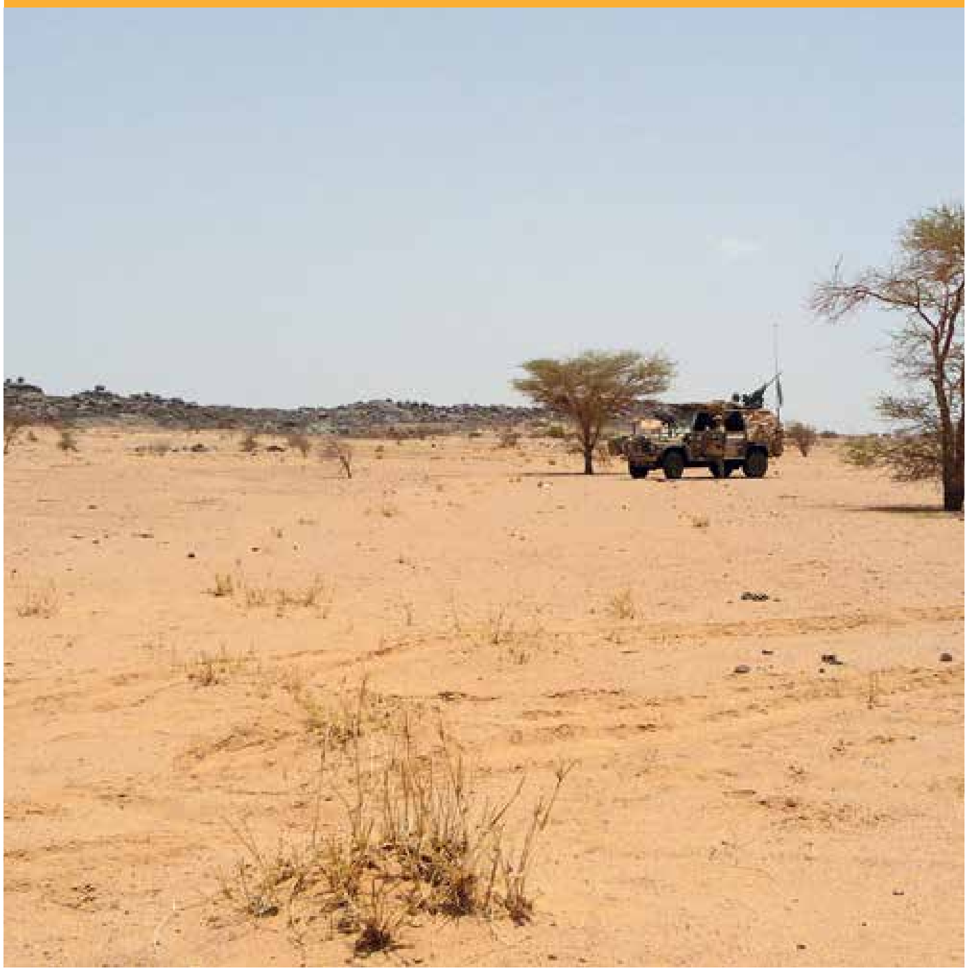
DUTCH
SAFETY BOARD

Mortar Accident Mali



Mortar Accident Mali

The Hague, December 2017

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The Dutch Safety Board

When accidents or disasters happen, the Dutch Safety Board investigates how it was possible for them to occur, with the aim of learning lessons for the future and, ultimately, improving safety in the Netherlands. The Safety Board is independent and is free to decide which incidents to investigate. In particular, it focuses on situations in which people's personal safety is dependent on third parties, such as the government or companies. In certain cases the Board is under an obligation to carry out an investigation. Its investigations do not address issues of blame or liability.

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N.B:
This report is published in the Dutch and English languages. If there is a difference in interpretation between the Dutch and English versions, the Dutch text will prevail.

CONTENT

SUMMARY

The accident

On 6 July 2016, members of a mortar squad from the Airmobile Brigade were conducting an exercise firing 60 mm mortar rounds. During the exercise one of the rounds exploded in the mortar. As a result, the two members of the mortar squad operating the mortar lost their lives and a third one was seriously wounded. The exercise took place near the UN camp in Kidal, Mali, where the Netherlands is participating in the UN Multidimensional Integrated Stabilization Mission in Mali (MINUSMA).

The Dutch Safety Board conducted an investigation into the cause of the mortar accident and the factors that contributed to it. Due to signals related to the quality of the medical care administered to the seriously wounded victim, the Dutch Safety Board also included this aspect in its investigation.

The unintentional detonation of the mortar round

The mortar round exploded (detonated) prematurely at the start of the acceleration in the launch tube. The technical investigation revealed that this premature detonation occurred while the fuze was in 'safe' position. Two mechanisms played a role in this: the occurrence of unstable reaction products within the round that detonated during the launch, and the barrier which does not prevent transfer of reaction to the lead charge in an unarmed position when the detonator fires prematurely. The fact that these mechanisms were able to occur makes it clear that there are weaknesesses in the design of the round. However, the investigation also demonstrated that the unfavourable storage and usage conditions in the deployment zone, with high temperatures and potential penetration of moisture, had a negative effect on the way the round functioned.

The mortar round that caused the accident is part of a batch of ammunition that was purchased in 2006, when a sudden and urgent need arose for a new stock of 60 mm mortar rounds due to the Netherlands participating in the mission in Afghanistan. Due to the urgent nature of this purchase a special procedure was followed, the Foreign Military Sales (FMS) procedure, which means the selection and procurement of the ammunition was placed in the hands of the US army. Since the Netherlands Defence organisation assumed that the US army was using the requested ammunition and had therefore adequately tested it for usability and safety, the usual quality tests were omitted.

However, the purchase contract that was signed on behalf of the Netherlands government at the end of 2006, explicitly mentioned that the ammunition concerned was not being used by the US army, that the US government could not guarantee its quality and safety and was not able to supply the technical specifications requested by the Netherlands. Nevertheless, the Netherlands signed the purchase contract and thus blindly made the purchase.

Internal quality steps, such as type classification, were also skipped after the purchase. Signs indicating problems with the purchased ammunition were not followed up on. Defects were discovered during the inspection prior to use, and irregularities came to light during initial performance tests. These recommendations merely resulted in changes to the instructions for use. Moreover, Defence appears to presuppose a longer lifespan and a higher maximum temperature for storage and use, than was prescribed by the manufacturer.

A part of the mortar rounds purchased in 2006 was not used during the mission in Afghanistan and was stored in the Netherlands until they were used in Mali. The intervening years were not used to conduct those tests on the rounds that were omitted when the rounds were purchased. Some of the stock was put into use again by the Dutch armed forces seven years after it was purchased, without any more knowledge about the ammunition's quality and safety being available than was the case when it was purchased.

The investigation revealed that, in Kidal, the ammunition was stored in a metal shipping container that did not comply with the transport and storage conditions established by Defence. Due to the lack of adequate protection from the sun and climate control, the maximum temperature prescribed by the arms manufacturer was exceeded considerably on multiple occasions. The prescribed temperature limit was also exceeded during the fatal firing exercise.

To summarise, the Board concludes that the omissions with respect to the concern for quality and safety of the ammunition during the three successive phases of procurement, storage and use, cumulatively formed the context in which the accident was able to occur.

Medical care for military personnel in the deployment zone

The two mortar gunners operating the weapon at the fatal moment were killed instantly. This was not the case for the third victim, who was seriously wounded by shattered shrapnel. Directly following the accident, colleagues rushed to the scene to administer first aid to the seriously wounded victim. The investigation revealed that the initial treatment at the scene of the accident was adequate. Following the initial stabilising interventions and a brief intermediate stop at a French first aid post, the victim was brought to the so-called "role 2 facility", a UN hospital intended for trauma treatment.

At the role 2 facility, which was manned by Togolese doctors, the staff was hesitant and insufficiently decisive, did not perform a visible assessment of the victim's condition and the seriousness of his injuries, and failed to apply the prescribed treatment principles for war injuries. Following the operation the victim was transported to Gao by helicopter, where he stayed briefly before being transported to the Netherlands.

When the military base in Kidal was being set up, it appeared that doubt already existed regarding the suitability of the Togolese hospital for providing medical assistance to victims of combat operations that complied with Dutch military standards. During the approval process, it was found that not all aspects could be tested and there was doubt regarding the deployment readiness and availability of the necessary materials. Therefore

Defence decided not to use the Togolese hospital for standard care, but did deem it suitable for Damage Control Surgery if its own timelines could not be met and in extreme circumstances. This is remarkable, because it is precisely this form of surgery that imposes the highest demands on personnel and material readiness. Based on the findings the Board concludes that the role 2 facility was wrongfully approved for Damage Control Surgery. Lastly, the Board finds that the assessments of the role 2 facility were carried out by Defence doctors with little experience. Consequently, Defence lacked an acute view of the quality of the medical care.

During medical planning for military operations in the area of Kidal, structural improvised use was made of a hospital that did not comply with Dutch military standards. It is clear to the Board that a mass casualty accident, conceivable in the high-risk area around Kidal, would far exceed the medical capacity of the Togolese hospital.

CONSIDERATION AND RECOMMENDATIONS

The Dutch armed forces have three tasks: to protect their country's territory and that of its allies; to promote the (international) legal order and stability and to provide assistance during disasters and crises. The Netherlands in this context participates in many other missions, besides the deployment in Mali. With respect to the deployment of the military organisation related to these tasks, the government and Parliament have detailed procedures in place for informing Parliament about individual missions or to acquire (parliamentary) support prior to deployment. In the latter case Parliament discusses with the government the conditions under which a mission is deemed justified. The government is in this connection responsible for assessing the risks of deploying personnel as effectively as possible and for taking measures, if any.

This investigation explains why a mortar round could explode prematurely during an exercise in Mali, fatally wounding two Dutch military personnel and seriously wounding a third. In addition to the technical explanation of the premature detonation, this report also addresses the mechanisms within the Defence organisation that resulted in ammunition purchased with urgency for a mission in Afghanistan being used years later in the mission in Mali under the wrong conditions, without the right checks having been conducted. At the time the consequence thereof manifested in the form of a fatal accident it also appeared that the medical care administered to the seriously wounded Dutch soldier did not comply with Dutch military standards.

The Dutch Safety Board acknowledges that military missions inherently involve risks. Failure to accept any risk whatsoever would make the mission de facto impossible. Yet, when preparing, planning and implementing military operations, account must be rendered of the (potential) risks, mitigating them as much as possible and making any residual risks as explicit as possible, and subsequently deciding whether or not to accept them. The investigation reveals that with regard to the mission in Mali the risks were inadequately examined or were explained away. During the years prior to the accident, the Defence organisation did not succeed in guaranteeing the safety of the ammunition concerned. Signals from worried staff were not heeded. Instead a paper reality was created in which matters appeared to be in order. This was not the case.

Managing the safety of the ammunition during its procurement, management and use, and arranging suitable and thus, safe medical care in a mission zone, are two very different task areas that both are the responsibility of the Dutch Defence organisation. Yet this investigation has revealed important similarities in the way in which Defence takes decisions and sets priorities within parts of the organisation. When new ammunition was introduced for the Dutch army, progress of the missions in Afghanistan and Mali took precedence over attention to safety; in the same way, the arrangement of appropriate and, thus, safe medical care in Kidal was of secondary importance to the mission's progress.

The investigation into the mortar accident in Mali is the third Defence investigation the Dutch Safety Board has conducted in the past three years. The Board previously investigated the 336 squadron of the Royal Netherlands Air Force[1] and the shooting accident in Ossendrecht.[2] Although these three investigations are not representative of the Defence organisation as a whole, the Board finds it remarkable that the high pressure on the armed forces played an explicit role in all the cases investigated. Moreover, the Board observes an insufficiently responsive approach to dealing with alerts and reports of defects. A constant willingness to learn from accidents also appears absent.

Due to their characteristic "can do" mentality, military personnel are prepared to accept risks while endangering their lives, even when the circumstances are far from optimal. Where the operational focus in the field constitutes an important added value, this attitude creates the risk that, during the decision-making processes at the higher level, missions are accepted where the associated risks cannot be sufficiently managed in advance. Based on its investigations the Board concludes that the Defence organisation is inclined to establish priorities and take decisions in line with what is desired, rather than to clarify the (residual) risks and accept them once substantiated. When it comes to problems "in the field", the primary underlying cause must therefore be sought in the way in which the decision related to the mission was taken, and not in the operation in the deployment zone.

Current geopolitical developments make it likely that the Dutch armed forces will continue to be structurally overburdened in the decades to come. In the Netherlands, the government bears ultimate authority over the armed forces and therefore, primary responsibility for the deployment of military personnel lies with politicians. Political consideration of the deployment of Dutch military personnel in UN missions should expressly also involve responsibility for the safety and health of the military personnel sent out to perform the political decision. This involves mutual dependence. The government must take a balanced decision, but can only do so based on adequate information from the department the decision concerns. This requires a self-aware organisation, which provides adequate recommendations on which deployments and risks are justifiable, regardless of international ambitions and its sense of responsibility. The government should create the conditions in which the Ministry of Defence can fulfil this role.

1 www.safetyboard.nl
2 www.safetyboard.nl

Recommendations

The Board has found serious shortcomings in the concern for the safety of Dutch military personnel during the mission in Mali, both with regard to management of the ammunition and to military healthcare. Previous investigations conducted by the Board have brought similar patterns to light. Therefore the Board is concerned about the Defence organisation's virtually indiscernible motivation to learn from events.

A culture of safety and safety awareness form important pillars for a safe defence organisation, in the Netherlands and beyond. The Minister of Defence is ultimately responsible for this matter.

The Board issues the following recommendations to the Minister of Defence.

1. Ensure risk management is suitable for the current and future deployment of Dutch armed forces. Implement the changes necessary to form an organisation that actively learns.
   a. Invest in an organisational structure and culture in which management is receptive to critical signals from staff. Provide operational management that converts reports of safety shortcomings into improvements. Encourage free communication about safety risks to create broad safety awareness within the defence organisation.
   b. Use incidents and accidents to learn lessons. Provide the capacity to evaluate incidents and accidents in an objective and independent manner, selecting and implementing points for improvement.

2. Prior to taking a final decision about participating in an international military mission, as well as when changes to missions occur, clarify whether, and in which way, the safety and health of the military personnel to be deployed will be safeguarded. Make this safeguard a prerequisite. Fulfil the role of ultimate responsibility for the safety and health of Dutch military personnel during international missions by, for example:
   a. drafting clear, verifiable criteria for the safety and medical care of Dutch military personnel during international missions;
   b. fully assessing the consequences for the safety of Dutch military personnel and the medical care available when taking crucial decisions about changes to international missions;
   c. actively monitoring safety aspects during missions, not from a distance, but in the deployment zone;
   d. increasing the effectiveness of current checks and balances related to the safety of Dutch military personnel by, for example, investing in substantive knowledge and the independent positions of inspectors and investigation commissions.

3. Improve care for weapons and ammunition so that they are suitable for use in the conditions that may occur during missions.
   In particular, ensure that:
   a. the mortar rounds currently in stock are checked to establish whether all safety procedures were followed correctly and - if this was not the case - carry them out;
   b. the established shortcomings in the organisation and regulations within the ammunition chain are eradicated;
   c. the storage, transport and use of ammunition is carefully documented, so that in the event of any seemingly unsafe performance all the ammunition concerned is traceable;
   d. the procurement process for weapons and ammunition is carefully documented and archived, so that it is possible to reconstruct how decisions were taken;
   e. the remaining stock of 60 mm HE80 rounds is no longer used;
   f. other countries that use these rounds are informed about the findings of this investigation.

4. Improve the acute medical care available during international military missions by:
   a. further defining the quality of medical care that must be available for Dutch contributions to UN missions and developing criteria for assessing this quality. When doing so, do not accept any dependence on medical care provided by UN Member States that is not able to meet with Dutch military standards;
   b. establishing the availability of the required care potential as a precondition before allowing a mission to begin;
   c. being aware of the consequences to medical care when relocating/extending missions;
   d. improving the care-related assessment of role 2/3 treatment facilities through standardisation and using specialist medical personnel with knowledge and experience of military trauma treatment and trauma surgery.

mr. T.H.J. Joustra
Chairman Dutch Safety Board

mr. C.A.J.F. Verheij
General Secretary

1 REASON FOR THE INVESTIGATION AND PURPOSE

During a mortar exercise conducted in Mali on 6 July 2016, a 60 mm calibre round exploded in its mortar. The accident occurred near the camp in Kidal, a forward post almost 300 kilometres from Gao, where the main base of the Dutch contingent of the UN mission is located. In the accident two army personnel lost their lives, a 29-year-old sergeant first class and a 24-year-old lance corporal, both from the Thirteenth Infantry Battalion of the Eleventh Airmobile Brigade in Assen. A 23-year-old private first class from the same battalion was seriously wounded.

1.1 Why is the Dutch Safety Board conducting an investigation?

The legal duty of the Dutch Safety Board is to establish the causes of accidents or near accidents, with the aim of preventing similar kinds of accidents recurring in the future. The Dutch Safety Board explicitly does not focus on guilt or responsibility, but considers which lessons can be learned from what happened. The Dutch Safety Board has statutory powers that allow the Board to collect information it deems relevant.

Besides the devastation resulting from the dramatic outcome of the mortar exercise it has also led to uncertainty among colleagues of the military personnel involved with whom the Board has spoken. How could the accident have happened? Were the weapon and ammunition the military personnel were using safe? The questions illustrate how the accident has impacted on the feeling of safety experienced by the military personnel involved and their colleagues. The above questions must be answered in order to restore trust. Any structural safety-related shortcomings that come to light during the process could lead to improved safety for military personnel.

On 26 July 2016, the Dutch Safety Board decided to investigate the mortar accident in Mali for both these reasons - the affected feeling of safety and potential improved safety.

The defence organisation has decided not to use the weapon system while the investigation is being conducted.

1.2 Investigative approach

First and foremost, the Board reconstructed how the accident occurred. Following the accident an investigator from the Dutch Safety Board visited the location. The Board used statements drafted by the Royal Netherlands Marechaussee, reports from the Commission of Investigations (CvO) (Defence) and photographs and video recordings of the accident made by a member of the mortar squad. The Board also interviewed various people who were involved.

The Board commissioned the Netherlands Forensic Institute (NFI) and the Netherlands Organisation for Applied Scientific Research (TNO) to perform a technical investigation. Use was also made of information related to legislation and regulations and documents concerning the mortar and the rounds.

1.3 Reading guide

The Dutch Safety Board conducted an investigation into the cause of the mortar accident and the factors that contributed to it. Due to signals related to the quality of the medical care administered to the seriously wounded victim, the Dutch Safety Board also included this aspect in its investigation.

Because of the international relevance the technical part of the investigation that focuses on determining the cause of the accident is translated in English. The other parts are not translated.

2 THE ACCIDENT

The accident

The evening before

On the evening of Tuesday, 5 July 2016, a preliminary briefing on the exercise to be conducted the following morning took place in Camp Nassau in Kidal. The plan was for part of the Special Operations Land Task Group (SOLTG) to practice a combat scenario in which a group of quads (four-wheel drive, manoeuvrable terrain vehicles) would make combat contact with an enemy unit, while at the same time a mortar group would bombard the same enemy with rounds. Two medics[3] and one general military nurse (AMV) would be present at the exercise to provide any medical assistance needed. The necessary equipment was already placed in the vehicles to facilitate a quick start the next morning. For the mortar squad, which had an armoured patrol vehicle (Bushmaster) at its disposal, this equipment consisted of, inter alia, a 60 mm mortar and four ammunition boxes, each with ten mortar rounds. The AMV loaded a medic bag on to his quad, and a stretcher for transporting the wounded.

The first deployment of the mortar group on 6 July 2016

The following morning, the mortar group left the base at 07:00 hours and arrived at the shooting location about 10 minutes later in order to ready it. The location is open ground, located at 2.5 km from the base. A public road runs through the field, which had to be guarded on both sides to prevent passing civilians entering the danger zone. For this exercise, shooting targets were placed against a stony ridge at about 900 meters from the shooting position (Figure 1). The mortar squad consisted of four mortar gunners, each with their own function. The group had been trained in the Netherlands to operate an 81 mm mortar. Three gunners are necessary for this type of mortar, and perform the roles of munitions handler, gun layer and unit commander. The squad commander maintains supervision. However, in Mali, the smaller 60 mm mortar is used, which is operated by two instead of three mortar gunners. This is why there was one man too many at the mortar exercise. In this case the extra man took photographs and made video recordings of his colleagues shooting. The fixed role distribution was released during the exercise, in order to alternate the two persons operating the mortar.

3 The special forces medic is a military personnel member with the medical secondary task of administering first aid to sick or wounded colleagues in a tactical, hostile environment. He or she is the specialist in treating trauma injuries, such as bullet wounds and injuries resulting from explosions.

Figure 1: Exercise location: in the background the stony ridge where the targets were positioned (Photo: Defence)

At 07:30 hours, the members of the mortar squad started the first series of shots.The procedure is as follows: the gun layer sits on the floor with the mortar launch tube between his legs. He uses his hands to aim the mortar and try and hit the target (in this case about a kilometre away). The second man, the loader or assistant, is in a position lying down next to the gun layer. He takes a mortar round from the ammunition box, removes the packaging, removes the safety cover, inserts it into the muzzle of the mortar barrel and drops it. A fraction of a second later, the round is fired from the mortar barrel at high speed. The mortar gunners look where the round explodes in the field, after which the gun layer adjusts the aim, in order to hit the target more accurately with the next shot.

After the gunners fired ten shots in this way, the loader took over the mortar. A colleague took up position next to him to assist him. This duo fired seven shots from the second ammunition box. The seventh shot of this series was a so-called 'dud'. This is a round that leaves the mortar in the normal way, but does not explode the moment it impacts the target or the ground. As no unexploded ammunition may be left on the ground, the mortar gunners interrupted the shooting exercise to give specially trained soldiers (demolition experts) from the Engineers the opportunity to detect and destroy the projectile. There were still three of the ten rounds left in the second ammunition box. The men loaded these rounds back into the vehicle.

The mortar group now took a break to let the demolition experts do their job. The men used the time to remove the packaging from the rounds in the third and fourth ammunition boxes. Meanwhile, the quad group prepared to join in the exercise.

At 08:00 hours, the quads started their manoeuvres. The intention was to combine the exercise with that of the mortar group after an hour, but things went differently. At 09:11 hours, one of the quads overturns, resulting in a passenger injuring his ankle. The AMV decided to take the man back to camp to examine the nature of the injury. He took one of the two medics with him.

After the break

After the departure of the AMV, the medic and the injured person, there were too few quads left to continue the exercise. However, for the mortar squad the accident with the quad was no reason for terminating the shooting exercise. Moreover, the absence of the AMV and the medic was not considered problematic, as they were able to reach the location from the nearby camp within ten minutes in case of an emergency.

At 09:27 hours, a hundred and five minutes after the break caused by the dud, the men restarted the shooting exercise. They invited the squad commander to operate the 60-mm mortar as the gun layer.

The squad commander is not part of the mortar group, but he did find it useful to be instructed in the weapon's use by the experienced mortar gunners.

The squad commander, aided by the loader, launched four mortar rounds from the third ammunition box. The men placed the ammunition box with the remaining six grenades back in the vehicle and cleaned the mortar barrel with the cleaning rod. Two members of the mortar squad retrieved the fourth and last ammunition box containing ten rounds, with their packaging already having been removed. To equalise the number of rounds in the last two ammunition boxes they took two rounds from their ammunition box and placed them in the third ammunition box, with the six remaining rounds. The two other members of the mortar group took the place of the shooter and the loader.

The fatal explosion

The gun layer held the mortar barrel between his legs. To his right lay the loader, who loaded the mortar barrel with the rounds. Two meters behind the duo, a third member of the mortar squad was watching his colleagues' proceedings, while the fourth member of the mortar squad was recording videos with his camera approximately eight metres to the left of the firing position.

The men shot two mortar rounds in quick succession in this configuration. No anomalies were noted. At 09:37 hours the loader took the third grenade from the box. He placed the round into the muzzle of the mortar and released it. A fraction of a second later the round exploded at the bottom of the mortar. The two men operating the weapon died instantly. The man behind the gunners was thrown backwards by the pressure wave but was not injured. The man with the camera was hit by shattered shrapnel and suffered serious injuries to his abdomen and thighs.

3 CAUSE OF THE MORTAR ACCIDENT

This chapter describes the technical part of the investigation that focuses on determining the cause of the accident. In order to understand the successive research steps an explanation is provided of the operating principles of the mortar and mortar round, including that of the fuze.[4]

3.1 Operation of the mortar and mortar round

3.1.1 Mortar

A mortar is a weapon that consists of a metal launch tube with a base plate that is positioned on the ground by a gunner, held at an angle and directed at the target the gunner wants to strike. When the mortar is aimed at the target, a loader drops a mortar round into the launch tube. At the bottom of the mortar there is a firing pin, which strikes the percussion primer at the bottom of the round. A propellant (powder) charge in the tail assembly of the round ignites as a result of the impact and drives the round at high speed out of the tube by means of gas pressure. The mortar round follows a high-arching trajectory in the air, after which it explodes at the moment it hits the ground or an object.

The mortar used in Mali was a *Hotchkiss-Brandt* Commando type. Figure 2 is a picture of the 65 cm long mortar. The base plate of the mortar is seen on the right side of the picture; the left side of the picture shows the muzzle (which can be sealed with the black cover).

Figure 2: 60 mm Hotchkiss-Brandt Commando type mortar. (Picture: TNO)

4 The explanation here given is concise; a detailed description of the functioning of the weapon system is presented in Appendix C (Dutch report).

3.1.2 Mortar round

The used mortar round is designated HE 80 (Figure 3). These rounds are produced by the Bulgarian manufacturer Arsenal JSCo. This company produces both the shell and the fuze (the ignition device at the tip of the round). The production of the shell is based on technical design drawings provided to Arsenal JSCo about twenty years ago by the Austrian arms manufacturer Hirtenberger Defense Systems.[5] The production of the fuze is based on design drawings obtained from the Soviet Union about thirty years ago.

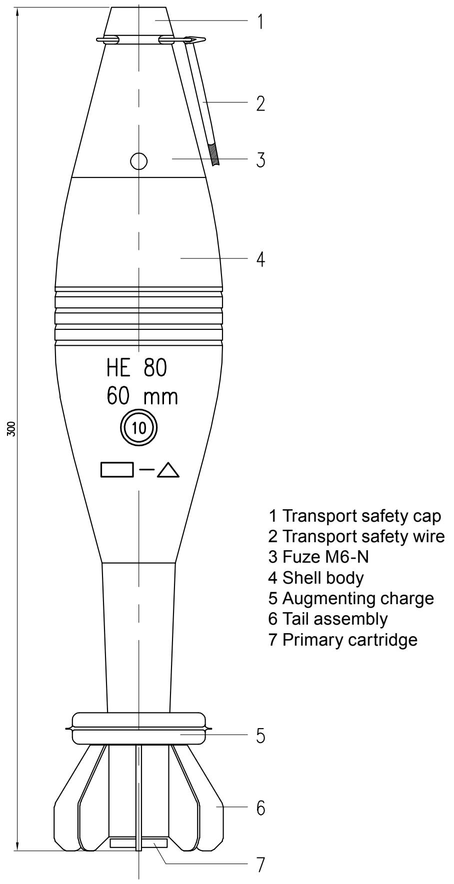


Figure 3: HE 80 mortar round (Source: Ministry of Defence)

Mortar round design

The round consists of three parts. The central part, the shell body, is a convex cylinder that contains the main charge (TNT). At its lower end the shell body is connected to the tail assembly with propelling charge (primary cartridge and augmenting charge), to fire the round from the mortar. Fins on the tail assembly provide stability during flight. The fuze is mounted on top of the shell body and contains a mechanism with a dual function: it guarantees safe handling and firing of the round and it initiates the detonation of the explosive charge at the desired moment. Therefore the fuze mechanism has a 'safe' (or unarmed) position and an armed position.

5 On enquiry, Hirtenberger Defence Systems maintains that it does not perform monitoring or inspection of the design; it is not involved in the processes, developments, sub suppliers, manufacturing steps and quality control at Arsenal.

Safety
The basic safety principle of the round is based on the physical separation between the explosive main charge and the relatively small initiation charge (the detonator) in the fuze. The main charge consists of the relatively insensitive 'secondary' explosive TNT. The initiation charge in the detonator consists of a highly sensitive 'primary' explosive. For safety reasons, the size of the initiation charge is small and not powerful enough to initiate the main charge by a shock. Therefore, a lead charge and a booster are situated between the initiation charge and the main charge. This initiation sequence of explosives is referred to as 'explosive train' and is shown schematically in Figure 4; left in safe position ('off line'), and right in the armed position ('in line'). In safe position, the sensitive detonator is out of line with the firing pin, lead charge, booster and main charge, so that the detonator cannot be struck by the firing pin, and furthermore, is separated from the lead charge by a barrier. This explosive train interrupter consists of a metal disk, which prevents initiation of the lead charge - booster - main charge, if the detonator for some reason fires prematurely.

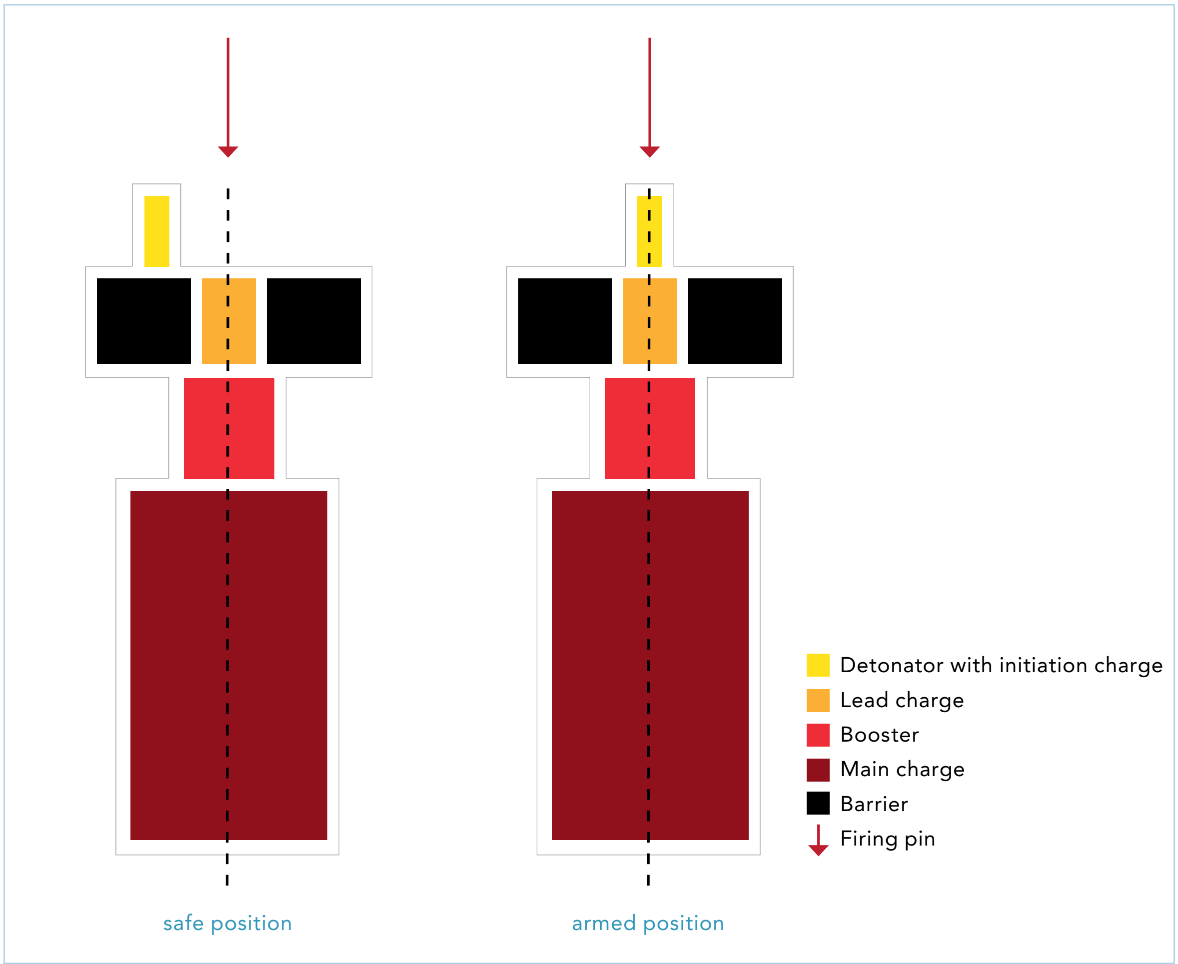


Figure 4: Explosive train in safe position (left) and in armed position (right). (Source: TNO)

When fired, the fuze moves to the armed position ('in line', on the right in Figure 4). The arming mechanism inside the fuze is set in motion by the acceleration of the round during launch.[6]

The arming mechanism holds a delay, which ensures that the round arms during flight when it is no longer accelerated by the propelling charge. The purpose of this delay is to generate distance between the round and the operators in order to prevent them from being hit by the lethal effects of a round exploding prematurely.

In the armed position, the detonator containing the initiation charge has moved in line with the firing pin and the lead charge (Figure 4, right). When the round hits a target, the firing pin strikes the detonator, which sets off the explosive train from lead charge, via the booster to the main charge. As a result of the explosion (detonation) of the main charge the steel casing of the shell body shatters into around five hundred fragments. Combined with the blast wave of the explosion the fragments deliver the desired destructive effect on the target.

3.2 Cause of the accident

3.2.1 Introduction

Three different sources of information were available to the Dutch Safety Board for its investigation into the direct cause of the accident. Firstly, there are the witness accounts. At the time of the accident there were six people in the immediate vicinity of the mortar. Two of them were killed. Three of the four survivors saw the accident happen. Moreover, these three persons were directly involved in the shooting exercise and could therefore also describe the events that preceded the accident.

One of the members of the mortar squad took photographs and recorded a video of the actions of his colleagues. Of the 24 mortar rounds fired during the exercise, he photographed two and recorded nine on video, including the fatal explosion. The pictures and video footage constitute the second source of information.[7]

Both the witness accounts and the images make it absolutely clear that an explosive reaction of ammunition occurred inside the mortar. The round and the mortar fragmented as a result of the reaction. Pieces of metal were scattered around the firing location at high velocity. Some of the fragments were found in the clothing, the body armour and the bodies of the victims. The remnants of the mortar and the recovered fragments represent the third source of information for reconstructing the cause of the accident.

6 The operation of this arming mechanism is described in detail in Appendix C (Dutch report).
7 Photographs and video footage of the actions on site immediately after the accident were also preserved.

3.2.2 Analysis of the images and debris

Analysis of the video footage of the accident shows that the descent of the fatal round in the mortar was normal (Appendix E). At the bottom of the launch tube contact with the firing pin ignited the primary cartridge. At that moment, or very shortly after the round began its acceleration in the tube, the energetic main charge (TNT) detonated.

The first video frame after the reaction occurs shows both the burning powder of the primary cartridge and a black cloud of combustion products. Because this image could only be made up to 0.033 seconds after the start of the reaction[8], an expansion rate of combustion products can be calculated that points at a detonation[9] of the main and booster charge of the round.

One of the photographs taken after the accident shows the tail assembly of the mortar round, which was found at about 10 meters from the site of the explosion. In the immediate vicinity of the tail assembly is a horseshoe-shaped object of which the shape and size correspond with that of an augmenting charge, the additional propellant cartridge that was originally attached to the tail assembly (Figure 5).

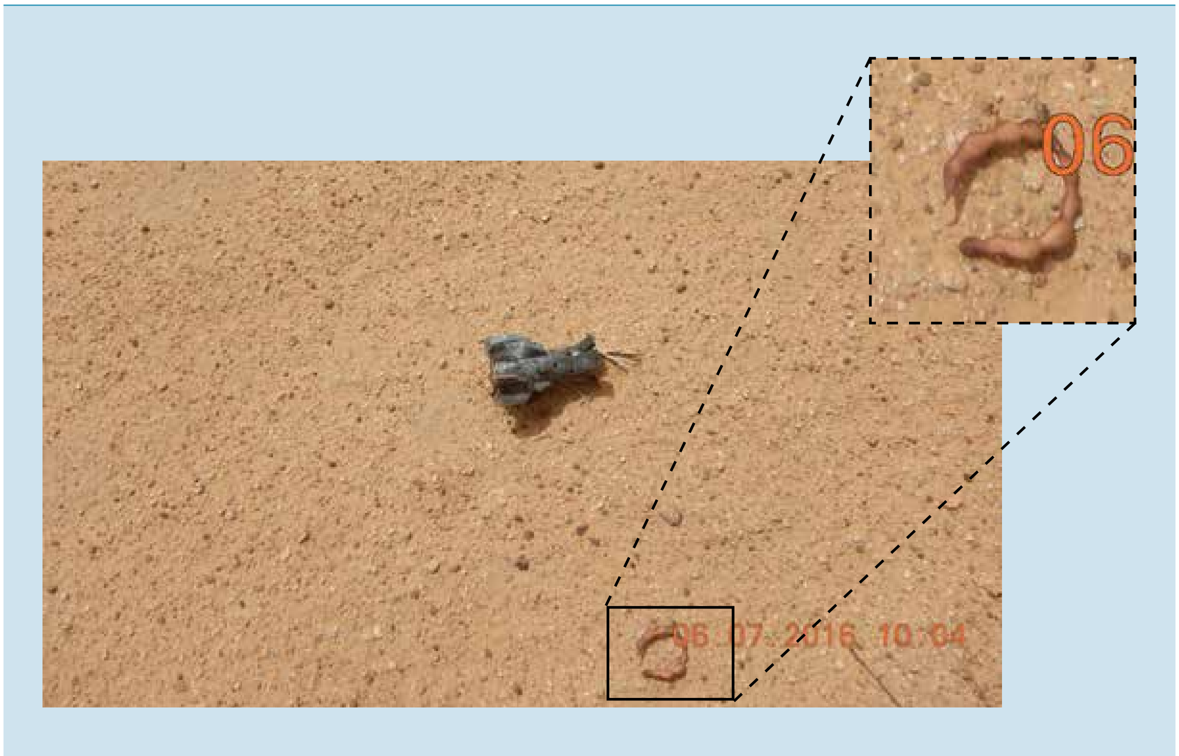


Figure 5: Object near the remnants of the tail assembly, photographed after the accident.
(Picture: Ministry of Defence)

8 The GoPro camera was set to a frame rate of 30 frames per second
9 See Appendix E for an explanation of the terms explosion, deflagration and detonation.

Under normal firing conditions no recognisable remnants of an augmenting charge can be found because the charge is completely consumed. If the horseshoe-shaped object is indeed the remnant of the augmenting charge this would demonstrate that the combustion process of the propellant charge was interrupted by the detonation of the main charge.

The damage pattern to the mortar (see Figure 6) and to the tail assembly of the round, and an imprint of the fragments of the steel shell body on the inside of the launch tube, point to a detonation of the main charge.[10] Moreover, no traces of unburned or partially burned explosive compounds (TNT) were found around the site of the accident, as would be expected in case of a deflagration or a fire.

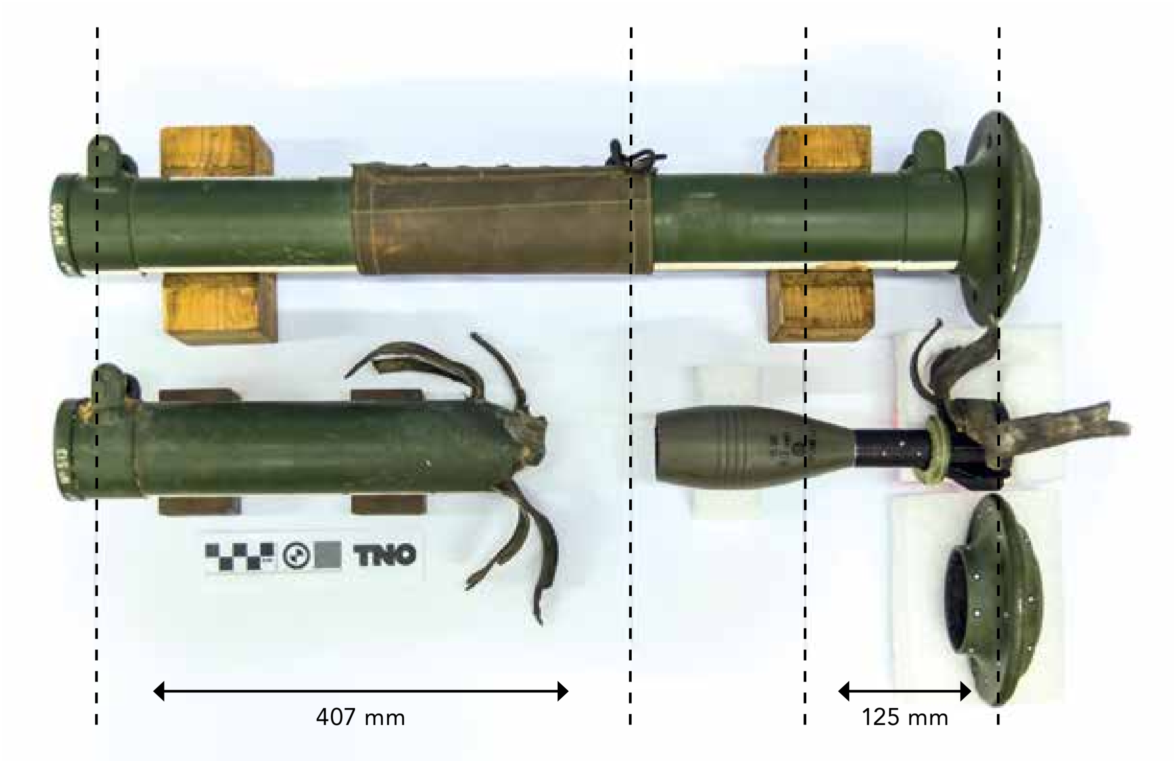


Figure 6: Position of the mortar round aligned with the remnants of the muzzle end and baseplate end of the mortar. An intact mortar is positioned above the reconstruction for comparison. The presented dimensions relate to the muzzle and baseplate ends of the mortar. (Picture: TNO)

Reference tests, performed by the Knowledge Centre for Weapon systems and Ammunition (KCW&M), show that only a detonating round can cause this kind of damage (see Appendix E). Figure 7 shows, on the left, the remnants of a mortar destroyed by the detonation of a 60 mm mortar round. On the right, Figure 7 shows a mortar in which a mortar round has deflagrated. Due to the internal pressure the mortar expands and the sight unit is blown off, but the mortar does not fragment.[11]

10 See Appendix E.
11 KCW&M Project Report on the 60 mm Mortar HE- 80 CvO, Document No. 26240, December, 2016.

Figure 7: Mortar after an internal detonation (left) and deflagration (right) of a 60 mm mortar round based on reference tests by KCW&M. (Pictures: KCW&M)

Interim conclusion
The descent of the fatal mortar round in the mortar was normal. Contact with the firing pin on the baseplate ignited the propellant charge in the normal way. At the start of the acceleration in the launch tube, the main charge of the round detonated prematurely.

3.2.3 Scenarios

The question then arises: what triggered the premature reaction of the main charge, as described above. Possible causes can be divided into human action and technical causes.

Human action may include sabotage - deliberately disabling the ammunition - or human error when operating the mortar. Technical causes can be divided into malfunctioning of the weapon (the mortar) or the round. This chapter discusses these scenarios in more detail.[12]

3.2.4 Human action

The mortar squad followed an ad hoc training course for the 60 mm mortar in Mali.[13] Since this course was brief and concise, incorrect operation of the weapon being the cause of the accident cannot be ruled out on forehand.

The most common fatal operating error is a so-called double loading.[14] In the case of double loading, a round remains at the bottom of the mortar without triggering of the propelling charge (a 'misfire'). If the gunners fail to notice a misfire and drop a second round on top of the first one, then it is possible that one or both rounds react inside the mortar.

12 Some scenarios, which can be refuted or considered (highly) unlikely, are provided in Appendix K.
13 The mortar squad was trained in the Netherlands to operate an 81 mm mortar.
14 See Appendix M: Previous accidents involving mortar rounds (Dutch report).

The possibility of double loading can be excluded for several reasons. Firstly, it is unlikely that the operators would have failed to notice a misfire. Throughout the exercise they operate in a calm and controlled manner, while two or three colleagues are also continuously monitoring their actions. Since the mortar rounds are gravity fired with a fixed firing pin instead of being trigger fired (where the gunner manually fires the round after loading) it is not possible for the gunner to 'forget' to fire a round. Secondly, no duplicate parts or fragments were recovered from the site of the accident indicating the presence of a second round. Thirdly, a second round loaded in the mortar would have had a shorter travel in the tube than the travel of a first round to the bottom of the tube. An analysis of the video footage of the accident reveals that a reduced travel did not occur (see Appendix E). Strong evidence that there was no double loading is presented by the imprint in the percussion primer of the primary cartridge in the recovered tail assembly of the mortar round, see Figure 8. This imprint demonstrates that the mortar round was not dropped on top of a previous round but that it reached the firing pin on the baseplate of the mortar.

Figure 8: Imprint of the percussion primer of the primary cartridge in the tail assembly of the mortar round (left), with a microscopic magnification of the percussion primer (right). (Picture: TNO)

There are also no indications of incorrect actions that could have resulted in over pressurising the weapon. According to witnesses all rounds were provided with no more than one augmenting charge, in line with regulations,[15] as is observed on the video footage. The gas pressure resulting from one augmenting charge is well below the burst pressure of the launch tube.[16] Throughout the exercise, the firing rate of the rounds is also well below the prescribed maximum of twenty rounds per minute.

Finally, it can be concluded that it is highly unlikely that the accident was caused by sabotage or criminal activity.[17]

15 Fire Support Bulletin 07V2013, MORTAR 60 mm HOTCHKISS-BRANDT TYPE COMMANDO, C-OTCo with number 2013024622, 13 December 2013.
16 Ministry of Defence internal investigation.
17 See Appendix K (Dutch report).

Interim conclusion
The accident was not caused by double loading or any other incorrect operation of the mortar or the mortar round. Sabotage or criminal activity are highly unlikely.

The mortar squad was not aware of all the instructions for use of the mortar rounds. There was little knowledge with regard to the short arming distance of the round[18] and the related operational limitations. An analysis of the course of the mortar exercise[19] shows that some of the rounds were removed from their packaging well in advance and were placed in the sun, in open boxes, without a cover. This makes clear that the mortar squad was not aware of the instruction to shield the ammunition from solar radiation, or was at least not aware of the importance of it.

The effect of heat on the functioning of the ammunition is addressed later in this chapter.

3.2.5 Technical causes

Besides human error, various other possible causes for the accident are conceivable. The Dutch Safety Board compiled as many alternative scenarios as possible and investigated their probability. The following scenario categories are considered:

1. Mortar round incompatible with the mortar;
2. Irregularities of/in the mortar;
3. Arming of the fuze, before use, due to shocks and/or vibrations from a fall or during transportation;
4. Manufacturing defects of the fuze.

The Dutch Safety Board concludes that the scenarios in category 1 and 2 are (highly) unlikely or impossible.[20]

The scenarios in category 3 and 4 all relate to the fuze and follow the same line of reasoning, namely that at the time of the accident the fuze was in armed ('unsafe') position and that the acceleration during launch resulted in the fatal detonation.

In order to determine whether the scenarios in category 3 and 4 could have occurred it is important to verify whether the fuze of the accident round was actually in the armed position. Recovered remnants of the fuze were examined to provide an answer to this question. The following items are considered:

1. a part of the inner wall of the fuze;
2. the firing pin;
3. the housing of the slider;
4. the explosive train interrupter (metal barrier).

18 Chapter 4 (Dutch report) provides an explanation of the limited arming distance of the mortar round.
19 Appendix D (Dutch report).
20 For brevity of the main text they are elaborated in Appendix K (Dutch report).

The part of the wall, the firing pin and the slider housing were recovered from the scene of the accident along with other fragments; the barrier is recovered from the body armour of one of the victims. For the investigation the recovered parts were compared with analogue parts from two fuzes that were fired inside a TNO bunker, respectively, in armed and in unarmed position.

1. The inner wall of the fuze

A prominent imprint of the slider and slider spring is visible on the inner wall of the fuze from the round involved in the accident. The slider and slider spring also made an imprint on the inner wall of the fuze tested in armed position, but it is less prominent than that of the fuze from the accident, see Figure 9.

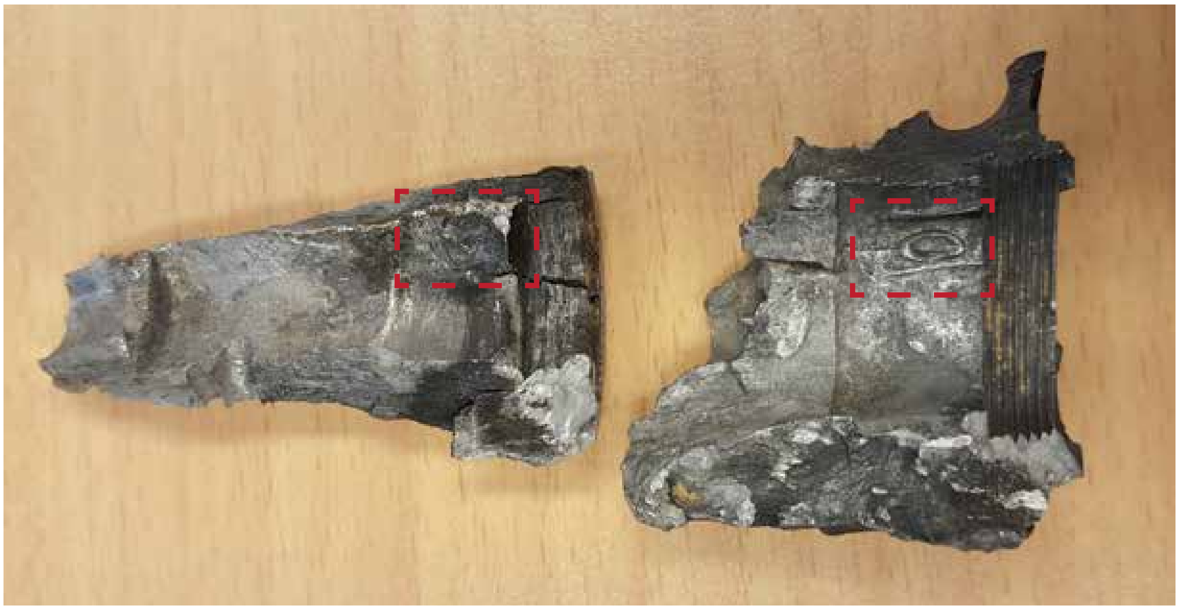


Figure 9: Imprint of the slider and slider spring on the inner wall of the fuze tested in armed position (left) and on the inner wall of the fuze from the round involved in the accident (right). (Pictures: TNO)

The difference between the two imprints can be explained with Figure 10. When the detonator fires, the slider breaks into two parts: the part on the left of the detonator is accelerated to the left and the part on the right of the detonator is accelerated to the right. Since in armed position the slider and slider spring are positioned at some distance from the inner wall of the fuze (Figure 10, left), firing of the detonator leaves an imprint on the inner wall that is less prominent than in safe position, where the slider and slider spring are already in contact with the inner wall (Figure 10 right). Accordingly, this is a strong indication that the accident round detonated in safe position.

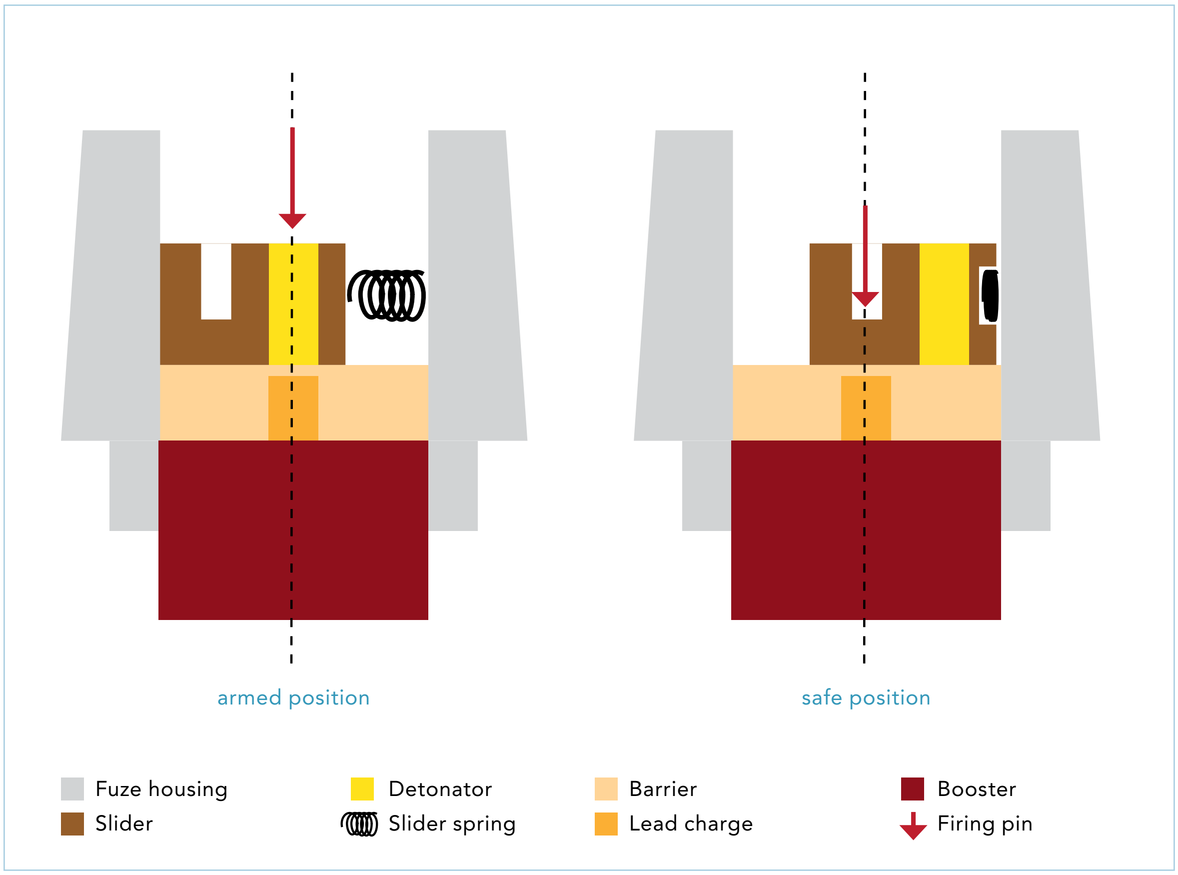


Figure 10: Cross section of (a part of) the fuze in armed position (left) and safe position (right). (Source: TNO)

2. The firing pin

When the detonator fires in safe position (right in Figure 10) the section of the slider with the recess for the firing pin is accelerated to the left. The firing pin will significantly deform or shear off because its tip resides in the recess of the slider. Figure 11 shows three firing pins, an unused firing pin (left), the firing pin from the test in armed position (centre) and the firing pin from the accident round (right). The latter has sheared off just below the lower thickened section. This is a strong indication that the accident round detonated in safe position.

Figure 11: Different firing pins: left an unused firing pin, in the centre a firing pin from the test in armed position and right the firing pin from the accident. (Picture: TNO)

3. The slider housing

The lower end of the slider housing is circular with a rectangular recess in the centre in which the slider moves, see Figure 12 (left). When the detonator fires due to the impact of the firing pin the housing deforms. In armed position this deformation is imposed on the centre of the housing. The deformation is virtually symmetrical in radial direction, see Figure 12 (centre). The remnants of the slider housing from the accident round also display deformation, see Figure 12 (right). This deformation deviates from the radially symmetric and centred deformation that is found in the test in armed position. This is an indication that the accident round detonated in safe position.

Figure 12: Different appearances of the lower end of a slider housing: an unused housing (left), a housing from the test in armed position (centre) and the housing from the accident (right). (Pictures: TNO)

4. The barrier

The effect of a detonation of the detonator on the barrier (explosive train interrupter) depends on the position of the detonator at the moment of detonation. In armed position the detonator has moved to the centre of the barrier and is in line with the lead charge (see Figure 10, left). The shock from the detonator propagates through the barrier and initiates the lead charge, creating a large central hole in the barrier, see Figure 13 (left). In safe position the detonator is positioned eccentric on the barrier (see Figure 10, right). When the detonator fires this leaves an imprint in the top of the barrier. As a result of inadvertent transfer through the barrier the lead charge reacts and the thin metal layer covering the lead charge is blown away. This also creates a central hole, which is however smaller than that in armed position. The imprint and relatively small central hole are observed in an explosive transfer test in safe position (Figure 13, centre) during which the lead charge reacted without initiating the booster. A similar imprint and small central hole were also observed in the barrier of the accident round (Figure 13, right).

Figure 13: Different appearances of the top of a barrier: from the test in armed position (left), from the test in safe position (centre) and from the accident (right). The barrier from the accident was recovered in one piece, but was cut in half for further examination. (Picture: TNO)

The presence of an imprint adjacent to the centre and the absence of a large central hole in the centre of the barrier, show that the accident round was in safe position when it was launched.

Additional evidence is provided by the variation of the deformation of the central hole over the thickness of the barrier. In armed position the detonator is in line with the lead charge. When both charges detonate, the explosive force on the barrier is largest in the area where both charges are in close proximity. Therefore, the radial deformation is larger at the top side of the barrier than at the bottom side, where the deformation is determined only by the lead charge, see Figure 14 (left). This variation of radial deformation over the thickness of the barrier is not observed in the central hole of the barrier from the accident round; this is clearly cylindrical, which indicates a reaction of the lead charge only. This observation also demonstrates that the accident round was in safe position at the time it was fired.

Figure 14: The barrier from the test in armed position (left), and that from the accident (right). The barrier from the test in armed position is broken as a result of the detonation, the barrier from the accident was recovered in one piece, but was cut in half for further examination. (Picture: TNO)

In summary it can be concluded that the deformations observed on all the recovered parts of the fuze of the accident round (wall, firing pin, slider housing and barrier) unequivocally point to the fact that the accident round was in unarmed ('safe') position when it was fired.

Interim conclusion
The accident round detonated when the fuze was in unarmed ('safe') position.

This conclusion, that the fuze of the round was in unarmed, 'safe' position, leads to the next question: how could the round have detonated. To answer this question an investigation was conducted into the type and functioning of the energetic compounds in the round.

Initiation of the energetic charge
Information about the type of the energetic compounds inside the round was obtained directly from the manufacturer Arsenal JSCo.[21] The Dutch Safety Board had this information verified.[22]

The main charge of the round consists of the shock- and friction-insensitive secondary explosive TNT. It is virtually impossible for TNT to detonate by the shock (set back) of the launch because this shock is far less powerful than the explosive shock that is required to initiate TNT.[23] Initiation due to the propellant charge is also very unlikely, as demonstrated through testing by the Ministry of Defence following the accident. To set off the main charge a strong explosive shock is needed, which can only have originated from the detonating booster (see Figure 5 at the beginning of this chapter).

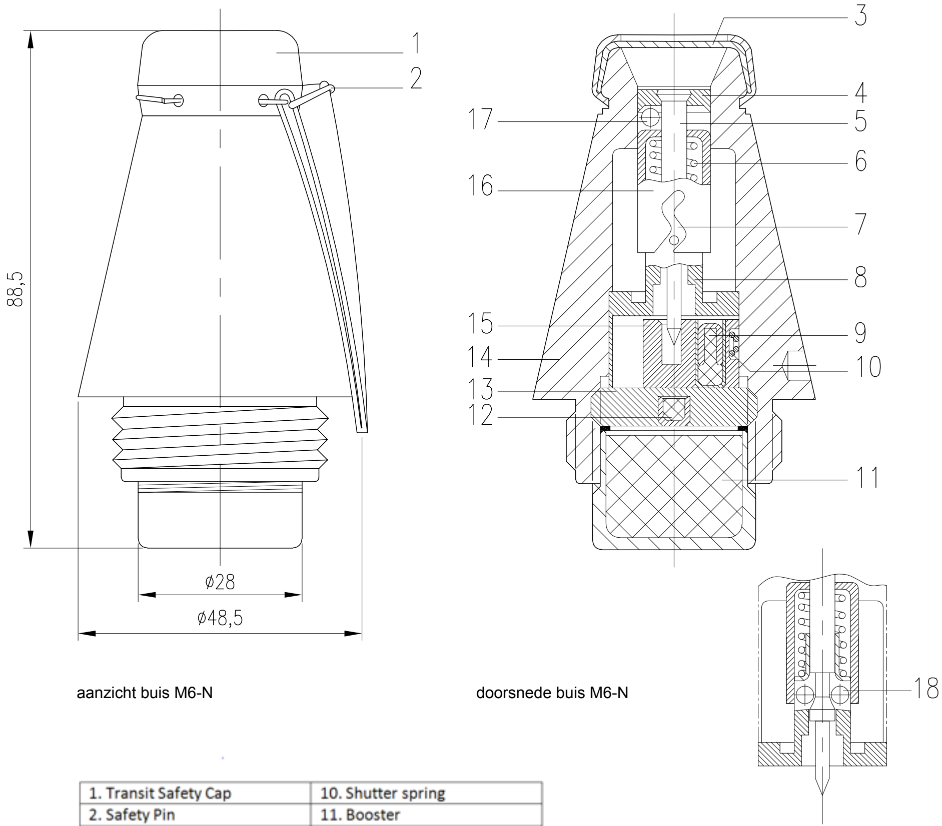
The booster consists of the secondary and insensitive explosive RDX[24], which also requires a powerful shock to set it off. According to the principle of the explosive train (see paragraph 3.1.2) this shock is provided by the lead charge residing in the barrier. The lead charge consists of PETN (penthrite). This explosive compound is more sensitive than TNT and RDX, but less sensitive than primary explosives, and is also set off by means of a shock. In design mode of the fuze this shock originates from the primary explosives in the detonator (primer), which ignites when struck by the firing pin, at the moment the round hits the ground or the target.

Based on this analysis of the energetic compounds it seems unlikely that the explosive train was initiated by a component other than the detonator.

21 Visit to Arsenal on 9 February 2017.
22 Verification of the elements was performed by the TNO using a Fei Nova NanoSEM 650 and Noran System Six microanalysis system. The composition was established using a Buke D8 Advance X-ray diffractometer.
23 Trajectory analysis is applied based on the muzzle velocity and the length of the launch tube; the acceleration is approximately 400 g for a duration of 15.6 ms and 1,100 g for a duration of 9 ms for augmenting charge 0 and charge 1 (see Appendix E).
24 Trinitroperhydrotriazide.

The detonator consists of impact- and friction-sensitive explosive compounds (see Appendix H for a description of these compounds). For a properly functioning fuze these compounds ignite when struck by the firing pin, converting a combustion into a detonation, which sets off the lead charge. This in turn initiates the rest of the explosive train.

According to the ammunition safety principle the explosive train must be aligned ('armed') to allow for detonation of the main charge.[25] The above makes clear that the round was in the unarmed ('safe') position instead of the armed position. In that case there is a physical barrier inside the fuze between the detonator and the lead charge, in the form of a steel disk (Figure 15), which should prevent unintentional transfer of reaction. Because the barrier in the accident round could not prevent detonation of the main charge it is subjected to microscopic examination.[26]



1. Transit Safety Cap	10. Shutter spring
2. Safety Pin	11. Booster
3. Membrane	12. Transfer charge
4. Limiter	13. Closing plate
5. Firing Pin	14. Fuze body
6. Spring	15. Shutter
7. Zigzag groove	16. Arming Delay Sleeve
8. Firing Pin Housing	17. Delay Sleeve Retaining Ball
9. Duplex detonator	18. Firing Pin Retaining Balls

Figure 15: The M6-N fuze with detonator (9), barrier (13) including lead charge (12).

25 See Appendix C (Dutch report).
26 P.A. Hooijmeijer, E. Kroon, R.H.B. Bouma, TNO Memorandum 17EM/0041 Microscopic examination of the M6-N fuze barrier, January 2017.

Figure 16 shows a schematic cross-section of the barrier that is screwed into the lower end of the M6-N fuze. There is a cup in the central recess, which contains the lead charge. The central recess is closed at the top by a thin metal layer (marked A in Figure 16).

When the fuze functions normally, this layer is blown away by the detonator, and the lead charge is set off by the shock wave. The latter propagates via detonation of the lead charge into the booster. The detonation of the booster initiates the main charge, resulting in detonation of the round.

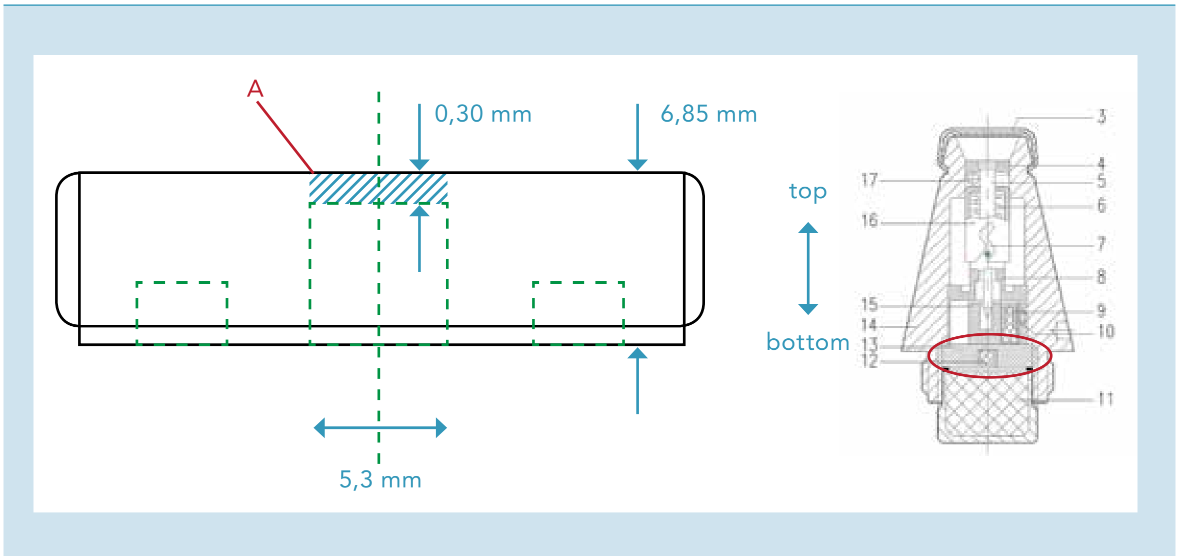


Figure 16: Schematic cross-section of the barrier (not to scale). (Source: TNO)

Figure 17 displays the explosive trains for a fuse in unarmed (left) and in armed position (right), occurring, respectively, before and after the launch of the mortar round.

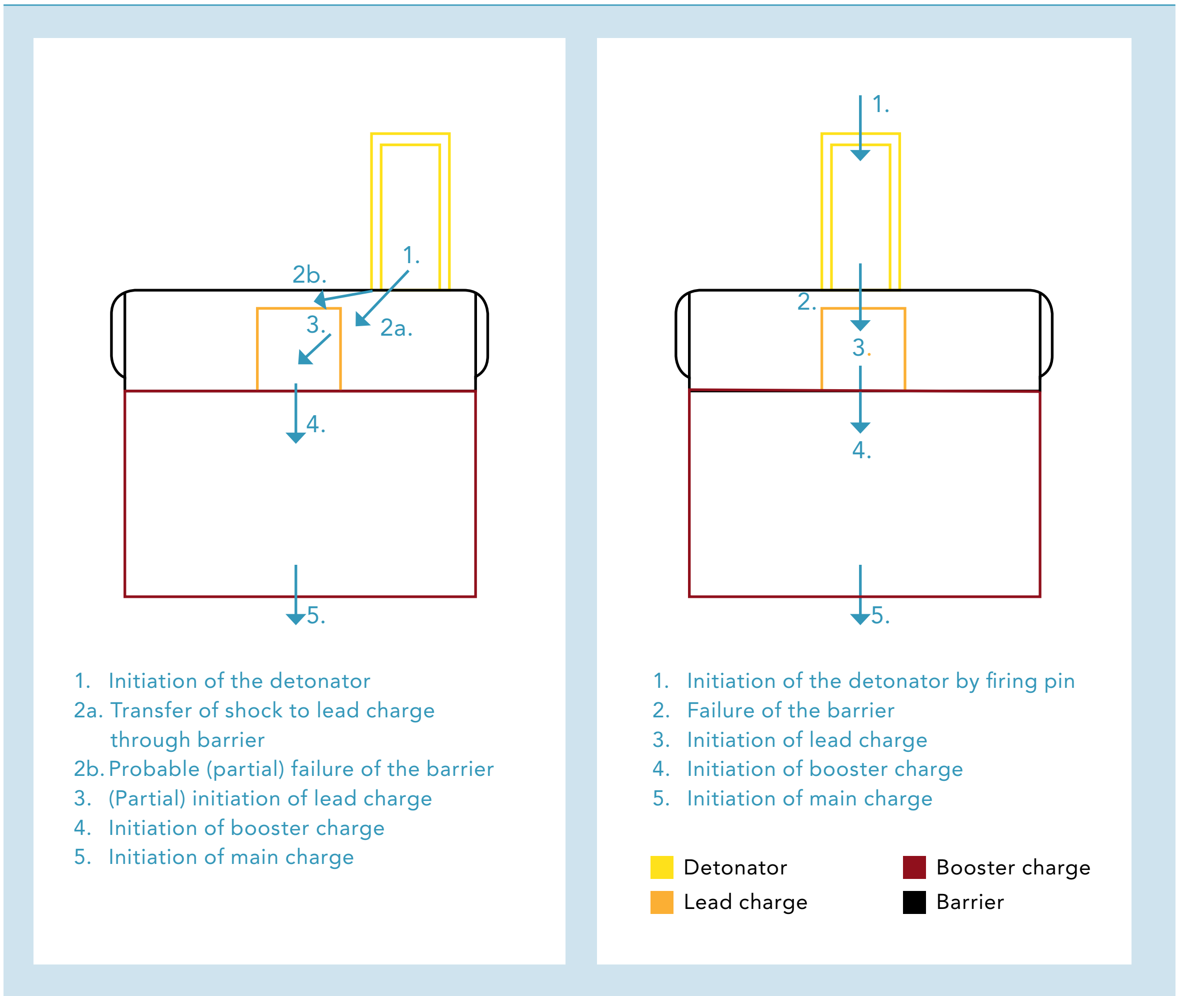


Figure 17: Explosive train for an unarmed fuze (left) and an armed fuze (right). (Source: TNO)

Microscopic examination of the central hole in the barrier provided several indications that the shock wave propagated top down, i.e., from the detonator above the barrier to the lead charge below the barrier.[27]

The barrier was cut in half over its centre line with a diamond saw, to allow for visual inspection of the central hole. Details of the two parts of the barrier were subsequently photographed, which provided indications how the metal layer above the central recess (layer 'A') was blown away.

Figure 18 shows the central hole of one of the barrier parts. A thin edge can be seen (A) on the top side of the hole. This edge is the remnant of the original layer 'A', blown away by the detonation of the energetic compounds during the accident. The thin edge is slightly bent downwards - the downward bending is easily seen on the picture at point B.

27 Appendix G (Dutch report).

The inside of the central hole is largely covered by a different material, with a more shiny surface. This material runs from just below the rim (layer 'A') almost to the bottom of the barrier (red dashed line). This material is the remnant of the cup that contained the lead charge. Upon ignition of the lead charge this cup was partially pressed against the wall of the central hole and stayed behind. Other parts were blown away or melted due to the reaction of the charge.[28]

Microscopic observations of the remnants of the cup in greater detail (Figure 19) show that the lower edge of the cup wall is extremely thin, which indicates that there was a downward tensile load on the wall of the cup. A shock wave in the other direction, with an upward load (initiation of the lead charge by the booster or main charge) would have caused a different deformation, which would have crushed the edge of the cup (by the upward load) as shown in Figure 18.

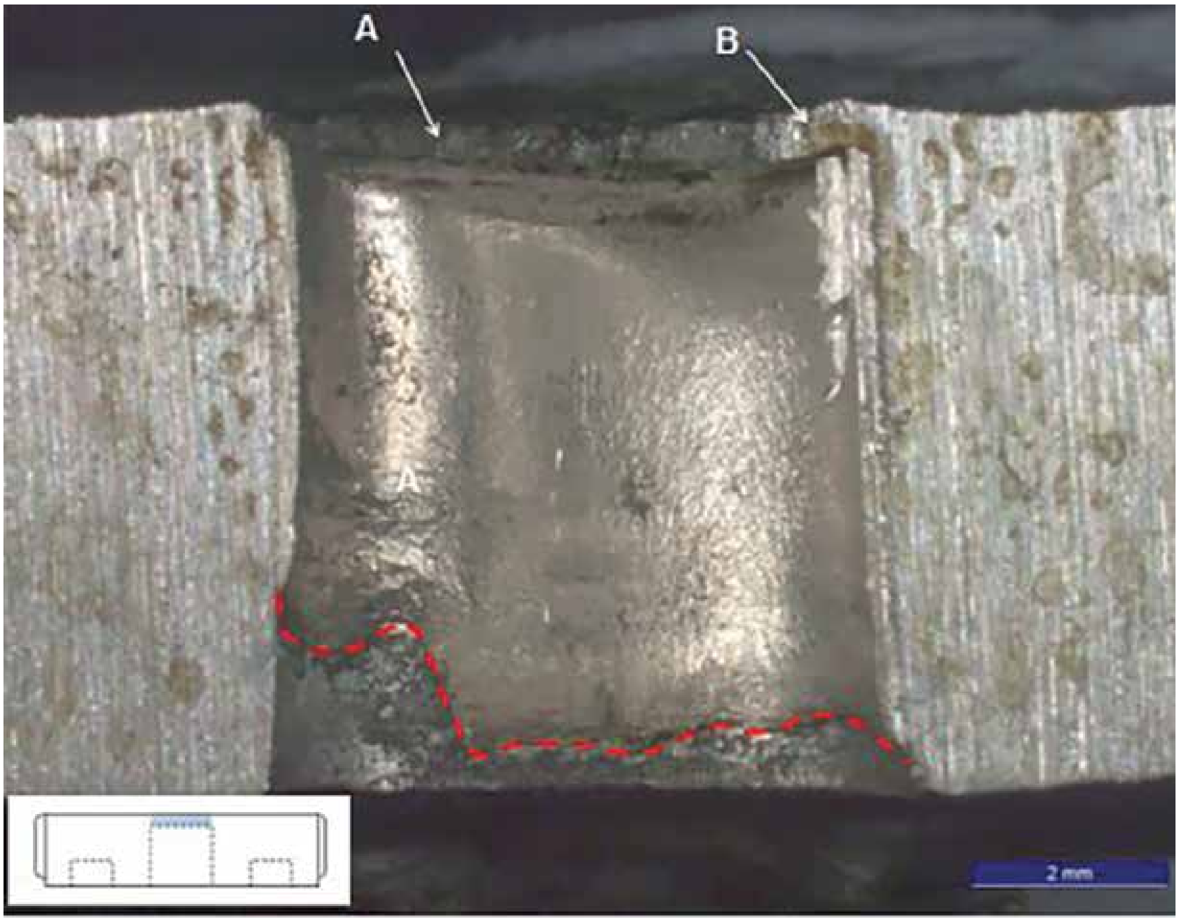


Figure 18: Central hole of the barrier with edge blown away at A, downward bending at B. and a red dashed line (shiny surface with the remnants of the lead charge cup - see Figure 19). (Picture: TNO)

28 P.A. Hooijmeijer, E. Kroon, R.H.B. Bouma, TNO Memorandum 17EM/0041 Microscopic examination of the barrier of the M6-N fuze, January 2017.

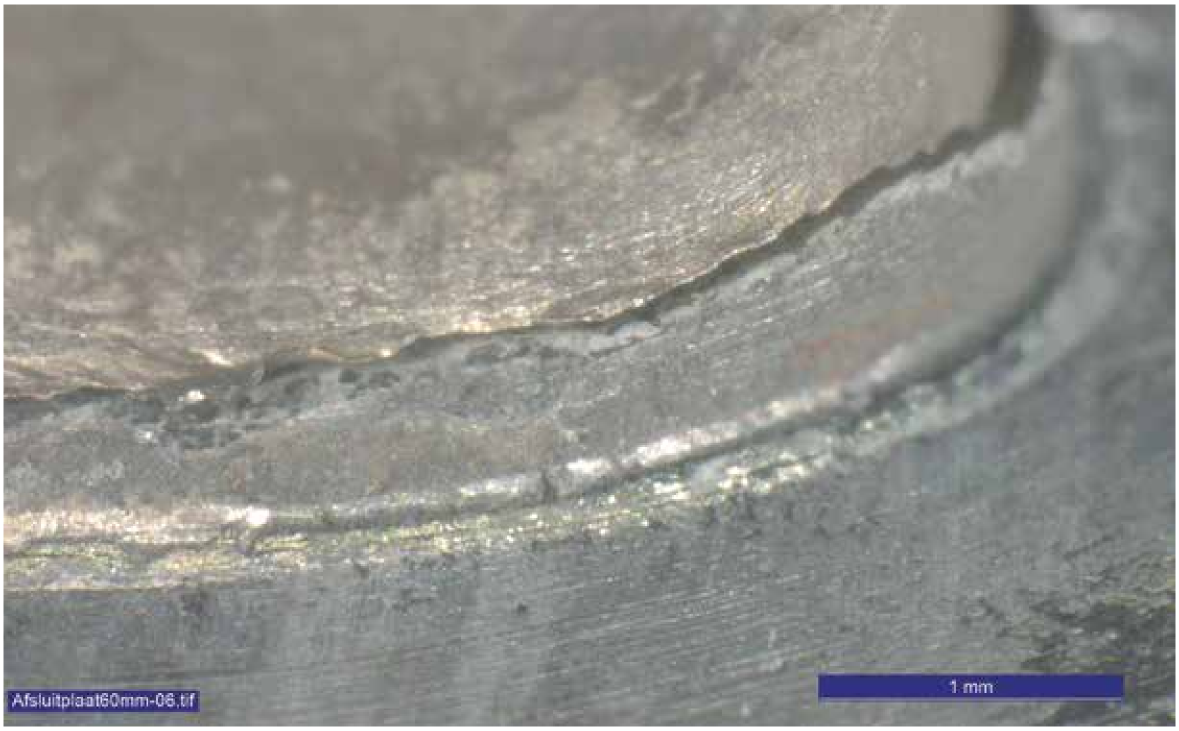


Figure 19: Lower edge of the lead charge cup (red line in Figure 18) on the inside of the central hole of one of the parts of the barrier. (Picture: TNO)

In summary, multiple deformations were discovered in the central hole indicating that a downward load acted on this central section of the barrier and the lead charge. This load caused the part of the barrier over the central recess (layer 'A') to deform and fail, and initiated the lead charge resulting in a shock wave propagating top down. This excludes the possibility that the explosive train fired in the opposite direction (bottom up).[29]

Interim conclusion
The reaction of the fatal round was initiated in the detonator of the fuze. The shock wave propagated downwards through the barrier.

The combination of the two preceding interim conclusions means that the reaction of the round was initiated by the detonator in unarmed position. This leads to two further conclusions related to the functioning of the fuze. The first is that in its eccentric position the detonator was out of line with the firing pin and could not have been initiated by the impact of the firing pin. Therefore the ignition must have been caused by the detonator itself, potentially caused by earlier transformation of the energetic compounds from the detonator into shock-sensitive reaction products. This will be described later in this report.

29 P.A. Hooijmeijer, E. Kroon, R.H.B. Bouma, TNO Memorandum 17EM/0041 Microscopic examination of the barrier of the M6-N fuze, January 2017.

Interim conclusion
The primer inside the detonator fired without mechanical interaction with the firing pin.

The second conclusion is that the barrier of the fuze failed to function as intended, namely as an explosive train interrupter that should have separated the detonation of the detonator from the rest of the explosive train when the fuze is in safe position. The shock wave created by the initiation of the detonator propagated through the metal of the barrier (Figure 17, left). This set off the lead charge, booster and main charge of the round.

Interim conclusion
The barrier failed to function as intended, namely to prevent the transfer of reaction from the initiating detonator to the lead charge with the fuze in safe position

Cause of the malfunctions
The next question is what caused the discovered malfunctions, namely the accidental initiation of the detonator and the transfer of reaction through the barrier. Since external conditions could have had an effect on the chemical composition and thus the functioning of the explosive compounds, the environmental factors and their potential impact were studied in more detail.[30]

Temperature during storage and use
The fatal round (along with other ammunition) was stored in Kidal in a white shipping container without a sun roof. Prior to use the fatal round was exposed to sunlight. Despite the effect of heat on the ammunition quality, the temperature in the storage container in Kidal was not measured and registered. The temperature during storage and operational use was therefore estimated using the TNO climate tool.

On summer days the temperature is high in Kidal. Meteorological records show that on 6 July 2016 the temperature reached a maximum of 43.5°C. The week before the accident the afternoon temperature rose to an average of 42.3°C.

Figure 20 shows the daily ambient temperature profile and, as calculated using the TNO climate tool, the temperature inside the shipping container at the time of the accident. (Source: TNO)

30 J.S. Henzing, E. Kroon, P.A. Hooijmeijer, R.H.B. Bouma, TNO 2017 R10104 Mortar exercise accident Mali: Climatic conditions and potential effects, March 2017.

Taking into account the position of the sun, the white colour of the container, minimal air circulation inside the container, storage of the rounds in carboard tubes and wooden boxes and the most representative climate for this period, calculations show that the temperature in the shipping container during the first week of July could have reached 63°C on a daily basis and that, as a consequence, the mortar rounds could have been heated up repeatedly to approximately 60°C (Appendix H).[31]

A similar temperature analysis was performed for the mortar rounds during their operational use. A reconstruction of the course of the mortar exercise[32] revealed that the rounds in the last two boxes were removed from their packaging during a break of one and three quarters of an hour between the firing of the seventeenth and eighteenth round. The 24th round caused the accident. Because the unpacked rounds were put back in the boxes without the cover, it is clear that the last rounds were exposed to direct sunlight for some time. Taking into account the green paint on the steel shell body and the intensity of the solar radiation, it is calculated that the body and the energetic main charge could potentially have heated up to about 80°C (Appendix H). However, as the mortar rounds were loaded with bare hands during the exercise it is unlikely that the rounds actually reached this temperature.

The entire process of heat absorption and emission to the shell body and the surrounding air is too complex for an accurate estimate of the fuze temperature. However, it is certain that the fuze heated up to over 50°C and probably to over 60°C.[33] For validation, temperature measurements were carried out in Rijswijk on an HE 80 shell body filled with TNT and fitted with an inert M6-N fuze. The measurements show that as a result of insolation, the steel body heats up to 60°C in approximately twenty minutes at an ambient temperature of 30°C and that the aluminium fuze leads with roughly 5°C relative to the steel casing. Due to this relatively fast increase in temperature, the relatively high intensity of the sun and the ambient temperature (40°C) in Kidal, the temperature of the fuze definitely increased to over 50°C in the minutes prior to the accident (see Appendix J).

The maximum temperature specified by the manufacturer Arsenal JSCo for storage and use of the fuze is 50°C.[34] This temperature was thus exceeded during storage and operational use of the round.

31 The AECTP climate for Kidal is A1 (very hot). In this climate the temperature in the shipping container could rise to approximately 70°C. However, the maximum temperature of 50°C that corresponds to A1 appears not to have been reached in Kidal. An A2 (hot dry) climate seems more accurate.
32 Appendix D (Dutch report).
33 For verification an (inert) aluminium fuze was placed in an oven and heated to just above 60°C. It was subsequently established that this fuze could be handled with bare hands.
34 http://bulcomersks.com/index.php/military-products/ammunition-components/50-ammunition-components/fuzes/488-fuze-af62-fpdsq2-m6n (15-3-2017).

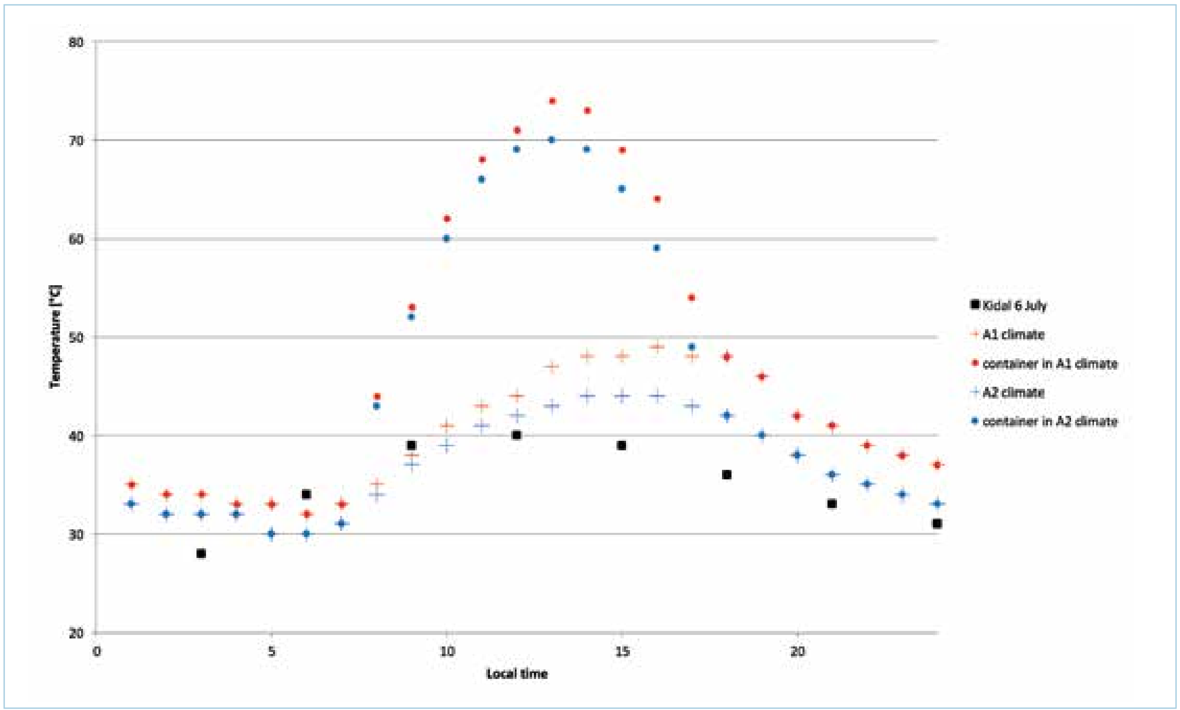


Figure 20: Expected temperature profile in the container during the days around 6 July 2016. (Source: TNO)

Interim conclusion
The maximum temperature of the fuze as specified by the supplier (50°C) was exceeded during storage and operational use of the mortar rounds.

The effect of temperature and moisture
An analysis was performed of the effect of temperature on the energetic materials in the mortar round. When heated to 70 - 80°C the TNT main charge melts and exudation may occur. This is the process through which energetic compounds ooze out and migrate through the screw thread between the fuze and the shell body. Since the melting point of TNT depends on the quality, exudation could also occur at lower temperatures. In a temperature test performed on a HE 80 mortar round it was visually confirmed that the exudation of the TNT main charge starts at 74°C. At 79°C the TNT liquefies and drains from the shell body. It is concluded that the TNT is of good quality (Appendix J). Since the exact temperatures during storage and use are unknown, it is impossible to determine whether exudation and/or melting actually occurred in Kidal. However, it is unlikely that exuded TNT caused a deflagration, since no large fragments of the shell body were found (Appendixes H and J).

The possibility of initiation of the energetic materials due to the shock of the launch at elevated temperature was also considered. This initiation is very unlikely because the autoignition temperature of the energetic materials is significantly higher than the temperature during the exercise. One reference was found in literature suggesting that PETN, present in the detonator and lead charge, might become more sensitive at an elevated temperature.

Besides high temperatures, moisture could also affect the quality of the energetic materials in an ammunition article. During visual inspection of the ammunition in Gao following the accident corrosion was observed; one round showed corrosion on the transport safety cap and one round showed corrosion between the fuze and the shell body.[35] These are indications that some rounds may have been exposed to moisture at some point in time.

When disassembling the fuze of twenty rounds from storage in the Netherlands, visual inspection by the Ministry of Defence Commission of Investigations (CvO) did not reveal any irregularities. There was however slight corrosion on the slider and the detonator of one round, which resulted in the detonator being stuck in the slider. This observation is an indication that moisture can penetrate the fuze of a mortar round.

In October 2007, the Weapon Systems and Ammunition Testing Department (ABWM) found an article with rust stains in a collection of new mortar rounds.[36] The rusty round was found in an unopened container together with nine other rounds that were unaffected. It cannot be ruled out that the rust had already formed before the rounds had arrived in the Netherlands.

Based on these observations it is likely that there have been mortar rounds that were exposed to moisture at some point in time - it is impossible to establish when and where - and that the moisture is able to reach the primer inside the detonator. The most likely route for moisture to penetrate is through the tip of the fuze; here the barrier consists of the adhesive layer in between the membrane and fuze body (the transport safety cap is a loose part and does not act as a moisture barrier). Due to the many barriers it is less likely that moisture penetrated via the screw thread of the fuze, the screw thread of the booster, the screw thread of the barrier and the two rubber sealing rings. Both routes are displayed in Figure 21 (on the left).

35 Ministry of Defence internal investigation.
36 Year of manufacture 2006, see chapter 4 (Dutch report).

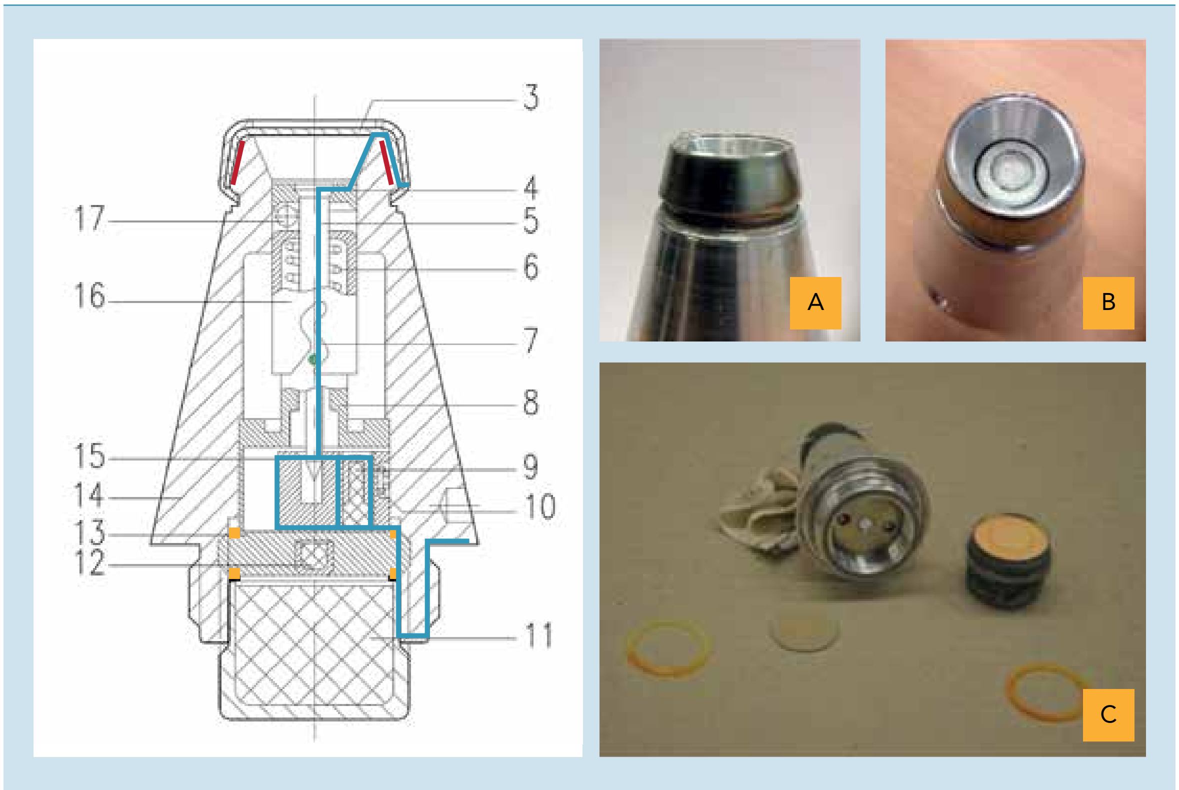


Figure 21: Cross section of the fuze with potential routes (blue) for moisture penetration via the adhesive layer (red) and sealing rings (yellow). Picture A: adhesive layer for the membrane, picture B: opening between the firing pin and the housing and picture C: underside of the housing with the barrier, booster with cardboard disk and two rubber rings. (Source: TNO)

Although adhesive and rubber rings are both permeable, moisture penetration through a layer of adhesive is easier than along three screw threads and two sealing rings. Two simple leak tests were performed for confirmation. First, five empty fuzes were positioned with their nose facing down and filled with water; they were all watertight, despite the fact that KCW&M exposed them to environmental loads to which they can be subjected during their life cycle. The five fuzes were subsequently mounted on an inert shell body, and subjected to five drop tests from a height of about one metre with a random orientation upon impact with the ground. After removal from the shell body the fuzes were again filled with water; the adhesive layer of one of the five fuzes was found to be leaking, see Figure 22. It is possible that the preloading of the fuzes contributed to the leakage.

Figure 22: The adhesive layer of one of the five M6-N fuzes is leaking after a drop test from about one metre height with random impact orientation. (Picture: TNO)

These tests revealed that moisture penetration is possible through the adhesive layer of the membrane towards the energetic material inside the detonator if the mortar round is exposed to moisture after a shock. It is likely that also without a shock, the adhesive layer ages over time, which allows moisture to penetrate more easily (Appendix H).

Interim conclusion
The seal of the fuze is vulnerable. It is possible for moisture to penetrate the adhesive layer of the membrane at the tip of the mortar round and reach the energetic charge inside the detonator. The risk of moisture penetration increases when the round is subjected to one or more shocks.

Copper azide formation
A possible explanation for the initiation of the detonator is the presence of copper azide. This is a highly sensitive compound that can react as a result of a mild impact or shock. Copper azide can form due to the transformation of the lead azide inside the detonator, in the combination with the copper-based components of the fuze. Literature describes several fatal accidents linked to the formation of copper azide.[37] Copper azide was determined as the cause of accidental reactions involving 81 mm mortar rounds of the Royal Netherlands Navy in 1974. Since the processes that led to this incident may be analogous to the accident in Mali, this case is here explained in more detail.

Den Helder (1974) spontaneous reaction of corroded fuzes
The referenced ammunition had arrived in Den Helder after a stay in the Antilles.[38] The rotor that ensures arming after leaving the launch tube (part of the safety and arming mechanism) had projected through the cardboard packaging for a number of rounds (see Figure 23). The investigation revealed that the detonators of the fuzes were corroded, resulting in the formation of copper azide. It was concluded that the brass[39] components around the detonator had reacted with the lead azide in the aluminium detonator. As a result of internal friction, probably caused by vibration during transport, the copper azide reacted, leading to the initiation of the primer charge in the detonator causing the rotor, which ensures safe arming distance, to project through the packaging. The main charge was not activated because the fuzes were in safe position. In contrast to the accident round in Mali, the safety mechanism of these fuzes did function.

37 Kabik, I. and Urman, S. (1973) Hazards of copper azide in fuzes. In: Proceedings of Minutes of the 14th Explosive Safety Seminar, New Orleans, Louisiana – Department of the Defence Explosive Safety Board.
38 Josseling de Jong, Examination of fuzes type V-9 and type V-19, manufactured by Hotchkiss-Brandt, TNO report TL 1976-15, 18 November 1976.
39 Brass is an alloy of copper and zinc.

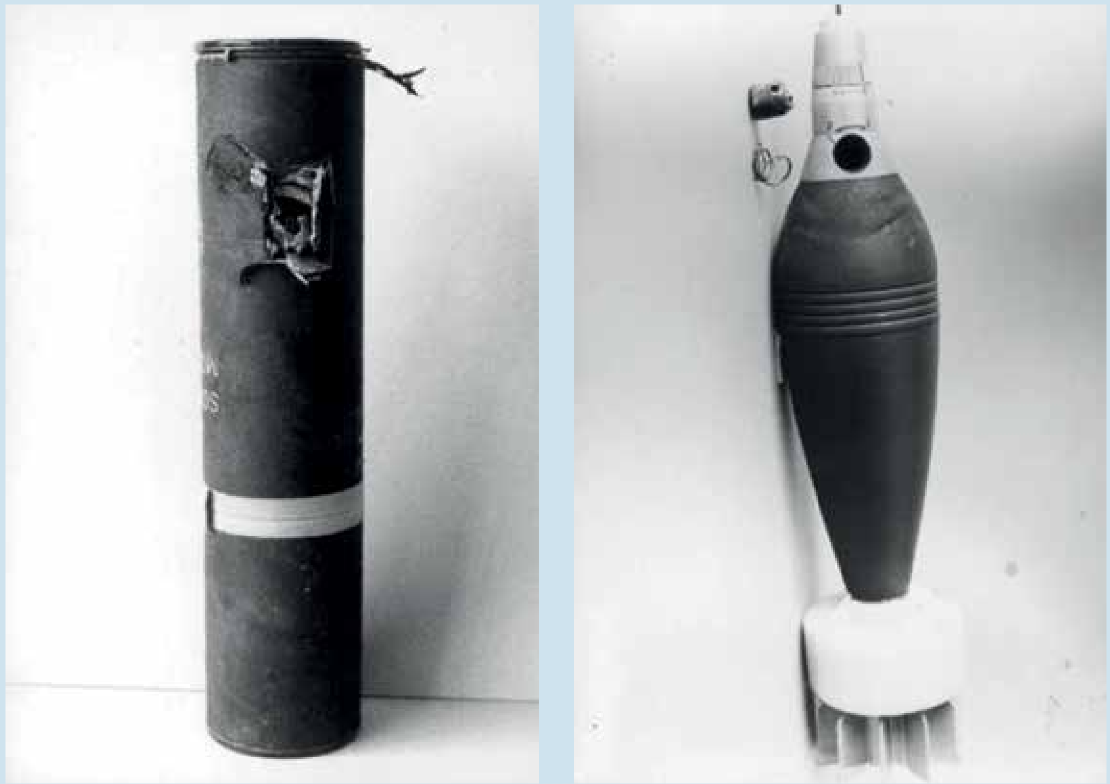


Figure 23: Perforated packaging and projected rotor of the arming and safety mechanism of an 81 mm round (Pictures: TNO).

The ammunition was on board of a ship of the Royal Dutch Navy located at the Antilles for 18 months. The prevailing high temperature and humidity caused the reaction of the lead azide with water vapour in the atmosphere. The reaction is seen on the top view of the detonator in the brass casing in Figure 24. Traces of the primer are visible as grey and white crystals, possibly mixed with aluminium compounds from the detonator. Traces of the red lacquer (sealant) are also visible. The green crystals indicate copper compounds including the highly sensitive copper azide and the non-explosive copper hydroxide and copper oxide.

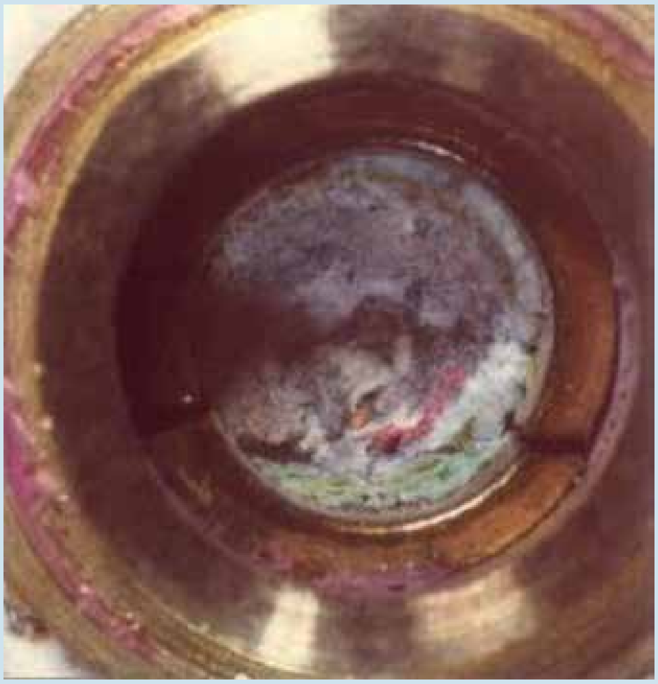


Figure 24: Top view of the aluminium detonator in the brass casing from fuze type V-19. (Picture: TNO)

The investigation conducted at the time concluded that there was a major risk when handling the 81 mm rounds affected by corrosion and that the presence of copper in the immediate vicinity of lead azide must be considered unacceptable.[40]

Analogy with Mali

The above case raises the question of whether this reaction could have played a role in the accident in Mali. In the case of the M6-N fuze the primer is contained in an aluminium cup placed in a holder made of Melchior, an 80:20 copper-nickel metal alloy. This material is highly resistant to corrosion in air, water and seawater. However, copper-nickel alloys are prone to accelerated corrosion in water containing sulphide or ammonia, which can result in the formation of copper oxides. It is noted that the composition of the primer contains (antimony) sulphide that would accelerate potential corrosion of the Melchior cup. It was also noted that several metals containing copper reside near the detonator: the aluminium primer cup, the copper-nickel cup holder, the copper-based brass slider and the zinc-galvanised carbon steel barrier. The presence of these materials was established by TNO using electron microscopy and X-ray microanalysis. This investigation revealed that the barrier was contaminated with sulphur and zinc oxide. A green deposit was observed on the slider, which consisted of copper oxide and zinc oxide. Sodium was also found on the corroded surface area of the slider.[41] The presence of sodium in combination with water promotes corrosion (Appendix H).

40 Josseling de Jong, Examination of fuzes type V-9 and type V-19, manufactured by Hotchkiss-Brandt, TNO report TL 1976-15, 18 November 1976.

41 There are three potential sources that could explain the presence of sodium: (1) external penetration of, for example, salty air, (2) insufficient rinsing and filtering of sodium nitrate that is used to produce lead azide (present in the detonator), (3) traces of sodium if the galvanised steel barrier is passivated with sodium dichromate for additional corrosion protection.

These observations confirm that the initiation of the detonator can be caused by processes resembling the case of the rounds in Den Helder. In that case, moisture penetrated the fatal round somewhere during its lifespan leading to corrosion and degradation of the aluminium primer cup and the Melchior holder. It is not possible to establish when or where the components of the fuze were affected, but based on the inspections by the Ministry of Defence Commission of Investigations of the mortar rounds that stayed behind in Kidal, it is likely that they have been exposed to moisture at some point. The investigation of TNO also made it clear that the M6-N fuzes are vulnerable to moisture penetration (see Appendix H). The corrosion process can be accelerated by high temperatures during storage. As a result of moisture, hydrogen azide forms due to hydrolysis of the lead azide in the primer in the detonator. The hydrogen azide reacted with the copper in the Melchior cup holder and/or in the brass slider, resulting in the formation of the highly shock-sensitive copper azide. Moreover, under elevated temperatures the tetrazene in the detonator can evaporate, potentially causing crystal formation elsewhere in the detonator. The copper azide (together with the tetrazene crystals) is possibly detonated by the shock of the launch of the round, resulting in the initiation of the primer charge (see Appendix H for more details).

Interim conclusion
The detonator in the fuze of the round involved in the accident was possibly initiated by highly shock-sensitive copper azide that formed as a result of a corrosion process, related to moisture and heat.

Transfer of reaction in unarmed position
It was previously concluded that the explosive train was set off by the detonator in unarmed position. This means that the detonator was physically separated from the lead charge by the metal of the barrier. Therefore, the barrier failed to function as intended, namely as the interrupter of the explosive train in case of a prematurely initiating detonator. The next question is how the explosive train was initiated as a result of transfer of reaction through the barrier with the fuze in unarmed position.

Figure 25 illustrates the two hypothetical reaction transfer routes from the detonator to the lead charge: straight through the slider, or along a 'bridge' of copper azide (and possibly tetrazene and/or the compounds exuded from the shell body) between the primer and lead charge, both with the fuze in safe position. In both cases the reaction transfer leads to the detonation of the booster and of the main charge.

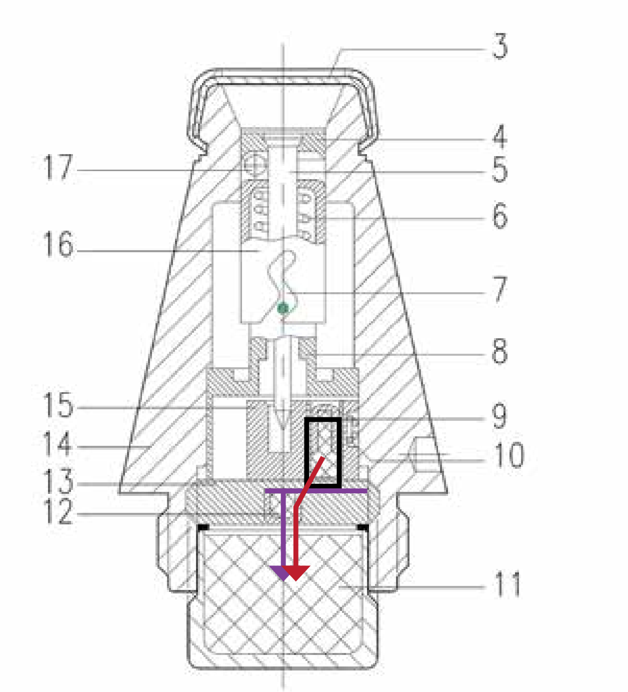


Figure 25: The detonation of the copper azide when the mortar round is launched detonates the primer (red) or detonates the primer and the 'bridge' of copper azide (and possibly tetrazene) between the detonator and the lead charge (purple). (Source: TNO)

Laboratory tests performed by TNO (at circa 12°C) show transfer of reaction of the primer to the lead charge with the fuze in unarmed position (five tests). The steel disc that should form a barrier between the detonator and the lead charge, appeared not to function as such in these tests. However, there was no transfer of reaction to the booster charge (two tests); see Appendix I.[42] Because transfer of reaction to the lead charge in safe position is not allowed[43], the design of the fuze does not comply with NATO standard.

The tests demonstrate that transfer of reaction through the barrier does not lead to detonation of the main charge at a relatively low temperature (12°C). Presumably, operational use at temperatures exceeding the maximum temperature as specified by the manufacturer could result in setting off the entire explosive train. This supposition is based on the potential increased sensitivity of the PETN lead charge at higher temperatures (Appendix H).

The above assumes that the presence of copper azide initiated the primer. However, further examination of the corrosion on the sliders of reference fuzes reveals that friction between the firing pin and the slider in safe position could have been the cause of initiation. In this case, prior to the accident, energetic compounds migrated from the detonator to the surface of the slider. This hypothesis is described in detail in Appendix J.

42 E.J. Kroon, R.H.B. Bouma, P.A. Hooijmeijer, TNO 2017 R10363 Mortar Exercise Accident Mali: M6-N fuze output tests, March 2017.
43 See NATO Standardisation Agreement (STANAG) 4187.

In summary, the explosive train can be partly set off in unarmed position at a low temperature and possibly fully set off at a temperature exceeding the specified maximum operating temperature. In an attempt to get a definite answer, a reaction transfer test was performed on an unarmed fuze that was heated in an oven. Once a thermocouple registered a temperature of 70°C inside the fuze, the oven was removed and the duplex detonator was initiated immediately using a detonation cord inserted through a small hole that was drilled in the fuze. Although there was transfer of reaction to the lead charge, resulting in a large dent in the RDX booster (deeper than at a low temperature), the booster did not detonate. It is noted that only one experiment is performed. This result does not provide statistical substantiation that transfer of reaction to the booster is always prevented at an elevated temperature (Appendix J).

Interim conclusion
In safe position the barrier of the fuze does not prevent transfer of reaction from the detonator to the lead charge. This is not allowed according to NATO regulations.

It is possible that the entire explosive train of the fatal round was set off due to use at a temperature exceeding the specified maximum operating temperature.

3.3 Conclusion

A combination of three categories of causes led to the premature detonation of the mortar round. These are: weaknesses in the design of the fuze, storage under uncontrolled conditions and use at a too high temperature.

Two weaknesses were identified in the design of the fuze. The first is the seal at the top of the fuze, which provides no guarantee against moisture penetration. Moisture inside the fuze can result in a corrosive process that leads to the formation of highly sensitive explosive compounds. The second is the barrier, which in contrast to NATO regulations, does not prevent transfer of reaction to the lead charge in an unarmed position when the detonator fires prematurely.

During storage the mortar round was exposed to temperatures higher than the maximum storage temperature specified by the manufacturer. The high storage temperature promoted the corrosive process that, in combination with moisture penetration led to the formation of highly sensitive explosive compounds inside the fuze, probably copper azide. The shock of the launch resulted in initiation of these explosive compounds in the fuze.

During operational use of the mortar round the temperature of the fuze exceeded the maximum operational temperature specified by the manufacturer. The high temperature resulted from ambient temperature combined with direct exposure to solar radiation. At elevated temperatures the explosive power of energetic compounds increases. As a consequence the shock wave could have initiated the entire explosive train causing detonation of the round.

APPENDIX E

TECHNICAL RESEARCH QUESTIONS REGARDING THE DEBRIS

On the basis of an exploratory investigation the Dutch Safety Board formulated an initial set of research questions with respect to the remnants of the weapon system and the mortar round. The DSB requested the Netherlands Organisation for Applied Scientific Research (TNO) to answer both sets of questions. To facilitate the investigation the DSB provided the recovered remnants of the mortar and the round to TNO.

This report answers the initial set of research questions and the additional technical questions formulated by the DSB.

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TNO-report

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Mortar exercise accident Mali: General technical research questions regarding the debris

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Summary

Following the fatal accident during a mortar exercise in Mali on 6 July 2016, the Dutch Safety Board (DSB) formulated a number of technical questions and submitted them to the Netherlands Organisation for Applied Scientific Research (TNO). To facilitate the answer to these questions, the DSB provided the recovered remnants of the mortar round and the mortar (launch tube), the video footage of the accident and an intact mortar to TNO.

On the basis of the available information and debris, TNO concludes that the accident was caused by the premature detonation of the 60 mm High Explosive (HE 80) mortar round that was dropped into the mortar.

This conclusion is based on the analysis of the information provided by the DSB, which shows that:
- no double loading occurred, i.e. the round was not dropped on top of a previously loaded round that had not been fired;
- the launch tube displays no irregularities;
- there are no defects on the firing pin in the base plate of the mortar;
- the damage to the launch tube is consistent with the position of the main charge reacting at or near the moment the round reached the bottom of the mortar;
- the main charge of the mortar round detonated.

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1 Introduction

1.1 General

On July 6, 2016, a fatal accident occurred during a mortar exercise in Mali. On the basis of an exploratory investigation, the Dutch Safety Board (DSB) decided to launch an investigation into:

- the cause of the accident;
- the underlying factors;
- the (medical) assistance provided to the military personnel involved.

To investigate the cause of the accident, the Dutch Safety Board formulated an initial set of research questions with respect to the remnants of the weapon system and the mortar round. Subsequently, the DSB formulated an additional set of technical questions (DSB document dated 13 September 2016). The DSB requested the Netherlands Organisation for Applied Scientific Research (TNO) to answer both sets of questions. To facilitate the investigation the DSB provided the recovered remnants of the mortar and the round to TNO on November 8, 2016.

This report answers the initial set of research questions and the additional technical questions formulated by the DSB.

1.2 Objective

The objective of the present project is to use the recovered debris to establish whether the possible cause of the accident relates to the mortar round (including the fuze) and/or the weapon system (mortar).

1.3 Structure of the report

Chapter 2 answers the research and technical questions formulated by the DSB. Chapter 3 presents the conclusions.

2 Analysis

Each paragraph of this chapter answers a research question as formulated by the DSB. Paragraphs refer to each other in case of a link or an overlap between the different research questions.

2.1 Identification of the debris

Technical research question V1.1
Is it possible to identify the recovered fragments?

Answer
An inventory was made of the recovered debris (see Appendix A). The origin of each fragment is described. The small fragments and parts recovered during the second search of the accident site several days after the accident occurred, are excluded from the inventory, because they do not assist in answering the research questions in this project.

Based on the inventory the following parts were identified:

Mortar
- Muzzle end of launch tube (no. 513), with petalled strips of metal at the bottom;
- Mortar base plate, with screw thread sheared off, and including the firing pin;
- Lower end of the launch tube, including the screw thread which connects to the base plate; with petalled strips of metal at the top;
- Three petalled strips with screw thread, belonging to the baseplate end of the launch tube (circumference is incomplete);
- Two petalled strips, belonging to the muzzle end of the launch tube;
- Flange with mounting bolt for the lanyard, belonging to the baseplate end of the launch tube.

Sight unit
- Part of the setting wheel to attach the sight unit to the mortar;
- Connecting pin belonging to the part that connects the sight unit with the mortar barrel;
- Setting wheel for adjustment of the sight unit;
- Four parts of the sight unit housing;
- Setting wheel with separate level for adjustment of the elevation of the sight unit.

Mortar round
- Aluminium tail assembly;
- Various aluminium parts of the fuse body;
- Screw thread connection between shell body and tail assembly;
- Transport safety pin ribbon.

Other
- Canvas hand protecting sleeve;
- Parts of the lanyard.

Unidentified
- Elongated piece with screw thread;
- Deformed thick, cylindrical metal disk (possibly the explosive train interrupter from the fuze);
- Deformed thin, cylindrical metal disk (possibly the cover plate of the booster);
- Steel ring (not a part of the sight unit);
- Various smaller pieces recovered from the victims' bodies.

Not examined
- Body armour and boots of the victims.

2.2 Reconstruction

Technical research question V2.1
Reconstruct and measure the various projected parts of the mortar in conjunction with the recovered muzzle and baseplate end, in order to determine the position of the main charge, measured from the base.

Answer
Based on an analysis of the recovered debris a reconstruction was made of the damaged mortar. In Figure 1 this reconstruction is positioned next to an intact mortar. The reconstruction reveals a similar damage pattern to the muzzle end and to the baseplate end of the launch tube (at both sides of the sight unit). The largest missing part of the tube corresponds to the original location of the sight unit. The absence of these parts is an indication of the level of fragmentation of this tube section. The fragmented, smaller parts of the tube are harder to find and were therefore probably not recovered during the search at the site of the accident. It is also possible that smaller fragments from the tube are still in the body armour or among the remaining, smaller fragments that were recovered from the bodies of the victims. Large parts of the sight unit are also missing. Figure 1 shows a reconstruction of the recovered parts of the mortar. As a reference an intact mortar is also displayed.

The actual positioning of the mortar round is described in paragraph 2.9, which answers the additional research question AV1.1.

Figure 1 Reconstruction of the recovered parts of mortar No. 513 (bottom) and an intact mortar No. 500 (top).

2.3 Measurements of the base plate and firing pin

Technical research question V2.2
Measure the profile on the inner side of the mortar base plate, in conjunction with the profile of the firing pin.

Answer
The base plate was mapped using a digital 3D scanner[1]. This scanner provides an accuracy of 0.04 mm. The generated 3D model allows for performing measurements to the base plate. Some images from this scan are displayed in Figure 2.

Figure 2 Screenshots from the 3D model of the base plate.

[1] 3D scanner data: ATOS compact scan 5M (blue light scanner) manufactured by the firm GOM.

The 3D scan of the base plate was used to produce a cross-section over the centreline of the base plate and the firing pin. The firing pin is screwed into the base plate; the cross-section in Figure 3 shows how far the firing pin extends from the central plateau, namely 1.73 mm. The firing pin must extend 1.5 - 1.8 mm from the central plateau [ref. 1].

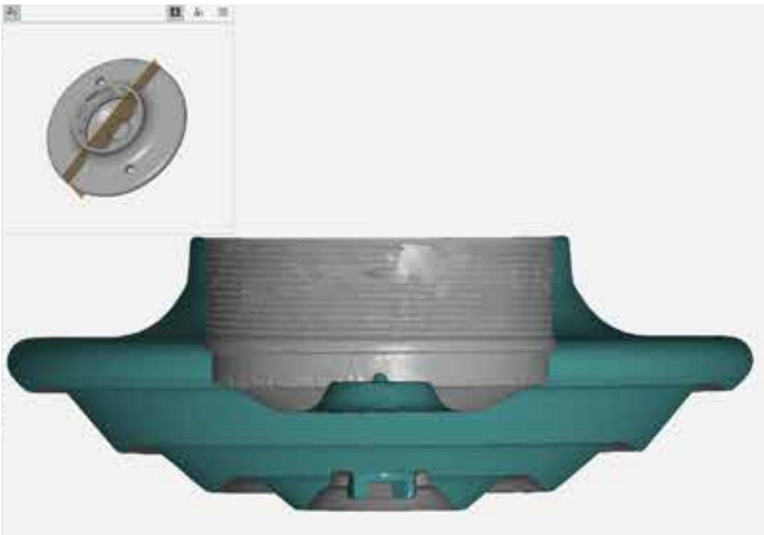

Figure 3 Cross-section of the base plate over its centreline.

The firing pin was unscrewed from the based plate to measure the profile of the pin. The firing pin is photographed together with a firing pin from the intact mortar; see Figure 4.

Figure 4 Comparison of the two firing pins (left: reference, right: accident).

The firing pins are both straight with respect to the screw thread, but a difference is observed between the shape of the tip of both firing pins; the firing pin from the reference weapon is flattened compared to the tip of the firing pin from the damaged mortar; see Figure 4 and Figure 5. It is assumed that the tip of the firing pin flattens with the number of rounds fired. Therefore it is likely that more rounds were fired with the firing pin from the reference mortar than with the firing pin from the mortar involved in the accident. The dimensions of both firing pins were mapped and the measurements are given in Table 1.

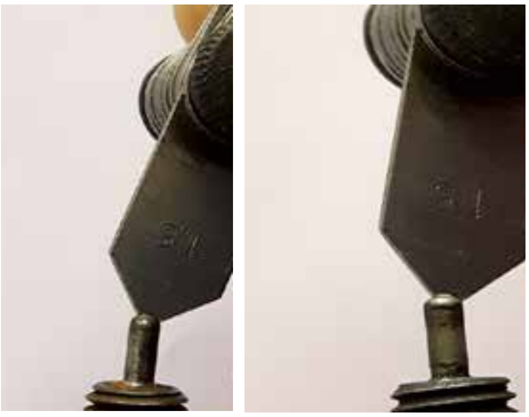

Figure 5 Measured dimensions of the firing pin from the mortar involved in the accident (left) and from the reference mortar (right).

Table 1 Dimensions of the firing pin from the mortar involved in the accident and the reference mortar.

Firing pin dimensions	Accident mortar No. 513	Reference mortar No. 500
Diameter top [mm]	2.98	2.99 - 3.00
Diameter centre [mm]	2.97	2.98 - 3.00
Diameter bottom [mm]	2.96 - 2.97	2.83 - 2.87
Radius of curvature [mm]	1.5	> 1.5
Length of the firing pin [mm]	7.94	7.55
Length of the firing pin + screw thread [mm]	19.56 - 19.60	19.27 - 19.28

2.4 Measurement of the tail assembly

Technical research question V2.3
Determine the deformation of the tail assembly of the mortar round.

Answer
The tail assembly was also mapped using the 3D scanner previously mentioned. Figure 6 shows two screenshots from the 3D model.

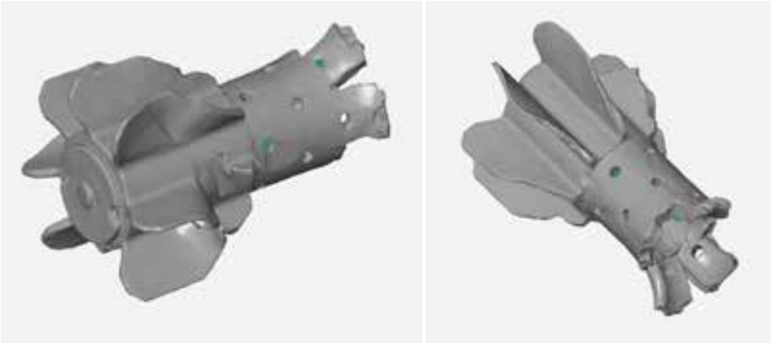

Figure 6 Screenshots from the 3D model of the tail assembly of the mortar round.

2.5 Metallurgical examination of the fracture surfaces of the mortar

Technical research question V3.1
Determine through metallurgical examination of the parts of the mortar whether the fractures were already present or generated by the explosion (determine the type of fracture).

Answer
This question was omitted for this phase of the investigation, in consultation with the DSB.

2.6 Metallurgical examination into ageing of the mortar

Technical research question V3.2
Determine through metallurgical examination of the parts of the mortar whether these parts had aged.

Answer
This question was omitted for this phase of the investigation, in consultation with the DSB.

2.7 The striking of the percussion primer by the firing pin

Technical research question V3.3
Determine by means of destructive testing, whether the firing pin has struck the primer.

Answer
A visual and microscopic inspection of the tail assembly is conducted. The tail assembly displays substantial damage as a result of the accident.
The reaction of the main charge caused deformation of the tail assembly, damage due to impacting fragments and the surface is affected by high temperatures and combustion gases. The visual and microscopic inspection revealed an indentation in the percussion primer of the propelling charge (primary cartridge); see Figure 7.

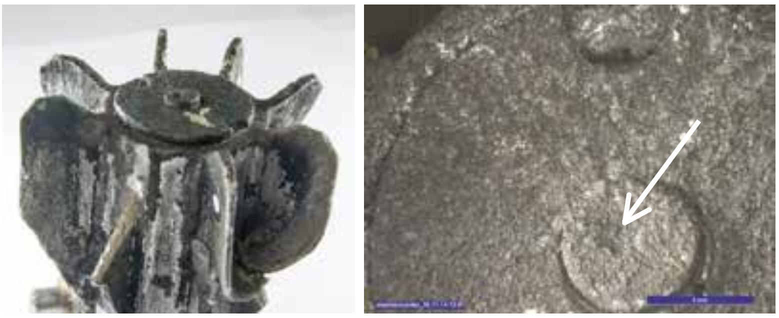

Figure 7 Indentation in the percussion primer of the propelling charge in the tail assembly of the mortar round (left), with a microscopic magnification of the percussion primer (right).

The firing pin has struck the percussion primer slightly off-centre. It is clearly seen that the percussion primer has tilted with respect to surface of the propelling charge. The indentation leads to the conclusion that the mortar round has reached the bottom of the mortar.

For the research question AV1.2 in paragraph 2.10 it is determined that the time of the travel of the round in the tube corresponds to the time required to reach the base plate. When functioning correctly the indentation will cause ignition of the propelling charge. Paragraph 2.11 describes the combustion process of the propelling charge and augmenting charge.

2.8 Profile of the firing pin

Technical research question V4.1
Determine the profile of the firing pin by taking a cross-section photo.

Answer
See paragraph 2.3.

2.9 Position of the core of the explosion

Additional research question AV1.1
Is it possible, based on the fragments of the mortar, to determine the position of the core of the explosion in the mortar?

Answer
The position of the mortar round inside the tube at the moment the reaction occurred has been determined. The exact position is based on:

- The video footage of the accident: it was established that the time the round travels through the tube is sufficiently long for the round to reach the base plate;
- Indentation of the primer: analysis of the primer demonstrated that the firing pin has struck the primer;

- The reconstruction of the recovered parts: the damage to the mortar, visualised by the reconstruction, demonstrates that the center of the explosion was situated at the location of the sight unit attached to the launch tube;
- The reaction of the main charge: it is established that the main charge (and not the propelling charge) of the mortar round was the source of the reaction.

A reconstruction was made of the possible position of the mortar round at the moment of the accident; see Figures 8a and 8b. In Figure 8a, the damaged upper section of the launch tube and base plate of mortar No. 513 are aligned with the muzzle end and base plate of the reference mortar No. 500. In Figure 8b, both the damaged upper and lower section of the launch tube of mortar No. 513 are aligned. A 60 mm mortar round without a fuze is shown in both figures with the base of the tail assembly placed against the bottom of the tube.

The dotted lines in Figures 8a and 8b mark the positions to which the metal strips would extend in their unbent state. In between these dotted lines the reaction has occurred. As this reconstruction also shows the mortar round, it is seen that the shell body with the main charge of the round (olive green) for the larger part is situated in between these lines. In Figures 8a and 8b, the tail assembly is at the bottom of the launch tube and the shell body is slightly to the right of the dotted lines. It is not possible to conclude with certainty that the main charge detonated in this position. It is also possible that the mortar round was already accelerating (towards the muzzle end of the mortar) when the reaction of the main charge occurred; the upper and lower side of the main charge may therefore also correspond to the dotted lines in Figures 8a and 8b. In other words: the dotted lines provide an indication of the potential position of the main charge of the round at the time of the reaction.

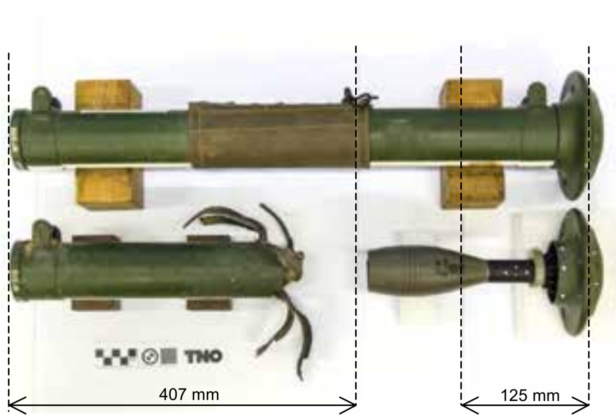

Figure 8a Position of the mortar round with the tail assembly situated against the base plate and relative to the upper part of the damaged mortar No. 513. For comparison the intact mortar No. 500 is placed next to the reconstructed mortar. The dimensions are given relative to the upper and lower side of the mortars.

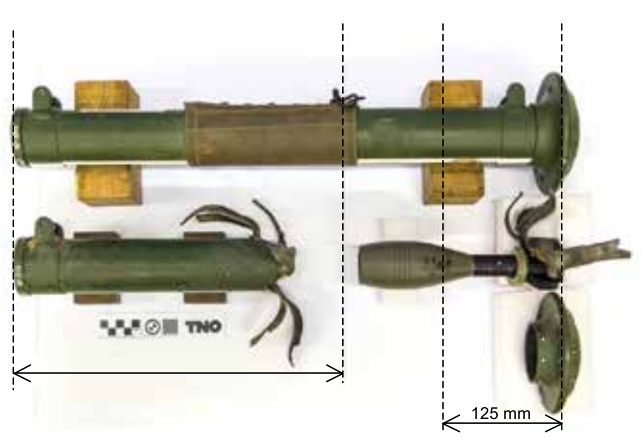

Figure 8b Position of the mortar round with the tail assembly aligned with the damaged lower section of the launch tube and base plate and relative to the upper part of the damaged mortar No. 513. For comparison the intact mortar No. 500 is placed next to the reconstructed mortar. The dimensions are given relative to the upper and lower side of the mortars.

2.10 Explosion of one or two rounds

Additional research question AV1.2
Is it possible, using the fragments from the mortar, to determine whether one or two rounds exploded in the launch tube?

Answer
It was established that one mortar round was in the launch tube at the moment of the accident. Various aspects were considered (remnants of the mortar, remnants originating from one or two grenades, video footage and travel time versus time to the reaction) to reach this conclusion.

2.10.1 Remnants of the mortar
Based on the damage to the mortar, paragraph 2.9 concluded that the reaction took place in the lower section of the mortar. In case of a double loading this would mean that only the mortar round at the bottom reacted and that the mortar round on top of it was expelled or fired from the mortar. The latter is not seen on any of the available frames of the recording of the accident. This is in contrast with the recordings of the firings prior to the accident on which the rounds are seen exiting the mortar[2]. This presents another indication that there was no second round in the mortar at the time of the accident.

2.10.2 Fragments from one or two rounds
No identical, uniquely identifiable fragments or parts of mortar rounds were found which would demonstrate that there was a reaction of two rounds in the mortar at the moment of the accident.

[2] The various GoPro videos from different cameras have a frame rate of between 25 and 29.97 frames per second. This frame rate enables the GoPro to capture the mortar round when it exits the mortar.

2.10.3 *Video footage*

From the available video footage it is not clear whether double loading may have occurred because the preceding shot is not shown (ref. GoPro video: GOPR0253.MP4).

On the basis of all available GoPro video and camera images the impression is obtained that the correct procedures are followed by the two soldiers who loaded and fired the round under supervision of a third and fourth soldier (film maker). For most of the GoPro images it is observed that preceding the fatal shot, the transport safety cap is removed, the round is dropped in and subsequently exits the mortar.

The firing rate is low (far below the permitted firing rate of 20 rounds per minute [ref. 2]), which makes a double loading unlikely. It is also noted that the risk of double loading is less for a gravity fired mortar with a fixed firing pin than for a trigger-fired mortar. For in the case of a trigger-fired mortar the round is fired by the gunner after a certain interval after loading, while for a gravity fired mortar the round is automatically launched when the percussion primer strikes the fixed firing pin in the base plate (without intervention by a gunner). Because a mortar with fixed firing pin requires no interaction between a loader and a gunner there is a reduced risk that the loader drops a second round before the previous round is fired.

One of the photos taken after the accident shows that the transport safety caps have been removed from the remaining five mortar rounds in the ammunition box. Presumably these caps were all removed in between the video footage taken from the right side of the firings before the accident and the footage taken during the accident without any intermediate rounds being fired. Is it noted that the firing doctrine 07V2013 [ref. 2] does not explicitly prohibits this course of action. One of the safety regulations namely states that the fuze safety pin may only be removed just prior to loading the round. The phrase "… just prior to … " is not specified in detail. Besides, it does not seem unusual to prepare a number of mortar rounds in advance given the following text from the American mortar field manual FM 23-90 [ref. 3]: 'Before firing, the gunner must remove the safety wire of the M888 (standard point-detonating fuse). Safety wires should be reinserted into all cartridges that have been prepared for firing but not used. Powder increments that have been removed should be replaced. Cartridges should be returned to their original packing and marked accordingly (these cartridges should be used first in subsequent firings)'.

2.10.4 *Travel time*

Based on the GoPro frame rate it is possible to calculate the time between the moment of release of the mortar round and the moment the reaction occurs. The travel distance to the bottom of the mortar is longer than the distance to a tip of a fuze of a round in the launch tube in case of a double loading.

The video showing the accident (ref. GoPro video: GOPR0253.MP4) has been analysed frame by frame. The frame where the mortar round starts descending is indicated as frame 0. A reaction is instantaneously visible on frame 12. The frame rate obtained from the Codec[3] of the MP4 file from the GoPro is 29.97 images per second. This means that each frame takes 0.0334 seconds.

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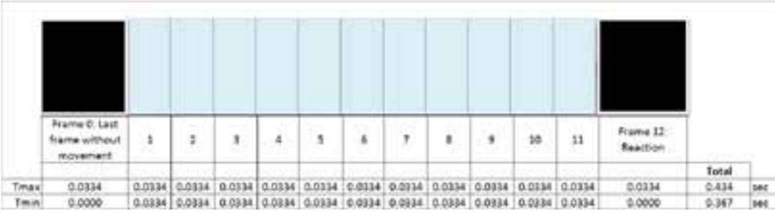
[3] Software for coding/decoding or compressing/decompressing data.

Based on the speed of the occurring processes the following is observed:

- The moment at which the rounds starts descending occurs between the beginning and end of frame 0 (a period of 0.0334 seconds);
- The precise moment of the reaction occurs between the beginning and end of frame 12.

This means that, based on the video footage, a small variation in the time to reaction needs to be take into account. This time span is between a minimum of 11 frames x 0.0334 seconds/frame and a maximum of 13 frames x 0.0334 seconds/frame, i.e. between 0.367 seconds and 0.434 seconds. This is schematically illustrated below, in Figure 9.



	Frame 0: Last frame without movement	1	2	3	4	5	6	7	8	9	10	11	Frame 12: Reaction	Total	
Tmax	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.434	sec
Tmin	0.0000	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0334	0.0000	0.367	sec

Figure 9 Calculation of the time until the reaction based on the GoPro frames.

The length of the launch tube measures 650 mm. The video footage shows that the loader inserts the round with approximately 190 mm of its length in the tube before release. The travel distance between the percussion primer and the firing pin at the bottom of the tube then measures 460 mm, see Figure 10.
In case another round was already present inside the tube, the distance to cover is only 160 mm, because the length of a round equals 300 mm. The travel distance in case of double loading measures only one third of the normal distance.

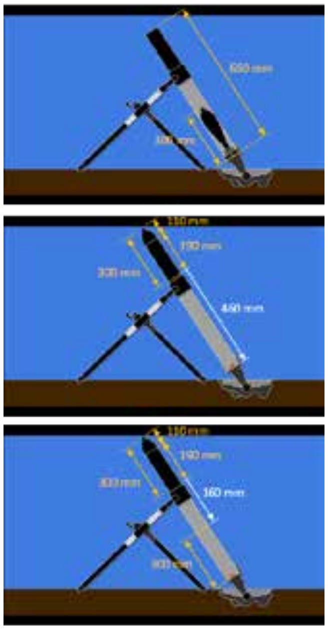


Figure 10 Dimensions of the launch tube and mortar round (top image) and distance travelled (in white) by the round in the tube for a single loading (center image) and double loading (lower image).

The travel time is determined by the distance the mortar round descends towards the bottom of the launch tube, gravitation (F_g=m·g) and friction between the round and the interior of the launch tube, F_f. At the moment of the accident the mortar was at an angle of 70 degrees with the horizontal; see Figure 11. The force of gravity F_g, based on this angle, can be divided into a force perpendicular to the axis of the tube (F_{pe}) and a force parallel to the axis of the tube (F_{pa}), as follows from:

$$F_{pe} = \cos\alpha \; F_g \qquad (1)$$

$$F_{pa} = \sin\alpha \; F_g \qquad (2)$$

with

F_g	Gravitation [N]
α	Elevation of the launch tube (with respect to horizontal) [degrees]

The force F_{pe} determines the frictional force to which the round is subjected using:

$$F_f = \mu F_{pe} \qquad (3)$$

with

- F_f Friction force [N]
- F_{pe} Force perpendicular to the tube [N]
- μ Dynamic friction coefficient [-]. This is 0.57 [ref. 4].

The resulting force F_{res} under which the round descends in the tube is F_{pa} minus the friction force F_f, and can be derived from the equations (1), (2) and (3):

$$F_{res} = mg(\sin\alpha - \mu\cos\alpha) \qquad (4)$$

with

- m Mass of the mortar round of 1.6 kg
- g Standard gravitational acceleration of 9.81 ms^2

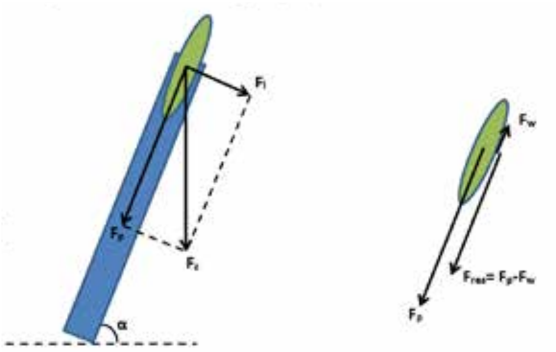


Figure 11 Balance of forces acting on the mortar round.

The resulting force F_{res} drives the round to the bottom of tube. This F_{res}, combined with the mass m of the mortar round, determines the average acceleration a of the mortar round, according to Newton's first law of motion: F_{res}= m·a, or:

$$a = \frac{F_{res}}{m} = \frac{mg(\sin\alpha - \mu\cos\alpha)}{m} = g(\sin\alpha - \mu\cos\alpha) \qquad (5)$$

An object that accelerates over a certain time period, travels a distance of x starting from rest, according to:

$$x = \frac{1}{2}at^2 \qquad (6)$$

When applied to the round in the tube, this means that the necessary time to cover the 460 mm to the bottom of the tube, can be determined by combining equations (5) and (6):

$$t = \sqrt{\frac{2x}{g(\sin\alpha - \mu\cos\alpha)}} = \sqrt{\frac{2\cdot 0.46}{9.81(sin70 - 0.57\cos 70)}} = 0.355 \text{ seconds} \qquad (7)$$

Based on this relatively simple analysis it can be concluded that the time until reaction derived from the video footage between 0.367 and 0.434 seconds, corresponds closely to the calculated time for a 1.6 kg mortar round to travel a distance of 460 mm.

For the calculation a dynamic friction coefficient of 0.57 is used and it is assumed that the round was 190 mm inserted in the barrel at the moment of release. A sensitivity analysis was applied to the calculation to ensure that variation in these assumptions does not result in an overlap with the travel time for double loading. See Figure 12; because literature reports a (static) friction coefficient for steel on steel between 0.5 and 0.8, the calculation is repeated for these values, also including a variation of 50 mm on the travel distance. As Figure 12 shows, the corresponding travel time for double loading is between 0.18 and 0.25 s, and between 0.33 and 0.39 s for single loading. Only the latter corresponds with the time derived from the video footage.

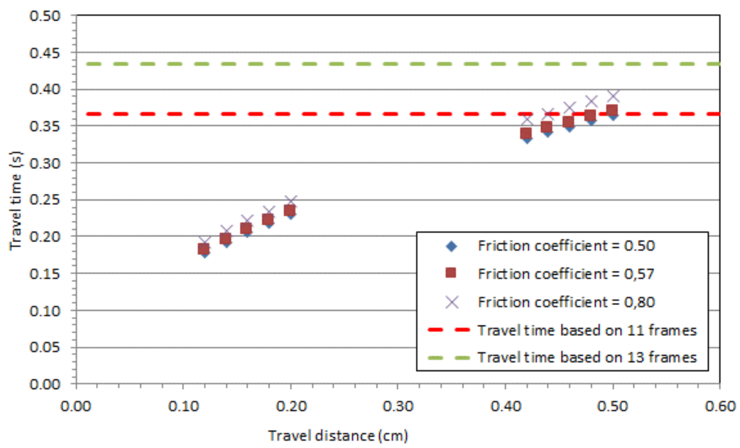


Figure 12 Sensitivity analysis of the travel time versus the travel distance for single loading (around 46 cm) and double loading (around 16 cm).

This analysis demonstrates that double loading has not occurred and that the mortar round that is dropped into the mortar as seen in the video footage, was the cause of the observed effects.

2.10.5 *Summary*

It is concluded that double loading has not occurred, based on:

- The general impression of the orderly loading process of the mortar and the low rate of firing;
- The calculated travel time of the round in the tube that is consistent with the loading of a single round;
- The damage to the mortar;
- The recovered fragments/parts that originate from a single round.

2.11 Damage resulting from the main charge or propelling charge and type of reaction

Additional research question AV1.3
A fragment was recovered from the bottom section of the mortar. At a relatively low point the launch tube has ruptured and was bent outwards. How can this be explained - was it caused by the main charge or by the propelling charge (primary cartridge and augmenting charge)?

Answer
The damage to the launch tube was caused by a reaction of the main charge. This conclusion is based on the analysis of the facts from several angles as described in the following paragraphs.

2.11.1 Propelling charge

The mortar round is fired when its percussion primer strikes the firing pin at the base of the tube. The primer initiates the primary cartridge, which consists of 0.3 grams of black powder. Its combustion generates a flame inside the mortar tail and also gas pressure, which, through the ventholes in the tail, fills the space underneath the round. The flames that extend from the ventholes ignite the augmenting charge that is wedged around the tail[4]. The augmenting charge consists of 8 grams of smokeless gun powder. The combustion of the primary and augmenting charge together generate the propelling force for the mortar round to leave the launch tube and reach its target.

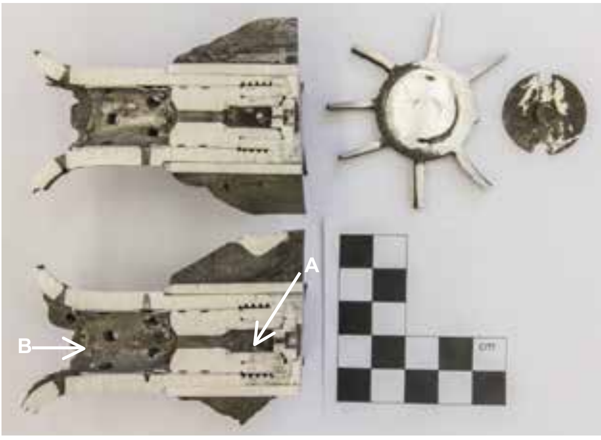


Figure 13 Cross-section photo of the tail assembly.

A cross-section was made of the recovered tail assembly; see Figure 13. No intact powder was discovered on the inside of the tail assembly. Combustion products were however present inside the combustion chamber in the tail assembly ('A' in Figure 13). It is not possible to determine whether the powder burned as a result of the normal initiation route via the percussion primer or as a result of the heat released by a reaction of the main charge.

[4] The loader is supposed to push the augmenting charge to the bottom of the tail assembly just prior to loading.

The top of the inner cartridge casing ('B' in Figure 13) displays plastic deformation, which indicates that stress was applied from the forward end of the tail assembly. This deformation is probably caused by the shock wave resulting from the detonation of the main charge.

The gas pressure that is generated underneath the shell body accelerates the round and launches it from the launch tube according to the functional design of the mortar. This gas pressure is below the burst pressure of the launch tube and delivers insufficient pressure to cause the damage to the tube as observed after the accident.

On one of the pictures taken after the accident (ref. DSCN2971.JPG) an object is seen with a similar shape as an augmenting charge. Figure 14 shows an intact augmenting charge and
Figure 15 shows the object in the immediate vicinity of the remnant of the mortar round tail assembly, as found after the accident. It is possible that this object is the remnant of an augmenting charge. For a normal ignition process it is unlikely that remnants of the augmenting charge are found because it is completely consumed. If this object is the actual remnant of an augmenting charge it implies that the combustion process was incomplete during the accident; i.e. that the ignition process was disturbed or interrupted by the reaction of the main charge.

Figure 14 Intact augmenting charge.

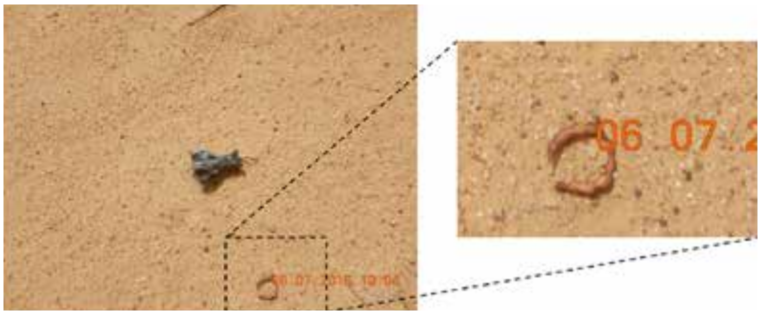


Figure 15 Object near the remnant of the tail assembly, found after the accident.

2.11.2 Location and the extent of damage to the launch tube

The reconstruction revealed that the source of the reaction was located at the position of the missing part of the mortar. Here the fragmentation of the tube and sight unit was most severe. Above and below this location the damage pattern was similar. This damage does not consist of complete fragmentation of the launch tube, but of longitudinal shearing of the metal; see Figure 16. The shell body with main charge is positioned at the location with severest fragmentation. This combination of damage to the launch tube and the position of the shell body points at a reaction of the main charge.

Figure 16 Damage to the launch tube.

2.11.3 Details of the damage to the launch tube

Two details were discovered in the remnants of the launch tube that support the indication that the main charge reacted violently.

1. Fragmentation damage to the baseplate end of the launch tube

The recovered baseplate end of the launch tube consists of a part, including screw thread, which connects the launch tube to the base plate. Three elongated metal strips are still attached to the part with the screw thread; see Figure 17.
The damage to the end of the elongated strips is typically caused by the impact of fragments. The damage to these metal parts is displayed in Figure 18 for the three elongated strips. This damage is caused by the fragmentation of the shell casing of the mortar round. The high speed impact of the shell casing fragments on the inner side of the launch tube causes the damage as displayed in Figure 18. This impact damage contributes to the further fragmentation of the launch tube because crack initiation occurs at the impact locations. This is also the reason why this damage is only found at the end of the elongated metal strips.

Figure 17 Recovered base plate end of the launch tube.

Figure 18 Damage to the elongated strips from the lower end of the launch tube.

Figure 19 schematically illustrates how the fragments from the shell casing are accelerated in different directions and subsequently strike the inner side of the launch tube; see point A in Figure 19. At this point there is a free path for the shell casing to expand, fragment, accelerate and impact the inside wall of the tube at high speed due to the reaction of the explosive charge.

It should be noted that the typical damage shown in Figure 18 is not found on the metal strips that are still attached to the remnants of the *muzzle end* of the launch tube (point C in Figure 19). This difference is probably caused by the larger amount of explosive present at the forward end of the mortar round; at point C, the launch tube is fragmented into smaller pieces, as a result of which the pieces with this typical damage are no longer attached to the remnants of the muzzle end of the launch tube.

The amount of explosive is less at point A in Figure 19 as a result of which the metal strips with this typical impact damage at their ends, are still attached to the remnants of the baseplate end of the mortar.

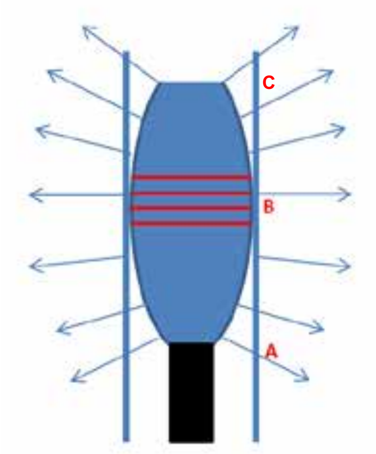


Figure 19 Expansion of the main charge and fragment directions.

In 2016 TNO performed a series of tests to investigate how a controlled deflagration can be achieved in a sealed steel tube filled with a Plastic Bonded Explosive (PBX) [ref. 5]. These tests demonstrated that a contained explosive can be set off to a full detonation, a partial detonation and a deflagration. Figure 20 is reproduced from ref. 5; it shows the damage to the tube after a detonation and deflagration. The explosive is initiated with a pyrotechnic charge on the right side of the tube, after which the left side was initiated with an explosive shock from a detonator. As a consequence, the explosive deflagrated on the right side, and detonated on the left side. Figure 20 shows that only the left side of the tube fragmented as a result of a detonation.

The launch tube from the accident has fragmented at the location of the main charge of the mortar round. The information from [ref. 5] supports the conclusion that the main charge detonated instead of deflagrated.

Figure 20 Damage to a sealed tube following a detonation (left) and deflagration (right).

Reference tests, performed by the Knowledge Centre for Weapons Systems and Ammunition (KW&M), substantiate that only a detonating round can cause this kind of damage pattern [ref. 10]. Figure 21 shows on the left, the remnants of a mortar which is blown apart by the detonation of a 60 mm mortar round. Because the round was released (remotely) into the mortar with its fuze in armed position, the round detonated at the bottom of the launch tube at the moment the primary cartridge hit the firing pin. On the right in Figure 21, a mortar is shown in which a mortar round has deflagrated. The deflagration was enabled by drilling a 5 mm diameter hole in the casing of the shell. When the round is fired (with its fuze in unarmed position) the flames and gas pressure from the ignited powder charge reach the main explosive charge through this hole in the casing, causing the main charge to burn while still in the launch tube. The launch tube bulges due to the build-up of the internal pressure and the sight unit is blown away, but the launch tube does not fragment.

Figure 21 Mortar after an internal detonation (left) and deflagration (right) of a 60 mm mortar round [ref. 10].

2. Imprint of the shell body on the launch tube
The recovered debris also includes a fragment that features a number of parallel lines in the metal. This fragment was removed from the body of one of the victims following the accident. It is a fragment measuring approximately 3 x 5 cm and with a thickness corresponding to the thickness of the wall of the launch tube. Based on the thickness, colour and the surface texture[5] it is concluded that this fragment originates from the section of the launch tube that severely fragmented. The lines of the imprint (with barely tangible relief) on the fragment have a spacing of about 6.3 mm. This spacing corresponds with that of the grooves on the exterior of the shell casing[6], see Figure 22.

At the moment the main charge explodes, the exterior of the shell casing strikes the interior of the launch tube and leaves an imprint with four grooves. This location is marked as 'B' in Figure 19. At location B, the space between the main charge and the inside of the launch tube is very small (in contrast to location A). At the moment of impact, the shell casing of the main charge has not yet fragmented, but it expands elastic-plastically due to the reaction of the explosive compound. For this reason the damage pattern due to fragment impact of the casing on the inside of the tube, as shown in Figure 18, is absent on this fragment of the tube.

[5] This pattern stays on the metal after the manufacturing process. It is only visible under a magnifying glass (and not on the photo in Figure 22).
[6] These are the so-called centering rings which guide the round through the launch tube and act as a gas seal [ref. 6].

Figure 22 Imprint on the fragment of the launch tube, originating from the grooves on the shell casing when the main charge explodes.

2.11.4 *Video footage of the accident*

The individual frames of the GoPro video (ref. GoPro film: GOPR0253.MP4) recorded right before the accident were examined. The speed and severity of the reaction are striking. Figure 23 displays the first frame showing the reaction and the preceding frame side by side. The time span between the frames is only 0.0334 seconds. The expansion of gases and projection of fragments in this timeframe measures roughly 2 m. This means that the speed of the expansion of the reaction products or fragments is at least 60 m/s. This speed may be higher but the frame rate of the GoPro is too low to be able to draw this conclusion.

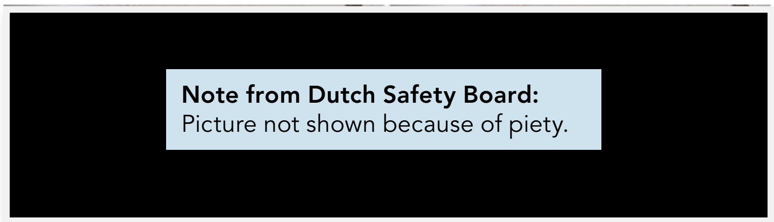


Figure 23 Frames just before and at the moment of the reaction.

The video footage is also compared with an estimate of the volume of the reaction products. The main charge of the round consists of 200 g TNT, the booster charge in the fuze consists of 16.6 g TNT. The primary cartridge contains 0.3 g black powder and the augmenting charge contains 8 g of smokeless powder. The calculation of the volume of the reaction products is based on 216.6 g TNT and 8.3 g nitrocellulose. The specific volume of the reaction products under atmospheric conditions is 825 L/kg for TNT and 871 L/kg for nitrocellulose [ref. 7]. An equivalent radius r_{eq} can be derived from the total volume of reaction products V_{gas}:

$$r_{eq} = \sqrt[3]{\frac{3 \cdot V_{gas}}{4\pi}} \qquad (9)$$

In Table 2 the volume of the reaction products and equivalent radius are shown for three scenarios. Comparison of the equivalent radius in this table with the cloud of reaction products in Figure 23 (right), indicates a reaction of at least the main charge and booster charge. The reaction of only the powder charge seems unlikely, because the dimensions of the cloud of reaction products are larger than the length of the mortar.

Table 2 Volume of reaction products and equivalent radius for three scenarios.

Scenario	Mass energetic material	V_{gas} [L]	r_{eq} [m]
100% powder charge	8.3 g NC	7.2	0.12
100% main and booster charge	216.6 g TNT	179	0.35
full shot	216.6 g TNT and 8.3 g NC	186	0.35

Moreover, no traces of explosive compounds or partially burned explosive compounds (TNT) were found at the site of the accident, as would be expected in case of a partial detonation, explosion, deflagration or fire. This points to a detonation of the main charge in accordance with the definition in Appendix B.

2.11.5 Summary

Based on the preceding analysis it is concluded that the main charge detonated. The main arguments to support this are:

- The speed of the reaction;
- The extent of the damage and fragmentation to the launch tube and sight unit;
- The fragmentation pattern and remnants of the baseplate end of the launch tube;
- The imprint of the grooves in the shell body on the remnants of the launch tube;
- The cloud of reaction products that is consistent with a reaction of the main and booster charge;
- The absence of traces of explosive compounds at the site of the accident.

2.12 Inner side of the launch tube

Additional research question AV1.4

Are there irregularities visible on the inside of the launch tube (remnants) that could explain why the round did not exit the tube in the normal way?

Answer

A visual inspection was performed of the remnants of the launch tube No. 513 and of the reference tube No. 500. Both tubes display extensive oxidation. It is not possible to determine when the oxidation occurred. It may have occurred in the time between the accident and the investigation described in this report.

At the location of the increased wall thickness of the intact launch tube a ring is observed with a near black colour. It is assumed that this ring is situated at the location where the combustion gases of the primary cartridge and augmenting charge transfer the greatest heat to the tube when the mortar round functions normally. This ring cannot be observed on the remnants of the launch tube of the accident, because that section of the tube fragmented and was not recovered.

The inside surface of both launch tubes has a rough texture. In the tube of the accident several very minor irregularities were observed; see Figure 24. These are dispersed circumferentially and have a random appearance. It is assumed that these irregularities are the result of the accident, possibly caused by the impact of small fragments during the reaction of the main charge.

Using a micrometer gauge the inside diameter of the tube was measured at several locations; the diameter varies between 60.56 and 60.60 mm.

No irregularities were found that indicate the mortar round could not have been launched in a normal way.

Figure 24 Several minor irregularities on the inside of the remnants of the launch tube No. 513 after the accident.

2.13 Mortar round remnants of one or two rounds

Additional research question AV2.1
Do the mortar round remnants originate from one or two rounds?

Answer
There is no indication that the mortar round remnants originate from two rounds. See paragraph 2.10 for detailed explanation.

2.14 Fuze components

Additional research question AV2.2
Was the fuze recovered, or were parts of it recovered? If so, is it possible to determine from these parts whether the fuze was armed at the moment of the explosion? If not, how can this be explained?

Answer
Relatively large aluminium fragments were found in the body armour of the victims. The body of the fuze is made of a cone-shaped aluminium part. Several fragments are identified as being parts of the fuze body, see Figure 25. Especially the screw thread (Figure 25, two lower parts) and a groove on some of the other parts (Figure 25, top four parts) are characteristic for the fuze.

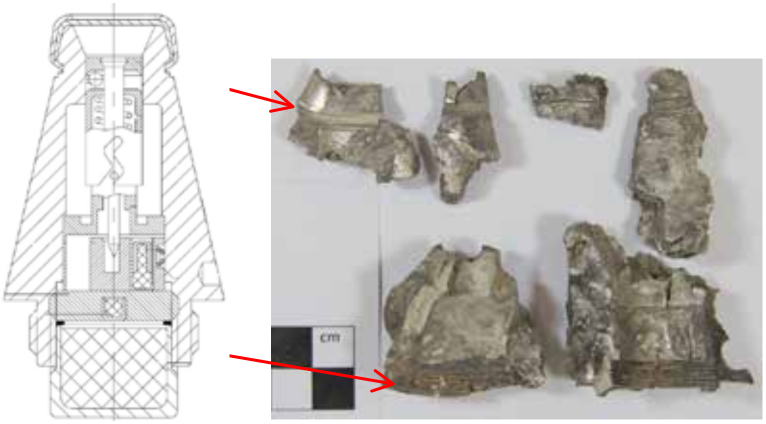


Figure 25 Aluminium fragments originating from the fuze.

Two components were also recovered, see Figure 26 and Figure 27, which possibly originate from the fuze. The confirmation that these parts respectively represent the explosive train interrupter[7] (metal barrier) and cover plate[8] of the booster, can be obtained by making a direct comparison with an original fuze. This comparison is not possible since no (inert) original fuze is available to TNO at the time of writing of this report.

At this stage of the investigation it cannot be verified from the recovered and positively identified parts of the fuze whether it was armed at the moment of the accident.

[7] It is impossible that this component (Figure 26) stems from the remaining mortar rounds that were destroyed since it was recovered from the body armour of one of the victims. If the presumption is confirmed that this is the metal barrier of the fuze, the hypothesis is that the lead charge in the metal barrier has functioned, since the metal above it has disappeared (blown away by the lead charge).
[8] If the presumption is confirmed that this is the cover plate of the booster (Figure 27), the hypothesis is that the lead charge has initiated the booster. Because it is unlikely that the plate originates from one of the mortar rounds destroyed after the accident. In that case the detonation shock front (which causes the deformation) comes in from the main charge and not from the lead charge.

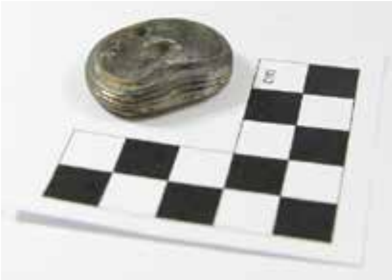


Figure 26 Presumed explosive train interrupter from the fuze.

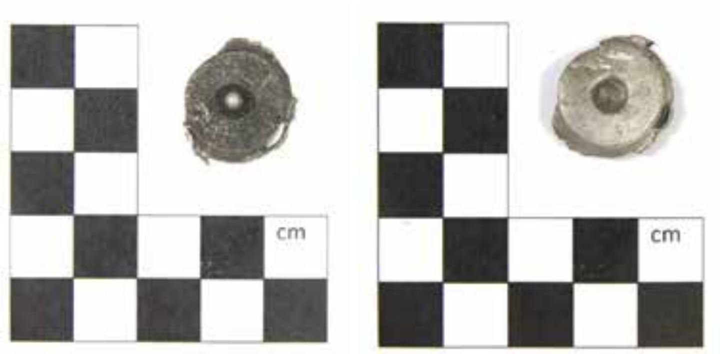


Figure 27 Presumed booster cover plate from the fuze, photographed from two sides.

2.15 Explanation of the damage to the tail assembly

Additional research question AV2.3
The forward end of the tail assembly displays severe petalling, similar to skin of a banana that is peeled half way. How can this be explained as there is no explosive charge in this section of the mortar round. The petalling cannot be explained by the explosion of the primary cartridge or the augmenting charge, since the lower section of the tail assembly is still intact.

Answer
The recovered remnants of the tail assembly of the mortar round shows different types of damage; see Figure 28.
Nearly the entire outer metal surface is affected by the explosive reaction. The released heat and combustion gases have affected the surface and resulted in a dark grey layer of oxide.

Figure 28 Remnants of the mortar round tail assembly.

Moreover, there are several localised deformations of the fins and central section of the tail assembly. These are caused by impact with other metal parts (such as the launch tube in which the shell was dropped and the base plate), probably immediately following the reaction and the dispersal of the fragments of the launch tube, the sight unit and the shell.
A distinct damage pattern was found on the forward end of the tail assembly (towards the main charge). On the forward end a section of the tail assembly is missing. For indicative purposes: an intact tail assembly has a total of four rings with perforations (flash holes) one above the other, see Figure 29. The section of the tail assembly between the second ring with flash holes and the shell body is missing, with the exception of three petalled strips of steel between the first and second ring with flash holes. The tail assembly is partially sheared off at the first ring and partially at the second ring.

During production, a short screw thread is machined at the bottom end of the shell body[9]. The tail assembly is screwed to the shell body using this thread. When the main charge detonates a shock wave travels through this connection. Rarefaction waves (reflected shock waves) will cause fracture and fragmentation. The flash holes represent weak points in the tail and are therefore vulnerable to crack initiation and fracturing. Due to the rarefaction wave the tail failed at the flash holes.

The combination of the damages to the tail assembly can be explained by a reaction of the main charge. This reaction resulted in a shock wave, heat and combustion gases, the dispersal of fragments and the failing and the deformation at the forward end of the tail assembly.

[9] This piece of screw thread was recovered after the accident (Serial No. 22 inventory Appendix A).

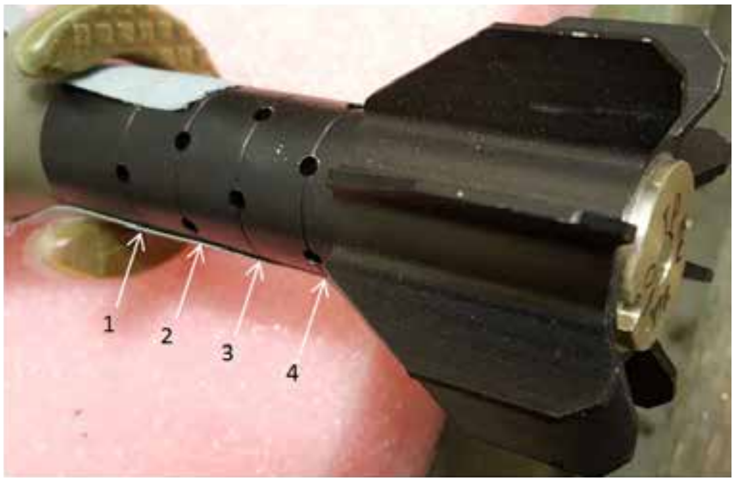


Figure 29 Intact tail assembly from an HE80 mortar round.

In 2012, TNO performed experiments [ref. 8] with the HE80 60 mm mortar round without a fuze. In these experiments the main charge was detonated using a plastic bonded explosive (at the location of the booster) and a detonator. The experiments were carried out in bunkers, which allowed for easy recovery of the fragments. The tail assemblies of the rounds were recovered after the experiments. These assemblies display damage patterns (see Figure 30) similar to the tail assembly recovered after the accident (see Figure 28); also in these experiments the tail failed at the first and second row of flash holes[10].

This confirms that the damage to the recovered tail assembly is caused by a detonation of the main charge.

Figure 30 Recovered tail assembly of the HE80 mortar round after a TNO experiment in 2012.

[10] In the TNO detonation experiments of 2012, variation was observed in the failure location; in some cases the tail assembly only partially sheared off at the first row or second or third row of flash holes.

3 Conclusions

To investigate the cause of the accident, the Dutch Safety Board formulated an initial set of research questions with respect to the remnants of the weapon system and the mortar round. Subsequently, the DSB formulated an additional set of technical questions (DSB document dated 13 September 2016).

Both the initial research questions and subsequent technical questions are answered in this report. The following main conclusion and sub-conclusions have been drawn on the basis of the analysis of the video footage and the debris.

Main conclusion:
- Based on the available information and the debris, TNO concludes that the accident was caused by the premature detonation of the 60 mm High Explosive (HE 80) mortar round that was dropped into the mortar.

Sub-conclusions:
- The handling of the launch tube and the loading procedure of the mortar round were performed in an orderly manner; no second mortar round was loaded (double loading) before the first round was fired;
- The mortar round that caused the accident reached the bottom of the launch tube; the firing pin in the base plate of the mortar has struck the percussion primer of the round;
- No irregularities were found in the launch tube;
- No defects were found to the firing pin in the base plate of the mortar;
- The combustion process of the powder in the primary cartridge and augmenting charge had probably not completed due to interruption by the reaction of the main charge;
- The damage to the launch tube is consistent with the position of a reaction of the main charge, at or near the moment the mortar round reached the bottom of the launch tube;
- The main charge of the mortar round detonated[11].

[11] Determination of the cause of the initiation of the main charge is beyond the scope of this report.

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5 Signature

Rijswijk, 14-12-2016

TNO Technical Sciences

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A Inventory of the recovered debris

This appendix contains a list of the debris from the accident supplied by the DSB.

Table A1 Inventory overview of the recovered debris directly relevant for answering the research questions.

Code Royal Netherlands Marechaussee	Short description	Originating from	Originating from	Remarks
AABV5257NL	Launch tube muzzle end	Launch tube	1st search FRA	
AABV5257NL	Launch tube base plate end	Launch tube	1st search FRA	
AABV5257NL	Base plate	Launch tube	1st search FRA	
AABV5257NL	Muzzle cover	Launch tube	1st search FRA	
AABV5257NL	"Safety"pin to remove transport safety cap	Mortar round	1st search FRA	
AABV5257NL	Metal ring	Unknown	1st search FRA	Outer diameter 50 mm
AABV5257NL	Tail assembly	Mortar round	1st search FRA	
Ontbreekt	Canvas protective cover	Launch tube	1st search FRA	
AABV5256NL	Lanyard	Launch tube	1st search FRA	several parts
AABV5498NL	Fragment launch tube	Launch tube	1st search FRA	Center section launch tube, muzzle end
AABV5498NL	Fragment launch tube with external screw thread	Launch tube	1st search FRA	Base plate end launch tube
AABV5498NL	Connecting ring for lanyard in three parts	Launch tube	1st search FRA	
AABV5498NL	Elongated metal part with screw thread	Unknown	1st search FRA	
AABV5498NL	Miscellaneous parts sight unit	Launch tube	1st search FRA	Setting wheel, level and connecting ring, clamping-pin
AABV5265NL	Miscellaneous parts including three caps, part of green shell body	Miscellaneous	2nd search CVO	Potentially from other rounds, smoke has light green shell body. Potentially explosive train interrupter of the fuze
AABV5296NL	Miscellaneous (incl. clamping screw sight unit)	Miscellaneous	2nd search CVO	Potentially from other rounds
AABV5296NL	Clamping screw sight unit	Launch tube	2nd search CVO	
AABV5499NL	Part of sight unit	Launch tube	Body armour	
AABV5260NL	Part of sight unit	Launch tube	Body armour	
AABV5260NL	Presumably part of sight unit	Launch tube	Body armour	
AABV5259NL	Part of sight unit	Launch tube	Body armour	Threaded wheel, imprint from disk in the paint
AABV5495NL	Corroded part with screw thread	Mortar round	Body armour	Connection main charge with tail assembly of the mortar round
AABV5495NL	Disc with external screw thread, one hole two cavities	Presumably fuze	Body armour	Thickness 6.95 mm, diameter max 29.5 mm, diameter min 24.5 mm. Potentially explosive train interrupter of the fuze
AABV5499NL	Loose parts, potentially aluminium parts of fuze and sight unit	Miscellaneous	Body armour	Potentially part with groove just below the protective cover
AABV5499NL	2 safety pins most likely not originating from the accident	Mortar round	Body armour	Likely originating from previous firings
AABV5296NL	Thin metal plate	Presumably fuze	2nd search CVO	
AABV5296NL	Potential parts of fuze and sight unit	Miscellaneous	2nd search CVO	From plastic cup of serial nr 16, non-magnetic

Table A2 Inventory overview of the recovered debris not directly relevant for answering the research questions.

[redacted]

Note from Dutch Safety Board:
Picture not shown because of piety.

B Types of reaction

A differentiation is made between different types of reactions of ammunition. The following descriptions provide a definition of the different types of reactions.

Detonation (Type I)
The most violent type of explosion. A supersonic decomposition of the energetic material that causes an intense shock in the surrounding medium, such as air or water, and rapid plastic deformation of metal casings followed by extensive fragmentation. All the energetic material will be consumed. The effects include large ground craters for munitions on or close to the ground, perforation / fragmentation of adjacent metal plates and blast damage to nearby structures.

Partial detonation (Type II)
The second most violent type of explosion. Some, but not all, of the energetic materials react as in a detonation. An intense shockwave is formed; some cases are broken into small fragments; a ground crater can be produced, adjacent metal plates can be damaged as in a detonation and there will be blast damage to nearby structures. A partial detonation can also cause large case fragments, such as occurs in a violent pressure rupture (brittle fracture). The amount of damage, relative to a full detonation, depends on the portion of material that detonates.

Explosion (Type III)
Ignition and rapid burning of the confined energetic material builds up high local pressures leading to violent pressure rupturing of the confining case. Metal cases are fragmented (brittle fracture) into large pieces that are often thrown for long distances. Unreacted and / or burning energetic material is also thrown about. Fire and smoke hazards will exist. Air shocks are produced that can cause damage to nearby structures. The blast and high velocity fragments can cause minor ground craters and damage (breaking, tearing, gouging) to adjacent metal plates. Blast pressures are lower than for a detonation.

Deflagration (Type IV)
Ignition and burning of the confined energetic material leads to non-violent pressure release, as a result of low case strength or venting through the case. The case might rupture but does not fragment; closure covers might be expelled, and unburned or burning energetic material might be thrown about and spread the fire. Propulsion might launch an unsecured item, causing an additional hazard. No blast or significant fragmentation damage to the surroundings; only heat and smoke damage from the burning energetic material.

Fire (Type V)
The least violent type of explosion. The energetic material ignites and burns, non-propulsively. The case may open, melt, or weaken sufficiently to rupture non-violently, allowing mild release of combustion gases. Debris stays mainly within the area of the fire. The debris is not expected to cause fatal wounds to personnel or be a hazardous fragment beyond 15 m.

APPENDIX H

CLIMATIC CONDITIONS AND POTENTIAL EFFECTS

The Dutch Safety Board (DSB) requested the Netherlands Organisation for Applied Scientific Research (TNO) to analyse the climatic conditions during storage and operational use. The purpose of this analysis was to establish whether the climatic conditions contributed to the premature initiation of the mortar round during the exercise.

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TNO-report

TNO 2017 R10104

Mortar exercise accident Mali: Climatic conditions and potential effects

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Summary

On 6 July 2016, a fatal accident occurred in Kidal, Mali during an exercise involving a 60 mm High Explosive mortar round (HE 80) with a M6-N (H) fuze. Commissioned by the Dutch Safety Board (DSB), the Netherlands Organisation for Applied Scientific Research (TNO) analysed the climatic conditions during storage and use to establish whether these contributed to the premature functioning (detonation) of the mortar round.

For this analysis the TNO climate tool and analytical equations were used to calculate the temperature of the mortar rounds in storage and during use. The calculations show that the 60 mm mortar rounds, stored in the shipping container in Kidal, likely reached a temperature over 60°C. This also occurred in the days just before and after July 6.
It was also calculated that out of storage and during use, the steel casing and the TNT main charge can reach a temperature of 80°C due to exposure to sunlight. As the mortar rounds were loaded with bare hands it is unlikely that the rounds actually reached such a high temperature during the exercise.
As a result of exposure to sunlight it is likely that during use, the temperature of the fuze increased to over 50°C and possibly even exceeded 60°C.
Based on the analysis it is concluded that during storage and use, the maximum allowable fuze temperature of 50°C as specified by the supplier was exceeded.

It is unlikely that, due to heating of the TNT main charge, exudate reached locations below or above the explosive train interrupter (metal barrier)[1] of the fuze. If it had, it is unlikely that combustion of the exudate due to the shock of the launch caused detonation of the main charge.

Initiation of the RDX booster charge or the PETN lead charge due to the shock of the launch is highly unlikely, also at an elevated temperature.

Moisture may penetrate through the adhesive layer of the membrane at the tip of the mortar round and reach the energetic materials (primer) inside the detonator, especially if the round is subjected to one or more shocks.

Moisture can cause (galvanic) corrosion, which leads to degradation of the aluminium primer cup (detonator) and the copper/nickel (Melchior) cup holder. This process potentially accelerates at an elevated temperature. Moisture can also result in hydrolysis of the lead azide inside the primer, creating hydrogen azide. The hydrogen azide can react with the copper in the Melchior cup holder and in the brass slider causing formation of extremely sensitive copper azide. It is anticipated that hydrolysis of the lead azide is promoted by the destruction of the primer cup under the influence of a (galvanic) corrosion process.

[1] In the event of premature initiation of the detonator, this metal barrier must prevent transfer of reaction to the main charge in the unarmed (safe) position of the fuze.

Corrosion of the Melchior cup holder may be accelerated by the presence of (antimony)sulphide in the primer. At elevated temperatures, tetrazene may sublimate, resulting in the possible formation of crystals inside the fuze away from the detonator.
If copper azide (and tetrazene) is formed, it will likely detonate due to the shock of the launch and initiate the primer. Transfer of reaction to the lead charge through the metal barrier or through a 'bridge' of copper azide (and tetrazene) between the primer and the detonator's lead charge in unarmed position, results in the initiation of the booster and detonation of the main charge. The probability of transfer of reaction may be temperature dependent.

Table of contents

1 Introduction

On 6 July 2016, a fatal accident occurred in Kidal, Mali during an exercise involving a 60 mm High Explosive (HE) mortar round with a M6-N (H) fuze. As part of the technical investigation, the Dutch Safety Board (DSB) requested the Netherlands Organisation for Applied Scientific Research (TNO) to analyse the climatic conditions during storage and operational use.

The purpose of this analysis is to establish whether the climatic conditions contributed to the premature initiation of the mortar round during the exercise. The analysis is based on a comparison between the calculated temperature during storage/use and the temperature requirements for transport/storage and use according to Table 1.

Table 1: Temperature requirements for transport/storage and use.

Reference	Application	Temperature requirements		
		Transport / storage [°C]	Use [°C]	Climate zones [STANAG 2895][2]
Correspondence, 2006	Mortar round	-46 to +63 [STANAG 4225]	-46 to +63 [STANAG 4225]	A2, A3, C2
Life Cycle Description (LCD), 2006	Mortar round	-46 to +71	-46 to +49 excluding solar radiation, with solar radiation currently +63	A1, A2, A3, C2
Arsenal, 2017[3] [Bulcomersks, 2017]	M6-N fuze	-50 to +50	-50 to +50	---

The TNO climate tool was used to estimate the temperature of the 60 mm HE80 mortar round during:
- storage of the ammunition in the white shipping container in Kidal, Mali
- use and exposure to solar radiation.

This analysis is provided in Chapter 2.

Chapter 3 describes the potential effect of moisture and temperature on the mortar round's ability to function correctly. Chapters 4 and 5 present conclusions and recommendations.

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[2] A1 = very hot, A2 = hot dry, A3 = intermediate, C2 = cold [STANAG 2895].

[3] Arsenal 2000 JSCo verbally communicated that, in accordance with Russian design principles, at least a 20% margin is usually applied to the ammunition requirements issued to the customer, such as maximum (gas) pressure of the weapon and maximum operating temperature. This means that the maximum operating temperature for the M6-N fuze is 60°C. Nevertheless, Arsenal 2000 JSCo advises its customers to respect the specified maximum operating temperature [Company visit to Arsenal, 2017].

2 Temperature during storage and use

This chapter provides an analysis of the estimated temperatures during storage and use in paragraphs 2.1 and 2.2. The applied climatic data was generated with the TNO climate tool. At any place on earth, weather conditions such as temperature and humidity are determined from hour to hour through a combination of model calculations with measurements on the ground and by satellite. The flexible climate tool converts these time series into directly interpretable static parameters, such as for example the probability of exceeding a certain temperature limit in different seasons.

2.1 Storage

Material exposed to sunlight heats up to a higher temperature than the ambient air. The temperature inside a car parked in the sun quickly exceeds the ambient temperature with 20 degrees centigrade and a room with a dormer window heats up more than other rooms. This is because the atmosphere is transparent for solar radiation and material (partially) absorbs the sunlight. The increase in temperature is not unlimited because the material radiates heat in the form of long-wave radiation[4]. The radiated energy depends on the type of material and its temperature. In addition to the thermal radiation, temperature differences between material and the ambient air produce vortices and air flow that carries away energy. These flows are here referred to as convection. Material exposed to sunlight continues to heat up until incoming and outgoing energy are balanced. If we ignore forced ventilation from, for example, wind or movement, the equation is:

$$a(\text{solar radiation})E_{\text{sun}} \downarrow + a(\text{infrared})E_{\text{air}} \downarrow = E_{\text{material}} \uparrow + E_{\text{convection}} \uparrow \qquad (1)$$

The incoming energy, the left-hand side of equation 1, comprises two terms. The first term indicates the amount of solar energy absorbed. The second term relates to thermal radiation from the surroundings. The right-hand side of the equation provides the energy loss terms as a result of thermal emission and convective cooling. The four terms are explained below.

Not all the energy E that reaches a material is absorbed. The factor *a*, is the fraction of electromagnetic radiation that is absorbed. The factor a is also referred to as the absorption coefficient. The absorption of sunlight is difficult to understand in the literal sense, so the more intuitive reflection coefficient *r* is also often used. The relationship between the two is simple *a* + *r* =1. Some typical reflection coefficients for solar radiation are: r_{asphalt} = 0.15; r_{concrete} = 0.3; $r_{\text{white paint}}$ = 0.58; $r_{\text{aluminium}}$ = 0.71; $r_{\text{dark green}}$ car = 0.5.

[4] The wavelengths of this long-wave radiation are in the infrared part of the spectrum and therefore, we cannot see them. The warmer the material, the shorter the wavelength of the radiation. For light bulbs and stars (the sun!) the wavelength of the emitted radiation is so short that it lies in the visible part of the electromagnetic spectrum. We call this radiation light.

The shipping container in which the mortar rounds were stored is white; see Figure 1. The following absorption coefficient seems most appropriate for this paint:

a (solar radiation) **= 0.42**

Higher reflection factors also exist for white paint. The final calculations are therefore based on a range of absorption coefficients. The selected absorption coefficient applies to visible sunlight.

Figure 1 Ammunition storage in a shipping container in Kidal, Mali. The container with the mortar rounds is positioned in between two other shipping containers [KMAR, 2016].

$E_{\text{sun}}\downarrow$ is the incoming solar radiation. It is made up of direct sunlight and diffuse light from all directions. Approximately 1,367 W/m^2 of solar radiation enters the top of the atmosphere. The amount of energy on the surface depends on the angle of the incoming solar radiation and the degree of absorption and dispersion that takes place in the atmosphere. Around noon in the southern subtropics, the sun shines perpendicular at the surface. If we assume the atmosphere is relatively free of dust an accurate estimate of the maximum amount of radiation on the ground is:

$\boldsymbol{E}_{\textbf{sun}}\downarrow = E_{\text{direct}}\downarrow + E_{\text{diffuse}}\downarrow =$ 1,120 + 112 = **1,232 W/m^2**

The position of the sun is taken into account for the calculations for different times of day. The variation throughout the day displays a sinus-like correlation. If there is more dust in the atmosphere the sun is slightly hazier and $E_{\text{direct}}\downarrow$ decreases. The sunlight however, is barely absorbed but dispersed as diffuse sunlight. This can easily be seen by the sky no longer appearing blue, but white yellow. The larger the dust particles, the more the light is dispersed forward. This is why, for windblown mineral dust, the amount of radiation that reaches the surface is not as strongly related to the amount of particulate matter in the air than one might initially think.

In the second term of equation (1), $E_{\text{air}}\downarrow$ is the thermal radiation from the air. The atmosphere radiates heat like all other materials. The long-wave radiation that originates from a cloud relates to the cloud's temperature. For clear skies the energy received in the form of long-wave radiation is usually somewhat lower. The radiation frequently corresponds to the temperature one would find at a height of between 2-6 kilometres. Measurements demonstrate that a maximum of 400 W/m^2 of long-wave radiation is received in the subtropics when the skies are clear but highly polluted. For Kidal the following value is realistic for July 2016:

$\boldsymbol{E}_{\textbf{air}}\downarrow =$ **350 W/m^2**

As mentioned above, the outgoing energy, the right-hand side of equation 1, also consists of two terms. The first term $E_{\text{material}} \uparrow$ is the cooling as a result of thermal emission. We use the law of Stefan-Boltzmann for long-wave emissive cooling:
$E = e\sigma T^4$, in which *e* is the emissivity of the material, σ = 5.67 10^{-8} W/m^2K^4 the Stefan Boltzmann constant and T the temperature of the material. Kirchhoff has shown that material that absorbs a lot of electromagnetic radiation also emits a lot of radiation in the same wavelength spectrum; the emissivity is equal to the absorption coefficient, *e* = *a*. Solar radiation and the thermal radiation of objects cover a different part of the spectrum. The a (solar radiation) is thus not equal to the emissivity we need here.
The shipping container is made of steel. The radiation emitted however originates from the few micrometres thick surface layer, which in this case consists of white paint. White paint can be purchased in different compositions and the emissivity at room temperature usually varies between 0.82 and 0.95. The high value applies to a paint that easily loses heat through emission. Therefore, white paint absorbs relatively little sunlight as *a*(solar radiation) = 0.42 but emits relatively high amounts of long-wave radiation *a*(infrared)=0.9. For some materials, there is a strong relation between emissivity and temperature. For white paint, the temperature dependence in the temperature range up to 100°C is low compared to the variations between different compositions of white paint. For this reason the temperature dependence is here disregarded.

Note: for shiny metals, a low absorption coefficient in the visible part of the spectrum also corresponds to a low absorption coefficient in the infrared part of the spectrum. Therefore a shiny metal surface absorbs little sunlight, but the light it does absorb is not easily emitted. This is why shiny metal surfaces heat up to relatively high temperatures when exposed to sunlight.

The last term in the energy balance equation (1) is convective cooling. $E_{\text{convection}} \uparrow$. The term for heat loss as a result of air flows due to heat differences between materials and air is the least obvious term. Energy loss can be calculated as the product of a factor *h* and the temperature difference between the material in the sun and the ambient air temperature, i.e., $E_{\text{convection}} \uparrow = h\Delta T$. The factor *h* is referred to as convective heat transfer coefficient.
The convective heat transfer coefficient relates to the geometry of the object and the temperature difference between the object and the ambient air in a complex way. In case of minor temperature differences, no flow will be induced and the heat will only be released by thermal diffusion. In the latter case, *h*=0 and therefore $E_{\text{convection}} \uparrow=0$. The temperature increase will be the highest for this hypothetical case. The temperature increase of the metal exterior of the roof is effectively transferred to the inside of the roof (ceiling) and the adjacent air in the container quickly reaches the same temperature because the heat capacity of the air in the container is low.

Table 2 displays the calculated air temperatures for a number of different assumptions for the applied paint; the calculations are based on the sun being at its highest position. For the paint on the container we assume that an absorption coefficient of 0.42 is most appropriate. However, there are many 'off-white' paints with a lower absorption coefficient, such as 0.35. The best paint for this application would have an absorption coefficient of 0.25 or lower.

For a representative ambient temperature we find, when disregarding convective cooling, that the temperature inside the container would be 41°C higher than the outside ambient air. Selecting a whiter paint (low absorption coefficient for visible light) would be very effective in preventing the temperature rise in the container. Without convective cooling (h=0) we find that the temperature inside the container is only 16°C higher than the outside ambient temperature if whiter paint is used. Obviously, the most effective solution would be to create shadow with proper ventilation underneath. In that case the temperature would marginally rise above the ambient temperature.

The emissivity of white paint, too, has a considerable range. Two additional calculations are performed for the lowest and highest emissivity that are still realistic. Table 2 shows that the calculated temperature difference with the ambient air would be five degrees higher or three degrees lower when estimated emissivity is lower (0.82) or higher (0.95), respectively. Accordingly the calculated temperature rise of the container is less sensitive to variation in the assumed emissivity than to variation in the assumed absorption of sunlight.

Table 2 Calculated air temperatures for a number of different assumptions for the applied paint; the calculations are based on the sun at its highest position.

Temperature difference between the external air (shadow) and the air in a shipping container painted white. The calculations apply to noon, with a solar radiation of 1,232 W/m^2 and atmospheric thermal radiation of 350 W/m^2. The values regarded most representative are printed in bold.			
Absorption coefficient *a*(solar radiation)	Emissivity *e*(infrared)	Temperature difference [°C]	
		h = 0	*h* calculated
0.25	0.9	16	10
0.35	0.9	31	20
0.42	**0.9**	41	**26**
0.42	0.82	46	28
0.42	0.95	38	24

Calculations are also performed for the shipping container having a convective heat transfer coefficient calculated on the basis of published scientific experiments. Many studies consider cylinders and unusual geometrics or flat horizontal hot objects, but the dimensions considered are too small for this study [Corcione, 2007]. Here we use an article by [Lloyd, J.R. and W.R. Moran, 1974]. This article derives a convective heat transfer coefficient from experimental data.
The article is exceptionally useful because it considers large objects. For this study, we adopt the relation for a rectangular plate:

$$Nu = 0.15Ra^{1/6} \qquad (2)$$

Nu=hW/k is the dimensionless Nusselt number, h the convective heat transfer coefficient we are looking for, W the width of the plate (roof of the container) and k the thermal conductivity coefficient of the air.

Ra is the Rayleigh number that depends on the temperature difference between the plate and the ambient air. In our calculations:

$$Ra = g\beta(T_{roof} - T_{external\ air})W^3/\nu\alpha \qquad (3)$$

with g being the gravitational acceleration, β the thermal expansion coefficient of air, v the kinematic viscosity of air and α the thermal diffusivity of air.

This study assumes a windless situation for which natural (free) convection applies. Free convection can be laminar or turbulent. The transition takes place at a Rayleigh number of approximately 10^7. Natural turbulent convection applies to the shipping container because of its dimensions, equation (2) is therefore applicable.

Due to the absorbed solar radiation the roof heats up and emission of heat will increase. After a while the temperature of the roof becomes so high that spontaneous convection starts to occur. The equilibrium temperature in which we are interested cannot be determined analytically but needs to be calculated numerically. The results of the numeric modelling, using equations (2) and (3), are included in Table 2. The spontaneous convective cooling causes the temperature difference between the air inside the container and the outside ambient air to be reduced with approximately 15°C to 26°C.

During the week of 6 July 2016 temperatures reached 43°C on a daily basis, but on 6 July it was actually 40°C in Kidal. Based on the calculations we therefore conclude that on 6 July it was approximately 66°C inside the storage container. Also on the days just before and after 6 July, the specified maximum temperature for transport/storage and use of 63°C was exceeded when there was no wind around noon.

The wind on the days before and on 6 July, is known to have been very calm around Kidal. The localised wind across the roof of the container is not known. This is a very important detail as wind dissipates heat very effectively. As an example: if the wind is relatively moderate - three on the Beaufort scale - the convective heat transfer coefficient doubles and the temperature inside the container would be reduced from 26°C higher than the outside ambient temperature to 16°C higher than the outside ambient temperature. A moderate wind of 4 m/s would be able to reduce the temperature in the storage container to 56 - 59°C during the week of 6 July. As mentioned above, there was little wind, so it seems likely that the specified temperature for storage and transport was exceeded inside the container.

The end of June and beginning of July 2016 were the hottest time of that year in Kidal, as illustrated in Figure 2.

Figure 2 Maximum (green) and minimum (blue) temperatures recorded per week in 2016 (52 points connected by lines).

In the 30-year period from 1980 to 2010, there were just ten days on which the temperature was higher than in the first week of July 2016; moreover, on these days it was only slightly warmer, see Figure 3 and Figure 4[5]. On such relatively hot days the temperature in the storage container likely exceeded 63°C. The temperature difference of 26°C is only reached when there is maximum insolation. Therefore we cannot simply assume that all hours with a temperature higher than 37°C also result in exceedance of the threshold temperature of 63°C; according to Figure 4 this would occur for 1,000 hours per years, i.e., well over 10% of the time. In practice there are regular winds, but temperatures also often exceed 37°C later in the day, when the sun is low.

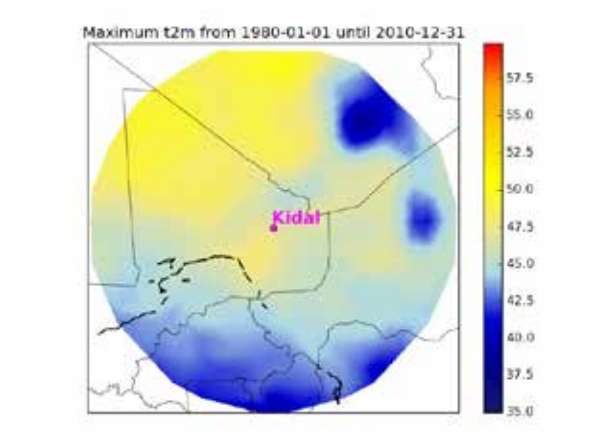

Figure 3 Climatic (1980-2010) maximum temperature in the region of Kidal.

[5] The AECTP climate for Kidal is A1. In this climate the temperature in the shipping container can rise to approximately 70°C. However, it seems that the maximum temperature of 50°C corresponding to A1, has not been reached in Kidal. An A2 climate seems more accurate.

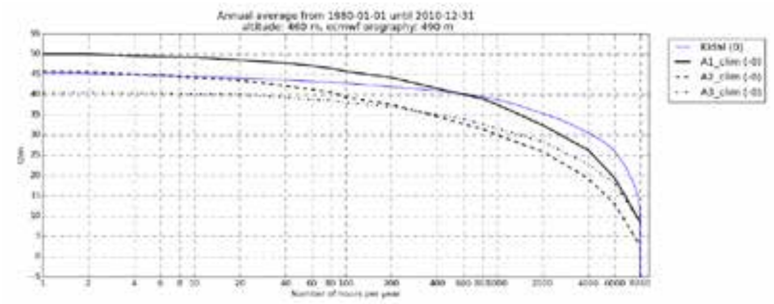

Figure 4 The number of hours per year that the temperature during the period 1980-2010 exceeded a certain maximum according to the TNO climate tool (blue) and according to several AECTP 200 climates. For example: in Kidal the temperature rises above 35°C for 2,000 hours a year and above 45°C for just four hours a year.

The air inside the shipping container follows the roof temperature almost instantaneously. Adjacent to the roof (i.e., the interior's ceiling), the maximum temperature is reached as calculated. Without circulation inside the container, the temperature near the bottom is significantly cooler than at the top. However, the front (entrance) of the container is also exposed to sunlight. The amount of exposure depends on its orientation towards the sun. Like a heating element, the elevated temperature of the front side will induce circulation, which balances the temperature inside the container. The front side is not exposed to solar radiation when the sun is at its highest point. Similarly, when the sides of the outer containers are exposed to sunlight, the center container holding the mortar rounds is in the shade and the inside circulation is suppressed. Therefore the maximum temperature may not have been reached near the bottom of the container. However, at least some circulation is expected and therefore it likely that the stacked boxes with mortar rounds have been exposed to temperatures above 63°C in the days around 6 July.

The mortar rounds and the energetic materials at the core of the rounds do not heat up as quickly as the temperature of the air inside the container. The wooden boxes will level off the daily temperature profile of the stored rounds. Without the thermal insulation of the wooden boxes and cardboard tubes, the mortar rounds would reach the ambient temperature within twenty minutes given their thermal capacity and conductivity. The core of the rounds would likely need more time to reach this temperature. The tubes and the wooden boxes in particular, will cause the temperature of the rounds to lag behind. The lag time is much more than twenty minutes and possibly in the order of hours. Therefore it is important to consider the temperature profile throughout the day.

Figure 5 displays the expected daily temperature profiles. The profile for 6 July 2016 is presented with three hour time steps. The ambient temperature peaked at 40°C. Figure 5 also shows the profiles for the AECTP climates A1 and A2. Kidal has an A1 climate according to the Leaflet series. However, the A2 climate seems more representative, especially when based on the maximum temperatures.

The temperature difference between the container and the ambient air is calculated for every hour of the day and added to the daily temperature profile of the A1 and A2 climates. At the beginning and end of the day the insolation is too weak (or absent) to increase the temperature inside the container. Around noon the temperature difference increases to a maximum of 26°C. The time frame during which the specified maximum temperature of 63°C for transport/storage and operation is reached, measures approximately five hours (from 11:00 to 16:00), for both climates A1 and A2. Within this time frame the temperature peaks at 70°C for climate A2 and 73°C for A1 climate A1. Its duration is likely sufficient to heat up the mortar rounds to over 60°C. Since the A2 climate in Figure 5 is representative for the days immediately before and after 6 July heating to over 60°C occurred regularly.

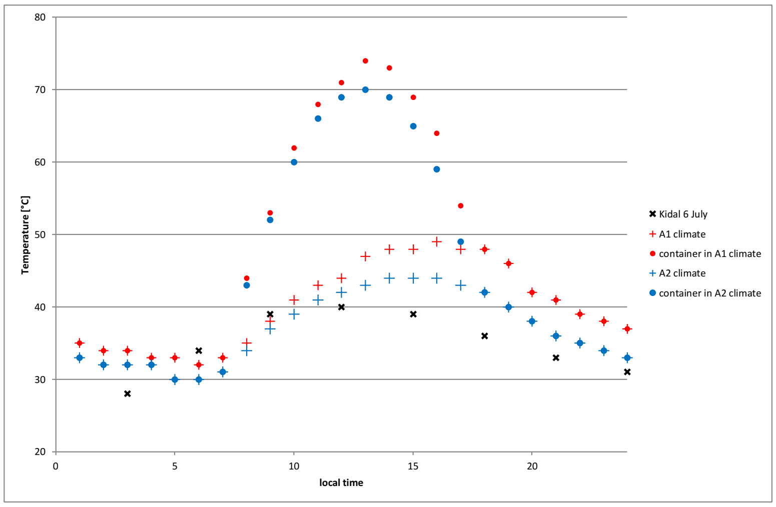

Figure 5 Expected daily temperature profile inside the container plotted for 6 July 2016.

2.2 Operational use

Figure 5 also presents the calculated ambient temperature for Kidal on 6 July. It shows that at the time of the accident (around 9:30) the temperature was approximately 40°C. Besides heating up due to the ambient temperature, the mortar rounds also heat up through solar radiation. As demonstrated by Figure 6 the rounds were exposed to sunlight during operational use.

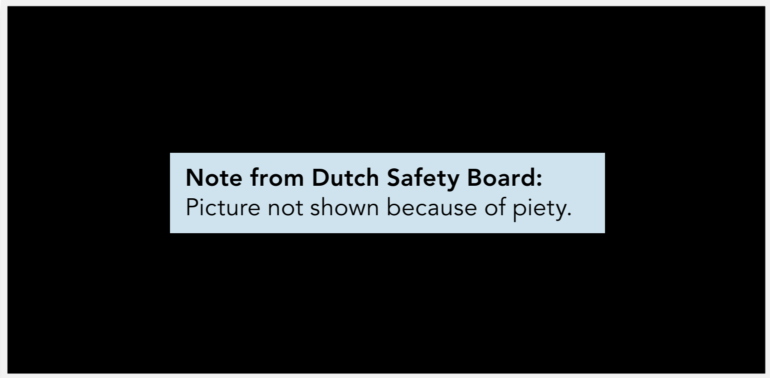

Figure 6 Use of the 60 mm HE80 mortar round during the exercise in Kidal on 6 July 2016.

A mortar round exposed to solar radiation will heat up quickly. The green paint on the shell body has a higher absorption coefficient than the white paint on the container; a(sunlight)=0.5. Furthermore, the green paint reduces the emissivity to 0.7. The net result is that the casing of the round can reach a temperature of 80°C if placed in full sunlight. The steel casing readily transfers the heat to the explosive fill causing its temperature to rise quickly. Since the mortar rounds were loaded with bare hands during the exercise (see Figure 6) it is unlikely that they actually reached a temperature of 80°C.

The fuze at the tip of the mortar round is made of aluminium. Aluminium absorbs relatively little sunlight; a(sunlight)=0.3. However, since its emissivity is very low (ε=0.1), aluminium is unable to release heat by emission. Aluminium may therefore reach a temperature of over 100°C. The fuze will release part of its heat to the shell body by thermal conduction. Besides, spontaneous air flows will originate and carry away heat. The entire process of heat absorption and emission to the shell body and the surrounding air is too complex for an accurate estimate of the fuze temperature within the scope of this project. It is likely that when the mortar rounds are placed in the sun, the maximum operational temperature of the fuze exceeds the maximum storage temperature, i.e. to over 60°C. This is especially true when the cover from the ammunition box is removed. It can be stated with certainty that the fuze heats up to over 50°C when the mortar rounds are exposed to sunlight on a hot day.[6]

[6] For the purpose of verification an (inert) aluminium fuze was placed in an oven and heated to just over 60°C. It was subsequently established that this fuze could be handled with bare hands.

3 The potential effect of moisture and temperature

In [Bouma, Hooijmeijer, Kroon, 2017] it is concluded that the effect of a temperature increase up to 70°C on the spring constant, and thus on the arming mechanism of the fuze, is negligible. Therefore this chapter does not focus on the mechanical functioning of the fuze, but on the energetic materials inside the mortar round.
High temperature and moisture potentially affect the quality of the energetic materials in an ammunition article. In chapter 2, it was calculated that the 60 mm HE mortar rounds were exposed to high temperatures during storage and operational use. In [Klaver, 2016] it was established that the 60 mm HE80 ammunition in Gao, Mali, has three different lot numbers. During inspection the following was observed: 'one round with slight corrosion on the transport safety cap and one round with slight corrosion between the fuze and shell body'. [CvO, 2016] states, after disassembly of the fuze from twenty rounds, that ‘No irregularities were found during visual inspection. Slight corrosion was however observed on the slider and the detonator in the slider of round number 14’ and 'round number 14 was excluded [for testing purposes] as the detonator was stuck in the slider'. Based on these findings it is likely that there may have been mortar rounds that at some point in time were exposed to moisture, which can penetrate the round and reach the detonator.
The most likely route for moisture to penetrate and reach the detonator is through the tip of the round; here the barrier consists of the adhesive layer in between the membrane and fuze body (the transport safety cap is a loose part and does not act as a moisture barrier). Less likely is the penetration of moisture via the screw threads between the fuze and the shell body, booster and explosive train interrupter (metal barrier) and the two rubber sealing rings. Both routes are shown in Figure 7.

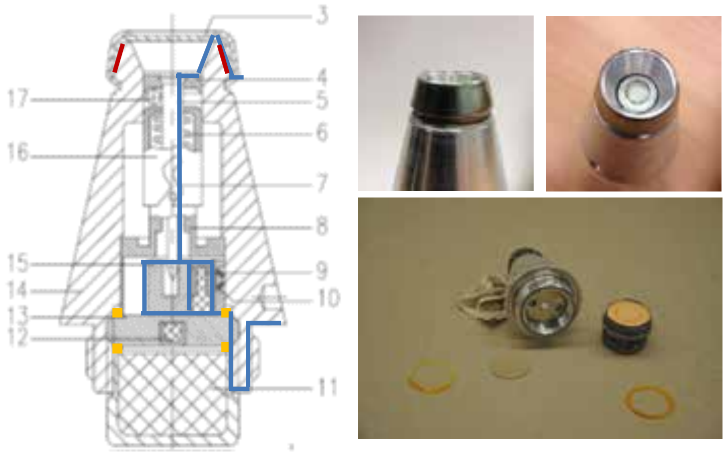

Figure 7 Cross-section of the fuze with potential routes (blue) for moisture penetration via the adhesive layer (red) and sealing rings (yellow) (left), adhesive layer for the membrane (top centre), the opening between the firing pin and the fuze body (top right) and underside of the fuze body with metal barrier (disk), booster with cardboard insert and two rubber rings (bottom right).

Although adhesive and rubber rings are both permeable, moisture penetration through a layer of adhesive is much easier than along three screw threads and two sealing rings. Two simple leak tests were performed for confirmation. First, five empty fuzes were positioned with their nose facing down and filled with water; they were all watertight. The five fuzes were subsequently mounted one by one on an inert shell body, and subjected to five drop tests from a height of about one meter with a random orientation upon impact with the ground. After removal from the shell body the fuzes were again filled with water; the adhesive layer of one of the five fuzes was observed to be leaking; see Figure 8.

Figure 8 The adhesive layer of one out of five M6-N fuzes is leaking after five drop tests from about one meter height and random impact orientation with the ground.

These drop tests demonstrate that penetration of moisture through the adhesive layer of the membrane towards the detonator is possible if the mortar round is exposed to moisture after a shock. It is likely that also without a shock, the adhesive layer ages over time, which allows moisture to penetrate it more easily[7].

Paragraph 3.1 describes the potential effect of moisture and temperature on the main charge and booster. Paragraph 3.2 describes this effect on the energetic materials in the fuze.

3.1 Main charge and booster

The main charge of the 60 mm HE mortar round consists of TNT and the booster is made from RDX. These are both relatively shock and friction insensitive (secondary) explosives, which under normal operation are initiated by a so called shock to detonation transition. Impact or friction (less powerful stimuli than a detonation) will cause (loose) TNT and RDX crystals to burn instead of detonate.

[7] The potential effect of moisture resulting from condensation (caused by temperature changes) from the air inside the empty parts of the fuze (see Figure 7) are anticipated to be negligible. The amount of condensate relates to the volume of the air chamber and is therefore very small. Accumulation of moisture is unlikely; condensation is a reversible process as it alternates with evaporation.

3.1.1 *TNT main charge*

TNT is almost insoluble in water, has a melting point of around 81°C and a deflagration temperature of 300°C [Meyer, 2007]. The maximum temperature of 80°C calculated in paragraph 2.2 is just below the melting temperature of TNT. Furthermore, during the exercise the mortar rounds were handled with bare hands; therefore it is unlikely that the 'accident round' was fired with a liquified main charge. TNT explosive is very stable. During production of TNT asymmetrical trinitrotoluene (such as 2,3,5 TNT) and dinitrotoluene (DNT) are formed. These compounds are mutually soluble. The level of impurities determine the reduction of the melting point [Rosen *et al*., 1959]. The difference in density between crystalline TNT (1.654 g/cm^3) and liquid TNT (1.47 g/cm^3) [Meyer, 2007] is relatively large, and the corresponding volume change when it melts is 12.5%. Exudation (oozing) is therefore a process that typically occurs for TNT explosive charges or charges based on TNT. Exudation is defined in [AOP-38, 2009] as 'the process through which an energetic material oozes out through openings such as screw threads, fuze cavity, etc.' Exudation starts at temperatures near the melting point; around 80°C for TNT and around 70°C for DNT; the quality of the TNT charge[8] determines the exact temperature at which exudation occurs. The melting temperature of the exudate itself may be significantly lower; [DGA] reports melting occurring at temperatures from 46°C.
When the main charge is heated to 70-80°C (and higher), an oily melt of the by-products originates in which 'regular' TNT is partially dissolved. The migration of TNT crystals from the main charge via this exudate is possible. After the exudate cools, fine crystals of TNT and of the by-products are produced that could be sensitive and therefore dangerous, especially if they are located between the screw thread of the shell's body and the fuze. Combustion of this exudate caused by the shock of the launch might result in deflagration of the booster and the main charge. Detonation of the main charge (as occurred) is highly unlikely because a shock originating from the booster charge is required. Detonation of the booster is unlikely because it requires a shock from the lead charge.

Figure 9 shows two other potential routes for the exudate; one to locations below the metal barrier and one to locations above the metal barrier. It is considered unlikely that the exudate penetrated the screw thread of the booster and the sealing ring below the metal barrier (lower red line in Figure 9) and that combustion of the exudate, due to the shock of the launch, initiated the lead charge (which subsequently caused detonation of the booster and main charge). This is unlikely because the lead charge requires a shock for initiation. This is also true when RDX crystals from the booster have migrated with the exudate (see paragraph 3.1.2).

It is even more unlikely that the exudate migrated via the screw thread of the booster and the sealing ring, the screw thread of the metal barrier and the (second) sealing ring and subsequently settled between the metal barrier and detonator and around the detonator. In this scenario a 'bridge' of energetic compounds would be formed between the primer and the lead charge (top red line in Figure 9).

Although the flame-sensitive lead styphnate in the primer (see paragraph 3.2) could cause the primer to detonate due to combustion of the exudate, the metal barrier

[8] Arsenal inserts the TNT main charge in the shell body by pressing and screw extrusion at room temperature [Company visit to Arsenal, 2017].

should prevent initiation of the lead charge in safe position of the fuze (in which the detonator and lead charge are out of line).
In this case the bridge of exudate will combust without initiation of the lead charge. The transfer of the shock by the exudate from the primer to the lead charge (with subsequent initiation of the booster and main charge) is considered unlikely. This is also true in case RDX crystals from the booster have migrated with the exudate (see paragraph 3.1.2).

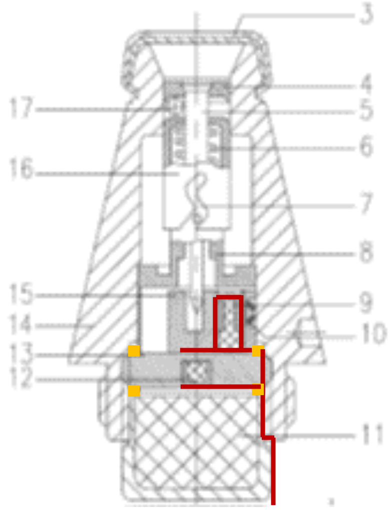

Figure 9 Potential but unlikely routes for exudate to locations below and above the metal barrier.

When exudation occurs the migration of compounds could create cavities in the main charge. Because the acceleration during the launch of a mortar round is relatively low compared to the firing of large calibre shells (e.g. with a Howitzer), collapse of these cavities due to setback forces is unlikely to create initiation of the main charge. Substantiation is provided in [Naval ordnance lab, 1959], which concludes: 'At 75°C, two samples of Grade I TNT showed 5.2% and 7.4% liquid TNT. A purified sample of TNT showed no liquid at the same temperature'. [Naval ordnance lab, 1959] also states: 'Exudation may produce a cavity in the loaded weapon, which is perhaps the major abjection to it. If the cavity is under the booster, the charge may fail to detonate'.

It is unlikely that the heating of the TNT main charge to approximately 60°C in storage or up to 80°C during operational use (see paragraph 2.2) caused the accident with the mortar round.

3.1.2 *RDX booster charge*

The booster charge consists of RDX[9] [Company visit to Arsenal, 2017]. RDX is insoluble in water, has a melting point of 204°C [Meyer, 2007], a self-ignition

[9] Tetryl is an alternative booster explosive. This explosive compound is practically insoluble in water and has a melting point of 129.5 °C [Meyer, 2007]. The deflagration temperature is way above below the calculated temperature for storage and use. Climatic conditions are not expected to influence the stability and functioning of tetryl when used as a booster charge.

temperature of 316°C [Weinheimer, 2002] and a high degree of chemical stability. Initiation of the booster charge (and therefore of the main charge) as a result of the shock of the launch is extremely unlikely, also at an elevated temperature.

3.2 Energetic compositions in the fuze

3.2.1 PETN lead charge

The metal barrier contains a lead charge of PETN (penthrite) [Company visit to Arsenal, 2017]. Penthrite is a secondary explosive which is initiated with an explosive shock. Impact or friction will cause (loose) PETN crystals to combust instead of detonate. PETN is more sensitive to impact and friction than TNT and RDX, but less sensitive than primary explosives.

Penthrite is insoluble in water [Meyer, 2007], has a melting point of 141.3°C [Foltz, 2009], and a self-ignition temperature of 272°C [Weinheimer, 2002]. It is very stable with regard to decomposition during storage at low temperatures. A half-life of 12 million years is predicted at a temperature of 30°C. However, thermal decomposition is reported far below the melting temperature and a usable operational service temperature is determined at 70 – 75°C [Foltz, 2009]. Potential ageing due to moisture is unlikely because it is difficult for moisture to reach the lead charge (see Figure 7). Initiation of the lead charge (leading to the initiation of the booster and the main charge) due to the shock of the launch is extremely unlikely, also at an elevated temperature.

3.2.2 Detonator

The (duplex) detonator has a primer charge consisting of three parts:

- the upper part consists of an impact and friction-sensitive mixture of (from top to bottom):
  - Lead styphnate
  - Tetrazene
  - Barium nitrate
  - Antimony sulphide
- the center part consists of lead azide
- the bottom part (adjacent to the metal barrier) consists of penthrite (see paragraph 3.2.1).

With the exception of penthrite, these energetic materials are all primary explosives. The (loose) crystals of these compounds can detonate as a result of a flame, heat, an impact, friction or electrostatic discharge.

The relationship between these energetic materials and moisture and temperature is described as follows:

- Lead styphnate is sensitive to flame, is practically insoluble in water and has a deflagration temperature of 275 to 280°C [Meyer, 2007].
  Lead styphnate is used in primer compositions in both its normal and its basic form [Oyler *et al.*, 2015]. It is unknown which form of lead styphnate is used in the M6-N fuze. For the structural formula of both forms of lead styphnate, see Figure 10.

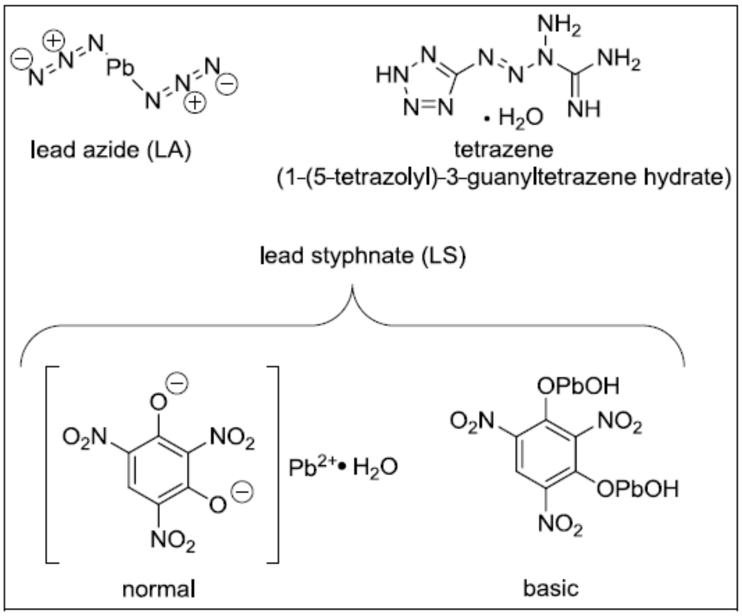

Figure 10 Structural formula of lead azide, tetrazene, normal lead styphnate and basic lead styphnate [Oyler *et al*., 2015].

- Tetrazene is a sensitising compound that is practically insoluble in water and deflagrates at 140°C [Meyer, 2007]. Although unstable, tetrazene is used as a sensitizer in cap compositions because to date no suitable alternatives have been found [Agrawal, 2010]. Tetrazene will decompose at higher temperatures. The sublimation of tetrazene with crystal formation at distant locations was experimentally observed [Duvalois, 2017].
  [NAVSEA, 2002] provides the analysis of a primer's operational lifespan; it was measured that 20% of the tetrazene has decomposed when exposed to 89°C for nine days.[10].
  [Yan *et al*., 2014] compares the thermal decomposition of tetrazene with MTX-1. 5-Aminotetrazole (5-ATZ) is already known to be an initial decomposition product. The potential decomposition routes were studied by establishing the activation energy through Differential Scanning Calorimetry and Thermogravimetric measurements and by performing quantum-chemical calculations. The potential decomposition routes of tetrazene and MTX-1 are shown in Figure 11. According to the quantum-chemical calculations, 1*H*-tetrazole, N_2 and aminocyanamide are initially formed.
  NH_2 in the form of cyanamide can react with 1*H*-tetrazole to produce 5-ATZ and hydrogen cyanide (HCN) at low temperatures. This is consistent with the observed formation of 5-ATZ after six days of heating tetrazene to 90°C [Yan *et al*., 2014]. This reference does not illustrate the full decomposition equation.

[10] Based on the presented activation energy of 180 kJ/mol, the Arrhenius equation can be used to estimate that the same conversion (20%) occurs in 4.5 years at 60°C, and in 0.7 years at 70°C.

As for each molecule of tetrazene, two nitrogen molecules and two hydrogen molecules remain, nitrogen, hydrogen, ammonia, hydrogen azide and/or protons will be formed.

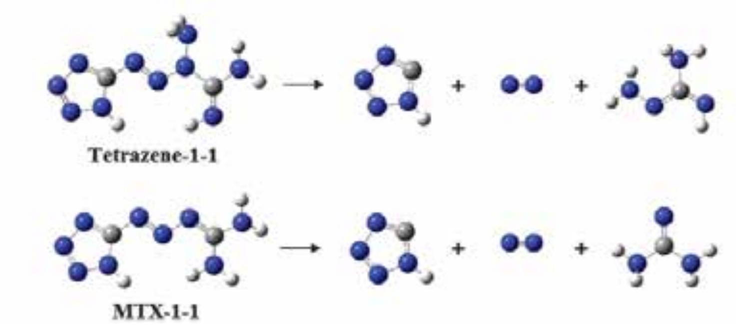

Figure 11 Initial decomposition routes of tetrazene and MTX-1 [Yan *et al.*, 2014].

[Matyáš, Pachman, 2013] reports that the decomposition of tetrazene in boiling water results in a variety of products including the highly sensitive primary explosive 5-azidotetrazole, stating: 'Some explosions of decomposition solutions have been reported after cooling down the water with what was believed to be innocent decomposition products.'

The ignition primer VH4/1 with a composition of 44% barium nitrate, 27% composition RD 1303 (i.e., lead styphnate), 27% antimony sulphide and 2% tetrazene is described in [DEF-STAN 13-179, 1995]. A requirement for processing tetrazene is 'when drying tetrazene either alone, or in a mixture, the temperature of the tetrazene shall not exceed 55ºC'. For Cap Composition EP 41 [DEF STAN, 13-173, 1995] with a composition of 39% barium nitrate, 38% lead styphnate, 11% calcium silicide, 5% antimony sulphide, 5% lead dioxide and 2% tetrazene, the manufacturing requirement is: 'when drying tetrazene either alone or in a mixture, the temperature of the tetrazene shall not exceed 50ºC'. The thermal and hydrolytic stability of a tetrazene/lead azide mixture was examined and compared with a 2-picryl-5-nitrotetrazole (PNT)/lead azide mixture [Elischer, 1984]. The quantitative determination of tetrazene or PNT in a mixture based on DSC measurements, and the determination of the ignition sensitivity (stab sensitivity) following thermal ageing or exposure to moisture, implicitly show that lead azide is more stable than tetrazene. After six weeks of exposure to a temperature of 89ºC the stab initiation energy[11] increases from 3.6 mJ to 110 mJ. After six months of exposure to a relative humidity of 78 to 80%, at a temperature of 20ºC, the stab initiation energy increases from 3.3 to 4.1 mJ.
The tetrazene/lead azide becomes less sensitive after exposure to very high temperatures or a high degree of humidity, which is attributed to the decomposition of tetrazene.

[11] 'Stab' initiation is one of the possibilities to start the detonation train in a mechanical fuzing system. It is also used in the M6-N fuze. Stab initiation involves a striker pin that pierces the detonator casing and penetrates the primary explosive compound which is stab sensitive and reacts explosively [AMCP, 1969].

- Barium nitrate is a non-hygroscopic oxidizer [Oyler, *et al.*, 2015] and has a melting point of 592°C [Meyer, 2007]
- Antimony sulphide is a fuel that is practically insoluble in water, with a melting point of 550°C [ESPI, 2016].

Both the composition VH4/1 and EP 41 are related to the ignition primer (the mixture at the upper part of the detonator). The maximum allowed percentage of volatiles in these compositions are 0.05% and 0.2% respectively. The constituents of the EP 41 premix absorb moisture. Therefore the requirement is that '.. the premix shall not be exposed to the atmosphere, at any stage of manufacture, filling or storage, when the relative humidity exceeds 70%' [DEF STAN, 13-173, 1995]. Besides, lead styphnate is produced by reacting styphnic acid with lead oxide, and there is a requirement for the maximum percentage of free styphnic acid.

- Lead azide (center part of the detonator) is not hygroscopic, is insoluble in water, has a deflagration temperature of 320 to 360°C and a high thermal stability [Meyer, 2007].
  In the past lead azide was associated with the formation of the extremely sensitive copper azide. [Shaneyfelt, 1984] states that lead azide does not corrode most metals in dry condition. However, if moisture is present lead azide can react with copper, mercury, tin and zinc and form extremely sensitive and hazardous azides. An example is provided in [Kroon, van Ham, Bouma, 2015]:
  Copper azide is an extremely sensitive compound that may react to mild impact or shock. In 1974, TNO analysed the accidental reactions involving the 81 mm mortar of the Royal Dutch Navy [Josseling de Jong, 1976]. During maintenance of this ammunition, which had returned to Den Helder from a mission in the Antilles[12], it was observed for a number of rounds that the rotor that ensures arming after firing (part of the safety and arming mechanism) was projected through the cardboard packaging; see Figure 12. The investigation revealed that the detonators of the fuzes had corroded, resulting in the formation of copper azide. It was concluded that the brass components near the detonator (percussion cap) had reacted with the lead azide inside the aluminium detonator. As a result of internal friction, probably caused by transport vibration, the copper azide reacted and initiated the primer charge and the delay charge. The main charge was not activated because the fuze was in safe (unarmed) position.

[12] The Antilles feature a tropical savanna climate representative for areas near the equator (http://www.klimaatinfo.nl/curacao).

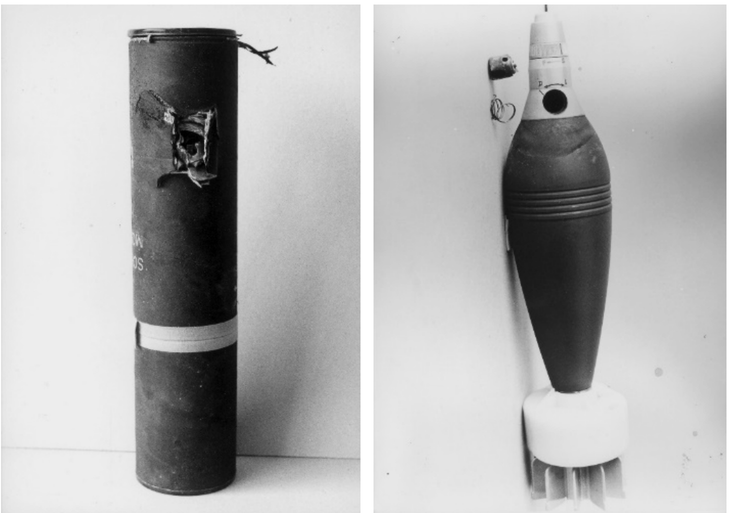

Figure 12 Perforated carboard packaging and projected rotor of the arming and safety mechanism of the 81 mm mortar round [Josseling de Jong, 1976].

The ammunition was on board of a ship of the Royal Dutch Navy located at the Antilles for 18 months. The prevailing high temperature and humidity caused the reaction of the lead azide with water vapour in the atmosphere. The reaction is seen on the top view of the detonator in the brass casing in Figure 13. Traces of the primer (antimony sulphide and potassium chlorate) are visible as grey and white crystals, possibly mixed with aluminium compounds from the detonator. Traces of the red (sealant) lacquer are also observed. The green crystals indicate copper compounds such as copper azide and the non-explosive copper hydroxide ($Cu(OH)_{(2}$) and copper oxide (CuO).

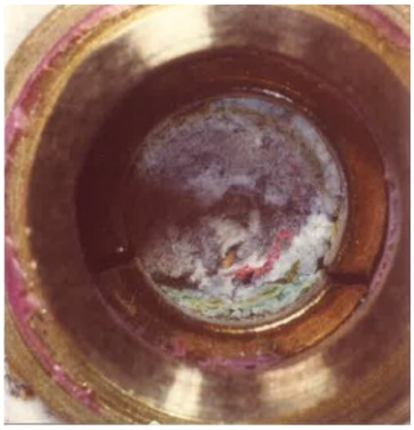

Figure 13 Top view of the aluminium detonator in a brass casing of fuze type V-19 [Josseling de Jong, 1976].

In this condition the ammunition can no longer be used because reliable functioning has become impossible and handling of the ammunition poses a great risk. However, this is a temporary effect; copper azide will continue to react with water (vapour) until copper oxides are eventually formed, at which point all explosive properties are lost.
This means that if moisture is able to reach the primer composition of the detonator and metals containing copper are present, there is the possibility of the *temporary presence* of the extremely sensitive copper azide.

For the M6-N fuze the primer is held by an aluminium cup that is positioned in a casing made of a copper-nickel metal alloy (with a typical 70:30 ratio), known as Melchior [Company visit to Arsenal, 2017]. Melchior is highly resistant to corrosion in air, water and seawater. However, copper-nickel alloys are prone to accelerated corrosion in water containing sulphide or ammonia, which can result in the formation of copper oxides [Powell & Michels, 2000]. It is noted that the composition of the primer contains (antimony) sulphide that would accelerate potential corrosion of the Melchior cup.

It is also noted that several metals reside near the detonator:
- Aluminium (primer cup and fuze body)
- Melchior, copper/nickel (cup holder)
- Copper-containing brass (slider)
- Steel (metal barrier).

Moisture can cause (galvanic) corrosion,[13] which results in degradation of the aluminium and the Melchior. The combination of moisture with elevated temperature could result in thermo-galvanic corrosion, for which the rule of thumb applies that an increase of 10°C doubles the rate of corrosion.
Moisture can also result in hydrolysis of the lead azide creating hydrogen azide.[14] The hydrogen azide can react with the copper in the Melchior cup holder and in the brass slider and form copper azide. In the first stage of this process extremely sensitive compounds can be formed, which at a later stage convert to less sensitive compounds, which, in addition to copper and azide, can also contain hydroxyl groups, water molecules and possibly carbonate groups [Lamnevik, 1967]. The green tarnish around the detonator in Figure 13 is an indication of these copper compounds.

According to [Josseling de Jong, 1976], the copper azide compound with the white colour remarkably is the most sensitive. A white tarnish on the detonators and adjacent parts may be not dangerous (such as aluminium oxide), but also extremely dangerous (copper azide) [Kabik & Urban, 1972]. It is suspected that hydrolysis of the lead azide is promoted by the destruction of the detonator under the influence of a (galvanic) corrosion process.

---

[13] Metals connected in an electrolyte (the connection between two poles (anode and cathode)) form a so-called galvanic couple. This results in accelerated corrosion of the least precious metal caused by an increase in potential, while the corrosion of the most precious metal is inhibited due a decrease in potential.
[14] Hydrogen azide has a boiling point of 37°C; below this temperature it is a liquid and above this temperature it is a gas.

[Josseling de Jong, 1976] demonstrated that corrosion also occurred in the brass cup that contained the aluminium detonator; see Figure 14.

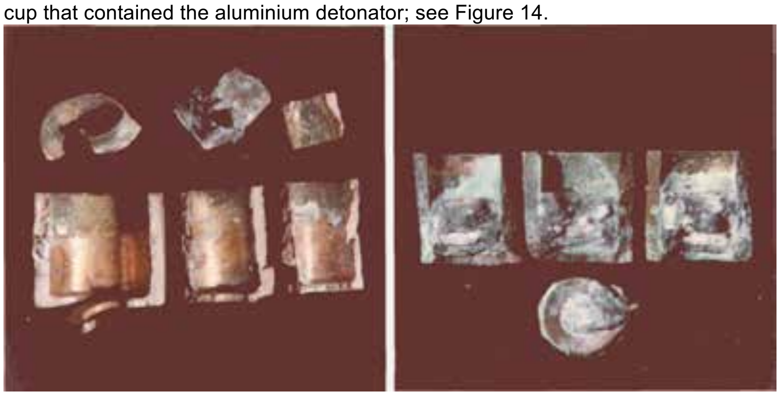

Figure 14 Brass cups (left) and aluminium detonators (right) from the V-19 fuzes originating from the Dutch Antilles [Josseling de Jong, 1976].

Figure 14 displays the brass cup (left) and aluminium detonators (right). The yellow colour on the brass cups clearly shows where the detonator resided in the cup. Above it, a green tarnish is observed. The contents of the detonators are for the greater part still present. Also here, a green tarnish is observed.

The green tarnish was found all over the brass components, also in the space between the brass housing and the brass cup and also on the top side of the brass fire channel, as shown in Figure 15. The green tarnish above the detonator was examined for azide and carbonate. Both were found[15]. This azide could possibly have originated directly from the lead azide in the detonator. The green crystals between the brass housing and the brass cup also gave a positive reaction for azide; copper was also found. This azide cannot have originated directly from the lead azide in the detonator. Figure 15 demonstrates that copper azide can form at some distance from the detonator as a result of degradation. [Josseling de Jong, 1976] concludes that one can generally state that the presence of copper in the direct vicinity of lead azide must be considered unacceptable, also when in the form of brass and with an airspace in between.

[15] The composition of the primer inside the detonator was lead azide in the lower part and a mix of antimony sulphide and potassium chlorate in the upper part.

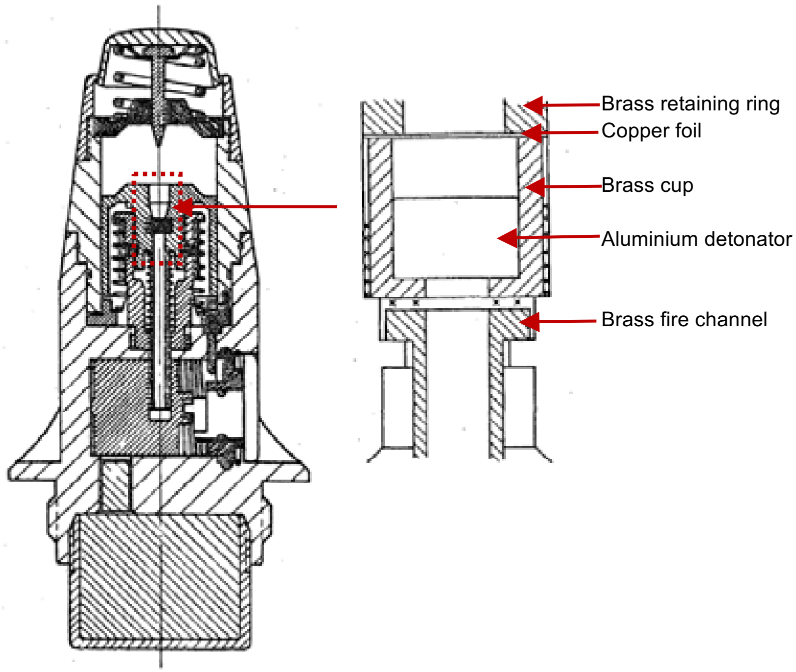

Figure 15 V-19 fuze in safe position (left) and position of the detonator (right) with azide containing green tarnish indicated with x, which cannot have originated directly from the lead azide in the detonator [Josseling de Jong, 1976].

If copper azide actually formed in the M6-N fuze there are two possible ways to set off the explosive train (detonator - lead charge – booster - main charge). See Figure 16; due to the shock of the launch of the mortar round the copper azide detonated, which resulted in the initiation of the detonator (black):

- with transmission of the shock through the metal barrier (indicated with red arrow) to the lead charge, where the metal barrier failed to function according to the safety and arming design principle. This intrinsic safety was not verified by Arsenal by means of an *explosive train interruption test*[16] [Company visit to Arsenal, 2017]
- with the transmission of the shock along a 'bridge' between the detonator and the lead charge (indicated with purple arrow) over the metal barrier, with the bridge (in contrast to exudate) consisting of compounds with explosive properties, such as copper azide possibly supplemented with a residue of sublimated tetrazene.

[16] For example, in accordance with AOP-20 ed.1, 2002 Manual of tests for the safety qualification of fusing systems.

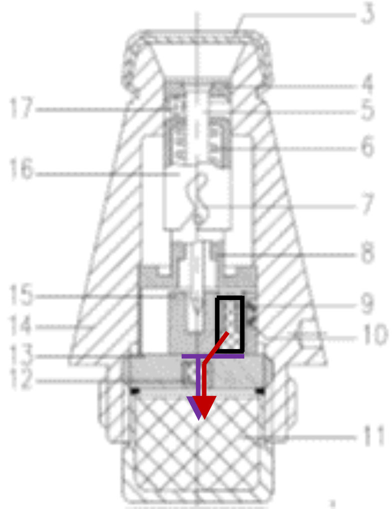

Figure 16 The copper azide detonates when launching the mortar round, resulting in detonation of the primer (red) or detonation of the primer and the 'bridge' of copper azide between the primer and the lead charge (purple).

In Figure 16 both routes for potential shock transmission relate to the sensitivity of the lead charge (and booster), which may increase for temperatures above 50 to 60 °C (or higher). Figure 17, reproduced from [Zhang & Weeks, 2010], provides an indication for this; the impact sensitivity of PETN is approximately twice as high at a temperature of 65°C than it is at room temperature.

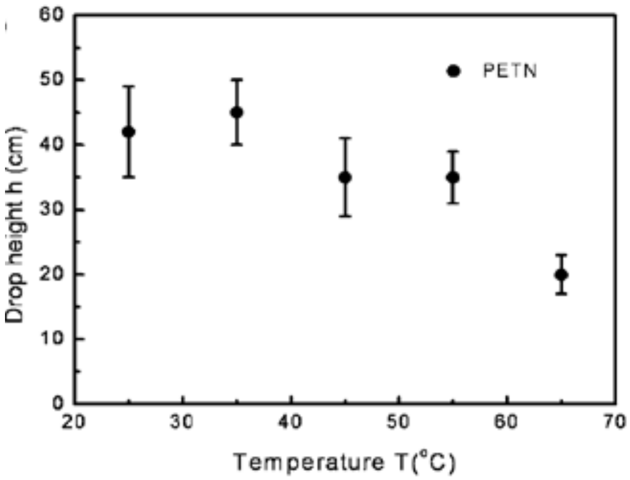

Figure 17 Drop height at which PETN reacts versus temperature [Zhang & Weeks, 2010].

4 Conclusions

On 6 July 2016, a fatal accident occurred in Kidal, Mali during an exercise involving a 60 mm High Explosive (HE) mortar round with a M6-N (H) fuze. As part of the technical investigation the Dutch Safety Board (DSB), requested the Netherlands Organisation for Applied Scientific Research (TNO) to analyse the climatic conditions during storage and operational use.

The purpose of this analysis is to establish whether the climatic conditions contributed to the premature functioning (detonation) of the mortar round during the exercise. For this analysis the TNO climate tool and analytical equations were used to calculate the temperature of the mortar rounds in storage in Kidal and during operational use.

The calculations show that the 60 mm mortar rounds probably reached a temperature above 60°C while stored in the shipping container in Kidal. This also occurred in the days just before and after July 6.
It was also calculated that out of storage and during use, the steel casing and the TNT main charge can reach a temperature of 80°C due to exposure to sunlight. As the mortar rounds were loaded with bare hands it is unlikely that the rounds actually reached such a high temperature during the exercise.
As a result of exposure to sunlight it is likely that during use, the temperature of the fuze increased to over 50°C and possibly even exceeded 60°C.
Based on the analysis it is concluded that during storage and use, the maximum allowable fuze temperature of 50°C as specified by the supplier was exceeded.

It is unlikely that, due to heating of the TNT main charge, exudate reached locations below or above the explosive train interrupter (metal barrier) of the fuze. If it had, it is unlikely that combustion of the exudate due to the shock of the launch caused detonation of the main charge.

Initiation of the RDX booster charge or the PETN lead charge due to the shock of the launch is highly unlikely, also at an elevated temperature.

Moisture may penetrate through the adhesive layer of the membrane at the tip of the mortar round and reach the energetic materials (primer) inside the detonator, especially if the round is subjected to one or more shocks. It is expected that also without shocks, the adhesive layer ages over time, which makes moisture penetration easier.

Moisture can cause (galvanic) corrosion, which leads to degradation of the aluminium primer cup (detonator) and the copper/nickel (Melchior) cup holder. This process potentially accelerates at an elevated temperature. Moisture can also result in hydrolysis of the lead azide inside the primer, creating hydrogen azide.

The hydrogen azide can react with the copper in the Melchior cup holder and in the brass slider causing formation of extremely sensitive copper azide[17]. It is anticipated that hydrolysis of the lead azide is promoted by the destruction of the primer cup under the influence of a (galvanic) corrosion process.

Corrosion of the Melchior cup holder may be accelerated by the presence of (antimony)sulphide in the primer. At elevated temperatures, tetrazene may sublime, resulting in the possible formation of crystals inside the fuze at some distance from the detonator.
If copper azide (and tetrazene) is formed, it will likely detonate due to the shock of the launch and initiate the primer. Transfer of reaction to the lead charge through the metal barrier or through a 'bridge' of copper azide (and tetrazene) between the primer and the detonator's lead charge in unarmed position, results in the initiation of the booster and detonation of the main charge. The probability of transfer of reaction may be temperature dependent.

[17] As was previously found inside V-19 fuzes that returned from the Dutch Antilles, which caused part of the safety and arming device to project from the fuze, probably due to transport vibration.

5 Recommendations

To calculate the temperature inside the shipping container assumptions are made regarding the geometry and composition of the paint. The model that was made for the calculations can be calibrated with measurement data. This can be done using a measured temperature profile inside the shipping container over the course of a single day. The temperature sensor must be reliable and the way in which the container is enclosed and exposed to solar radiation must be similar to the situation around July 2016. The container must be identical with regard to the steel walls and the applied paint. It is not necessary for the ambient temperature to be the same as around July 2016, sunny weather with a temperature above 20°C on a random day is sufficient. Following calibration the model produces a more accurate result for the calculated temperatures.

The insulation of the wooden boxes in which the mortar rounds were stored is important for obtaining a more accurate calculation of the temperature of the rounds. In addition to a temperature profile in the shipping container a temperature profile in a wooden box must also be measured.

The temperature requirements related to storage and operational use relate to the ambient air. Therefore it does not seem necessary to investigate the temperature lag between the explosive fill and the ambient air. However, the temperature of the core seems to be the relevant temperature, instead of the ambient temperature or that of the shell body. For this reason one could consider establishing the relationship between the temperature of the ambient air and of the explosives for ammunition articles that are considered temperature-critical.

Verification of the safety and arming principle of the M6-N fuze can be performed through an explosive train interruption test ('transmission' test), at room temperature as well as at elevated temperature. For this test the detonator in the M6-N fuze must be initiated from outside the fuze.

Verification of the formation of copper azide and sublimation of tetrazene can be done in a climate chamber by subjecting an M6-N fuze to a humid environment and high temperature.

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7 Signature

Rijswijk, 23-03-2017

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APPENDIX I

EXPLOSIVE TRAIN INTERRUPTION TESTS M6-N IMPACT FUZE

In phase one of the investigation, based on the available information and debris of the mortar and the mortar round of the accident, it was concluded that the accident was caused by the 60 mm High Explosive (HE 80) mortar round functioning (detonating) prematurely in the mortar. Further investigation in phase two provided a strong indication that it is highly likely that the duplex detonator of the fuze involved in the accident was initiated while the fuze was in safe position. Since the main charge detonated in the accident, it seems likely that during the launch of the round, the safety mechanism in the fuze failed and transfer of the reaction of the duplex detonator occurred through the explosive train interrupter (barrier) resulting in initiation of the entire explosive train.

In this project, explosive train interruption tests were performed to experimentally establish whether initiation of the duplex detonator in an unarmed M6-N fuze can result in a reaction in the other components of the explosive train.

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TNO-rapport

TNO 2017 R10363

Mortar exercise accident Mali: Explosive train interruption tests M6-N impact fuze

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Contracting authority	Dutch Safety Board
Project name	Mortar exercise accident Mali
Project number	060.27417

Summary

Following the fatal accident during a mortar round exercise in Mali on July 6, 2016, the Dutch Safety Board (DSB) formulated a number of technical questions and submitted these to the Netherlands Organisation for Applied Scientific Research (TNO). In phase one of the investigation, based on the available information and debris of the mortar and the mortar round of the accident, it was concluded that the accident was caused by the 60 mm High Explosive (HE 80) mortar round functioning (detonating) prematurely in the mortar. Further investigation in phase two provided a strong indication that it is highly likely that the duplex detonator of the fuze involved in the accident was initiated while the fuze was in safe position. Since the main charge detonated in the accident, it seems likely that during the launch of the round, the safety mechanism in the fuze failed and transfer of the reaction of the duplex detonator occurred through the explosive train interrupter (barrier) resulting in initiation of the entire explosive train.

In this project, explosive train interruption tests were performed to experimentally establish whether initiation of the duplex detonator in an unarmed M6-N fuze can result in a reaction in the other components of the explosive train.

M6-N fuzes were modified in such a way that initiation of the duplex detonator could be achieved in safe position. Two initiation methods were applied: using a detonation cord and mechanical initiation using a firing pin. Five experiments were conducted at a temperature of approximately 12°C; in three of these the booster charge was replaced by an aluminium cap while an original booster charge was used in the other two.

On the basis of the experimental investigation it was concluded that:
- In each of the five explosive train interruption tests, initiation of the duplex detonator in safe position results in a reaction of the lead charge, regardless of the initiation method used;
- In the two tests with the original booster charge, the lead charge had a mechanical effect on the booster, but did not cause it to detonate.

Visual inspection of the barrier following the explosive train interruption tests revealed:
- A strong similarity in the damage caused to the upper side of the barrier from the accident and to those from the experiments;
- Fragments of the lead charge cup in the central hole in the barrier from the accident are similar to the fragments left behind in the barrier from the experiments.

This inspection verifies the hypothesis that it is highly likely that the duplex detonator was in safe position at the time of the accident.

The test results have been compared with the pass/fail criteria for the '*train interruption test*' according to the Allied Ordnance Procedure (AOP) 20 in accordance with the NATO Standardisation Agreement (STANAG) 4157.

The experiments result in a NO PASS for the barrier (as an explosive train interrupter) in the M6-N fuze based on the findings (and not permitted in accordance with the AOP-20):

- Reaction of the lead charge;
- Localised discolouration of the booster charge;
- Metal fragments in the booster charge.

In the two tests with the original booster charge, the reaction of the duplex detonator was insufficient to cause a (full) detonation of the lead charge with enough power to initiate the booster charge. Due to the limited number of tests and the observed variation in the shape and depth of the imprint in the barrier resulting from initiation of the duplex detonator, it cannot be concluded that a transfer of reaction *with* initiation of the booster is always and under any temperature condition prevented.

The explosive train interruption tests described in this report were performed at a temperature of approximately 12°C. Although a reaction was observed in the lead charge in all tests, it is not possible to conclude that the design of the fuze is unsafe because the booster charge showed no detonation from the initiation of the duplex detonator in safe position. Possibly, initiation of the booster charge will occur at a higher temperature, such as above the maximum operating temperature of 50°C specified by the supplier. Further research into the effect of an increased temperature is recommended.

Table of contents

1 Introduction

1.1 Background

Following the fatal accident during a mortar round exercise in Mali on July 6, 2016, the Dutch Safety Board (DSB) formulated a number of technical questions and submitted these to the Netherlands Organisation for Applied Scientific Research (TNO). In phase one of the investigation, based on the available information and debris of the mortar and the mortar round of the accident, it was concluded that the accident was caused by the 60 mm High Explosive (HE 80) mortar round loaded during the accident, which detonated prematurely [1].

Phase two of the investigation paid special attention to the accelerations necessary to arm the impact fuze. As a result of this investigation it was concluded that it is highly unlikely that the impact fuze could be armed accidentally during storage or transport [2]. Further, analysis of the climatic conditions showed that the temperature load on the ammunition during the mission in Mali possibly had an effect on the energetic materials in the impact fuze [3].
At the same time, microscopic examination of the explosive train interrupter (barrier) from the impact fuze involved in the accident conducted in phase two showed that the duplex detonator initiated the lead charge and not vice versa. Localised damage to the top surface of the barrier provided a strong indication that the duplex detonator functioned while the impact fuze was unarmed [4].

Based on the knowledge acquired up to that moment it was decided in phase three of the investigation, to determine the possibility of transfer of the reaction of the energetic components in the explosive train in an unarmed M6-N fuze. This report describes the approach and the results of this investigation.

1.2 Objective

The objective of the investigation is to verify experimentally whether initiation of the duplex detonator could result in a reaction of the lead charge and subsequent components in the explosive train of an unarmed M6-N fuze.

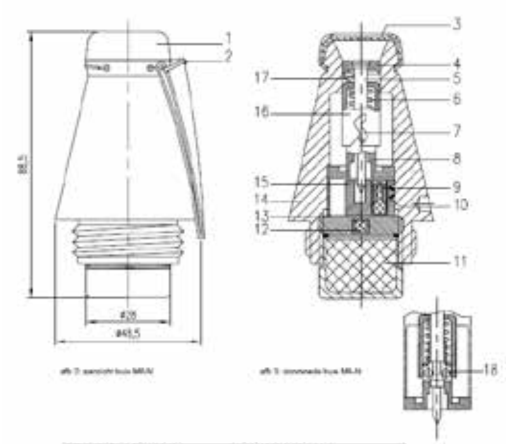
1.3 Structure of the report

Chapter 2 provides some background to the explosive train interruption tests and the configuration of the present test program; Chapter 3 provides and discusses the results of the test program. Chapter 4 contains conclusions and recommendations.

2 Explosive train interruption tests

2.1 Background

The safety mechanism in the M6-N fuze is designed in such a way that the impact fuze is unarmed as long as the duplex detonator (9) is out of line, see Figure 1. With the duplex detonator out of line it is impossible for the firing pin (5) to come into contact with, and initiate, the duplex detonator. When a mortar round is launched from a mortar the acceleration causes the impact fuze to arm, by the duplex detonator moving in line with the firing pin and the lead charge (12). At impact on the target the firing pin initiates the duplex detonator, which initiates the lead charge through (the very thin section of) the barrier, thereby initiating the booster charge, which, in turn, initiates the main charge. This series of initiating explosive charges is referred to as the 'explosive train'.



1. Transit Safety Cap	10. Shutter spring
2. Safety Pin	11. Booster
3. Membrane	12. Transfer charge
4. Limiter	13. Closing plate
5. Firing Pin	14. Fuze body
6. Spring	15. Shutter
7. Zigzag groove	16. Arming Delay Sleeve
8. Firing Pin Housing	17. Delay Sleeve Retaining Ball
9. Duplex detonator	18. Firing Pin Retaining Balls

Figure 1 Technical drawing of the M6-N impact fuze.

The duplex detonator and the lead charge are separated by the steel of barrier (13) as part of the safety mechanism incorporated in the design of the impact fuze, see Figure 1. The horizontal distance between the centre line of the duplex detonator and the centre of the barrier with the lead charge is approximately 6.8 mm. Phase two of the investigation into the possible cause of the accident demonstrated that the impact fuze very likely functioned in the unarmed position. Since the main charge detonated in the accident, it is likely that the initiation of the duplex detonator initiated the explosive train of the impact fuze in the unarmed position. Therefore, this investigation focuses on the safety mechanism of the M6-N impact fuze.

2.1.1 STANAG 4187, 4157 and AOP-20

NATO countries have produced a number of standards to which fuzing systems must comply in the framework of the *Safety and Suitability for Service (S3) of Munitions, Explosives and Related Products*, i.e., the suitability and safety during usage.
STANdardisation AGreement STANAG 4187 [5] describes design requirements for the safety of fuzing systems. STANAG 4157 [6] describes the requirements imposed on fuzing systems in the assessment of the *Safety and Suitability for Service*. Allied Ordnance Publication AOP-20 is the *Manual of Tests for the Safety Qualification of Fusing Systems* [7]. This manual is directly linked to STANAG 4157.

STANAG 4157 contains a list of mandatory tests to be performed on fuzing systems, as well as recommended tests. It includes a general criterion for compliance with STANAG 4157, namely: *'The general criterion for passing any of the mandatory and recommended tests is that an unsafe condition not be observed during the test or upon examination of the fuse after the test. Given the relative small sizes generally employed, one observed unsafe condition generally constitutes a failure. Depending upon the fuse or system design requirement, a small decrease in fuse performance may be acceptable, if safety is not affected; large degradations in fuse performance indicate that the fuse is not acceptable for service use. Pass / fail criteria are provided in AOP-20, where appropriate.'* The list of mandatory tests is shown in Figure 2. The M6-N fuze has a safety mechanism and the *Explosive Train Interruption* is one of the mandatory tests.

MANDATORY TESTS

1.	Explosive Train Interruption	For fuzes with interrupted explosive trains
2.	No-Fire Threshold	For fuzes with electro-explosive devices
3.	Safety Overpressure Firing	For fuzes fitted to mortar and gun projectiles
4.	Fuze Arming Distance	For fuzes for which an arming distance is required
5.	Arming Delay Time	For fuzes for which an arming delay is required
6.	Mortar Double-Loading	For all mortar fuzes, conducted on complete munition
7.	Barrel Cook-Off	For gun-launched projectiles fitted to munitions
8.	Electrostatic Discharge	For all fuzes with electro-explosive components; can be required for fuzes in both armed and unarmed configurations
9.	RF Radiation	For all fuzes with electro-explosive components; can be required for fuzes in both armed and unarmed configurations
10.	Jolt	For all projectile fuzes transported separately
11.	1.5 m Drop	For fuzes that are transported separately and for fuzes fitted to munitions in tactical configuration
12.	12 m Drop	For fuzes or fuzed munitions, in logistic package configuration
13.	Sequential Environmental Test Programme	See Para 7e. of STANAG
14.	Transportation Vibration	For bare fuzes or fuzes installed in munitions, as defined by manufacture-to- target sequence
15.	Transportation Vibration of Packaged Fuzes	
16.	Transportation Handling of Packaged Fuzes	

Note: The above tests are mandatory in the sense that they either must be performed, where applicable, or justification provided as to why they were not carried out.

Figure 2 List of mandatory tests in accordance with STANAG 4157 ed. 2 [6].

Test D1 *Primary explosive component safety* in AOP-20 gives details on the mandatory test for the explosive train interruption and is also called the explosive train interruption test. With this test it is verified that the safety mechanism functions properly. In other words: this test verifies whether the explosive train of the unarmed impact fuze is effectively interrupted.

The criteria for passing the test are: *'There shall be no detonation, fragment penetration, perforation, burning, charring, scorching or melting of any explosive component after the explosive train interruption. There shall be no ejecta which could cause serious personnel injury or initiation of adjacent fuses.'* [7].

A typical test configuration for performing a train interruption test is shown in Figure 3. A similar configuration applies to the M6-N impact fuze.

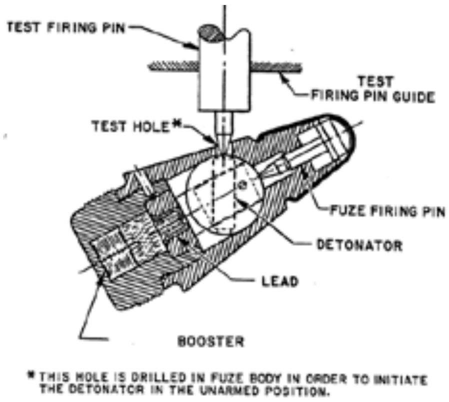


Figure 3 Typical configuration for a train interruption test [7].

Based on the train interruption test prescribed in AOP-20, a test program was compiled for the M6-N impact fuze, in which initiation of the duplex detonator was realised M6-N fuze in the unarmed position. The initiation of the duplex detonator, the test program, and the description of the test configuration, are outlined in paragraphs 2.2, 2.3 and 2.4.

2.1.2 Applicability of the train interruption test

Two STANAGs are important for the applicability of the train interruption test in AOP-20 to the M6-N fuze in the context of the Dutch situation, see Table 1. For the STANAGs to be applicable to The Netherlands they must be ratified by the Netherlands, promulgated by NATO, and finally implemented by the Netherlands[1].
Both STANAGs were implemented by the Netherlands at the beginning of the 2000s[2], although the date of implementation of STANAG 4157 is unknown. Besides, two earlier editions of STANAG 4187 and one earlier edition of STANAG 4157 had been implemented in the previous century.

AOP-20 is a *stand-alone* document, and is not ratified by individual countries; AOP-20 is promulgated with its cover STANAG 4157.

[1] The standardisation process within NATO is described in AAP-03 Production, Maintenance and Management of NATO Standardisation Documents. The current version is Edition J Version 3 from December 2015.
[2] It is noted that the Netherlands was the 'custodian' for STANAG 4157; this means the Netherlands presided the compilation of this STANAG.

Table 1 STANAGs [5, 6] relevant to the train interruption test, and ratified by the Netherlands.

STANAG	Edition	Title	Applicable to	NLD per
4187	3 (2001)	Fuzing systems: Safety design requirement	Development of new fuzes, for which development started after promulgation	sep-01
4157	2 (2002)	Fuzing systems: test requirements for the assessment of safety and suitability for service	Fuzes for which the requirements of STANAG4187 are applicable	Unknown

The *aim* and *agreement* sections in the STANAGs are of great importance.
At first glance, both STANAGs do not appear to be relevant to impact fuze M6-N, because 1) STANAG 4187, containing design requirements for the safety of fuzing systems, applies to fuzing systems newly developed after promulgation of this STANAG, and 2) the *aim* of STANAG 4157 is to standardise the assessment of fusing systems to which the design requirements in STANAG 4187 apply.

However, the *agreement* in STANAG 4157 explicitly states that it applies to: '…*the development and acquisition of fuzing systems commenced after promulgation*…' [6].
This leads to the conclusion that STANAG 4157 is relevant for the development as well as the acquisition of fuzing systems that began after the promulgation of STANAG 4157.
The acquisition of the 60 mm mortar with the M6-N impact fuze began after the promulgation of STANAG 4157. Therefore this standard does seem to apply to the acquisition of the M6-N fuzes for the 60 mm mortar, even if the design of the M6-N dates back to the previous century.

2.2 Initiation of the duplex detonator

The duplex detonator consists of two small metal cups[3] with one slid into the other, the inner cup of which contains the mixture of the energetic materials, see Figure 4.

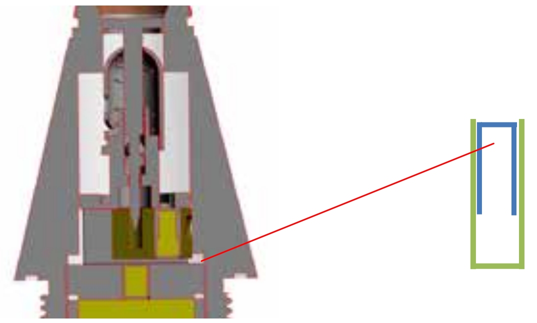


Figure 4 The duplex detonator consists of two metal casings with one slid into the other.

[3] The inner casing that contains the energetic materials is made from aluminium. The outer metal casing is made from a copper-nickel metal alloy (Melchior).

To initiate the duplex detonator from the top side in the train interruption tests, energy must be inserted in the energetic material from the outside through a thin layer of metal. Two methods were used in the test program of five train interruption tests to initiate the duplex detonator from the top side.

2.2.1 Initiation using a non-disruptive detonating cord

In the first two experiments, initiation was achieved using a specific type of detonating cord, a *non-disruptive detonating cord* (detcord). The detcord consists of a metal tube, with a diameter of 2.3 mm, filled with an explosive substance. A small booster (measuring 9.0 x 2.9 mm) is placed on the end of the metal tube, see Figure 5, which ultimately realises the transfer of energy to the duplex detonator.

Figure 5 Non-disruptive detonating cord (diameter 2.3 mm) with booster.

A number of preparatory experiments were conducted to establish full initiation of the duplex detonator. For a correct application of the detcord it is important that the energy transferred from the detcord has an effect solely on the duplex detonator and not on other components in the fuze; an unintended contribution to the transfer of the reaction of the duplex detonator to the lead charge in safe position must be avoided.

The preparatory experiments confirmed that the combination of the detcord and booster causes negligible damage in the radial direction of the detcord, and that the detcord is able to initiate a duplex detonator in the axial direction. Therefore the combination of the detcord with the booster is found to be a suitable initiation source for the train interruption tests. Appendixes A and B describe the preparatory experiments in greater detail.

The detcord must be inserted in the fuze with the booster positioned directly on the top side of the duplex detonator. The decision was taken to remove the membrane (3), the firing pin (5), spring (6) and the arming delay sleeve (or setback cap) (16) (see Figure 1) during the first two experiments. This allowed for the detcord to be inserted via the opening created at the tip of the impact fuze, allowing it to be positioned on top of the detonator. It was assumed that the removal of these components from the impact fuze would not affect the initiation behaviour of the detonator and the effect thereof on the barrier and lead charge.

A small hole was made in the firing pin housing (8) directly above the position of the duplex detonator with a diameter equal to that of the booster of the detcord. The final position of the detcord is shown in Figure 6.

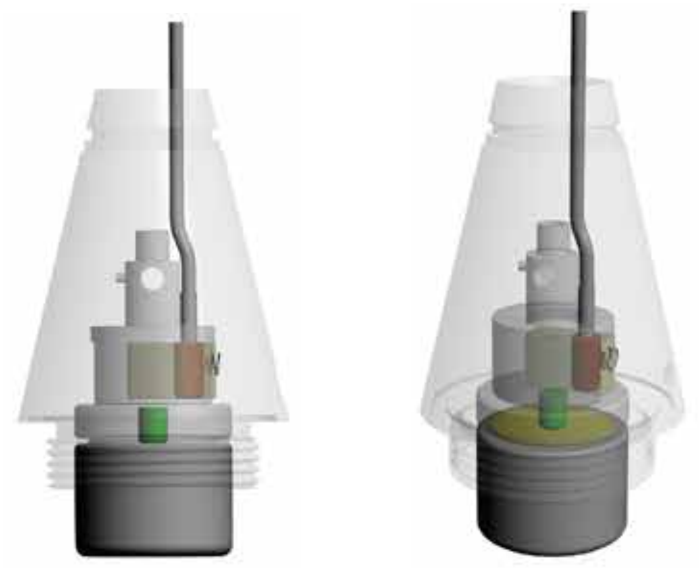


Figure 6 Position of the detcord in the M6-N fuze (left: side view, right: 3D image).

2.2.2 Mechanical initiation using a firing pin

In normal operation, the duplex detonator is initiated by the impact of the firing pin on its top side. The penetration of the firing pin's tip in the energetic material and the resulting friction initiates the detonator. No (chemical) energy is added, as is the case for the initiation using the detcord.

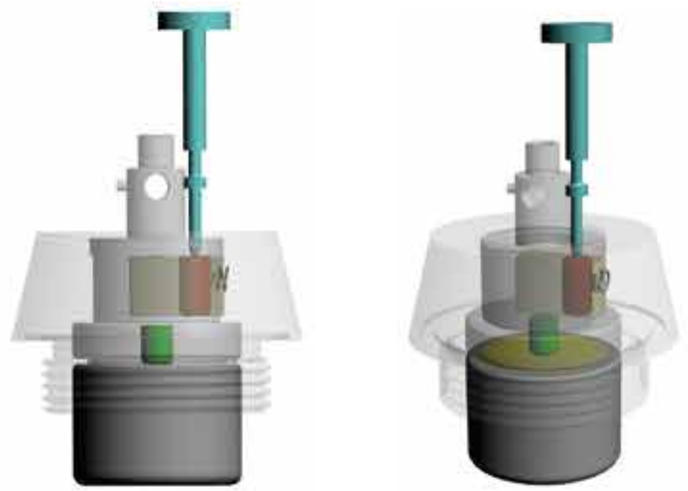


Figure 7 Prepared impact fuze for mechanical initiation (left: side view, right: 3D image).

In addition to the removal of the membrane, firing pin, spring and arming delay sleeve (setback cap), the upper section of the fuze body was machined off for effectuation of the mechanical initiation. The original firing pin was then used to initiate the duplex detonator through a small hole made in the firing pin housing, see Figure 7. The original firing pin was used to impose a similar deformation condition to the duplex detonator as in the normal functioning of the mortar round.

2.3 Test program

Five fuze bodies and the mechanical components of these five impact fuzes were made available to TNO. In addition, a total of eight duplex detonators, eight lead charges and two booster charges were supplied. The test program is provided in Table 2.

Table 2 Test program train interruption tests.

Test	Description	Initiation	Lead charge	Booster
-	Initiation test of the duplex detonator	Detcord	-	-
1	Explosive train interruption test	Detcord	Original	Inert
2	Explosive train interruption test	Detcord	Original	Inert
-	Initiation test of the duplex detonator	Firing pin	-	-
3	Explosive train interruption test	Firing pin	Original	Inert
4	Explosive train interruption test	Firing pin	Original	Original
5	Explosive train interruption test	Firing pin	Original	Original

Two detonators were used to verify that the initiation of the detonator was achieved by the detcord as well as by the firing pin with a drop weight (see Appendices A and B). In total, five actual train interruption tests were performed, experiments two and five being duplicates of experiments one and four, respectively.

All the tests were performed at ambient temperature. It should be noted that the experiments were conducted in a bunker in Rijswijk in March 2017. The temperatures in the bunker were usually around 12°C.

To rule out a contribution of the detcord to the transfer of reaction in the impact fuze, the three remaining experiments were performed using mechanical initiation.

The last two columns of Table 2 indicate the presence of an original lead charge in the train interruption tests and whether an original or inert booster charge was used. The inert booster charge consists of an aluminium cap that is screwed in an identical manner into the bottom housing of the fuze against the bottom of the barrier with the lead charge.
Initially, an inert booster charge was used from a safety perspective. A second reason to do so is that 37 grams of RDX is involved in the detonation of the booster charge; this will cause considerable damage to the fuze body that may mask important details (damage pattern, deformation, etc.). The aluminium cap can also serve as witness of a possible reaction of the lead charge.

2.4 Test configuration

All explosive train interruption test are carried out in a bunker on the TNO site in Rijswijk.

2.4.1 Initiation using a detcord

The fuzes were assembled in the bunker's workshop, as indicated in Figure 6. The detcord is 260 mm in length and extends far beyond the tip of the impact fuze. The impact fuze was secured in a laboratory clamp placed at the screw thread, where the impact fuze is normally screwed into the mortar round body. The impact fuze was placed in a vertical position, with the tip pointing upwards. The bottom of the fuze rests on a steel surface.
A small booster was also placed on the other end of the detcord. An electric C2 detonator was affixed to it using tape. The C2 detonator was connected to a long firing cable that allows the explosives supervisor to remotely initiate the C2 from outside the bunker.
A simple camera was mounted to observe the experiment from outside the bunker.

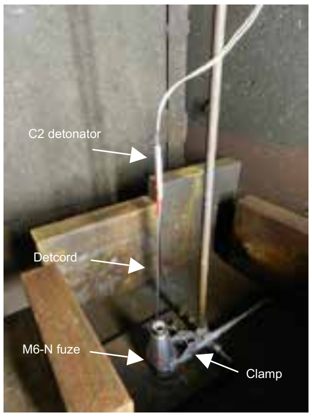


Figure 8 Test configuration with initiation using a detcord.

2.4.2 Initiation using a firing pin

A simple test configuration was used to allow a drop weight of approximately 1.7 kg to fall on top of the firing pin through a vertical drop tube. The drop height used was approximately one metre. This drop height delivers the correct velocity of the drop weight when it hits the firing pin; the resulting velocity of the firing pin is comparable to the velocity of the mortar round when it is dropped into the mortar, and for which it is known that it initiates the duplex detonator and results in detonation of the main charge [9].

The configuration is designed in such a way that the drop weight is caught by two steel blocks on either side of the impact fuze and the firing pin can be pressed a maximum of 9 mm downwards into the detonator. Under normal functioning the firing pin can also travel this distance (in an armed impact fuze).

A metal pin was inserted through the upper side of the tube and served as safety pin. A rope was connected to the metal pin and enabled the explosives supervisor to pull the pin out of the tube from outside the bunker and thus enable the drop weight to fall downwards through the tube onto the firing pin.

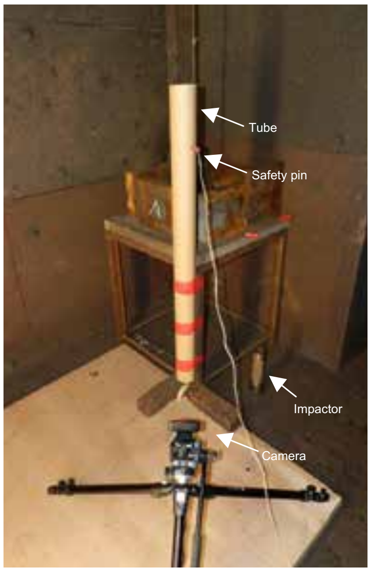


Figure 9 Test configuration using mechanical initiation. After the safety pin is removed a drop weight of approximately 1.7 kg falls through a tube onto the firing pin.

A simple camera was mounted during experiment 3. In the case of experiments 4 and 5, a high speed camera was installed, its frame speed set to 5,000 frames per second, to be able to observe and record the experiment from outside the bunker.

3 Results

3.1 Initiation using a detcord

The first two experiments were performed using a detcord. In both experiments an inert aluminium cap was used instead of a booster charge. The experiments with initiation using the detcord were performed using the test configuration described in paragraph 2.4.1.

Experiment 1
After the experiment the impact fuze is still clamped in the test configuration. No damage is visible to the exterior of the impact fuze. The aluminium cap is stuck in the screw thread, and has to be removed with force.
Once the cap is removed the bottom of the barrier becomes visible. The latter displays traces of expansion gases. Only a thin, circular piece of metal is present at the position of the lead charge. It appears that this is the base of the lead charge cup. The explosive lead charge has disappeared. The metal of the barrier above the lead charge has been blown away. This means that a transfer of reaction from the duplex detonator to the lead charge has occurred. The aluminium cap displays a slight indentation, caused by the reaction of the lead charge. Figure 10 shows some pictures of the impact fuze after the experiment.

Figure 10 Some pictures of experiment 1, from top left, clockwise: impact fuze after the experiment and removal of the aluminium cap; bottom surface of the barrier with fragment of the lead charge cup; dent in the aluminium cap; top surface of the barrier with indentation at the location of the duplex detonator.

After the experiment the impact fuze was further disassembled. The top surface of the barrier displays a clear indentation at the location of the out of line positioned duplex detonator.

Experiment 2

In experiment 2 also a transfer of reaction from the duplex detonator to the lead charge is observed. The effect of this is clearly visible directly after the experiment. The fuze body was expelled from the laboratory clamp into the bunker as a result of the initiation. The force released during initiation and the transfer of reaction to the lead charge resulted in the aluminium cap being thrown from the fuze body damaging the screw thread. The cap was recovered from a different part of the bunker. The bottom surface of the barrier is directly visible and again displays traces of expansion gases. The central cavity in the barrier is empty and the metal above the lead charge has been blown away. The top surface of the barrier displays a clear indentation at the position of the duplex detonator. Again, the aluminium cap displays a slight indentation, caused by the reaction of the lead charge. Figure 11 shows some pictures of the impact fuze after the experiment.

Figure 11 Some pictures of experiment 2, from top left, clockwise: impact fuze after the experiment; bottom surface of the barrier; dent the aluminium cap; barrier with the indentation at the position of the duplex detonator.

3.2 Initiation using a firing pin

The experiments with mechanical initiation using the firing pin were conducted in accordance with the test configuration described in paragraph 2.4.2. An aluminium cap was used once more in experiment 3. Experiments 4 and 5 were conducted with the original booster charge.

Experiment 3

The first experiment using mechanical initiation and an inert booster charge gives a similar result as experiments 1 and 2. After the experiment, the aluminium cap is still affixed to the fuze body. The cap displays a slight indentation caused by the reaction of the lead charge.

After removal of the cap and the barrier the indentation in the top surface of the barrier at the location of the duplex detonator becomes visible and transfer of reaction from the duplex detonator to the lead charge has occurred.
The metal above the lead charge was blown away. Figure 12 shows some pictures of the impact fuze after the experiment.

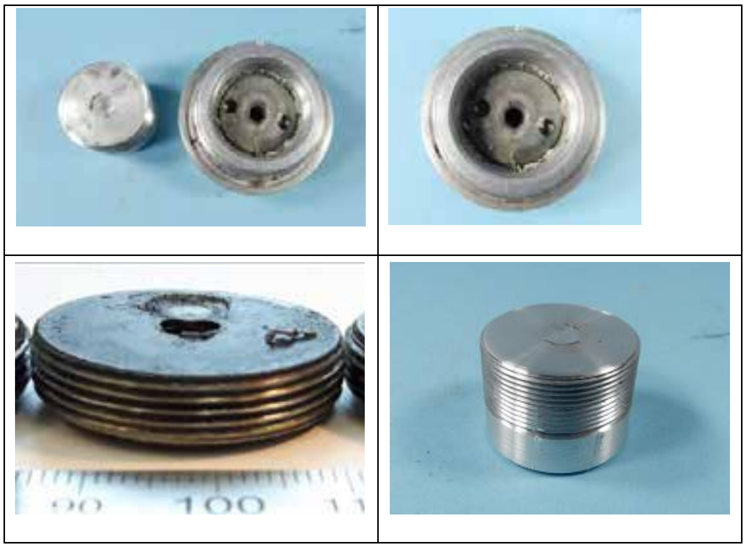


Figure 12 Some pictures of experiment 3, from top left, clockwise: impact fuze after the experiment; bottom surface of the barrier; dent in the aluminium cap; barrier with an indentation at the position of the duplex detonator.

Experiment 4
An original booster charge was used in this experiment. The purpose of the experiment was to establish whether initiation of the duplex detonator and the subsequent reaction of the lead charge would be followed by a reaction of the booster charge. The booster charge is the last step in the explosive train that (in normal functioning) ultimately ensures the detonation of the main charge.

After the experiment it was determined that the booster charge did not detonate. The RDX explosive charge remained intact. The booster charge is still connected to the fuze body. After removal of the booster charge, the top side of the latter displays a damage pattern resulting from the reaction of the lead charge, see Figure 13, below. The base of the lead charge cup has been pushed into the RDX charge. This has produced a considerable crater in the RDX. On the top side of the booster charge debris was found of the (partially burned) piece of cardboard[4], which is inserted between the booster charge and the barrier during assembly.

The other impact fuze components display similar results as in experiments 1 and 2. The metal of the barrier above the lead charge has also been blown away by the transfer of the reaction from the duplex detonator to the lead charge. Figure 13 shows several pictures of the impact fuze after the experiment.

[4] A cardboard disk is inserted by default in an M6-N shock tube, but is not shown in Figure 1.

Figure 13 Several pictures of experiment 4, from top left, clockwise: impact fuze after the experiment; bottom surface of the barrier with debris of the lead charge cup; indentation of base of the lead charge cup in the booster charge; impacted barrier with an indentation at the location of the duplex detonator.

The high-speed video made of the experiment does not reveal any irregularities. As soon as the firing pin is hit by the drop weight the duplex detonator initiates instantaneously.

Experiment 5
The result of experiment 5 is similar to the result of experiment 4. No detonation of the booster charge is observed. The booster charge cup is still intact and connected to the fuze body. When removed, the top side of the booster displays a damage pattern resulting from the reaction of the lead charge. The cardboard has completely disappeared. The base of the lead charge cup has impacted on the RDX charge of the booster, although the indentation is considerably smaller than in experiment 4. The base of the lead cup is left behind in the RDX, see Figure 14, bottom right.
There is a clear indentation in the top surface of the barrier at the location of the duplex detonator, but its shape is different from that observed in the other experiments. Transfer of the reaction from the duplex detonator to the lead charge was observed once more.
The images recorded by the high-speed camera did not reveal any irregularities.

Figure 14 Several pictures of experiment 5, from top left, clockwise: impact fuze after the experiment; bottom surface of the barrier with debris of the lead charge cup; indentation of base of the lead charge cup in the booster charge; impacted barrier with an indentation at the location of the duplex detonator.

3.3 Analysis of the results and discussion

3.3.1 Analysis of the barriers

The five impact fuzes were disassembled after finalizing the experiments. The five barriers have been placed side by side in Figure 15. They very clearly display an indentation caused by the reaction of the duplex detonator. Although a slight variation in the shape and depth of the indentation is observed, it can be stated that the initiation method (detcord versus mechanical) did not result in any clear difference in indentation.

Figure 15 also clearly shows that the metal above the central cavity has been blown away in each of the five barriers. In some cases the duplex detonator has also caused deformation to (the edge of) the central cavity.

Figure 15 Barriers from the five experiments (left to right: experiments 1 through 5).

It is now possible to compare the visible damage in the top surface of the barriers from this investigation and that from the barrier of the impact fuze involved in the accident. The damage to this barrier was analysed earlier in [4].

In Figure 16, the barrier from the accident (left) is placed next to the barrier from experiment 3 (right). The barrier involved in the accident, in which the entire mortar round detonated, is not perfectly circular. The explosive train interruption tests were performed with the duplex detonator in safe position. Now a similar indentation in the barrier (A) has been demonstrated, it can be stated with certainty that the duplex detonator in the mortar round involved in the accident exerted a high explosive effect on the barrier. There is a striking effect from the initiation of the duplex detonator on the edge of the central cavity; a small upward edge (B) can be identified in both the barrier from the accident and the barrier from experiment 3.
Based on this comparison, the hypothesis in [4] that the duplex detonator was in safe position at the time of the accident has been verified.

Figure 16 Comparison of the barrier from the impact fuze involved in the accident (left) with the barrier from the impact fuze used in experiment 3 (right).

3.3.2 Analysis

Experiments were performed with three inert and two original boosters, see Figure 17. The indentation in the aluminium cap below the lead charge indicates a high explosive effect of this charge. There is visible variation in indentation, with the largest indentation occurring in experiment 2. The indentation in the original booster charges is also clearly different, with the largest indentation occurring in experiment 4.

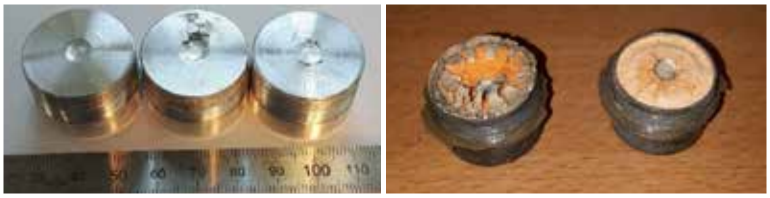


Figure 17 Effect of the lead charge on boosters from experiments 1 through 5 (left to right). Three aluminium caps as inert boosters in the picture on the left and two original boosters charges in the picture on the right.

Although the effect of the duplex detonator and the lead charge are different in each of the experiments, the result is a cylindrical, symmetrical indentation of the (inert or original) booster.
This means that the most likely route of the initiation of the lead charge appears to be: transfer of the shock wave from the duplex detonator through the barrier to the lead charge (route A in Figure 18). The (shortest) distance between the duplex detonator and the lead charge and / or the thickness of the metal above the lead charge are insufficient to prevent a reaction of the lead charge. There was no transfer of the shock wave of the duplex detonator through the barrier directly to the booster charge (route B in Figure 18). The thickness of the barrier appears adequate to prevent this from happening.

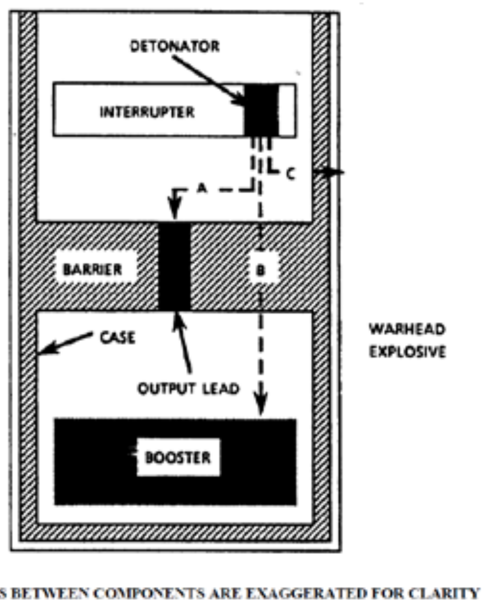


Figure 18 Three possible routes for shock wave transfer from the out-of-line detonator. Route A is from the detonator to the lead charge, route B is via the barrier to the booster charge and route C is directly from the detonator to the main charge (and only applies to a fuzing system built into the main charge [6].

Optical microscopy was used to examine the surface of the booster charge, see Figure 19. The top picture shows localised discolouration[5] at the edges of the crater in the booster charge and near the impact of a relatively large metallic fragment. Spherical particles have also been identified, with a typical diameter of 150 to 250 μm (Figure 19, bottom) and with minuscule metal particles in the surface. These are indications that the booster charge encountered a (localised) thermal load.

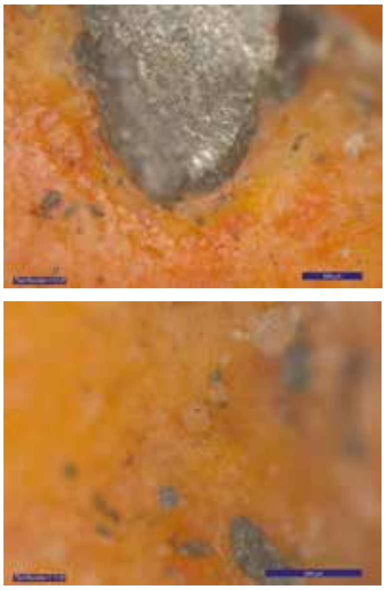


Figure 19 Experiment 4; colour differences in the surface of the booster near a metallic fragment (top), and spherical, relatively transparent particles with small metallic fragments in the surface (bottom).

The base of the lead charge cup was left behind in the booster charge. Reference is made once more to [4]. The wall of the lead charge cup was still present in the central cavity of the barrier from the accident. The bottom edge of this remnant of the lead charge cup shows that the base of the cup has been blown downward, see Figure 20, left. The similarity with the base of the cup in the booster is clear, see Figure 20, right.

[5] RDX has no orange or red color. A colored wax is presumably used to press a granulate into a booster charge with the desired density.

Figure 20 Left: central cavity of the barrier from the accident with remnant of the lead charge cup [4]. Right: the base of the lead charge cup in the booster after experiment 5.

3.3.3 Discussion

During normal functioning the explosive train in the M6-N fuze consists of four steps, which are:

1. Initiation and detonation of the duplex detonator;
2. Initiation and detonation of the lead charge with transfer of the reaction to the booster charge;
3. Initiation and detonation of the booster charge, amplifying the shock in the direction of the main charge;
4. Initiation and detonation of the main charge.

The results of the explosive train interruption tests show that a transfer of the reaction takes place between steps one and two; even in safe position the lead charge initiates upon initiation of the duplex detonator. In the explosive train interruption tests initiation of the original booster charge due to the reaction of the lead charge did not occur (and a connected main charge would not have detonated). In these tests the output of the duplex detonator, positioned out of line, was insufficient to cause a (full) detonation of the lead charge, powerful enough to initiate the booster charge. Due to the limited number of tests and the observed variation in the shape and depth of the indentation in the barrier resulting from the initiation of the detonator, it cannot be concluded that transfer of the reaction *with* the initiation of the booster charge will be prevented under all conditions. Especially, the difference in temperature of the energetic charges in the mortar round between the experiments and those during the accident, render it impossible to conclusively state this without performing additional research.

The results of the explosive train interruption tests enable a comparison with the criteria in AOP-20 D1.3.1 for passing the explosive train interruption test: '*There shall be no detonation, fragment penetration, perforation, burning, charring, scorching, or melting of any explosive component after the explosive train interruption. There shall be no ejecta which could cause serious personnel injury or initiation of adjacent fuzes. Smudging of the surfaces or fragment penetration of the explosive components after the interrupter, as well as indentation of their containers, is not, in itself, a sufficient cause for stating that the fuze has failed*' [7].

Relevant parts of this criterion are discussed.

- *'There shall be no detonation of any explosive component after the explosive train interruption'*
  - No detonation of the booster charge was observed;
  - The reaction type of the lead charge is unknown; the lead charge itself has not been recovered from any of the five experiments. Indentation in the aluminium caps and impact of the base of the lead charge cup in the RDX of the booster charge was observed. The indentation in the aluminium indicates a high explosive effect from an explosive substance (from the lead charge) in the immediate vicinity.

- *'There shall be no fragment penetration of any explosive component after the explosive train interruption'*
  - The metal of the barrier above the lead charge has been blown away and was possibly accelerated into the lead charge;
  - The base of the lead charge cup was accelerated and pushed into the booster charge;
  - Small, metal fragments are visible in the booster charge, especially in experiment 4, the first test using the original booster charge. A metallic fragment was also visible in experiment 5 in a radial crack in the booster charge.

- *'There shall be no perforation of any explosive component after the explosive train interruption'*
  - The metal of the barrier above the lead charge has been blown away and was possibly accelerated into the lead charge;
  - The base of the lead charge cup was accelerated and pushed into the booster charge (penetration). However perforation did not take place.

- *'There shall be no burning, scarring, scorching or melting of any explosive component after the explosive train interruption'*
  - The explosive material of the lead charge was not recovered in any of the five experiments. The lead charge reacted, although the exact type of reaction[6] is unknown;
  - The bright orange discoloration of the energetic material in the booster charge in experiment 4 indicates that the wax may have melted. The booster charge consists of RDX, but it is assumed that this mix included wax. This presence of wax is assumed because RDX is white or transparent, while the booster charges had an orange colour.

- *'There shall be no ejecta which could cause serious personnel injury or initiation of adjacent fuzes'*
  - The fuze in experiment two was launched as a whole. The resulting initiation of a possible adjacent fuze appears unlikely but personal injury cannot be excluded.

The previous analysis is summarised in Table 3.

[6] The reaction types range from detonation, partial detonation, deflagration to combustion.

Table 3 Overview with PASS / FAIL for the M6-N impact fuze according to AOP-20 criteria.

M6-N barrier	AOP-20 criterion (after the explosive train interruption)				
	There shall be no detonation of any explosive component	*There shall be no fragment penetration of any explosive component*	*There shall be no perforation of any explosive component*	*There shall be no burning, scarring, scorching or melting of any explosive component*	*There shall be no ejecta which could cause serious personnel injury or initiation of adjacent fuzes*
Assessment	Inconclusive	Fail	Inconclusive	Fail	Inconclusive

The experiments result in a NO PASS for the barrier (as a train interrupter) in the M6-N fuze on the basis of the following findings (and not allowed according to AOP-20):

- The reaction of the lead charge;
- The localised discolouration of the booster charge;
- The metallic fragments in the booster charge.

4 Conclusions and recommendation

Explosive train interruption tests were performed to experimentally verify whether detonation of the duplex detonator can result in a reaction of the lead charge in an unarmed M6-N impact fuze, and whether this can result in the initiation of the entire explosive train.

Based on the results of the experimental investigation it was concluded that:
- In each of the five explosive train interruption tests, initiation of the duplex detonator in safe position results in a reaction of the lead charge, regardless of the initiation method used;
- In the two tests with the original booster charge, the lead charge had an effect on the booster charge, but did not cause it to detonate.

Visual inspection of the barriers following the explosive train interruption tests revealed:
- A strong similarity of the damage to the top surface of the barrier from the accident and to those from the experiments;
- Comparable remnants of the lead charge cup in the central cavity in the barrier from the accident and remnants left behind in the RDX booster charge experiments.

This inspection verifies the hypothesis that it is highly likely that the duplex detonator was in safe position at the time of the accident.

The test results have been compared with the pass / fail criteria for the '*train interruption test*' as specified in the Allied Ordnance Procedure (AOP) 20 in accordance with the NATO Standardisation Agreement (STANAG) 4157. The experiments result in a NO PASS for the barrier (as a train interrupter) in the M6-N impact fuze on the basis of the following findings (and not allowed in accordance to AOP-20):
- The reaction of the lead charge;
- The localised discolouration of the booster explosive charge;
- The metallic fragments in the booster explosive charge.

The AOP-20 criterion *There shall be no detonation of any explosive component* cannot be tested because the reaction type of the lead charge was not established. The AOP-20 criterion *There shall be no perforation of any explosive component* cannot be tested because the direction of the metal blown away from the barrier is unknown.

In the two tests conducted with the original booster charge, the output of the duplex detonator was insufficient to cause a (full) detonation of the lead charge powerful enough to initiate the booster charge. Due to the limited number of tests and the observed variation in the shape and depth of the indentation in the top surface of the barrier resulting from the initiation of the duplex detonator, it cannot be concluded that transfer of the reaction *with* the initiation of the booster charge will be prevented under all conditions.

The train interruption tests described in this report were performed at a temperature of approximately 12°C. Although transfer of the reaction from the duplex detonator to the lead charge was observed in all the tests, it is not possible to conclude that the design of the fuze is unsafe because the booster charge was not detonated by the initiation of the duplex detonator in safe position.
It is possible that initiation of the booster charge will take place at an increased temperature, such as above the maximum operating temperature of 50°C, as specified by the supplier.

The explosive train interruption tests described in this report were all performed at a temperature of about 12°C. It is recommended that an extensive series of train interruption tests be performed on minimally adapted impact fuzes in safe position, with a booster charge and at an increased temperature of up to 70°C.

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6 Signature

Rijswijk, 5 April 2017 TNO Technical Sciences

P. Hendriksen
Head of department

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A Preparatory tests non-disruptive detonating cord

Introduction
A number of preparatory tests were performed in advance of the explosive train interruption tests with the non-disruptive detonating cord, with the aim to establishing whether the cord transfers any unintended energy to the impact fuze and negatively affects the result of the explosive train interruption test. The preparatory tests serve to analyse the effect of detonation from the detcord in a radial direction, and the difference of the effect of the detcord with and without a booster. The preparatory tests also serve to establish whether the detcord can actually initiate the duplex detonator.

Experiments
The detcord[7] consists of a metal tube measuring 250 mm in length with a diameter of 2.3 mm. The type of explosive in the detcord is unknown. There is a small booster on one end of the detcord; a separate booster may be placed at the other end. The boosters measure 9 mm in length and have a diameter of 2.9 mm, see Figure 21.

Figure 21 Booster at the end of the non-disruptive detonating cord.

The effect of the detcord in the radial direction and the effect of using or not using a booster on the detcord, were tested in two experiments by securing the detcord against an aluminium sheet and placing the end (once with and once without a booster) perpendicular to the surface of a PMMA cylinder, see Figure 22.

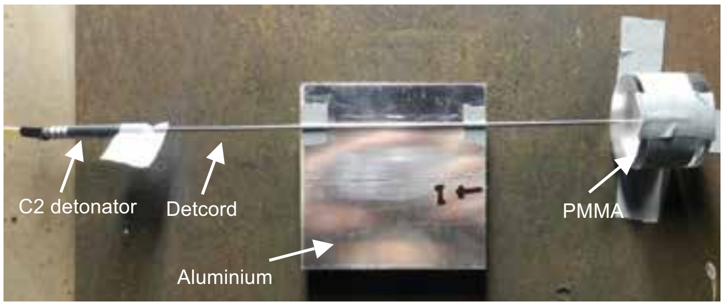

Figure 22 Test configuration to determine the effect of the detcord.

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[7] Miniature Non-Disruptive Detonating Cord, 40 lengths each 250 mm long 2.3 mm diameter. Batch 557 Manufactured DERA / FH. March 2000. Total NEC 3.0 g.

The experiments showed that the effect of the detcord in the radial direction is negligible; the detcord leaves behind a small groove on the surface of the aluminium plate, the detcord itself does not fragment.
Figure 23 shows the effect on a PMMA cylinder from a detcord with a booster (left) and without a booster (right). The effect with a booster is clearly more prominent.

Figure 23 Damage to PMMA cylinders caused by the detonation using the detcord with (left) and without (right) a booster.

This difference in the effect was also tested by positioning the detcord with and without a booster against the base of a C2 detonator, with the underlying idea that the C2 detonator could simulate the duplex detonator that needs to be initiated. The base charge of the duplex detonator will be ‘comparable’ to the base charge of the C2 detonator; both require sufficient shock-sensitivity for initiation and adequate output to initiate a subsequent charge in the explosive train. The result is shown in Figure 24. The detonator without a booster is only able to damage the metal casing of the C2 detonator. The charge of the C2 detonator does not detonate, in contrast to the experiment in which the detcord with the booster cup was used.

Figure 24 Effect of the detcord without a booster (left) and with a booster (right), positioned against the base of a C2 detonator.

Based on these results it was decided that the detcord with a booster is an effective initiation source to initiate the duplex detonator, without causing unintended secondary damage inside the impact fuze.

B Initiation tests of the duplex detonator

The preparatory tests described in Appendix A led to the selection of the detcord with a booster as an initiation source for the duplex detonator. Before the detcord was applied to a completely assembled impact fuze, initiation of a duplex detonator was first tested separately in a brass[8] block.

For comparison the effect of the detcord with a booster was also determined using the brass block only. A hole with the diameter of the booster (2.9 mm) and a depth of 9 mm was drilled into the brass block, see Figure 25, left. No deformation of the brass was found after the experiment. (NB: The black mark top left of the hole was caused by the detcord that came to rest on the surface of the block due to the effect of the booster in the hole next to it, leaving behind some combustion products.)

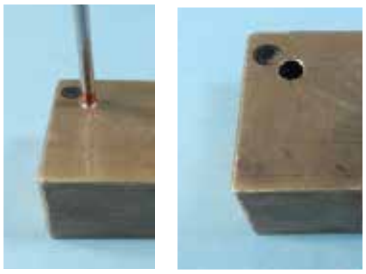

Figure 25 Effect of the detcord with a booster sunk into a brass block; configuration before the test (left) and the result after the test (right).

Subsequently, a hole was drilled in the brass block with the same dimensions as the duplex detonator. The detonator was inserted into the hole and the detcord with booster was positioned on top of the duplex detonator, see Figure 26.

Figure 26 Detcord with booster positioned on top of the duplex detonator sunk into the brass block.

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[8] Brass was selected because the slides, in which the duplex detonator is placed in the fuze, is also made of brass.

The duplex detonator initiated following the detonation of the detcord. The effect of the detonator on the brass block is significant, see Figure 27. While the booster of the detcord did not display any deformation of the hole in which it was inserted in the brass block, the duplex detonator deforms and cracks the brass block. The detonator's longitudinal effect is also easily identified.

Using a simple analysis based on the volume of the booster cup of the detcord in comparison to the volume of the duplex detonator, it is estimated that the energy content of the booster was only 15% of that of the duplex detonator. It is expected that the effect of the booster will not influence the outcome of the explosive train interruption test.

The detcord with a booster attached to its end is an effective initiation source for the duplex detonator during the explosive train interruption tests.

Figure 27 Damage to the brass block following detonation of the duplex detonator.

C Design principles

STANAG 4187 [5] includes design principles for the safety of fuzing systems. Even in case this STANAG is not applicable in the acquisition phase of a fuzing system, compliance with the safety requirements in this STANAG is recommended. STANAG 4187 actually describes a number of safety requirements that apply to all fuzing systems. In particular for modern fuzing systems, whenever possible, two environmental stimuli are required to arm the fuze. These environmental stimuli must be independent of each other.

In the M6-N impact fuze, only one independent environmental stimulus is used, and which is based on acceleration / deceleration in the longitudinal direction of the mortar round. In a rifled launch tube it is possible to apply rotation as second and independent external influence. However, the 60 mm mortar round is fired from a smooth bore and rotation does not occur. However, new fuzes are in development for also providing fusing systems fired from a smooth-bore launch tube with a second, independent environmental stimulus. A recent example of this is shown in [8], see Figure 28.

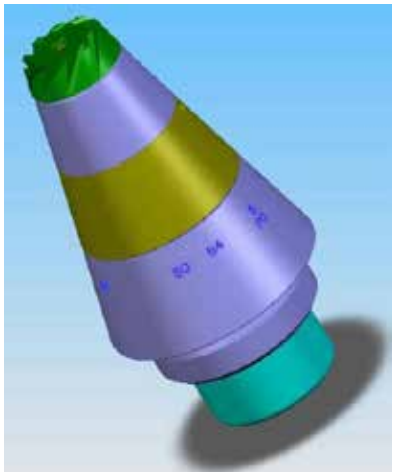

Figure 28 Fuze that generates a rotational movement only after obtaining velocity in flight; see the green section at the top of the fuze with inclined grooves [8].

STANAG 4187 also requires the selection of qualified explosive substances, specifically referring to the requirements for lead and booster explosives. For both the primary and booster explosives, it is not allowed for the sensitivity to increase significantly throughout the entire life cycle, beyond the level for which permission for operational use has been granted.

Specifically for fuzes with an interrupted train, STANAG 4187 emphasizes to determine the effectiveness using the *Explosive Train Interrupter Safety Tests* and *Progressive Arm Tests* from STANAG 4157.

Paragraph 2.1.1 refers to the *Safety and Suitability for Service (S3) of Munitions, Explosives and Related Products*. Within NATO, the Safety and Suitability for Service is covered by AC/326, the Ammunition Safety Group of the Conference of National Armament Directors. AC/326 provides standards with requirements for generic ammunition types including mortar rounds, initiation systems including fuzing systems, and energetic materials, and also provides standards for performing tests, and the assessment thereof. Of particular importance are the documents from Sub-Group/B Ammunition Systems Design and Assessment, and Sub-Group/A Energetic Materials & Initiation Systems, see Figure 29. NATO-promulgated standards can be consulted on the public section of the NATO website [11].

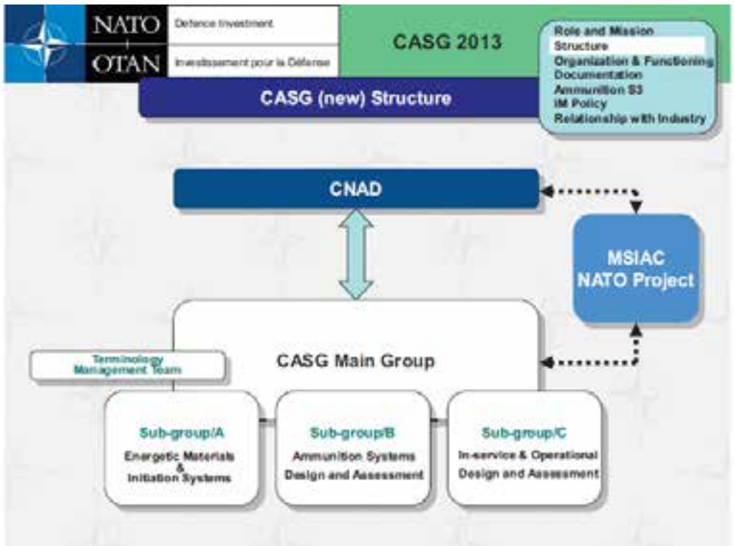

Figure 29 Structure of the CNAD Ammunition Safety Group [10].

The relevant and most important standards from Sub-Group B related to mortar rounds are:

- STANAG 4297, Edition 2, 2001, Guidance on the assessment of the safety and suitability for service of non-nuclear munitions for NATO armed forces;
- AOP-15, Edition 3, 2009, Guidance on the assessment of the safety and suitability for service of non-nuclear munitions for NATO armed forces;
- STANAG 4225, Edition 2, 2001, The safety evaluation of mortar bombs;
- STANAG 4433, Edition 1, 2001, Field mortar munitions, design safety requirements.

The relevant and most important standards from Sub-Group A, Initiation Systems team, related to mortar rounds are

- STANAG 4187, Edition 4, 2006, Fuzing systems, safety design requirements.
- AOP-16, Edition 4, 2007, Fuzing systems: guidelines for STANAG 4187;
- STANAG 4157, Edition 3, 2017, Safety, arming and functioning (SAF) systems testing requirements;

- AOP-20, Edition B, Versions 1, 2017, Safety, arming and functioning systems manual of tests;
- STANAG 4363, Edition 3, 2013, Initiation systems: testing for the assessment of detonating explosive components;
- AOP-21, Edition 3, 2011, Initiation systems: characterisation and safety test methods and procedures for detonating explosive components.

The relevant and most important standards from Sub-Group A, Energetic materials team, related to mortar rounds are

- STANAG 4170, Edition 3, 2008, Principles and methodology for the qualification of explosive materials for military use;
- AOP-7, Edition 2, 2003, Manual of data requirements and tests for the qualification of explosive materials for military use;
- STANAG 4147, Edition 2, 2001, Chemical compatibility of ammunition components with explosives (non-nuclear applications).

In addition to NATO standards, there are also standards with design principles for fuzing systems in use in, for example, the United States, including:

- MIL-STD-331, Fuze and fuze components, environmental and performance tests for
- MIL-STD-1316, Fuze design, safety criteria for

and in Great Britain, a.o.;

- DEF-STAN 13/131, Ordnance board safety guidelines for weapons and munitions.

APPENDIX J

ADDITIONAL INVESTIGATIONS

Commissioned by the Dutch Safety Board (DSB), TNO conducted additional investigations into the cause of the 6 July 2016 mortar accident in Mali. This report describes the following (stand-alone) topics of these investigations:

- Explosive train interruption M6-N impact test at 70°C;
- Initiation test with M6-N fuze in armed position;
- Alternative cause of the accident;
- Exudation and melting of the TNT main charge;
- TNT exudation test;
- Deflagration to Detonation Transition (DDT);
- Degradation/corrosion of the M6-N fuze;
- Mortar round temperature measurements;
- Hazard classification of the HE80 mortar round;
- Literature study.

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TNO-report

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Mortar exercise accident Mali: Additional investigations

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Table of contents

1 Introduction

Commissioned by the Dutch Safety Board (DSB), TNO conducted additional investigations into the cause of the 6 July 2016 mortar accident in Mali. This report describes the following (stand-alone) topics of these investigations:

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- Degradation/corrosion of the M6-N fuze;
- Mortar round temperature measurements;
- Hazard classification of the HE80 mortar round;
- Literature study.

2 Explosive train interruption test at 70°C

The results of the explosive train interruption tests at 12°C with the M6-N fuze in safe position are provided in [1][1]. It was observed that transfer of reaction occurs from the duplex detonator to the lead charge, but not to the booster charge. The latter, however, was damaged.

As a follow-up to these tests, one additional explosive train interruption test is carried out at 70°C. The aim of this test was to establish whether an elevated temperature would cause the transfer of the detonation to the booster charge.

2.1 Preparation of the M6-N fuze

The fuze is prepared in such a way that the duplex detonator can be initiated in safe position during the test. Two methods to realize initiation are desrcribed in [1]. The option selected is the initiation by means of a metal detonation cord, filled with pentaerythritol tetranitrate (PETN). This method causes the least disruption to the structure of the fuze. Figure 1 gives a cross-section of the fuze, showing how the detonation cord is positioned directly on top of the duplex detonator. In contrast to [1], the entire safety and arming device is present inside the fuze; in order to get access to the detonator from the outside a 4 mm hole is drilled in the top of the fuze body and a hole of 3 mm in the firing pin housing, directly above the duplex detonator.

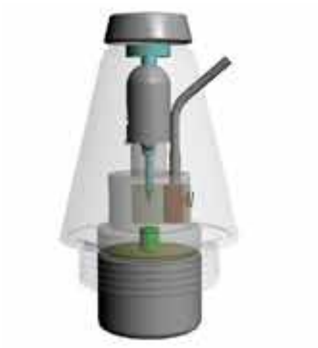

Figure 1 Positioning of the detonation cord in the M6-N fuze.

A booster charge is attached to both ends of the detonation cord. The detonation cord is initiated with a C2 detonator, thereby initiating the duplex detonator.

2.2 Test configuration

The experiment is conducted in a bunker in the TNO facilities in Rijswijk. A cylindrical, electric oven is placed around the fuze, see Figure 2. This oven can be operated remotely. The test configuration is such that once the fuze is heated to the desired temperature, the oven can be lifted from outside the bunker. The heated

[1] This fuze was removed from an HE80 mortar round that had been stored at TNO since 2012.

fuze then becomes visible to a high speed camera. The camera is placed behind armoured glass and records film at a rate of 5,000 fps.

To verify that the fuze actually reaches a temperature of 70°C, a thermocouple is inserted in the fuze through the hole drilled in the top of the fuze body.

Figure 2 Explosive train interruption test configuration at 70°C.

2.3 Result

The fuze is heated to 70°C in a period of several hours. After lifting the oven, the detonator is initiated using the detonation cord. The pictures from the high speed camera reveal that the booster charge does not detonate.

After the experiment the booster charge is removed from the fuze. It is observed that transfer of reaction from the duplex detonator to the lead charge has occurred. The lead charge has punched a crater in the RDX/wax of the booster and remnants of the lead charge cup are left behind in the RDX/wax, see Figure 3.

Figure 3 Booster charge that was dissembled after the test.

The crater in the RDX/wax is deeper than in previous experiments [1]. This can be explained by the higher temperature, which softens the wax in the booster charge.

2.4 Conclusion

No initiation of the booster is observed following the transfer of reaction from the duplex detonator to the lead charge in the M6-N fuze in safe position at 70°C.

Note that only one experiment is conducted. The conclusion does not provide any statistical substantiation for the prevention of detonation transfer to the booster charge at elevated temperatures.

3 Initiation test with M6-N fuze in armed position

3.1 Test configuration and implementation

On Tuesday, 5 September 2017, TNO has conducted a test with an M6-N fuze in armed position. With the exception of the membrane and the three retaining balls, all components up to and including the booster charge are used. During assembly, the slider is positioned in such a way that the energetic components of the detonation train (detonator - lead charge– booster charge) are all in-line (Figure 4).

Figure 4 M6-N fuze with slider in armed position.

Finally, the spring, setback cap and firing pin are inserted through the open tip of the fuze, at which stage the ability of the firing pin to move freely through the firing pin housing is verified. To prevent the firing pin being forced out of the fuze by the spring, the firing pin is secured in its position using duct tape. A steel cylinder with the same diameter as the tip of the firing pin is placed above the firing pin so that the firing pin can be pushed down far enough to reach the detonator with its tip, see

Figure 5. By the impact of a drop weight of 1.7 kg onto the cylinder through a vertical drop tube, the firing pin will strike the detonator resulting in the initiation of the complete detonation train. The test is conducted in a bunker; by pulling a steel pin out of top side of the tube the drop weight is released from outside the bunker. It was shown that the complete detonation train, including the booster, functioned. The remnants of the fuze are compared with those from the accident.

Figure 5 M6-N fuze with booster, secured firing pin and cylinder, placed beneath the drop tube.

3.2 Inner wall of the fuze body

The imprint of the slider and slider spring on the inner wall of the fuze body from the test in armed position is less prominent than the imprint observed on the inner wall of the fuze body from the accident mortar round, see Figure 6.

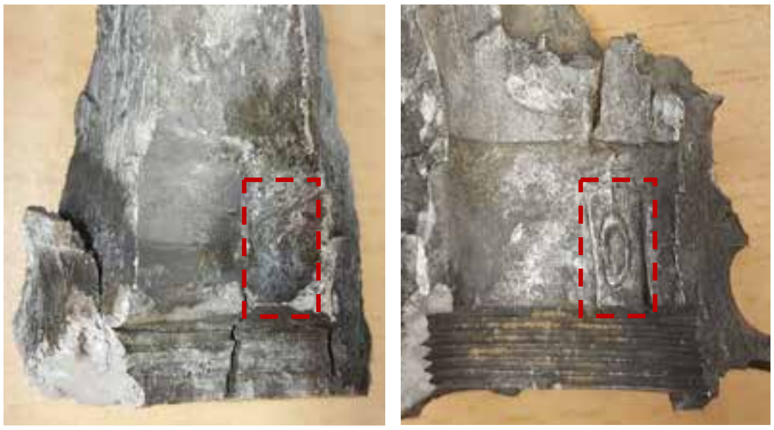

Figure 6 Imprint of the slider and slider spring on the inner wall of the fuze body from the test in armed position (left) and on the inner wall of the fuze body from the accident mortar round (right).

See Figure 7; upon functioning of the detonator the slider is broken into two parts; the part on the left of the detonator is accelerated to the left and the part on the right of the detonator is accelerated to the right. Since in armed position the slider and slider spring are positioned at some distance from the fuze body inner wall, the imprint on the fuze body inner wall is less prominent than when the detonator functions in the slider in safe position, when the slider and slider spring already make contact with the inner wall of the fuse body. This is a strong indication that the accident mortar round detonated with the fuze in safe position.

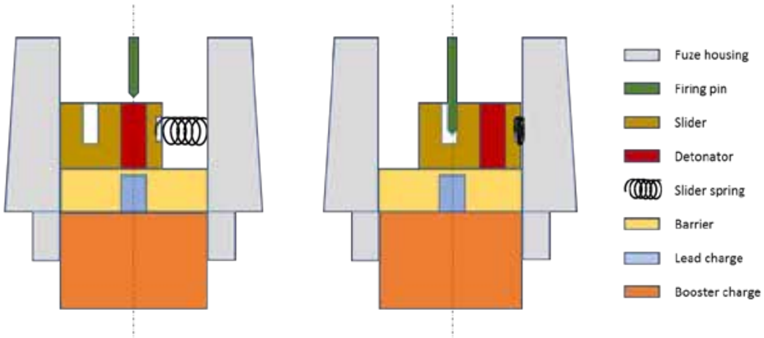

Figure 7 Cross-section of (part of) the fuze in armed position (left) and in safe position (right).

3.3 Firing pin

When the detonator functions in the slider in safe position (right in Figure 7) the part of the slider with the recess for the firing pin is accelerated to the left. As a result, the firing pin will deform substantially or break. Figure 8 shows three firing pins; an unused firing pin (left), the firing pin from the test in armed position (centre) and the firing pin from the accident mortar round (right). The latter has sheared off just below the lower thickened section. This is a strong indication that the accident round detonated in safe position.

Figure 8 Unused firing pin (left), firing pin from the test in armed position (centre) and from the accident mortar round (right).

3.4 Firing pin housing

The bottom of the firing pin housing is circular with a rectangular recess in the centre in which the slider moves, see Figure 9 (left). When the detonator functions due to the impact of the firing pin the housing is deformed. In armed position this deformation is imposed on the centre of the housing. The deformation is virtually symmetrical in the radial direction, see Figure 9 (centre).

The energetic materials in the detonator transfer a flame in the top section of the detonator to a detonation in the bottom section of the detonator. This is why the deformation is largest at the bottom of the housing. The remnants of the housing from the accident also show a deformation, see Figure 9 (right). It deviates from the symmetrical and centred deformation that is obtained in the test in armed position. This is an indication that the accident mortar round detonated in safe position.

Figure 9 Bottom view of an unused firing pin housing (left), from the test in armed position (centre) and from the accident mortar round (right).

3.5 Explosive train interrupter (barrier)

The effect of a functioning detonator on the explosive train interrupter (barrier) varies with the position of the detonator at the time of detonation. In armed position the detonator is above the centre of the barrier and in line with the lead charge (see Figure 7 left). The shock originating from the detonator propagates through the barrier and initiates the lead charge, thus creating a large central hole in the barrier, see Figure 10 (left). In safe position the detonator is positioned eccentric on the barrier (see Figure 7 right). When the detonator functions it leaves an imprint in the top surface of the barrier. As a result of the transfer from the detonator through the barrier the lead charge reacts and the metal of the barrier directly above the lead charge is blown away. This also results in a central hole, although smaller than with the detonator in armed position. The imprint and relatively small central hole are observed in an explosive train interruption test in safe position (Figure 10 centre) where the lead charge reacted without initiating the booster. A similar imprint and small hole are also observed in the barrier of the accident mortar round (Figure 10 right).

The *presence* of an imprint *off* centre and the *absence* of a large central hole *in* the centre of the barrier, demonstrate that the fuze from the accident mortar round was in safe position at the moment of the accident.

Figure 10 Top surfaces of the barrier from the test in armed position (left), from the test in safe position (centre) and from the accident (right). The barrier from the test in armed position is broken as a result of the detonation, the barrier from the accident was recovered in one piece, but cut in half for further examination.

Additional evidence is provided by the variation in the deformation of the central hole across the thickness of the barrier. In armed position the detonator is in line with the lead charge. When both detonate the explosive force exerted on the barrier is greatest since both charges are in close proximity. Therefore, the radial deformation is larger near the top surface of the barrier than near the bottom surface, where the deformation is caused solely by the lead charge, see Figure 11 (left). This variation of radial deformation across the thickness of the barrier is not observed in the central hole of the barrier from the accident mortar round, see Figure 11 (right); this hole is clearly cylindrical, which indicates a reaction of only the lead charge. This finding also demonstrates that the fuze from the accident mortar round was in safe position at the time it was fired.

Figure 11 Top surface of the barrier from the test in armed position (left), and from the accident (right). The barrier from the test in armed position is broken as a result of the detonation, the barrier from the incident was recovered in one piece, but cut in half for further examination.

3.6 Conclusion

Based on a comparison between the remnants from the fuze tested in armed position and the remnants of the fuze from the accident mortar round, it is concluded that the fuze from the accident mortar round was in safe position at the time of the accident.

4 Alternative cause of the accident

After disassembly of twenty mortar round it is stated in [2], that "Visual inspection does not reveal noteworthy details. There was slight corrosion on the slider and the detonator in the slider of mortar round number 14" and "mortar round number 14 is eliminated [*for testing*, *ed.*] because the detonator was stuck in the slider". Figure 12 shows two optical micrographs of slider number 14 in which the signs of corrosion are visible.

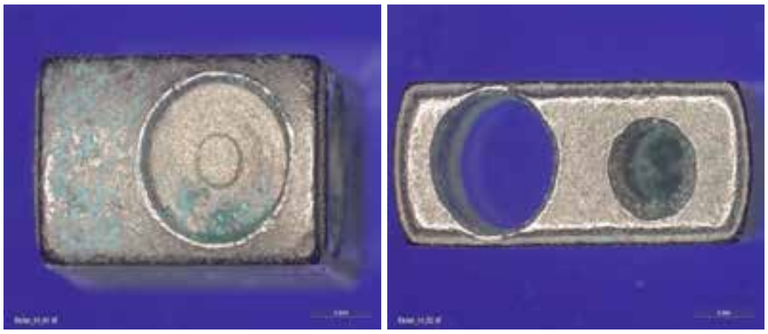

Figure 12 Optical micrographs of slider number 14. Corrosion is visible on the side wall and in the recess for the slider spring (left) and on the top, on the edge of the hole for the detonator and on the edge of the recess for the firing pin (right).

4.1 Chemical analysis

Slider number 14, along with slider numbers 11, 15 and 20 [2] has been examined with a Scanning Electron Microscope (SEM), using Energy Dispersive X-Ray Analysis (EDX).

The sliders are examined at several locations for the chemical composition of the slider body and the signs of corrosion. The slider body is made of brass with a mass ratio of 80% copper and 20% zinc. The slider is nickel-plated. It is determined that the pale green deposit is copper oxide, which is a corrosion product. Zinc oxides are also found. The element sodium is found in most of the corroded locations, often in a relatively high content[2]. The elements sulphur and lead are found to a lesser extent in the corrosion/deposit. Additional analyses of the bottom surface of the slider body (that rests on the steel barrier), show that corrosion of the nickel layer has occurred to such extent that copper from the brass alloy is exposed at the surface. Sodium is also found in this position. Most of the corrosion products are found at the edge of the hole for the detonator. For illustration purposes, Figure 13 shows an SEM photo of the edge of the firing pin recess of slider number 15. The corresponding results of the element analysis are provided in Table 1.

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[2] In an attempt to determine the origin of the sodium, a chemical element analysis has been performed on the packaging materials that are inclosed with the mortar round in the tubular transport container. The packaging materials appeared to be organic in nature and do not comprise sodium containing compounds.

The following elements are measured: carbon (C), nitrogen (N), oxygen (O) sodium (Na), sulphur (S), nickel (Ni), copper (Cu), zinc (Zn) and lead (Pb).

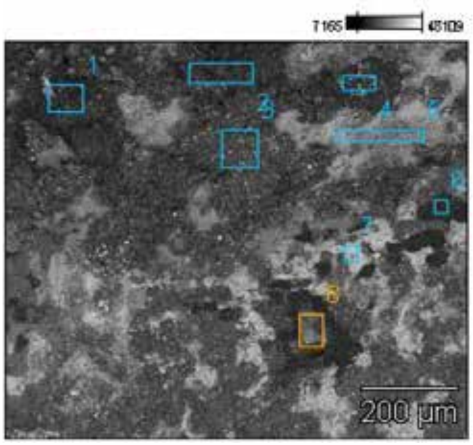

Figure 13 SEM photo with measurement areas for chemical element analysis at the edge of the firing pin recess of slider number 15.

Table 1 Chemical element analysis (in weight percentages) at the edge of the firing pin recess of slider number 15.

	C-K	N-K	O-K	Na-K	S-K	Ni-L	Cu-L	Zn-L	Pb-M
Slider 15 edge firing pin hole_pt1	14.4		44.9	31.0					9.7
Slider 15 edge firing pin hole_pt2	16.7		48.0	35.3					
Slider 15 edge firing pin hole_pt3	3.7		36.7		1.7		27.3	24.3	6.3
Slider 15 edge firing pin hole _pt4	17.7		46.6	35.7					
Slider 15 edge firing pin hole _pt5	6.4		23.9	6.8	1.1	10.1	8.5	6.9	36.2
Slider 15 edge firing pin hole _pt6	41.6	19.6	34.1	1.8			2.9		
Slider 15 edge firing pin hole _pt7	4.3		6.4			89.3			
Slider 15 edge firing pin hole _pt8	41.7	21.0	35.9	1.4					

Table 1 shows that the elements lead and nitrogen occur on the edge of the firing pin recess of slider number 15. These elements were also found on the surface of slider number 15 and on the surfaces of slider numbers 11, 14 and 20, see Table 2 [3].

Table 2 Overview of locations on slider numbers 11, 14, 15 and 20 where traces of lead and/or nitrogen were found.

Slider number	Surface	Detonator hole	Firing pin recess
11		Lead	
14	Lead and nitrogen		
15	Lead	Lead	Lead and nitrogen
20			Lead

The combination of lead and nitrogen are only present in the form of the molecules lead azide and lead styphnate (primary explosive compounds), which both reside in the duplex detonator.

The combination of lead and nitrogen is not expected to be found at the hole for the duplex detonator in the slider, on the external surface of the slider, or at the recess for securing the firing pin. Therefore it is likely that these primary explosives have migrated from the duplex detonator to the surface of the slider.

In [4] it is stated that (galvanic) corrosion may occur under the influence of moisture, which results in degradation of the detonator. In addition hydrogen azide may be produced under the influence of moisture from the hydrolysis of lead azide. The hydrogen azide may react with the copper in the Melchior cup holder of the detonator and with the copper in the brass slider and form the extremely sensitive copper azide. According to [5], a layer of copper azide of 0.40 mg/cm^2 was found to be the 'critical threshold', thicker layers will lead to detonation after initiation.

4.2 Tolerance on firing pin

During careful examination of the safety and arming mechanism, a small tolerance is found on the firing pin enabling it to move 1 or 2 millimetres between the retaining balls underneath the setback cap. See Figure 14 left; in safe position the tip of the firing pin is secured by a recess in the slider. The force from the slider spring forces the right wall of the recess against the tip of the firing pin. The firing pin is secured vertically by two retaining balls that are locked between the setback cap and the recess in the firing pin, see Figure 14 centre [6]. As shown in the image on the right in Figure 14 there is a small gap of one or two millimetres between the retaining balls and the recess in the firing pin. As a result of the pressure from the spring under the setback cap (Figure 14 centre) the firing pin is forced upwards and the retaining balls downwards; the firing pin accordingly is situated in the upper position and the two retaining balls in the lower position.

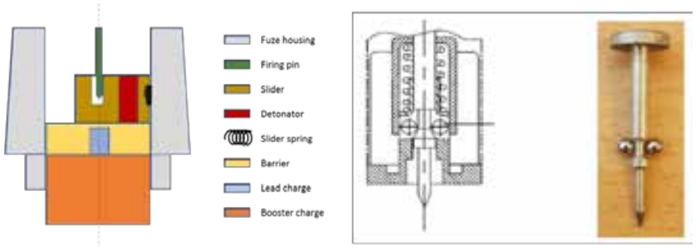

Figure 14 Cross-section of part of the M6-N fuze in safe position (left), cross-section of the part with the setback cap, spring, retaining balls and firing pin (centre) and firing pin with the retaining balls in the recess of the firing pin (right).

At the moment the mortar round is accelerated during launch, both the setback cap and the firing pin move downwards. The latter will move 1 to 2 millimetres downwards until the two retaining balls reach the top edge of the recess (as in Figure 14 on the right). During this movement the tip of the firing pin slides against the right side wall of the firing pin recess in the slider. If the extremely sensitive copper azide is present near the edge of the firing pin recess or on the wall of the firing pin recess, friction may result in its detonation. In contrast to a prematurely functioning detonator, a detonation in the firing pin recess is straight above the lead charge and thus in line with the detonation train. This can result in a propagation of reaction through the barrier with initiation of the lead charge, with subsequent detonation of the booster and main charge.

It is also possible that detonation of copper azide in the firing pin recess initiates the detonator, and that the combination of both detonations results in propagation of reaction to the lead charge.

Explosive train interruption tests with a detonator that functions prematurely did not result in detonation of the booster charge with the fuze in safe position, even at an elevated temperature. Since the main charge of the accident mortar round detonated, a transfer of detonation to the booster charge has definitely occurred in the accident. The preceding alternative cause offers an explanation for this difference.

It is also noted that the damage inflicted to the mortar in the accident and to the mortar used by the Knowledge Center for Weapons and Ammunition (KCW&M) to fire a round with an armed fuze, differ to some extent [7]. See

Figure 15; the petalled metal near the base plate of the accident launch tube are longer than those from the test by KCW&M using an armed fuze (red frame), while the muzzle end of the launch tube from the accident is shorter (blue frame). This seems to indicate a slightly higher point of detonation in the launch tube involved in the accident in comparison to the test by KCW&M. These differences can be explained by the alternative cause of the accident as described above; for the firing pin to move downwards (and for the tip to slide against the wall of the slider) a powerful acceleration over a small distance is required that is generated by the gas pressure from the burning propellant in the tail assembly of the mortar round. In contrast, an armed fuze already detonates at the moment the tail of the mortar round reaches the base plate, because the firing pin can move freely and directly initiates the detonator.

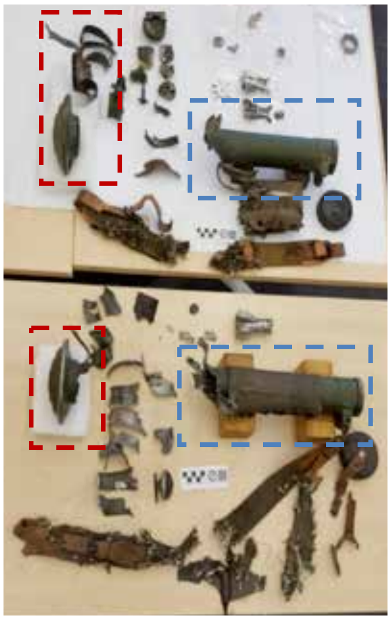

Figure 15 Damage to the mortar from the accident (top) and to the mortar after the test with the fuze in armed position by KCW&M (bottom).

4.3 Conclusion

Signs of corrosion are found on several brass sliders. There are also indications of migration of explosive compounds from the detonator to locations on the slider, including the firing pin recess that is located straight above the lead charge, in line with the detonation train. Due to the tolerance on the firing pin, the latter can initiatie copper azide potentially formed in/around the firing pin recess in the slider during launch of the mortar round. This can result in a propagation of reaction through the explosive train interrupter and premature initiation of the detonator in safe position.

5 Exudation and melting of the TNT main charge

Following a discussion with NATO MSIAC (Munition Safety Information and Analysis Center), the possibility of the occurrence of TNT exudation is further examined.

The main charge of the HE80 mortar consists of 200 grams of TNT. It is known that exudation may occur in TNT, see [4]. TNT exudation starts at temperatures around 70°C. The exact temperature at which exudation starts is an indication of the TNT quality. The presence of other compounds/impurities in TNT lowers the melting point.

5.1 Test configuration

An HE80 shell body (a mortar round without a fuze and tail assembly) is positioned at an angle above a table in a bunker. A cilindrical oven is placed around the shell body, in such a way that there is sufficient space for molten TNT to flow out of the opening into a drip tray. Figure 16 provides a schematic representation of the test configuration.

A thermocouple is inserted into the TNT against the inner wall of the casing to determine the temperature at which the TNT starts to flow. A webcam is installed near the test configuration to observe the TNT melting from outside the bunker. For safety reasons the bunker is closed during the experiment and can only be entered after extensive ventilation.

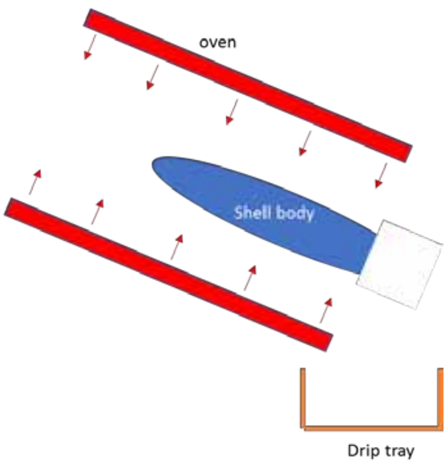

Figure 16 TNT leak test configuration.

A photograph of the test configuration is provided in Figure 17.

Figure 17 Photograph of the TNT leak test configuration.

5.2 Result

It is established using a thermocouple that exudation of the TNT starts at 74 °C. At 79 °C the TNT liquefies and flows out of the casing. It is concluded that the TNT in these mortar rounds is of good quality, with reference to the 80.8 °C melting point of pure TNT.

5.3 Conclusion

The calculations in [4] ascertain that the 60 mm mortar rounds stored in the sea container in Kidal, probably reached temperatures in excess of 60 °C on more than on occasion. It has been calculated that the steel casing and the TNT main charge can reach a temperature of 80°C due to exposure to direct sunlight when outside the storage container or in use. Since the mortar rounds were loaded with bare hands at the time of the accident it is unlikely that the mortar rounds actually reached this temperature during the exercise in Mali. Since the exact temperatures during storage or use are unknown, it is impossible to determine whether exudation and/or melting may have occurred in Kidal.

6 TNT exudation test

In [4] it is stated that it is unlikely that the mortar rounds have reached a temperature prior to launch, at which TNT start to exude. It is also stated that in case TNT exudate has formed, its combustion during launch is unlikely to result in detonation of the main charge. A TNT exudation test is performed to verify the second claim.

6.1 Test approach

An exudation test is performed to verify whether combustion of the exudate on the outside of the casing or between the screw thread of the fuze and the mortar shell body can result in the detonation of the main charge. TNT exudation is realised by heating an HE80 mortar round (excluding tail assembly) in an oven. The round is fitted with an aluminium dummy (inert) fuze without the application of a sealant or loctite on the screw thread, see Figure 18.

Figure 18 HE80 shell body with an aluminium dummy fuze.

The temperature of the casing turned out to be difficult to control due to heat loss at the front and rear of the oven (configuration is similar to the one in Figure 16). Several heating cycles were necessary to obtain visible exudation, see Table 3.

Table 3 HE80 shell body heating tests.

Test No.	Oven temperature [°C]	Casing temperature [°C]	Heating time [hours]	Exudate visible [N/Y]
1	70	55	3	N
2	90	70	7	N
3	100	76	7	N
4	120	90	5	Y

Exudate is not observed on the exterior of the shell body up to a casing temperature of 76 °C. The exact temperature at which the exudate is formed is unknown but higher than 76 °C.
Figure 19 shows the HE80 mortar round. Exudate is visible in the form of re-crystallised TNT on, and several centimetres next to, the grooves on the exterior of the casing, with fine white crystals on both sides of the TNT. A thin line from the interface between the fuze and the shell body marks the path along which the molten TNT has flown (at the bottom side of the round during heating).

Figure 19 HE80 shell body with dummy fuze with TNT exudate.

The shell body with exudate was subsequently placed in a tray and covered with a thermite basedon a titanium/carbon powder (in a 4/1 ratio) composition, see Figure 20. The thermite is ignited in a bunker with a pyrotechnic fuse. The burning process is monitored using a real-time video link.

Figure 20 Shell body with exudate, covered with a thermite charge.

Figure 21 shows snapshots of a recording that is made of the burning process.

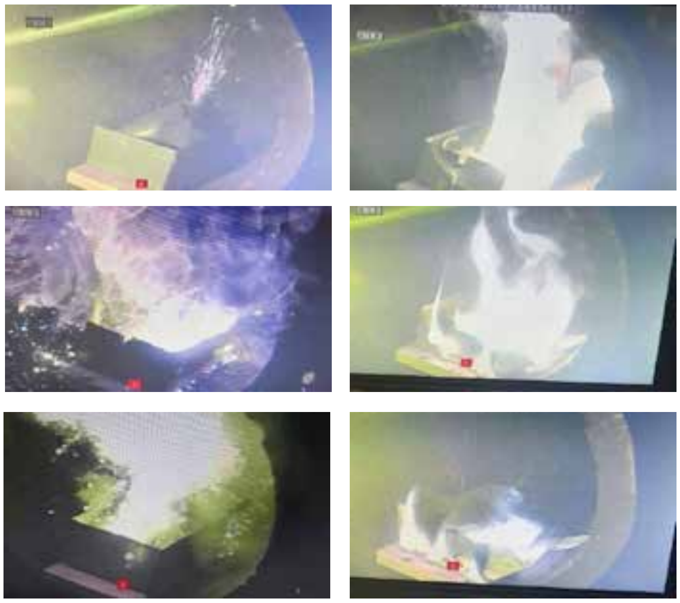

Figure 21 HE80 shell body with exudate in a burning thermite charge. From top to bottom: the left column shows the ignition and burning of the thermite charge; the right column shows the burning and dying of the thermite charge.

6.2 Result

No deflagration or detonation of the TNT main charge has occurred during the burning of the thermite charge for approximately one minute. The dummy fuze is removed from the shell body after the test. See Figure 22 ; an estimated 20% of the TNT main charge has flown out via the fuze screw thread during the exudation test. The colour of the TNT at the top of the main charge has changed from yellow/orange (prior to the test) to brown (after the test). Re-crystallised TNT is found on the screw thread and the bottom surface of the aluminium dummy fuze.

Figure 22 20% of the TNT main charge has flown out via the screw thread on the fuze (left); re-crystallised TNT on the bottom surface and the screw thread of the aluminium dummy fuze (right).

6.3 Conclusion

The exudation test demonstrates that it is highly unlikely that TNT exudation has resulted in the detonation of the main charge.

7 Deflagration to Detonation Transition (DDT)

In [7], it is concluded that the main charge of the mortar round detonated. This paragraph focuses on the question whether it is possible that instead of an accidental 'Detonation' a 'Deflagration to Detonation Transition (DDT)' of the main charge could have occurred. When a DDT occurs the explosive compound behaves differently than in a (full) detonation. In case of a detonation, the entire explosive charge detonates instantaneously, resulting in the fragmentation of the steel casing into a large amount of small fragments. In case of a DDT, the explosive charge inititally combusts rapidly (deflagration) which subsequent transition into a detonation. The confinement of the explosive charge (such as in the casing of the mortar round) plays a major role in whether and how a DDT will develop. In case of a DDT, relatively large fragments will be recovered from the part of the casing where the main charge deflagrated in addition to small fragments from the part of the casing where the main charge detonated.

7.1 Results

If exudate is present, e.g. on the exterior of the round, it could ignite as a result of the combustion of the propellant charge. Figure 23 [8] shows that flames and hot gases from the propellant charge move past the round during firing and extend from the muzzle, even before the mortar round leaves the launch tube. In case exudate is also present on the fuze's screw thread, this flame could conceivably reach the main charge[3]. If the TNT main charge subsequently ignites, this may develop from a Deflagration into a Detonation due to the full confinement of the main charge inside its metal casing.

Figure 23 Flames and hot gases move ahead of the mortar round (photo left) and extend trom the muzzle, before the round leaves the launch tube (photo right) [8].

KCW&M has examined the possibility of a DDT. Instead of igniting the main charge via exudate, two tests were performed with a drilled hole in the casing of the main charge (of 2 and 5 mm respectively, see Figure 24 [2]). Flames and combustion gases from the propellant charge can reach the TNT main charge via this hole.

High speed video footage of the experiment with the 2 mm hole reveals that the mortar round exits the launch tube in the normal way, and upon impact of the mortar round in the field a detonation is observed. The two millimetre hole therefore has no effect on the functioning of the mortar round.

[3] It should be noted that this route is considered unlikely because the fuze is screwed onto the shell body with a sealant or a form of Loctite.

On recordings of the experiment with the casing with a 5 mm hole, a deflagration of the mortar round in the launch tube is observed, see Figure 25. The launch tube sustains severe damage; the sight unit is dislodged during launch as the tube bulges due to the high internal gas pressure. The mortar round does not fragment, probably because the accumulating gases in the shell body escape through the 5 mm hole and insufficient pressure builds up for a transition into a detonation. Fragmentation does not occur because the mortar round does not detonate.

These tests illustrate that, in the case of the 5 mm hole, the TNT has ignited prematurely, but no DDT of the main charge has occurred.

Figure 24 Drilled holes of 2 mm (left) and 5 mm diameter (right) in casing [2].

Figure 25 Deflagration during launch of the mortar round with the 5 mm hole in the casing [2].

7.2 Conclusion

The severely damaged mortar and fragmentation of the mortar round into small fragments, indicate that a DDT is unlikely to have occurred in the accident in Mali[4].

[4] Besides the fact that the fuze is firmly connected to the shell body (probably using Loctite or a similar screw thread sealant), which makes potential exudation via the screw thread unlikely.

8 Degradation/corrosion in the M6-N fuze

The M6-N fuze used for the explosive train interruption test at 70°C has been disassembled at TNO. It is removed remotely from its shell body using special tooling, after which the fuze itself is disassembled for further examination.

8.1 Visual inspection of the fuze

After removal of the booster and a cardboard disk, a brown/orange coloured substance was found on the bottom surface of the barrier. This was also obeserved on the top surface of the cardboard disk, see Figure 26. The rubber O-rings that are reside in the fuze also display this discolouration. Figure 26 at the right, shows the bottom surface of the barrier with the brown/orange deposit, also around the lower end of the explosive lead charge.

Figure 26 Discolouration of the O-rings and cardboard disk (left) and deposit on the bottom surface of the barrier (right) in the M6-N fuze used in the 70°C explosive train interruption test.

8.2 SEM analysis

An analysis using a Scanning Electron Microscope (SEM) and Energy Dispersive X-Ray (EDX) shows that the deposit is on the surface of the barrier. At various locations it has spread out, but also individual, and 'dried-up' particles are found. Element analysis of the deposit reveals the presence of carbon (C) and oxygen (O). This indicates that the deposit is certainly not a corrosion product (rust), but is an organic material. Traces of zinc (Zn) and iron (Fe), originating from the steel barrier with a zinc coating, are also found. No elements (such as nitrogen (N)) from an explosive compound are found.

The potential source of the deposit is the wax (paraffin) from the booster[5]. The wax probably migrates through the cardboard to the surface of the barrier.

Further disassembly of the fuze revealed a green deposit on the brass slider, as was found on some of the sliders used in the tests in [1]. Brass contains copper and the green deposit is certainly copper oxide, see also [3]. A leak test performed on the fuze shows that it is waterproof.

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[5] This is a composition of crystalline alkanes with 16 to 57 carbon atoms and linear chains [9]. A typical component of paraffin is $C_{31}H_{64}$ [10].

8.3 Conclusion

Upon the dissambly of a waterproof fuze, signs of degradation are observed on the slider (copper oxide) and beneath the barrier (probably wax that migrated from the booster).

9 Mortar round temperature measurements

In June 2017, two temperature measurements have been carried out with a HE80 mortar round in its original wooden ammunition box at the TNO site in Rijswijk. Table 4 provides details of the temperature measurements and the components of the HE80 mortar round.

Table 4 Details of the temperature measurements and conditions of the mortar round.

Time	Weather conditions	Ambient temperature [°C]	Components of the HE80 mortar round
Monday 19 June, between 12:00 and 14:00	Sunny, no clouds and nearly windless	29 – 30	Without fuze, empty casing (i.e. without TNT charge), without tail assembly
Thursday 22 June, between 13:15 and 14:15	Sunny, moderate winds with cirrus clouds	28	With inert fuze, with TNT charge, with tail assembly

During the measurements the effect is determined of a combination of the ambient air temperature and direct sunlight on the steel casing and aluminium fuze body.

9.1 Test set up

Temperature measurements are conducted using thermocouples. The correct temperature reading of the thermocouples is verified using a hand-held infrared thermometer. For the first measurement, on Monday 19 June 2017, thermocouples are attached to the inside and outside of the empty steel casing. For the second measurement, on Thursday 22 June, the thermocouples are attached to the casing and an inert original M6-N aluminium fuze, see Figure 27.

Figure 27 Temperature measurement on the inside and outside of the empty steel casing (left) and on the TNT-filled casing and the inert fuze of the HE80 mortar round (right).

9.2 Result

At an ambient air temperature of 29 to 30 °C, the steel casing of an empty HE80 shell body heats up in approximately 15 to 20 minutes to a maximum of 59 to 60 °C as a result of direct sunlight at 'Dutch intensity levels', not shielded by cloud clover. The temperatures on the inside and outside of the casing are nearly identical.

At an ambient temperature of 28°C, the steel casing of a TNT-filled HE80 mortar round heats up in approximately 60 minutes to a maximum of about 42°C as a result of solar radiation at 'Dutch intensity levels' impeded by by cirrus clouds. It is determined that under these conditions, the temperature of the aluminium M6-N fuze leads with roughly 5 °C relative to the steel casing, and reaches a temperature of circa 47 °C after 60 minutes.

It is observed during the measurements that the casing and fuze temperatures drop by several degrees due to wind and/or increase in cloud cover.

9.3 Conclusion

As a result of direct sunlight the steel casing of the HE80 mortar round heats up in a short period of time. This also applies to the aluminium fuze, which is several degrees ahead of the casing. These findings are consistent with the information in [4]. The ambient temperature in Mali at the time of the accident is about 10°C higher than during the measurements in Rijswijk. The intensity of solar radiation is also higher. It is concluded that the temperatures calculated in [4] of the HE80 casing and the aluminium M6-N fuze resulting from ambient temperature and solar radiation are realistic.

10 Hazard classification

In 2012, TNO performed a research project regarding protective measures for preventing the transfer of an accidental detonation of one munition article to adjacent articles (sympathetic detonation) [11].

10.1 Sympathetic detonation tests

A 1.1F Hazard Classification (HC) has been issued by the manufacturer Arsenal2000JSCo for the HE80 mortar round with the M6-N fuze. This classification is relevant for storage and transport in the accompanying wooden ammunition box. The designation 1.1 means that the item holds a mass detonation hazard. The designation F means that a secondary detonating explosive compound is present with its own means of initiation.

When conducting the study into the occurrence of sympathetic detonation for the HE80 mortar round, different positions and orientations of the rounds relative to each other have been tested; the main charge of one round (donor) is aligned with the booster and with the main charge of the adjacent round (acceptor) (see Figure 28). This study concluded for both test configurations that detonation of an HE80 mortar round did not result in a sympathetic detonation.

These results indicate that the HE80 TNT main charge is insensitive and cannot easily be set off. Even the effects of the shock and fragmentation originating from an adjacent and detonating HE80 round does not result in a reaction of the main charge. It is noted that Great Britain, the United States and Canada use the 60 mm mortar round with an HC of 1.2E. The designation 1.2 means that fragment projection occurs without mass detonation. The designation E means that there is a secondary detonating explosive present which does not have its own means of initiation. Since no sympathetic detonation occurs, this seems to be a more reasonable classification.

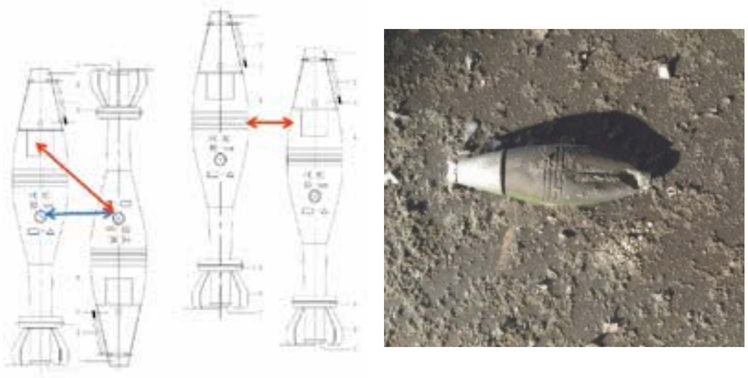

Figure 28 Experiments with the HE80 mortar round: main charges aligned and main charge aligned with the booster (left). An adjacent HE80 round is severly deformed but a sympathetic detonation does not occur (right) [11].

10.2 Conclusion

The TNT main charge of an HE80 mortar round is insensitive because it is not easily set off by an external stimulus. The 1.1F classification for mass detonation appears to be unjustified.

11 Literature study

The types of copper azide, conditions for copper azide formation and accidents caused by copper azide, are described in literature, see [12]. Relevant sections from [12] are reproduced below.

11.1 Types of copper azides, colour and detection

Figure 29 presents the types of copper azide, corresponding colour and a detection technique to demonstrate the presence of copper azide in corrosion products.

The lead azide-copper reaction has been known since 1913 (1). Lead azide will react with moisture to produce hydrazoic acid (HN_3). This volatile acid (b.p. 35°C) (2) attacks copper and copper-containing metals with the formation of sensitive explosive products on the metal surface. While attack is usually concentrated in the vicinity of the source of lead azide, diffusion of the vapor can occur and result in the formation of the corrosion products at some distance from the lead azide container.

The chemistry involved in the corrosion process is set forth in the equations of 1. Hydrazoic acid is formed by the action of moisture on the lead azide. The hydrazoic acid attacks copper to give cuprous azide, CuN_3, which appears as a white film (3). Early literature reported the conversion of CuN_3 to normal cupric azide, $Cu(N_3)_2$, but recent work has proven that the cuprous azide is oxidized to monobasic cupric azide $Cu(N_3)_2.Cu(OH)_2$, a yellow-brown compound. X-ray diffraction study of corrosion layers on copper and brass has revealed cuprous azide located as the layer nearest the metal surface, with an outer coating of basic cupric azide (3). Further corrosion products, depending on the construction of the system, are the di-, tri-, or octa-basic cupric azides, yellow-green to green to blue-green in color (Figure 2). The presence of light accelerates the transformation of cuprous azide to the various cupric forms. After a period of time in ventilated containers the corrosion products observed are the di- or tri-basic cupric azides. Thus the tendency is for the very sensitive forms to be oxidized to insensitive varieties. All phases must, however, be presumed to exist together so that their varying degrees of sensitiveness must be considered.

A simple test to confirm the presence of copper azide is to apply one drop of aqueous ferric chloride solution which develops into an intense red coloration if copper azide is present in the corrosion.

Figure 29 Types of copper azide, corresponding colour and a detection technique [12].

11.2 Conditions for the formation of copper azide and sensitivity

Figure 30 and Figure 31 respectively present the conditions for the formation of copper azide and its sensitivity.

Moisture for the hydrolysis of lead azide can come from inefficient drying of the lead azide itself, from the air, from direct exposure to water or water vapor, and from other fillings in the same weapon. Due to temperature changes, a fuze can "breathe" permitting ingress of moist air. There is also frequently sufficient moisture available from the H.E. fillings of conventional ammunition. Sometimes moisture can come from packing materials. The formation of copper azide is favored by high humidity. Temperature has less effect per se. At relative humidities higher than 90%, corrosion is quite rapid; at less than 80% RH the rate of corrosion is very slow. A bare copper strip will be corroded in 24 to 48 hours when hung above wet lead azide in a sealed beaker. When the strips are exposed to open flames, audible "pops" are heard. The rate of hydrolysis of lead azide is increased by traces of acidity. It has been shown that under adverse conditions of storage (120°F with added water), lead styphnate will increase the level of acidity and greatly accelerate the rate of hydrolysis of lead azide. Lead styphnate is commonly used with lead azide in priming mixtures and as an ignition charge in detonators.

Figure 30 Conditions for the formation of copper azide.

Studies have shown that the sensitiveness to impact and friction of copper azide deposits varies greatly. Lamnevik's (3) Impact and Friction data (Figure 3) indicate that cuprous azide is at least twice as sensitive as lead azide to both impact and friction. Monobasic cupric azide is twice as sensitive to impact but less sensitive to friction than is lead azide (3). The dibasic variety of cupric azide is however, less sensitive than lead azide to both impact and friction. Propagation from local ignition is more likely to occur during the initial stages of the corrosion cycle when cuprous and the monobasic cupric azide are present. Cuprous and monobasic cupric azide propagate in layers as thin as 0.85 mg/(cm^2) (4). Copper azides are very sensitive to electrostatic discharge. A piece of foil corroded with copper azide has been fired consistently from a 60 volt -20 erg discharge and occasionally at energies as low as 1 erg. Various "dropping" and "slamming" tests have demonstrated the increase in sensitiveness of samples corroded with copper azide over those covered with lead azide crystals.

Figure 31 The sensitivity of copper azide.

11.3 Accidents caused by copper azide

Appendix A reproduces a number of incidents and accidents from [12] caused by copper azide, followed by a discussion, conclusions and recommendations.
Figure 32 presents two of these accidents that are relevant to the mortar round accident in Mali:

1. With respect to the three inch fuze (used in English ammunition) it is stated that a well-designed slider can prevent premature detonation of the main charge in case the detonator functions prematurely in safe position. However, tests have shown that *if premature firing occurs during the arming cycle, the warhead may be detonated*;
2. With respect to the M52A1B1 impact fuze (used in American 81 mm mortar rounds), it is stated that the effect of high temperatures and moisture on the lead azide inside the M18 detonator can lead to the formation of hydrogen azide resulting in the formation of copper azide on the brass slider. *Tests revealed the feasibility of the copper azide formed on the slider being initiated by friction encountered in the arming cycle*.

3-Inch Fuze. Copper azide was found in 1959 in inservice 3-inch fuzes manufactured in 1952 and 1954. The fuze has an out-of-line mechanism. It contains an upper lead azide-filled detonator, a delay pellet, and a lower lead azide-filled detonator. Both detonators are in copper containers. These fuzes were involved in premature bursts. The rounds involved had been stored at Hong Kong. The investigation was started by breaking down 500 fuzes available in the United Kingdom and 1000 fuzes stored and present in Hong Kong. The Hong Kong investigation was started in April 1959. Copper azide was identified in 40% of the fuzes examined in Hong Kong and corrosion was found in all but 65 rounds.* Examination of firing records of rounds stored at Hong Kong revealed that between 1 January 1959 and April 1959, 7100 rounds were fired; six premature and 265 duds were noted. Copper azide was found in 32% of the 500 fuzes examined in the United Kingdom. Therefore, an experiment was arranged with 200 fuzes known to be from groups contaminated with copper azide.** The fuzes were modified, by removing the firing pins and all explosive components except the detonators and delay charge, and then were fired over water for recovery. Sixty-four fuzes were found with both detonators fired and the delay charge burned. An additional 40 were found with evidence of partial burning. Approximately 1100 other tests for possible causes of prematures other than copper azide were performed all with negative results. It was concluded by the British Ordnance Board that "there is no doubt that copper azide corrosion of the detonator can be held responsible for the prematures and blinds.*** The results of these field type firing tests taken together with the results of the laboratory tests with the 40-mm fuze as cited above, indicate that a well-designed shutter can eliminate prematures of warheads if the fuze detonator should fire prematurely in the out-of-line condition. The tests also show, however, that if premature firing occurs during the arming cycle, the warhead may be detonated.

* This corrosion was not necessarily copper azide.
** From data presented above, one would presume that copper azide corrosion was present in 30 - 40% of the fuzes tested.
***Blinds in British terminology is equivalent to duds in U.S. usage.

M52A1B1 Mortar Fuze. The M52A1B1 Mortar Fuze, used in 81-mm ammunition, was involved in a premature explosion in 195[illegible] (8). Two marines were killed in a training mission when a round exploded 25 feet from the mortar. No precise cause was found by the board of inquiry. However, subsequent laboratory tests revealed that the effects of high temperature and humidity on lead azide of the M18 detonator and the M52 fuze could cause formation of hydrazoic acid and result in copper azide formation on the brass fuze slider. The M18 detonator consists of lead azide priming mix, lead azide, and tetryl in an aluminum cup. The laboratory tests (9) revealed the feasibility of the copper azide formed on the slider being initiated by friction encountered in the arming cycle.

Figure 32 Relevant accidents from [12].

11.4 Conclusion

From literature it is concluded that a combination of lead azide and metal parts containing copper can result in a sensitive form of copper azide when exposed to moisture and elevated temperatures. Investigation into accidents caused by copper azide reveal that copper azide can:

- occur on a brass slider;
- initiate as a result of friction during the arming cycle of the fuze;
- lead to detonation of the main charge.

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13 Signature

Rijswijk, 12 September 2017

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A Incidents and accidents caused by copper azide

A number of incidents and accidents caused by copper azide are presented in [12], followed by a discussion, conclusions and recommendations. These are reproduced below.

A. U.K. Ordnance

British 20-mm Ammunition. The United Kingdom has had a number of incidents involving copper azide corrosion in 20-mm ammunition. Their troubles became apparent after WWII when ammunition was returned from storage overseas and later after storage in their country. The fuze involved in the British incidents was their fuze No. 254. The U.S. Mk 26 Mod 0 fuze was copied from it in WWII and is virtually identical. Fuze Mk 26 Mod 0 is shown in Figure 4. It can be seen from the figure that this fuze has no detonator safety. The sensitive primary explosive is not shuttered from the insensitive tetryl in the magazine. Thus the fuze is armed at all times, and, without benefit of a firing pin, detonates when target impact fires the detonator. The British fuze is constructed entirely of brass. The nose is closed with a brass disc, and the detonator cup is also made of brass. The fuze and detonator are unsealed and the detonator contains lead azide. The fuze contained in a 65-lb block can be dropped 30 feet without firing the detonator.

(a) ROF Swynnerton, 21 January 1948. Two men were killed from an explosion during the breakdown of 20-mm High Explosive Incendiary ammunition containing Fuze No. 254 (5). The "service operator" placed filled boxes, containing about 60 rounds each, on their sides on a felt covered table. The rounds were then spread over the felt to enable the operator feeding the breakdown machine to easily pick them up. After the machine separated the shell from the cartridge, the propellant powder was poured out of the cartridge into a hopper. Investigation of the accident revealed that a hole had been blown in the table top. This indicated that the explosion had occurred on or close to the table. Medical evidence revealed that the "feeding operator" had his arms outstretched and had half turned facing the service table. Involved in the accident was approximately two pounds of propellant in the propellant hopper and seven rounds of ammunition. Investigation showed that other rounds from the lots being broken down were badly corroded and that the cases containing the ammunition had been wet. The British concluded that the accident was caused by the presence of sensitive copper azide which fired when the "feeding operator" was in the act of feeding the breakdown machine. He had probably dropped a round only a few inches onto the felt covered table top. No attempt to actually identify the presence of copper azide in the corroded rounds was made. However, it is obvious from the fuze construction, i.e., the lack of a firing pin and no normally moveable parts, and from the normal insensitivity to impact of the round that something had occurred to make the round supersensitive. The most logical explanation would be the formation of copper azide known to be easily capable of being formed in this ammunition.

(b) ROF Swynnerton, 4 May 1949. Four men were killed when a box of 20-mm HE Ammunition exploded while being loaded from a conveyor into a railway truck (6). The loading of the boxes, was carried out by six men. Two men lifted the box and placed it cornerwise on the conveyor. Two other men, one on either side of the conveyor, pushed the box up the inclined portion of the conveyor. Here it was held until the third pair of men lifted the box from the end of the conveyor and stacked it in the railway car. If the box was not immediately grasped by the last two men, one corner of the box could tilt over the edge of the conveyor and strike the bottom of the car or the top of the stack -- a maximum fall of six inches. Examination of the evidence showed that the box involved in the accident was at the top of the conveyor when the explosion occurred. The medical evidence showed that the middle two men still had their hands and arms close to the box. The last two men had not yet grasped the box and had their backs turned to it. The number of rounds exploding was less than the amount in a single box. It was probable that corroded rounds were present in the box which exploded. Other rounds being loaded were found in a corroded condition. The conclusion of the investigators of the accident was that the mishap was caused by one corner of the box of ammunition tilting over onto the floor of the van. This caused a detonator, over-sensitive because of copper azide corrosion, to fire. The detonation of one round then lead to the detonation of other rounds. No attempt was made to identify copper azide in the remaining rounds.

(c) ROF Swynnerton, 30 June 1952. A pile of 20-mm ammunition awaiting disposal exploded spontaneously. The ammunition was in extremely bad condition and many of the shells were heavily rusted. The most likely cause was attributed to the ignition of copper azide corrosion and the resultant firing of the detonator. The cause of the ignition was believed to be the high temperature of the day (7), which could have caused relative motion of parts by differential thermal expansion.

40-mm Ammunition at ROF Pembrey and Irvine. No accident occurred with this ammunition. However, copper azide corrosion was found and identified in the fuze. The fuze consists of the detonator, a lead azide filling separated by a shutter from a lead of tetryl in brass. Investigations revealed that the risk of ignition by copper azide of the tetryl lead was remote (20). This was demonstrated by exposing shutter assemblies to hydrazoic acid. When the copper azide formed was ignited, it did not initiate the tetryl filling on the warhead side of the shutter.

3-Inch Fuze. Copper azide was found in 1959 in inservice 3-inch fuzes manufactured in 1952 and 1954. The fuze has an out-of-line mechanism. It contains an upper lead azide-filled detonator, a delay pellet, and a lower lead azide-filled detonator. Both detonators are in copper containers. These fuzes were involved in premature bursts. The rounds involved had been stored at Hong Kong. The investigation was started by breaking down 500 fuzes available in the United Kingdom and 1000 fuzes stored and present in Hong Kong. The Hong Kong investigation was started in April 1959. Copper azide was identified in 40% of the fuzes examined in Hong Kong and corrosion was found in all but 65 rounds.* Examination of firing records of rounds stored at Hong Kong revealed that between 1 January 1959 and April 1959, 7100 rounds were fired; six premature and 265 duds were noted. Copper azide was found in 32% of the 500 fuzes examined in the United Kingdom. Therefore, an experiment was arranged with 200 fuzes known to be from groups contaminated with copper azide.** The fuzes were modified, by removing the firing pins and all explosive components except the detonators and delay charge, and then were fired over water for recovery. Sixty-four fuzes were found with both detonators fired and the delay charge burned. An additional 40 were found with evidence of partial burning. Approximately 1100 other tests for possible causes of prematures other than copper azide were performed all with negative results. It was concluded by the British Ordnance Board that "there is no doubt that copper azide corrosion of the detonator can be held responsible for the prematures and blinds.*** The results of these field type firing tests taken together with the results of the laboratory tests with the 40-mm fuze as cited above, indicate that a well-designed shutter can eliminate prematures of warheads if the fuze detonator should fire prematurely in the out-of-line condition. The tests also show, however, that if premature firing occurs during the arming cycle, the warhead may be detonated.

* This corrosion was not necessarily copper azide.
** From data presented above, one would presume that copper azide corrosion was present in 30 - 40% of the fuzes tested.
***Blinds in British terminology is equivalent to duds in U.S. usage.

B. U. S. Ordnance

Mk 77 Mod 2 Fire Bomb. Between 27 June and 15 September 1966, there occurred at least four explosive incidents involving the use of the M157 fuze and M15 igniter. These items are components of the Fire Bomb Mk 77 Mod 2. The M157 fuze (Figure 5) contains the M26 Stab Primer which has lead azide in a gilding metal cup. This primer initiates a black powder booster charge. A burster containing lead azide and tetryl is in the M15 igniter (see Figure 6). Loud noises, flashes, and arcs occurred when the igniter and fuze were being assembled to the bomb. The explosive devices of the fuze and igniter were still intact afterwards. Copper azide was found and positively identified on the primers but this did not satisfactorily explain the incidents nor why the explosive devices had not fired. On 29 September 1966, after some fire bombs had been assembled, a marine was picking up the expended arming wires and brass Fahnestock clips, which are part of the fuze, when one clip exploded in his hand and flew about 50 feet. Investigation revealed the presence of copper azide corrosion on the clips. (See Figure 7.) The copper azide resulted from the attack of the hydrazoic acid vapor generated from lead azide in the burster. It was concluded and verified experimentally that the "cracking and flashing" of the clips resulted from static or RF initiation of the copper azide.

M52A1B1 Mortar Fuze. The M52A1B1 Mortar Fuze, used in 81-mm ammunition, was involved in a premature explosion in 195[illegible] (8). Two marines were killed in a training mission when a round exploded 25 feet from the mortar. No precise cause was found by the board of inquiry. However, subsequent laboratory tests revealed that the effects of high temperature and humidity on lead azide of the M18 detonator and the M52 fuze could cause formation of hydrazoic acid and result in copper azide formation on the brass fuze slider. The M18 detonator consists of lead azide priming mix, lead azide, and tetryl in an aluminum cup. The laboratory tests (9) revealed the feasibility of the copper azide formed on the slider being initiated by friction encountered in the arming cycle.

20-mm - NAD McAlester, 25 January 1971. Three men were killed during the demilitarization process of 20-mm AA projectiles Mk 3 fuzed with the fuzes Mk 26 Mods 0, 1, and 2. (See Figure 4.) The fuze Mk 26, as already noted, was adopted from the British fuze No. 254 and thus is very similar to it. A significant exception is that the detonator containers are nickel-plated brass* in the Mod 0 version, and aluminum in the Mods 1 and 2. As in the 254 fuze, the detonators themselves are not hermetrically sealed. The United States 20-mm round is manufactured to withstand a 40-foot drop. The demilitarization process normally involved six men. At the time of the explosion only three men were operating the equipment. One operator was taking projectiles from an open box and placing them on a belt feed conveyer which took the projectiles to the furnace. The projectiles had been previously separated from the cartridge cases and were repacked in metal boxes. Each box normally contained 680 rounds. The most probable cause of the explosion was a projectile, over sensitive with copper azide corrosion, firing when it was accidentally dropped. The exploding projectile set off adjacent boxes on the roller conveyor and then a pallet load of ten boxes (10). Copper azide was formed during storage of the unsealed projectiles in a humid atmosphere.

M404A2 Fuze - NAD Hawthorne, 25 May 1971. Three persons were killed on the renovation line of a 3.5-inch bazooka round, the fuze of which has an in-line explosive train (11). In the fuze, lead azide is in a copper cup with a copper disc seal and a brass triangle with a copper strip and firing pin immediately above. (See Figure 6, The most likely cause of the explosion was determined to be a reworked and improperly assembled rocket that fired when it was carelessly allowed to drop and impact against the bottom plug of the container into which it was being placed. Copper azide was only remotely suspected. Investigations revealed the presence on the copper parts of a blue discoloration which was believed to be the copper salt of a fatty acid (12).

IV. Discussion of Accidents and Incidents

Copper azides situated on moving parts can be initiated by friction. If present on exposed surfaces they can be initiated by static electricity as well. In weapons with in-line explosive trains this can cause catastrophic accidents during the handling process, or be a cause of premature detonations upon firing, for instance, within a gun barrel. A review of the accidents cited above reveals that fatalities

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* Very early models used brass detonator cups that were not plated. Some fuzes containing such detonator cups may still have been in the rounds for demilitarizing.

have occurred only in weapons incorporating uninterrupted explosive trains.* It is likely, in these accidents, that copper azide initiated the sensitive detonator and the complete explosive train, including the main charge filling, then functioned as it was designed to do. Fuzes designed according to accepted safety principles, such as those of MIL-STD 1316, preclude in-line explosive trains. New in-line fuzes should not get into military systems. It would seem wise to get rid of all in-line fuzing systems now used by the services. Due caution should be used in any demilitarization program involving uninterrupted fuze trains.

The assessment of the effects of the corrosion on safety and proper functioning of explosive trains with interrupted systems is more complex. Since hydrazoic acid can be a gas under military storage conditions any copper-bearing material in a fuze in which hydrazoic acid is formed may be subject to attack; this attack is not limited to materials directly in contact with the lead azide. In fact, there have been incidents where corrosion has been found on shutters of fuzes. That this corrosion can be ignited during the arming cycle has been demonstrated. Firing of copper azide in well-designed, shuttered fuzes is not likely to lead to serious accidents from main charge firings but will lead to duds.** However, if the azide corrosion is ignited late in the arming cycle of the fuze, prematures could conceivably occur before safe separation*** and cause serious and even fatal accidents. The accident reported in reference (8) is a possible example.

Available evidence shows that copper azide corrosion does occur and that the most sensitive of the corrosion products occur early in the corrosion process. Later these are transformed to more insensitive compounds. The rate of formation and transformation will vary from item to item depending on the individual item's temperature and internal humidity. These facts may account for the difficulty often experienced in proving that items from the same lots involved in accidents show no evidence of supersensitivity.

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* The accident with the mortar fuze M51A1B1 might well be an exception to this but cannot be proved. It seems only fortuitous that the British did not have fatalities with the three-inch fuze involved in so many prematures, including muzzle bursts.

** In a well-designed fuze, safe separation between weapon and launcher occurs before the fuze explosive train can communicate detonation to the warhead.

*** i.e. with improper fuze design.

The use of lead azide in primers and detonators became wide-spread a few years after World War II. The incompatibility of lead azide with copper (and many other metals) was known at the time that it was first put into Navy systems. Thus, the Navy loaded lead azide only in cups of aluminum or stainless steel. These are metals with which lead azide is compatible. However, early designers of detonators and fuzes containing lead azide did not appreciate the fact that one product of lead azide hydrolysis, namely hydrazoic acid, was gaseous well below normal storage temperatures. Because of this we find examples of detonators containing lead azide loaded in compatible cups but then inserted into unsealed systems containing copper, brass, and other high copper content metals. Such systems are potentially subject to copper azide formation because the gaseous hydrazoic acid can diffuse from the site of its formation and attack the copper.

When the gaseous nature of hydrazoic acid was understood Navy in-house designs of azide-containing explosive trains were accomplished, for the most part, without the use of copper or copper alloys. There are some recent designs of hermetically sealed Navy primers and detonators containing lead azide that have azide-compatible tin or silver plated copper containers. The plating and the solder seals are believed to be effective methods of avoiding copper azide corrosion.

Lead azide is the best initiating military explosive available. It has exceptional thermal stability, extremely rapid build up to detonation, high density, good flow properties, good priming ability, reasonable compatibility with other explosives and priming mixture ingredients, and is inexpensive and readily available. There is no suitable replacement material for it at present. That is why it is so widely used. The incompatibility problems with lead azide can be overcome by using only those construction materials with which it is compatible and/or by sealing it hermetically in its container so that moisture does not reach it and hydrazoic acid is not formed. The Navy is supporting effort on the hermetic sealing of nonelectric detonators by ultrasonic welding. Electric items are already being hermetically sealed by soldering and welding. These are effective techniques and are proving highly worthwhile. It is expected that the Navy will shortly issue an instruction prohibiting the use of lead azide in situations where copper azide could form unless the lead azide is hermetically sealed in its container. It is understood that the Army has recently prohibited the use of copper and copper alloys in fuzes containing lead azide.

Other methods for preventing copper azide corosion products have been investigated. Thesa include non-metallio protactive coatings such as varnishes, lacquers, and plastics, metallio platings such as tin, chemical inhibitors, sacrificial metals, and explosivas other than laad azide. In ganeral thasa methods have not lead to satisfactory explosive component, fuze train, and fuze dasigns.

V. Conclusions and Recommendations

This review has convincad us that copper azide formation in weapons does pose a threat and that consideration must be given to tha prevention of copper azide in weapons.

Although copper azide has been the cause of many handling accidents, and although it must ba considered a major suspect in accidents with unshuttered fuzes where it can ba formed, it is not the only possible cause of such accidents. Other mechanisms for accidental firings oan be conceived, and each accident must be investigatad for its own peculiar circumstances.

Based on our findings the following recommendations are made:

(a) The military should as rapidly as feasible remove from service all weapon fuzes containing unshuttered explosive trains that employ primary explosives. If these trains contain laad azide and copper or copper-bearing metals they must be treated as being extremely hazardous.

(b) A review should be made of all in-service weapon fuzes to identify those that have potential copper azida problams.

(c) A research program should ba undertakan to develop a new primary explosive having the good attributes of laad azide (sensitivity, density, build-up rate, thermal stability, etc.) and, in addition, having compatibility with the usual materials of construction for fuzes and explosive trains.

(d) Insofar as possible, fuze train explosive components (primers, detonators, delays, laads) should be designed to incorporate hermetic seals.

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