Article

The fireworks disaster in enschede
Part 2: Safety & pyrotechnics

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Saturday afternoon May 13, 2000 a major fireworks incident occurred at the company S.E. Fireworks in the city of Enschede, the Netherlands. Twenty-two people were killed and more than seven hundred were injured. Within a radius of hundreds of meters houses were destroyed by the blast and debris generated by the explosions and burnt because of the scattered fireworks. Within an hour the incident developed from a moderate fire and some initiating fireworks in one of the buildings into a series of three explosions of increasing violence. Many people witnessed the accident and numerous video recordings from different angles were made.

The possible causes, safety regulations and safety control were investigated. By order of the Public Prosecutor the Netherlands Forensic Science Institute (NFI) and TNO Prins Maurits Laboratory (TNO-PML) performed the forensic and technical investigations into the reconstruction and the cause of this disaster. The observed explosion effects, the inventory of the damage in the area and all the forensic evidence were analysed. They form the basis for the reconstruction of the disaster. Scenarios for possible causes of each of the events were developed and analysed. The events and effects were presented in the first paper (Weerheijm and De Bruyn[1]). This second paper deals with the most probable chain of events and the lessons to be learned concerning the (bulk) storage of pyrotechnics in general and fireworks specifically.

1. Introduction

In the first paper the sequence of events was described. Starting with a fire in the central storage building, the ignition of the fireworks in container E2, within a minute followed by the explosion of the garage boxes and 66 seconds later the devastating explosion in cell C11 of the central building. The layout and identification numbers of the storage cells are given in Fig. 1.

In this paper the focus is on the reconstruction of the chain of events. For the major events the possible initiation mechanisms and possible consequences will be discussed. Lessons and general conclusions are drawn from these analyses.

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The paper only gives a summary of the research and highlights the main research steps. The research is reported in Weerheijm[6].

It should be noted that there is no complete certainty about the stored quantities and type of fireworks. The licensed quantities are given in paper 1.

2. Initiation and possible consequences of fire in C2

In spite of the extensive forensic research and hearings no evidence is obtained for the cause of the fire in the firework preparation and reparation cell, C2. On Saturday 13th of May the company and the terrain were closed (see also the comments in paper 1). Therefore we start with the facts that the fire was noticed at about 14:45 hour when activated firework was ejected and landed outside the S.E. Fireworks (S.E.F.) premises. A small fire in a garden was reported. When the fire brigade arrived the doors of cell C2 were open at both sides

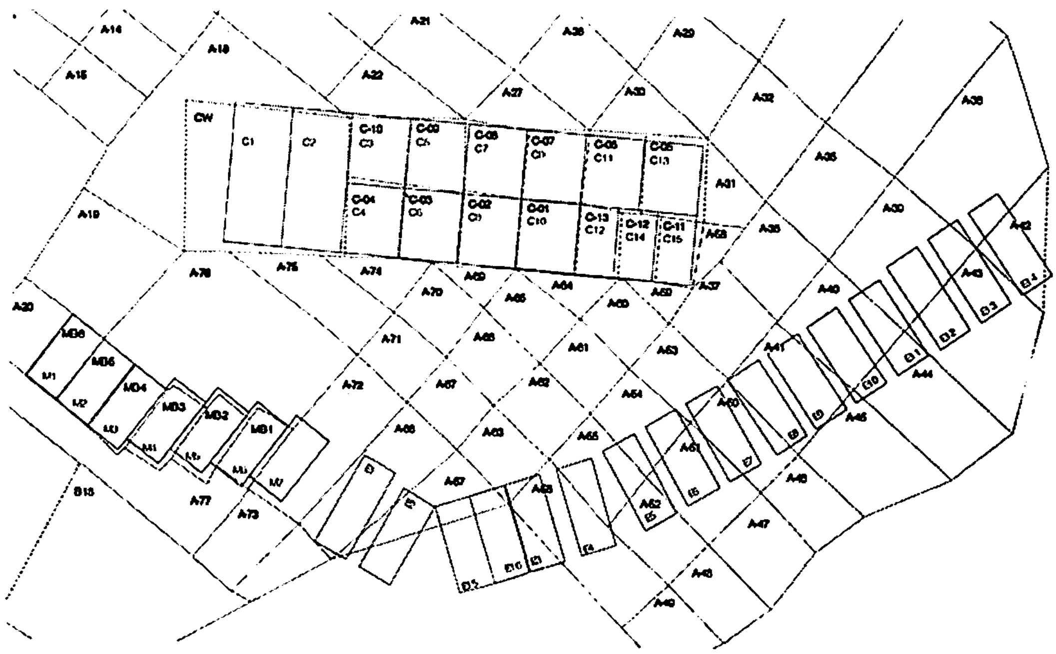

Fig. 1 Scheme of the storage cells and containers of S.E. Fireworks

and the plastic skylights were gone. Some fast pressure build up must have occurred because the doors on both sides were blown out. No external blast damage was noticed. The fire was fought at both sides of the central building. The firemen at the north side (side of garage boxes) were killed in the accident; no direct witness reports of the fire development at the north side are available.

The effects of the fire in C2 are:

1. Fire; heat loading on walls of adjacent cells.
2. Fire jet and heat radiation directed to the opposite garage boxes and containers;
3. Ejected fireworks, with possibility of fire ignition;

The following comments are made concerning these effects

Ad 1: The wooden doors of the other cells were closed and locked; the internal walls of cast reinforced concrete had a thickness of 200 mm and were fire resistant. Only the wall between cells C2 and C4 had an opening (diameter 70 mm). Afterwards concrete samples were taken from the floor slabs of the central building. Laboratory research showed no evidence for heat loading. Combined with the fire brigade reports, the conclusion was drawn that the fire in the central building was not passed on to other cells except to C4. Fire in C4 started before 15:28.

Ad 2: Dependent on the content of C2 and the intensity of the flame jet and heat radiation, fire may be initiated in the opposite garage boxes with thin corrugated steel doors. However, there are no indications that the firemen observed any fire effects.

Ad 3: At the north side small fires were noticed and extinguished. Firemen reported that in between the containers E1 and E2 smoke development was observed and fire was fought (15:28 hour).

On the S.E.F. premises the effects of the fire in C2 were most probably limited to the fire passed on to C4 and the initiation of small fires due to the ejected articles.

The effects of the fire in C4 are similar as reported for C2 with the comment that C4 was a storage cell, while C2 was the workshop with no licensed storage capacity after working hours.

The performed analyses confirmed that the building (cast concrete, 20 cm thick walls and roof) provided sufficient heat resistance between the storage cells. Of course openings between the cells are not allowed. The analyses also confirmed the requirement on fire resistance of doors. Automatic fire suppression systems like sprinklers should be a standard requirement.

Finally, one should be aware of the large area with potential fire hazards when the ejection of fireworks can occur. Requirements on fire resistance of other facilities are paramount as will be clear from the events in the container E2.

3. Initiation and possible consequences of reaction in E2

The following initiation mechanisms were examined theoretically:

- External fire;
- Fireworks on and, or under the container;
- Burning magnesium (ejected from the workshop) on top of container;
- Fireworks before door slit.

From previous research it was known that the resistance of steel ISO containers to the standardised fire loading is limited to a few minutes. However, in the current investigation the intensity, size and duration of the external fire were the parameters. The TNO Centre of Fire Research performed theoretical calculations and the very poor fire resistance of the steel containers was stressed. Considering the timeframe, the very limited fire resistance of the container, the presence of an old small trailer with wooden floor between E1 and E2, a small fire was possible and sufficient to initiate a fire and fireworks in E2. The other potential initiation mechanisms appeared to be less likely and were rejected.

The successive effects of the E2 reaction were: smoke from door slit, strong smoke development followed by intensive firework reactions, flame jet (in two pulses), ejected fireworks and very severe (external) massive reaction of firework. Similar effects were observed and reported by Merrifield and Myatt[1] with 1.3G fireworks tests. Figure 2 illustrates these effects.

For the possible consequences of the E2 reaction the following effects were theoretically examined:

1. Ejection of debris (doors);
2. Failure of container (fragments and blast);
3. Flame jet (and possible external fireball);
4. Ejected fireworks.

Ad 1: If a container door is ejected from E2 and impacts on a door of the central storage building, this door will fail and cause damage to the stored firework packages. The successive fire jet and heat radiation could initiate the contents of the cell. The possible consequences were predicted assuming that the burning pyrotechnics led to an explosive reaction. The calculated local and structural failure modes however did not correspond to the observed effects and post accident damage.

Ad 2: The blast effects due to door failure or roof/wall failure were calculated. The blast level proved to be insufficient to cause damage to the doors of the garage boxes or central building.

Ad 3: The first jet had a duration of 2 s and a length of 17 –30 m (distance to central building was 17 m, the jet was deflected upwards leading to a total length of 30 m and a diameter in the order of 20 m). A few seconds later the reaction intensified and a second jet was formed with a length of 35 m and duration of 1 s. The thermal loading on the doors of the other cells and the stored fireworks

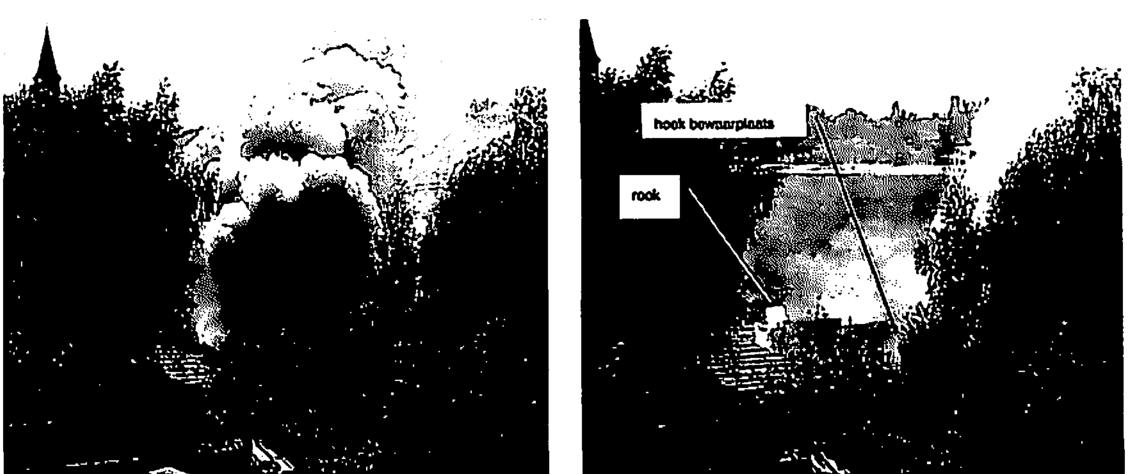

Fig. 2 Effects of E2 reaction (video by G.Poort, enhanced by NFI)

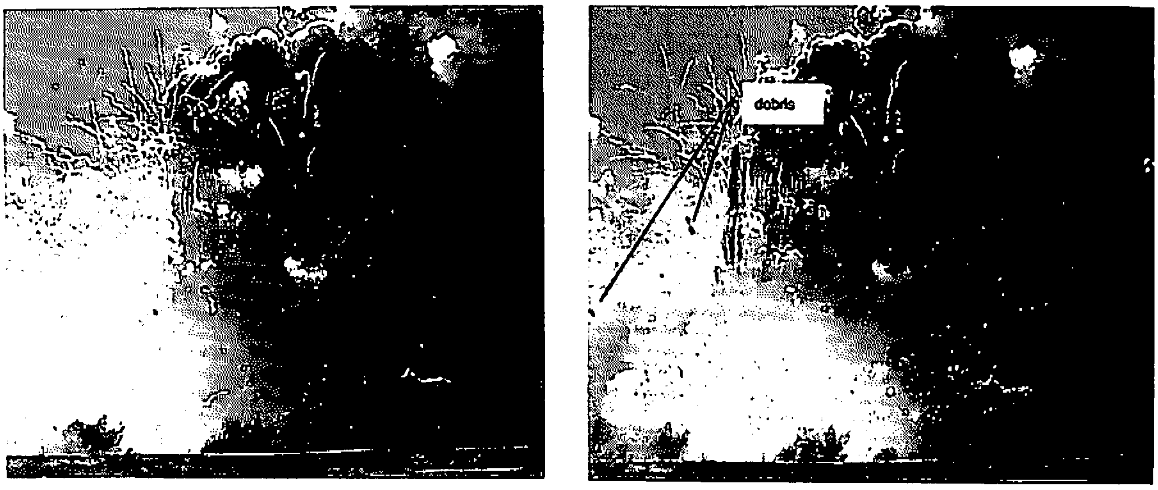

Fig. 3 Effects of explosion in garage boxes (video by G.Poort, enhanced by NFI).

was calculated. Experiments were performed to determine the thermal load behind the steel sheet doors and the required duration to ignite the packages or fireworks. The required loading time proved to be in the order of 12 s. Consequently escalation of the accidents to the garage boxes or containers could be excluded. The possible escalation to the central building was rejected because of the considerations mentioned at "ad 1".

Ad 4: The hearings learned that in E2 shells were stored of at least 6 inches. The video recordings confirmed the presence of mortar shells. The ejected fireworks caused fire and damage in a wide area. Because the accident escalated within a minute after E2, the possible local "breaching" damage of mortar shells to wooden and garage doors was examined experimentally. Note that the contents of E2 were unknown at the time of the experiments. 8 and 12 inch mortar shells and 3 inch titanium report shells were tested. The 12 inch shell had a devastating effect on both door types; the other shells caused severe damage but not complete failure. It is most likely that multiple hits and loading by the latter shells would lead to door failure and ignition of the cell contents.

Conclusion on E2 effects for the escalation of the accident is: No definite evidence is found for a fast escalation to the garage boxes. Most likely is the breaching of the M7 door by multiple shell reactions.

The performed analyses and tests confirmed and learned that:

- steel ISO containers have negligible fire resistance and are not suitable for storage or transport of flammable goods without additional counter measures;
- planning the lay out of a firework storage facility one should count with the combined threat of

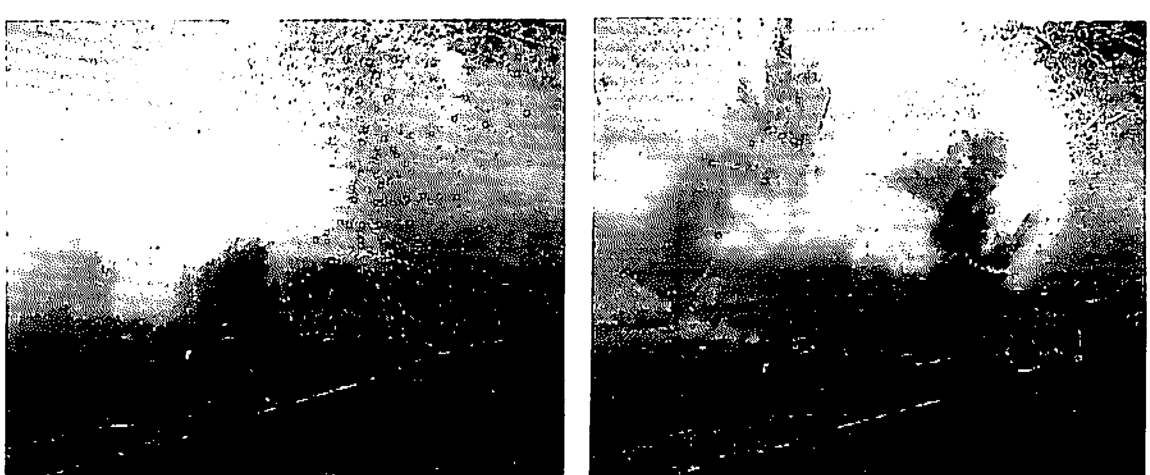

Fig. 4 Mass explosion in central building (video by G.Poort, enhanced by NFI)

door debris and flame jet (1.3 bulk storage)

- when 1.3 G articles in a storage cell react, the pressure build up can be sufficient to throw the contents out which leads to extensive external effects and a considerable increase of the risks.
- The pressure effects at short distance of reacting shells can be sufficient for local damage and breaching of wooden or steel sheet doors is possible. Consequently the out throw of shells lead to new risks. Strength requirements for doors are recommended.

4. Possible consequences of reaction in garage boxes M7 to M1

The initiation possibilities in the garage boxes from the fire in the central building and the effects from E2 were already mentioned. In this section we focus on the sympathetic reactions in the garage boxes. For the damage and observed effects see paper 1, Weerheijm[1].

The damage proofs that the most severe explosion occurred in M7, but the local damage clearly showed that no detonation occurred. The observed debris velocity of 200 m/s was related theoretically to the required reaction velocity of pyrotechnics and the local damage to the remaining floor slabs. These aspects could be related without any contradictions. It is evident that the "required reaction velocity" can be achieved by the properties of the pyrotechnic materials themselves, and/or the number of ignition points and/or the 3D expansion of the reaction front and thus the length scale and size of the storage cell.

The next question was about the mechanism to initiate the contents of the other garage boxes. Most likely is that the 5 cm thick walls (of prefab box M7) failed and were launched with an initial velocity in the order of 100 m/s. The resulting severe crushing of the fireworks in M6 and thermal loading caused the sympathetic chain reaction of the fireworks in M6, and subsequently in the other cells. The reactions in the garage boxes occurred in the time frame of less than 0.5 seconds.

The effect of the explosion was a blast, equivalent to a TNT explosion of 800 kg. A fireball was formed with a radius of 85 meter. The garage boxes were completely destroyed and fragmented into small debris. The combined blast and debris formed a severe loading for the central building and the containers. In combination with the thermal loading and ejected burning firework articles escalation of the accident was inevitable.

Conclusions and discussion on the sympathetic reactions in the different cells are given in the next section about the explosion in the central storage building.

5. Initiation and explosion effects of explosion in central storage building

Considering the central building, the strength of the explosion in the garage boxes was far sufficient to blow the wooden doors into the cells

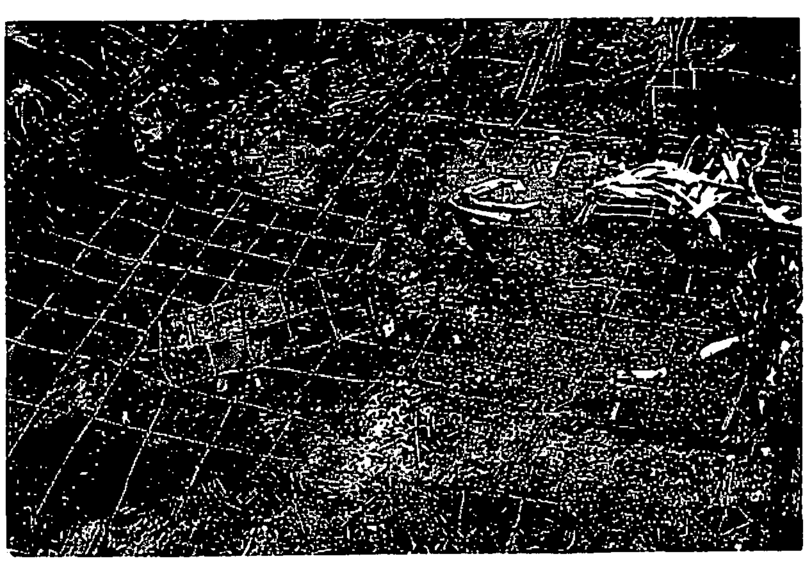

Fig. 5 Overview explosion area (Picture SFOB)

and the fireball engulfed the whole building. The contents of all cells could have been ignited. The local damage however showed clearly that the explosion in storage cell C11 was most severe and dominant. A single explosion in C11 and the sequential sympathetic reactions in the other cells can explain the total damage. In analogy with the garage box analysis, the required local pressure and gas pressure were related theoretically to the required reacted mass of pyrotechnics per second to explain the observed damage and the sympathetic reactions in the adjacent cells. Crucial in the explanation is the reaction velocity of the fireworks in C11. Hypotheses to explain the devastating mass explosion in C11 are:

1. Storage of firework of the transport class 1.1;
2. Combined storage of 1.3G and 1.1 fireworks;
3. Fireworks of the class 1.3G were stored, but due to door impact the packages were severely damaged and the firework obtained the 1.1 characteristics;
4. After initiation of the stored 1.3G class fireworks, temperature and confinement conditions accelerated the deflagration process towards a detonation-like reaction.

None of these hypotheses was proven during the technical research program for the ministry of Justice. It should be noted that UN transport classification tests were performed on a selection of firework articles based on the sales list of S.E. Fireworks. Some of the tested fireworks obtained the 1.1 transport classification. The second comment is that the hearings learned that in C11 6-inch mortar and 6 inch titanium report shells were stored. The tested report shells were classified as 1.1.

In order to learn from the observed effects let us discuss the effects in storage cell 11 in more detail.

- Crater: The evidence for the local pressures is given by the crater. The crater extended to the adjacent cells but the shape of the crater showed that it was caused by a single explosion and that the reactions in the neighbouring cells did not contribute to the crater. Relating the strength of the explosion in C11 with a TNT detonation by the crater dimensions, the explosion strength is in the range of 750 –2000 kg TNT equivalent. Please note that the concrete floor was not breached, so the local pressures in the firework reaction were much lower and not comparable with the pressures in a TNT reaction.
- Acceleration of walls and roof: Due to the shock wave of the explosion the roof will be torn from the walls and the walls from the foundation. Referring to the crack pattern and damage to the floor slab, the walls and roof were broken most probably into small debris. No good prediction of the debris velocities was possible. From explosion test with concrete ammunition storage cells it is known that the velocities are in the range of 100 – 300 m/s. For the C11 reaction, the debris velocity had the same order of magnitude.
- The effect on the adjacent cells: The floor slabs were pushed downwards which proofs that the explosion pressure of C11 expanded through the failed walls to the adjacent cells. The required pressure to deform the floors was definitely sufficient to brake and eject the roofs and walls. However, the explosion pressure of C11 would never be able to throw the roofs of the next adjacent walls. Time is needed for the failure process and in the mean time the explosion pressure in C11 has vented through the door opening. Consequently, the conclusion must be that sympathetic reactions occurred in the adjacent cells.
- Blast pressure and damage: The explosion in C11 produced severe blast, but it must be excluded that the total blast damage in the surrounding living area (equivalent to damage of a 4000 – 5000 kg TNT explosion) was caused by the single explosion in C11. Referring to the licensed quantity to store 7000 kg gross weight (1.4G) fireworks, 50% net weight and estimating a TNT equivalence of 0.5 for the stored fireworks, a rough number for the (maximum) explosion strength is 1750 kg TNT.
- Fireball and firework projections: The observed fireball had a diameter of 135 m. The storage capacity of C11 was too limited that a single explosion in C11 could produce a fireball of this size.

It is clear that sympathetic reaction occurred in most of the cells in the central building (and containers). A likely but still unproven explanation emerge from the above given facts and observations. The explosion in C11 caused failure of the walls, these were blown into the adjacent cells (velocities in the order of 100 m/s). It is most likely that due to the impact, severe friction because of the non-uniformly distributed load, and also combined with the subsequent thermal load, large quantities of fireworks were initiated. High pressures were generated in short time leading to the break-up of the building and contributing to the total explosion blast and fireball.

From the firework disaster in Enschede and the observations made it emerges that international research effort is needed to understand and quantify the explosion effects of firework in bulk storage conditions. Consequences of mixed loading, confinement and scale have to be known to define safety regulations and evaluate the current UN transport classification methodology. It is mentioned that recently a joint research project of TNO, HSL (UK) and BAM (Germany) on these topics was granted by the European Commission.

6. Concluding remarks

- If the situation at S.E. Fireworks would have been in conformity with the licenses, the fire in the workshop of the central storage building never could have escalated to the disaster May 13th, 2000.
- Much more firework of the class 1.3G was stored (and probably also class 1.1) than licensed. The facility was not suited to control and contain the effects.
- The minimal fire resistance of the containers and the lay out of the premises, containers and garage boxes at short distance and opposite to the central building, contributed to the escalation of the fire accident.
- The fireworks disaster is caused by the transition of firework fires into mass explosions. This happened in the garage box M7 as well as in the storage cell C11. Hypotheses were defined but could not be proven so far. Initiatives are taken to study the reaction characteristics of 1.4G and especially 1.3G fireworks in bulk storage conditions. If necessary the UN classification methodology for transport classification have to be modified in order to be suitable for safety regulations of bulk storage and bulk transport of fireworks.
- For the storage and transport of fireworks fire resistant containers have to be required.
- When 1.3G fireworks are stored, impact resistant doors are recommended in order to prevent demolition by close-in firework reactions.

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■目次　上より4番目の論文題名
(誤)The fireworks disaster in enschede → (正)The fireworks disaster in Enschede
■目次　上より5番目の論文題名
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(誤)362 → (正)354
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