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Report Concerning 60mm Mortar Accident Investigations

[redacted] MRSC, CChem, MIExpE

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Author Note

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Summary

On 6th July 2016 members of the Netherlands Airmobile Brigade were conducting firing exercises near Kidal in Mali, where they were deployed as part of the United Nations Multidimensional Integrated Stabilisation Mission. An explosion occurred during firing of a 60mm mortar round. As a result, two members of the firing crew lost their lives and one was seriously injured. The Dutch Safety Board (DSB) investigated the accident to identify the cause. They concluded that decomposition of the energetic materials within the M6-N fuse fitted to the HE 80 round which exploded, was the immediate cause of the accident, though the root cause was procurement of an ammunition design which did not meet the safety standards stipulated in Netherlands requirements. A separate investigation carried out by the Knowledge Centre of Weapons Systems and Ammunition (KC W&M) agreed that the M6-N fuze was unsafe, but proposed a quite separate cause; their view being that, due to inadequate manufacturing control, the fuze detonator was already in the armed position when the round was loaded into the mortar tube and firing initiated the explosion. The current report was commissioned to obtain an independent subject matter expert view of the alternative explanations and to identify if significant considerations were unidentified by the previous investigations.

The author considers that the chemical decomposition mechanism proposed by the DSB report is very much better supported by the known facts concerning the accident, in particular the chemical analysis of other M6-N fuzes and the demonstrable failure of the fuze to meet agreed NATO standards for fuze safety. The explosive decomposition processes proposed have been identified in previous accidents and the need for an effective initiation interruption system in fuzes of this type is well documented.

The alternative, mechanical explanation for the accident, is considered very much less likely, as no direct physical evidence exists to support it and it requires dismissal of much well- supported physical evidence. However, the author notes that the evidence for the favoured explanation is not completely indisputable; legitimate doubt concerning the full mechanism responsible for explosions often remains, given the very nature of such accidents and is, regrettably, well precedented from other, similar investigations.

Inadequate design of the M6-N fuze with respect to major safety aspects including: required temperature range, protection against moisture ingress, initiation interruption and very short safe arming distance is indisputable. In addition, quality concerns identified through the service history of the HE 80 mortar grenade with the Netherlands forces, reinforce the view that the root cause of the accident was procurement and retention of a mortar grenade which failed to meet agreed standards or required safety levels.

Report Concerning 60mm Mortar Accident Investigations

List of Abbreviations

ABMW	Netherlands Testing of Weapon Systems & Ammunition Department
AOP	Allied Ordnance Publication
CVO	Investigation Commission of the Ministry of Defence
DSB	Dutch Safety Board, also Onderzoekraad voor Veiligheid, OVV
FMS	Foreign Military Sales, US weapon procurement process
KC W&M	Knowledge Centre of Weapons Systems and Ammunition
KMar	Royal Netherlands Marechaussee
LOA	Letter of Offer and Acceptance, part of the purchase contract
NATO	North Atlantic Treaty Organisation
NFI	Netherlands Forensic Institute
NRV	Non-return valve, also known as the arming delay sleeve
OVV	Safety Investigation Council, also DSB
PETN	Pentaerythritoltetranitrate, lead/transfer (waxed pellet), powder in detonator
RDX	Cyclo-1,3,5-trimethylene-2,4,6-trinitramine, present as a wax mixed pellet
SME	Subject Matter Expert
STANAG	NATO Standardisation Agreement
TNO	Dutch organisation for Applied Scientific Research
TNT	2,4,6-trinitrotoluene, main charge of the HE 80 mortar bomb

1. Introduction

1.1 Background

On 6th July 2016 members of the Netherlands Airmobile Brigade were conducting firing exercises near Kidal in Mali, where they were deployed as part of the United Nations Multidimensional Integrated Stabilisation Mission. An explosion occurred whilst a detachment was firing 60mm mortar rounds. As a result, two members of the firing crew lost their lives and one was seriously injured. The Dutch Safety Board (DSB) investigated the accident to identify the cause. They concluded that decomposition of the energetic materials within the M6-N fuse fitted to the HE 80 round which exploded, was the immediate cause of the accident, though the root cause was procurement of an ammunition design which did not meet the safety standards stipulated in Netherlands requirements. A separate investigation carried out by the Knowledge Centre of Weapons Systems and Ammunition (KC W&M) agreed that the M6-N fuze was unsafe but proposed a quite separate cause; their view being that, due to inadequate manufacturing control, the fuze detonator was already in the armed position when the round was loaded into the mortar tube and firing initiated the explosion. The Public Prosecutor's Office Oost Nederland commissioned this report to obtain an independent subject matter expert (SME) view of the alternative explanations and to identify if significant considerations were unidentified by the previous investigations.

1.2 Scope of Report; Prosecutor Questions

The fatal accident of 6th July 2016 required multiple aspects of the deployment of Netherland personnel and equipment in Mali to be considered. Besides the safety of the ammunition involved in the explosion, there were also issues concerning the medical provisions to treat the injured personnel. This second issue is beyond the scope of the current report which is limited to the 60 mm mortar ammunition and its use during the Mali deployment.

To ensure their concerns were addressed by this independent report, the Public Prosecutor Office framed a series of questions [Reference 1] which are listed below:

(1) **What can be concluded, based on the investigation data, about the cause of the premature detonation of the accident grenade and the circumstances that have contributed to that cause? If several causes and circumstances are possible, please indicate the extent of probability of the different causes and circumstances.**

(2) To what extent of probability can the cause for the accident be found in factors that the OVV summed up?

(a) What can be concluded about the investigation method, the investigation data and the findings of the OVV?

(b) To what extent of probability does the cause for the accident (also) lie in the ingress of moisture into the interior of the fuze?

(c) To which extent of probability does the cause for the accident (also) lie in the functioning of the cover plate that, by way of derogation from the NATO prescription, didn't prevent discharge to the transfer charge?

(d) To which extent of probability does the cause for the accident (also) lie in the exposure of the accident grenade to higher temperatures than allowed, in accordance with the guidelines of the manufacturer, during storage of the mortar grenade?

(e) To which extent of probability does the cause for the accident (also) lie in the exposure of the accident grenade to higher temperatures than allowed, in accordance with the guidelines of the manufacturer, during the specific handling processes up to and including firing of the accident grenade on the day of the explosion?

(f) How valid are the findings of the KC W&M with regard to the manner, in which the OVV carried out its investigations, and to the findings of the OVV?

(g) What is the validity of the reaction given by the OVV – which is (also) based on research performed by TNO – to the KC W&M report?

(h) To which extent of probability do the parts (of the detonator) that were investigated by the OVV come from the accident grenade?

(3) To which extent of probability does the cause for the accident (also) lie in factors as mentioned by the KC W&M?

(a) What conclusions can be drawn with regard to the investigation method, the investigation data and the findings of the KC W&M?

(b) To which extent of probability does the cause for the accident lie in the combination of measure deviations of elements of the accident grenade?

(4) To which extent of probability have other causes and/or circumstances, other than mentioned by the OVV and the KC W&M, led and/or contributed to the premature explosion of the accident grenade?

These questions will be addressed after the proposed causes of the premature initiation have been considered.

1.3 Report Terminology

The complexity of weapon design requires that terminology be fixed if clarity is to be achieved. In this report the terminology used in the UK and US is preferred to minimise risk of confusion.

For weapons, ‘safe’ requires a particular definition and the author uses ‘the freedom from hazards to personnel and materiel at all times, recognising the considerations of operational necessity as a limiting factor' [2]. 'Fuze' is used to describe the ammunition arming and initiation device at component level. The Public Prosecutor's Office has provided the author with reports and other documentation in both Dutch and English and the various authors have differing preferences for terminology, in particular the Dutch word 'schokbuis' has been translated as both 'shock pylon' and 'fuze'. For consistency, the latter term is used through this report other than in direct quotations. The term 'Explosive Train' is used for the set of energetic materials whose sequential initiation serves to achieve detonation of a weapon in its intended design mode.

2. General Considerations

2.1Explosive Safety Protocols

Most explosives used in current weapons systems were developed during or between the World Wars of the 20th Century. The invention and initial exploitation of these materials was accompanied by many accidents which were often fatal and caused great damage. Through this learning process scientists and engineers developed sufficient understanding of initiation processes -both intended and inadvertent – such that these energetic materials could be exploited in 'safe' weapons designs which can be deployed worldwide by users having little understanding of their underlying chemical and physical principles. The risk of unintended initiation which would put military users and/or the public at great hazard is generally negligible and such accidents are extremely rare, particularly in nations which follow NATO agreed protocols. However, one consequence of this success is the principles which enable safety are not generally understood by many procurement teams and military users and, when safety principles are ignored, serious accidents can occur.

During the development of an energetic material, the responsible scientist will aim to identify and best quantify the conditions under which their material will initiate. This will include a multiplicity of possible failure modes such as impact, shock, temperature and chemical compatibility. A safe ‘working envelope’ will be established whereby the explosive can be manufactured and processed into a ‘safe’ weapon. This safety envelope is largely developed by experience and experiment rather than by modelling and its boundaries will be marked out by specifications, approved processes and, at the highest level, by international agreements such as NATO STANAGs. The consequences of unintended initiation being so catastrophic, the safety envelope will be necessarily highly conservative; i.e. the allowable thresholds will be set significantly lower than those which will certainly induce failure. Therefore, deviation outside, for example, by exposure to a higher than specified temperature, will rarely lead to an accident and this can lead to dangerous complacency. There is a multiplicity of factors which will cause one round to fail catastrophically whilst many, apparently identical ones, will not. For example, slight differences in impurity levels or density (perhaps on an explosive batch basis or due to differing prior thermal histories) may allow spontaneous initiation of decomposition which is sustained through to full detonation for some rounds, whilst others may either not undergo externally apparent decomposition at all. Where such variable decomposition occurs in the explosives train within a fuze, the underlying problem may only be experienced as an increasing ‘dud’ rate whereby the weapon fails to detonate in design mode because its explosive function has been interrupted. Most importantly, for a given weapon ‘insult’, be it thermal overexposure, bullet impact or any other, inadvertent initiation will only rarely occur at a single specific and reproducible threshold; i.e. the response is generally stochastic in nature rather than being conveniently deterministic. Therefore, when the design safety envelope is disregarded, the user is taking an unquantified (and, practically unquantifiable, risk) which will be apparently without consequences until a major accident happens. Where this is the case with a ‘general munition’ (defined as a widely issued and very frequently fired munition – for example, a mortar grenade or an artillery round) continued disregard of safety limitations is much more likely to result in an accident eventually being experienced during service. In contrast, more complex weapons, such as missiles, are procured in low numbers and rarely fired; therefore, underlying safety problems may never actually result in accidents. However, whenever a munitions accident does occur, due to this stochastic nature of the energetic material initiation and sustainment, it will rarely be certain why the accident round failed when multiple, perhaps tens of thousands, apparently identical ones, fired safely and performed satisfactorily. This uncertainty is almost inevitable since the damaging energy release caused by an energetic material accident, particularly one where full detonation occurs, will leave little evidence and that which survives can frequently be interpreted in multiple ways. This produces doubt concerning the actual cause of the accident, inability to achieve a consensus opinion, including amongst experts, and an apparently inconclusive investigation.

For example, the UK experienced a damaging explosion during a missile firing from a Royal Navy Destroyer in 2004 and although a satisfactory general explanation was found, there was long standing disagreement amongst SME concerning the exact failure mechanism and the significance of different underlying factors. Multiple attempts to reproduce the failure mode did not reproduce the accident severity. Consequently doubt, causing serious service limitations, persisted until the missile was retired from service.

2.2 Application of NATO Standards

2.2.1 Explosives Qualification; STANAG 4170

The requirement to define and adhere to ‘safety envelopes’ for energetic materials is explained above. However, excepting the United States, no NATO nation has the industrial capacity to meet its entire weapon requirements from indigenous capability. Testing weapons is an expensive, often lengthy process, and to fully characterise and specify the safety characteristics of all imported weapons would be unrealistic in terms of cost and other resources. This is one of the reasons for the development of the architecture of munitions STANAGs and AOP developed by the NATO nations, including the Netherlands and the UK. Even where information exchange between the buying nation and a foreign based Design Authority is limited, knowledge that the weapon was designed and tested to meet common, internationally agreed requirements, should provide legitimate confidence that the weapon as designed is ‘safe’. Additionally, where the weapon and its energetic materials are manufactured in a NATO nation and, particularly where the manufacturer is EU based, a common approach to safety, quality and reliable functionality is likely.

The application of STANAG 4170, Principles and methodology for the qualification of explosive materials for military use, should ensure that every service energetic material has been assessed by a National Authority body ([3] 2007, Netherlands authority was Matlogco/LBBKL/Munitiebedrijf) which approves all military explosives as being safe and suitable for their intended purpose. STANAG 4170 is also aimed at ensuring explosives safety through the service life and that limitations (such as upper thermal limits) or incompatibilities (such as may be present in a fuze arming mechanism) are identified before the energetic material enters service. The continuity of quality is addressed by the following recommendation:

The Qualification of an explosive material relates to a defined specification from a particular manufacturer and manufacturing location and using a particular manufacturing process. Where there is a change to: (1) the specifications; (2) the source of raw materials; (3) the manufacturing process; (4) the manufacturer or manufacturing location; or there has been a loss of manufacturing know-how, it should not be assumed that the original judgement remains valid; requalification or partial requalification may be required.

Where procurement is planned from a new source without a proven history of successful supply to NATO standards, particular care in eliminating the risk that inadequate quality control could lead to inconsistency in safety characteristics is needed. Since the most easily initiated explosives in a weapon are likely to be the primary explosives in the warhead, particular care in ensuring their quality is needed. The author’s experience leads him to suspect that ex- Warsaw Pact manufacturer’s approach to energetic material quality control can be less rigorous than that of historic NATO nations. For example, in 2015 the author found that an Ex- Warsaw Pact source of explosive train components for fuzes was recovering explosives from old, demilitarized weapons and refitting them into ‘new’ weapons. The manufacturer in question was not that involved the 60mm mortar rounds used by the Netherland forces, but the example serves to illustrate standards which would not be acceptable to NATO can still persist.

2.2.2 Fuze Safety; STANAG 4187and 4157;

A fuze is defined as a device designed to control the initiation of a main charge. For small munitions, such as mortar grenades, the function of the fuze is to ensure the munition is safe when being stored, transported, handled or fired, but will be initiated reliably at the target.

Because the fuze will contain both relatively easily initiated, primary, explosives and also secondary explosives (less sensitive than primaries but in greater quantity) in close proximity, its key design intent will be to ensure the risk of inadvertent initiation of the secondary explosive is vanishingly low. This will require that the initiation of its primary explosives in any fuze condition other than armed, will not be communicated to the secondary explosive; this function is termed 'explosive train interruption'. Tube launched munitions (e.g. mortars and large calibre guns) will often be fired in large numbers and the design life may last for decades. Their fuzes may also require many explosive and inert components made using large numbers of batches, therefore, the fuze design must ensure that there is no marginality in the effectiveness of train interruption. The protocols for NATO nations to establish fuze safety are detailed in various STANAGs but 4157, Safety, Arming and Functioning Systems Testing requirements [4] is the most appropriate for assessing of the 60mm mortar fuze. It is considered a reasonable assumption that an established fuze supplier to NATO standards will have proof of compliance before making the fuze available to purchasers. In particular, the 'mandatory' Explosives Train Interruption Test would generally be considered of primary importance in establishing safety of a mortar fuze. This is because mortar launch does not impart significant spin (unlike rifled artillery barrels, for example) and fuzes for these weapons will often be designed with a single safety mechanism (operated by launch setback) rather than having the preferred, two independent mechanisms, requirement. Additionally, mortar operations do have a significant accident history [5, Appendix M] and the safety and reliability of the fuzes from an unfamiliar source would be expected to be subjected to particular scrutiny. This should include requiring a new supplier to provide data to prove that the both design of the fuze was compliant with standards and that manufacturing quality control ensured the design safety was always met.

2.3 Procurement of ‘Light’ Weapons

The author has no knowledge of Netherlands weapons procurement processes beyond that provided by writing the current report. However, he participated in weapon procurement during the deployment of UK forces in Afghanistan around the time of the Netherlands HE-80 mortar grenade/M6-N Fuze combination purchase. In both Netherlands and UK, many weapons systems were procured at high speed to equip the many military formations deployed on active operations. In the UK, routine weapon and explosives test protocols were shortened and test facilities prioritised those weapons seen as posing a particular safety risk. It was the experience of the author that scientific and test resources were focussed on ‘complex weapons’ such as missiles, often with novel energetic materials or design aspects unfamiliar to UK SME. Less sophisticated, ‘light’ infantry weapons were often procured with less examination and formal consideration of safety. This was because safe operation of these weapons is largely controlled by the operational procedures of the armed forces themselves reacting to the conditions they encounter. Consequently, specialist scientific expertise will be less readily sought by the units requiring the weapons who may (rightly or not) consider themselves possessing the needed expertise. In the case of the UK, this is particularly true of airborne and specialist forces whose operational requirements may only be fully appreciated by their members. A related issue is that light infantry weapons often operate on relatively simple principles and it may be considered that an old, established design is necessarily safe by its very availability. This can cause assumptions to be made concerning the origin and testing of the components used and the innate safety of such weapon systems. It was certainly true of UK procurement during this time that ‘new’ infantry weapons were subjected to less (or deferred) safety regulatory scrutiny than would have been the case under the procurement processes operated in peacetime conditions.

Once the UK operational activity had decreased in Afghanistan it was often difficult to resource safety and 'type' qualification (the Netherlands use the term 'type classification' which has a separate meaning in the UK) testing when it had been deferred. It was considered by some members of the procurement regime that the relevant weapons were now 'qualified by use' and their safety demonstrated by failure to have accidents. In the case of the UK, the weakness of such arguments was established by a major aircraft accident and the subsequent public enquiry [6] whose recommendations included less reliability on subjective assumptions of safety.

3. Consideration of the HE 80 Mortar Grenade with M6-N Fuze

The Dutch Investigation Board Report [5] includes a comprehensive description of the Weapon System and explosive components involved in the accident. It is not the intention of the author to reproduce this but it is necessary to provide sufficient description to aid understanding.

3.1 The Hotchkiss-Brandt Commando 60mm Mortar Tube

The mortar grenade launcher involved in the accident was a well-established design, the Hotchkiss-Brandt Commando. The launch tube is 65 cm long and of steel construction (see Figure 1) and the ammunition, the mortar grenade, is dropped into the muzzle end. The base plate, which rests on the ground during firing, incorporates a firing pin (see Figure 2) which, on being struck by the percussion cap situated at the base of the grenade tail, initiates the grenade's primary propulsion cartridge. Consequently, there is no external firing mechanism and the weapon is served by a crew of two: an aimer who holds the tube and guides the firing angle and a loader who picks up the mortar grenades and drops them into the tube.

3.2 The HE 80 Mortar Grenade

The mortar grenades suitable for the mortar tube are available from various sources; the accident round used by the Dutch army was the HE 80 grenade (rounds of this type are also referred to as 'mortar-bombs'). This ammunition, both the explosive grenade and its fuze, is supplied by the Bulgarian Company, Arsenal JSCo; a design sketch is included as Figure 3. The DSB records that the design of the mortar grenade is based on drawings supplied 'about 20 years ago' by Hirtenberger Defence Systems, a well-known, Austrian based, supplier of mortar weapons to many NATO nations (including the UK). However, the DSB report includes the statement: [5, Section 3.1.2, Note 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.

Management of weapon safety requires clarity of where responsibility lies for weapon safety through all the phases of service life. The most vital role is that of 'Design Authority' who should understand the design including all aspects of its safety, including the design 'safety factors' thus ensuring that normal operations are within the capability of the weapon and the risk of accident is low. This understanding will be reflected in the limitations the Design Authority notifies his customers of concerning the weapon such as upper operating temperature and service life of, in this case, the mortar grenade. The author concludes that, for the HE 80 mortar grenades, Design Authority status, rested solely with Arsenal JSCo. Also, as manufacturer of both mortar grenade and fuze, they held responsibility for safe realization of the design and maintenance of safety by quality control measures.

The HE 80 grenade itself is entirely conventional for ammunition of this type comprising a convex steel cylinder which houses the main explosive charge (TNT). At the lower end (in launch) is an aluminium fin assembly which lends the grenade stability in flight and, in its perforated central axis, houses the primary propelling cartridge and the percussion cap which initiates launch. Like most mortar systems, firing range can be operator adjusted by fitting additional augmenting cartridges (up to four per round). These are plastic 'horseshoe' rings filled with single base propellant powder fitted above the tail fin. As described in Section 3.6, Dutch Authorities had limited the number of augmenting cartridges to zero or one.

3.3 The M6-N Fuze

For 'tube' launched ammunition, the safety and arming device, known as the fuze, performs multiple safety critical roles. Primarily, it should ensure design mode detonation is impossible unless the round has been successfully launched and reached a safe separation distance from the firing crew. For mortar weapons, reliability in this function is particularly important as the launch tube provides no protection to the firing crew in the event of early explosion of the round. Since spin is not launch imparted, the design scope for safety mechanisms is relatively limited for mortar fuzes.

Once beyond the minimum safe separation distance (a general requirement for most weapons but not, apparently, for the HE80/M6-N) the fuze then performs its arming device role whereby the explosive train is arranged to ensure design mode detonation is achieved on contact with the target. A high degree of confidence in this function is also required, as failure to detonate at target (known as a 'dud' round) risks littering the field/range with munitions of uncertain safety status whose disposal puts a major burden on specialist forces.

The location of the M6-N fuze when fitted on the HE 80 round is shown in Figure 3 whilst Figure 4 is a cutaway sketch to enable its construction and the naming of parts to be understood (KC W&M refer to the same fuze as M-6H, the DSB name is used through this report).

Although the M6-N fuze was manufactured by Arsenal JSCo on the basis of '…drawings obtained from the Soviet Union about thirty years ago' [5, Section 3.1.2] its origins are very much older. TNO having access to a USSR Manual concerning the M6 fuze dated from1957 [7, Section 3, note 35].

The design mode operation of the fuze and its explosive train are explained in the relevant DSB [5, Appendix F] and KC W&M [8, Annex 2] reports and the description below is limited to those aspects most relevant to this report.

The essential design factor is that the detonator is kept in a 'safe' position, out of line with the firing pin through the entire life of the fuze until the round leaves the mortar tube. For the detonator to reach the armed position a sequence of two events are necessary. See Figure 5.

When the percussion cap ignites the primary propelling charge (and, by hot gas transfer, the augmenting cartridge) the round is accelerated up the mortar tube. However, due to the inertial effect operating on them, the spring (part number 6) and the arming delay sleeve (part number 16, also known as a setback cap or a non-return valve, NRV) travels down the firing pin housing (part number 8, red arrows illustrate this movement) at a speed governed by movement of the arming delay sleeve zig-zag slot (numbered as 7) as guided by the housing cross-pin (not numbered but shown in green on Figure 5). The spring strength and arming delay sleeve mass are fixed, such that, within the Design Authority declared limitations for the round (for example maximum safe drop height) only the high acceleration of launch will allow sufficient relative movement to allow the delay sleeve retaining ball (part number 17, shown in blue in Figure 5) to fall free. Once the mortar round leaves the mortar tube, the propelling gases provide no more acceleration and the arming delay sleeve, under the influence of the arming spring, moves back up the firing pin housing but to a new, higher position due to the absence of the retaining ball. As it reaches this new position, the arming delay sleeve will no longer retain the two firing pin retaining balls (part number 18 in Figure 4, lower inset sketch). Since these balls were serving to restrict its movement, the firing pin can now move further up the fuze with its lower tip leaving its shutter recess, and, in doing so, the pin no longer locks the shutter slider. The slider, under the influence of the shutter spring (part number 10 in Figures 4 and 5 where it is only visible in its fully compressed position) slides the detonator under the firing pin. The fuze is now fully armed. Impact will drive the firing pin into the detonator, where the stabbing energy and/or friction will initiate decomposition of the primary explosives present, which will progress through the explosive train, culminating in design mode initiation of the HE 80 TNT main explosive charge.

3.4 Energetic Material in HE 80 Mortar Grenade with M6-N Fuze

To understand the safety of the mortar grenade in design and accident modes it is necessary to consider the energetic materials which constitute the explosives train. The design aim of this train is to achieve maximum reliability in commanded detonation of the relatively insensitive (that is, difficult to initiate) TNT main charge, whilst minimising the possibility of inadvertent initiation. The firing pin stabbing the detonator initiates the most sensitive (that is, easy to initiate) explosives housed in the detonator within which chemical decomposition is accelerated to reach full detonation. This detonation shock is transmitted through the upper surface of the interrupter/cover plate to detonate the lead/transfer pellet which, in turn, detonates the booster charge which detonates the main TNT charge. Minimising the quantity and isolating the stages using the more sensitive explosives, reduces the risk of inadvertent initiation. For a well-designed fuze, whose manufacture is executed successfully, this risk should be vanishingly low under Design Authority approved conditions.

The energetic materials contained in the explosive train of the HE 80 mortar grenade fitted with an M6-N fuze are listed in Table 1.

These compounds are well known and routinely used by regular suppliers to NATO nations. All have disadvantages but they are collectively consistent with design and manufacture of a safe mortar grenade. The purpose of qualification in accordance with STANAG 4170 is to best ensure this aspiration is realized.

3.5 Procurement of the HE 80 Mortar Grenade

The process followed in procurement of the HE 80 grenade is relevant to the failures which led to the accident.

The accident mortar grenade was procured in 2006 under a ‘sudden and urgent need for a new stock of 60 mm mortar rounds…’ [5] required for Netherlands forces deploying in Afghanistan. Since their previous source was unavailable, the Netherlands Defence organization approached the United States using the Foreign Military Sales (FMS) procedure whereby existing rounds from US Army stock would be made available to Netherlands. The advantage of this process is not only speed, in that manufacture is not required, but the confidence that the weapons have already been designed, made and tested to the agreed NATO standards (including STANAGs such as 4170 and 4157). Therefore, the Netherlands forces could be assured that the weapons could be deployed and used without reduction in the safety levels which would have been achieved if the Netherlands had procured the rounds under their national requirements. The author can confirm that, at this time, the UK were following the US FMS process for other weapons.

The attempted FMS procurement failed, as the US could not supply the ammunition, although a US contractor was able to identify an alternative, the HE 80, from Arsenal JSCo, a Bulgarian company. The US forces did not use the HE 80 themselves and could give no assurances regarding its safety or capability and, critically, there was no transfer of technical data from the US and/or Arsenal JSCo [5, Section 4.1]. Since the FMS safety and quality argument was no longer applicable, Netherlands processes, in parallel with other nations' NATO protocols would have required a 'type classification' process designed to establish safety and suitability for service. This would have included assessment of compliance with various STANAGs including 4170 and 4157. The author considers it almost certain that the quality and stability issues identified during the accident investigation would have emerged during a competent type classification process. It is clear that the Netherlands procurement authorities knew what information was required to provide the necessary assurance:

The Dutch acquisition team drew up a list of documents that they wanted to have annexed to the LOA. This desired documentation related, inter alia, to technical specifications, safety data, date of energetic substances and type classification documents

However, the procurement was made without this data being supplied or generated within a type classification programme.

The failed FMS procurement also seems to have enabled an apparent misinterpretation regarding the limitations of the HE 80 round. As stated above, the Design Authority plays the critical role in defining the safe limits for the weapon. Where there is a user intention to take a weapon beyond the Design Authority limitations, it is clearly inappropriate to rest responsibility for consequence of that extension on the Design Authority; such ‘user authorized service extensions’ should only be possible with clarity of responsibility and evidence for safety being assessed by a competent National Authority; that is, a Netherlands based SME. It would appear that the original FMS aspiration regarding environmental range and service life included the temperature range +63 to -46°C with a ‘maximum durability’ of 15 years. This upper temperature limit would be consistent with a requirement for Afghanistan operations in climatic zone A2 and 15 years would be an attractive service life if offered by a Design Authority; 10 years is more commonly offered. Whether these aspirations originated in the Netherlands or the US, they are irrelevant to the HE 80 procured from Arsenal JSCo who state a maximum shelf life of 10 years and a temperature range for storage and use of +50 to -50°C [5, Section 4.2]. The author considers that issuing an operational instruction beyond the Design Authority (that is, Arsenal JSCo) limits set for the HE 80 was a major failure. Additionally, it is considered that the very quotation of the +50 to -50°C limitations should have provoked questioning from a competent SME. These limits are inconsistent with NATO climatic zone classification (that is, they do not encompass Afghanistan and Mali maximum induced air temperatures [10]) and the scientific/engineering basis of these limits should have been queried as to how they could have been derived and considered suitable for Afghanistan deployment. This could have caused a SME to enquire whether the manufacturer actually possessed the competence to fulfil the safety responsibilities expected of a weapon supplier. This enquiry may have exposed the failure of the HE 80 design to meet standards set in Netherlands approved STANAGs.

The DSB [5]and the KC W&M [8] reports report come to entirely different explanations for the initiation of the accident round however they are in agreement that the procurement of the HE 80 with M6-N fuze was inconsistent with Netherland munition safety requirements. Despite the urgency of the requirement, a more thorough procurement process including a 'type classification' and STANAG 4157 compliance assessment in 2006 would certainly have identified failures in design and/or manufacture which ultimately led to the accident.

A further opportunity to identify safety shortcomings with respect to the M6-N fuze with the HE80 was missed in 2007 during preparation for introduction of the weapon to Netherland forces service. This related to Safe Arming Distance (also referred to as both 'mask safety' and 'reinforcement distance' [5]). In response to Netherlands enquiries, Arsenal JSCo stated that the arming distance was between 0.75 and 10 metres; these distances are alarmingly close to the launch point for a fragmenting weapon and should have provoked further questioning concerning the testing to validate this safety critical information. It should be understood that the minimum arming distances relate primarily to the possibility of mortar grenade design mode detonation in contact with leaves, rain or any airborne impact. In view of the simplicity of the arming stimulus – first application and then reduction of launch acceleration, the distances quoted by Arsenal are certainly plausible but would, in the author's experience, have led to difficulty in framing operational instructions which would pass safety risk assessment. There is evidence to prove the low safe arming distance was taken into account - the instruction of 2007 that the round had not be fired through trees or in bad weather [5, Section 4.1). Whether the minimum distance is, in-itself, unacceptable will depend on individual national requirements. Based on the information in the DSB report [5, Section 4 Para 2.4] it would not appear that a minimum arming distance is mandatory for fragmentation weapons used by the Netherlands forces although this requirement may exist elsewhere.

3.6 Identification of Quality Issues Prior to Afghanistan Deployment

On arrival in the Netherlands depot, a technical inspection of the ammunition was carried out between June and September 2007. The DSB Report states [5, Section 4.1]:

In eight in-inspection reports, the ammunition technician reports that the ammunition is incorrectly classified, several codes and batch numbers fail or are illegible, a NATO Stock Number lacks, several batches are mixed, the ammunition is composed of different sublots, partial loads lack and the ammunition is wrapped up indecently so that humidity and dirt may touch the ammunition. The ammunition technician has doubts about the suitability of the ammunition, to shoot it with mortars of the air force and recommends to block the stock for usage, due to its deficiencies.

The author is not in a position to judge how unusual these observations were but finds it surprising that no action was taken. This view is perhaps influenced by his experience of unacceptable practices by former Warsaw Pact manufacturers (his experience does not include Arsenal JSCo.) in manufacturing weapons from variously procured components, but considers that any notification of anomalous sub-lotting should have provoked detailed enquiry into build standard and quality. Identification of poor-quality packaging ‘so that humidity and dirt may touch the ammunition.’ should have been highly concerning. It is the author’s experience that depot technical inspections frequently identify apparent anomalies with ammunition from regular, NATO nation suppliers. However, reports would always require attention and, if related to a new source, attention from senior specialists with authority to reject stock or prevent issue would have been expected.

In October 2007, the Netherlands Testing of Weapon Systems & Ammunition Department (ABWM) conducted functional tests of the HE 80 mortar grenade to verify suitability with the existing Hotchkiss-Brandt mortar launch tube. It is noteworthy that ABMW used the Arsenal nominated temperature extremes (+50/-50°C) demonstrating awareness at this point of these limitations [5, Section 4.1]. During this trial (whose function was stated to be ballistic suitability and not overall safety) further observations were made:

ABWM notices that the ammunition batches are composed of several sub lots for critical components, such as the propelling charge and the shock pylon. Plus, the shock pylons come from two different factories, i.e. from supplier Arsenal and from Arcus, a second Bulgarian arms manufacturer.

These observations are consistent with the depot ones (which provoked a 'reject' recommendation) but additionally, with highly unusual evidence of a second manufacturer of the fuzes (shock pylons). It is considered that this observation demonstrated such a major deviation from generally recognised standards that it should immediately have provoked a technical investigation. Whilst there is no evidence the Netherlands procurement authorities obtained evidence of the safety and STANAG compliance of the Arsenal manufactured items, the appearance of fuzes from additional sources should have raised issues concerning whether the HE80 specification and quality control was consistent with safety requirements. Understanding the criticality of fuze quality and consistency in maintaining safety requires only a rudimentary understanding of weapons safety. A competent weapons technician would be expected to raise immediate objections to deploying such ammunition. However, the DSB report states:

ABWM recommends to regroup the grenade load as to all possible combinations and to number them again. ABWM does not draw any further consequences from the hybrid composition of the ammunition load.

The importance of this failure to appreciate the safety risk being passed to Netherlands forces in accepting the HE 80 shipment into service is considered a major failure.

It is noted that, as a result of their trials, ABWM imposed a restriction: no more than one propellant augmenting cartridge should be fitted to the HE 80 although Arsenal JSCo permitted up to four. It is possible that this was due to doubts concerning the pressure of higher propellant weights exceeding the pressure capability of the mortar launch tube. However, this may also have related to maximum operating temperature reservations since, for a fixed propellant weight, the higher the firing temperature, the higher the operating pressure in the launch tube. It is also possible that the propellant weight limitation relates to concern regarding the robustness of the M6-N fuze to survive the setback acceleration on launch, but, if ABWM had reservations on fuze capability, it is reasonable to assume they would have tested them directly rather than simply limiting propellant load. However, without evidence, this is speculation, though it is reasonable to assume the limitation was rooted in a safety concern. It is unfortunate that implementation of this limitation – which was within the Design Authority limitations - did not provoke considerations concerning prohibiting use outside Design Authority temperature limits.

3.7 Post Afghanistan Deployment of HE 80 Stock

Although the procurement of the HE 80 system did not comply with Netherlands and NATO standards, it is noteworthy that Netherlands MoD can state that ‘approximately 25,000 of these 60mm grenades were shot almost without any problem and none of the grenades detonated prematurely’ [11]. This is consistent with the DSB statement that approximately 10,000 rounds remained at the end of the Afghanistan deployment (in 2010, the original FMS contract stating the requirement as 37,017 rounds so it can be reasonably concluded that the entire HE 80 stock originated from the single 2006 order). This large number of firings without recorded accident may be interpreted as suggesting the reservations regarding HE80/M6-N safety noted above are overstated in the context of a military deployment which was, of its essence, highly dangerous for the participating personnel. This view would however miss the fact that a dangerous round is an unnecessary risk. When this risk is actually realized, as in the Mali accident, it was not accepted as an inevitable consequence of active military operations and, on this basis, a history of firing 25,000 rounds prior to the accident is not relevant. That is not to say that this history is without value in considering the cause of the accident. For example, if the cause were to be a quality issue due to inadequate dimensional control in manufacture, it might be considered the fault would be randomly distributed through the stock and therefore encountered during mass firing, i.e. in Afghanistan. If, however, an essential element of the failure mode was related to ageing or decomposition, such failure would be more likely experienced towards the end of service life. However, the author does not consider the evidence supports a major weight being placed on arguments based on the age of the accident round, there is no direct evidence it was a factor. This is not to contradict the view that any credible failure mechanism must explain why it was possible to fire 25,000 rounds during the Afghanistan deployment without an HE 80 round detonating within the mortar launch tube. The DSB report also identifies that the intervening period between Afghanistan (2010) and Mali deployments (2014) was a period where gaps in the safety evidence allowed during the original, urgent, procurement could have been filled. For example, by a ‘type classification’ or STANAG 4157 fuze testing. This evidence from the DSB report show that problems with the HE 80 were known but no action taken [5, Section 4.1]:

These were reports from training grounds about refusers, duds and grenades with broken supplemental cartridges. The Defence Ammunition Company stated in a reaction on the incident reports ‘that the problems are known, but that, unfortunately, there is no

better ammunition available and that, awaiting replacement, the problems with the 60 mm grenades are accepted'. No subsequent action followed.

The author agrees that the period between the deployments could have been used to test the HE80/M6-N in accordance with agreed standards and it would certainly have failed to meet them. In the context of the post-Afghanistan deployment, it may be the case that the Netherlands had 'urgently' procured a number of other weapon systems and that gaps in normal safety testing evidence existed for many of them. In this context, appetite to spend limited resources on 'combat proven' weapon systems may have been limited. The author experienced considerable reluctance from UK weapon users to resource such work for equivalent UK weapons during the same period.

3.8 Deployment of HE80 in Mali from 2014

The climate of Afghanistan is highly varied but includes hot, desert zones and weapons would ordinarily be tested for suitability in A1 or A2 ranges before deployment. This is also true of Mali where the majority of the country, including the area around Gao and Kidal, are classified as 'desert, arid, hot'. In this case, weapon suitability for A1 or, at least, A2 climates would be appropriate. When the Netherlands selected weapons to support their 2014 Mali deployment, it is considered that the HE 80 Design Authority upper temperature limitation of +50°C should have led to doubt about the suitability of the weapon. However, the remaining stock was transferred to Gao with part of the stock being transferred further to Kidal where around 70 rounds were available the day of the accident.

4. The Accident, Kidal, 6th July 2016

At around 07:00, part of the Special Operations Land Task Group began an exercise requiring a mortar shoot. To this end, a 60 mm mortar and four ammunition boxes, each holding ten HE

80 mortar rounds, was delivered to the practice area. The mortar squad consisted of four mortar gunners in accordance with the 81mm mortar system they had been trained to operate in the Netherlands. The light, 60 mm, mortar system only requires a crew of two however and the squad arranged to rotate duties, including a camera operator to record the firing exercise.

At 07:30, the first sequence of firings started with 10 shots fired at a target around 900 metres away. This firing set was completed satisfactorily and then the firing crew were rotated before a further 7 shots were fired. The final shot was a 'dud' (the round did not detonate on impact in the target area). In accordance with range safety requirements, demolition specialists were called to render safe the dud round whilst the mortar detachment removed the packaging from the rounds in the third and fourth boxes which had been kept in their Bushmaster vehicle.

At 09:27 hours, a hundred and five minutes after the break caused by the dud round, the exercise restarted and four more rounds were fired. The squad then returned the ammunition box with six grenades back in the vehicle and cleaned the mortar barrel with a cleaning rod. Two members of the mortar squad retrieved the fourth and last ammunition box containing ten rounds, as noted above, the packaging from these had already having been removed.

Two more rounds were fired in quick succession. At 09:37 hours: the loader picked the third mortar grenade and placed it into the muzzle of the mortar and released it. A fraction of a second later the round exploded. The aimer and loader were killed and the crew member operating the camera severely injured.

5. Evidence from the Accident Site

The DSB investigation categorized the evidence into three sources. The photographs and video capturing various rounds fired before as well as during the accident, provide clear evidence that correct drills were followed. Additionally, knowledge of the camera video speed provides reliable timing information with respect to the loading cycle; this enables calculation of the position of the mortar grenade at the time the explosion occurred. This information clearly eliminates the possibility of ‘double-shotting’ whereby two rounds are loaded, the second initiating explosion of the first. Since this a well precedented cause of mortar accidents, it assisted the investigation considerably that this possibility could be eliminated [5, Appendix E].

The second source of information is witness testimony; there were six people in the vicinity of the accident and three provided witness evidence. This is not directly quoted in the DSB report but provides explanation of the timings and ammunition processes followed the day of the accident.

The third source of evidence is the physical remains from the burst mortar tube and the accident round itself. It is necessary to consider this aspect in detail as there is dispute concerning the evidence which is significant in determining the cause of the accident.

5.1 Searches for Evidence and Destruction of HE 80 Rounds near the Accident Site

On the 6th July 2016, immediately after the accident and removal of casualties, the accident scene was searched and there is photographic evidence of Netherlands and Czech personnel carrying out this process. Pieces of the burst mortar tube were recovered as well as, apparently simultaneously, pieces of the failed mortar grenade and its M6-N fuze, including the steel cover plate (explosive train interrupter plate) as well as remnants of the aluminium fuze body, the shutter casing and a piece of the firing pin.

Later that day, French specialists destroyed five HE 80/M6-N rounds remaining from the accident exercise using explosives. There were then further searches, both the same day and later. The Investigation Commission visited the scene on 19th July. Physical evidence from the accident was transferred to the National and Foreign Units Investigation Service Brigade Unit of the Royal Netherlands Marechaussee (KMar) and then subjected to technical investigations by The Dutch Forensic Institute (NFI) and the Dutch Organisation for Applied Scientific Research (TNO) as ordered by the Investigation Council.

A subsequent investigation with the primary aim of designing a safe disposal process for the remaining Netherlands HE 80 stock is reported in the KC W&M report [8] where it is concluded that the physical remains of the M6-N fuze from the accident round referred to were in fact incorrectly attributed to the accident round. KC W&M state, on the basis of their experience, that the fuze would be torn off the steel mortar grenade at the top thread ('thinnings', across the line of the explosive train interrupter plate) and, at, '…high speed due to the detonating TNT, be moved in an axial direction.' They attribute the purported fuze residues as follows:

Problematic in this context is that after the accident, 5 pieces of 60 mm HE80 mortar grenades were destroyed by French staff of the Explosive Ordnance Disposal Unit. This destruction by French Explosive Ordnance Disposal Unit staff members took place on 06 July, after the 1st search after the accident but prior to the 2nd search on 12 July 2016, as a part of the CVO investigation.

They conclude that the French staff selected a single set of post explosive disposal fuze components recovered from their disposal trench, giving them to Netherlands personnel who then mixed them with the evidence gathered at the actual accident site. The fuze residues were then incorrectly attributed to the accident and any conclusion regarding accident cause based on this evidence is therefore unsound; the NFI and TNO were actually examining residues from an explosion initiated externally to the HE 80 rounds during this disposal.

This different origins of the 'accident fuze' evidence is central to the different causes of the accident proposed by the DSB (based on the Investigation Council study) and KC W&M.

5.2 Consideration of the KC W&M Explanation of Fuze Evidence

The KC W&M explanation was that the accident fuze failed at the 'thinning' and, remaining a single piece, was projected a considerable distance - which is why it was not found by the search teams. If the fuze had broken up during this ejection, the light components would have had neither the momentum nor the aerodynamic qualities required to fly so far. The KC W&M (who refer to the fuze as the M-6H) conclude:

Based on experience, it can, however, be argued that the parts of a shock pylon M6-H, including the firing pin, can only be found on the site in the event of a buried or covered controlled detonation. With a detonation in different circumstances, such as the accident, during which the grenade detonated inside the mortar, the parts of the detonator are not present on the site of the detonation.

The author's own experience of munition residues after detonations and explosions is that fragments of aluminium components can survive and be found in vicinity of the explosion after non-buried trials. Consequently, he would not support such a definite conclusion regarding the fate of the accident fuze. On detonation of the HE 80 grenade inside the tube, the steel casing would be likely be accelerated very much more quickly than the KC W&M proposed ballistic projection of the fuze. It is clear from the degree of disruption to the mortar tube that a detonation of the TNT main fill occurred. The detonation velocity of TNT is around 6900 m/s

[22] and the localized disruption of the steel grenade in proximity to the accident fuze would have been occurring at great speed. It is considered unlikely to produce a symmetrical disruption of the 'thinning' allowing the gas propelled ejection through the tube muzzle of an unbroken, single fuze unit in a consistent direction as proposed by KC W&M. Even if such a projection were initiated, its velocity would only have been of the order of hundreds of metres per second, not sufficient to ensure the certain escape of detonation projected steel from grenade and tube, which the KC W&M proposal assumes. The evidence from the remains of the accident mortar tube show almost complete disruption in the area of the main charge detonation and, in the author's view, whilst gas pressure induced, long distance ejection of a fuze unit may be possible it is considered much less likely than disruption and shorter distance projection of fuze fragments. Aluminium fragments will be severely damaged, whilst steel ones will be less damaged and likely will be recovered.

The author's conclusion additionally supports the later considerations of TNO who both calculated likely fuze debris projection distance and carried out trials which actually identified fuze debris [7, Section 1.2].

The second element of the KC W&M explanation is that French soldiers searched their disposal trench to produce a single set of fuze components which were presented to Netherlands personnel. These personnel, must, at some stage have been investigators, presumably from KMar., who then, proposing enormous carelessness, allowed them to be mixed with actual accident evidence, thus largely invalidating their investigation. This explanation is supported by attribution of evidence to different searches which ended in different barcoded evidence collections before mixing. The author cannot completely disregard the KC W&M suggestion that KMar ignored the basic principles of evidence management but, from his own experience of accident aftermath, considers both the French personnel collecting a set of fuze fragments and investigators mixing them with actual evidence, highly unlikely.

Further consideration of the KC W&M explanation of the origin of the fuze debris has been produced by TNO [7, Section 1.1]. It is particularly significant that the remains of the rubber cover of the sights of a Colt rifle, which video and photographic evidence proves was within two metres of the accident, was photographed being collected at the site several minutes after by Netherlands troops. Ultimately this was located with the fuze residues. This is shown in Figures 6 and 7. Since the origin of the Colt sight rifle cover cannot reasonably be disputed, these pictures of the evidence collection provide strong justification that the M6-N fuze residues with which it is pictured should be attributed to the accident. In conclusion, the author considers the proposal that the fuze remnants are all demolition remainders collected after the accident, donated by French specialists and mixed with actual accident remnants is not credible.

There is however some evidence which apparently supports the KC W&M attribution of some of the evidence and this requires consideration.

5.3 Consideration of the Origin of M6-N Fuze Explosive Train Interrupter Plate

During their considerations, KC W&M, identified a very close similarity between the explosive train interrupter plate, which they call the cover plate, identified by DSB (and TNO) as evidence remaining from the accident fuze and the same component recovered from an externally initiated explosive demolition. This is demonstrated in the Figures 8 and 9; it should be noted that the cover plate, on the left side, and attributed to the accident, had been sectioned for forensic examination. The KC W&M attribution for this component was additionally reinforced by an error in the DSB report where it was stated that this component was recovered from an accident victim's protective jacket. Such an origin would be almost unquestionable evidence of attribution but it is likely that this component was actually found on the ground and not from a jacket. Figure 10 shows evidence of what is apparently sand in the damaged thread and KC W&M pointed that this was inconsistent with the jacket attribution. It was later accepted by DSB in a formal erratum [12] that the cover plate did not originate from the jacket but from the ground during a search after the accident. However, in its assessment of the cover plate, KC W&M go beyond this discussion of origin and conclude:

Based on the oval shape and the dent in the cover plate, it may be gathered that the distortion must have been generated from outside the shock pylon M6-H, such as with a buried or covered controlled detonation.

The author agrees that there is certainly a close resemblance between the interrupter plate attributed to the accident and that from external explosive demolition but does not consider the evidence supports the view that it could not have been generated by the accident. The accident involved detonation of around 200g of TNT in immediate proximity to (though still 'outside') the fuze. This detonation would have involved acceleration at high speed of steel fragments from the mortar grenade with the forward internal thread being in particularly close location (but separated from) the interrupter/cover plate. Figure 11 shows a fragment recovered from the mortar tube which has been deeply scored by the grenade centring rings. This serves to illustrate the degree of damage to steel components the detonation could create. It is possible (but not proven) that grenade fragments as well as mortar tube fragments or high-speed ground impact produced the damage to the interrupter/cover plate attributed to the accident. The same causes may also have produced the distortion noted in the external demolition; thus, explaining the similarity. However, whilst the author accepts that no evidence exists to support this, it is also the case that no evidence exists to prove the KC W&M apparent certainty that only external demolition will produce the denting pattern as Figure 9 and 10.

This argument is especially significant as forensic examination of the 'accident attributed' interrupter/cover plate provides significant confirmation of the accident cause in the DSB report. It is the conclusion of the author that the likelihood is that this attribution is likely correct but, the KC W&M evidence is sufficiently strong that their explanation for the cover plate denting cannot be ignored. However, their assertion that this accident would provide a particular outcome in terms of both location and debris damage pattern is not supported by author experience. When explosives are initiated accidently, the damage outcome will be stochastic in nature; it will likely derive from complex interactions relating to the shock wave magnitude and propagation path. The precise confinement pattern will change dynamically throughout the event path, influencing the debris field.

6. Proposed Causes of the Accident

During the accident investigation, the DSB identified and tested a wide range of possible causes of the accident. They eliminated multiple alternative possibilities and concluded that the accident resulted from the chemical degradation of the M6-N fuze energetic materials. On the basis of an Investigation Commission (CVO) of the Ministry of Defence investigation and their own examination and testing, KC W&M concluded that the cause was quite different, being caused by mechanical deficiencies in the build of the accident fuze. At root, both explanations agree that the HE-80 with M6-N fuze was unsafe for use by Netherlands forces and did not meet the safety standards expected for NATO STANAG compliant munitions. At this level therefore, there is agreement that the accident was ultimately caused by the procurement of an unsafe weapon. However, the differences in the detailed mechanism are so fundamental as to lead to different conclusions on how the management of the weapon influenced the accident and, therefore, what actions, beyond general procurement process, would best prevent further munitions accidents.

6.1 Chemical Degradation of Detonator Energetic Materials

6.1.1 General M6-N Detonator Description and General Points

The detonator within the M6-N is a highly complex device in its own right which serves to transfer the stab/friction action of the firing pin, which causes ignition in the first stage to full detonation of powdered PETN in the detonator final stage. The vital intermediate function in generating the detonative, as opposed to the much slower, igniferous reaction, is performed by lead azide, a compound which was developed before the Second World War and still finds worldwide detonator application. The design and location of the detonator in the M6-N fuze is illustrated in Figure 12 where it will be seen the detonator consists of two metal caps. The inner cap, in intimate contact with the various chemical stages, is of aluminium whilst the outer one is of Melchior, a copper-nickel alloy. This design is entirely conventional and typical of stab detonators of the post-war period used by both NATO and Non-NATO nations. The complex explosive mixtures within it were largely derived empirically in wartime circumstances when large quantities of highly sensitive primary explosives were being processed; safe manufacture and reliable functionality were the priority. The level of scientific understanding expected in modern times was not a priority. In wartime and post war conditions, munition expenditure was so great that only relatively short service lives were required and ammunition was often sea dumped after overseas deployment. Use of empirically derived detonator compositions may still be necessary, particularly for simple, 'general munitions' such as mortar grenades but the limitations of these designs should be recognized when deciding service life and deployment limitations to meet modern safety standards. In particular, a deeper understanding of explosive chemical processes than was originally required, specifically regarding chemical compatibility, is essential if safety is to be maintained at the levels expected in NATO forces. In recent decades, European armed forces have been deployed in demanding climates. Frequently these are hot, humid environments. These deployments can last many years and the weapons issued should be capable of long service life and operation in the environments where they are needed. These observations are relevant to the M6-N fuze detonator and particularly important when considering its lead azide constituent.

6.1.2 Lead Azide Chemical Instability, Formation of Copper Azide

The DSB concludes that the initiation of the accident round was caused by a multi-step decomposition reaction originating in the lead azide in the M6-N detonator. In the first step, the lead azide reacts with water to form hydroazoic acid (also known as hydrogen azide). Hydroazoic acid is both volatile (boiling at around 36°C) and highly reactive, particularly with copper, with which it readily reacts to produce copper azide. Copper azide is a primary explosive itself with an initiation threshold lower than lead azide. The DSB report proposes that, in the accident round, initiation of copper azide was induced by the launch shock acceleration on, or shortly after ignition of the primary propelling charge. The copper azide initiation, in turn, initiated the full explosives train. This led to detonation of the HE 80 main charge (approximately 200g of TNT) within the mortar tube which spread shrapnel from both mortar grenade and launcher.

In actuality, and as the DSB report acknowledges [5, Appendix H, Section 3.2] the reaction mechanism may be more complex than the process explained above. The M6-N fuze also contains a brass (an alloy of copper and zinc) slider which houses the detonator as well as the Melchior sleeve. Any reaction with copper from either source may require promotion, for example by antimony sulphide, present from the detonator first stage compound. The various metals within the fuze (mainly steel and aluminium) may also enable galvanic corrosion promoting formation of copper azide. Additionally, the presence of tetrazene from the same source may produce further sensitization. The UK historically used tetrazene in the primer VH4/1 and found its stability in explosive compositions was highly complex with the possibility of forming volatile, unstable products at temperatures above 50°C, particularly where moisture and lead azide were present. These studies were largely aimed at ensuring safety in manufacture and reliable specification and great care was imposed by UK munition safety organisations (Ordnance Board, Chief Inspector Naval Ordnance/Defence Ordnance Safety Group) in controlling the through life environment of weapons containing mixtures of tetrazene and/or lead azide. The author notes that tetrazene often forms a very low proportion of igniferous mixtures (2 to 5% in typical UK Compositions) but its sensitizing capabilities are entirely disproportionate; the UK Services Textbook describes them as being ‘remarkable’ [2. Chapter 5]. However, being present in such tiny amounts makes evidence of its role in the aftermath of accidents almost impossible to prove.

DSB conclude that the presence copper azide, possibly in combination with tetrazene products, was the factor which enabled the initiation with the accident round.

6.1.3 Evidence for the Presence of Copper Azide in the Accident Fuze

The thermal and impact damage to the accident round remnants eliminates any possibility of direct proof that copper azide was actually present. The evidence in support of this hypothesis and a consideration of the value each element is given below:

6.1.3.1 Chemical Analysis of M6-N Fuzes

The Chemical Laboratories at TNO disassembled four M6-N fuzes and carried out visual and chemical analysis of the recovered components. Figure 13 shows a slider; the presence of corrosion in the form of copper oxide is clearly evident. Chemical analysis also confirmed the presence of significant quantities of zinc oxide (likely to originate from brass or the galvanizing coating on the steel interrupter/cover plate). This serves as confirmation that galvanic corrosion is likely taking place. Additionally, the presence of sodium ion, also in significant amounts, is consistent with promoting corrosion. The origin of this sodium was not proven but, if internal to the fuze, is considered likely to originate from inadequately washed process liquids such as a water-based machining fluid or a passivating solution. Alternatively, if the sodium had been left after external moisture ingress, this would reflect poorly on the fuze sealing arrangements. With respect to chemical species from the detonator, lead and sulphur were found in small quantities and most of the residues were found at the edge of the detonator cavity, this being consistent with migration from the detonator and the possibility of further reaction to copper azide. On two of the four sliders, scanning electron spectroscopy, found evidence of both lead and nitrogen, elements whose presence is most credibly attributed to migration of lead azide and/or lead styphnate. These observations serve as very strong evidence that the proposed failure mechanism, that is, copper azide generation, is not only credible, but almost certain to have occurred. Both copper oxide, evidencing corrosion, and the detonator lead compounds evidencing migration of reaction ingredients into the area of the firing pin recess are present external to the actual detonator. This location is particularly significant as movement of the firing pin caused by launch setback against copper azide in this recess, could start the initiation process in axial proximity to the transfer/lead charge. The pin movement exists as the arming balls have some slight freedom between the thickened sections of the firing pin (around one or two millimetres [5, Appendix J, Section 4]).

This analysis provides strong evidence that copper azide can be formed and migrate inside the fuze into locations where it can be initiated. It does not prove however that the quantities of the reaction precursors identified are consistent with the proposed accident mechanism.

TNO carried out an experiment to assess the susceptibility of the detonator to exposure to high temperature and humidity [7]. On attempted sectioning, this detonator was inadvertently detonated, unlike the control, unaged detonator which was sectioned normally, without incident. The TNO expert opinion was that the sensitiveness of the artificially aged detonator was exceptionally high, with behaviour similar to one (out of twenty) Second World War German landfill recovered detonators when sectioned. This experiment demonstrates that high temperatures and humidity do induce formation of extremely dangerous, highly sensitive compounds within the M6-N detonator. These compounds are shown to detonate on a stimulus insufficient to function a control, unstressed, M6-N detonator or 19 of 20 landfill recovered, approximately 77-year-old, detonators. This supportive evidence is consistent with a TNO translated 1957 USSR manual for this fuze which '…explicitly states that during storage and transportation, projectiles with M6 tubes must be protected against moisture, atmospheric precipitation and sunlight'. [7, Section 3]. It is difficult to interpret this stipulation other than a concern that the sealing arrangements preventing external moisture ingress into the M6 fuze design were not considered completely reliable.

6.1.3.2 Water Ingress or Process Contamination of M6-N Detonators

Generation of copper azide requires the presence of water to convert lead azide to the reactive and volatile hydroazoic acid intermediate. The evidence for this comes from different sources within the investigation reports.

The risk of copper azide generation should have been considered at different stages through the service life of the HE 80/M6-N with the Netherlands forces. The weapons procurement authority should have been sufficiently aware of the background and accident history of lead azide [1, Section 4.1] to make particular demands of a new supplier. Evidence should have been produced regarding the manufacture and quality control of the lead azide in itself and during its process flow through detonators into fuzes. Specifically, the importance of moisture control in safe lead azide application are so well known that it is considered reasonable to expect that the National Authority for Energetic Materials, in accordance with STANAG 4170 would have sought evidence of process control in this regard (Section 2.2.1 refers). This concern may have been addressed within the request for information concerning '…safety data, date of energetic substances…' made by the acquisition team but this was, apparently, never delivered. The reason this failure is particularly relevant is that clear evidence of quality failure relevant to moisture control was identified on delivery of the stock. During 2007 inspection:

'…the ammunition is composed of different sublots, partial loads lack and the ammunition is wrapped up indecently so that humidity and dirt may touch the ammunition.'

During 2007 functional testing:

'ABWM discovers among the test grenades one grenade with rust stains on the outside (Figure 28). ABWM mentions the rust in its report but doesn't associate it with doubts about the quality of the ammunition.'

The round showing the rust is shown in Figure 14 of this report. The author has frequently encountered rounds showing rust at the end of service or after arduous ‘type’ testing, however, such clear evidence of poor moisture/corrosion control with the small population of new rounds used for this programme, together with the identification of multiple sourcing (‘shock pylons come from two different factories’) should have provoked immediate attempts to find if the stock met moisture control requirements. These investigations should have examined whether moisture control within the fuze was adequate. Later examination proves it was not. The KC W&M report [8, Section 4.5.3] states:

‘In addition, in several detonators, scale of the cooling agent, used during the manufacturing was found. Also, stains were found in several detonators on different parts (shutter, shutter casing, firing pin). These stains were probably formed due to moisture ingress or reaction products of different metals that are in touch with each other.’

These examinations were carried out after the accident but the same observations would likely have been made at any time if the fuzes had been examined by specialists understanding the particular moisture derived dangers of lead azide.

From the above it can be concluded that the manufacturer’s processing or quality control were not sufficient to exclude the possibility of moisture ingress into the fuze and there is clear evidence from the corrosion products (Section 6.1.3.1 refers) and the examination of the fuzes that such moisture was present within the fuzes. The identification by KC W&M of process agent material is particularly concerning. This is because these are usually water solutions of surfactant materials (often referred to as ‘suds’) which, in the munition’s suppliers familiar to the author, would be removed by thoroughly by degreasing and effective drying processes. This suggests moisture was 'built into' the fuzes but the separate possibility of ingress of external moisture into the M6-N fuze during its life cycle since manufacture also exists.

A separate possibility is that the moisture necessary for generation of copper azide within the accident fuze permeated to the detonator lead azide from the external environment. The round shown in Figure 14 clearly demonstrates that the HE 80 ammunition was not secure from external, atmospheric or other moisture before delivery and there is no evidence of specific measures to protect the HE80/M6-N from water (as stated by the USSR 1957 manual). The issue of external water penetration into the fuze is considered in detail in the DSB report [5, Section 3.2.5] and the evidence is somewhat mixed.

Of twenty Netherlands fuzes examined after the accident, there were no irregularities proving external moisture penetration. One round did show slight corrosion on a slider and also on the detonator, which was stuck in its slider. These observations are concerning with respect to this single fuze but the author does not agree unreservedly that 'This observation is an indication that moisture can penetrate the fuze of the mortar round' since the responsible moisture could have been present in the round since manufacture. As described (Section 6.1.3.1 refers) environmental stressing in terms of high temperature combined with humidity (which the author considers could arise from internal or external sources) will cause dangerous copper azide to form. However, because of the small free volume within the fuze and thus the small amount of moisture which could be enclosed at manufacture, it is understandable that external moisture ingress is considered the most likely source. The possible leak paths are shown in Figure 15.

Of the two possibilities, ingress from the top side of the fuze (i.e. past the adhesive layer shown in red in the figure) is considered the most likely and experiments were carried out to explore the integrity of this potential leak path by KC W&M.

First, five emptied fuzes were positioned nose down and filled with water; none of these leaked, even after ‘representative’ environmental loading. A more extreme trial was then carried out where the fuzes were mounted on inert shell bodies ‘…and subjected to five drop tests from a height of about one metre with a random orientation upon impact with the ground.’ The nose down water filling test was then repeated and the result, one of the five leaking, is shown in Figure 16.

The author’s view is that, whilst this test shows that water ingress past the adhesive layer after aggressive testing can happen, the extent to which this test can be assumed representative of the environment experienced by the accident round is low; he is certainly unsure whether existing, NATO Nation sourced fuzes, would survive this test retaining their moisture integrity on all occasions. However, if the fuze sealing had frequently been of poor quality, it might be reasonable to expect that accidents due to copper azide would have occurred with greater frequency on firing the Netherlands HE 80 stock. Additionally, as the DSB report suggests [5 Section 3.2.5], the rounds being at least nine years old, the integrity of the moisture seal could reasonably be predicted to decline with age. The prolonged storage at high temperatures experienced in Mali could have exacerbated sealing adhesive weakness permitting more moisture ingress into such rounds.

In addition, the unarguable evidence of poor-quality control during manufacture does not permit complete confidence that the seal provides the moisture integrity which will guarantee safety through service life; a view consistent with the USSR manual’s requirements to protect the fuze from moisture. The author considers it plausible, but not proven, that external moisture could have penetrated the accident fuze, enabling the proposed decomposition.

6.1.4 Previous Accidents Attributed to Copper Azide

When the inadvertent initiation of any munition containing lead azide occurs, it is entirely likely that SME will identify copper azide formation as a prominent candidate to be the cause of the accident. This is because those nations which have historically placed a large reliance on lead azide within their detonators are likely to have experienced such accidents. The experience in the UK has been of several fatal accidents some of which are recounted in a TNO report [5, Appendix J]. The consequences of these accidents in the UK is that munitions design, testing, in-service management, surveillance and disposal are significantly organized around avoiding the possibility of copper azide formation. Where its presence is at all possible, for example in damaged munitions, copper azide risk will likely be the primary determinant of the safety plan for transport/local disposal. Where its generation is a certainty, for example in sunken ships off the UK coastline, the potential for it causing accidents has been a persistent concern for the author, requiring frequent review. There is no legitimate doubt that the incompatibility of lead azide with copper or its alloys in the presence of moisture produces highly sensitive compounds prone to inadvertent detonation [2, Chapter 5]. The specific chemical definition of the compound initiating particular accidents is much debated [5, Appendix J, [13] as many possibilities exist. Also, as the detonative reactive products are not stable indefinitely, in the presence of sufficient water, if they do not initiate, they will decompose to progressively less sensitive compounds, for example basic cupric azide, and eventually to inert hydroxides and oxides. This progressive desensitization is referred to in [8, Section 4.5.2:

But occurrence of copper acid in a moist environment is only a temporary effect. In a moist environment, copper acid will continue to react and turn into copper oxide. After this reaction, the crystals are no longer sensitive to shock, bumps and friction, and due

to the absorption of moisture, the detonator will be less sensitive than in its original condition.

Whilst this statement is quite true, it may lead to the incorrect conclusion that the dangerous copper azide phase will be brief and pass without incident, leaving a mortar grenade which is safe but will not detonate, the explosives train having been broken with the destruction of the lead azide. Unfortunately, numerous UK and US accidents where the presence of copper azide has been confirmed, attest that it can exist for long enough to present a critical danger. Due to 'its exceptionally strong initiating properties, viz 0.0004 g only of this substance is sufficient to detonate penthrite.' [13] a very small quantity of copper azide can lead to the detonation of the booster (noting that 'penthrite' is an alternative name for the PETN used as lead/transfer charge in the M6-N fuse). Therefore, if left indefinitely and with a renewing source of moisture in a cool enough environment, the desensitisation described by KC W&M would likely occur. The frequency and severity of copper azide attributed accidents should prevent munition owners from relying on this desensitization process when considering the safety of either service or recovered munitions. Additionally, the certain dangers of these materials have limited the amount of laboratory experimentation which could be safely attempted, therefore extreme caution wherever copper azide may exist is imposed in the UK.

The DSB report describes a Netherlands precedent (Den Helder (1974) spontaneous reaction of corroded fuzes) in some detail [5, Appendix H] and is directly relevant. The author has little to add to the analysis presented, agreeing with the conclusions, but would make one observation. The photograph (Figure 17) showing the top of a detonator from the 1974 incident munition batch shows a wide range of colours reflecting the presence of many compounds, likely including explosive ones such copper azide and inert ones such as copper hydroxide and oxide. In this case there is no doubt that the detonator initiated inadvertently, during transportation/storage of the munitions. In this weapon however, the fuze performed in its design function and there was no transmission of detonation to the main charge. As a result of multiple accidents, the absolute necessity for fuzes containing lead azide based detonators to have completely effective train interruption design has been appreciated for decades [5, Appendix J, Section 11.3]. On the basis of the incident history and current practice cited, the author concludes that precedent provides very strong evidence that the root cause of the Mali accident was production of copper azide in the accident round. However, there are additional factors which should also be considered.

6.1.5 Implications for the Presence of Copper Azide on the HE 80/M6-N Stock

The KC W&M Report [8, 4.5.1] explains that 1,138 M6-N fuzes were disassembled for purposes of destruction in Mali. Additionally, 140 were disassembled in Netherlands in support of the investigation and:

‘During the dismantling, the mortar grenades, including the shock pylons, were checked on a possible presence of crystals.’

Since no evidence of crystals was found, KC W&M consider that this serves as evidence that, if any decomposition of lead azide were taking place, it would be ‘trapped in the duplex detonator’. This viewpoint is contradicted by the analytical evidence of TNO (Section 6.1.3.1 refers) where sensitive compounds external to the detonator are evidenced. However, failure to find an unequivocally decomposed detonator (as per Figure 16) does suggest that, if the Mali accident HE-80 round had equivalent decomposition levels to the photographed Den Helder 1974 rounds [5], [14], it was quite unrepresentative of the large stock sampled by KC W&M. This reasoning would suggest that, whilst the HE80/M6-N stock may be prone to development of small quantities of copper azide, predominantly within the detonator itself, these quantities are too small to make this a plausible mechanism for the accident. The author understands this reasoning; but it must also be recalled that copper azide has exceptional detonating power, even in very small quantities. The detonator contains around 0.38 g of lead azide and, noting the evidence that 0.0004 g of copper azide can initiate detonation of PETN, the proportion of conversion does not have to be high. This would suggest that a dangerous level of copper azide could exist without being visible in the form of crystals; the staining reported [8, Section 4.5.4] and attributed to oxidation, could contain dangerous amounts of copper azide. This argument is made in the TNO report of Sept 2019 [7] where it is stated that azides '…are not always … visible. Preferably, detection is carried out by means of an iron (III) chloride test.'

In conclusion, it has been proven that elevated temperatures combined with humidity cause the M6-N detonators to become dangerous and analytical evidence shows that lead compound migration occurs out of the detonator into areas where both moisture and corrosion product of copper occur. The proposed reaction mechanism is known to have occurred historically on a number of occasions and other NATO nations design munitions policy to avoid its possibility. Scientific literature also evidences that tiny quantities of copper azide can initiate lead/transfer explosives. Therefore, the author considers the proposed mechanism highly plausible. Whilst he understands the concern of KC W&M that more compelling visual evidence of the proposed decomposition external to the detonator was not found on disassembly of large numbers of fuzes, explosives accident investigations are only rarely assisted by ready identification of large numbers of rounds unequivocally in 'near accident' condition. This is discussed above (Section 2 refers) and the author suggests that, given the fortunate rarity of such accidents to personnel from NATO Nations; when an explosive accident does occur, its causes will often include apparently unlikely elements.

6.2 Consideration of Storage and Operation Temperature of the Accident Round

The KC W&M report [8, Section 4.7.2] report contains the statement:

The KC W&M read data loggers for 3 years in Mali. The measures were never higher then over 50 °C in this period of time, which was included in the CVO report.

This evidence is in contradiction of the TNO calculation included in the DSB report [5, Appendix H] which the KC W&M reports describes as an 'unvalidated calculation model'. Since both thermal history and reaction temperature are often critical parameters causing explosives events, it is necessary to consider the evidence in some detail.

6.2.1 Storage Temperature of HE80 Mortar Rounds in Kidal

The model used to calculate the storage temperatures of the HE 80 rounds by TNO is detailed in the DSB report [1, Appendix H]. The author has considered this calculation and concluded it is entirely appropriate and properly executed. Consequently, the author has no doubt that the expected daily temperature profile and peaks for Kidal in July, 2016 (maximum temperature inside shipping container using A2 climate around 70°C, Figure 18) has been accurately modelled. Additionally, the author can testify the calculated temperatures are plausible based on his own experience of UK Munitions storage in shipping containers in A1 and A2 climates. The UK expertise (based in the Defence Ordnance Safety Group) has developed a very similar model to support UK military deployment and their calculations are routinely validated by use of sensors both external and internal to weapons packaging. The author is therefore content to set aside the reservations of KC W&M that the model is unvalidated. The author is surprised that the data loggers referred to by KC W&M never recorded temperatures above 50°C but would question whether they were appropriate in design or positioning. This view is consistent with the additional discussion [7, Section 2] where witness testimony and photographic evidence of temperatures exceeding 50°C is produced. The author is therefore content to accept a peak temperature internal to the shipping container of 70°C was experienced and, further, since Kidal in July fits the climate zone A2, an induced maximum temperature within the ammunition stock of 60°C is an entirely plausible and perhaps slightly conservative estimate. In accordance with the TNO calculation, it is likely this temperature was experienced for around four or five hours for each July day in Kidal. This duration is quite sufficient to ensure temperatures above 50°C will be conducted into all the explosive materials in the mortar round including those housed in the fuze. The author is therefore clear that the Design Authority temperature maximum for the HE 80 round (maximum 50°C) was repeatedly exceeded during the storage experienced prior to the accident.

6.2.2 Temperature of the Accident Round

The temperature of the ammunition involved in the accident is also modelled by TNO in the DSB report [5, Appendix H]. The calculation uses the basis of an ambient temperature of 40°C as the baseline temperature, to which is added the effect of solar radiation from the bright sunlight acting on a green painted, steel grenade body with an aluminium fuze. TNO conclude that a temperature of 80°C could be induced in full sunlight for the ammunition. However, since it is known the ammunition was handled using bare hands, TNO conclude the radiated heating was less than this maximum. They concede that an entirely accurate modelling of the grenade and fuze temperature under the precise local conditions at the time of the accident is impossible and conclude:

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.

This estimation was tested experimentally in Netherlands [5, Appendix J, Section 9] where it was demonstrated that, from a baseline of 28°C, the steel case of an HE 80 round reached a maximum of 42°C in around 60 minutes with the fitted aluminium fuze reaching 47°C in the same time. Since this experiment was carried out under ‘solar radiation at 'Dutch intensity levels' impeded by cirrus clouds’, this experiment is entirely consistent with an assumption that, at the time of the accident, the M6-N fuze significantly exceeded 60°C. The author concludes with certainty that the Design Authority 50°C maximum was exceeded.

6.2.3 Consideration of Design Authority Maximum Temperature Limit

It is stated above (Section 2 refers) that disregarding Design Authority recommendations is likely to increase the risk of an accident occurring. It is appropriate to consider the origin of this Design Authority upper temperature limitation.

The DSB report [5, Appendix H] includes the following explanation:

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]

Whilst this provides the arithmetic explanation for the 50°C limit, this is not a scientifically based argument and the design requirement or failure mechanism underlying the quoted limit for the M6-N fuze is not given. In many NATO nation designs, the upper temperature limits for mortar ammunition generally originate in either the stability of the propellant powder or the maximum pressure produced by propellant combustion. It would be unprecedented in the author's experience for the 50°C limitation to originate in detonator chemical stability or fuze interruption limitations. Those explosive compounds used in the HE 80 grenade and its M6-N fuze are the same as those used in NATO nation designs capable of use in A1 climate (to 71°C). Unless the actual explosives used by Arsenal in its products are inferior in quality, for example due to impurities or age since original manufacture, the author doubts that the 50°C limit originates in a specific concern regarding fuze chemical stability or fuze safe operation. However, as stated, Design Authority recommendations should only be set aside with full understanding of the safety risks being taken and this was not the case for the HE80 in Mali.

6.2.4 Consideration of Temperature in the Proposed Accident Mechanism

It is accepted that the accident round saw temperatures above those supported by the Design Authority in both storage and use. It is necessary to consider the consequences of such an exceedance on the safety of the HE80/M6-N mortar grenade.

6.2.4.1 Chemical Reaction Rate and Activation Energy

For chemical processes relevant to explosives, the rate of a reaction will be increased as temperature increases. A general approximation which can often usefully be applied is that reaction rate doubles for every 10°C increase in temperature. This is referenced in the DSB report [5, Appendix H, Section 3.2.2] where it is applied to rate of corrosion inside detonators.

The possibility of further reaction with hydroazoic acid to produce copper azide is also discussed. This effect of temperature is understood in terms of the need to overcome an Activation Energy barrier for a reaction to proceed. This can be illustrated (in a very generalised argument) for the purposes of chemical reactions (including detonations) as Figure 19 [2, Chapter 2]. When the temperature of the reacting compound (in this case, unreacted explosive) is increased, the initial energy (left side of Figure 19) is raised with respect to the Activation Energy 'peak' which is unchanged, thus reducing the energy barrier and allowing the reaction to proceed faster. This acceleration of rate is illustrated, again from the UK Services Handbook of Explosives in Figure 20. This diagram illustrates the general rule that primary explosives, such as lead azide and lead styphnate (both present in the M6-N detonator first stage) tend to be more reactive within the lower part of the normal service temperature range but do not usually have a critical temperature above which rate of reaction increases dramatically. The latter does occur where secondary explosives, such as RDX in the M6-N fuze booster or TNT in the main charge, are heated beyond a critical point. However, in the case of the accident round, the author considers the temperatures experienced during storage and use were too low to cause the secondary explosives to deteriorate chemically or undergo exudation. Additionally, the temperatures seen should not have caused dangerous reaction to the primary explosives present unless moisture had been introduced into the fuze either during manufacture or, via ineffective fuze nose sealing, during storage.

From this very general explanation, it can be understood why reactions generally proceed faster at higher temperature and any decomposition of lead azide to enable copper azide production would have been assisted at elevated temperatures such as experienced in Mali. Also, as noted, the high temperature would assist the migration of the volatile and reactive hydroazoic acid to the vicinity of copper in the fuze and also possibly in combination with tetrazene. However, it is not possible to quantify the extent of this thermal reaction rate acceleration and, whilst the general rule of doubling for every 10°C may have been true, it is speculation to go beyond noting the reaction rate, and thus the amount of copper azide produced would increase with temperature. Whilst the decomposition of this copper azide (to more inert products) would also be increased, its extreme friction and impact sensitivity as well as its exceptionally strong initiating properties [13] would not be decreased and may reasonably be assumed to have been increased by temperature.

6.2.4.2 The Effect of Temperature on Explosive Train Performance

In addition to the effect of temperature on chemical reactions and explosive decomposition, there is another consideration with respect to the accident in Mali. That is, whether the high temperature of the accident round enabled the detonation of the TNT main charge by functioning elements of the explosive train which would not have enabled the full detonation at lower temperatures. This is described in the DSB report [5, Appendix H] and the figure reproduced as Figure 21:

'…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.'

The author agrees with this interpretation of the data presented but notes the stimuli used was impact and not shock initiation, which is more relevant to the proposed accident mechanism. There is only limited relevant work on temperature effects on the accident explosives but, one study showed the effect of temperature on detonation propensity is not always so pronounced.

Figure 22 [15] used barrier thickness at which 50% go/no go detonative response is achieved at across a wide temperature range. The results, those for PETN and RDX, are both relevant to the HE 80, show very much lower temperature sensitisation even over a higher temperature range. There has been more recent work which, for RDX explosives, suggests shock sensitivity actually decreases in the range 25-110°C because of binder softening [16]. It is considered therefore that temperature is not a primary determinant of detonation susceptibility. If another, not directly temperature related factor, for example, the presence of initiating sensitizing sites (known as 'hot-spots') is dominant, the effect of increased temperature on explosive train functionality may be marginal. This observation is significant because attempts to reproduce the accident both at ambient (12°C) and elevated temperatures (70°C by TNO [5, Appendix J, Section 2] and 30 firings at 63°C by KC W&M [8, Section 4.7.3]) all failed to detonate the M6-N fuze booster and thereby would not function the main charge as actually occurred in the accident. This failure has been considered a cause to doubt the chemical mechanism proposed within the DSB report for the accident. The author would suggest that the explosives train functionality, particularly for the RDX/wax booster, may be significantly less sensitized by the temperatures experienced in Kidal and as suggested by Figure 21. These trials are considered in Section 6.9 below.

In the DSB report [5, Conclusions, Section 1] it is stated:

Because of the too high temperature of the grenade, the detonation shock could continue to the rest of the explosion chain, which led to the detonation of the main charge, at the bottom of the mortar.

With respect to the role of the elevated temperature in the accident, the author considers that, if the presence of copper azide in dangerous quantities is accepted in the accident round, it is not possible to make confident quantitative projections. The exceptionally high sensitivity of copper azide prevents systematic evaluation of its thermal properties and very little data exists. It is reasonable, on the basis of a general activation energy explanation as outlined, to predict temperature will increase both copper azide sensitivity and its initiating properties. However, the author could not find data which can quantify this expectation and it may be too dangerous to attempt the necessary experiments. Therefore, there is little evidence to verify whether the actual temperature exceedance was a primary or secondary contributor to the accident round detonation.

The effect of temperature exceedance on the firing of the mortar grenade may also have had one influence not referred to in the TNO analysis. Propellant performance is generally rather temperature dependent [17] and firing the mortar grenades above 60°C may result in the propelling powder producing an initial acceleration in excess of the design intent. The accident round tail, including the chamber which held the primary charge, was recovered and sectioning showed no evidence of failure. Therefore, the author considers this was not a major factor in the accident although it is very likely that the pressure within the mortar tube when firing the accident round would have been higher and achieved more quickly than would result if the Design Authority limitation of 50°C had been followed. The consequence would likely have been a greater setback load experienced by the M6-N fuze producing a greater initiating shock. The author considers this would likely have been a minor factor with no large influence in the accident but feels it should be mentioned for completeness.

With respect to train interruption tests which have been carried out, their temperature dependence is a function of the energetic materials present in the trial rounds. If these did not contain quantities of copper azide similar to those proposed to be present in the accident rounds, they do not provide proof of the explosive train sensitivity of the accident round.

6.3 KC W&M Explanation of HE80/M6-N Unintended Initiation

The KC W&M report [8] records that, separate to the OVV Investigation, which led to the DSB report, an Investigation Commission (CVO) of the Ministry of Defence carried out investigations of the mortar accident in Mali:

CVO itself assumes that a mechanical deficiency caused by a manufacturing error is the most probable cause of the armed detonator M6-H. (Author note; KC W&M fuze designation)

The report then provides a justification for this conclusion using measurements made of M6-N. In early 2018, 1,138 fuzes were disassembled in Gao and the components measured. Additionally, 140 fuzes were dismantled in The Netherlands (Section 6.1.5 refers). Figure 23 shows the breakdown of the components with indications of the measurements made. A total of 6460 measurements were made and the dataset analysed. KC W&M present their measurement of firing pin and non-return valve lengths as critical to the cause of the accident:

The firing pin has an average length of 29 mm (measured from the top to the bottom of the bullet's location and a tolerance of 2.42 mm; this tolerance is quite large. The non-return valve has an average length of 21.02 mm and a tolerance of 1.92 mm; this tolerance is also quite large. The length of the firing pin in combination with the length of the non-return valve must give certainty that the arming bullets remain secured. The collective (added up) tolerance of the firing pin and the non-return valve may never be bigger than the diameter of a bullet. If the added tolerance is bigger than the diameter of an arming bullet, this arming bullet will drop out of its location and the detonator is unintendedly armed. In the tolerance of the firing pin (2.42 mm) and the tolerance of the non-return valve (1.92 mm) are added up, then the total tolerance is 4.34 mm. The

diameter of the arming bullets is 3.95 mm. This added up tolerance is bigger than the diameter of an arming bullet.

If this argument were correct, such a combination would not house the arming balls, the firing pin movement would then allow the slider to locate the detonator under the pin and the fuze would be in armed condition. When an armed round is dropped into the mortar tube, impact with the firing pin at the base of the mortar tube (Figure 2) would cause the fuze firing pin to stab the detonator. This would produce full detonation of the explosive train within the launcher as occurred in the accident. However, consideration of the dimensions as quoted suggests the proposal is likely incorrect. The statements defining the lengths of both firing pin and non-return valve are unclear, but apparently describe a range of lengths; they certainly do not describe a tolerance. Clearly, for the mechanism proposed to be valid, only those firing pin and non-return valve combinations leading to minimum overlap of the firing pin housing, permit the escape of the arming balls. A TNO assessment [7] supports interpretation that KC W&M are using the total range 'total tolerance (4.34 mm) is based on the difference between the maximum and the minimum length of the firing pin'.

A further point is relevant: the use of the word 'tolerance' in describing a mechanism means 'an allowable amount of variation in the dimensions of a machine or part' [18]. Use of the term 'tolerance' ('tolerantie') in the argument presented by KC W&M implies that the dimensional variation originates in the design specification when it does not. The values are measurements made under the control of KC W&M and, although they may well accurately define the sample measured (though it is noted that some of the measurements may be difficult due to component shape) they cannot be considered as representative of the design intent as administrated by the Design Authority, and manufacturer, Arsenal JSCo.

The author does not have access to the original KC W&M data; however, this has been examined by TNO [19] and they state:

The results are laid down in the KC W&M report and in an Excel file. TNO analysed these data and establishes that the mathematical substantiation of KC W&M is incorrect and that, based on these data, it can't be concluded that the deviation of the measures is inadmissible. It is a fact that, with large measurement deviations as mentioned by KC W&M, the mechanism of the shock pylon can't be composed.

The reasons for TNO dismissing the KC W&M proposed failure mechanism are quoted below [7, Section 4]:

TNO studied the underlying mathematical substantiation and comes to the conclusion that it is incorrect. The 'total tolerance (4.34 mm) is based on the sum of (a) the difference between the maximum and the minimum length of the firing pin (2.42 mm) and (b) the difference between the maximum and the minimum length of the non-return valve (1.92 mm), as measured for all pins and caps. However, the sum of these ranges is the wrong inspection parameter, because it is the deviation of the measure of the composite combination of firing pin and non-return valve that is determining for the safety of the mechanism. The assessment of the chances for unintended arming must, therefore, be based on the measurements of unique pin-cap combinations. It can, therefore, not be concluded, based on the mathematical substantiation of KC W&M, that the deviation of the measures is inadmissible.

The author agrees with the TNO conclusion (crucially, it is the firing pin and non-return valve dimensions in any given fuze build that defines the freedom of the arming balls -assuming these are of fixed diameter- to escape) and rejects the KC W&M failure mechanism on this basis. Additionally, although the author does not have access to a set of components, consideration of the fuze design (Figures 4 and 5) makes it apparent that very major dimensional deviations would make it impossible to construct the fuze mechanism. TNO state [7 Section 4]:

TNO established experimentally that when there are large measure deviations, as mentioned in the KC W&M report, the mechanism of the shock pylon can't be composed.

On this basis, the specific failure mechanism proposed by KC W&M [8, Section 4.5.4] and justified by their measurements is rejected by the author.

However, other KC W&M points require further consideration. In particular, the violent, full charge detonation which occurred in the accident does appear more consistent with the operation of the explosive train in the detonator armed position than the experiments in the 'safe' condition carried out during the accident investigation. Also, the large degree of variation in their measurements of fuze component dimensions KC W&M combined with their own (plus prior) HE 80/M6-N, quality concerns (Section 3.6 refers) supports a reluctance to dismiss entirely a mechanical explanation of the accident. Their concerns about Arsenal JSCo quality control are legitimate, but they have not actually provided evidence of a specific, credible mechanical failure mechanism.

6.4 Mechanical Failure Modes of the M6-N Fuze

The components which control the 'safe/armed' status of the M6-N fuze are pictured in Figure 24. The centre line of the cross-pin is shown and it is the movement, following the zig-zag path, of the non-return valve down and up past this pin which should ensure arming is only possible after the HE80 round decelerates after launch and thus provides the safe separation distance. If a fuze build were possible where dimensional mismatch allowed the bottom of the non- return valve to sit above the cross-pin whilst still enabling the valve movement with respect to the pin housing, it would be possible to arm the fuze with a low external shock. Figure 25 shows such a build made to show this by KC W&M and the limited retention of the arming balls is visible. Similarly, if it were possible to build a fuze without a cross-pin fitted, the same condition could occur with very limited external shock permitting arming of the fuze. Attempts by TNO to remove the cross pin [5, Appendix K] proved that this requires such a great force that it can be considered unlikely to have occurred in service. The author is content to eliminate this particular possibility.

If, however, it was actually possible to build the fuze with the cross pin below the non-return valve zig-zag slot, or if the pin were never fitted to the firing pin housing, it could be possible for fuzes in armed condition to enter the Netherlands stock. This would require Arsenal JSCo manufacture operations to fail in at least three separate respects as evidenced in their information supplied to DSB [5, Appendix L]:

- The in-process control operations during the assembling processes that Arsenal state are carried out manually on 100% of the manufactured assemblies;
- The free spring-loaded motion of the firing pin mechanism that is 100% controlled, ensuring correct assembly and operational reliability;
- The acceptance process carried out for each lot, including a jolting test and a drop test (3 metres onto a steel plate). Both require post-test inspection to prove ‘safe’ arming status.

Various evidence has been produced of the poor quality and questionable practices (multiple suppliers, being the most concerning to the author) during the accident investigation. However, failure in both, apparently 100%, controls, where the proposed cross-pin misplacement or absence would be visually obvious would be of an order worse in neglect in manufacturing control. The author considers the possibility of such a fuze build causing the accident as being of very low probability, but not entirely impossible. This view also appears to be the one advocated by TNO [7, Section 5]. However, assuming the failures in the Arsenal JSCo processes detailed above, it is necessary to consider the implications of the possibility of the fuze being mis-assembled as proposed and delivered to the Netherlands Armed Forces.

6.5 Implications of Cross Pin Not Engaging Zig-Zag Slot in a Mortar Grenade

As part of the accident investigation, TNO carried out a systematic evaluation of the forces required to arm and function the M6-N fuze in its design operation with the HE 80 mortar grenade. These calculations are discussed below (Section 6.7 refers). TNO also carried out further calculations to predict the fuze behaviour with the detonator in the armed condition [5, Report Appendix F, Annexe B]. TNO state:

The compression of the spring after the mortar grenade has fallen into the barrel, is shown … where the vertical axis is maximised to 14.8 mm. The maximum compression of the spring is, however, 20.9 mm. From the calculation follows that the required compression of the spring is sufficient for an impact of the firing pin on the duplex detonator.

Therefore, this calculation leads to the conclusion that every round with a fuze in the armed condition will detonate when dropped into the mortar tube. When considering the proposed failure mode, the absence or non-operation of the cross-pin significantly lowers the frictional resistance to the non-return valve to movement. This has been subject to experimentation and leads TNO to the conclusion [5, Appendix K]:

In addition, it was experimentally established that for a shock pylon, once it’s armed, the firing pin hits the detonator during a fifteen to twenty centimetres drop, so, with a considerably smaller shock than required for realising the arming of a shock pylon

without a cross pin. Therefore, it seems improbable that a mortar grenade with a shock pylon, once it's armed, can withstand transportation without detonating on the way.

A further consequence of the certainty of detonation when an armed round is dropped into the firing tube is that such an accident might be seen earlier in the firing sequence than one initiated by the set-back shock produced by firing gas pressure profile. This would explain why the damaged launch tube produced by a KC W&M test (detonator armed) would show more damage near the base plate and a longer muzzle end section than the remains from the accident. This has been identified by TNO [5, Appendix J, Section 4.2] who contrasted the armed test evidence with the less damaged base plate structure but shorter remaining tube length from the actual accident; suggesting the accident occurred further up the launch tube and thus less likely to be caused by an armed detonator. The comparison is seen in Figure 26 but measurement evidence would be required before greater weight could be placed on this argument.

Therefore, in addition to every round in the proposed condition detonating once it struck the bottom of the launch tube, they would have been highly susceptible to detonation during any handling or transporting shock due to the reduced resistance of the proposed cross-pin free non-return valve. It is known that the accident round did survive the road (or possibly helicopter) journey to Kidal [5, Appendix K]:

In Mali, the mortar grenades were transported by lorry from Gao to Kidal (note: Sometimes, grenades are also transported by helicopter). During this three day journey (on unpaved roads), the grenades were exposed to heavy shocks and vibrations.

Therefore, if the proposal of missing or ineffective cross-pin due to manufacture error is correct, it is surprising that an inadvertent initiation had not been experienced in the 24,500 grenades fired successfully or in transport of the remainder. There is also no evidence that an armed fuze was found on the visual examination and disassembly of 1278 rounds by KC W&M; presumably such a discovery would have been obvious, not least from the ‘rattle’ of the free arming balls within the fuze. Since such a discovery would be incontrovertible proof of the CVO/KC W&M proposed mechanism, the author thinks it likely none were found. Additionally, TNO evidence [5, Appendix K, Figure K3] shows that ‘armed’ would be easily differentiated on X-Ray examination from ‘safe’ status and, again, none have been reported. Therefore, failure to actually find rounds in similar condition to that proposed (as shown in Figure 25, right hand side) is a major argument against the mechanical explanation. Since the Netherlands rounds originate in a single large delivery from 2007, there would likely have been a high commonality of component batching and date of manufacture. Yet no other round, including the other ex- Kidal rounds examined after the accident – (batch, 04/07 A11) have been found with the same defect. The same argument may be applied to the chemical mechanism but less persuasively; the chemical explanation would suggest that old rounds with cumulative damage permitting moisture ingress and explosive migration are the most dangerous. The mechanical explanation would, suggest dangerous rounds could be distributed at random through the stock as a function of anomalous components and aberrant process control. On that basis, they would have been more likely to have been encountered in the Afghanistan deployment where much of the stock was fired. If, however, it is considered the accident round was either the only, or one of very few rounds with the mechanical defect, it is unlikely this defect would have been encountered during ‘type classification’ testing since this uses relatively small numbers to evaluate the design itself, not eliminate the possibility of occasional, dangerous process failures in manufacture. It would have depended on other issues such as quality or explosive train interruption to prevent the HE 80/M6-N entering Netherlands service.

6.6 Evidence of Armed or Safe Status of the Accident Round

The most significant distinction between mechanical and chemical explanations for the accident is, in the former, the detonator is in the armed position and in the latter, the ‘safe’ position. Consideration of the physical evidence, that is, the recovered debris from the accident fuze, would ordinarily have been unequivocal. The evidence is now considered on the basis, following the author’s conclusion (Section 5.2 refers) that it does originate from the accident. The order of evidence used in the DSB report is followed:

6.6.1 The M6-N Inner Fuze Wall

The aluminium piece attributed to the accident (shown on the right-hand side of Figure 27) can be compared the comparable piece recovered from a fuze fired in the armed condition (from a TNO experiment, no TNT main charge). The accident fragment clearly shows the rectangular slider outline with the imprint of the slider spring being exceptionally pronounced. Since springs are generally made of steel (although not universally; the material is not identified in the investigation report), the attribution of the shape to a compressed spring, as would be expected in the ‘safe’ position is considered reasonable. If the slider and spring were in the armed condition, it is not unexpected that the detonator force would project this piece back in the direction of the inner fuze wall. However, with the separation distance attenuating the force, impact might be expected to leave a less distinct impression. This explains the fainter marking of the armed position comparator piece. It is not disputed that this evidence was produced with the detonator in the ‘safe’ position.

6.6.2 The Firing Pin

The firing pin attributed to the accident is (shown on the right-hand side of Figure 28) compared the firing pin recovered from a fuze fired in the armed condition (centre, from a TNO experiment, no TNT main charge) and an unused firing pin (left-hand side). In the ‘safe’ position the point of the pin rests in the slider recess, therefore detonation (and thus sideways projection of the slider) would be expected to shear the pin. In the armed position, it is expected the pin would be projected upwards thus presenting a different damage pattern. It is not disputed that this evidence was produced with the detonator in the ‘safe’ position. In this case, the author is not certain that armed position firing would always produce a firing pin as shown in centre of Figure 28 and would require more samples to accept this unreservedly. However, the evidence is sufficiently strong for him to accept the accident evidence firing pin was produced by detonation in the safe position.

6.6.3 Firing Pin Housing

The firing pin housing attributed to the accident (shown on the right-hand side of Figure 29) can be compared with the firing pin housing recovered from a fuze fired in the armed condition (centre, from a TNO experiment, no TNT main charge) and also an unused firing pin housing (left-hand side). With a detonation originating in the armed position, it is expected that this component would be disrupted in a radially symmetric manner and this is proven experimentally (centre picture). Where the detonation proceeds from the ‘safe’, off-centre, position, this disruption will be more likely asymmetric and this is consistent with the accident attributed evidence. It is not disputed that this evidence was produced with the detonator in the ‘safe’ position and the author agrees with this attribution.

6.6.4 Explosive Train Interrupter Plate/Barrier

In the M6-N fuse design, the slider positions the detonator directly above the interrupter plate. In the armed position, the detonator is central and in the ‘safe’, it is off-centre. The design intent is to separate the detonator from the lead/transfer charge (fixed centrally within the lower face of the interrupter plate) sufficiently that unintended initiation of the detonator will not communicate detonation to the lead/transfer charge. The interrupter plate attributed to the accident is (as shown on the right-hand side of Figure 30) compared with the interrupter plate recovered from a fuze fired in the ‘safe’ condition (centre, from a TNO experiment, booster present but no TNT main charge) and an interrupter plate from a fuze fired with the detonator in the armed position (left-hand side). The accident plate, which was sectioned for forensic analysis, clearly shows an off-centre imprint matching the detonator ‘safe’ position. The difference between these two and with the detonator in the armed position (left hand side) is very marked. In the latter, a substantially bigger, though reasonably symmetrical, hole is made. This author considers this to be compelling evidence that the detonator was in the ‘safe’ position when the right-hand interrupter plate fuze was initiated.

An additional factor is important in considering the interrupter plate evidence; both the safe position experiment and the accident evidence plates show the detonator actioning has caused the lead/transfer charge to react and the steel which was above this charge has been swept away. The interrupter plate is shown in section (in Figure 31) and, as shown in Figure 30, it can be seen that a 0.3 mm section has been lost. This is contrary to the design intent and the interrupter plate has failed in its function. In the DSB proposed mechanism, this enables a detonation of unstable copper azide, caused by launch set back shock, to be transmitted to the lead/transfer charge which, in turn led to the booster and main charge detonation. This aspect of the evidence is discussed in detail in Section 6.8 below.

6.6.5 Overall Conclusion from Evidence from Accident Fuze

The evidence the DSB consider recovered from the accident is quite clear; the residues are from an HE 80/M6-N which detonated with the detonator in the safe position. The KC W&M report does not disagree, but considers the evidence originates from a demolition explosion. The author does not consider this credible (Section 5.2) and accepts there is a very high probability that the evidence originates from the accident. Therefore, given the evidence from the fuze inner wall, firing pin, pin housing and interrupter plate, it is considered with an equal probability that the fuze was in the safe condition when the accident occurred.

6.7 The Design of the M6-N Fuze

The M6-N fuze does not meet the requirement of fully effective train interruption although DSB and KC W&M disagree about the role this played in the accident. It is appropriate to consider the evidence regarding the overall effectiveness of the design of this fuze to assist consideration of the KC W&M view that other, unconnected, design deficiencies, caused the accident.

TNO carried out series of experiments and calculations concerning the safety of the mechanical aspects of the M6-N fuze [5, Appendix F]. The spring constant (Part 6, Figure 4) was calculated and also measured, although the difference was not great (144.7 N/m calculated versus 178.8 N/m experimentally) TNO used the experimental measurement as this included the rotational element imposed by the cross-pin movement along the zig-zag slot. Using this constant with the appropriate component weights, fuze and launch tube dimensions, physical and ballistic forces, TNO calculated the conditions necessary to arm the M6-N fuze. It is apparent that the design is competent to enable safe firing. For example, vertical drop of the mortar grenade into the launch tube enables non return valve movement of 4.0 mm. This compares to the 8.9 to 9.6 mm movement range to release the delay sleeve retaining ball in the first stage of the arming sequence. Further calculations demonstrate the arming sequence will be reliably started by firing of the primary propelling cartridge but that fully armed status cannot be achieved until the launch acceleration is lost as the mortar grenade exits the launch tube. TNO also calculated the drop heights (relevant to mortar grenade handling) and calculated a drop height below 1.25 metres would not arm the mortar grenade. This calculation is conservative in that it does not fully take into account frictional forces in the fuze mechanism and the failure to arm the mortar grenade during experimental drops of up to 4.5 metres is not surprising. It is noted that Arsenal JSCo state [5, Appendix L] that each batch is tested to confirm it is not armed on 3 metre drop and this aspect of the design is therefore confirmed. In addition, TNO also modelled transport shock as would be required under method 403 in [AECTP 400, 2006] and concluded the fuze would not arm. This requirement is aimed at gaining assurance that the rounds will be safe after undergoing shocks which might be experienced in transportation. These calculations were validated by a series of tests carried out by KC W&M whereby drop test, loose cargo test (test 406 in AECTP 400, 2006), impact test, sinus sweep vibration test and vibration test, tactical wheeled vehicle-all terrain (method 401 of AECTP 400) were tested on HE 80/M6-N mortar grenades without arming of the fuze.

The author has checked the methodology and calculations performed by TNO and considers that they are appropriate and properly conducted. He concludes that, with respect to its mechanical elements, the design of the M6-N fuze is competent to achieve the level of safety accepted for a fuze of this general type. Fuze safety requires that the explosive aspects of its design and component specification must also be competent if safety is to be assured.

6.8 Explosive Train Interruption Requirements

It is apparent from the information presented in Section 6.6 that the M6-N fuze does not meet the critical explosive safety requirement. The necessity for explosive train interruption was explained in Section 2.2.2 above; the relevant NATO Standardisation Agreement being STANAG 4157. The criteria to pass Explosive Train Interruption tests are detailed in AOP 20 whereby:

'There shall be no detonation, fragment penetration, perforation, burning, charring, scorching or melting of any explosive component after the explosive train interruption'

TNO designed an appropriate test arrangement and carried out the testing using both detonation cord and firing pin stimuli to initiate the detonator of the M6-N fuze [5, Appendix I]. An example of the results is shown in Figure 32 where the off-centre indentation made by the detonator in the interrupter plate is clearly seen (picture lower left). As can be seen (pictures upper right, lower left and lower right respectively) the transfer/lead charge has completely reacted, leaving no remains although the base of the cup in which it was held has been projected into the booster. The card cover from the upper booster charge face has been partially burned off but the booster charge itself (RDX/wax explosive) has not reacted.

TNO sentenced their experimental results following the AOP 20 criteria and concluded the data set constituted a 'NO PASS' result:

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.

The author has considered the data presented and would have sentenced the results similarly. On this basis the M6-N fuze fails to meet agreed NATO standards and the author would have approved neither importation of the fuzes nor their deployment.

It is noted that that the mechanical aspects of the fuze appear competently designed and the TNO calculations and measurements confirm this. It is considered surprising that the explosive train interruption plate so clearly fails to provide assurance against full initiation with the detonator in the safe position. The design apparently originates from USSR in the 1950's [TNO Memorandum] and its deployment was likely, by modern standards, in huge numbers; reflecting the then Warsaw Pact force levels. The marginal safety of this design would create dangers in use and transportation. The author has consulted UK expertise in the formulation of lead/transfer PETN and booster RDX/wax compositions, but no likely explanation for the design failure was found. However, one speculation is that, either the chemical nature of the compositions employed or the proportion/type of wax used has changed since the fuze was designed. In the first case, for example, a tetryl pellet in the role of the lead/transfer charge would be expected to be less likely initiated/ignited with the detonator in the safe position. Alternatively, modifications of the wax type and/or proportion in both lead/transfer and in the booster charge could influence initiation takeover performance. The UK spent considerable effort in developing its RDX/wax ('Debrix'; DEsensitised BRIgewater eXplosives) boosters and found initiation sensitivity and explosive train function were highly sensitive to wax type, application and quantity. On this basis it might be considered that, whilst the drawings used to construct the mechanical aspects of the M6-N fuze may have been preserved effectively through many decades, the chemical compositions and/or sensitivities of the explosives used may have changed since original design definition. The author emphasises that this is only speculation and has found no UK data which would evidence this explanation for the explosive train interruption or pronounced variability in violence of response identified in the full set of explosive train interruption trials by TNO and KC W&M.

6.9 Failure to Achieve Booster Initiation in Explosive Train Interruption Trials

The chemical decomposition mechanism proposed by DSB requires that the detonator be in the safe condition in the accident round. This mechanism proposes that, reaction of that chemically degraded detonator was transmitted through the explosive train interrupter plate and initiated the lead/transfer charge and in turn the booster and main charge causing the accident. This mechanism is illustrated in Figure 33, left hand side where it can be compared with explosive train operation with the detonator in the armed position on the right-hand side.

The failure to initiate the booster in the two TNO trials (carried out at 12°C) where a booster charge was fitted, and in a later single repeat trial carried out at 70°C [5, Appendix J] in closer emulation of the accident condition, causes reasonable doubt in the ‘safe’ position detonation mechanism (shown on the left-hand side of Figure 33). In contrast, every test of the M6-N fuze with the detonator in the armed condition produced full detonation of booster and main charge (where fitted) and there is no doubt from the photographic and physical evidence that the accident was such a detonation. To explore this issue further, KC W&M carried out 30 explosive train interruption tests at 63°C and none produced detonation of the RDX/wax booster charge. In some experiments the booster was fully or partially combusted (Figure 34) but in all these cases there was no deflagration to detonation transition. This evidence is a major element in KC W&M rejecting an explanation with the detonator in 'safe' position and proposing that only an armed detonator position (as Figure 33 right hand side) is consistent with the accident.

These additional tests were considered by TNO, who noted the greater violence (for example, in RDX combustion) than was seen in their own tests. They concluded [7, Section 3]:

TNO is of the opinion that this may indicate a vehement reaction of the explosive in the booster, like a combustion or deflagration, and this is an indication for doubtfulness of the inherent safety of the M6-H shock pylon. Combustion or deflagration of the explosive in the booster is possibly a reason for combustion or deflagration of the TNT main charge, with, in worst case scenario, a transfer to detonation of the main charge (by pressure increase as a result of entrapment in a steel sheathing).

Their interpretation is that that the most violent reactions in the KC W&M experiments may actually support the possibility of main charge detonation.

The author examined the full data set of TNO and KC W&M explosives train interruption trials and concludes that it is not possible to be completely certain that the 'safe' detonator position will enable the main charge detonation but he considers that this explanation is most consistent with the overall evidence.

One possibility may be that the key variable is the extent to which the energy of the lead/booster charge is partitioned between deflagration and detonation. When the detonator is in the armed position (Figure 33, right hand side), the PETN booster is efficiently detonated, maximum shock energy is transmitted to the booster which detonates in turn. Where the detonator is in the ‘safe’ position, its energy is to some extent attenuated and, although ignition of the PETN is achieved in most cases and the 0.3mm steel on the interrupter plate fully or partially ‘swept away’, only a low, if any, proportion of the lead/transfer charge decomposition actually reaches full detonation velocity. In the case of a detonator with significant copper azide content however, a much more violent detonation will occur (as previously, ‘its exceptionally strong initiating properties, viz 0.0004 g only of this substance is sufficient to detonate penthrite.’ [13]) with a more effective lead/transfer charge initiation leading to a greater probability of booster, and in turn, main charge detonation. Additionally, should migration of copper azide extend significantly along the slider, its efficiency in promoting detonation of the PETN lead/transfer charge could be enhanced, increasing the probability of booster detonation.

On this basis, only those few, likely late service, fuzes which had been moisture exposed via damaged or ineffective adhesive sealant would have sufficient copper azide to produce booster detonation on the explosive train interruption test. The majority of rounds, containing predominantly or entirely lead azide would not be effective in detonating the booster in this test. Where copper azide had been produced but had decomposed further to more inert compounds, firing the round would have produced a ‘dud’. Unfortunately, it is not known whether the dud rate was increasing in the HE 80 rounds but it is known that a dud was fired the day of the accident and that the dud rate had caused KC W&M concern (‘the above-average number of duds with these mortar grenades’ is recorded in [8, Section 4.5.3]. However, the author emphasises that this proposal is conjecture and, as very few experiments have been carried out under controlled conditions with copper azide, it is not possible to quantify the extent of its ‘exceptionally strong initiating properties’.

7. Questions from EMSOM

(1) What can be concluded, based on the investigation data, about the cause of the premature detonation of the accident grenade and the circumstances that have contributed to that cause? If several causes and circumstances are possible, please indicate the extent of probability of the different causes and circumstances.

The author concludes that the most likely cause of the premature detonation of the accident mortar grenade was the chemical degradation of the lead azide within the M6-N fuze detonator to produce the unstable and strongly initiating copper azide explosive. This compound was likely concentrated in the detonator, but analytical evidence supports the possibility that a proportion spread under the fuze slider to achieve closer proximity with the lead/transfer charge. The author considers the probability of the chemical explanation being the cause of the premature detonation to exceed 90%. The major element leading to reservation concerning the validity of the chemical mechanism is failure to achieve full detonation takeover in explosive train interruption trials, particularly those carried out at 63°C and 70°C with the detonator in the 'safe' position and the author has considered this issue in detail. Although he is satisfied that he can explain these results with confidence, there is necessarily limited evidence (due to the highly dangerous nature of copper azide) enabling quantitative comparison of the initiating powers of copper azide compared with lead azide. Consequently, the author recognizes why other specialists may incline to mechanical explanations whereby the accident round was in the armed condition. He has considered the proposed build and quality failures which could support this mechanism, but considers them highly unlikely. He concludes the likelihood of the mechanical explanation (as advocated by KC W&M [8]) is less than 1%.

He has considered other mechanisms including double shotting, TNT exudation, propulsive charge initiation, sabotage and considers none of these alternatives are credible.

(2) To what extent of probability can the cause for the accident be found in factors that the OVV summed up?

The author has failed to identify any principle factors which have not been considered in the OVV report. Deeper consideration of certain areas, for example the composition and sensitivity characteristics of the lead/transfer and booster explosives may have enabled easier understanding of the explosive train interrupter trials. However, this could equally have been a diversion which produced negligible value. Although the author has identified minor nuances, no principle factors have been excluded from the OVV investigation in his judgement.

(a) What can be concluded about the investigation method, the investigation data and the findings of the OVV?

The author considers the investigation method has been highly competent and consistently objective. Throughout the investigation, data has been examined with particular scientific competence and a due degree of objectivity in its analysis. The technical contribution of TNO is considered to have been of exceptional diligence and competence. The author has worked with major explosive laboratories in the UK, France, Australia and US amongst others and the TNO work presented in this investigation stands comparison extremely well.

(b) To what extent of probability does the cause for the accident lie in the ingress of moisture into the interior of the fuze?

The author accepts that the cause of the accident was almost certainly formation of copper azide in the M6-N fuze. Without ingress of external moisture, this could only have come from inadequate process control by the manufacturer leaving internal moisture trapped within the fuze. There is evidence (from both chemical analysis and KC W&M inspection) of internal moisture and the author considers it possible, but unlikely, to have enabled the production of sufficient hydroazoic acid to cause the accident. Therefore, he considers external moisture ingress is likely an essential precondition of the accident. By far the most probable cause of moisture ingress was leakage around the aged adhesive sealing at the top of the fuze. This ingress could have been facilitated by the high temperatures experienced in Mali. Alternatively, cumulative ageing could have been a factor; the accident round was near the end of its Design Authority life and sealing inevitably deteriorates with age in even the most carefully manufactured weapons. The evidence presented also shows the sealing in the M6-N was not completely reliable.

The author considers the age of the rounds, the evidence of poor-quality control, the presence of lead azide detonators (noting the USSR Manual recommendations [8]) in a weapon which had not been ‘type -classified’ should all have been factors in deciding the suitability of the HE 80 for the Mali deployment. He concludes it is unlikely that an SME would have had sufficient confidence with respect to the essential requirement for moisture ingress prevention (amongst other quality concerns) of the HE 80 stock to support this deployment.

(c) To which extent of probability does the cause for the accident (also) lie in the functioning of the cover plate that, by way of derogation from the NATO prescription, didn't prevent discharge to the transfer charge?

The author considers the poor functioning of the explosive train interrupter/cover plate was a major factor in the cause of the accident. Although the design intent would not have been to ensure a copper azide initiation would not propagate into the main charge, it is certain that a cover plate design with sufficient margin in design (i.e. minimising communication of detonator initiation to the lead/transfer charge) would have reduced the probability of the propagation which occurred in the accident. Experience from previous accidents with lead azide detonators has demonstrated the absolute necessity for the fuze design to prevent the possibility of full train initiation from the 'safe' position [5, Appendix J, Section 11.3]. The author considers the probability that a cover plate fulfilling NATO standards would have prevented the accident to be of the order of 90%. The author acknowledges this is an estimate as the experimental data does not provide clear proof.

(d) To which extent of probability does the cause for the accident (also) lie in the exposure of the accident grenade to higher temperatures than allowed, in accordance with the guidelines of the manufacturer, during storage of the mortar grenade?

The author considers the temperature exceedance was likely a factor in the development of the concentration of copper azide in the accident round necessary to cause the accident. TNO carried out a thermal analysis which they reported with due conservatism, whilst acknowledging the possibility of greater exceedance. The author has personal experience of temperatures beyond 71°C in weapons stored in shipping containers in A1 and A2 climatic regions. In a recent case, a UK weapon failed catastrophically after such an exceedance, the failure being attributed to the storage overtemperature. However, the HE 80 Design

Authorities thermal maximum is not scientifically justified and the consequences of a repeated (of the order of 15°C) exceedance on the HE 80/M6-N cannot be quantified on a scientific basis. However, it is also the case that the majority of the international precedents for copper azide attributed accidents had been stored in high temperature climate zones. Therefore, the author can justify 90% confidence that the high temperature experienced in storage in Mali contributed to the accident, but has lower, only greater than 50% confidence, that the temperature exceedance from Design Authority/manufacturer requirement was a factor. This lower confidence relates more to lower estimation of the scientific justification of the Design Authority/manufacturer 50°C upper limit than reserve concerning the accident mechanism.

(e) To which extent of probability does the cause for the accident (also) lie in the exposure of the accident grenade to higher temperatures than allowed, in accordance with the guidelines of the manufacturer, during the specific handling processes up to and including firing of the accident grenade on the day of the explosion? (note wording of question modified in accordance with author enquiry [21])

The author has considered this aspect and attempted to find relevant information from other sources. The open scientific literature concerning the role of temperature in propagation of shock induced detonation is limited, but all the relevant reaction processes will be accelerated to some extent by increased temperature. The author considers that there is a significant possibility the accident fuze aluminium components exceeded 70°C, which is a major exceedance from the 50°C limitation of the Design Authority/manufacturer. Since actual firing is a more dynamically demanding process than storage, (see question (d) above) the author considers exceeding Design Authority/manufacturer recommendation a more serious safety failure.

The literature is not in universal agreement, with some sources identifying a decrease in shock sensitivity of explosives as temperature increases in the relevant range. However, the higher temperature will certainly maximise the energy liberated by decomposition of fuze explosives. The author considers, on balance, that the likelihood that temperature exceedance beyond Design Authority/manufacturer limitations was more than 50% likely to be a cause of the accident.

(f) How valid are the findings of the KC W&M with regard to the manner, in which the OVV carried out its investigations, and to the findings of the OVV?

The author recognizes that a degree of objective scepticism is appropriate when considering any scientific argument. In this case such caution is particularly relevant because of the significant weight the OVV proposed failure mechanism places on copper azide; which is not easily identified and also, the failure to reproduce the full detonation during the explosive train interruption trials. However, the KC W&M rejection of many aspects of the OVV investigation and apparent certainty regarding their own conclusions, with regard to the following:

- The origin of the physical evidence
- The certainty on nature and distribution of fuzes after mortar tube explosions
- The presentation of fuze measurement data ranges
- The interpretation of ‘tolerance’ and calculation of ball release movements
- The statement regarding upper storage temperature

These produce a cumulative lack of confidence in the KC W&M findings when compared with the caution of the OVV (and objectively presented TNO evidence). Certain aspects of the KC W&M argument are easily dismissed, for example their upper temperature statement:

The KC W&M read data loggers for 3 years in Mali. The measures were never higher then over 50 °C in this period of time, which was included in the CVO report.

This is refuted comprehensively in the TNO report [7] as is their firing pin/non return valve 'tolerance' argument.

Overall, those logical and appropriate arguments contained within the KC W&M report are diminished by an apparent intention to reject every OVV arguments. The author accepts this may be unfair and that more balanced analyses may have been presented by KC W&M elsewhere; however, his judgement is based on [8].

The KC W&M findings with regard to both the manner and findings of the OVV report are inadequately balanced, considered or convincing.

(g) What is the validity of the reaction given by the OVV – which is (also) based on research performed by TNO – to the KC W&M report?

The author considers the response to the KC W&M report [20] appropriate and correct. The only significant point it fails to make is that no convincing specific mechanism for the KC W&M mechanical explanation for the accident has been provided. It appears most unlikely that a fuze could actually be constructed with the measurement deviations suggested. In the event this actually proved possible, it is highly unlikely that even the most negligent of inspections would have missed the deviation as the cross-pin position and non-return valve movement would be highly anomalous. Accepting the assumption however, that such an armed/easily armed fuze was delivered to the Netherlands forces, it is surprising it survived its entire duty cycle for nine years, including an arduous journey to Kidal without detonating the mortar grenade. Additionally, the apparent, entirely singular nature of the purported defect within one large delivery batch from 2007 remains unexplained. The chemical mechanism proposed by the DSB report gives a specific causal chain with a more convincing explanation for the singularity of the accident occurring late the stock history. The rebuttal of the KC W&M arguments in the TNO letter and Memorandum [7,19] is compelling and an appropriate response by a scientific organisation. The fact that the TNO response notes the concerning deviations measured by KC W&M and does not state the chemical mechanism is the certain cause is judicious and appropriate; there is no complete certainty in any of the explanations. The author has pointed out that this is often the case in explosives accidents. Scientific objectivity requires caution even regarding highly credible and well evidenced explanations. This reserve can be misinterpreted as placing significant confidence in less well explained and evidenced alternatives.

(h) To which extent of probability do the parts (of the detonator) that were investigated by the OVV come from the accident grenade?

The author's confidence that the elements of the fuze described in the DSB report and appendixes come from the accident grenade exceeds 99%. In the case of the explosive train interrupter/cover plate which was initially mistakenly reported, his confidence that it originates in the accident round exceeds 90%.

(3) To which extent of probability does the cause for the accident (also) lie in factors as mentioned by the KC W&M?

The author understands the KC W&M reservations concerning the OVV conclusions. However, he does not consider the proposed KC W&M mechanism consistent with the accident or that a fuze with the dimensional variations suggested could actually be manufactured. Therefore, with due regard for appropriate scientific caution, he considers his estimation of the probability of the KC W&M mechanism being correct as less than 1% is appropriate.

(a) What conclusions can be drawn with regard to the investigation method, the investigation data and the findings of the KC W&M?

There are elements of the DSB identified accident mechanism which are open to legitimate doubt. Specifically, other rounds with clearly visible lead azide decomposition (as in the rounds from den Halder, 1970 [5, Appendix H]) were not found and also the failure to reproduce booster detonation in explosive chain interruption trials. The KC W&M report identifies these and details inspections, measurements and explosive train interruption trials. However, the report presented lacks evidence of scientific balance. Its conclusions, for example regarding additive ‘tolerance’, do not appear well considered and the cumulative disagreement with almost every element in the OVV report serves to diminish confidence in the objectivity and credibility of the KC W&M conclusions. The issues noted (and discussed by TNO [7],[19]) would better have been addressed before the KC W&M report was issued.

(b) To which extent of probability does the cause for the accident lie in (the combination of measure deviations of elements of the accident grenade?

As noted above, the author considers the likelihood of the measurement deviations discussed in the KC W&M report as being part of the cause of the accident as less than 1%.

(4) To which extent of probability have other causes and/or circumstances, other than mentioned by the OVV and the KC W&M, led and/or contributed to the premature explosion of the accident grenade?

The author has considered this and can identify no significant original causes or circumstances which were not identified in the investigation. There are nuances which TNO may have been reluctant to point out due to reservations regarding scientific reliability. For example, the detonation initiation qualities of copper azide versus lead azide are unknown though consideration of accidents and limited data suggests copper azide is more powerful. Ideally, a scientific proof would be based on a fuller understanding of copper azide occurrence and properties. Realistically however, it is too dangerous to make sufficient quantities of copper azide to quantify its explosive initiation powers. Additionally, the OVV report does not point out that explosive accidents are often imperfectly understood. The author's experience of explosives accidents, including ones which have resulted in fatalities and legal prosecution, have frequently produced investigations where entirely legitimate doubt remained about some aspects of the accident mechanism. In the case of the Mali, 60 mm mortar grenade, the author considers the immediate cause (chemical decomposition of the detonator explosive) and the root cause (failure to procure a weapon of safe design, manufacture and quality standard) have been identified.

The above answers should not mask the agreement between the various investigations that the HE 80/M6-N should not have been deployed by Netherlands forces. Its procurement process did not pay due regard to agreed standards designed to ensure weapon safety. The failure to address the safety implications of the observations concerning poor quality was a second opportunity to avoid the accident. Finally, the retention of the weapon after the Afghanistan deployment without attempting to fill the gaps in knowledge of its safety characteristics enabled the deployment of an inadequate weapon, close to the end of its service life, in the challenging environment of Mali.

The author feels these failings were correctly identified by DSB and an appropriate recommendation included in their investigation report [5, Recommendation 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.

Since the primary function of the investigation was to identify means of preventing re-occurrence of accidents sharing the same root causes and the DSB have captured the author’s concerns, he agrees efficient implementation of this recommendation will serve this purpose.

Experience proves that major accidents are inevitable where explosives are inappropriately procured, inadequately tested and improperly controlled.

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[4] STANAG 4157 Safety, arming and functioning systems testing requirements, Edition 3, 2017.

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[7] TNO Memorandum, 19EM/0041, September 2019.

[8] KC W&M Document 28267 Version 2, January 2019

[9] Requirement for type classification of ammunition …etc. referenced in note 15 of [5, Section 4.1] as version 1, 2016. Author not aware of original date of this requirement.

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[19] TNO letter, reference 19PMW670, September 2019

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[21] [redacted], 27th July 2020

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Table 1: Chemical Compositions Comprising Explosives Train

Informal Name	Formal Name	Role	Quantity	Comment
TNT	2,4,6-trinitrotoluene, $C_7H_5N_3O_6$	Main Charge	200g	Relatively Insensitive Secondary Explosive
RDX	Cyclo-1,3,5-trimethylene-2,4,6-trinitramine, $C_3H_6N_6O_6$	Booster Charge	16.6g/25g*	Intermediate Sensitivity. Present pellet as a mixture with Wax
PETN	Pentaerythritol tetranitrate, $C_5H_8N_4O_{12}$	Lead/Transfer Charge	Approx. 0.25g	Shock Sensitive Explosive. Present as a powder pelleted with wax
PETN	Pentaerythritol tetranitrate, $C_5H_8N_4O_{12}$	Detonator Final Stage	0.08g	Primary Explosive Powder
Lead Azide	Lead azide, $Pb(N_3)_2$	Detonator Mid Stage	0.38g	Primary Explosive Powder – translates first stage detonator ignition response to detonation
Lead Styphnate	Lead trinitroresorcinate, $PbC_6H_3N_3O_9$ (as monohydrate)	Detonator First Stage Igniferous Mixture - highly friction/stab sensitive		Initiating compound
Tetrazene	Tetrazolyl guanyltetrazene hydrate, $C_2H_8N_{10}O$			Very low quantity, typically 2-5% of compound, sensitises lead azide
Barium Nitrate	Ba(NO3)2			Oxidiser
Antimony Sulphide	Sb_2S_3			Pyrotechnic fuel

*Weight of Booster charge is not consistently reported in references:

[5, Appendix E, Section 2.11.4] ‘the booster charge in the fuze consists of 16.6 g TNT’ (error noted)

[5, Appendix I, Section 2.3] ‘37 grams of RDX is involved in the detonation of the booster charge’

[11, Number 13] IC response: ‘approximately 25 gram of RDX’

[8, Annex 2] ‘booster contains 25 gram of RDX’

Figures

Figure 1: 60 mm Hotchkiss-Brandt Commando type mortar. (Picture: TNO)

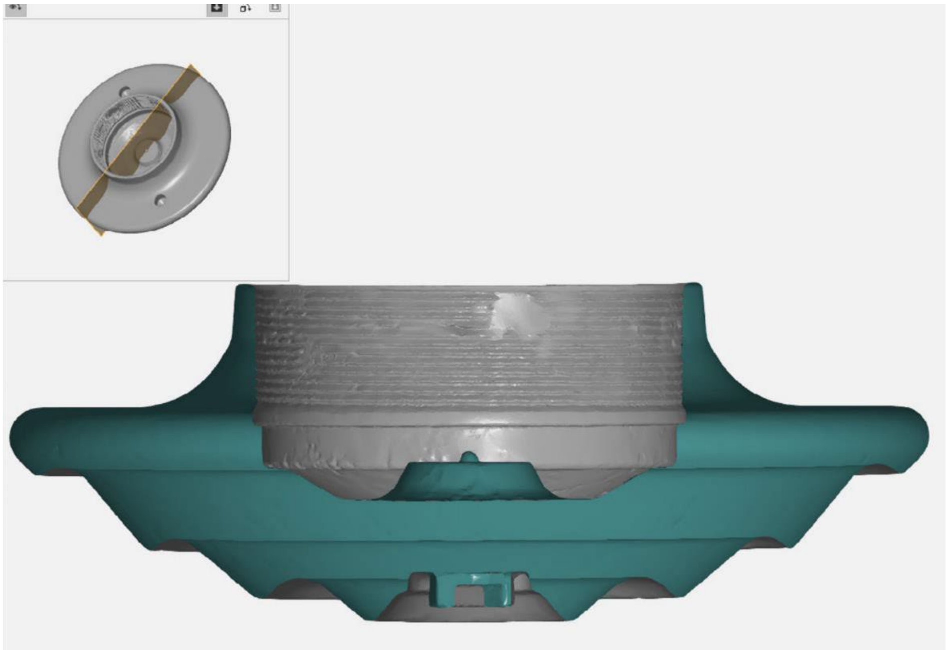


Figure 2: Cross-section of the base plate over its centreline. (Picture: TNO)

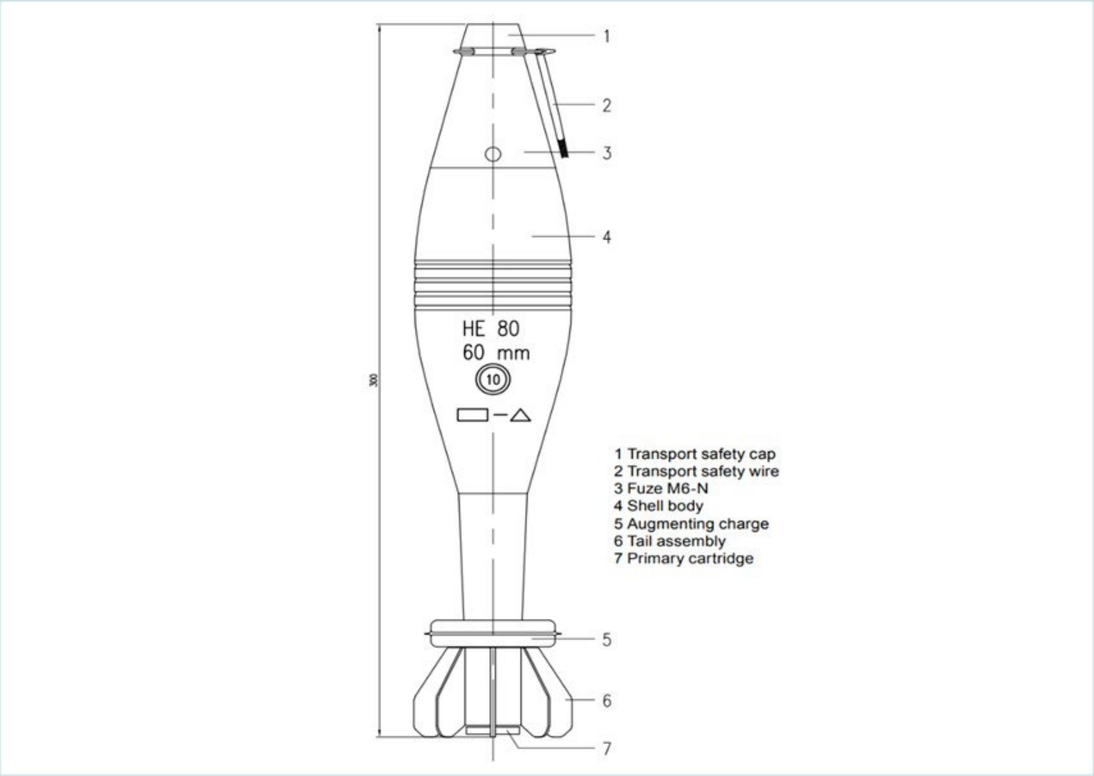
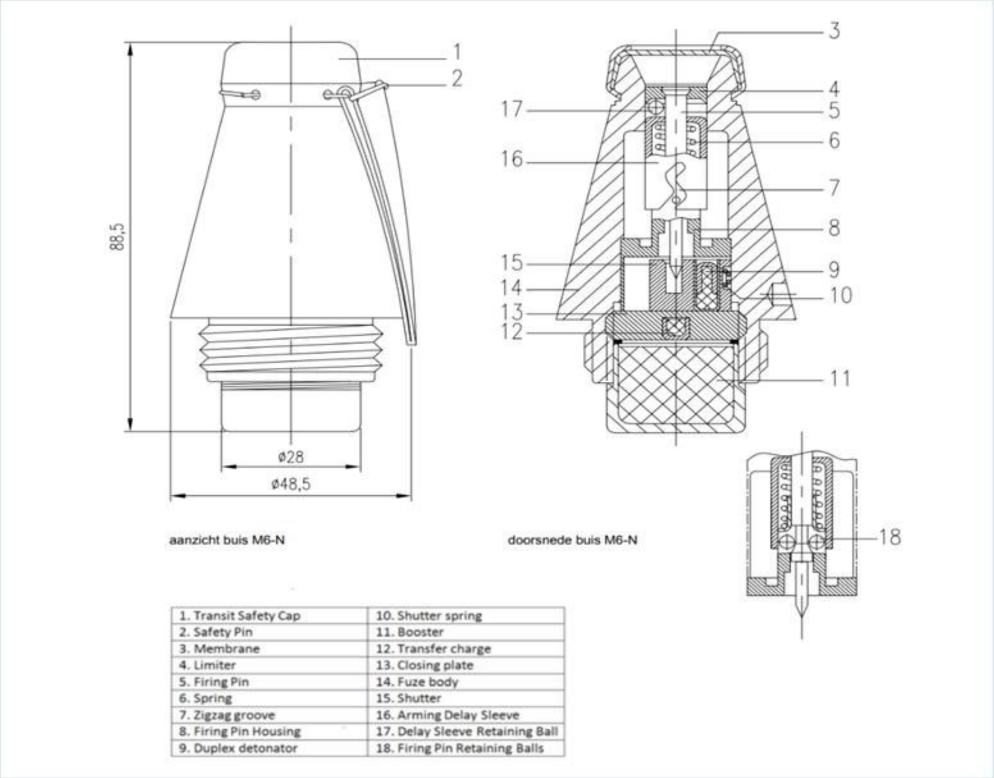


Figure 3: HE 80 mortar Round. (Source: Netherlands Ministry of Defence)



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 4: The M6-N fuze with detonator (9) in ‘safe’ position. (Source DSB Report [5])

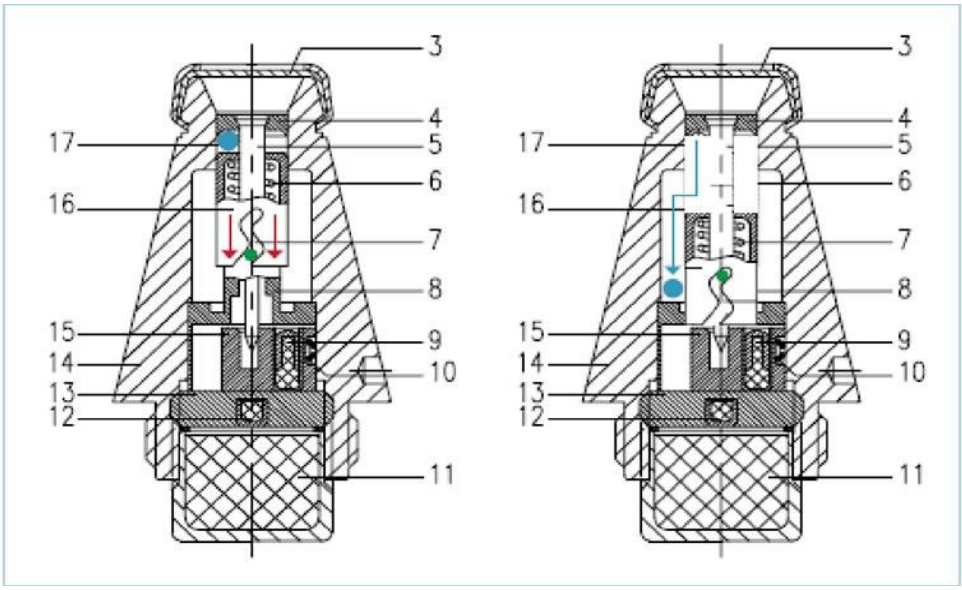


Figure 5: Position of the safety mechanism in the fuze at the moment before the acceleration begins, direction shown with red arrows (left) and at the end of acceleration at leaving the mortar tube (right). Cross pin (not numbered) shown in green. (Source: Ministry of Defence/TNO)

Figure 6: Content of the paper bag: visible are fragments of a shock pylon, a part of a shoe, rounds, a magazine spring, (probably) a cover of the mortar, straps of the transport safety of the grenade and the rubber cover of the sights of a Colt rifle. (Picture: TNO)

Figure 7: Content of the paper bag: visible are the same parts as in Figure 6, parts of a magazine and (probably) a part of the carrier/firing belt of the mortar. (Picture: TNO)

Figure 8: Left explosion train interrupter plate; DSB-report; right explosion train interrupter plate; controlled destruction. (Picture KC W&M)

Figure 9: Left explosion train interrupter plate; DSB-report; right explosion train interrupter plate; controlled destruction. (Picture KC W&M)

Figure 10: Enlargement of the cover plate shows possible presence of sand in the thread. (Picture: TNO)

Figure 11: Imprint on the fragment of the launch tube, originating from the grooves on the shell casing when the main charge explodes. Figure illustrates the steel fragments produced during detonation of an HE 80 mortar round. (Picture: TNO)

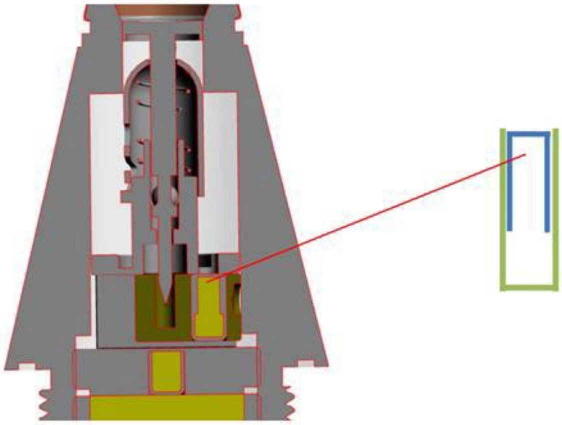


Figure 12: M6-N Fuze. The duplex detonator consists of two metal casings with one slid into the other. The inner casing that contains the energetic materials is made from aluminium. The outer metal casing is made from a copper-nickel metal alloy (Melchior). (Picture: TNO)

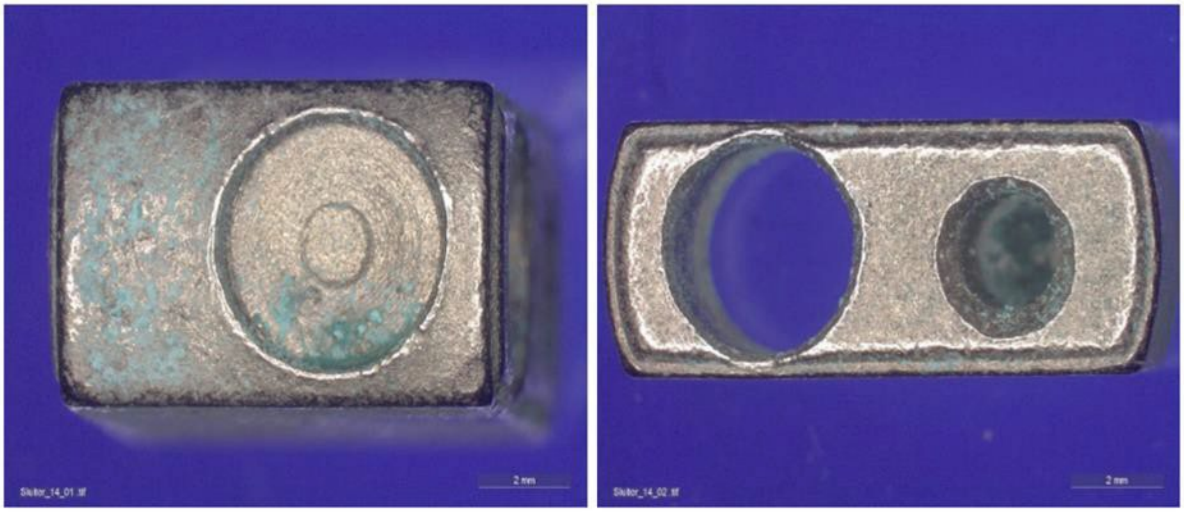


Figure 13: Optical micrographs of slider. Corrosion is visible on the side wall and in the recess for the slider spring (left) and on the top, on the edge of the hole for the detonator and on the edge of the recess for the firing pin (right). (Picture: TNO)

Figure 14: HE 80 Round. Corrosion identified during 2007 testing of new rounds. (Picture: Netherlands Ministry of Defence)

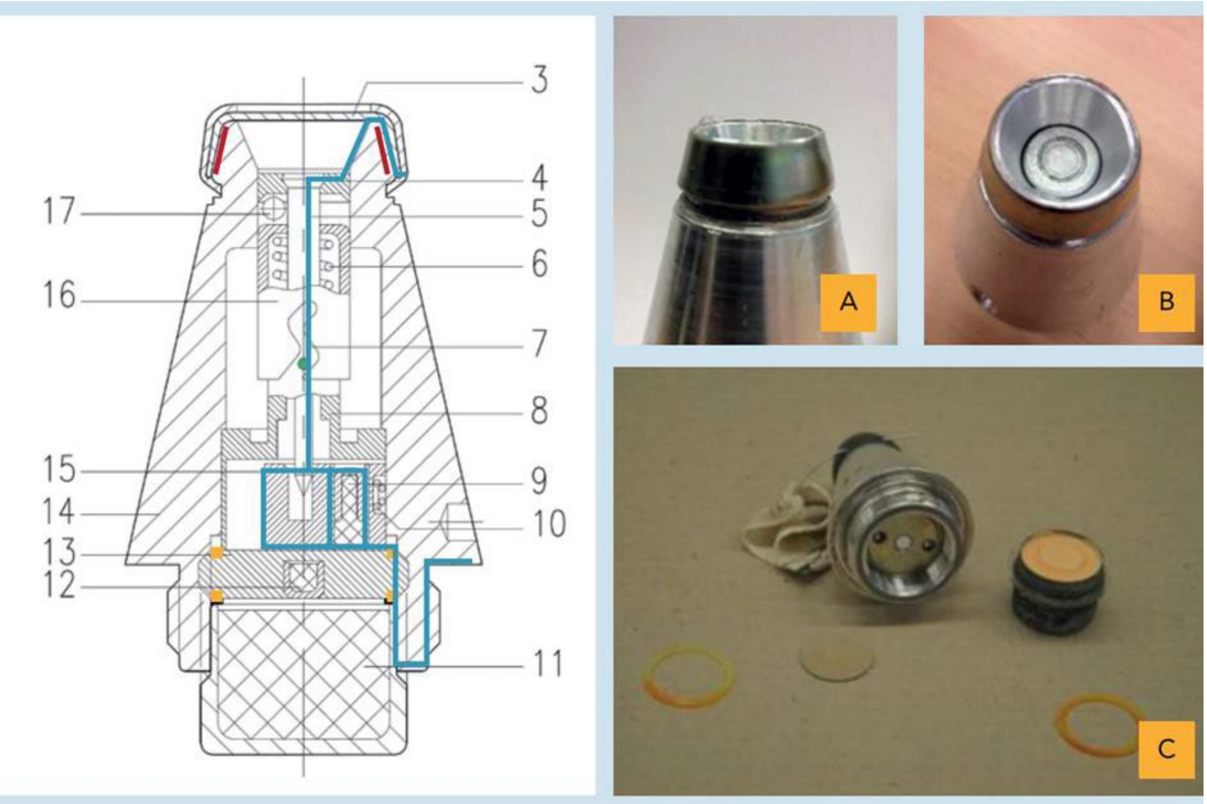


Figure 15: Cross section of the fuze with potential routes (blue) for moisture penetration via the adhesive layer (red) and sealing rings (yellow). Picture A: adhesive layer for the membrane, picture B: opening between the firing pin and the housing. Conclusion is that moisture ingress more likely via top of fuze. (Source: TNO)

Figure 16: Filling the top of the M6-N fuze with water to show leakage. The adhesive layer of one of the five fuzes tested is leaking after a drop test from about one metre height with random impact orientation. (Picture: TNO

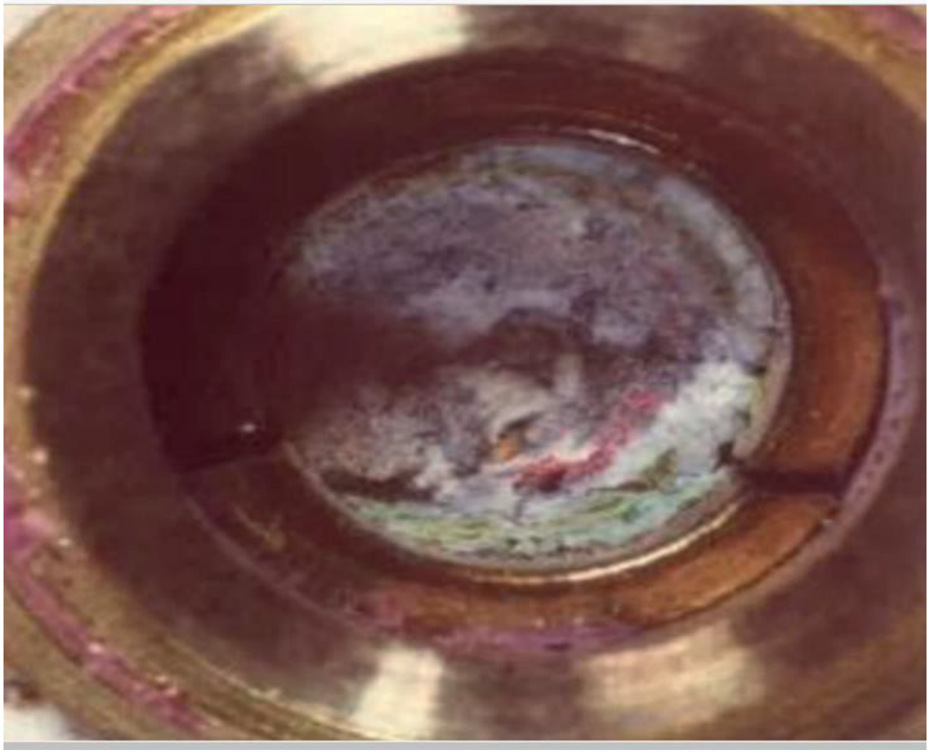


Figure 17: Top view of the aluminium detonator in the brass casing from fuze type V-19. Den Helder (1974) spontaneous reaction of corroded fuzes. (Picture: TNO)

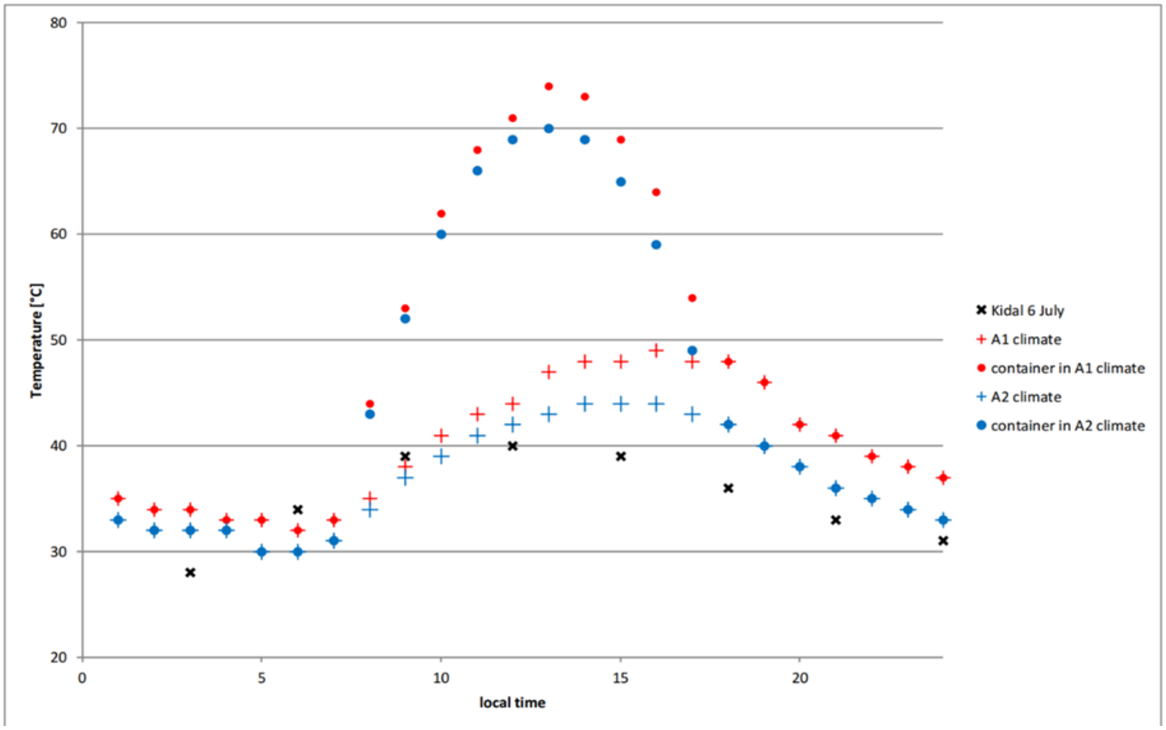


Figure 18: Expected temperature profile in Kidal storage container during the days around 6 July 2016. (Source: TNO)

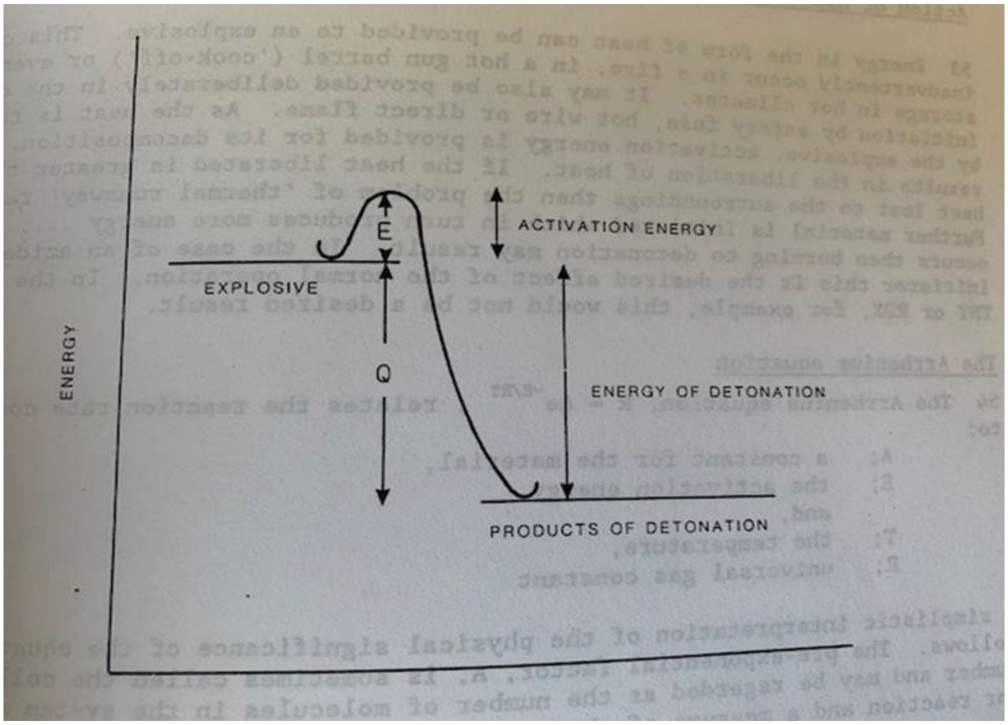


Figure 19: Explanation of need to provide Activation Energy to initiate explosives. Simplified explanation taken from JSP 333, UK Services Textbook of Explosives.

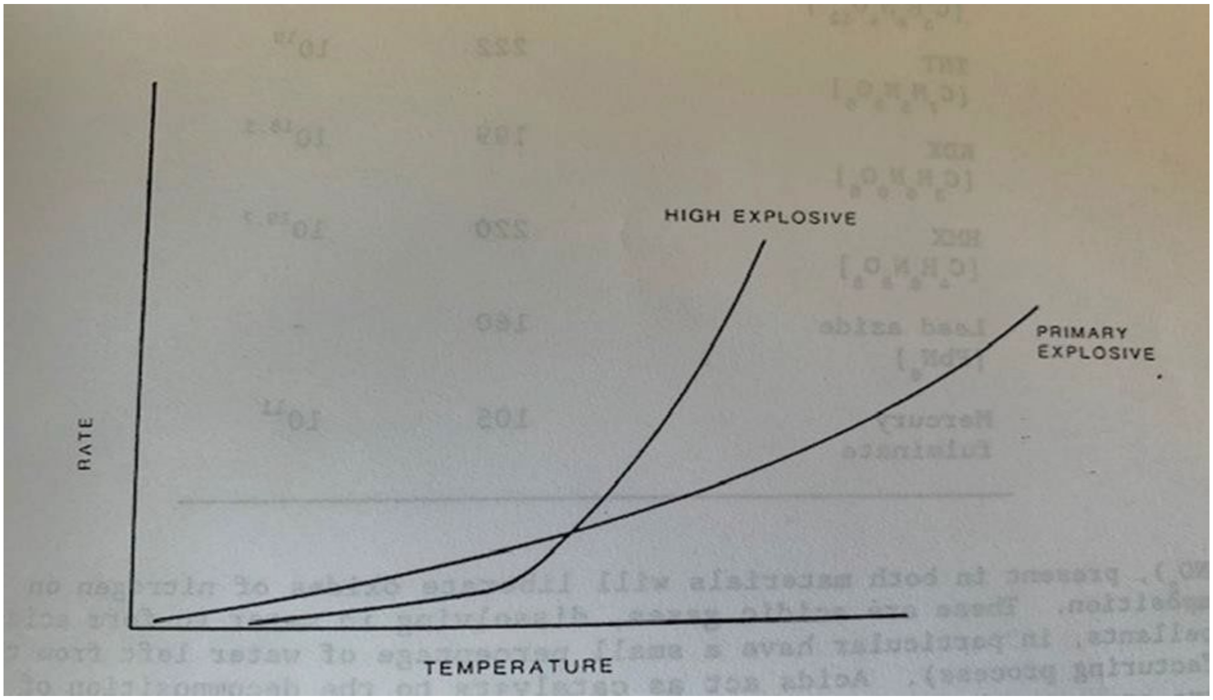


Figure 20: Comparison of effect of temperature on rate of explosives decomposition. Simplified explanation taken from JSP 333, UK Services Textbook of Explosives.

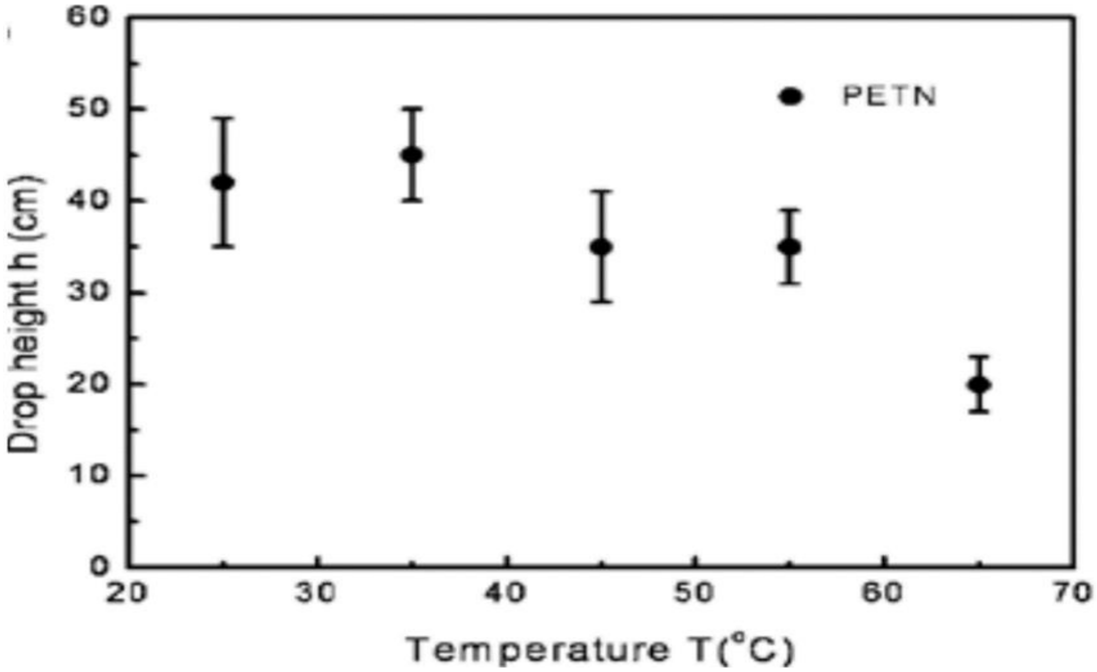


Figure 21: 7 Drop height at which PETN reacts versus temperature [Zhang & Weeks, 2010]. Note large increase in sensitivity above 55°C. (Source: TNO)

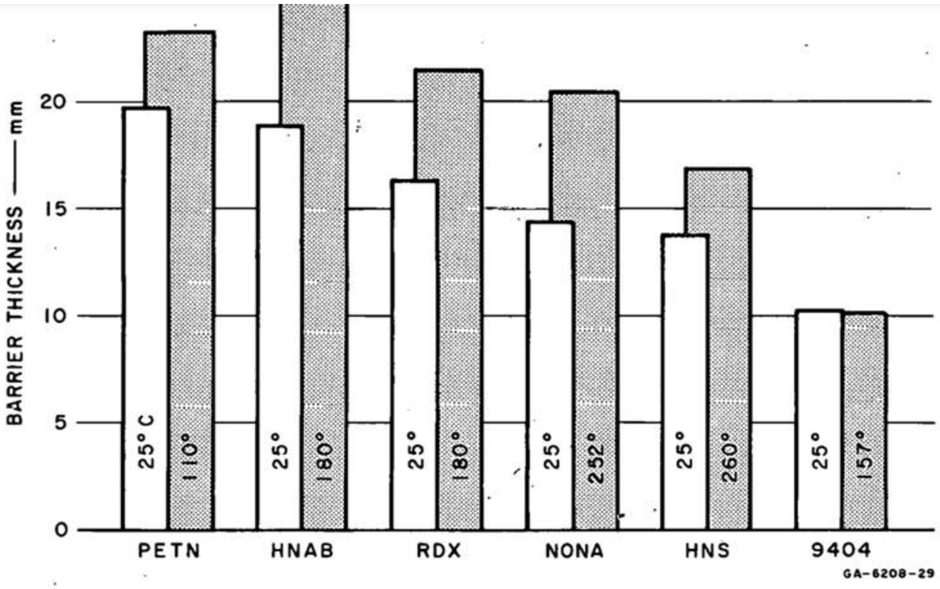


FIG. 20 GAP TEST SENSITIVITY AT ELEVATED AND ROOM TEMPERATURES FOR SIX EXPLOSIVES. Barrier thickness has been used as a measure of sensitivity.

Figure 22: Shock Sensitivity of various explosives against temperature. Influence for PETN and RDX is of secondary order. (Source: Roth and Blackburn, 1967)

Figure 23: Fuse M6-N, Breakdown and dimensions measured by KC W&M. (Picture: KC W&M)

Figure 24: M6-N fuze mechanism composed of correctly positioned zigzag cross-pin at the beginning of the first “knee” of the zigzag slot (Picture: TNO)

Figure 25: Combination firing pin and non-return valve; left correct; right incorrect (Photo: KC W&M)

Figure 26: Damage to the mortar tube from the accident (top) and after the test with the fuze in armed position by KC W&M (bottom). The picture contrasts the length of ‘petaling’ of the tube remnants near the base plate (red boxes) and the lengths of the residual tube from the muzzle end (blue boxes). (Picture: TNO)

Figure 27: 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). (Picture: TNO)

Figure 28: Unused firing pin (left), firing pin from the test in armed position (centre) and from the accident mortar round (right). (Picture TNO)

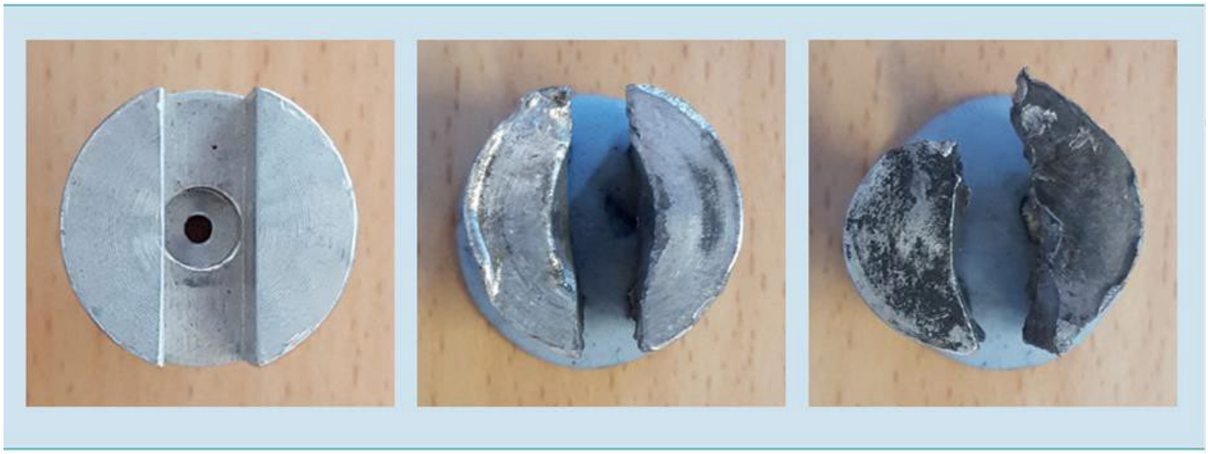


Figure 29: Bottom view of an unused firing pin housing (left), from the test in armed position (centre) and from the accident mortar round (right). The greater asymmetry in the accident round can be interpreted as reflecting the detonator being off-centre in the 'safe' position. (Picture: TNO)

Figure 30: Top surfaces of the explosive train interrupter plate from the test in armed position (left), from the test in safe position (centre) and from the accident (right). The plate from the test in armed position is broken as a result of the detonation, the plate from the accident was recovered in one piece, but cut in half for further examination. The off-centre dent in the accident plate is thought to demonstrate the detonator fired in the 'safe' position. (Picture: TNO)

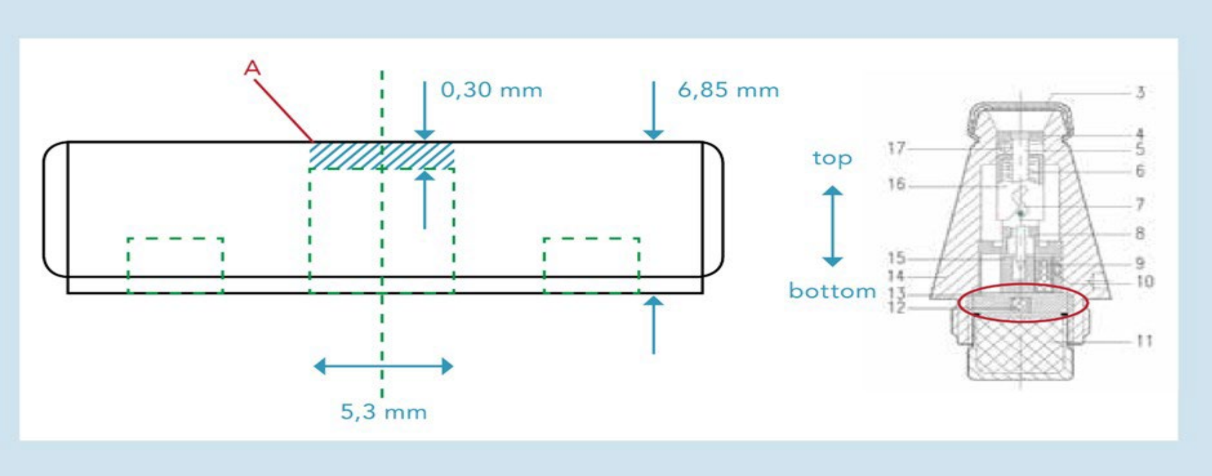


Figure 31: Cross-section drawing of M6-N explosive train interrupter plate showing location of 0.3mm steel swept away in Figure 30 plates. Location of plate shown (circled red) on drawing, right hand side. (Source: TNO)

Figure 32: Pictures from TNO Explosives train interruption test, 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 interrupter plate with an indentation at the location of the duplex detonator. (Picture: TNO)

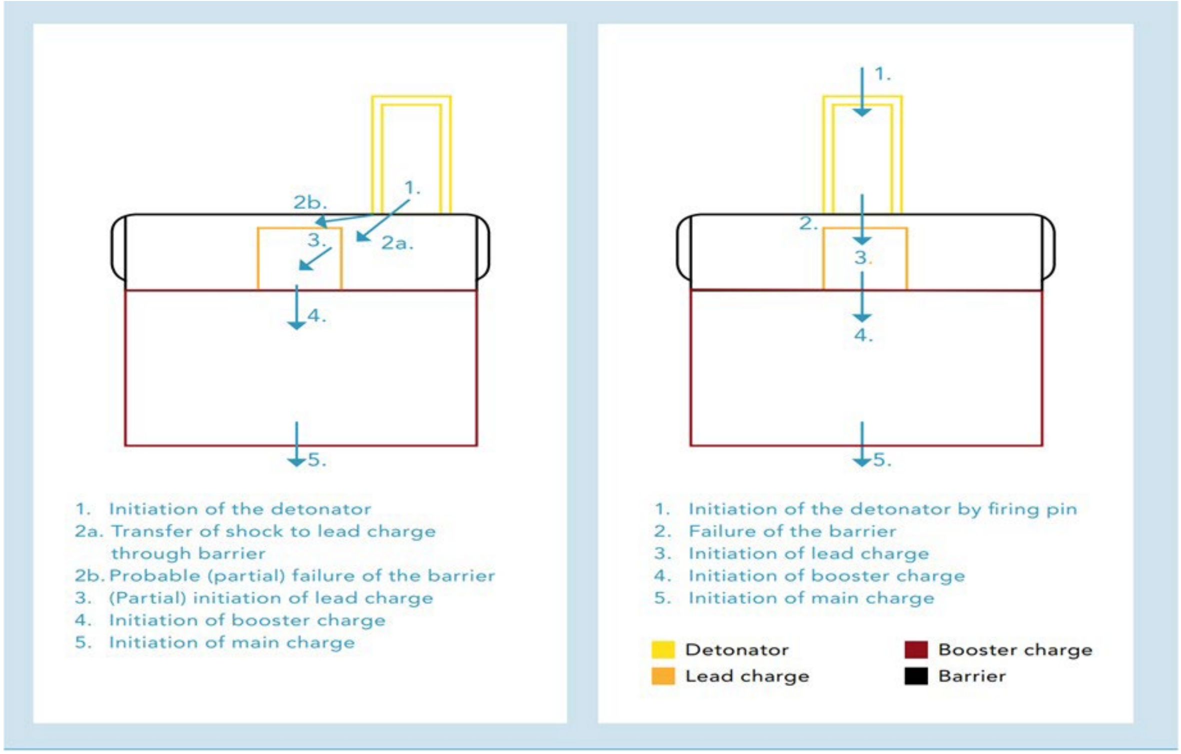


Figure 33: Explosive train for an unarmed fuze (left) and an armed fuze (right). (Source: TNO)

Figure 34: Explosive train interruption test carried out at 63°C by KC W&M. The booster charge has not detonated but it has fully combusted. In a higher confinement condition, as in an HE 80 round, transition to detonation may have occurred. (Picture: KC W&M)