Investigation Report

Fire in a Petroleum Tank Being Cleaned

JNIOSH Japan National Institute of Occupational Safety and Health

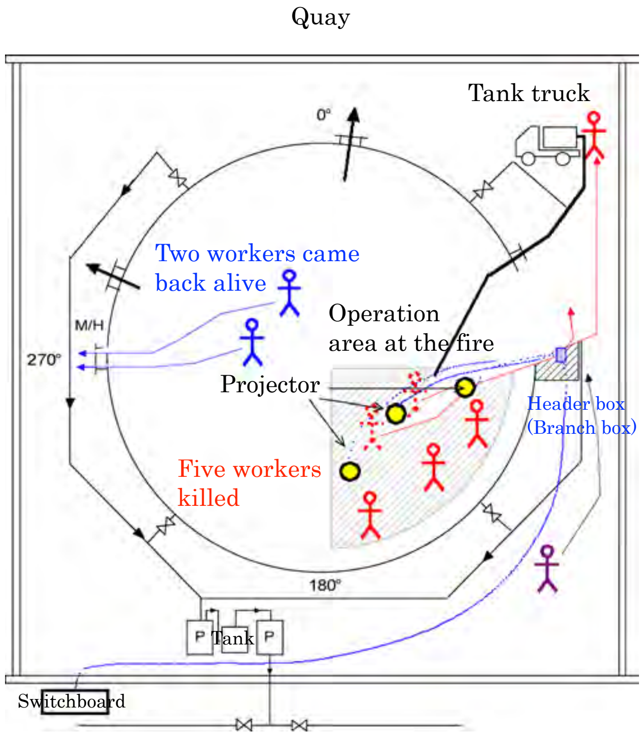
1. Overview

A fire occurred when seven workers were cleaning a floating roof petroleum tank (diameter 75 m, height 25 m, capacity 100,000 kL). The cleaning, part of a legal inspection, removed the solid precipitate (sludge) on the bottom of the tank. The workers entered the tank and began scraping the sludge using scrapers. Two of them escaped from a nearby manhole, suffering minor injuries. The others (five workers), who were working near the fire, were killed (see Figure 1). The surviving workers testified that in the beginning of the afternoon, they heard a sound, and found that a projector had fallen into the sludge. One survivor said, "After the fire started, a pale blue flame began to spread rapidly."

Two of the five workers who were killed might have escaped from the tank, but they had whole body burns. The others (three workers) died in the tank because interior metal heating tubes, electrical wiring, and air hoses for gas masks were in the way of their escape.

The sludge was softened with solvent oil (light oil or heavy oil A) before cleaning. The combustible vapor from the solvent oil was exhausted from two manholes using explosion-proof electric blowers that were just outside the tank. There is a company (local) rule that workers cannot enter a tank when the concentration of flammable vapors is more than 1,400 ppm (the reference value). At 8:30 am on the day of the disaster, 700 ppm of the concentration was measured near the manhole when the workers entered the tank. It seems that the concentration was not measured again after the first measurement. The explosion-proof projectors were sitting on a temporary table in the tank to light the inside. All workers wore waterproof antistatic raincoats and gas masks with air hoses. The temperature was 10.7°C and the relative humidity was 48%. At the first investigation, it was thought that radiant heat from a light bulb or a spark caused by the fall of the projector were the ignition sources, but there was no proof for this.

From disaster case analyses, we have a good understanding of the risk of static electricity being released from metal with an insulating coating, and we investigated the possibility that a scraper was the ignition source.



(a) Location of workers when the fire started

(b) Tank manhole (c) Projector (explosion-proof)

Figure 1. Diagram of the accident

2. Estimation of the ignition source

A photograph of the same type of scraper as the ones used at the disaster is shown in Figure 2. The metal shaft of the scraper is coated with polypropylene plastic. Grabbing the shaft with gloves can cause a charge separation between the gloves and the coating (Fig. 3 (a)). Some of the charge remains in the coating after the shaft is released. This residual charge causes an induction charge on the metal shaft. The induction charge increases electric potential and distributes a charge on the shaft heterogeneously (Fig. 3 (b)). Moving the scraper close to ground metal produces a spark discharge (Fig. 3 (c)). Charge separation is caused not only by grabbing, but also by the shaft rubbing against an object (clothing, duster, etc.).

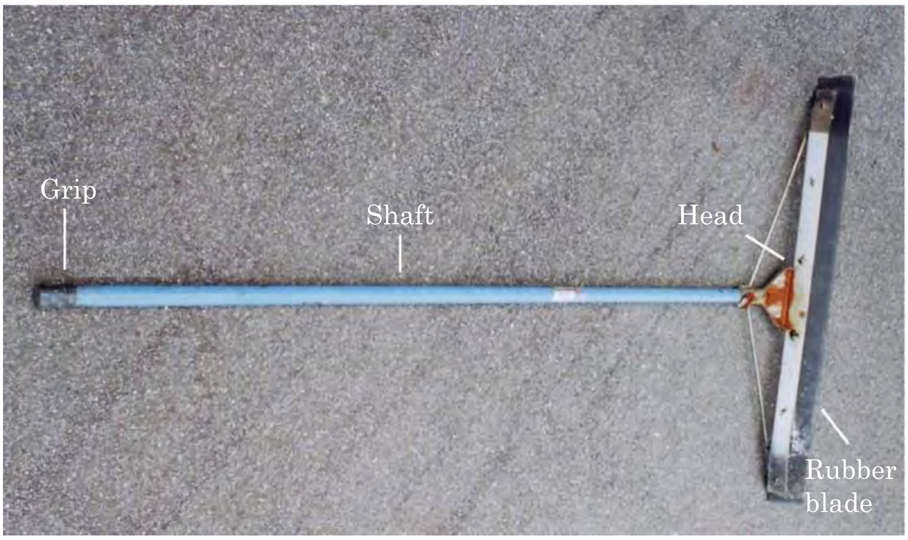
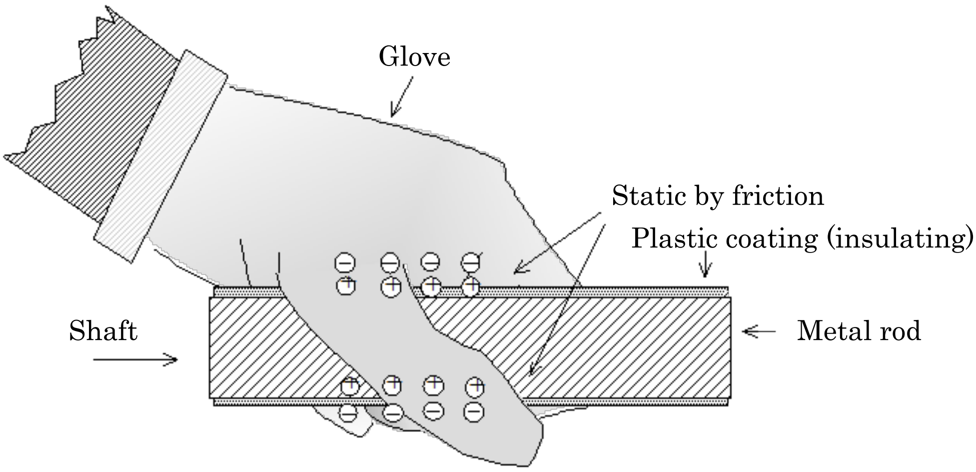
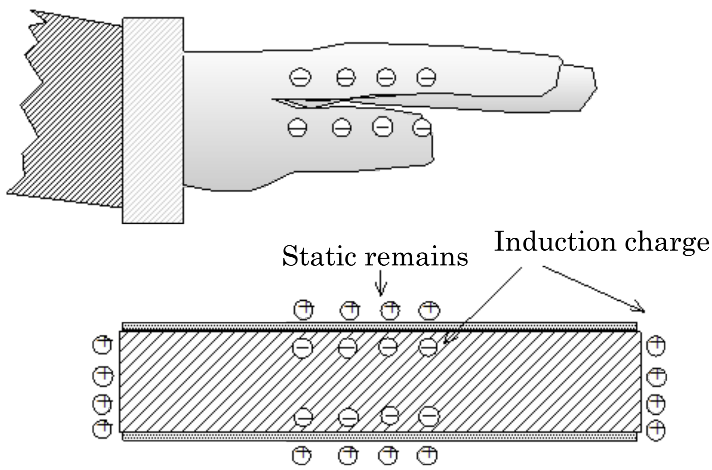


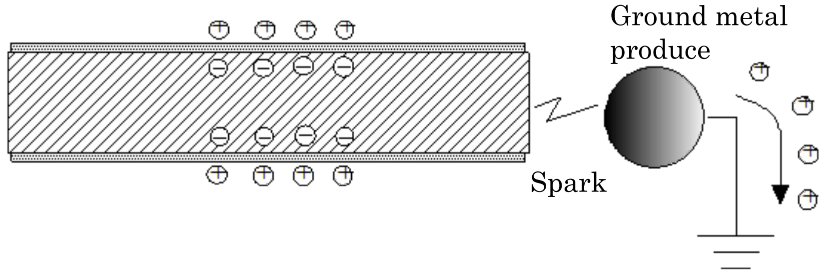
Figure 2. The same type of scraper used



(a) Friction between glove and plastic coating causes static.



(b) A static charge remains in the coating on the metal rod after the shaft is released (induction charge).



(c) Moving the rod close to ground metal produces a spark discharge.

Figure 3. Principle of electrostatic charge on metal parts with an insulating coating (shaft)

3. Samples and Experimental Methods

For our tests, the sample oils used were the sludge collected at the disaster site, as well as petroleum and solvent oils (light oil and heavy oil A). The petroleum was the same quality as the oil in the tank. The same type of scrapers (used and new), the same type of clothing (unused), and the gloves (used) of the victims were obtained.

3.1. Liquid sample

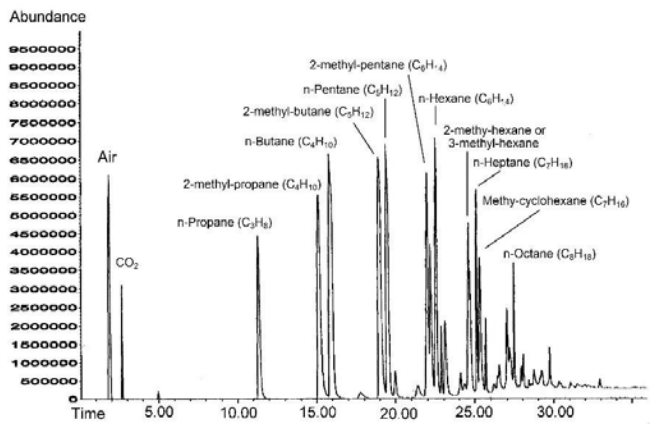
The measured values of the flashpoint, auto-ignition point and the conductivity of the sludge, petroleum, light oil and heavy oil A are shown in Table 1. These values were measured in accordance with the Fire Service Act test manual for hazardous materials, ASTME-659, and the guide for electrostatic safety. Ignition energy of the petroleum vapor was measured by an original method devised by our institute. The result of the experiment: at 13°C the vapor concentration reached 3.7 vol%. The minimum value (0.8 mJ) of ignition energy of this concentration was measured. The concentration of the sludge vapor was not enough to measure ignition energy.

Table 1. Characteristics of the materials

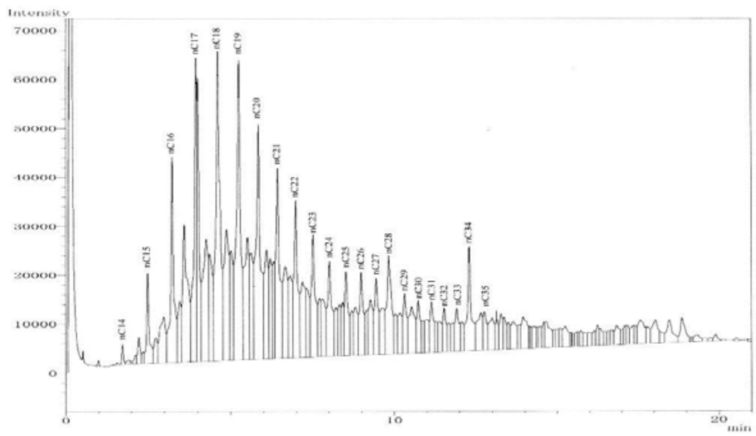
Material	Flashpoint (°C)	Auto-ignition point (°C)	Conductivity	Remarks
Sludge (top layer, liquid)	-6.0	343	1.0×10^{-8}	Sample in the tank
Sludge (bottom layer, mud)	Not measured	Not measured	7.7×10^{-5}	Sample in the tank
Petroleum	-20	233	2.7×10^{-8}	Equivalent from the tank depot
Heavy oil A	68.5	230	1.3×10^{-12}	Solvent oil
Light oil	69.0	221	8.3×10^{-10}	Solvent oil

The volatile flammable vapors from the sludge and residue on the dirty scraper shaft were analyzed. The dirty shaft was simulated by wiping it with sludge and then wiping this off with a cloth. The results of our analysis are shown in Figures 4 (a) and (b). These results show that the hydrocarbons (up to C8) are volatilized from the sludge, and that this formed an explosive atmosphere with the ignition energy (0.8 mJ) at the same temperature as that during the disaster. Also, the existence of petroleum wax (C14 ~ C35) on the shaft was suggested.

Incidentally, industrially purified petroleum wax is used as an electrical insulating material due to its very high resistivity: $10^{13} \sim 10^{17}\ \Omega m$.



(a) Composition of the sludge vapor



(b) Composition of non-volatile components of the sludge (petroleum wax)

Figure 4. Composition of sludge

3.2. Static characteristics of the outfits

The results of measuring the volume resistivity and surface resistivity of the coating on the shaft (peeled from the rod), the gloves and the clothing (antistatic raincoats) are shown in Table 2. Two types of samples of coating were prepared. One of them was cleaned ("clean"). Another was dirtied with sludge and wiped with a cloth ("polluted"). It should be noted that surface resistivity of the "polluted" coating was higher than that of the "clean" coating. Figure 4 (b) shows that the difference in resistivity is caused by the remains of the sludge, which contains much petroleum wax with high insulating properties. This result was difficult to anticipate from sludge conductivity (Table 1). In addition, the amount of the charge generated was measured by the tumbler method defined in the standard for antistatic work wear (JIS T 8118). It was 0.26~0.38 μC. This value is less than the reference value (0.60 μC) in this standard. Therefore, the antistatic performance of the raincoats was confirmed, despite the fact that they did not pass the test in the standard.

The rubber blade of the scrapers is made of chloroprene. A conductive coating was painted on the rubber tip and the shaft to measure the resistance of the scraper. It was 2×10^{12} Ω or more. Therefore, the scrapers were electrically insulated from the floor of the tank.

Table 2. Static characteristics of the non-conductive components

Component	Material	Thickness (mm)	Volume resistivity (Ω·m)	Surface resistivity (Ω)
Shaft coating (clean)	polypropylene	0.5	5.3×10^{14}	6.4×10^{12}
Shaft coating (polluted)	polypropylene	0.5	5.3×10^{14}	1.2×10^{13}
Gloves	vinyl chloride	1.0	3.9×10^{8}	3.9×10^{12}
Raincoat (antistatic)	nylon	0.12	5.8×10^{12}	1.6×10^{12}

3.3. Experimental method for electrostatically charging the scrapers

Based on interviews with workers, the work using these scrapers was reproduced and the potential of the metal shaft of the scraper was measured. For scraping, brushing (Figure 5(a)) motions and rest (Figure 5(b)) were repeated alternately. To reproduce the atmosphere at the time of the disaster, experiments were conducted at 10°C with a relative humidity (RH) of 50%.

3.4. Ignition experimental method

The ability of a spark to cause an ignition near petroleum was examined (Figure 6). Petroleum was poured into a metal pan (60 cm × 40 cm × 10 cm). A scraper was charged from a DC high voltage power source. A spark was created on the inner wall of the oil pan near the liquid surface. This experiment was carried out at 8.2°C at 21% relative humidity (RH).

4. Results and Discussion

4.1. Potential changes and electrostatic energy in the operation

Six pairs of gloves (used), eight scrapers (two were used; six others were unused) were tested. The scrapers were tested under both the "clean" and "polluted" conditions. The potential change during these operations was measured.

A typical example of the potential change is shown in Figure 7. During scraping, the potential barely increased, but the potential did rise the moment there was pause in scraping and the scraper was released from one hand. As discussed in Section 2, an electrostatic charge was generated between the gloves and the coating on the scraper’s shaft, and an electrostatic induction occurred in the metal rod of the shaft from the charge remaining in the coating when it was released. Charge relaxation was slow because the resistance of the rubber is high.

A plot of the maximum value of the potential obtained in each combination is shown in Figure 8. Items 6 and 7 are used scrapers. Figure 8 shows clearly that a "polluted" scraper had much higher potential than a "clean" one. This was an effect from the petroleum wax components. The surface resistivity increase from the wax was a factor in the difference in the potential (as described above).

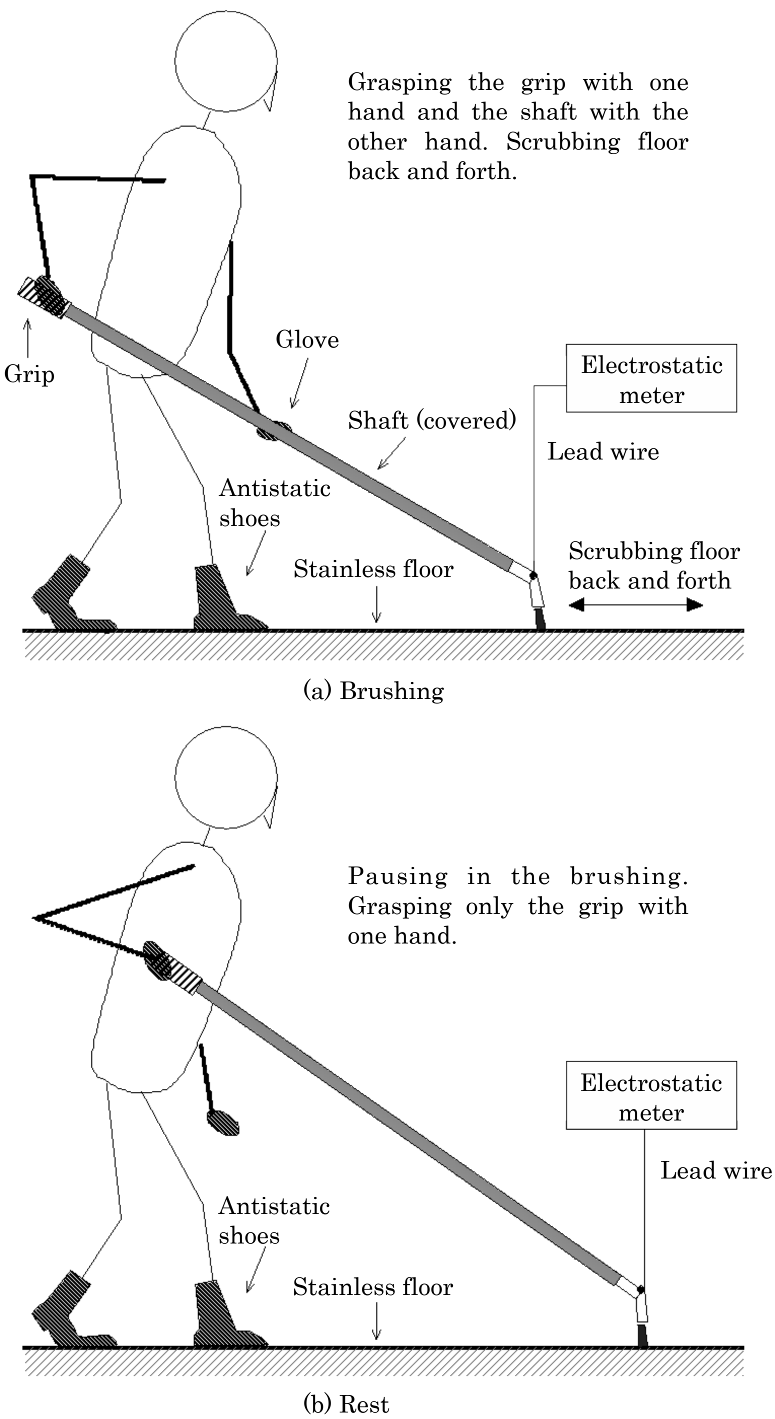


Figure 5. Experiment to determine static electricity generated during scraping

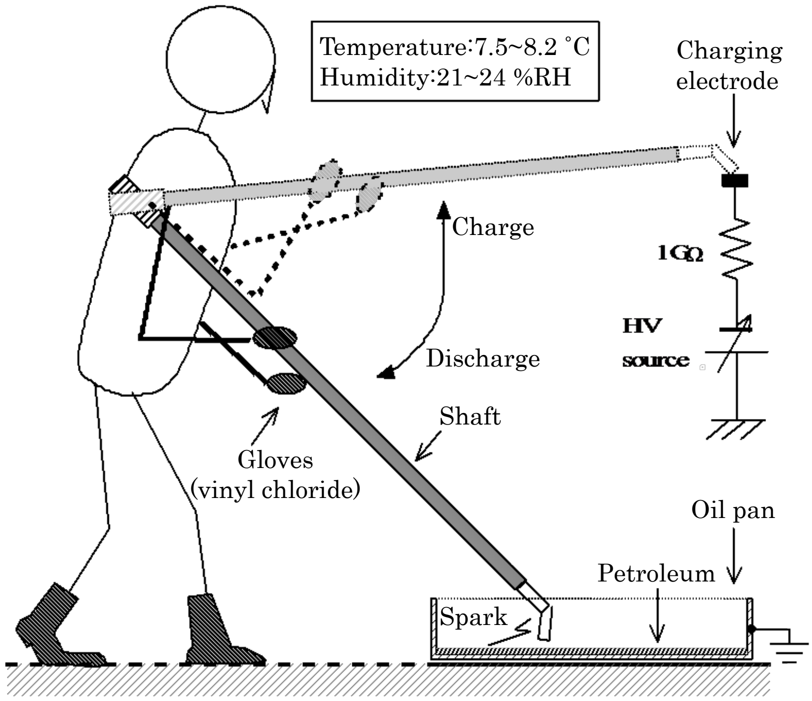


Figure 6. Ignition test of petroleum with charged scraper

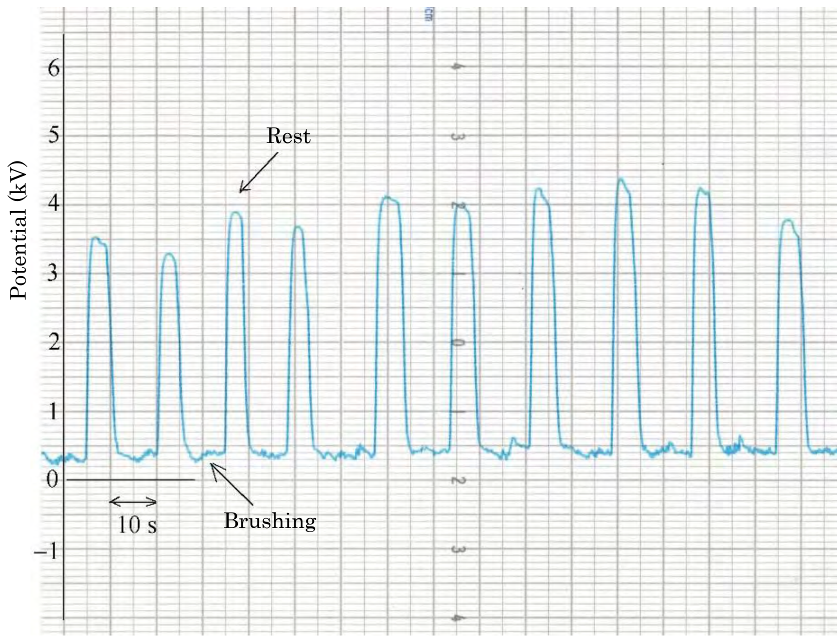


Figure 7. Potential change of the scraper during scraping

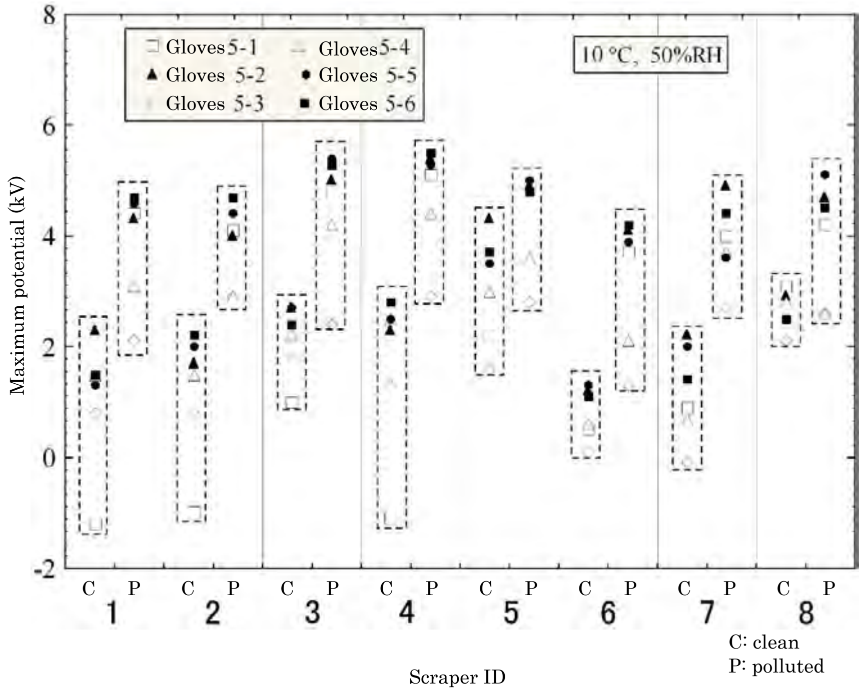


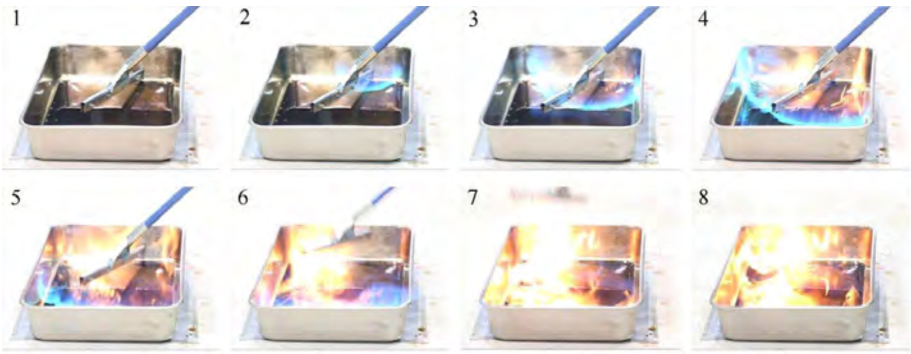
Figure 8. Difference in potential between "clean" and "polluted" shafts

The charge generated was 0.26~0.36 μC. The electrostatic energy was 0.51~0.91 mJ. These values were calculated from the capacitance 52~70 pF of the scraper at rest (Fig. 5 (b)) and the maximum potential 4.7 ~ 5.5kV obtained for the "polluted" scraper. Based on the supposition that the effective contact area between the shaft and the gloves was 100 cm^2, the average surface charge density was estimated to be 36 $\mu C/m^2$ at the maximum. In theory, the charge density of the conductor surface is 27 $\mu C/m^2$ at the maximum because it is limited by discharge into the air. (The dielectric breakdown field of air is 3 MV/m.) However, in this case, thin insulation on the surface of the metal rod suppressed the potential and the electric field at the surface of the insulating layer. This can cause higher surface charge density.

4.2. Ignition test

Scrapers with charging potentials of 5 kV, 6 kV, 6.5 kV and 7 kV were tested for their ability to cause an ignition. The potential of 5 kV or 6 kV could not ignite petroleum. The potential of 6.5 kV and 7 kV ignited and caused the petroleum to burst into flames, as shown in Figure 9. Discharge energy at ignition was estimated to be 1.3 mJ and 1.5 mJ, respectively. These values were slightly higher than the minimum ignition energy (0.8 mJ) shown in Section 3.1. The reason for this difference could be the instability of vapor concentrations in an open space. In Section 4.1, the maximum electrostatic energy obtained by simulating the operation was 0.91 mJ, which is higher than the minimum ignition energy (0.8 mJ).

It is notable that in the testimony (see Section 1) of a survivor he said, "A pale blue flame began to spread rapidly." In this test, after ignition a pale blue flame on the liquid surface was observed. During cleaning in the tank there would have been a flammable premixed gas on the sludge surface.



1: Just before ignition

2-4: Flame propagation in premixed gas (blue flame)

5-8: Diffusion combustion (orange flame)

Figure 9. Ignition of petroleum with charged scraper

4.3. Discussion of the high number of fatalities

The number of people killed in this disaster (five) is high. Two of those killed could have escaped from the tank but all of their clothing was burned and they were almost naked when they were found. One of the raincoats of the victims is shown in Figure 10. The victims wore these raincoats over their work clothes (cotton coveralls). Their clothing was considered to be both antistatic and nonpolluting. Sample pieces (320 mm × 50 mm) of these clothes were tested by the A-4 method for the combustibility of fiber products (JIS L 1091). The results of the test showed that they were "gutted" within

10 seconds. Therefore these clothes were highly flammable. Their characteristics made these clothes easy to burn and caused the spread of damage in this disaster. To prevent a reoccurrence of this disaster, antistatic coverall should be incombustible or flame retardant where there is a risk of fire.

Figure 10. Raincoat**s that the victims wore (antistatic)**

5. Prevention of a similar disaster

This disaster was probably caused when volatile components of petroleum or sludge formed a flammable mixture and a spark ignited that mixture. (There is a high possibility that the spark came from a static electricity discharge from a scraper.) Based on this belief and the information gathered about this accident, the prevention of the same kind of disaster is discussed below, from the point of view of safety management.

5.1. Organizing problems from the viewpoint of safety management

Two points were the main focus: problems with safety management and preventing a similar disaster. These points are summarized below.

a) This fire occurred during the cleaning of a petroleum tank (a part of maintenance).
- Could the fire have been predicted?
- If it could not, why could the fire not be predicted?

b) This operation was outsourced (subcontracted).
- Were the workers aware of the risks?

5.2. Measuring management problems (by factor)

Below is a list of items —human factors, equipment management, work environment, and management factors— that need to be addressed to prevent a reoccurrence of this type of disaster.

(1) Human factors

a) The workers' understanding and awareness of the risks
- All workers must be told at a briefing about hazardous materials, ignition sources, and safe handling methods, etc.

b) Information exchange between workers
- Information about the sources of risk (hazards) and found risks caused by mistake must be shared with each other.

c) Confirmation of emergency response
- To be prepared for emergencies, all workers must confirm and be certain of their respective roles (evacuation routes, communication procedures, etc.).

d) Compliance with regulations
- All workers must wear regulation clothes and shoes (if necessary, antistatic wear).

(2) Equipment management factors

a) Safe handling of equipment (support equipment: the projectors in this disaster)

- Equipment must be used according to the manual (compliance with the conditions of use).
- Equipment must not be modified unnecessarily (in particular, any modifications that affect explosion protection are strictly prohibited).
- Equipment must be installed to prevent objects from falling. (The projectors were not fixed in place. They must be secured to prevent them from falling even if it interferes with work.)
- It is necessary to prevent equipment from igniting, even after a fall (isolated from the sludge, etc.).
- A substitute for the equipment should be used (Find another equipment for this objective).

b) Understanding the characteristics of the equipment

- Workers must understand the characteristics of all equipment (especially to prevent heating by particular use or misuse).
- Explosion prevention and fire protection must be considered separately. These measures must be implemented without fail.

(3) Work environment factors

a) Improvements must be made to the work environment (dark, small or narrow spaces, unstable scaffoldings, etc.).

b) Securing evacuation routes (including location of projectors)

c) Characterization and risk assessment of materials to use

- A prior risk assessment (and confirmation) of the work must be carried out (with workers).
- Workers must understand the characteristics of the substances (including the flashpoint, and the risk factors to reach it, etc). Understanding these characteristics is necessary to anticipate fires, etc. due to the fall of projectors.

(4) Management factors

a) Safety guidance for workers (not only the confirmation of the work procedures but the understanding and attention to sources of risk)

- Daily safety management (such as confirmation before work) must not be routinized.
  - Routine daily meetings decrease awareness of risks.
  - Reconfirm guidance daily. (Absence of a problem yesterday cannot mean that today is safe.)
- Make certain every worker, regardless of experience, understands the operation (purpose, intent, and risks of the work).
- Inform workers of the characteristics of the work environment (safety equipment, the purpose of the work clothes, etc.) (e.g., reason for wearing antistatic clothing).

b) Risk confirmation onsite (understanding of the sources of risk)

- Not only a briefing in the office, but onsite “toolbox” meetings should be held. In those meetings, every worker should confirm and share information on risk factors (hazards).
- Supervisors must guide, educate and monitor workers at the operation site (also related to the revised Industrial Safety and Health Act).

c) Confirmation of supervisor's location

- Supervisors must monitor the work onsite (in order to discover early on the risks of the work in progress).
- Supervisors must not leave the monitoring location during important operations on safety management (or delegate this responsibility, such as appointing an assistant supervisor).
- One supervisor *must not* be responsible for multiple areas that require safety management. (It is easy to miss administrative issues).

d) Discussion of emergency action

- Securing evacuation routes, procedures for escape, firefighting, and the rescue of workers must be confirmed.

5.3. Support based on the Industrial Safety and Health Act

Article 31(2) of the revised Industrial Safety and Health Act took effect in April 2006, and prescribes the duties of an "orderer." The duties (responsibilities) are that when an order is given for modification, renovation or cleaning of equipment or product or to handle hazardous chemicals, the orderer must notify the contractor about occupational safety and health issues to prevent industrial accidents involving these chemicals (informing by ordering party, management duties). For reference, an accident that occurred before the act was revised, shows the importance of the duties, as follows. The duties are the agreement of the importance of informing the contractor and ensuring that these are carried out.

Reference: Revised Industrial Safety and Health Act (Article 31(2))

The orderer of works for alteration of facilities manufacturing or handling chemical substances or preparations containing chemicals and defined by the Cabinet Order, or other works as provided for by the Ordinance of Ministry of Health, Labour and Welfare, shall take necessary measures concerning said substances to prevent workers of contractors of the said works from industrial accidents.

5.4. Problems clarified and future issues

The problems clarified by this investigation and future issues are summarized as follows.

1) Problems clarified

a) The importance of finding and identifying risks in the workplace (hazards overlooked in the planning).

b) The necessity of prior risk assessment for maintenance work.

2) Future issues

a) Setting up methods to identify hazards liable to be overlooked in the risk assessment of normal operations.

In this disaster, the risks during cleaning were overlooked.

- Risks during maintenance operations are hard to identify at the design (or planning) stages.
- The risk surrounding operational mistakes were assumed (and discussed) during the design, but risks in abnormal situations, such as maintenance (cleaning in this case), were overlooked and safety measures were not discussed.

b) Introduction of standards for risk identification

- Considering deviations from standard procedures (for example, misuse of equipment, operational mistakes) is a good starting point for risk analysis (identification and assessment).
- Risks could be identified by using guide words, as follows:
  "Equipment", "Operation", "State" changed by the operation

c) The importance to draw up a safety check procedure at the workshop

- The hazard to identify by inspections must be considered on the risk assessment.
- Explosion prevention must be distinct from fire protection.

6. Summary

The ignition source of the fire disaster in a petroleum tank under cleaning was investigated. As a result, there is a possibility that the fire occurred because the scrapers that were used had an insulating coating that was charged electrostatically by the simple gesture of gripping the handle. The metal parts of the scraper received a high potential by electrostatic induction. Finally, an electrostatic spark generated from the metal parts ignited the volatile components of the sludge.

To prevent a reoccurrence of this kind of disaster, it is important to avoid using cleaning tools that have an insulating coating. In addition, to mitigate potential harm to people, clothing should be flame retardant or incombustible.

Before beginning this kind of operation, an appropriate risk assessment is important. This will be useful when considering the items listed in Section 5 (above).