experienced the higher damage (its engine wagon was derailed and tumbled in the slope next to the rail lines) while those of the freight train (FT1 and FT2) exhibited less damage. It is clear from the cracks that a significant amount of the transformer oil has been spilled in the area, post impact. Considering that overall there are 3 x 2400 kg of oil and the different time history of each transformer post impact, it is difficult to estimate with accuracy the rate of spillage and hence the time it took for it to occur. Simple order of magnitude estimates indicate that within the 10 sec of the fireball lifetime only a small (some 10s of kg) amount of transformer oil could spill out. We will return to this point later, in Section 4.

3. Aerosol Generation

Transformer oil spilled from all transformers. The possibility of an aerosol spray generation though seems to be more likely to happen from the PT1 transformer which was exposed to more violent impacts. All transformers contain 2400 kg of transformer oil.

Aerosol generation requires sustained fluid jets emanating from the cracks, which subsequently would disintegrate at their edges due to fluid mechanical instabilities (somewhat similar in a broad sense to the water jets that the firefighters use) and produce droplets of sizes that depend on the nozzle opening (here the crack, which in a broad sense acts as a slit-nozzle or the hole apertures that can be approximated by circular nozzles), the fluid surface tension, the viscosity of the liquid, the jet velocity at the exit and the fluid density, as these parameters determine the dimensionless numbers that govern the phenomenon, namely the Weber number and the Ohnesorge number.

The Weber number defines the balance between inertia and surface tension, determining if a jet remains stable or breaks into droplets:

$We = \rho U^2 D / \gamma$

Where:

- U = jet velocity (m/s)
- D = nozzle diameter (m)
- ρ = fluid density (kg/m^3)
- γ = surface tension (N/m)

The Ohnesorge number (Oh) measures the relative influence of viscosity to surface tension:

$Oh = \mu / \mathrm{sqrt}(\rho \gamma D)$

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Where:
- μ = dynamic viscosity (Pa·s)
- ρ = fluid density (kg/m³)
- γ = surface tension (N/m)
- D = characteristic diameter of the jet (m)

These numbers define various operating areas of traditional spray systems (ie those that are based on well defined nozzles, operated under pressure with or without air-assist dispersion). The large sizes of the cracks observed in the transformer casing point to larger "droplet" sizes (better described as "splashes") that upon the influence of the prevailing fluid mechanical environment may break down to smaller sizes.

At this stage we need to assemble the rheological properties of Bayer Baysilone M50 EL at the operating temperature of 90 °C. We will also compare these to those of water in order to have a better intuition of the phenomenon of aerosol generation.

According to the Baysilone Fluids M technical brochure (https://dcproducts.com.au/wp-content/uploads/2020/12/BayerBaysiloneFluidsBrochure.pdf) , the kinematic viscosity (ν) of a 50 cSt silicone fluid (like the Bayer Baysilone M50 EL) at 50 °C is 30 mm^2/s (cSt), and at 100 °C, it is 16 mm^2/s (cSt). Interpolating between these values, the kinematic viscosity at 90 °C would be approximately 18.8 mm^2/s (cSt). The Bayer Baysilone M50 EL consists of only PDMS (Polydimethylsiloxane). The density is given as 960 kg/m^3 at 25 °C, 900 kg/m^3 at 100 °C and 840 kg/m^3 at 175 °C and upon interpolation and application of $\mu = \rho\,\nu$ we obtain the dynamic viscosity as well, as shown in the Table below.

Temperature (°C)	**Kinematic Viscosity (cSt), ν**	**Density (kg/m^3), ρ**	**Dynamic Viscosity (mPa·s or cP), μ**
50	30	940	28.2
90	18.8	908	17.07
100	16	900	14.53

The surface tension of Bayer Baysilone M50 EL is 19 to 21 mN/m at 25 C and decays linearly with temperature [Sauer, B. B.; Dee, G. T. Molecular Weight and Temperature Dependence of Polymer Surface Tension: Comparison of Experiment with Theory. Macromolecules 1991, 24 (8), 2124– 2126, DOI: 10.1021/ma00008a070] approximately to 14 mN/m at 90 °C. For comparison the data for water at 25 °C are [https://en.wikipedia.org/wiki/Water_(data_page)]

Property	Water	Bayer Baysilone M50 EL
Dynamic Viscosity	0.890 cP	17.07 cP
Density	997 kg/m³	908 kg/m³
Kinematic Viscosity	0.8937 cSt	18.8 cSt
Surface Tension	71.97 mN/m	14 mN/m

As the oil is more viscous but with lower surface tension than water we cannot readily conclude on its atomization potential vs water in general. At high velocities when inertia is important we expect it to be more easy to atomize than water, however in this case the pumping energy (ie the pressure needed) will be much higher due to the viscosity difference.

Based on these considerations we can proceed by considering the generation of a transformer oil aerosol as a possibility and anticipate the droplet sizes to be in the mm range. As we are interested in a parametric study we will consider transformer oil droplet sizes from 10 micron to 4 mm and study their lifetime as a function of environmental temperature.

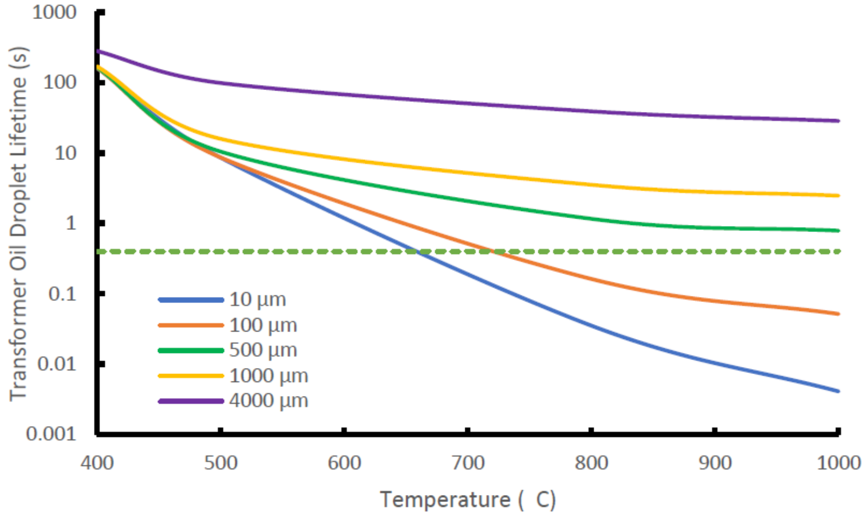
4. Transformer oil thermal oxidation

Despite the fact that the transformer silicone oil has a very high flash point and no past incidents are available in the literature to demonstrate ignition of the particular oil (PDMS) in open space and low (~10 C) environmental temperature, we examine the conditions for thermal oxidation of the silicone oil in order to generate the observed fireball.

The thermal oxidation of PDMS has been studied with Thermogravimetric Analysis in [G. Camino, S.M. Lomakin, M. Lazzari, Polydimethylsiloxane thermal degradation Part 1. Kinetic aspects, Polymer 42 (2001) 2395–2402, https://doi.org/10.1016/S0032-3861(00)00652-2]. We have extracted the data from this paper and fitted an Arrhenius model to describe the kinetics of the thermal oxidation of PDMS. Then the kinetic model of the droplet thermal oxidation is combined with a heat transfer model for the heating of the droplet and the coupled heat transfer-reaction kinetics differential equations are solved until the droplet vanishes, at which point we define the "droplet lifetime" in the particular environment of a given temperature.

We have run parametric studies of the numerical model for temperatures of 400, 500, 800 and 1000 C and droplet sizes from 10 μm, 100 μm, 500 μm, 1000 μm and 4000 μm. The results are shown in the following Figure. The dotted line at 0.4 sec serves to remind us that by that time the fireball had developed, so lines above the dashed line cannot have lead to the development of a fireball.

For the very small droplet sizes 10 μm and 100 μm thermal oxidation is possible if they encounter an environment much hotter than 650 C and 700 C respectively. In this assessment we make the ultra-conservative assumption that the droplet lifetime is the time needed for the droplet material to react completely (actually it degrades in the hot environment producing the D3, D4 and D5 volatile compounds).



Considering the time that was required for the fireball to appear (0.4 sec) there is a need to justify the existence of a homogeneous/constant "hot environment" of at least 650 °C from the beginning of the accident into which hypothetical aerosols of fine droplets of 10 μm and 100 μm would have been exposed and burned. All larger and more plausible droplet sizes need much more time (several times) than 0.4 sec leading to the conclusion that they would not form a fireball.

In other words, the calculations of the PDMS droplet lifetimes assume the existence of a hot temperature environment of varying temperature (400 – 1000 °C), but in practice the existence of such an environment and the presence of the droplets in it during the initial 0.4 sec needs to be independently proven.

It is instructive to consider the possibility of ignition of the entire silicone oil (2400 kg) in the transformer. To this end we calculate (see Appendix 1) the fraction of oil mass needed to be burned in order to bring the temperature of the remainder oil mass in the transformer to a temperature of 400 °C where thermal degradation/oxidation of the oil sets in.

The results from Appendix 1 indicate that at least a mass of ~43 kg of spilled (cf. Section 2) transformer oil is required to burn in order to increase the temperature of the remaining oil from 90 °C to 400 °C. If we assume that this mass is spilled over the metallic surface of the transformer container and provides its heat to the rest of the mass without any losses, we can pose the question: how fast can it be heated in order to burn and promote the ignition of the rest of the oil?

The energy required to heat the 43 kg from 90 to 400 °C is approximately 20 MJ or 5.56 kWh. This implies that even with an industrial high power High-Energy Plasma or Arc Heater of 500 kW it would take about 40 sec to heat it, much longer than the emergence of the fireball.

5. The missing SiO_2 if the transformer oil were responsible for the fireball

In the previous paragraphs we came to the conclusion that the ignition and duration of the fireball is very fast, a feature that makes it impossible for the transformer oil to spill/splash, generate an aerosol of fine droplets, ignite and sustain a fast combustion giving rise to the fireball.

However, in the highly improbable case that this would have occurred, a huge amount of SiO_2 powder would be covering the area as the residue of PDMS combustion as explained below.

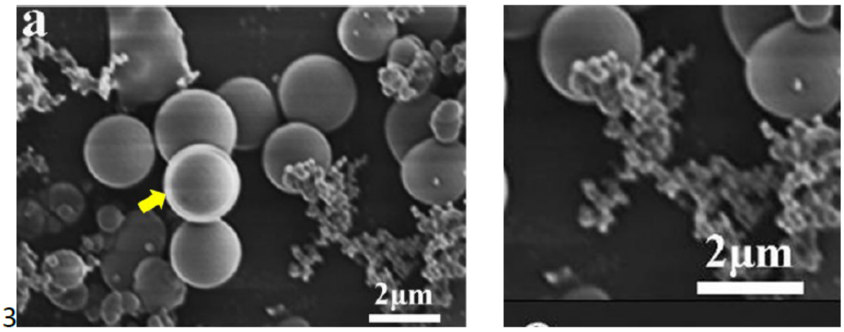
Polydimethylsiloxane (PDMS) contains silicon (Si) as a key component, along with oxygen (O), carbon (C), and hydrogen (H). When PDMS burns in the presence of oxygen (O_2), the carbon and hydrogen form CO_2 and H_2O, while silicon oxidizes to form silicon dioxide (SiO_2).
PDMS has the general chemical formula: $(CH_3)_3SiO(CH_3SiO)_nSi(CH_3)_3$.

For simplification, we use the basic repeating unit of PDMS to calculate the amount of SiO_2 generated: $[SiO(CH_3)_2]_n$.

- Molecular Mass of basic repeating unit =28.085+16.000+24.022+6.048 =74.155 g/mol.
- Si Fraction=28.085/74.155 = 37.85% of PDMS mass is silicon, meaning in 1000 kg of PDMS, there is ~378.5 kg of Si available for oxidation.
- The rest of the PDMS mass (~63%) is carbon (C), hydrogen (H), and oxygen (O), which upon burn-off they become CO_2 and H_2O.
- Each kg of Si then forms ~2.14 kg of SiO_2.

To obtain an idea on how thermally oxidized/burned PDMS residue (SiO_2) looks like we can draw from the work of [K. Ding, X. Shi, C. Li, X. Gao, J. Han, H. Wang, H. Dou, J. Pan, Study on the combustion products of dimethyl silicone oil as anode materials for lithium ion batteries, Int. J. Electrochem. Sci. 13 (2018) 10859–10872.] where PDMS is combusted for that very purpose: to generate SiO2 particles that would subsequently be employed as anode materials in batteries.

This is another aspect of Aerosol Technology where we on purpose try to synthesize useful materials, frequently employing “raw materials” that are developed for other applications (here PDMS whose high temperature resilience offers unique advantages in the synthesis procedure).



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It is interesting to observe the well known to aerosol and particle technologists morphologies: Single spherical particles (micron sized) and "fluffy" aggregates of nanoparticles (shown in detail on the right).

Notice that some of the spherical particles feature a "denser" skin (shown as whiter region due to higher density in the electron microscopy photograph on the left with a yellow arrow). This layer forms as PDMS undergoes thermal degradation, offers a barrier to oxygen diffusion and assists in the overall thermal resilience of PDMS.

Burning 1000 kg of PDMS results in ~791.8 kg of SiO_2 ash/residue, hence the 2400 kg of transformer oil would produce approximately 1.94 metric tons of silicon dioxide (SiO_2) as combustion residue, which would be dispersed over all surfaces and give a characteristic white, dusty texture everywhere. This was not observed at scale, except for a few very localized areas where transformer oil was burned.

It is my opinion therefore, that no ignition of transformer oil occurred within the initial 0.4 sec that the fireball was generated and no contribution of the transformer oil into the initial fireball generation exists.

I would also like to remark that a quantity of 1.94 metric tons of SiO_2 released within the area of the accident would have generated an enormous exposure of the people on the scene to SiO_2 particles and at levels that are many times higher than the USA, Occupational Safety and Health Administration (OSHA) Permissible Exposure Limits for SiO_2 (Appendix 2).

I am not aware of any biological or toxicological study that would examine if such a massive exposure had occurred and whether it modulates potential future health impacts of the accident on survivors, since SiO_2 is responsible for a number of adverse health impacts of the respiratory system (e.g. silicosis, cancer, chronic obstructive pulmonary disease) as well as kidney disease [https://www.osha.gov/silica-crystalline/health-effects].

6. Fireball

The observed final size fireball (80 m) using the computational tools of the U.S. Nuclear Regulatory Commission [https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/s1/index.html] is found to be consistent with a mass~ 2600 kg of flammable fuel of vapor density 3.35 kg/m^3 and a duration of 8.5 sec. These are order of magnitude estimates that fall very close to those reported publicly. For more precise calculations the method of Computational Fluid Dynamics (CFD) are recommended. For reference, vapor densities of some volatile flammable compounds are given below and it is clear that there are many potential mixtures that can match the volatility of the observed fireball.

Compound	Vapor Density (kg/m^3)
Acetone	2
Benzene	2.8
Gasoline	3.49
Hexane	3
Toluene	3.1
Xylene	3.7

7. Conclusions

The large fireball at the Tempi railroad accident that occurred within 0.4 sec from the collision of the trains, cannot be attributed to the transformers oil (PDMS) which although combustible at sufficiently high temperatures (as stipulated by its technical specification document > 400 °C) it could not have ignited in the prevailing environment during the 0.4 sec that the fireball occurred due to insufficient time for the required reaction kinetics.

Furthermore, the absence of white dust (Silicon dioxide, SiO_2) at the scene of the accident, in quantities that would justify the combustion of a large quantity of silicone oil, is another clear indication that such an occurrence did not take place.

Hence the origin of the fireball consistent with a few tons of a flammable volatile fuel needs to be searched elsewhere.

APPENDIX 1

Calculation of PDMS Mass Required to Burn in order to Heat Remaining Mass to 400°C

1. Introduction

This Appendix provides the calculation for determining the mass of PDMS from the total 2400 kg that must burn in order to raise the temperature of the remaining mass from 90°C to 400°C using the energy balance equation.

2. Given Data

Total PDMS mass: $M_{total} = 2400$ kg
Final Temperature: $T_{final} = 400$°C
Initial Temperature: $T_{initial} = 90$°C
Specific Heat Capacity of PDMS: $Cp = 1500$ J/kg·K
Heat of Combustion of PDMS: $Hc = 25.65 \times 10^6$ J/kg
[https://technical.gelest.com/brochures/silicone-fluids/conventional-silicone-fluids/]

3. Energy Required to Heat Remaining PDMS

The heat energy required to raise the temperature of the remaining PDMS from 90°C to 400°C is:
$Q_{required} = (M_{total} - M_{burn}) \times Cp \times \Delta T$
$\Delta T = T_{final} - T_{initial} = 400 - 90 = 310$ K
$Q_{required} = (2400 - M_{burn}) \times 1500 \times 310$
$Q_{required} = (2400 - M_{burn}) \times 465000$

4. Energy Balance Equation

The energy released by burning PDMS is:
$Q_{released} = M_{burn} \times Hc$
Setting $Q_{released} = Q_{required}$:
$M_{burn} \times 25.65 \times 10^6 = (2400 - M_{burn}) \times 465000$

5. Solving for M_burn

Expanding the equation:
$25.65 \times 10^6 M_{burn} = (2400 \times 465000) - (465000 \times M_{burn})$
$25.65 \times 10^6 M_{burn} + 465000 M_{burn} = 1.116 \times 10^9$
Factoring M_burn:
$M_{burn} \times (25.65 \times 10^6 + 465000) = 1.116 \times 10^9$
$M_{burn} = (1.116 \times 10^9) / (26.115 \times 10^6)$
$M_{burn} \approx 42.73$ kg

6. Final Answer

Mass of PDMS that must burn: ≈ 42.73 kg
Mass of PDMS remaining after burning: ≈ 2357.27 kg
Total heat required: 1.116×10^9 J

Heat released per kg of burned PDMS: 25.65 MJ/kg

7. Note

This calculation assumes 100% combustion efficiency. For real-world scenarios with heat losses, the result will be a higher mass than 42.73 kg

APPENDIX 2

Air Required for Complete Combustion of PDMS

1. Introduction

This Appendix provides a detailed step-by-step calculation to estimate the amount of air required to completely burn 1 kg of Polydimethylsiloxane (PDMS). The calculation follows mass balance principles and assumes complete oxidation of carbon and hydrogen present in PDMS.

2. Chemical Formula of PDMS

PDMS consists of repeating units of $[(CH_3)_2SiO]$. The molecular mass of one repeating unit is:

Element	Mass Contribution (g/mol)	Percentage
Silicon (Si)	28.085	37.85%
Oxygen (O)	16.0	21.58%
Carbon (C, 2×12.011)	24.022	32.39%
Hydrogen (H, 6×1.008)	6.048	8.16%
Molecular mass	74.155	100%

3. Oxygen Demand for Complete Combustion

Each element in PDMS requires oxygen for combustion according to the following reactions:

1. Carbon Oxidation: $C + O_2 \rightarrow CO_2$

2. Hydrogen Oxidation: $2H_2 + O_2 \rightarrow 2H_2O$

Using the mass fractions calculated earlier:

Carbon Combustion:

C fraction in 1 kg PDMS = 32.39% → 323.9 g of C

$C + O_2 \rightarrow CO_2$ (1 mol C requires 1 mol O_2)

323.9 g of C requires 863.3 g of O_2 (from molar mass ratio 44/12)

Hydrogen Combustion:

H fraction in 1 kg PDMS = 8.16% → 81.6 g of H

$2H_2 + O_2 \rightarrow 2H_2O$ (2 mol H_2 needs 1 mol O_2)

81.6 g of H requires 653.6 g of O_2 (from molar mass ratio 32/4)

Total Oxygen Required:

863.3 + 653.6 = 1516.9 g of O_2

Subtracting the oxygen already present in PDMS (21.58% or 215.8 g):

1516.9 - 215.8 = 1301.1 g of additional O_2 needed

4. Converting Oxygen Requirement to Air Requirement
Since oxygen comprises approximately 21% of air by mass, the total air required is calculated as follows:

Air Required = (1301.1 g O_2) / 0.21

Air Required = 6205.2 g = **6.21 kg of air per kg of PDMS**

5. Result
To completely burn 1 kg of PDMS, approximately **6.21 kg of air** is required, assuming complete stoichiometric combustion.

6. SiO_2 Concentration in Effluent Gas
When PDMS burns, silicon from its molecular structure oxidizes to form SiO_2. The concentration of SiO_2 in the combustion effluent can be estimated based on the total gas mass generated in a stoichiometric combustion process.

Total Mass of Gas Effluent:

Total Gas Mass = Air Used + O_2 from PDMS + SiO_2 Produced

Total Gas Mass = 6.21 kg + 1.30 kg + 1.94 kg

Total Gas Mass = 9.46 kg

SiO_2 Mass Fraction in Effluent Gas:

SiO_2 Mass Fraction = (Mass of SiO_2 / Total Gas Mass) × 100

SiO_2 Mass Fraction = (1.94 / 9.46) × 100 = 20.56%

SiO_2 Concentration in Effluent Gas (kg/m^3):

Assuming the standard density of combustion gases is similar to air i.e. 1.2 kg/m^3:

SiO_2 Concentration = Mass of SiO_2 / (Total Gas Mass / Gas Density)

SiO_2 Concentration = 1.94 kg / (9.46 kg / 1.2 kg/m^3)

SiO_2 Concentration ≈ 0.247 kg/m³

The estimated SiO_2 concentration in the combustion effluent is 20.56% by mass and approximately 0.247 kg/m³ by volume under standard conditions. This value assumes complete stoichiometric combustion and uniform gas mixing. Obviously in reality there is entrainment/dilution by additional air, however these number are indicative of the high aerosol particle load generated if PDMS combustion occurs. Even with additional dilution by air entrainment as shown below the mass concentrations of SiO2 are many times higher than occupational hazard limits. We remark that at these high concentrations the occurrence of coagulation is inevitable however as far as exposure limits are concerned these are mass based and coagulation does not change the mass load.

Table of SiO_2 Concentrations for Different Dilution Ratios

The table includes scenarios ranging from low dilution (AFR = 10) to extreme dilution (AFR = 1000), with comments on typical fire conditions where these dilution levels occur. The Tempi accident most likely lies somewhere between the AFR=50 and AFR=100 case. OSHA PEL is the Occupational, Safety and Health Administration of the USA Permissible Exposure Limit.

Air-to-Fuel Ratio (AFR)	Total Gas Mass (kg/kg PDMS)	SiO_2 Mass Fraction (%)	SiO_2 Concentration (kg/m³)	Exposure Ratio (Crystalline SiO_2 PEL)	Exposure Ratio (Amorphous SiO_2 PEL)	Typical Fire Scenario
10 (Low Dilution)	13.2	14.68%	0.17613	3522.5× Crystalline PEL	29.4× Amorphous PEL	Localized fires, poor ventilation
50 (Moderate Dilution)	53.2	3.65%	0.04381	876.2× Crystalline PEL	7.3× Amorphous PEL	Small well-ventilated fire
100 (Well-Ventilated Fire)	103.2	1.88%	0.02259	451.9× Crystalline PEL	3.8× Amorphous PEL	Moderate-sized pool fire

500 (High Dilution)	503.2	0.39%	0.00464	92.7× Crystalline PEL	0.8× Amorphous PEL	Large turbulent fire
1000 (Extreme Dilution)	1003.2	0.19%	0.00233	46.5× Crystalline PEL	0.4× Amorphous PEL	Outdoor wind-driven fire

OSHA Permissible Exposure Limits (PEL) for SiO_2:

- Crystalline SiO_2 (Quartz, Cristobalite, Tridymite): 50 µg/m³ (0.000050 kg/m³)
- Amorphous SiO_2: 6 mg/m³ (0.006 kg/m³)

Crystalline SiO_2 has a significantly lower exposure limit due to its increased risk of lung disease and silicosis. Amorphous SiO_2, though less hazardous, still has strict exposure guidelines to prevent excessive inhalation.

7. Conclusion

These results demonstrate that even under extreme dilution, PDMS combustion would have produced SiO_2 concentrations that far exceed permissible exposure limits for crystalline SiO_2 while limits for amorphous SiO_2 require extreme dilution, a highly unlikely situation at the Tempi accident.

Από την γνωμοδότηση του καθηγητή Κωνσταντόπουλου τεκμηριώνεται ότι η ανάφλεξη και η καύση των ελαιών σιλικόνης δεν θα μπορούσαν να συμβούν εντός του δεδομένου χρονικού πλαισίου της πυρόσφαιρας. Η γνωμοδότηση καταλήγει ότι η προέλευση της πυρόσφαιρας, η οποία συνάδει με μερικούς τόνους εύφλεκτου πτητικού καυσίμου πρέπει να αναζητηθεί αλλού.

Αυτό το συμπέρασμα υποστηρίζεται και από την ανάλυση στο κεφάλαιο 4.4.3.1. (462) Για παράδειγμα, στην εικόνα 60, αποτυπώνεται η θέση του μετασχηματιστή (με κόκκινο χρώμα) σε πολύ κοντινή απόσταση στην εστία της φωτιάς (με κίτρινο χρώμα) αλλά χωρίς να φλέγεται. Η θέση της εστίας της φωτιάς και του μετασχηματιστή αποτυπώνεται επίσης στην εικόνα 61. Σε αυτή φαίνεται ότι ο μετασχηματιστής εν τέλει δεν έχει καεί πλήρως αλλά μόνο στη μία πλευρά και, ενώ αντίθετα το βαγόνι του εστιατορίου που ήταν ακριβώς δίπλα έχει καεί ολοσχερώς.

Ακολούθως, για την καλύτερη μελέτη του φαινομένου της πυρόσφαιρας ως προς τα τρία διακριτά στάδια τα οποία καταγράφηκαν από τα βίντεο και για την διερεύνηση της επίδρασης της κάθε παραμέτρου (είδος καυσίμου, ταχύτητα και γωνία απελευθέρωσης, θέση στον τρισδιάστατο χώρο, επίδραση ανέμου κλπ), επελέγη η προσομοίωση υπολογιστικής ρευστοδυναμικής (CFD).

Η προσομοίωση υπολογιστικής ρευστοδυναμικής (CFD) είναι αναλυτικότερη και πιο ακριβής από τα απλά στατικά μοντέλα που μπορούν να εκτιμήσουν αυτό που ονομάζεται single stage release (όπως π.χ. BLEVE σε ένα κλειστό δοχείο).

(486) Για τον λόγο αυτό εκτελέστηκαν υπό την επίβλεψη της ΕΔΑΠΟ προσομοιώσεις υπολογιστικής ρευστοδυναμικής (CFD) σε μια προσπάθεια να αναδημιουργηθεί το συμβάν όπως καταγράφηκε από τις κάμερες, χρησιμοποιώντας μόνο μαθηματικά μοντέλα υπολογιστών και τα εργαλεία οπτικοποίησης τους:

- Το Fire Dynamics Simulator (FDS) είναι ένα μοντέλο CFD, μιας ροής ρευστού καθοδηγούμενης από τη φωτιά. Το λογισμικό λύνει αριθμητικά μια φόρμα των εξισώσεων Navier-Stokes οι οποίες είναι κατάλληλες για χαμηλή ταχύτητα, θερμικά καθοδηγούμενη ροή, με έμφαση στον καπνό και μεταφορά θερμότητας από πυρκαγιές.

- Το Smokeview (SMV) είναι ένα πρόγραμμα οπτικοποίησης που χρησιμοποιείται για την εμφάνιση της εξόδου των προσομοιώσεων FDS και CFAST

(487) Τα προηγμένα χαρακτηριστικά των μοντέλων CFD (όπως ο χειρισμός πολύπλοκων τρισδιάστατων γεωμετριών και περιβάλλοντα, που αναλύουν αντιδραστική ή μη δραστική ροή συμπιεστών ή μη συμπιεστών ρευστών) είναι αποδεκτά και έγκυρα επιστημονικά εργαλεία για την υποστήριξη της δυναμικής εκτίμησης συνεπειών στην προοπτική εφαρμογής σε προηγμένες μελέτες ασφάλειας που αφορούν πυρκαγιές, εκρήξεις και τοξικές διασπορές. Αυτό επιβεβαιώθηκε από εμπειρογνώμονες από τα πανεπιστήμια της Πίζας και της Γάνδης, με τα οποία επικοινωνήσαμε κατόπιν σύστασης

του Τεχνολογικού Πανεπιστημίου του Ντελφτ (TU Delft), το οποίο μας τα σύστησε ως διεθνώς γνωστά για την εξειδίκευσή τους στον τομέα της μεθόδου CFD.

Συγκεκριμένα, ο ΕΟΔΑΣΑΑΜ ανέθεσε στο Πανεπιστήμιο της Γάνδης δύο έργα: Α. Να εκτιμήσει την εγκυρότητα της χρήσης CFD με FDS στην ανάλυση του συγκεκριμένου δυστυχήματος και Β. Να επαληθεύσει / επικυρώσει την ανάλυση CFD του ατυχήματος, η οποία έγινε από την ΕΔΑΠΟ, αποτελεί πνευματική της ιδιοκτησία, και για τους λόγους της διερεύνησης παρουσιάστηκε στην επιτροπή διερεύνησης.

Έργο Α: Το ερώτημα που τέθηκε στον καθ. B. Merci (καθηγητής Τμήματος Δομικών Μηχανικών Και Δομικών Υλικών - Ερευνητική Ομάδα: Επιστήμη Και Μηχανική Πυρασφαλείας, Σχολή Μηχανικών και Αρχιτεκτονικής του Πανεπιστημίου της Γάνδης, Universiteit Gent - UGent) ήταν : Εκφράστε μια επιστημονική γνώμη σχετικά με την εγκυρότητα της μεθόδου CFD για χρήση στην ανάλυση που της πυρόσφαιρας που εμφανίστηκε μετά τη σύγκρουση δύο τρένων στο ατύχημα των Τεμπών στην Ελλάδα στις 28 Φεβρουαρίου 2023. Ζητούμενο ήταν η γνωμάτευση εάν η μέθοδος CFD, και το συγκεκριμένο πακέτο λογισμικού, είναι κατάλληλο ως εργαλείο και μπορεί να χρησιμοποιηθεί για τη μοντελοποίηση των φυσικών διαδικασιών που εμπλέκονται στο υπό εξέταση σενάριο. Το Πανεπιστήμιο της Γάνδης υπέβαλε έκθεση σχετικά με την επιστημονική εγκυρότητα της ανάλυσης CFD για τη μοντελοποίηση της ανάφλεξής της πυρόσφαιρας. Αναλυτικά **(2.β.Ι της παραγγελίας σας)**:

FACULTY OF ENGINEERING
AND ARCHITECTURE

DEPARTMENT OF STRUCTURAL
ENGINEERING AND BUILDING MATERIALS
RESEARCH GROUP: FIRE SAFETY
SCIENCE AND ENGINEERING

Bart Merci
Senior Full Professor

E Bart.Merci.@UGent.be
T +32 9 264 98 46
M -

Campus Ardoyen
Tech Lane Ghent Science Park
Technologiepark – Zwijnaarde 60
B-9052 Ghent, Belgium

www.ugent.be

Bart ACCOU
Head of Support to Greece Task Force
European Union Agency for Railways

DATE
28 January 2025

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Assessment of the validity of the use of CFD with FDS in the analysis of the Railway accident on 28/02/2023 in Tempi (Greece) by HARSIA

As determined by the Greek accident investigation body HARSIA, the scenario under review is the railway accident that took place in Tempi, Greece, on 28 February 2023. The accident involved the collision of two trains (i.e., a passenger train and a freight train) and resulted in a huge fire ball with severe number of casualties and damage. Based on the available information, one of the involved investigators (Mr. Costas Lakafossis) has made an attempt to evaluate the fire ball created in this accident with Computational Fluid Dynamics (CFD) using the Fire Dynamics Simulator (FDS) code.

FDS (https://pages.nist.gov/fds-smv/) is a CFD code developed by the National Institute of Standards and Technology (NIST) in the USA. FDS has been developed to simulate fire-related scenarios involving low-speed flows (Mach < 0.3), with an emphasis on smoke and heat transport from fires and is currently the state-of-the-art CFD code when it comes to fire modelling and research in the context of fire safety engineering. The FDS documentation states[*]: "*FDS is designed for use solely by individuals with expertise in fluid dynamics, thermodynamics, heat transfer, combustion, and fire science, and is intended only to supplement the informed judgment of the qualified user. As a computer model, FDS may or may not accurately predict outcomes in a given situation. Inaccurate predictions could lead to incorrect conclusions about fire safety. Therefore, it is suggested that all CFD results should be evaluated by an informed user.*"

In the past, FDS has been validated[**] by NIST for a wide range of fire scenarios including, e.g., heat and smoke transport, fire plumes, liquid pool fires, compartment fires, tunnel fires, fire

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extinction, fire suppression, water sprays, flame spread and atmospheric dispersion among others. The FDS validation guide in particular also contains cases with a fire ball and with spray combustion (albeit at much smaller scale than the Tempi accident)***. Because FDS is only suited for flows with Mach below 0.3, it is not suited for simulating explosions.

The UGent team (i.e., Dr. Georgios Maragkos and Prof. Bart Merci) has reviewed the available information, as provided by Mr. Costas Lakafossis, concerning CFD simulations as performed for the Tempi accident. The findings of the analysis as performed by the UGent team are:

1. There is an 'initiating' event, preceding the creation of the fire ball, visible as a flash in the video footage. This initiating event is not known with sufficient detail for the UGent team to be able to confirm that the use of FDS is suitable to model it.

2. Notwithstanding finding 1, the resulting observed fire ball, fire plume and pool fires are all physical process for which CFD modelling with FDS is deemed suitable. The observed fire ball, fire plume and pool fires also involve velocities that are well within the range of validated applicability of FDS. If the fire ball was the result of the combustion of a spray of liquid fuel droplets, FDS contains in principle all the necessary sub-models to simulate such scenarios.

3. Given the many unknowns involved in the scenario (i.e., lack of clear video evidence, lack of precise information about the available load on the freight train, and lack of information on the exact atmospheric conditions (in particular wind), to name a few), using FDS for reverse engineering of the Tempi accident in order to try and determine the type and minimum required amount of fuel involved in the incident that led to the observed fire ball, will inevitably involve a high degree of uncertainty. It is indeed very likely that multiple different choices for the input data in the CFD simulations can lead to a fire ball that resembles the video footage with a reasonable level of accuracy.

The analysis as presented above is the technical opinion of the UGent team, based on their professional experience and expertise in the context of fire simulations with CFD, and based on the available information as provided at the date of writing this report. The findings of the analysis are the result of careful consideration of the available information and are subject to change if new information on the accident were to be disclosed.

Dr. Georgios Maragkos and Prof. Bart Merci

Ghent University, Belgium

*K. McGrattan, S. Hostikka, J. Floyd, R. McDermott, M. Vanella, E. Muller, Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation, NIST Special Publication 1018-3 Sixth Edition (2024).

**Taken from FDS documentation: "Validation is a process to determine the appropriateness of the governing equations as a mathematical model of the physical phenomena of interest and typically involves comparing model results with experimental measurement."

***Fire Dynamics Simulator (FDS) validation guide (accessed 15 January 2025): https://github.com/firemodels/fds/releases/download/FDS-6.9.1/FDS_Validation_Guide.pdf

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Έργο Β: Ζητήθηκε να επαληθευτεί ότι οι προσομοιώσεις CFD έχουν παραμετροποιηθεί σωστά και ότι έχουν χρησιμοποιηθεί εύλογα δεδομένα εισόδου.

(488) …Αυτή η ανασκόπηση κατέληξε σε μια αναφορά που παρείχε μια τεχνική γνώμη σχετικά με την εγκυρότητα των μεταβλητών και των παραμέτρων για μοντελοποίηση που είχαν χρησιμοποιηθεί μέχρι τώρα στις προσομοιώσεις CFD, προκειμένου να αναπαραχθεί το γεγονός όπως καταγράφηκε από τις κάμερες με τα πιο ρεαλιστικά σενάρια…

Αναλυτικά **(2.γ/δ της παραγγελίας σας)**:

FACULTY OF ENGINEERING AND ARCHITECTURE

HARSIA PROJECT

TASK 2 REPORT

Dr. Georgios Maragkos, Prof. Bart Merci

Faculty of Engineering and Architecture
Department of Structural Engineering and Building Materials (EA14)
Combustion, Fire & Fire Safety group

E Georgios.Maragkos@UGent.be, Bart.Merci@UGent.be
T +32 9 264 98 46

Tech Lane Ghent Science Park, Campus Ardoyen
Technologiepark-Zwijnaarde 60, B-9052, Ghent, Belgium

www.ugent.be

DATE
1/28/2025

LOCATION
Ghent - Belgium

GHENT UNIVERSITY

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Disclaimer

The analysis presented below is the technical opinion of the UGent team (Dr. Georgios Maragkos and Prof. Bart Merci), based on their professional experience and expertise in the context of fire simulations with CFD, and based on the available information as provided at the date of writing this report. The findings of the analysis are the result of careful consideration of the available information and are subject to change if new information on the accident were to be disclosed.

1 INTRODUCTION

After having analyzed the information, as made available by Mr. Costas Lakafossis, of the railway accident that took place in Tempi, Greece, on 28 February 2023, the aim of this report is for the UGent team (Dr. Georgios Maragkos and Prof. Bart Merci) to assess the validity of the CFD simulations that have been performed for the scenario. The CFD code Fire Dynamics Simulator (FDS), version 6.8, was used for the simulations of all the input files discussed in the report. The reviewed FDS input files are presented in the appendix.

The choice of the CFD code itself is deemed reasonable because FDS is currently the state-of-the-art CFD code, widely used for modelling of fire-related scenarios in the context of fire safety engineering. The considered FDS version is also fairly recent and hence up-to-date (i.e., 6.9.1 is the latest version). A detailed review of the different aspects (i.e., models, input data, boundary conditions, etc.) of the FDS input files, as provided by Mr. Costas Lakafossis, that were used for the CFD simulations is presented below. Emphasis is given on whether the choices made in the CFD simulations are reasonable and/or verifiable, based on the available information for the Tempi accident as provided to the UGent team. In the end, some general conclusions are provided for all the CFD scenarios considered.

2 ANALYSIS OF CFD SCENARIOS

A brief overview of the CFD scenarios reads:

- ✓ **Scenario Case06_03**: involves the release of liquid fuel (n-pentane) from two fire sources and the formation of a fire ball,
- ✓ **Scenario Case02_01_new**: illustrates the ignition of a benzene fuel source,
- ✓ **Scenario Case04_05b**: illustrates the lack of ignition of a silicone oil fuel source.

2.1 Scenario Case06_03

The main objective of this scenario is to estimate the total amount of fuel required in order to replicate the fire ball as observed in the video footage.

- **Size of computational domain** (length x width x height): 160 m x 100 m x 80 m.

  This is deemed a reasonable and verifiable choice based on the available video footage (i.e., the maximum diameter of the fire ball, as observed from the video, is on the order of 80 m). Therefore, the size of the domain is considered large enough to enable the undisrupted injection of fuel and the creation of the fire ball.

- **Geometry**: Two different fire sources are considered. The primary fire source injects fuel horizontally towards an inclined surface placed approximately 2 m away. A second fire source, positioned 10 m upstream of the primary fire source, injects fuel with a 45^o angle upward.

  From the video footage and other information on the Tempi accident, as made available to the UGent team, it cannot be verified whether the chosen geometry resembles, to within a reasonable degree of accuracy, what actually occurred in reality during the Tempi accident. In addition, it is unclear why the second fire source, injecting fuel in the same direction as the primary fire source (but from 10 m upstream), is needed in the simulations.

- **Grid size**: Local grid refinement (i.e., stretched 0.25 m x 0.25 m x 0.1 m grid size close to the fire sources and uniform 0.5 m grid size away from the fire sources).

  An overview of the considered local grid refinement and the cell size near the fuel sources is presented in Figure 1. In general, the use of cubic (uniform) cells is recommended in order to accurately capture turbulence and mixing which will, in turn, affect combustion. The use of local grid refinement and stretched cells can potentially affect the CFD solution (i.e., particularly in locations where there is a big jump in grid sizes). The aspect ratio (2.5) is higher than the value that can potentially lead to numerical instabilities as mentioned in the FDS documentation (i.e., a value of 2 is mentioned in the FDS user's guide [1]). Combined with some velocity oscillations observed in the flow field (see comment later), it is unclear whether the chosen mesh and grid sizes are reasonable to accurately simulate the scenario. Ideally, a grid sensitivity study needs to be performed to illustrate that the CFD predictions are grid-insensitive (i.e., the grid size does not significantly affect the shape/size of the predicted fire ball). Justification of the appropriate grid size can also be made a priori and a posteriori based on widely accepted criteria and metrics from the literature.

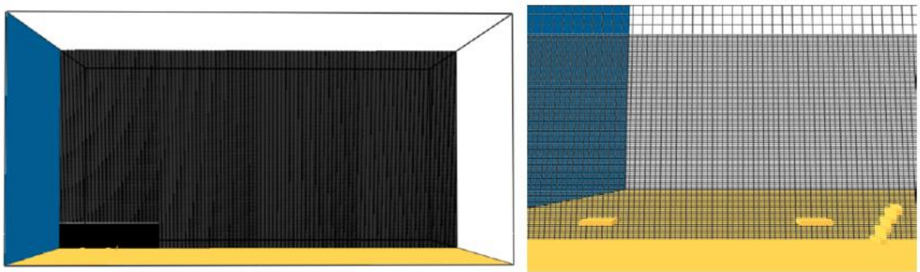
(a) (b)

Figure 1. Illustration of the (a) computational domain / mesh and (b) local grid refinement region used in the simulation of scenario Case06_03.

- **Running time**: 30 s.

  This is deemed a reasonable choice. The prescribed running time is sufficiently long to simulate the injection of the fuel and for the creation of the fire ball. The chosen value would have also been sufficient for having an established wind profile over the entire domain. However, this was not considered in the simulations (see point on "Initial conditions - Velocity" below).

- **Model selection**: default FDS models (in VLES mode).

  This is deemed a reasonable choice. FDS using the default models has been validated by NIST for a wide range of fire scenarios [2].

- **Initial conditions**
  - Ambient temperature: default FDS value (i.e., 20°C).

    Given the time and date of the accident (i.e., 28 Feb 2023 – at approximately 23:21 EET) and the available meteorological data from nearby weather stations (i.e., Larissa), the choice is not deemed entirely reasonable, as ambient temperature was most likely much lower. However, the impact of this parameter on the actual shape/size of the fire ball is not expected to be significant.

- Velocity: still air (0 m/s).

  This is not deemed a reasonable choice. As a consequence of this choice, there is no established wind-induced flow field inside the computational domain at the moment of the first fuel injection (see Figure 2). The simulation should allow for at least 1 flow through time to allow for any initial transient effects to have left the computational domain. Hence, the fuel injection inside the computational domain should ideally start after at least $t = L/u = (160\,m) \times (10\,m/s) = 16\,s$ or when the wind-induced flow field has visibly reached the right side of the computational domain.

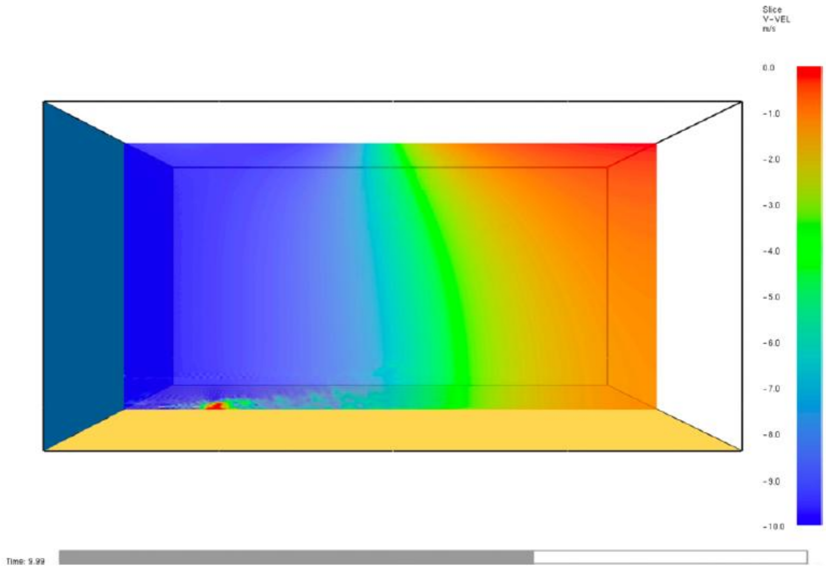

Figure 2. Velocity profile inside the computational domain just before the first fuel injection in the simulation of scenario Case06_03.

- Relative humidity: default FDS value (i.e., 40%).

  Given the time and date of the accident (i.e., 28 Feb 2023 – at approximately 23:21 EET) and the available meteorological data from nearby weather stations (i.e., Larissa), the choice is not deemed entirely reasonable, as the relative humidity was most likely higher. However, the impact of this parameter on the actual shape/size of the fire ball is not expected to be significant.

- **Boundary conditions**
  - Velocity: prescribed constant and uniform velocity of 10 m/s over one boundary of the computational domain.

    The modelling of the wind is not very realistic and hence is not deemed reasonable: there is no consideration of velocity variation as a function of height (although this is typically accounted for in atmospheric type of flows); and no velocity fluctuations are applied at the boundary to represent the turbulence in the wind velocity profile.

Moreover, the modelling of the wind profile in the simulations can have a noticeable and potentially significant effect on the predicted shape/size of the fire ball. This aspect requires further attention and would require a sensitivity study, using different approaches for modelling wind in the simulations.

The imposed wind velocity magnitude cannot be verified due to lack of officially recorded meteorological data at the exact location of the accident. Rather, the wind velocity magnitude has been estimated from testimonies of people present in the accident [3] which, inevitably, introduces a high degree of uncertainty. The imposed velocity magnitude is expected to have a significant effect on the predicted shape/size of the fire ball. This aspect requires further attention and would require a sensitivity study, using different wind velocity values in the simulations.

In addition, some (unphysical) velocity oscillations are observed in the simulations near the fuel sources and at the height of the local grid refinement. This could be related to the aspect ratio of the cells, as mentioned above. An illustration of such oscillations, taken at time $t = 5\,s$ in the simulations, is presented in Figure 3. These oscillations have been observed during the entire time period before fuel injection occurs, and it is unclear what effect they have on the predicted shape/size of the fire ball.

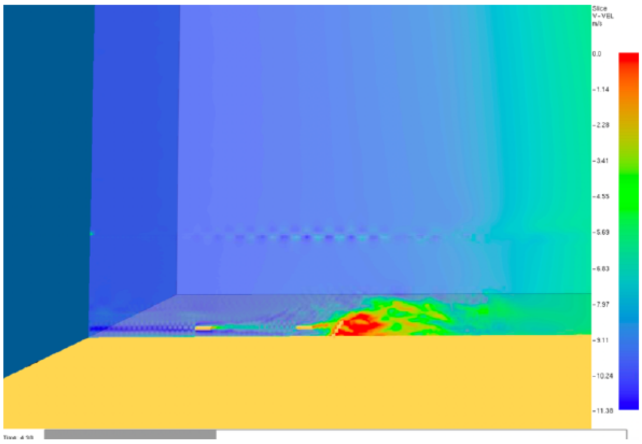

Figure 3. Illustration of some (unphysical) velocity oscillations near the fuel sources during the simulation of scenario Case06_03 (photo taken at time $t = 5\,s$).

- **Fuel**: liquid n-pentane (C_5H_{12}).

  The choice of liquid n-pentane as a potential fuel is deemed reasonable. Given the way FDS handles combustion (i.e., use of infinitely fast chemistry), setting the auto-ignition temperature (AIT) of the fuel to $0°C$, as was done in the simulations, will essentially allow for the ignition and combustion of any combustible (liquid/gas) fuel introduced in the CFD simulations. This type of modelling can be considered reasonable if ignition is not the main focus of the work but instead the goal is to roughly estimate the total amount of fuel that could result in the fire ball as observed in the video footage. However, this type of modelling cannot be used for reverse engineering in order to determine what type of fuel was present during the scenario, nor as to whether a certain (liquid/gas) fuel would ignite or not. According to [4], the heat of combustion for liquid n-heptane is $\Delta H_c = 42\ \mathrm{MJ/kg}$, the CO yield in well-ventilated combustion is $y_{CO} = 0.008$, and the soot yield is $y_{soot} = 0.033$ for n-pentane. While the choice for the heat of combustion is reasonable (i.e., 44 $\mathrm{MJ/kg}$), significantly higher values have been assigned for the CO (i.e., 0.05) and soot (i.e., 0.1) yields in the CFD simulations. Nevertheless, the choice of these parameters is not expected to have a significant effect on the predictions of the resulting shape/size of the fire ball.

- **Fuel injection method**: prescribed particle mass flux (with droplets with a constant diameter of 500 μm) from a given area with a specified injection velocity. Primary injection velocity with a particle mass flux of 4273.5 kg/m^2/s from a 0.3 m^2 area (with an injection velocity of 20 m/s) and a secondary injection with a particle mass flux of 952.3 kg/m^2/s from a 0.3 m^2 area (with an injection velocity of approximately 10 m/s with a 45^o angle upward).

  The case is essentially modelled as a spray combustion scenario (i.e., injected liquid n-pentane droplets with a given velocity). Given the unknowns and uncertainties involved in the Tempi accident, it cannot be verified whether it is a reasonable choice or not. It is also unclear whether the considered fuel injection areas (i.e., 1.5 m x 0.2 m = 0.3 m^2) are a reasonable choice for the scenario at hand. The choice of 500 μm as droplet diameter can be considered reasonable for large (coarse) spray droplets. However, a sensitivity study on this choice would be needed to demonstrate that this parameter does not (significantly) affect the resulting shape/size of the fire ball.

  Estimation of the total injected fuel mass inside the computational domain (based on the input data of the Case06_03.fds file in the appendix):

  - Primary fuel source: $m_1 = m_1'' A_1 t_1 = 4273.5\ \frac{kg}{m^2 s} \times 0.3\ m^2 \times 1.25\ s \approx 1600\ kg$
  - Secondary fuel source: $m_2 = m_2'' A_2 t_2 = 952.3\ \frac{kg}{m^2 s} \times 0.3\ m^2 \times 3.5\ s \approx 1000\ kg$
  - Total mass: $m = m_1 + m_2 = 1600\ kg + 1000\ kg = 2600\ kg$

  Based on an empirical correlation for fire balls [5], approximately 2600 kg would be needed to produce a spherical fire ball with a maximum diameter of 80 m (i.e., size similar to the one observed in the video footage of the Tempi accident [3]). This value is comparable to the total amount of fuel used in the simulations, hence, it is deemed a reasonable choice/starting point for the CFD study. Nevertheless, the potential impact of the considered total amount of fuel in the simulations on the shape/size of the fire ball needs to be demonstrated. A brief sensitivity study on this aspect, carried out by the UGent team, using half and double the amount of fuel, did not reveal significant qualitative differences in the resulting shape/size of the fire ball. Thus, CFD is a valuable tool for providing a rough estimate of the potential total amount of fuel required to replicate the fire ball, as observed in the video footage, but it cannot be easily used to precisely determine it. It also remains unclear whether the treatment of the fire source as a spill plume (i.e., without high injection velocity) would resemble (or not) the results obtained with current fuel injection method.

Notes: Simulations with the provided FDS input files give rise to some warnings that require attention:

- WARNING: Problem with units compatibility of SPATIAL_STATISITIC VOLUME INTEGRAL with the QUANTITY MASS FRACTION

2.2 Scenario Case02_01_new and scenario Case04_05b

The main objective of these two scenarios is to illustrate that the consideration of a benzene fire source can ignite and replicate the observed fire ball in the video footage, while a silicone oil fire source would fail to ignite. Hence, these two scenarios are discussed and analyzed together in this section.

In scenario Case02_01_new, liquid benzene fuel is injected horizontally from a (2 m x 1.5 m = 3 m^2) fire source with a prescribed mass flux. The injected fuel flows above a horizontal heat source (gas temperature above the heat source > 500℃), positioned approximately 2.5 m away, in order to ignite the fuel. In scenario Case04_05b, liquid silicone oil droplets are injected horizontally from a (2 m x 1.5 m = 3 m^2) fire source with a prescribed particle mass flux and a given velocity. The injected fuel droplets hit a vertical surface, positioned approximately 2.5 m away, which acts as a heat source (gas temperature near the heat source > 500℃) in order to ignite them. The geometry of the fuel and heat sources in the two scenarios is presented in Figure 4. The scenario involving the benzene fire source (Case02_01_new) successfully ignites and creates a large horizontal fire ball. On the other hand, the scenario involving the silicone oil fire source (Case04_05b) does not ignite.

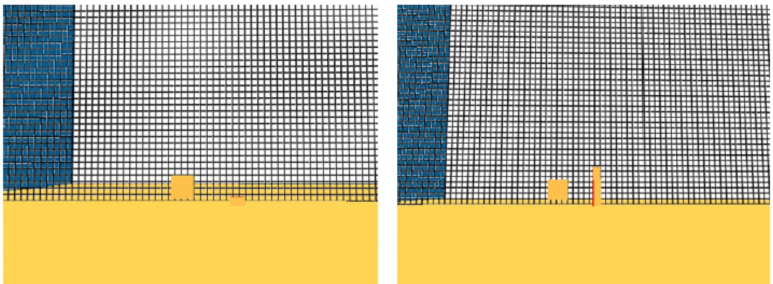

Figure 4. Mesh and geometry of the fire and heat sources used in the simulations for scenario (a) Case02_01_new and (b) Case04_05b.

The comments and analysis regarding the size of computational domain, running time, model selection, initial conditions and boundary conditions (for velocity only), as previously reported for the Case06_03 file, also apply here as well. It is noted that the computational domain for the benzene case (Case02_01_new) has a height of 60 m (not 80 m as the previous cases), but that is not an important issue because the resulting fire ball is issued horizontally. A uniform grid size (0.5 cm) is used in both scenarios. This choice can be considered reasonable for simulating large-scale fires or pollutant dispersion scenarios but can be potentially (too) coarse for accurately simulating spray combustion scenarios involving ignition and fire sources with limited number of cells across their diameter. A grid sensitivity study would be required to demonstrate that the CFD predictions are indeed grid-insensitive (i.e., the grid size does not significantly affect the ignition and the shape/ size of the predicted fire ball).

The main comments after reviewing the two above-discussed FDS input files are the following:

- The benzene scenario (Case02_01_new) does not use exactly the same setup as the silicone oil scenario (Case04_05b) (see Figure 4). More specifically, there is difference between a horizontal hot surface and a vertical hot surface for ignition. Hence, a direct comparison between the two scenarios is effectively impossible. In order to make a fair comparison, the exact same setup is required, with only the fuel changed.

- The way the heat source has been set up in the simulations of both scenarios (Case02_01_new and Case04_05b) is not the most typical approach used in modelling (i.e., not imposing a surface temperature but rather a heat flux). More specifically, a net heat flux of 1000 kW/m^2 and a heat transfer coefficient of 1000 W/m^2/K have been defined, which led to a maximum surface temperature at the heat source on the order of 1700℃. The resulting gas temperature in the vicinity of the heater surface is then on the order of 500℃ or higher. The resulting surface temperature, and subsequent gas temperature in its vicinity, as well as the duration of the heat source, are important with respect to fuel ignition. It is unclear whether the current way of modelling the fuel ignition is realistic, based on what actually happened during the accident. Ideally, a sensitivity study on the influence of the heat source temperature needs to be performed, considering a range of values that could have occurred during the accident due to, e.g., external heat source, sparks due to collision, or other.

- The auto-ignition temperature (AIT), a parameter defined in the FDS input file, corresponds to the physical AIT in case of spontaneous ignition (i.e., in the absence of an ignition source). In the context of the Tempi train accident, piloted ignition of the fire ball is deemed likely (i.e., due to hot sparks due to the high mechanical friction due to the impact, or due to an initial small flame). In such cases, the AIT parameter should ideally be lowered to the fire point of the fuel, in order to mimic the presence of the pilot ignition source. The value for the AIT parameter used for benzene in scenario Case02_01_new (298℃) is much higher than the range of fire points reported in the literature [4] and hence is a conservative choice (i.e., if ignition is observed in the simulations, then ignition is to be expected in reality as well). The value used for silicone oil in scenario Case04_05b, though, is 450℃, whereas the silicone oil (Bayer Baysilone M50 EL) used in the transformers of the trains has a reported fire point of approximately 350℃ [6]. This is not a conservative choice, and hence this is not deemed a reasonable choice. Moreover, simulations of scenario Case04_05b, with exactly the same setup and only changing the AIT value from 450℃ to 350℃, leads to ignition of the silicone oil fuel source (simulations carried out by the UGent team). It should be noted that if the accident was supposed not to involve a pilot ignition, and hence the AIT parameter should indeed correspond to the auto-ignition temperature of the fuel (and not its fire point), the value of 298℃ chosen for benzene is significantly lower than the value reported in the literature (i.e., 560℃ [4]). With the latter value, the benzene fire source in scenario Case02_01_new with the exact same input file does not ignite (simulations carried out by the UGent team). In short, if the AIT parameter is given a realistic value of the real AIT as reported in the literature, neither benzene nor silicone oil ignite in the simulations with the set-up at hand. On the other hand, if a realistic value for the fire point is used for the AIT parameter in the simulations, both fuels ignite with the set-up at hand.

- The prescribed critical flame temperature for both fuels (i.e., $T_{CFT} = 1900℃$) appears to be significantly higher than the ones reported in the literature (e.g., $T_{CFT} = 1537℃$ [4] for benzene). Hence this is not deemed a reasonable choice. Even though the effect of this parameter is deemed to be less important than the prescribed AIT value, a sensitivity study on the influence of this parameter should also be considered in the simulations.

In general, the ignition source (i.e., the gas temperature in its vicinity) will be important with respect to (liquid/gas) fuel ignition. The CFD user should be aware of the importance of the AIT parameter in the modelling with FDS. It is worth noting that FDS suggests decreasing the AIT value in case of very coarse meshes (e.g., cell size >10 cm) in the simulations because naturally the flame temperature cannot be accurately predicted on such grids. The grid used in the simulations of both scenarios is much coarser (i.e., 50 cm). There are also other important modelling aspects (e.g., related to radiation and extinction modelling among others) to consider when modelling ignition of (liquid/gas) fuels.

Notes: Simulations with the provided FDS input files give rise to some warnings that require attention:

- WARNING: SPEC SiliconOil_SimpleFormula is not in the table of pre-defined species. Any unassigned SPEC variables in the input were assigned the properties of nitrogen.
- WARNING: Droplet heat transfer is not predicted when a droplet is on a SURF with a specified ADIABATIC, NET_HEAT_FLUX, or CONVECTIVE_HEAT_FLUX.
- WARNING: Problem with units compatibility of SPATIAL_STATISITIC VOLUME INTEGRAL with the QUANTITY MASS FRACTION

3 CONCLUSIONS

A brief summary of the main conclusions of the report reads:

- The version (6.8) of FDS with the current input file (Case06_03) could in principle be used for reverse engineering in order to roughly estimate the required amount of fuel involved in the incident that led to the observed fire ball. However, it must be acknowledged that there are several significant uncertainties, including the wind conditions and the location, size, type and injection method of the initial fire source(s), among others.

- Determination of the amount of fuel that led to the fire ball (or a range of possible values for the amount of fuel) from CFD simulations requires a more comprehensive sensitivity study than what has been provided to the UGent team for review.

- The following settings are not deemed suitable, with potentially significant impact on the CFD simulation results, and require further investigation in the simulations:
    - grid cell size in all scenarios,
    - velocity boundary condition and fuel injection method in scenario Case06_03,
    - AIT parameter and heat source characteristics in scenarios Case02_01_new and Case04_05b.

- The following settings are not deemed suitable, with expected only little impact on the CFD simulation results, and it is recommended to adjust these settings in future CFD simulations:
    - ambient temperature and relative humidity in all scenarios,
    - time of fuel injection in scenario Case06_03,
    - critical flame temperature in scenarios Case02_01_new and Case04_05b.

- Given the overall uncertainties, it is not deemed possible to determine the type of (liquid/gas) fuel that led to the fire ball with a reasonable degree of reliability from the CFD simulations.

- The ignition of a (liquid/gaseous) fuel will strongly depend on the initial and boundary conditions of the problem, the type and characteristics of the ignition source, as well as on the defined thermophysical properties of the fuels and the selected models in the CFD simulations. With the current setups (Case02_01_new, Case04_05b), no concrete statements regarding the potential ignition (or not) of liquid fuels can be made. A more comprehensive sensitivity study is needed by incorporating the correct thermophysical properties of the fuels and by examining the influence of the heat source, among others.

REFERENCES

[1] S. H. J. F. R. M. M. V. E. M. K. McGrattan, „Fire Dynamics Simulator User's Guide," NIST Special Publication 1019 (Sixth Edition), 2025.

[2] S. H. J. F. R. M. M. V. E. M. K. McGrattan, „Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation," NIST Special Publication 1018-3 (Sixth Edition), 2025.

[3] C. Lakafossis, Interviewee, *Personal communication.* [Interview].

[4] C. Beyler, „Chapter: Flammability Limits of Premixed and Diffusion Flames," in *SFPE Handbook of Fire Protection Engineering (5th edition)*, New York, Springer, 2016, pp. 2-175, 2-183, 3-134.

[5] C. Beyler, „Chapter: Fire hazard calculations for large, open hydrocarbon fires," in *SFPE Handbook of Fire Protection Engineering (5th edition)*, New York, Springer, 2016, pp. 3-306.

[6] B. AG, „Bayer silicones Baysilone fluids brochure," [Online]. Available: https://dcproducts.com.au/wp-content/uploads/2020/12/BayerBaysiloneFluidsBrochure.pdf. [Geopend 23 January 2025].

APPENDIX: FDS INPUT FILES

The FDS input files which were reviewed in the report are included in this section.

- **Scenario Case06_03**

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&TAIL /

- **Scenario Case02_01_new**

Case02_01_new.fds
Generated by PyroSim 2023.3.1206
6 Ιουλ 2024, 11:38:51 π.μ.

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&RAMP ID='BlowLiquid_RAMP_MF', T=12.0, F=0.0/

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&TAIL /

- **<u>Scenario Case04_05b</u>**

Case04_05b.fds
Generated by PyroSim 2023.3.1206
6 Δεκ 2024, 6:19:40 π.μ.

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Ερώτημα για το προαναφερθέν **Έργο Α** (επιστημονική γνώμη σχετικά με την εγκυρότητα της μεθόδου CFD), τέθηκε επίσης στον καθ. G. Landucci (αν. καθηγητής Χημικών Μηχανικών, Τμήμα Πολιτικών και Βιομηχανικών Μηχανικών, πανεπιστήμιο Πίζα, Università di Pisa). Ο καθ. G. Landucci απέστειλε ανεπίσημη γνωμάτευση σχετικά με την επιστημονική εγκυρότητα της ανάλυσης CFD για τη μοντελοποίηση της ανάφλεξής της πυρόσφαιρας.

Αναλυτικά **(2.β.ΙΙ της παραγγελίας σας):**

«Risk analysis of hazardous materials transportation involves the estimation of accident consequences using engineering and mathematical techniques. Consequences are aimed at determining the contribution of magnitude to the risk, representing the impact of the expected accidents, thus related to both vulnerability of territory and severity of scenarios.

Computational fluid dynamics (CFD) modelling is a consolidated tool to support industrial projects development and were recently adopted in the framework of consequence assessment and safety studies. The advanced features of CFD models, such as handling complex three-dimensional geometries and environments, analyzing reactive or non-reactive flow of compressible or non-compressible fluids, make them nowadays well accepted and valid tools to support dynamic consequence assessment in the perspective of implementation in advanced safety studies dealing with fires, explosions and toxic dispersions.

CFD models solve Navier-Stokes (N-S) equations of fluid flow (conservation of mass, momentum and scalar quantities) in a three-dimensional space. The problem is reduced to the solution of a system of partial–differential (or integral–differential) equations that need to specify appropriate boundary conditions and discretization methods for their numerical solution. CFD models may capture the interaction among the released hazardous substances and the geometry of the equipment, pipes, structures, as well as topography and vegetation surrounding an industrial site, where risk assessment is carried out. The advantage of CFD is also related to the dynamic nature of the results, which can be used to trace the transient evolution of the physical effects associated with the accident scenario.

Among the most diffused CFD-based tools specifically aimed at reproducing fire and explosion scenarios, Fire Dynamic Simulator (FDS) is one of the most widely applied in technical and scientific literature. FDS is a CFD code created by the National Institute of Standards and Technology (USA). The code, designed to reproduce the effects of combustion of solids or gases, is able to reproduce the movement of air and fluids and has extensive validation documentation for various uses. All documentation regarding the code, as well as its validation, are publicly available on the website https://pages.nist.gov/fds-smv/manuals.html.

FDS is based on the LES (large eddy simulation) approach for solving turbulent fluid dynamic equations. A distinctive feature of a CFD model is the regime of flow velocities (relative to the speed of sound) for which it was designed. Codes that reproduce high-speed flows, close to the speed of sound in the medium considered, must handle compressibility *effects and shock waves. For low velocities, however, it is possible to explicitly neglect the compressibility effects that give rise to acoustic (sound) waves. The N-S equations describe the propagation of information at low velocities, comparable to those that can be experienced during a fire (about 10 m/s), but also at high velocities, of the order of magnitude of sound wave transmission (for still air, about 300 m/s). Solving a discrete form of these equations would require extremely small time-steps to account for information traveling at the speed of sound, making practical simulations difficult. The FDS code solves the transport equations in low velocity approximations, much lower than the speed of sound, but sufficient to well predict the behavior of the fluid motion in case of diffusive flames, such as pool fires, or fireballs.*

The FDS software has been validated against experimental data for a wide range of scenarios. For each implemented model (pool fires and flaming jets, gas velocity, activation of fire-fighting devices, formation of gaseous combustion products, particulate matter and smoke, pressure, surface temperature, heat exchange, fire suppression, combustion velocity and fire propagation, atmospheric dispersion) the results of the code have been compared with the data obtained in the experiments. For more details on the experiments used for the validation of the models implemented in FDS, please refer to the code validation guide available at the link above.»

Σύμφωνα με τα συμπεράσματα της έκθεσης του Έργου Β από το Πανεπιστήμιο της Γάνδης, έγινε από την ΕΔΑΠΟ περαιτέρω προσαρμογή στις παραμετροποιήσεις των προσομοιώσεων CFD έτσι ώστε το τελικό μοντέλο να ικανοποιεί όλες τις παρατηρήσεις της έκθεσης. Αναλυτικά :

(488) … Η προσαρμογή ορισμένων από τις μεταβλητές και τις παραμέτρους σύμφωνα με τα ανωτέρω, οδήγησε σε ένα βελτιωμένο και πιο αξιόπιστο σύνολο προσομοιώσεων και αναλύσεων CFD, που οδήγησε στα ακόλουθα ευρήματα:

Α. Μεταξύ των διαφορετικών τύπων καυσίμων υδρογονανθράκων που δοκιμάστηκαν, διαπιστώθηκε ότι τα αποτελέσματα ήταν πολύ παρόμοια για πολλούς διαφορετικούς τύπους καυσίμων με παρόμοιες φυσικές ιδιότητες, με σημαντικότερη παράμετρο τη μάζα καυσίμου. Το υγραέριο, η βενζίνη, το μείγμα νάφθας κ.λπ. ίδιας συνολικής μάζας παρέχουν σχεδόν το ίδιο αποτέλεσμα (παρόμοιο μέγεθος και διάρκεια πυρόσφαιρας) με πολύ μικρές μόνο διαφορές στο σχήμα της πυρόσφαιρας.

Β. Οι υπολογισμοί, με τα μαθηματικά μοντέλα CFD, δείχνουν ότι μια ποσότητα τάξης μεγέθους 2500 κιλών κάποιου τύπου καυσίμων υδρογονανθράκων απαιτείται για την αναπαραγωγή των 3 διακριτών σταδίων (με 1000, 1200 και 300 κιλά αντίστοιχα) της αρχικής ανάφλεξης, της πυρόσφαιρας και των δευτερευουσών λιμνών φωτιάς που καταγράφηκαν στα 3 βίντεο που δείχνουν το συμβάν από 3 διαφορετικά γωνίες λήψης.

Γ. Η διάρκεια της απελευθέρωσης καυσίμου κατά το στάδιο 2 (περίπου 4 δευτερόλεπτα) και το παρατηρούμενο αποτέλεσμα (πυρόσφαιρα σε μέγεθος που *αυξάνεται από τα 40 στα 80 μέτρα σε διάμετρο) υποδεικνύουν μια ποσότητα καυσίμου που εκτιμάται με τις προσομοιώσεις CFD σε 1200 kg περίπου. Σε αυτή την περίπτωση, αποκλείεται η πιθανότητα υγρού καυσίμου (έλαιο σιλικόνης από το μετασχηματιστή ή οποιοδήποτε άλλο υγρό καύσιμο από άγνωστη πηγή) το οποίο θα μπορούσε να «περιλούσει»| το βαγόνι εστιατορίου, γιατί μια τέτοια ενέργεια δεν μπορούσε να κρατήσει επί 4 δευτερόλεπτα απελευθερώνοντας 1000 kg καύσιμο . Η μοναδική τέτοια πιθανότητα θα ήταν για το υγρό καύσιμο να εισέλθει στο βαγόνι του εστιατορίου από τα σπασμένα παράθυρά του. Όμως, το γεγονός ότι έξι επιβάτες του βαγονιού του εστιατορίου επέζησαν, δεν συμβαδίζει με αυτή την εκδοχή, όπως επίσης και το γεγονός ότι οι επιζώντες δεν υπέστησαν εγκαύματα που να συνάδουν με καύση ποσότητας καυσίμου της τάξης των 1000 kg στο εσωτερικό του βαγονιού.*

Δ. Περαιτέρω εκτιμάται ότι ποσότητα 300 κιλών καυσίμου υδρογονανθράκων μπορεί να ενεπλάκη στην λίμνη φωτιάς #2, καίγοντας το βαγόνι του εστιατορίου, που συνέχισε να καίει για περισσότερες από 2 ώρες τρεφόμενο επίσης (στη συνέχεια) και από το λάδι σιλικόνης και τα υλικά των εσωτερικών επενδύσεων του βαγονιού. Δεν είναι, ωστόσο, δυνατό να υπολογιστεί με ακρίβεια αυτή η ποσότητα λόγω του άγνωστου χρόνου δευτερογενούς ανάφλεξης των εμπλεκόμενων πρόσθετων καυσίμων, κάτι που ισχύει και για την ποσότητα καυσίμων που κάηκε στην άλλη λίμνη φωτιάς (δηλαδή δεν είναι δυνατόν να διαπιστωθεί από ποιά χρονική στιγμή συνεχίζουν να καίγονται τα υλικά του βαγονιού).

Ε. Η εξέταση των βιντεοσκοπήσεων και της αντίστοιχης ανάλυσης CFD για το 2ο στάδιο του ανάφλεξης, υποδεικνύουν μια ενιαία πηγή για το 2ο στάδιο της ανάφλεξης. Αν και δεν είναι δυνατό να επιβεβαιωθεί ότι το καύσιμο για το 1ο στάδιο ανάφλεξης έχει την ίδια προέλευση με το καύσιμο για το 2ο στάδιο, είναι πολύ πιθανό ότι και τα στα 3 στάδια του φαινομένου γίνεται καύση της ίδιας πηγής καυσίμου.

Επισημαίνεται ότι οι εκτιμήσεις αυτές δεν αποτελούν την μια και μοναδική λύση του προβλήματος, αφού είναι όντως δυνατόν να υπάρξουν περισσότεροι συνδυασμοί στον επιμερισμό των μαζών σε συνδυασμό με μικρές αλλαγές σε ταχύτητες και γωνίες διασποράς που να καταλήγουν σε προσομοίωση CFD η οποία να ταιριάζει επίσης ικανοποιητικά με τα καταγεγραμμένα βίντεο. Όμως η τάξη μεγέθους της συνολικής ποσότητας δεν αλλάζει. Προσομοιώσεις με πολύ μικρότερη ποσότητα καυσίμου έδιναν σαφώς μικρότερο μέγεθος και διάρκεια πυρόσφαιρας. Προσομοιώσεις με πολύ μεγαλύτερες ποσότητες (άνω των 5 tn) απαιτούσαν είτε πολύ διαφορετική (μη ρεαλιστική) γεωμετρία αρχικής απελευθέρωσης και πολύ μεγαλύτερη πυρόσφαιρα σε μέγεθος και διάρκεια, είτε ρεαλιστική γεωμετρία και ρεαλιστικές διαστάσεις και διάρκειες πυρόσφαιρας, όμως με εξαιρετικά μεγάλες ποσότητες καυσίμου να περισσεύουν από την πυρόσφαιρα και να πρέπει να καούν σε δευτερογενείς πυρκαγιές στο έδαφος. Αυτό το φαινόμενο που δεν επιβεβαιώνεται από τις καταγραφές των τριών βίντεο (και ειδικά του τρίτου βίντεο από την κάμερα "Μαλιακός-Κλειδί").

Η ανωτέρω ποσότητα των 2.500 κιλών αναφέρεται στο πόρισμα ως "τάξη μεγέθους" (order of magnitude). Επισημαίνεται ότι σε παρόμοια εκτίμηση ποσότητας καυσίμου (2.600

κιλά) καταλήγει η τεχνική έκθεση του καθ. Κωνσταντόπουλου, ο οποίος χρησιμοποίησε διαφορετική από το CFD μεθοδολογία (στατικά μοντέλα τα οποία εκτιμούν την ποσότητα με δεδομένο τη μέγιστη διάμετρο, τη διάρκεια της πυρόσφαιρας και το είδος του καυσίμου).

(489) Χρησιμοποιώντας τις υποθέσεις του RI.SE (484), εκτελέστηκε μια επιπλέον προσομοίωση CFD χρησιμοποιώντας τη μικρότερη αναφερόμενη διάμετρο σταγονιδίων (0,5mm) και πλήρη εξαέρωση ολόκληρης της μάζας του καυσίμου. Αυτή είχε ως αποτέλεσμα τα ακόλουθα ευρήματα:

- Το λάδι σιλικόνης του τύπου που χρησιμοποιείται στους μετασχηματιστές ισχύος των ηλεκτρομηχανών δεν μπορούσε να εκραγεί και να δημιουργήσει μια μεγάλη πυρόσφαιρα με οποιονδήποτε τρόπο. Ακόμα κι όταν προστέθηκαν πηγές μεγάλης θερμότητας και ενεργές φλόγες ως πηγή ανάφλεξης και ακόμη και όταν το λάδι σιλικόνης ψεκάστηκε με διάφορους τρόπους σε έναν τοίχο για να δημιουργήσει διασπορά και μικρότερα σταγονίδια, το μόνο δυνατό αποτέλεσμα ήταν μια πολύ σύντομη ανάφλεξη 0,3-0,4 δευτερολέπτων, η οποία δεν διαδόθηκε στην υπόλοιπη ποσότητα του λαδιού.

(490) Αυτό επιβεβαιώνεται περαιτέρω από την εξέταση του εξωτερικού κελύφους των τριών μετασχηματιστών, που δείχνει ότι η ποσότητα λαδιού σιλικόνης που θα μπορούσε να διαφύγει κατά τα πρώτα 0,3-0,4 δευτερόλεπτα δεν θα ήταν αρκετή για τη μεγάλη μπάλα φωτιάς που παρατηρήθηκε (Εικόνα Έκθεσης 67)

(491) Η παραπάνω προσομοίωση αντιστοιχεί επίσης με τη διαπίστωση ότι δεν υπάρχει μηχανισμός για τη δημιουργία μιας λεπτής ομίχλης σταγονιδίων σε αυτό το στάδιο, καθώς από το αρχικό σημείο πρόσκρουσης απέχουμε χρονικά 5-6 δευτερόλεπτα (στο παρελθόν), 30 μέτρα νότια (γεωγραφικά) και με τον άνεμο να πνέει προς την αντίθετη κατεύθυνση. Το γεγονός αυτό από μόνο του θα πρέπει να αποκλείει οποιοδήποτε καύσιμο με παρόμοια χαρακτηριστικά με λάδια σιλικόνης.

(492) Ακόμη και αν η υπόθεση της ανάφλεξης και της δημιουργίας της αρχικής πυρόσφαιρας μπορούσε να γίνει αποδεκτή, το 2ο στάδιο της πυρόσφαιρας είναι πιο δύσκολο να εξηγηθεί με το λάδι σιλικόνης ως καύσιμο: παρατηρείται ότι το νέφος φωτιάς βγαίνει από μια πηγή καυσίμου η οποία ήδη καίγεται έντονα, προφανώς χωρίς πρόσθετη πηγή θερμότητας και σε θερμοκρασία περιβάλλοντος. Επιζώντες από το βαγόνι του εστιατορίου δεν ανέφεραν καμία σημαντική αλλαγή θερμοκρασίας σε αυτό το στάδιο και δεν παρουσίασαν εγκαύματα λόγω ακτινοβολίας. Αυτά τα στοιχεία δείχνουν το γεγονός ότι το άγνωστο καύσιμο είναι πτητικό και πολύ εύφλεκτο.

Στοιχεία για τα ανωτέρω παρουσιάζονται στο Παράρτημα Β.

3. <u>Συμπεράσματα (Ενότητα 4.4.3.3)</u>

(494) Η παρουσία εύφλεκτης ουσίας με τα χαρακτηριστικά που καθορίστηκαν στις προηγούμενες αναλύσεις δεν αναφέρεται στα έγγραφα σχετικά με τα μεταφερόμενα εμπορεύματα της εμπορευματικής αμαξοστοιχίας 63503. Επίσης, τα πρόσφατα δημοσιευμένα βίντεο της αμαξοστοιχίας 63503, αν και δεν έχουν τεθεί ακόμη στη διάθεση του ΕΟΔΑΣΑΑΜ από τη δικαστική έρευνα, δεν υποδεικνύουν μεταφορά ποσότητα εύφλεκτου υλικού ορατή σε θέση που να συνάδει με τα παραπάνω ευρήματα. Ο ΕΟΔΑΣΑΑΜ αναγνωρίζει αυτό το γεγονός, αλλά αυτό δεν απορρίπτει τις παραπάνω παρατηρήσεις (Έκθεση 4.4.3.1) που είναι σαφώς τεκμηριωμένες.

(495) Αυτές οι παρατηρήσεις, μαζί με τις προσομοιώσεις που πραγματοποιήθηκαν, επιβεβαιώνουν το συμπέρασμα που κατέληξε και ο καθηγητής Κωνσταντόπουλος: «Η μεγάλη πυρόσφαιρα στο σιδηροδρομικό δυστύχημα των Τεμπών που σημειώθηκε σε 0,5 δευτερόλεπτο από τη σύγκρουση των αμαξοστοιχιών δεν μπορεί να αποδοθεί στο λάδι μετασχηματιστών (PDMS) το οποίο αν και είναι εύφλεκτο σε αρκετά υψηλή θερμοκρασίες (> 400) δεν μπορούσε -για λόγους κινητικής αντίδρασης- να αναφλεγεί στο περιβάλλον που επικρατούσε. Επιπλέον, η απουσία λευκής σκόνης (διοξείδιο της σιλικόνης, SiO2) στον τόπο του ατυχήματος, σε ποσότητες που θα δικαιολογούσε την καύση μεγάλης ποσότητας λαδιού σιλικόνης, είναι μια άλλη σαφής ένδειξη ότι ένα τέτοιο περιστατικό δεν πραγματοποιήθηκε. Ως εκ τούτου η προέλευση της πυρόσφαιρας, η οποία είναι συμβατή με μερικούς τόνους εύφλεκτου πτητικού καυσίμου, πρέπει να αναζητηθεί αλλού».

(496) Η μάζα αυτού του εύφλεκτου πτητικού υγρού έχει υπολογιστεί, μέσω της μοντελοποίησης CFD, περίπου στην τάξη μεγέθους των 2,5 τόνων. Μέχρι στιγμής, η έρευνα δεν έχει εντοπίσει καμία ουσία, με τις ιδιότητες και τη συνολική μάζα να υπήρχε στο τροχαίο υλικό, το οποίο θα μπορούσε να είχε αυτόν τον ρόλο. Παρόμοια με τα προηγούμενα βήματα (488), ο ΕΟΔΑΣΑΑΜ έχει ξεκινήσει τις διαδικασίες για να αναθέσει σε εξειδικευμένο Ινστιτούτο/Πανεπιστήμιο του εξωτερικού, να αξιολογήσει τις μεταβλητές και τις παραμέτρους που χρησιμοποιήθηκαν στην αναθεωρημένη ανάλυση Υπολογιστικής Ρευστοδυναμικής (CFD), του φαινομένου της πυρόσφαιρας (βλ. Δελτίο Τύπου 6/3/2025).

Ο ΕΟΔΑΣΑΑΜ έχει έρθει σε επαφή με εξειδικευμένα Ινστιτούτα/Πανεπιστήμια και αναμένει σχετικές δεσμευτικές προσφορές.

(497) Παρά την αβεβαιότητα σχετικά με την πηγή του παρατηρούμενου φαινομένου, ο ΕΟΔΑΣΑΑΜ επέλεξε ρητά να μην να αναβάλει τη δημοσίευση αυτής της έκθεσης. Αυτό έγινε γιατί πρώτα απ' όλα, η πυρόσφαιρα και η επακόλουθη φωτιά είχαν αντίκτυπο μόνο στις συνέπειες του ατυχήματος, χωρίς να συμβάλλουν στα αίτια του. Σημαντικότερα, το ελληνικό σιδηροδρομικό σύστημα πρέπει να γνωρίζει και να αποδεχτεί τα αποτελέσματα αυτής της διερεύνησης το συντομότερο δυνατό, προκειμένου να μπορέσει να ξεκινήσει την απαραίτητη διαδικασία βελτίωσης.

3. Κατάσταση με τα αναλυτικά στοιχεία και ειδικότητες επιστημόνων/συνεργατών οι οποίοι συνετέλεσαν - συνέβαλαν στην κατάρτιση/ολοκλήρωση της Έκθεσης.

Α) Μέλη της Επιτροπής Διερεύνησης:

1. Καπετανίδης Κωνσταντίνος: Πολιτικός Μηχανικός ΤΕ με μεταπτυχιακό στη «Διαχείριση τεχνικών έργων» (Ε.Α.Π.)

   Τωρινή θέση: Προϊστάμενος Μονάδας Μελετών και Διερεύνησης Ατυχημάτων - ΕΟΔΑΣΑΑΜ

   Εργασιακή Εμπειρία: 32 χρόνια ως σιδηροδρομικός μηχανικός (Ολυμπιακό Μετρό Αθηνών 1993-2001, ΕΡΓΟΣΕ Α.Ε. 2001 -20211, Ρυθμιστική Αρχή Σιδηροδρόμων 2011-2024, ΕΟΔΑΣΑΑΜ 2024-2025).

   Πιστοποιημένος από ΕΚΔΔΑ (Εθνικό Κέντρο Δημόσιας Διοίκησης και Αυτοδιοίκησης) ως «Εσωτερικός Ελεγκτής Δημοσίου Τομέα» (12/2021) και προϊστάμενος Μονάδας Εσωτερικού Ελέγχου στη ΡΑΣ (2019-2024).

   Συνδημιουργός και συντονιστής του Προγράμματος «Ασφαλής συμβίωση μαθητών με το Σιδηροδρομικό Δίκτυο» με σκοπό την μείωση των ατυχημάτων στο Ελληνικό Σιδηροδρομικό Δίκτυο με θύματα μαθητές. Η παρουσίαση δημιουργήθηκε από τρείς σιδηροδρομικούς μηχανικούς σε συνεργασία με την Διεθνή Ένωση Σιδηροδρόμων (UIC). Διεξήχθη υπό την αιγίδα του ΟΣΕ και της ΡΑΣ. Έλαβε έγκριση από το Υπουργείο Παιδείας τον Νοέμβριο του 2018. Το πρόγραμμα έως σήμερα έχει παρουσιαστεί σε 20.000 μαθητές, σε 130 σχολεία των νομών Αττικής, Λάρισας Πιερίας, Αχαΐας και Πέλλας. Η παρουσίαση βρίσκεται στο : https://www.youtube.com/watch?v=ZgAEFh6FROg .

   Δημοσιεύσεις για την ασφάλεια στον σιδηρόδρομο:

   A) "A study about Level Crossings in Hellas (2015-2019): statistical and geographical analysis and proposed measures to improve safety" https://www.globalrailwayreview.com/article/114655/greece-level-crossings-analysis/

   B) "How educating students in Greece will improve rail safety "

   https://www.globalrailwayreview.com/article/93203/educating-students-greece-rail-safety/

2. Accou Bart : Πολιτικός Μηχανικός (Vrije Universiteit Brussel, VUB, Βρυξέλλες) με διδακτορικό "Safety Science" (Delft University of Technology, TU Delft, Ντελφτ) και μεταπτυχιακό σε "Occupational Health and Safety management».

   Τωρινή θέση: Head of Unit, Safety and Operation, European Railway Agency (ERA)

   Εργασιακή εμπειρία: από Σεπτέμβριο 1993 έως σήμερα. Αναλυτικά στοιχεία στην ιστοσελίδα του ERA:

   https://www.era.europa.eu/sites/default/files/2025-01/bart%20accou%20-%20cv%202025.pdf

   Το διάστημα 11/2023 έως 12/2024 συμμετείχε στην επιτροπή διερεύνησης των Τεμπών ως «Head of the Support to Greece Task Force, ERA» κατόπιν σχετικής αίτησης του Συμβουλίου του ΕΟΔΑΣΑΑΜ στις 19/10/2023 σε συμμόρφωση με το άρθρο 22.5 της οδηγίας ΕΕ/2016/798 του Ευρωπαϊκού Κοινοβουλίου.

3. Carpineli Fabrizio : Βιομηχανικός Ψυχολόγος

   Τωρινή θέση: Ειδικός σε θέματα Human Organizational Factor, European Railway Agency (ERA).

   Εργασιακή εμπειρία: Εντάχθηκε στους βελγικούς σιδηροδρόμους στις αρχές της δεκαετίας του 2000 και ανέπτυξε πολλά εκπαιδευτικά μαθήματα ανθρώπινου δυναμικού, εργαλεία και διαδικασίες, κυρίως για κρίσιμες λειτουργίες ασφάλειας και ηγέτες. Το 2007 ξεκίνησε ένα ολοκληρωμένο πρόγραμμα βελτίωσης για έναν «καλύτερο χώρο εργασίας». Έγινε διευθυντής στο τμήμα «Talent, Behavior & Culture» Σιδηροδρομικής Υποδομής, το 2009. Παράλληλα, εκπαιδεύτηκε στο coaching (ICF) και ξεκίνησε ένα πρόγραμμα ανάπτυξης για ηγέτες. Το 2012, εντάχθηκε στην ομάδα Safety Manager για να αναπτύξει το πρώτο πρόγραμμα Safety Culture και να βελτιώσει την ενσωμάτωση των Ανθρώπινων και Οργανωτικών Παραγόντων (HOF) στις καθημερινές δραστηριότητες του Συστήματος Διαχείρισης Ασφάλειας. Έχει ενταχθεί στον Οργανισμό Σιδηροδρόμων της Ευρωπαϊκής Ένωσης (ERA) το 2019 και υποστηρίζει την ανάπτυξη έργων HOF, Safety Culture και Investigation. Είναι αξιολογητής στις αξιολογήσεις του Ενιαίου Πιστοποιητικού Ασφάλειας. Συμμετέχει στις δραστηριότητες παρακολούθησης της Εθνικής Αρχής Ασφάλειας. Αναπτύσσει υλικό έρευνας και εκπαίδευσης και είναι προληπτικός εκπαιδευτής, ειδικά για το HOF, το Safety Culture, το Just Culture και το Investigating SMS. Έχει δημοσιεύσει επιστημονικά άρθρα και συμμετέχει τακτικά σε ημερίδες και συνέδρια.

   Το διάστημα 11/2023 έως 12/2024 συμμετείχε στην επιτροπή διερεύνησης των Τεμπών ως «Member of the Support to Greece Task Force, ERA» κατόπιν σχετικής αίτησης του Συμβουλίου του ΕΟΔΑΣΑΑΜ στις 19/10/2023 σε συμμόρφωση με το άρθρο 22.5 της οδηγίας ΕΕ/2016/798 του Ευρωπαϊκού Κοινοβουλίου.

<u>Β) Αναπληρωματικά Μέλη της Επιτροπής Διερεύνησης</u>

1. Αλεξάνδρου Αστέριος: Πολιτικός Μηχανικός ΠΕ (ΕΜΠ, συγκοινωνιολόγος)

   Τωρινή θέση: Προϊστάμενος Τμήματος Διερεύνησης Σιδηροδρομικών Ατυχημάτων - ΕΟΔΑΣΑΑΜ

   Εργασιακή Εμπειρία: 21 χρόνια ως σιδηροδρομικός μηχανικός (ΕΡΓΟΣΕ Α.Ε. 2003 -2024, Προϊστάμενος Διευθύνουσας Υπηρεσίας, Επιβλέπων Μηχανικός)

   Τον Οκτώβριο 2024 προστέθηκε στην επιτροπή διερεύνησης των Τεμπών ως αναπληρωματικό μέλος.

2. Γαλανός Δημήτριος : Τεχνίτης Ηλεκτρολόγος ΔΕ

   Τωρινή θέση: Στέλεχος Τμήματος Διερεύνησης Σιδηροδρομικών Ατυχημάτων - ΕΟΔΣΑΣΑΑΜ.

   Εργασιακή Εμπειρία: 2 χρόνια στη ΣΤΑΣΥ ως τεχνικός ηλεκτρολόγος

<u>Γ) Εξωτερικοί ειδικοί/ πραγματογνώμονες οι οποίοι συνεισέφεραν στην επιτροπή</u>

1. Κωνσταντόπουλος Αθανάσιος, Καθηγητής στο Τμήμα Χημικών Μηχανικών , Εργαστήριο Τεχνολογίας Νανοσωματιδίων και Αερολυμάτων, Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης. Περισσότερα στοιχεία στην επίσημη ιστοσελίδα του ΑΠΘ: https://cheng.auth.gr/%CE%B4%CE%B5%CF%80-v1/konstandopoulos-athanasios/

2. Li, Ying Zhen (PhD, Tunnel Fire Safety, SP Technical Research Institute of Sweden, Southwest Jiaotong University), RISE Research Institutes of Sweden AB, Org. nr 556464-6874. Ανώτερος ερευνητής στο RISE (Κρατικό ερευνητικό κέντρο Σουηδίας) και αναπληρωτής καθηγητής (Docent) συνδεδεμένος με το Τεχνολογικό Πανεπιστήμιο Luleå. Προεδρεύει της Επιστημονικής Επιτροπής του Διεθνούς Συμποσίου για την Ασφάλεια και την Ασφάλεια Σήραγγας (ISTSS). Περισσότερα: https://www.ri.se/en/person/ying-zhen-li
3. Malin, Tove (PhD, Pharmacy) Director societal safety - RISE Research Institutes of Sweden. Κρατικό ερευνητικό κέντρο Σουηδίας RISE.
4. Merci, Bart, Senior Full Professor of Ghent University (Πανεπιστήμιο της Γάνδης). Department of structural engineering and building materials Research group: fire safety science and engineering. Περισσότερα: https://www.ugent.be/ea/structural-engineering/en/about-us/staff/merci.htm
5. Maragos, Georgios, Postdoctoral scientific staff of Ghent University (Πανεπιστήμιο της Γάνδης). Faculty of Engineering and Architecture Department of Structural Engineering and Building Materials. Περισσότερα: https://research.ugent.be/web/person/georgios-maragkos-0/en
6. Landucci, Gabriele, university of Pisa (Πανεπιστήμιο της Πίζας). Associate Professor at the Department of Civil and Industrial Engineering. Περισσότερα: https://unimap.unipi.it/cercapersone/dettaglio.php?ri=4987
7. Λακαφώσης Κωνσταντίνος, Μηχανολόγος - Αεροναυπηγός Μηχανικός MEng, μέλος Επιτροπής Διερεύνησης Ανεξάρτητων Πραγματογνωμόνων Οικογενειών (ΕΔΑΠΟ), ως πάροχος υπηρεσιών στον ERA στο πλαίσιο σύμβασης με αντικείμενο την τεκμηριωμένη καταγραφή και περιγραφή γεγονότων.

Με εκτίμηση,

Ο Αναπληρωτής Πρόεδρος
& Πρόεδρος Σιδηροδρομικού
Τομέα ΕΟΔΑΣΑΑΜ

Χρήστος Παπαδημητρίου