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PROJECT MANAGER
AMMUNITION
LOGISTICS

WL-TR-93-3510

EVALUATION OF STATE-OF-THE-ART HIGH SPEED DELUGE SYSTEMS PRESENTLY IN SERVICE AT VARIOUS U.S. ARMY AMMUNITION PLANTS

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SEPTEMBER 1993

Final Report for January 1993 - March 1993

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This technical report has been reviewed and is approved for publication.

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release, unlimited distribution.

4. PERFORMING ORGANIZATION REPORT NUMBER(S) WL-TR-93-3510

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION Donmar Limited

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION AF WL/FIVCF; Tyndall AFB, FL

6c. ADDRESS *(City, State, and ZIP Code)*

901 Dover Drive, Suite 120
Newport Beach, CA 92660

7b. ADDRESS *(City, State, and ZIP Code)*

139 Barnes Dr., Ste. 2
Tyndall AFB, FL 32403-5323

8a. NAME OF FUNDING / SPONSORING ORGANIZATION AF WL/FIVCF

8b. OFFICE SYMBOL *(If applicable)* WL/FIVCF

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract No. F08635-91-C-0217

8c. ADDRESS *(City, State, and ZIP Code)*

Mail Stop 37
139 Barnes Drive, Suite 2
Tyndall AFB, FL 32403-5323

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION N

11. TITLE *(Include Security Classification)* Evaluation of State-of-the-Art High Speed Deluge Systems (Including Detection and Suppression) Presently in Service at Various U.S. Army Ammunition Plants

12. PERSONAL AUTHOR(S) A. Donald Goedeke and Gary A. Fadorsen

13a. TYPE OF REPORT Final Task Report

13b. TIME COVERED FROM 1/1/93 TO 3/1/93

14. DATE OF REPORT *(Year, Month, Day)* September 1993

15. PAGE COUNT

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*

High Speed Deluge Systems
Fire Protection Systems
Detectors
Machine Vision
False Alarm Sources
Ammunition Plants

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

A brief study was made of ultra high speed deluge systems used in Army ammunition plants for fire protection against pyrotechnic and propellant material-type fires/explosions. The evaluation included both fire detectors and fire suppressant devices and technologies. It was found that the technologies being utilized today have not been optimized for the specific fire application. In general, it was found that there is a lack of information on the properties of the fire events themselves that detectors are supposedly designed to respond to. No data exists on spectral irradiances in the IR or UV spectral bands where the current detectors operate. A need exists to determine the sources that may be responsible for detector false alarms. Tests should be conducted on the performance of current systems and on other detection and suppression techniques, notably, Machine Vision Fire Detection. It is recommended that field testing of old and new hardware systems be conducted; modifications made to optimize currently installed systems; develop a new system capability which better meets the overall threat, performance, and reliability requirements; and that a thorough purchase description/performance specification be developed.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT

☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION Unclassified

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22c. OFFICE SYMBOL WL/FIVCF

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

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PREFACE

This report was prepared by Donmar Ltd., 901 Dover Drive, Suite 120, Newport Beach, CA 92660, under contract F08635-91-C-0217, Eglin AFB FL. A major contribution to the report was made by Gary A. Fadorsen, Pyrotech International. The sponsoring organization and project management office was Air Force WL/FIVCF-OL, Stop 37, 139 Barnes Dr., Suite 2, Tyndall AFB FL. The project Officer was Mr. Chuck Risinger.

The period of performance of this task was January 1 - March 8, 1993. The task was performed in support of the request of the HQ Army Armament Munitions and Chemical Command, through WL/FIVCF, Tyndall AFB FL.

The author appreciates the assistance received from Mr. Robert A. Loyd, AMSMC-SFP, Rock Island, IL, and the staff at the Army Ammunition Plant at Crane, IN.

The author also gratefully acknowledges the contributions of Mr. Charles W. Risinger and Mr. George F. Hall, Tyndall AFB FL.

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EXECUTIVE SUMMARY

A brief study was made of current fire protection systems employed in Army ammunition/propellant-related facilities and their abilities to meet fire protection performance requirements to minimize loss of life, financial loss, and downtime of fire protection systems and production lines. The study included (1) reliability to detect/suppress events, and (2) immunity to false alarms from nonfire objects and phenomena.

It was found that current fire detection and suppression technologies being applied in these facilities are, in general, not adequate and should be thoroughly reviewed with respect to the threat, required reliability, desired performance criteria, and overall mission success goals. Moreover, the fire/explosion threat needs to be defined in terms of the system performance requirements. Detailed performance specifications are needed and should be included in each and every purchase description/RFP. It was also apparent from the study that formal guidance is lacking for Hazard Class 1.3 protective features.

A review of past test results substantiated the need for faster and more reliable fire detection and suppression approaches. Current installed systems are, in general, not satisfactory for most types of pyrotechnic fire events. They lack the necessary speed, effectiveness, and reliability. False alarms/accidental releases of fire suppressant continue to occur, although records of their occurrences are either sparse or do not adequately describe their causes.

A major observation was that there is a lack of scientific data pertaining to the nature and properties of the fire/explosion events themselves, especially their radiant spectral emissions.

The study concluded with the recommendation that various types of fire detection and suppression systems should be field-tested to determine the optimum configuration for each major application. However, before the detection part of such systems can be adequately tested it is necessary to know the spectral irradiances from each type of pyrotechnic material fire. Without these data it is impossible to select with any scientific foundation the appropriate fire/explosion detection spectral bands. Setting a pyrotechnic fire and testing the responses of commercial UV and IR detectors that are designed for hydrocarbon fire detection will lead to erroneous conclusions.

A final recommendation was to test new technologies for these applications, such as machine vision fire detection, as well as to determine approaches to modify and update in-place fire protection systems to optimize their performance and reliability.

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INTRODUCTION

A. OBJECTIVE

The objective of this study was to analyze the capabilities of existing ultra high speed fire protection systems installed in Army ammunition plants. In meeting this objective, a brief feasibility analysis was required to determine whether or not the state of the art in current ultra high speed deluge fire protection systems can be improved, if needed, by incorporating such advanced technologies as machine vision fire detection and advanced fire suppression concepts being developed for other applications.

B. BACKGROUND

In general, the technology of fire detection and suppression, in use in some Army ammunition plants, has not fully kept up with advancements in new technologies for fire detection and suppression. It was found that, in general, new technology was not incorporated into those systems that have been modified (e.g. nozzle locations, piping configuration, water pressure, etc.). A major observation was that considerable improvements in detection time, false alarm reduction, and suppression time and efficiency could be attained by optimizing currently installed systems and adding new-technology hardware.

False alarms have occurred, but the causes have not been determined to any major degree. A survey of facilities to determine what nonfire radiation sources are present and what is their spectral emission features would be a major step forward in improving the overall performance of fire protection systems in general.

Time of response of existing detectors is evidently not consistent and may vary over a large range. Reasons for this non-consistency should be determined.

Detectors and suppression systems are purchased to non-military performance specifications without any detailed false alarm source immunity specifications or false alarm qualification testing procedures. A military purchase description and performance specification would help to increase reliability.

C. SCOPE

This brief study was aimed at evaluating current and past performance of installed fire protection systems. Evaluations were made to determine and recommend possible modifications, technology improvements, and tests which could better satisfy the performance requirements for the specific application.

It was concluded that field tests are necessary, as well as measurements of the spectral irradiances of pyrotechnic/propellant material fires/explosions. Detectors are being employed whose wavelengths may or may not be in consort with the actual emission bands of the fires they are to detect. These emission characteristics must be known to optimize response time of detection; they must also be known in conjunction with those from nonpyrotechnic material fire sources, false alarm sources, such as lights, tools, phenomena, objects, etc. that may exist in the vicinity of the detector.

Attention should be given to testing the IR detectors now in use for Army Fighting Vehicle Crew Compartment fire protection application, and in the development of a fast response Machine Vision Fire Detector, which is now being developed for slower response applications in the Air Force. Also, the new technologies associated with rapid release of fire suppressant, such as being developed for Air Force aircraft use, may have excellent potential for this pyrotechnic fire application. One new area of technology that offers considerable promise to the fire suppression and extinguishing industry is the solid propellant technology that is being applied for inflation of automobile air bags. These nitrogen producing gas generators can expel finely atomized water stored in a pressure vessel located in close proximity to the potential fire location. A small high pressure vessel, pressurized around 2500 psig, could expel suppressant moving at very high velocity in about 10 ms.

It was concluded from the study that there has been a lack of investment in R&D related to the problems of pyrotechnic fire detection, fire suppression, system performance, and overall system reliability.

The efforts recommended herein should be coordinated by the U.S. Army Armament, Munitions and Chemical Command Safety Office. This office has considerable knowledge on matters involving ultra high speed deluge systems and other issues for ordnance operations. Within the U.S. Army Materiel Command and throughout DoD, the HQ AMCCOM Safety Office has provided engineering and technical assistance/guidance, responded to questions, conducted fire protection engineering surveys, and developed policy for matters involving ordnance operations, venting, shielding, thermal protection, and ultra high speed deluge systems.

SECTION II

EVALUATION OF HIGH SPEED DELUGE SYSTEMS

A. INTRODUCTION

One of the most obvious problems with existing high speed deluge systems is the lack of attention to, or lack of knowledge about, the processes, product and operations present at the facility. No discussion of fire suppression systems in high energy chemical facilities is complete without discussion about the product and process involved. (Discussion of fire detection follows in Section III.)

B. ACTIVE FIRE PROTECTION

The typical fire protection systems, known as wet pipe and dry pipe systems, are common in buildings of every type and application. This type of fire protection system probably should <u>not</u> be the primary fire protection system in the pyrotechnic and propellant or explosives production facility. Its reaction time of several seconds to is too slow to be effective in suppressing a fire in high energy chemical facilities.

High-speed deluge systems are common in government and military facilities that process explosives, pyrotechnics and propellants, and munitions. Presently the definition of a high speed-deluge system is a system that has a reaction time of 100 milliseconds or less. ("Reaction time" is defined here as the time from fire "detection" to the suppressant reaching the nozzle.) While this is the accepted standard for high speed detector reaction, this is not an accurate definition for both reaction of the detector and suppression system. These systems utilize optical fire detection that allows for fast detection of flash or flame. In most cases, high-speed deluge can suppress a fire before it reaches dangerous proportions or possible detonation (in the case of high explosives).

The speed necessary to halt a pyrotechnic or propellant fire is dependent or many variables including the type of process (whether it is an enclosed vessel, an extrusion process, mixing, drying, pressing, etc.) and the proximity of the personnel and critical equipment. Sometimes the only alternative or option is to allow it to burn. Conversely, there are instances in which high-speed deluge is necessary to save lives and protect costly equipment.

With the many varieties of chemical fire suppressants available today, one may wonder why water is used for high energy chemical mixtures, explosives, pyrotechnics, etc. Almost all explosives, propellants, and pyrotechnic mixes contain the necessary oxygen for the burning process. Most high-energy mixtures are a combination of a fuel and an oxidizer. The oxidizers are the nitrate and chlorate families, i.e., potassium nitrate, potassium perchlorate, barium nitrate, potassium chlorate, ammonium nitrate, etc. Because of these oxygen-yielding substances, it is impossible to stop the propellant fire by suppressing the oxygen supply.

Why water? It is generally agreed that cooling is a principal factor because it prevents feedback of sufficient heat energy to maintain combustion. It is desirable to get the water to the actual burning surface; however, this is not enough, as the fire will burrow into the mixture and continue to burn, being shielded from the water by an outer layer of water soaked material. This makes it highly desirable to be able to apply the water rapidly before burrowing can occur.

Another factor which makes rapid operation essential is that water must reach the burning surface before the pressure of combustion gases is high enough to prevent water from reaching the source of the fire. This requires that the system operate in a matter of milliseconds. In some cases, especially with large bulk quantities of explosives, it may be necessary to flood the container from the bottom and the top or add a wetting agent to the water in the deluge system to allow penetration to the explosive.

In summary, the basic purpose of the water is to cool down and disperse the explosives or propellant. Applications for ultra-high-speed suppression are as many and as varied as there are high energy products.

Some factors that may influence the speed of deflagration are: mass of the compound; density; temperature; moisture or solvent content; the physical geometric shape or particle size of the compound; and whether or not the substance is contained. A good example of how different containments could affect the burning characteristics of high-energy mixtures is that of black powder. Black powder, one of the oldest and most versatile explosives, when burned in an open long train, is relatively slow burning and is sometimes used to make fuse. Confined in a tube with one end open for exhaust, black powder can be used as a propellant. When confined to a fairly rigid vessel, black powder can become explosive with deflagration speed almost reaching detonation.

C. PRODUCT & PROCESS

"Product" and "process" must be addressed by everyone involved in explosive safety from the project originators to the installing contractor.

Products encountered in high-energy chemical facilities can be quite varied and must be considered since the hazards associated with the individual products differ. An equally important consideration is that the hazard presented by an individual product may vary during the manufacturing of the product.

Risk can be managed by either minimizing the probability of an accident, or by minimizing the consequences of that accident. It is appropriate to look to minimizing both probability and consequence. Generally pyrotechnic accidents are the result of unintentional ignitions and the consequence of an accident is directly related to the amount of material accidentally ignited and the number of persons exposed to the accident. Thus, relative explosive safety can be achieved through a combination of those measures which reduce the chance of accidental ignitions, and when the amount of pyrotechnic materials and the number of people in work areas is kept to a minimum.

In the broadest categorization, high-energy chemical products can be placed into four categories. High explosive, low explosive, pyrotechnics and propellant. Products in each category have like characteristics of that category but can transcend or overlap to other categories. There are more accurate and better detailed methods of categorization of explosives, such as the U.N. numbering system. For the purpose of this discussion, only the basic four categories will be considered.

1. High Explosives

Examples of high explosives include but are not limited to ANFO (blasting agent) PETN, RDX, C4, TNT, etc. High Explosives often do not require a high-speed deluge system, as deluge systems would be ineffective due to the speed of a high order explosion. The speed of the detonation wave in high explosives is faster than the speed of sound, which, in general, is too fast to detect or extinguish with present methods. (Although the definition of detonation varies, it is generally accepted that a shock wave travelling at the speed of sound or greater is considered a detonation.) There are detection methods, however, that are used in Army fighting vehicle crew bays that operate routinely in the 2-5 millisecond time frame and Halon 1301 suppressors that release agent within 2-5 ms.

The first thoughts or reactions to high-speed deluge protection for high explosives is that there is no fire protection system that could stop the detonation process, when the explosive goes to a high-order state. In many cases, however, there is a fire before the explosion. Examples of high explosives process applications are extrusion dies for C-4 explosives or a TNT melt kettle. In these situations, there is a high probability that there will be a fire preceding the explosion. The fire could start and propagate until the pressure build-up was enough to achieve high-order detonation or a cook-off type of reaction. In this scenario, high-speed deluge would be feasible in stopping the initial fire which precedes a possible explosion. Again, when dealing with high explosives the processes must be considered. For example, a TNT melt kettle, in most cases, is a closed vessel with a steam heat jacket operating at approximately 180°. Often the enclosure is operated at a slight vacuum. Also, temperature and window cleanliness are apparent problems with many UV and IR detectors. Most UV and IR detectors have operating temperatures of less than 180°F, thus making it difficult to function within hot environments.

The TNT melt cast situation is a perfect example of the need to know the product and the process. In many cases it helps to investigate past history or similar systems at other facilities.

A prime consideration when making a study of the product and process is to determine the possible loss of life and equipment. Often the equipment is designed to withstand an explosion. If this is the case, we would key on the operator and protect human life. Conversely, there are situations where the operation utilizes sophisticated, remotely operated equipment in which no operators are present. In this scenario, efforts will be focused on protecting the equipment.

A large-scale TNT melt-and-cast operation is often performed in a three-story building. The upper floor houses the motors to drive the mix/melt kettles.

The second floor houses up to four steam jacketed mix/melt kettles.

The lower floor is the fill area where empty vertical bombs are filled with the molten TNT via nozzles in the ceiling of the first floor.

An operator on the second floor dumps the granulated or flaked TNT and, often, powdered aluminum into the kettle. When the ingredients are properly melted and mixed, they are poured into the empty bombs below. The pour nozzles are controlled by an operator on the first floor. This is a rather condensed description of the operation, but it helps to visualize what is occurring.

One way to attack the hazard has been to provide infrared detection within the melt kettle. Most commercially available infrared flame detectors are somewhat susceptible to background infrared radiation from hot bodies and simple ambient light sources. There are other military versions of IR-fast response detectors that operate in two or three spectral bands and have better discrimination capabilities (these detectors are discussed later in Section III).

If commercial type detectors are used, designers must find a way to disable the infrared detection when the melt kettle is open, either for cleaning or for adding material. Infrared detection is less susceptible to the attenuation from dirty lenses caused by steam, smoke or particles than its ultraviolet detector counterpart. A machine vision detector, operating in the visible, must see a flame, and smoke may affect its detection capability. However, a combination of IR and machine vision, or machine vision operating in the near IR band could solve this problem readily. (Machine vision is a new detector technology that is presently in its development/test stage).

Detection in the infrared band lends itself to a fairly good design option. Also, in the case of a TNT melt kettle, flooding of the kettle with water may be necessary, although this is a subject for further analysis. There is no need for special spray nozzle patterns. The objective would be to get as much water as possible into the kettle for the flooding action to extinguish the fire.

Deluge speed is essential because, with an enclosed vessel, a fire situation could build pressure rapidly. in the vessel. Possibly to a point high enough to cause detonation. One other option for melt kettles may be quick release venting. Either mechanical gate or rupture disc method. Recent study has shown that a detector within the melt kettle will only see surface flame although there is a good chance that the fire will start at the bottom. In view of these new facts, it is advisable to protect the operator as he fills the kettle using external detectors (such as UV or machine vision) and eliminate the internal detection. One should consider these options.

The more recent high-speed deluge systems have used external UV detectors with nozzles protecting the operators and the open kettle.

The first floor has detectors and nozzles that key on the fill ports.

Extrusion is a process encountered with explosives; for instance, extruding C-4 explosive blocks. One possible source of fire is at the extruder die. As the explosive leaves the extruder die, there is often friction and the explosive is under pressure making this a likely ignition point. High explosives are often pressed into warheads, shaped charges and grenade bodies. Dusting occurs with some types of high explosives. This can leave a fine layer of dust which can easily be ignited by friction or impact. Speed of detection or rapid water delivery are extremely important to preventing the burning dust from transitioning to a detonation or involving larger quantities of explosives. UV or possibly machine vision fire detection, with nozzles as close to the hazard as possible, would be a viable method to help prevent an incident.

High explosive melt-out or steam-out is a common application for high-speed deluge. The design would have to vary with the particular process involved, which is actually more dependent on the munitions involved in the meltdown. A demil (demilitarization) process often encountered is the belt flaker or "candy maker."

In the belt flaker the high explosive, often TNT or RDX is melted and extruded onto a stainless steel water cooled conveyor belt. As the conveyor moves along, the explosive solidifies and breaks off at the end and is either boxed or sent on to other processes. Detectors (such as UV) should be placed within the conveyor hood. Nozzles are installed within the hood as close as possible to the hazard.

Because of the presence of steam and vapors, air shields may be used to keep the detector lens clean and maintain the system's integrity.

2. Pyrotechnics/Low Explosives

Design considerations for low explosives will be combined with pyrotechnics, since many of the methods for detection and suppression are the same. Items that fall into the low explosive and pyrotechnic category are black powder, illumination flare mixtures, mag-tef flare mix, smoke mixes, first fire, delay mixes, fireworks, salute mixes, etc. Pyrotechnics and low explosives cover such vast extremes in characteristics and hazards that one must be careful to study each one individually. (For example, under certain conditions, mag-tef and salute mix, can detonate similar to high explosives.) A few of the processes involved in the manufacture of low explosives included grinding mixing, activation of binders, extruding, pressing, granulating and drying, these being some of the most common processes encountered.

The initial grinding process is probably the least hazardous due to the fact that, in most cases, the ingredients are still separated. For example, the oxidizers should be ground separately from the fuels. Processes such as roll milling or ball milling demand customized systems designed on a one-to-one basis. Each situation is unique and should be handled accordingly. Often encountered during pyrotechnic production is the use of solvents to activate binders. Solvents, are in most cases, flammable with flammable vapors. To compound the problem, certain vapors attenuate UV radiation emitted from the flame.

The characteristics of the solvent must be determined along with its effect on the detection system. In past explosions, the flammable solvent fumes were sometimes the initial source of fire that propagated to the pyrotechnic mix. Even though as a rule, solvent dampened compounds are less sensitive than dry, the problem of the flammable solvent fumes must be considered.

Grinding and granulation are a hazard because extreme physical force is exerted on the completed pyrotechnic mix. Chances for impact, friction and even static initiation is much greater at this point. Compounding the hazard during this step of the process is the fact that large bulk amounts of the product are involved. When protecting a container or hopper with large amounts of pyrotechnic product, it is recommended that the system apply water from the top and provide for flooding of the vessel from the bottom or the sides.

Composition pressing is a very common practice in pyrotechnics, especially in the case of smoke and flare compositions. During the pressing procedure, the pyrotechnic mixture is compacted at very high pressures exerting large physical force, up to thousands of PSI.

Although it is almost impossible to stop any [illegible]tion or deflagration in the press or in the object being pressed, it is often advantageous to suppress the propagation of the flame or explosion to bulk hoppers which contain mix yet to be pressed. The finished pressing machinery is designed and shielded to withstand initiation during the pressing procedure. In this situation, the objective would be to protect operators and counter propagation.

Application of "first fire" mix is fairly dangerous and often involves an operator in intimate contact with the hazard. The operator is working with a sensitive mixture, even though the mixture is wet.

If the first fire were to initiate, it could cause initiation of the parent product. One example would be the application of first fire to magnesium Teflon® flares. If done manually, the operator is directly exposed to the high temperature burning of the magnesium Teflon® flare. In this scenario, one option is to aim the fire suppression nozzles at the operator and use nozzles configured to drive the burning flare into a hopper or chute so that it is driven away from the operator. Because certain compositions, including magnesium teflon mixes, are hard to suppress with the water spray, it is best to separate the operator from the hazard.

Usually, the final stage in the production of a pyrotechnic mix is the drying phase. During this phase the solvents are removed from the final product or the product is allowed to cure. During the drying process the pyrotechnic mixture is often subjected to added heat to facilitate faster and more even drying. At this point, the pyrotechnic product is susceptible to ignition. Ignition may be due to spark, friction or impact but is sometimes caused by a chemical reaction during drying. In many cases this is an unpredictable reaction. High-speed fire suppression is a very good safety measure unless the cost of the product loss is low enough and equipment is built to withstand ignition. Then it may not be economically feasible to use high-speed fire protection unless operators are exposed to hazard.

Fires occur often during cleanup or equipment tear down. This should always be considered when designing an explosive prevention system or high speed deluge system so that the system will activate and do its job during the cleanup and tear down process if it is deemed a possible hazard. In most cleanup or repair situations, plant personnel are in the hazard area where explosive residue is present.

3. Propellants

Propellants offer some similarities to hazards explosive and pyrotechnic categories. However some processes are unique to propellant. Propellants are extruded with the same hazards as extruding high explosives, except that propellants will burn much more aggressively, although there is probably not as much of a chance of achieving detonation. A good rule of thumb is to assume that anywhere there is action (movement, friction impact, static discharge) there is a chance for initiation, i.e., where the propellant leaves the extruder die or the extrusions are being cut into pellets during the cutting action. For composite propellant mixing, high-speed fire protection flooding of the mixing bowl is advised. If using a closed mixer, infrared detection is presently the state-of-the-art method to use in the closed vessel. It offers faster reaction time and is less subject to blinding or obscuration.

Sometimes propellants are machined after casting or pressing. The propellant machining process should be monitored by ultraviolet type detection keying where the tooling comes in contact with the propellant and if operators are present, protect the operator, stop propagation to hoppers or to propellant feeds. Often the propellant pellets, especially the nitrocellulose type propellants, are coated with graphite to help their flow through processing equipment and to prevent possibility of static discharge.

The added graphite coating can cause two problems. (1) It can obscure the detector lens because it has the tendency to float in the air, and (2) it can inhibit deluge water penetration into the propellant mix due to its ability to shed water. In the case of graphite-coated propellants it may be advisable to use air shields on the detectors and provide penetrating and flood-type spray configurations.

Propellants are often involved during demil (demilitarization) operations. During the demil process, the munitions body is separated or opened so the propellant may be poured into a collection container. The equipment and operator should be protected while the projectile is pulled from the shell or cartridge. Also, during pouring of any propellant, there is a potential hazard because of friction and possible static initiation. There is also a chance that the propellant may have become more sensitive than normal. Large quantities of propellants when contained in hoppers or similar containers should receive deluge water both from above and flooding from within the container as with some of the pyrotechnic mixes.

The progressive burning and increasing burn velocity of propellants emphasizes the need for a fast fire protection system that will extinguish or suppress the flame before it is out of control and the gas velocity is such that it will not allow for water penetration.

"Thermal dehydration" during the propellant manufacturing process is another feasible and recommended application for high-speed deluge. If hooded equipment is involved, infrared detection may be an option.

Triple base propellant (consisting of nitrocellulose, nitroglycerin and nitroguanidine), double-based propellants (consisting of nitrocellulose and nitroglycerin) and single-base propellants (consisting mainly of nitrocellulose) do not exhibit differences in the ability to be extinguished by water spray, although the burning rates and temperatures vary. More testing would have to be done to verify the affects of the water spray (varying amounts and speed) on the different propellants. So far, water has proven to be very effective when delivered quickly enough. Composite mixtures, i.e., ammonium perchlorate and aluminum can be protected during pouring and casting and the mixing process. The system configuration would have to be determined specifically for the process.

4. Initiating Explosives

Explosives such as mercury fulminate, lead azide, lead styphinate, pose particular combustion hazards. They are very sensitive to heat, static, friction and impact initiation and seem to transcend the deflagration state and almost evaporate into a detonation.

With these compounds, probably the wisest safety measure would be small batches and isolating the material. High-speed deluge for these initiators would probably only be effective as a deterrent to propagation. Avoid using brass fittings and nozzles in lead azide areas as copper and brass; when combined with moisture, they may cause lead azide to form extremely sensitive copper azide.

As previously stated, general overall coverage type systems located high in the ceiling should be avoided except where there is chance of dust or explosive particles which had previously settled on equipment or parts of the building. A general-coverage high-speed deluge may help to eliminate the explosive hazard. Good housekeeping and a cleaner working environment would probably be a more cost-effective way to handle this problem.

If there is a chance of secondary explosion, i.e., an initial blast that is suppressed by the primary system, a secondary overall coverage system may help to eliminate this.

The preceding was a brief summary of a high-energy process applications where high-speed deluge may be incorporated. Although, many other substances and processes warrant the use of high-speed fire protection, this has been a review of some of the more common. Both the product and the process should be reviewed before designing and installing a high-speed fire protection system. Specifications for the systems should be written for each application. Generic specifications seldom provide an adequate system.

Whenever possible, it is suggested that actual burn tests be performed using the same high-energy substance and the same process situation for the test and design as will be used in the final application.

D. SOURCES OF IGNITION/ENERGY INPUT

Almost all accidental fires or explosions in explosive facilities are due to unwanted energy input externally or internally applied to the product during a certain point in the process.

Energy input occurs in many forms and can be a combination of different sources of energy input. The following is a list of some of the possible sources of energy input:

- Static
- Friction
- Impact
- Heat
- Thermo-Chemical
- Flame
- Pressure
- Catalytic/Chemical

Every process utilized in the manufacture of high-energy chemical product is a source of energy input. Under normal conditions, it is not a problem. The problems occur when the energy input, or combination of energy input, becomes great enough to cause ignition. Conversely, the product may have been altered or sensitized to a point where normally acceptable energy input can cause ignition. The key to effective fire suppression is to key on the part of the process where the energy input does or can occur.

Common operations used in the manufacturing of explosives and pyrotechnics should be studied as to their potential for energy input. The following list provides some examples:

Grinding
Mix/Blend
Press/Consolidate
Drying
Addition of Solvents
Transport
Pour/Fill Dry
Cast
Melt/Pour Liquid
Extrusion
Curing
Mandrel or Core Removal
Clean-Up
Storage
Machining
Rework

E. COMMON DEFICIENCIES FOUND IN EXISTING DELUGE SYSTEMS

1. Specification

One recurring problem found in existing high-speed deluge systems can be traced back to the original specification. Very often the specification will be generic, not one that applies specifically. Generic or "nonspecific specifications" render only an ineffective fire protection and a more expensive deluge system.

Consider the following example. The building requiring protection houses a "pull-apart" machine used to disassemble ordnance for either demilitarization or rework. The machine physically pulls apart the explosive device. The "pull-apart" machines are usually well shielded to protect the operation since the greatest chance of an event is during the separation and possibly the pouring of the propellant. A specification reads: "The high-speed deluge system in the pull-apart room shall provide water at a density of 0.5 gpm. and shall have a response time of 100 milliseconds or less." Also consider that the building is 22 feet x 22 feet with a 10-12 foot ceiling. According to specification, a contractor could provide a ceiling fire protection system consisting of 20 heads.

With a double-base propellant, the fire must be extinguished before the propellant exhaust gas becomes so great that it will not allow water penetration.

Further study of the process reveals that the greatest chance of fire will occur when the projectile is pulled apart and when the operator dumps the propellant.

Although the system reacts in 100 milliseconds, the nozzles may be 10 feet away from the hazard, severely increasing the time it takes to get water to the hazard.

Because the specification called for a density of 0.5 gpm. an increased amount of money is normally spent on a system with 20 nozzles and 4 detectors instead of a system with 4 nozzles and 2 detectors.

A preferred specification would explain the hazard as well as the operation. The specification should require that a detector be placed close to the point where the projectile is separated. A detector shall also be placed where it can view the propellant dump operation. Two nozzles shall be placed as close as possible to the separation point along with one nozzle to protect the operator when present and another to stop propagation to the powder accumulation area. A flow of 25 gpm. per nozzle shall be provided. Nozzles and detectors shall be placed as close as possible to the hazard but not be placed so they can easily be obstructed by machinery or operating personnel."

Although this simplified example only represents a small portion of the specification, it illustrates how a small amount of extra effort can greatly enhance the installed system and save government money.

In the past, it was common practice to copy existing specifications and revise them using the "cut & paste" method. Reworking a specification is an acceptable practice since there is no reason to "reinvent the wheel" each time, but extra care must be taken to assure that the final specification conveys the desired final product. Some actual specifications require 50 milliseconds response in one section and 100 milliseconds response in another.

In the perfect world, the specification should be used as a guide to allow both the government and contractor to work together to achieve the desired result. This is not the perfect world and when conflict arises, specification becomes the ultimate authority in settling the dispute.

A poor specification in the hands of a good contractor is less of a problem if the contractor is allowed to suggest changes and improvements. A poor specification in the hands of an inept or inexperienced contractor can be costly and endanger lives.

The contractor installing a high-speed deluge system must understand the product and process that is being protected. An experienced contractor and a well-written specification are essential for an effective system. This is true of both suppression and detection (see Section III).

Specification writing is very involved and is not in the scope of this report, although a comprehensive new specification is recommended for each major application. The purpose is to illustrate the importance of a well-written specification.

2. False Activations

Most false high-speed deluge system activations result from poor installation, ambient conditions not suitable for the detection system, degradation of equipment or poor system design.

False actuation due to ambient conditions depends upon the detection system being used. Two common types of detectors are in use, ultraviolet and infrared. The ultraviolet is most common. These are discussed in detail in Section III.

Common ambient sources of nonfire radiation (discussed in Section III in detail) that can cause false activation of UV detectors include:

- Long-duration lightning.
- High-voltage corona (transformers or high voltage insulators and lines).
- Static buildup on belts or conveyors (due to Van DeGraph effect.)
- Cracked lenses in high pressure sodium lights.
- Arc welding up to 1/2 mile
- Drill motors, commutator motors and contacts that emit arc or sparks.
- Sunlight if detector has deteriorated or shifted frequency.
- X-ray/ionizing radiations.

There are many sources of UV radiation. Fortunately, most of them (due to sparking or energy potential), should not be near pyrotechnics or explosives.

The IR detectors that are the state of the art in ammunition plants at this time, are susceptible to ambient light (both sunlight and artificial light) and black body radiation. This type of detector should be installed where there is little or no light. Disconnect switches must be employed if equipment is to be opened to ambient light.

Poor installation is a major cause of false activation. The following is a list of guidelines for detector installation:

- Use correct rated wire (especially insulation rating).
- Use all "home-runs," no splices.
- Do not share conduit with other devices.
- Do not install batteries in same enclosure with detector controller.
- Avoid hard pulls when pulling wire. It may cause

short, opens or insulation breakdown.

- Avoid floating or fluctuating ground potential.
- Use drain-seals at each device.
- Be sure the ambient environment is compatible with the detector, with respect to both physical (vibration, moisture impact) and optical (acceptable ambient lightning) parameters.

Age or other degradation of equipment can cause false actuation. Scheduled maintenance and trouble shooting can help prevent this.

False system activation is not always limited to detection. One must be aware of causes stemming from poor interface and control circuitry design.

Large inductive load switching and power source spikes may cause false activation.

False activation often occurs during maintenance and servicing. It is best to have systems in bypass with water off when maintaining systems.

New technology systems such as machine vision will be able to offer better discrimination and fast detection.

3. Time Testing

Time testing of high speed systems is a critical and necessary function of acceptance and maintenance, and these systems should be standardized.

Time testing is an essential aspect of acceptance testing and maintenance. There are many methods of time testing. System response time is a controversial issue. Probably the best way to determine if the deluge system is adequate is to run an actual fire test with the explosive or high-energy material utilizing a proposed suppression system. Often, this is not feasible. With exception to actual burn test, the second most accurate method of time testing would be using high-speed video cameras.

Some common high-speed cameras record approximately one frame every 8 milliseconds. Faster CCD cameras record in the 1000 - 2000 frames per second range. These faster CCD units would be used in the machine vision fire detector.

A high-speed camera is used to record and play back the event and the frames are counted to determine the response time. The propagation of the flame can be observed to the point of detection, the start of flow at the nozzle, and water spray as it progresses to the hazard. Spray patterns can also be observed. This system is sometimes not feasible for "in-field" application.

Lighting is sometimes inadequate and the expense of providing the technicians and shipping the equipment is often great.

With advances in technology, price and size of equipment are decreasing rapidly. So far, the most economical and reliable system for "in-field" time testing is a digital timer. Reaction time is defined here as "beginning at instant of detection and stopping at flow from nozzle." The timer is started by a signal from detection control and is stopped by a flow switch connected at the nozzle. This seems to be acceptable to most authorities for testing deluge systems "in-field" and for periodic maintenance testing.

A trend is developing in specifications to time the system from initiation of a saturating light source to receipt of "fire" signal to flow at nozzle. This method provides for the testing of the integrity and speed of the detection portion of the system. The preferred instrument set-up for this method would provide two timer readouts. The first would represent the detection time (saturation of detector to out-of-fire signal) and the second readout would represent deluge system response time (receipt of fire signal to flow at nozzle). When using this type of time test, the specification writer must consider the added detection time.

There are many ineffective systems presently installed at U.S. Army plants. The systems were originally installed according to specification. Time and recent innovations have rendered these systems obsolete. Many of the systems have a reaction time of more than 2000 milliseconds (2 seconds). A study of the cost or feasibility of upgrading these systems to the state of the art should be conducted.

Proper installation is also imperative to achieve a useful and functional fire protection system. One of the most critical areas is the electrical installation of the system, especially the detector's wiring and installation. False actuation or no actuation can result from a poorly installed detection system.

4. Reaction Time

Reaction time is defined as the total time required from initial fire event detection to the presence of water at the nozzle.

Overall reaction time can be broken down into segments.

By dividing the events of a pyrotechnic fire and deluge system actuation into individual time segments, one can better understand exactly what is being timed and what may be being ignored when the test is performed.

Time Segment 1:	The pyrotechnic mix is subject to excessive energy input.
Time Segment 2:	Deflagration begins at some point in the mix.
Time Segment 3:	The fire develops to a point that puts it in the detector's field of view.
Time Segment 4:	The detector begins to react to the fire.
Time Segment 5:	The detector "decides" that there is enough light energy radiated to be considered a fire.
Time Segment 6:	The detector sends out a fire signal.
Time Segment 7:	An interface unit (a unit that provides an output signal compatible with the suppression after receiving a "fire" signal from the detector or detector controller) receives the "fire" signal and activates a squib or solenoid valve, depending on the system type.
Time Segment 8:	Mechanical components within the deluge system go into motion.
Time Segment 9:	Water leaves the nozzle and travels toward the target (burning pyrotechnic mix).
Time Segment 10:	Water spray impinges on target.
Time Segment 11:	Water flow is maintained to achieve the desired effect. (cool down, dispersal and extinguishment.)

The first time test method uses high-speed video technology. It allows viewing and testing of Segment 3 through Segment 11.

The second time test method mentioned measures the point of detection to flow at nozzle. This method allows timing of Segments 6 through 9.

The third method, detector saturation to flow at nozzles, measures the total time of Segments 4 through 9.

The time tests are critically different. They all have advantages and disadvantages. The individual involved in providing, testing and specifying deluge systems must be aware of the methods and their shortcomings.

With the event divided into 11 short segments (the total time elapsed is usually less than 100 milliseconds (1/10 of a second) for all 11 segments, each segment can be analyzed to determine if the individual time segment's reaction time can be reduced.

Segment 1: Here the process and product must be reviewed to eliminate the possibility of excessive energy input and, if it does occur, design equipment so that it is visible as possible. This is next to impossible in most applications.

Segment 2: This will vary depending on batch size and process. In a propellant machining operation, it will be in view at the surface where it will be quickly seen. In some mixing applications, it may be at the bottom of the mix where a blade might hit the side wall or a foreign object.

Segment 3: Reaction time can be reduced by placing detectors as close as possible to the suspected origin of energy input, making sure equipment and personnel are not blocking the detector's view.

Segment 4: Different types of detectors have different reaction times. The reaction time depends upon the spectral irradiance being received by the detector, the detector's set threshold, any internal electronic gating or discrimination features, voting and other detector properties. The detector should be designed to detect the specific spectral bands of the emissions of the burning product and to "ignore" nonfire event radiation emissions to minimize false alarms.

Segment 5: The detector's logic must decide if the fire is intense enough to trigger its alarm threshold. The method of detection and discrimination can vary with each type of detector. Some use microprocessors. Others may use discreet switching or counting circuitry. In most cases the more discriminating the detector is, the slower it will be. Some detectors have sensitivity adjustments. This is an option in reducing reaction time. Reducing reaction time usually means increasing sensitivity, which may lead to false actuation.

Segment 6: After the fire decision is made, it is sent to the outside as a fire signal. This may be an electronic signal output or a mechanical relay output. The latter is slow and can take up to 20 milliseconds.

Segment 7: The interface unit is often described as a detonator or response acceleration module. The purpose of the interface is to process the detection signal and supervise the circuitry to the squib or solenoid, depending on the system. In the case of a squib activated system, the detonator sends a high current pulse to assure that the squib activates. The response acceleration unit sends a high voltage signal to the solenoid to speed response time. Both type modules (interface unit) should react in less than 1 millisecond. (See section on existing high speed systems.)

Segment 8: Mechanical components are effective with each type of system. Their differences account for reaction time differences. It should be remembered that reaction time must be balanced with the individual hazard, cost, ease of maintenance and ease of system reset.

The time sequence for each mechanical system is as follows:

The system that has a squib at each head (See Figure 1) operates in the following sequence:

a. Electric current heats the squib bridge wire.
b. The bridge wire ignites the squib pyrotechnic mix.
c. The energy release of the burning pyrotechnic mix (explosion) breaks either a glass bulb or a rupture disk at each head.
d. Water flow.

The systems that use a (Primac) single squib actuated valve operate in the following sequence:

a. Electric current heats the squib bridge wire.
b. The bridge wire ignites the squib pyrotechnic mix.
c. The energy release of the burning pyrotechnic mix (explosion) pushes the hold-down latch away.
d. The supply water pressure opens the valve.
e. The water pressure forces off the blow-off caps or breaks the rupture disks.
f. Water flow at nozzle.

The pilot-operated systems (See Figure 2) incorporate the following mechanical sequence:

a. Solenoid valves receive high-voltage pulse.
b. Solenoid valves open.
c. Pilot pressure is released.
d. Poppet in each deluge valve lift up.
e. Flow at nozzle.

Systems with a single explosive disk at supply operate in the following sequence:

a. Blasting cap bridge wire receives current.
b. Blasting cap explodes.
c. Blasting cap explosion detonates PETN high explosive in rupture disk.
d. Water flow. (This type valve may be used for flooding a vessel, in which case nozzles with blow off caps may not be present).

Propellant driven systems (See Figure 3) operate in the following sequence:

a. Electric current heats the squib bridge wire.
b. The squib pyrotechnic mix ignites.
c. The squib ignites the sodium azide propellant.
d. The propellant gases pressurize the water vessel.
e. The pressure ruptures the disk.
f. Water flow.

Although the previous sequence of events described for the mechanical system seems long and involved, all events actually occur in a matter of milliseconds.

Eliminating air in the Primac type system is very important. Eliminating air in the pilot line of the pilot-operated system is equally important.

Increasing water supply in almost all types of systems will speed reaction time.

Proper installation is critical to acceptable system reaction speed {of water allowed to flow}. Water contaminated with energetic nature is often a problem at ammunition plants. Excess contamination water may have to be dealt with.

F. IMPROVING EXISTING SYSTEMS

Improving existing systems must be done on an individual, one-on-one basis. Each system must be evaluated and studied to determine if it meets existing criteria. The existing systems vary greatly.

Some deluge systems could not react in less than 2 seconds (2000 milliseconds). When these systems were installed they did meet specifications and were state of the art. Extensive renovation would be required on such systems.

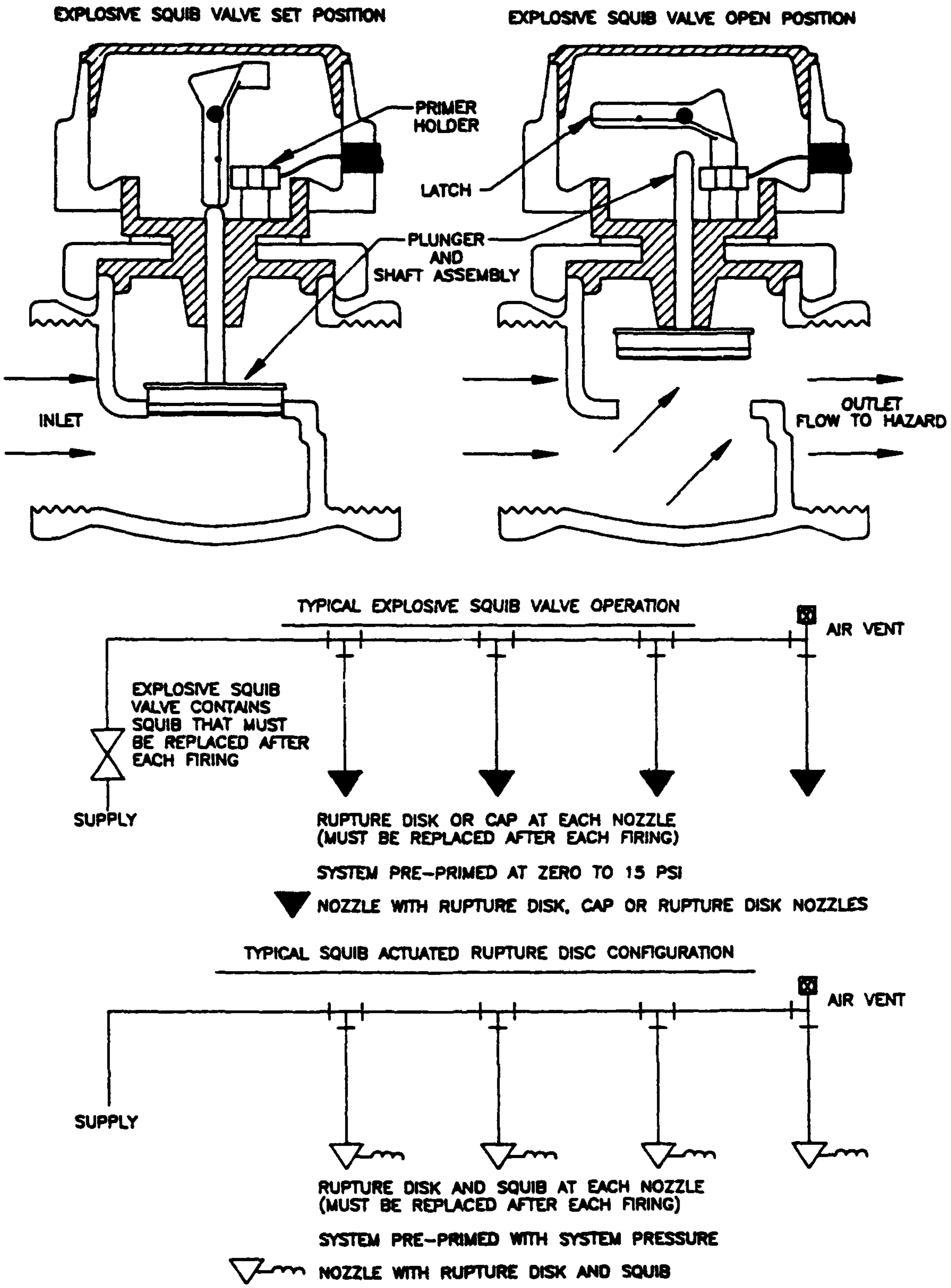

Figure 1. Typical Explosive Squib Valve Design and Operation

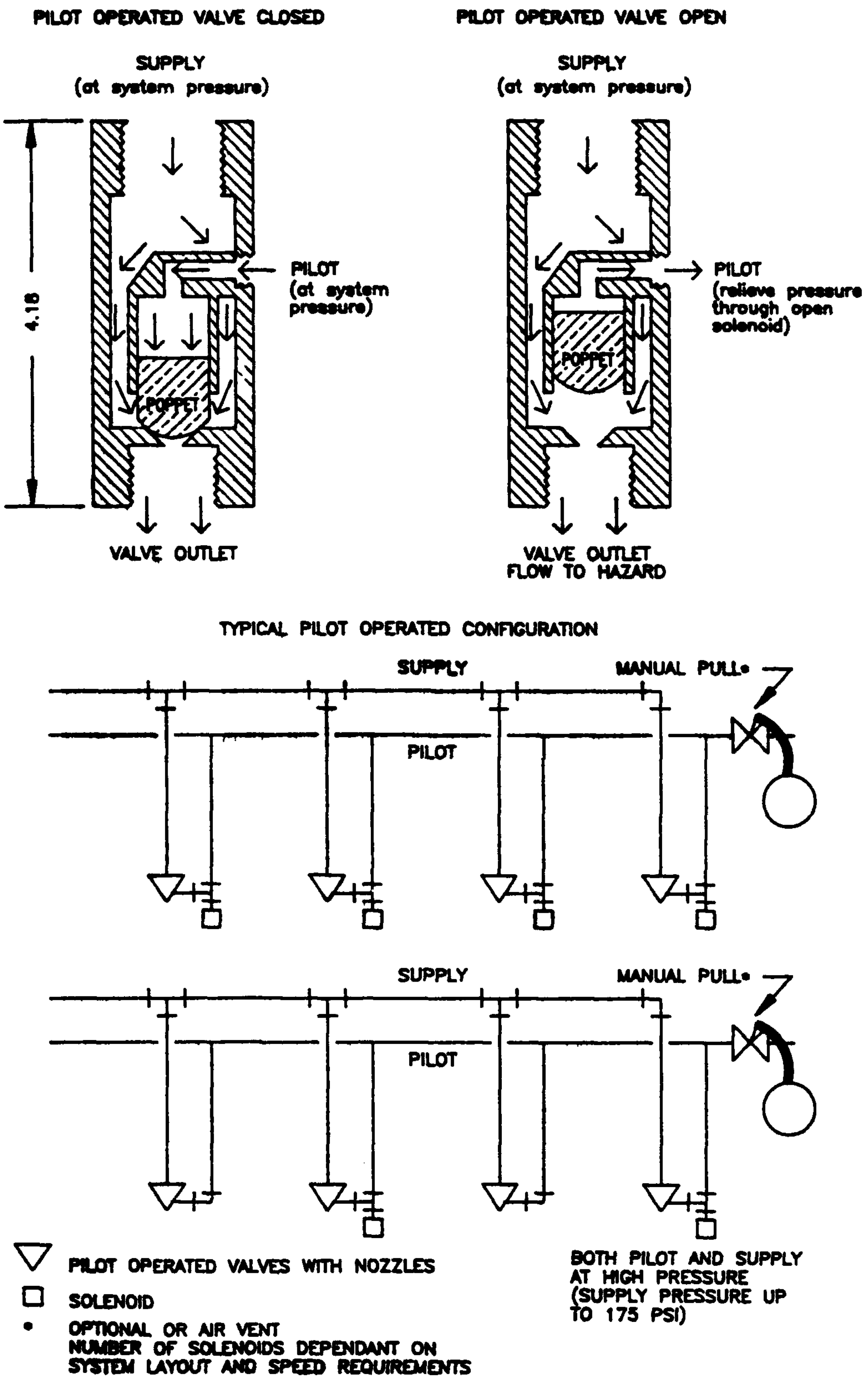

Figure 2, Pilot Valve Operations

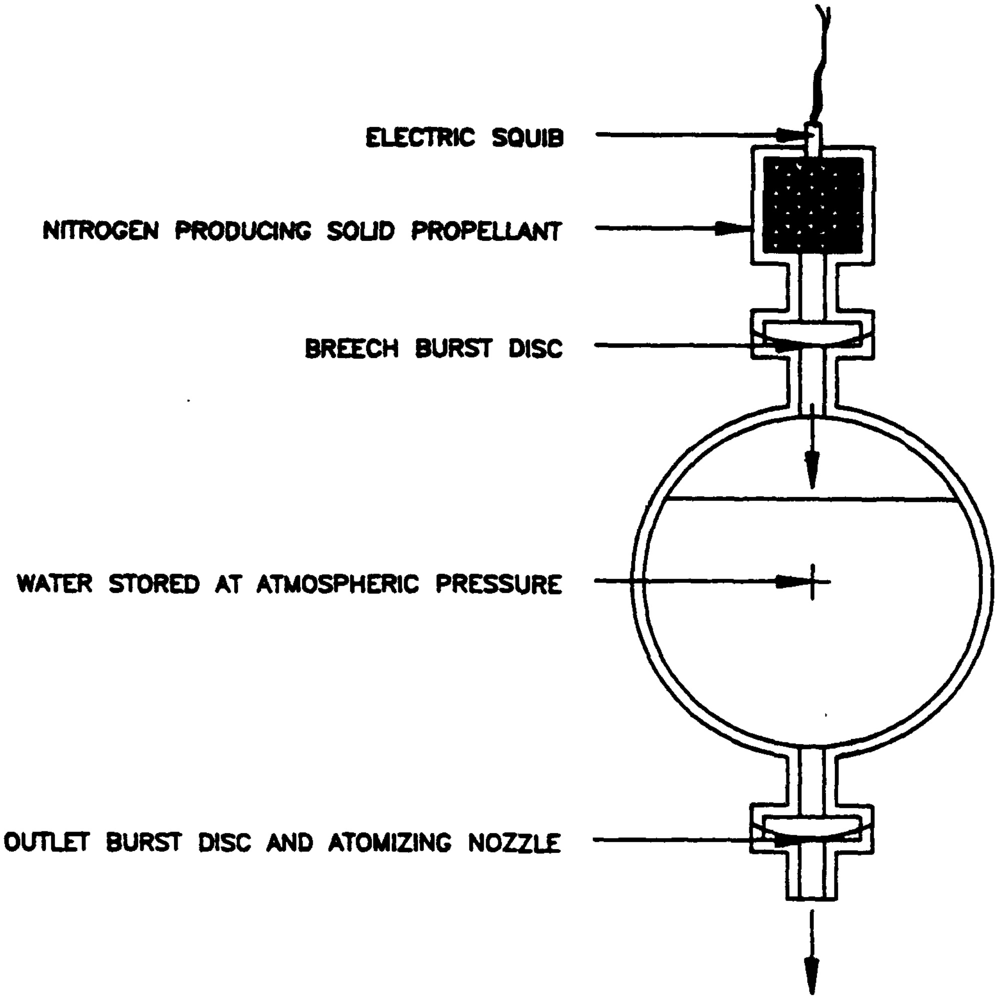

Figure 3. Solid Propellant Pressurized Water System

Other installed systems may need only minor adjustment and modifications such as:

- Relocate detectors.
- Relocate nozzles.
- Perform time testing.
- Reconfigure to achieve proper response time and flow characteristics.
- Change design criteria in cases where the hazard has changed.
- Rewire in areas where original wiring was incorrect.
- Retrofit with new detectors.
- Retrofit with new type of deluge system.
- Eliminate or enhance overhead deluge with dedicated "pin-point" deluge.
- Make existing systems more flexible and easier to configure.
- Study available underground supply, as smaller well designed systems may do a better job and require less water than a large poorly designed system.

G. SUMMARY OF TYPES OF HIGH SPEED SYSTEMS

Advancements in electronic fire detection in the past twenty years has made ultra-high-speed deluge systems for explosive facilities feasible and reliable. Discussed as follows are a few of the most popular ultra-high-speed fire suppression systems presently used in explosive facilities, along with a newly proposed propellant driven system. For the purpose of this report, ultra-high-speed is defined as: "A reaction time of less than 500 milliseconds, measured from the instant of fire detection to water flow at nozzle."

The evolution of deluge systems has been one of marked improvement. One of the first high-speed deluge systems was the open-head configuration that usually incorporated heat actuated detection. Reaction time of this type system was approximately 15 seconds to 2 minutes, depending on configuration and detection. Following this was the primed deluge system using optical flame detection (ultraviolet or infrared). Reaction time of this type system could be as fast as 1 to 2 seconds.

During the "60's" the squib actuated preprimed deluge was developed. At least two major companies were supplying deluge systems in this configuration. The squib actuated preprimed system coupled with flame detection could respond well within the 100-millisecond range when configured correctly, thus providing the first ultra high speed deluge.

This piping configuration consisted of single squib-actuated deluge valve, primed piping and nozzles utilizing either caps or gold rupture discs to hold priming water. Common trade names for these systems are Primac and Spectronic.

Another system that falls into the ultra-high-speed category is also squib-actuated, but the principle of operation varies greatly. It consists of preprimed piping with high pressure rupture discs at each nozzle and explosive squibs each rupture disc (nozzle). Upon fire detection, the squibs are fired, rupturing the disc, thus providing water at a very fast rate. This system can be preprimed at a much higher pressure than the Primac or Spectronic. Some versions of this system can be as simple as placing a squib or cap next to a glass bulb sprinkler. When the squib explodes, it breaks the glass bulb.

A system that has found its way into the explosive field is the solenoid actuated pilot operated preprimed deluge. The pilot operated system is essentially a pilot-operated deluge valve at each nozzle. The pilot-operated valve is a discharge valve that incorporates a pressure differential for "on-off" operation.

The pilot-operated deluge can be preprimed with very high pressure and reaction time is not affected by air in the supply piping (air must not be present in the pilot system), thus fast and constant response times can be achieved, well under 50 milliseconds.

Redundancy is a key factor providing system reliability and integrity, since the valves can be thought of as individual deluge valves, the total system does depend on one deluge valve for operation. The system will also operate even if all but one solenoid fails to fire.

1. Explosive Squib Actuated Valve

The Primac is a squib-actuated deluge valve. The system uses one large valve connected to a preprimed piping system utilizing nozzles with end caps or rupture discs. In Primac Systems using rupture discs at the nozzle, the rupture discs are burst by water pressure, not an explosive charge. The body of the Primac valve is that of a standard "globe" valve. The water seal is achieved by a piston entering the throat of the valve body. An "O" ring inserted in the same manner as a piston ring makes the piston watertight. The stem attached to the piston extends through the top of the valve. A swinging latch connecting this stem holds the valve in a closed position. The yoke supporting the latch is designed to accommodate a primer so positioned that when the primer detonates, the latch is forced off the stem and the water pressure under the piston opens the valve. NOTE: The stem "O" rings must be kept in good condition; a leak at this point may cause submersion of squib.

2. Explosive Rupture Disk

The explosive rupture disc system incorporates the same principle as Halon-type explosive disc systems, except that water is used as the extinguishing agent. This type of system is very effective in flooding large vessels quickly. In ultra-high-speed applications, where large coverage or many nozzles are required, there is a squib and rupture disc at each nozzle.

3. Pilot-Operated System

The solenoid-operated system does not use explosive squibs. Its principal of operation varies greatly from the previous two. When pilot pressure is relieved, all valves connected to the one pilot light open instantaneously and simultaneously. When the pilot pressure is restored, the nozzles close. A valve consists of a two piece body threaded together and sealed with an "O" ring.

The upper body has a connection for installation and standard pipe fittings and a ¼ inch NPT female connection from the pilot line. The cylinder and the poppet, that make up the differential valve, receive pilot pressure from the pilot-line system.

The poppet has a Teflon® face which seats against the orifice located in the lower body half of the valve. The lower body is interchangeable to accommodate various types of discharge devices. Male adapters are often used where there is a need for flange mount or to directly flood a melt kettle or mixer. The female adapter is most often used with the nozzles. When the valve is in its normally closed position, the poppet is held against the discharge orifice by the pressure within the poppet cylinder. When the pilot pressure drops, the main fire pressure overcomes the differential and forces the poppet up and instantly starts full discharge. When pilot pressure is restored, the poppet reseats, even against fire main pressure.

4. Propellant-Actuated System

A new area of technology that offers considerable promise to the fire suppression and extinguishing industry is the solid-propellant technology being applied for inflation of automobile air bags. Air bags (both driver and passenger) will be standard items on almost all vehicles in the next few years. These bags are inflated very rapidly (typically 30 milliseconds for a driver air bag and about 80 milliseconds for a passenger bag) by solid-propellant gas generators that produce gaseous nitrogen as the output product. The nitrogen is formed by the rapid combustion of pellets within the inflator that are comprised of sodium azide fuel with a suitable oxidizer such as iron oxide. Additional combustion products such as small amounts of ferrous oxide and sodium oxide are removed from the gaseous stream by passing the effluent through a filter system located internal to the inflator, and the resultant output is basically pure nitrogen gas. Nitrogen by itself is an adequate gas either to extinguish a combustion process by dilution and oxygen starvation or to dilute and inert a potentially explosive or flammable fuel air mixture (although not effective by itself in a pyrotechnic application).

The rapid operational time of these systems provides a unique means for storing large quantities of nitrogen at atmospheric pressure as opposed to gaseous nitrogen stored in conventional high pressure storage vessels that require large valves or exhaust ports to dump the gas in a short enough time period.

Two approaches could use the air bag inflator in fire/explosion suppression applications. The first approach would be to mount a correctly sized inflator near a potential fire/explosion zone and function the gas generator when the appropriate type of sensor detected a flame or spark. In the automobile application, the gas generators are initiated by an electrical squib mounted internal to the inflator, and a current flow of about 3.5 amperes to 2 to 3 milliseconds causes gas generator ignition.

This firing current requirement is totally compatible with most sensors that would be used, and either AC or DC power will cause the gas generator to function. A passenger side inflator that is 2.5 inches in diameter and 14 inches long produces about 7 cubic feet of nitrogen gas at ambient pressure at a temperature of about 600° F.

Discussions with individuals at Rocket Research Company involved in the development and production of these air bags' gas generators have indicated that they can be manufactured at almost any size required, and that the functioning time could be reduced to about 10 milliseconds or increased to several seconds or even minutes.

Another unique means for employing these nitrogen-producing gas generators in fire extinguishment applications would be to use the gas generators as a means for rapidly expelling and atomizing water stored in a pressure vessel located near a hazard. This method is more suitable for pyrotechnic fires. When the gas generator was electrically initiated by the fire/explosion sensor, the water reservoir would be rapidly pressurized to a pressure of around 2500 psig, which would rupture the diaphragm retaining the water in the reservoir and allow water to be expelled through the outlet port. The high operational pressures available would allow the outlet port to be designed as an efficient atomizing nozzle to disperse the water into fine droplets, which would increase the effectiveness of the system. Although this approach results in a "one-shot" device, several of the gas generator actuated vessels could be placed at each hazard to provide multishot capability. A potential advantage of these propellant pressurized water reservoirs would be the minimal amount of water that was expelled in each event.

The triggering of a large-capacity sprinkler system in an area containing hazardous chemicals (propellants, explosives, etc.) may result in excessive amounts of water being discharged. The water is then likely to become contaminated with the chemicals involved in the operation and would need to be treated as a hazardous waste. In most cases this situation is accounted for by use of water collections or automatic resetting systems. This may be a viable alternative where water must be kept to a minimum.

With the various systems available for the suppression of high energy chemical fires, there is a configuration suitable for almost any explosives, pyrotechnic or munitions facility.

H. SUMMARY

Standardization of specifications and testing methods require further study and improvement.

Future systems must be designed and specified with the individual hazard in mind. There has been much improvement in this area in recent years, i.e., detector and nozzle placement. A hazard analysis is recommended for any proposed system. The analysis should include a study of product and process.

At this time, there is not extensive available information on the various pyrotechnic, explosive and propellants used in the munitions industries. The type of information being: spectral wavelength emissions of the burning product, the effect of water in extinguishing fire in the various products, and the speed required to extinguish a fire involving the product and processes.

Due to the lack of specific information on the burn characteristics, a design goal is to get the most water to the hazard as quickly as possible. With better statistics and information relating to the individual burn characteristics, money may be saved by eliminating some systems or at least fine tuning (or optimizing) them to the hazard. With more data on frequency emissions, detector manufacturers could also design their detectors to be more specific to better match detection bands to those of individual pyrotechnic materials' emissions.

The next decade should provide advances in detection technology including machine vision or "intelligent detection."

SECTION III

FIRE/EXPLOSION DETECTION

A. REQUIREMENTS

The two most important requirements of the fire detector are fast detection of a pyrotechnic fire/explosive event and reliable, false alarm-proof operation. It is of utmost importance to identify the event in time to apply the suppressant to the developing fire event before a catastrophic situation occurs. It is also important that the detector does not false alarm to a nonfire event, thus causing the accidental release of the suppressant, which could result in an extended downtime of the fire protection system and production line, financial loss, and adverse environmental impact. This latter problem is becoming more severe with increasing knowledge of the effects of certain types of fire extinguishing agents on the atmosphere and water acquifers.

In addition to "speed of response" and "immunity to false alarms," other operational features should be considered in selecting a detector, or detection system, for any specific application. These include:

Ability to meet environmental and mil-specifications
Logistics: ease of installation and maintenance
High mission success reliability
Reasonable MTBF
Self-test

In general, many of these desirable features relate to the quality of parts, materials, processes, testing, and manufacturing. A "military standard" detector which meets such standards as Mil-Std-810D (environment), Mil-Std-461 (EMI), Mil-Std-462 (EMI test procedures), Mil-Std-454 (materials/workmanship), Mil-Hndbk-217 (reliability modeling), and Mil-Q-9858 (quality assurance), provide assurance to the government that the detector provides adequate performance and lifetime reliability.

These specifications are not required at present, although there are several reasons why it would benefit the user agency to incorporate these military standards and specifications into the purchase descriptions and performance specifications of fire detectors for this application.

B. DETECTOR BACKGROUND

The types of detectors used over the past 10 years in monitoring ammunition maintenance, storage, renovation, rework, processing, and manufacturing activities are basically the same detectors used for hydrocarbon fire detection such as in commercial and military aircraft facility applications. These conventional detectors are typically single band IR, single band UV, and, recently, a combination of both UV and IR. Their operational spectral bands are primarily those associated with hydrocarbon-based fires. The intensity of these radiations is used as a criterion to determine the presence of a fire of some minimum size at some distance. Due to the $1/r^2$ law it is impossible for such a detector to determine actual size, location, or even direction unless the detector functions in the video/image processing mode such as the machine vision detector being developed by Donmar Ltd. for the Air Force.

Hydrocarbon fires have broad wavelength band emissions across the ultraviolet, visible, and infrared portions of the electromagnetic spectrum. However, there are certain discrete emission characteristics such as the CO_2 emission "spike" near 4.4µm. Also, because the atmosphere absorbs most solar radiation in the 185 nm - 240 nm ultraviolet band, the relatively low level of ultraviolet emitted by hydrocarbon fires in this band (as compared to the IR emission at 4.4µm) can be distinguished above the background solar radiation. For these reasons, most commercial grade fire detectors used for hydrocarbon fire detection operate in the 185nm - 260nm ultraviolet band and in the 4.2µm - 4.7µm infrared band. These same detectors, when applied to the pyrotechnic fire application also use the same spectral bands, but not by design.

The spectral emission characteristics of hydrocarbon and pyrotechnic fuel fires are different, but there appears to be considerable overlap across the UV band and in the IR band near 4.4µm. There is a distinct emission near 4.35µm from propellant ignition. In general, however, there is insufficient pyrotechnic spectral irradiance information to design a detector to the specificity needed to optimize detection and discriminate of a pyrotechnic fire from other sources of the same radiations.

Commercial type detectors have been augmented, to some degree, in their "sensitivity" to detect pyrotechnic-type fires much faster than hydrocarbon fuel fires where the required time-of-response may be much longer (e.g., 5 seconds as compared to tens of milliseconds).

In the process of increasing the sensitivity, and therefore reducing the threshold of either count rate or spectral irradiance, an increase also results in the detector's sensitivity to respond to nonfire sources which radiate in the same spectral bands at a spectral irradiance level at the detector which is equal to or greater than the threshold for pyrotechnic event detection. Therefore, at some sensitivity level, the detector becomes sensitive to nonfire sources within its field-of-view and may lose its immunity to false alarms, thus becoming a liability rather than an asset to fire/ explosion protection. At this stage false alarms occur. This depends, however, on the nature and properties of the nonfire radiative sources in the detector's FOV. False alarms have evidently occurred in various pyrotechnic and ammunition facilities, but documentation is either scarce or is inconclusive as to the cause of the false alarm. Welding and lightning have been cited as causes on several occasions.

To provide discrimination capabilities in their hydrocarbon fire detectors, some detector manufacturers have added additional detection logic. This includes requiring the measured infrared radiation to vary in frequency between 1 Hz and 10 Hz (referred to as "flicker" or "chopping"). Another added detection discriminant is the requirement for the ratio between the IR irradiance and UV irradiance to be above some level after background has been subtracted. Also, as a means to reduce sensitivity to false alarms, electronic time gates are often used, but these result in delaying the fire detection time. There are other discriminant approaches that add specificity to fire detection vs. false alarm detection. In some instances, however, the use of some discriminants also make it difficult for the detector to "see" a fire when certain nonfire UV and IR sources are present. In the application to pyrotechnic fire detection, these additional discrimination features only slow down the detector's response and are self defeating to the performance goals.

Again, speed and reliability of detector response are the most important parameters in this fire detection application. There are basically three types of detectors that should be considered for this application, namely, UV, IR, and machine vision (either in the visible or IR).

C. UV DETECTORS

Historically, the UV detector has been used for pyrotechnic and propellant fire detection for the past 10 years. Its operational characteristics have been documented many times in reports pertaining to this fire protection problem. Because of its "Geiger-Mueller" detection morphology, it is a very sensitive detector that can respond to either a photon of energy equal to or greater than some "work function" energy associated with the cathode material, or charged particle that can interact directly with the gas molecules.

When a photon strikes the cathode, usually tungsten, an electron is emitted. Tungsten has a work function that will allow, as a minimum, a photon of wavelength 0.245μm (245nm) to cause an electron to be emitted from the cathode. The emitted electron is drawn to the positively charged anode and, enroute, strikes gas molecules which are then ionized, thus resulting in a current between cathode and anode. An avalanche/discharge occurs which can be interrupted by switching the power on and off or by reversing the charge on the cathode and anode.

The glass envelope, usually quartz, is opaque to wavelengths shorter than about 185nm. Therefore, the spectral UV sensitivity of the UV detector is usually between 185 nm and 245 nm, although the cutoffs extend to longer and shorter wavelengths. This type of detector is a relative intensity detector, that does not know the nature, direction, distance, or spectral irradiance of the source. It cannot discriminate spectral energy flux (spectral irradiance) because it will respond to all energies equal to or greater than the specific work function of the cathode and to any source that causes ionization of the fill gas(es) to occur.

One problem is that this type of UV detector may be too sensitive to extraneous UV, charged particles such as cosmic rays, and other ionizing radiations. To circumvent this sensitivity problem, the electronics can be programmed to activate an alarm/suppressant dump only when the count rate reaches some minimum level over some gated time sequence, which is normally above the estimated background count rate or other possible count rates caused by nonfire sources.

The UV detector has been tested in many pyrotechnic and propellant fire/explosion tests and has demonstrated a broad detection-time-range of about 20 ms to about 800 ms, depending upon the substance being burned and its properties, detector look angle, distance, number of detectors used in the detection scheme, and other parameters. "Detection time" is defined herein by the number of counts accumulated over some predetermined time period. The fewer the number of counts required to respond with a "fire decision," the more susceptible one detector is to false alarming to extraneous nonfire sources. However, if more than one detector were used to monitor the event and all detectors' counts were added together in real time, then the threshold minimum number of counts required to respond with a fire alarm would be reached faster, thus increasing the speed of the detection system. The more detectors looking at the fire threat area the faster would be the accumulation of the required number of counts. This approach has been tested but the results are not consistent and certainly not linear. The net result may be that detection time is faster but so is false-alarm time.

UV detectors are greatly affected by smoke in the path between the fire event and detector. In tests with burning smoke mixes, UV detectors were unable to "see" a flame signature for relatively long periods after ignition, sometimes seconds. In extreme cases, the flame was so obscured from the UV detector by the smoke from the mix burned, that more than two minutes elapsed before the detector responded. In other cases, the smoke was relatively dense around the detector's lens face, thus fooling the detector's BIT into "thinking" the lens was "dirty," thereby setting off a fault alarm.

Despite the problems with UV detectors, they are very effective in certain applications. Instead of designing the detector to meet the specific application, efforts have been devoted to modifying standard commercial hydrocarbon flame detectors to perform as pyrotechnic and propellant fire detectors or smoke/flame detectors. To some degree, these efforts have been successful, but the time of response and false-alarm immunity requirements remain to be satisfied. To optimize the detection morphology, (1) the detector's operating spectral bands should be the same as the spectral emission bands of the munitions/propellant substance fire; (2) the required count rate to assuredly identify a fire event should be minimized; and (3) the detector should be immune to nonfire sources.

D. IR DETECTORS

In addition to UV and visible radiation, fires also produce substantial amounts of infrared radiation in the near and mid-IR regions. Most of the emission characteristics pertain to "blackbody" emission which covers a broad range of the IR spectrum. Some "species-distinct" emission "spikes" occur, especially near 4.4μm. This emission characteristic is due to carbon dioxide. It is also an important fire feature to monitor because the atmosphere absorbs solar radiation in this wavelength region, thus minimizing the background. Another "window" region, sometimes used for IR detection, is near 1.2μm.

IR detectors can be very sensitive to almost any "hot" body because this body radiates across a broad spectrum of the near and mid-IR spectrum, taking the appearance of a bell-shaped curve whose peak intensity corresponds to a wavelength that varies with temperature. The IR spectral radiance of a pyrotechnic/propellant material fire is much greater than that in the UV, in fact, orders of magnitude greater. Also, IR detectors can "measure" the relative spectral radiance from an event, thus being able to associate "intensity" with relative size and/or distance of the fire source. UV detectors cannot function in this manner due to the work function of the material of the cathode and the cutoff energy of the tube's glass.

IR detectors, used in hydrocarbon fire detection, have not demonstrated, to a great degree, reliability to discriminate fire from hot bodies and nonfire sources. Two basic types of sensors are used in these detectors: thermopile and pyroelectric. The thermopile is similar to a thermocouple. Because many "thermocouples" can be connected in series on the same chip, such a detector can be very sensitive. They are, however, very sensitive to ambient temperature changes.

Pyroelectric detectors use photodiodes and operate on the basis of time rate of temperature change. The output depends upon the time rate of change in the detector's temperature rather than on the detector temperature itself. It is constructed of a pyroelectric crystal such as lithium tantalate or ceramic barium titanate. When these crystals are exposed to thermal gradients, they produce electrical current.

One characteristic of fire is "flicker." Flicker is the result of dynamic behavior of the flame and produces an intensity variation in the IR and visible in the range of 1-20 Hz. However, in tests conducted by Donmar, flicker can be seen to occur on even the highest frame rate video CCD cameras, certainly over 1000 frames per second (2 interlaced fields per frame). Because of this fire flicker property, almost all IR fire detectors require a flicker to exist in the IR signal processing. However, a flicker can respond to any motion such as walking or a moving vehicle in between the detector and the nonfire IR source to cause a false alarm. Another feature of fast ignition/growth pyrotechnic events is that the event is extremely intense in the far UV, visible and near infrared and does not contain flicker until the "fire" part of the event begins, some 50 milliseconds or so after substance ignition. Flicker, then, is not necessarily useful as a detection criterion, although it may be helpful as a false alarm discriminator if the time of response of detection is greater than 2-3 seconds.

Other infrared detectors, however, have not been incorporated into pyrotechnic fire detection. They are currently being used in Army Tanks and fighting vehicles to detect armor piercing ammunition and to discriminate them from "heat rounds" and other non-ammunition fire sources of infrared. These detectors operate in the 2-3 millisecond time period when responding to a small 5-inch x 5-inch fire at distances as close as 2 feet- 4 feet. However, the response times increase as distance increases. In a commercial fire detection application, the response times may be as long as 3-5 seconds for a 1 ft^2 pan fire at 40 feet distance.

In the Army Tank Crew Bay application, where the detection distance is small, such a detector can cause the Halon 1301 suppressant to be released in only a few milliseconds from extinguishers inside the crew's compartment. These detectors have been very successful in their respective application, but have not been thoroughly tested in environments where extraneous IR emissions may exist or where the distance from detector to fire is tens of feet. These "mil-standard" Army vehicle "explosion" detectors usually operate at 4.4μm, with sensors also at 0.9μm and 0.6μm. Emissions in the visible and near IR are very pronounced upon ignition of a munitions round and certainly much greater than the solar background in these wavelengths. The signal conditioning requirement may then require the 0.9μm and 0.6μm emissions to be much greater than some present threshold, such as from the sun, and that 4.4μm radiation is present to some minimum intensity level. Usually some type of logarithmic amplifier is used in the signal processing which will only saturate when an ammunition explosion, as seen within 6 feet, occurs. The manufacturers claim immunity of these detectors to solar radiation and many other sources of IR radiation.

The detector, as used in Army vehicles, is rarely exposed to external sources of IR, although it is required to pass certain false alarm immunity qualification tests. The following is a listing of sources and their distances from the fire detector, per Army performance specification, to which the detector must be proven immune.

RADIATION SOURCE	IMMUNITY DISTANCE FOR SMALL FIRE (MILLIMETERS)
Vehicle headlights-MS-53023-1	300MM
Sunlight	IAD
100W Incandescent frost. Lamp	150
100W Incandescent Clear Lamp	225
40W Fluorescent Light	150
4,000VAC, 60Hz, Electric Arc; 12mm gap	25
Vehicle IR Light MS-53024-1	600
Electronic Flash, Graflite 250	600
Electronic Flash Sunpack 411	450
Movie Light: Sylvania S.G.-55;650W QTZ DWY	1200
Red Dome Light: MS51073-1	IAD
Blue-Green Dome MS 51073-1 Rev.K	IAD
Flashlight MX 991/U	IAD
1500W Radiation Heater	900
1000W Radiation Heater w/fan	600
Arc Welding 4mm Rod; 300 Amps.	1500
Acetylene Welding: 00 tip; 16mm x 150 mm flame	1500
Lit cigar/cigarette	100
Wood match, including flare up	300

IAD=Immune at any distance

This list of false-alarm sources pertains to "fighting vehicle environments" and is certainly a minimum list when considering all the possible "other" types of lamps, tools, vehicles, phenomena, and mechanisms that can emit UV and/or IR radiation in or near a military facility or possibly ammunition/pyrotechnic material facilities. No test requirements are imposed that include two or more possible false alarm sources at the same time. Possible multiple sources, false alarm properties,and detector performance qualification specifications are discussed in detail in Final Report: "Characteristics of Optical Fire Detector False Alarm Sources and Qualification Test Procedures to Prove Immunity," Contract F08635-91-C-0129, CEL-TR-92-62, Sponsor HQ AFCESA/RACF, Tyndall AFB, October 1992, Goedeke, A. Donald, and H. Gerald Gross, Donmar Ltd., Newport Beach, CA.

Based upon the performance of these IR detectors in Army Tank applications, it would be prudent to test them against the pyrotechnic materials fire/explosion application to determine their response speeds and reliability to false alarm sources.

E. MACHINE VISION FIRE DETECTOR SYSTEM (MVFDS)

Machine vision technology provides the means by which information can be automatically extracted by computer processing of video imagery whereby certain preprogrammed patterns, spectral properties, or changes are searched for and, if found, provide the basis of some form of deduction and/or decision. The technology enables reliable and rapid discrimination of objects and phenomena from a very large variety of very similar objects and phenomena having almost identical spectral features in the visible region, although the infrared region can also be used.

Images/scenes, obtained by either color or black and white CCD (Charge Coupled Device) cameras, can be grabbed, stored, and processed with algorithms at very high frame rates. A machine vision system can be adaptive and "learn" to recognize images, spectral features, changes, and physical features, and to make decisions based upon these analyses. In other words, machine vision emulates the human process of "seeing" an object, action, or phenomenon with the eye, and determining with the brain what it is and what action to take. A human uses stored knowledge and experience to make these decisions. In a machine vision system, vision with the eye is replaced with a lens and Charged Coupled Device chip. Knowledge is replaced with stored information. Experience is replaced by algorithm processing and comparison. And decisions are based upon satisfying required yes and/or no answers, usually several in parallel. The differences between human and machine vision are: machine vision is much faster, more accurate, and more reliable.

The approach taken to fire detection is derived from physical models for the formation of images of fires and other stimuli. From these physical models various properties derivable from color or black and white image measurements that can be used to distinguish reliably fires from other events are defined and quantified. These properties can be computed at high-speed and together with a decision procedure form the basis of a fire detection system. This system is capable of rapidly identifying fire events (in the few millisecond time range) and determining in real time the corresponding size, growth rate, distance and location of the event in the scene. The effectiveness of these properties for fire identification has been demonstrated to the Air Force both analytically as well as experimentally on real fires, sequences of color images of fires, and possible false alarm sources.

As stated above, the MVFDS imaging system consists of a color charge coupled device (CCD) camera and the associated optics. The three dimensional scene is imaged as a spectral irradiance pattern onto the focal plane of the device. This spectral irradiance is proportional to the spectral radiance over corresponding patches in the scene. The CCD imager consists of two dimensional array of collection sites that are sensitive to light. Color filters are positioned over spatially adjacent collection sites to provide measurements of the intensities of red, green, and blue light at each location in the image. From these measurements the camera electronics produce three analog video signals corresponding to each of the component colors. Each of these signals is quantized both spatially and in amplitude by a frame grabber to produce a digital color image. For hydrocarbon fire application, spatial quantization is typically into 480 rows and 512 columns and amplitude quantization is between 5 and 8 bits per color per pixel. For current fire detection applications, the frame grabber is designed to acquire digital color images and store them in computer memory at the standard video rate of 30 frames per second. Only 3-4 frames are necessary to discriminate fire. Once the frames are in computer memory, the images may be analyzed by a digital processor. In applications such as pyrotechnic fires, using existing technology, speeds of only a few milliseconds can be attained. This fast speed detector is also being developed by the Air Force for aircraft munitions fire/explosion detection.

The color images acquired by the frame grabber are represented hierarchically as a set of two-dimensional blocks that are processed individually by the fire detection algorithms. Each block corresponds to a specific area in the monitored scene and the size of each block is proportional to the corresponding area in the scene. As frames are acquired, the system control structure incrementally updates the current status and characteristics of each block. Once a contiguous array of blocks is identified as corresponding to a fire event the system will activate an alarm, if required. When sufficient number of contiguous blocks are equivalent to a specified fire size, the system will take the appropriate programmed action, such as an automatic release of suppressant at the location of the fire. The detector also produces a video output, thus allowing manual override of any automated suppressant release action, if desired.

This process may seem long, but it actually occurs in only tenths of a second for hydrocarbon fire detection applications using very commercial, conventional, off-the-shelf hardware/software. For the application to detection of pyrotechnic/propellent fires and explosive events the algorithms are simplified according to the physical characteristics of the detonation/fire event. These data are available in fast speed color video and can be used to refine existing and develop new algorithms.

The Machine Vision Fire Detector System (MVFDS) is being developed by Donmar Limited for Air Force ground-based applications such as aircraft hangars and shelters, and will soon enter development for Air Force aircraft airborne applications, such as fire/explosion detection in aircraft drybays and engine bay compartments.

The Air Force ground-based application detector is designed to identify a small fire (e.g. 1-2 sq. ft.) at a distance of 100 feet in less than 1 second (about 0.3 sec); to determine the fire's size and growth in real time; and to determine the fire's distance and location. In addition to these performance goals, the detector is to be immune to false alarm sources. Such a device will be a major improvement over conventional hydrocarbon fire detectors that rely upon IR and UV emissions and are sensitive to nonfire sources of both radiations. The Air Force high speed response detector for aircraft application will be designed for approximately 20 ms response.

Hardware is presently available that can perform at speeds fast enough to capture three or more frames of an explosion in the 20 ms period. The CCD and CID devices can typically capture a full frame image from 1/60 second to as fast as 1/2000 second.

The MVFDS, in a fast-speed configuration, appears to be a potential high reliability detector of pyrotechnic and propellant events at their early ignition stage. The system provides so many other features in safety and fire protection that it should be closely examined for further development and test. These features include: intrusion detection; simultaneous video surveillance and fire detection; manual override of fire suppression system for slow burning, low threat fires; determination of location and distance of fire events, thereby allowing selective discharge of local fire suppressors and thus reducing cost and potential environmental effects. For more information on the characteristics of machine vision fire detection, refer to "Machine Vision Fire Detection System Development", Goedeke, A. Donald, Drda, B., and Healey, Glenn, Final Report, Contract F08635-91-C-0217, WL-TR-93-3514, Sponsor WL/FIVCF, Tyndall AFB, FL, March, 1993.

F. FALSE ALARM SUSCEPTIBILITY

As discussed above, the basic threshold of a fire detector is the spectral irradiance value set for the source to be detected, at its specified maximum distance from the detector. This spectral irradiance is usually determined for a spectral band which corresponds, or overlaps, with the wavelength regions where the detector's sensors operate. For instance, most UV detectors operate in the spectral band of about 185 nm - 260 nm. If the detector is required to identify some type of fire, for example JP-4 fuel, of a certain minimum size at some maximum distance in some maximum time period, the detector is responding to the spectral irradiance from the source at the distance of the detector. If the fire's spectral irradiance is equal to the threshold value at the detector's distance, say "x," then any spectral irradiance in the same spectral band that is equal to or greater than "x" will cause the detector to alarm. Likewise, any spectral irradiance from any other nonfire source will also cause the detector to respond. This "false alarming" potential is a problem in some applications and, especially, in locations where many nonfire UV and IR sources can exist, either singly or in multiples.

Some detectors, such as UV/IR dual band detectors, are less susceptible to false alarming because both their UV and IR spectral irradiance threshold bands must be satisfied before an alarm is activated or suppressant is released. In addition, most manufacturers have also added another feature, described earlier, that requires at least the IR radiation to show a modulation of some "flicker" in the 1-10 Hz range. However, as found in detector false alarm studies, this flicker requirement can also be satisfied simply by moving objects between the detector and the radiation source(s). Therefore, false alarms still occur, but are less frequent with this added flicker requirement.

Knowing the spectral irradiance then, of the type of fire/explosion source to be detected at some minimum specified distance in some maximum specified time, it would be a simple task to identify, and possibly eliminate, some, if not all, possible false alarm sources. For UV,IR and UV/IR detectors, this is possible if the spectral irradiance of the possible false alarm source is known. However, the only way to discriminate against such false alarm sources using UV, IR, or UV/IR detectors is to either locate the false alarm source further away from the detector, thus reducing their spectral irradiance to a value less than the threshold value of the fire to be detected, or replacing it with a more benign type, or simply eliminating it. In this manner, a facility can be designed to pose minimum false alarm problems to the fire detection system, especially if the system is a very fast reacting system that is very susceptible to only small values of spectral irradiances. A machine vision detector, however, can discriminate these false alarm sources even though they are in the detector's field of vision.

The number of possible false alarm sources covering the electromagnetic spectrum seems to indicate that sources in the visible region would pose a greater false alarm problem than sources in either the UV or IR. This may be true provided the method of detection is based upon intensity only. Machine vision, on the other hand, although it operates in the visible part of the electromagnetic spectrum (it can also use IR), relies on intensity and many physical, temporal, and spatial features unique to the fire event. While UV and IR emissions are commonplace and can come from any direction or even one object (e.g. incandescent 150W lamp), the visible radiation must be in the form of the image of the fire object itself and behave just as the fire object behaves. Pattern recognition, artificial intelligence, and computer image processing then play the predominant roles in machine vision fire detection, making it less susceptible to false alarms.

G. FALSE ALARM SOURCES

Many types of nonfire sources of UV, visible, and IR radiation could make optical fire detectors false alarm and cause the accidental release of suppressant. A list of such sources is given below. Several may not have application to Army munition fire detection, but these are included as reference.

Technical Categories of Possible False Alarm Sources

1. Lights

    1.1 High Intensity Discharge (HID) Lamps

        1.1.1 High Pressure Sodium
        1.1.2 Mercury Vapor
        1.1.3 Metal Halide
        1.1.4 Low Pressure Sodium
        1.1.5 Xenon

    1.2 Fluorescent Lamps (96 inch length)

        1.2.1 Cool White
        1.2.2 Deluxe Cool White
        1.2.3 Warm White
        1.2.4 Deluxe Warm White
        1.2.5 White
        1.2.6 Daylight
        1.2.7 Black Light

    1.3 Incandescent Lamps

        1.3.1 Quartz Tungsten Halogen

        1.3.2 Sealed Beam - Automotive:

            1.3.2.1 Headlamp
            1.3.2.2 Spotlamp
            1.3.2.3 Signal
            1.3.2.4 Light Bar
            1.3.2.5 Rotating Lights

        1.3.3 Flashlight
        1.3.4 Flashlight with Red Lens
        1.3.5 Rough Service
        1.3.6 Movie Projector
        1.3.7 Blue Green Dome Light
        1.3.8 Red Light

1.3.9 Vehicle Infrared Light

2. Reflected Light

Solar and/or artificial light reflecting from painted surfaces, metallic surfaces, plastics, standing water, ice and glass.

3. Natural Phenomena

3.1 Sunlight: direct, scattered, reflected
3.2 Lightning

4. Electrical Discharge

4.1 Arcing

4.1.1 Power Transformers
4.1.2 Motors
4.1.3 Electrical Devices
4.1.4 Faulty Wiring

4.2 Flashlamps
4.3 Carbon Arcs

5. Nondestructive Investigative Devices (NDI)

5.1 Scattered X-rays
5.2 Scattered Secondary X-rays, UV, Direct, Reflected

6. Electromagnetic Waves

6.1 Communication Devices/Walkie Talkies/Radios/TV
6.2 Radar
6.3 IR Emission from security surveillance devices
6.4 Electric Power Switching
6.5 EMI from Electronic Equipment:

6.5.1 Vehicle/Aircraft/Equipment Subsystems
6.5.2 Electronic tools/equipment
6.5.3 Microwave devices
6.5.4 Weapon Systems

7. Personnel Items (very doubtfully near facility)

7.1 Lighted Cigarette, Cigar, Pipe
7.2 Matches (paper and wood)
7.3 Butane Lighter

8. Tools/Operations

8.1 Welding Operations

    8.1.1 TIG
    8.1.2 Arc
    8.1.3 MIG

8.2 Acetylene Welding and Cutting Operations

9. Hot Bodies, Blackbody Radiators

9.1 Vehicle Engines, Manifolds, Exhausts, Radiators, Mufflers
9.2 Ground Equipment Engines, Manifolds, Exhausts, Radiators, Mufflers from such equipment as:

    9.2.1 TTU 228/E Hydraulic Test Stand
    9.2.2 MA3 Air Conditioner
    9.2.3 AM 32A95 Gas Turbine Compressor
    9.2.4 MHU 83CE Truck Lift
    9.2.5 AM 32A60B Gas Turbine Generator
    9.2.6 MC2A Diesel Rotary Air Compressor
    9.2.7 H1 Gasoline Heater
    9.2.8 AF/M32T-1 Aircraft Tester
    9.2.9 MC2A Gasoline Air Compressor
    9.2.10 MC1A Compressor
    9.2.11 AM 32A-86 Generator Set

9.3 Thermal Heating Blankets/Welding
9.4 Radiation Electric Heaters (1.0 and 1.5 Kw with Fan)
9.5 Radiation Kerosene Heater (70,000 BTU with Fan)
9.6 Hot Lamps
9.7 Hot Welding Materials

10. Security Personnel Weapons

10.1 M-16 Rifles
10.2 M-60 Machine Guns
10.3 M-79 Grenade Launchers
10.4 38 Caliber Pistols
10.5 12-Gauge Shotguns

11. Fire/Explosive Events Associated with Vehicle and Ground Equipment Engine Wet Starts/Backfires

Among the many types and varieties of potential false alarm sources, many were subjected to laboratory measurements and tests by Donmar Ltd. in a recent detailed study. (See Final Report: "Characteristics of Optical Fire Detector False Alarm Sources and Qualification Test Procedures to Prove Immunity," Goedeke, A.D., and H. G. Gross, Contract No. F08635-91-C-0129, CEL-TR-92-62, Sponsor HQ AFCESA/RACF, Tyndall AFB, FL., October, 1992.) Some of the particular radiation sources studied are listed in Table 1.

These sources, of course, include items not normally found in or near an ammunition/ pyrotechnic facility, but are included herein as examples. The fire to be detected was assumed to be a JP-4 fuel fire of size 2 feet x 2 feet at a distance of 100 feet (it is understood that the spectral emissions from JP-4 are different than those from a pyrotechnic material fire, especially at the onset of the event; they are used here for reference).

Table 1

Radiation Sources Studied in the Laboratory

	ITEM	MODEL	WATTAGE
1.	Metal Halide Lamp	MVR 1000/U	1000 Watts
2.	Mercury Vapor Lamp	H33HL-400/DX	400 Watts
3.	High Pressure Sodium Lamp	Lucalox, LU1000	1000 Watts
4.	Metal Halide Lamp	MH 250/U	250 Watts
5.	Metal Halide Lamp	MVR 1500/HBU/E	1500 Watts
6.	Low Pressure Sodium Lamp	SOX35W, L70RB-35	35 Watts
7.	Mercury Vapor Lamp	H39KB-175	175 Watts
8.	F-16 Landing Light	GE4581	450 Watts
9.	F-16 Refueling Light	4028-1	15.4 Watts
10.	Aircraft Parking Lamp	1829	3.92 Watts
11.	Quartz Tungsten Halogen Lamp	T-3	300 Watts
12.	Truck Headlamp	GE4811 (43 Watts low beam; 53 W High	
13.	Yellow Strobe Lamp	Tandy 49-527	2.4 Watts
14.	Red Flashing Warning Lamp	Tandy 42-3040	40 Watts
15.	Ultraviolet Black Light	FEIT Electric 75A/BL	75 Watts
16.	Soft White Incandescent	GE	150 Watts
17.	Clear Incandescent Lamp	GE	150 Watts

18.	Dual Fluorescent Lamps	Sylvania F40	69 Watts
19.	Electric Hot Plate	Hamilton Beach 813-4	75 Watts
20.	Electric Hot Plate	Eastern Electric	1000 Watts
21.	UV Insect Light	Electrocutter BK-50	-
22.	Flashlight with IR Lens		
23.	Infrared Heat Lamp		250 Watts

1. Measurement Data and Computed Irradiances

Exitance measurements were made of each source in the bands 254 nm, 300 nm, 365 nm, 405 nm, and 450 nm, respectively. Because atmospheric transmittance can be changing considerably in the UV and IR bands of interest, both the inverse square law and the Lambert-Beer-Bouguer law were applied simultaneously to the measured values to derive the corrected values. Figures 4, 5, and 6 show only a few of the many spectral irradiance curves measured in the three spectral bands of interest. As seen in the curves, the most drastic falloff occurs over the range close to each source. It is important then that appropriate correction be made for atmospheric transmission over the distance of the measured and computed exitance values.

The data in Figures 4, 5 and 6 are plotted for two UV bands and one IR band. The UV fire detectors respond to the burning JP-4 or pyrotechnic material irradiances in the 200 nm and 254 nm bands. The IR band at 4.4 micrometers likewise is a well known feature of burning hydrocarbon fuels and pyrotechnics, being specifically considered because of high atmospheric transmittance in this region.

One of the most common performance criteria set for most fire detectors is that it must be able to detect a 2-foot x 2-foot square pan fire of JP-4 fuel or gasoline at a distance of 100 feet in 5 seconds or less (after the fire has reached full size). The horizontal straight line across each figure corresponds to the irradiance value from such a "design performance fire" for the spectral band being considered. Where two horizontal lines occur, which defines a "band", this helps to point out that there is no single unique value of irradiance for burning JP-4 (or pyrotechnic material) at 100 feet distance or any distance. Each pan fire can vary in this respect, depending on a variety of conditions, such as wind and humidity. Hence, a spread of values is to be expected. The horizontal lines used here are based upon the actual JP-4-burn measurements.

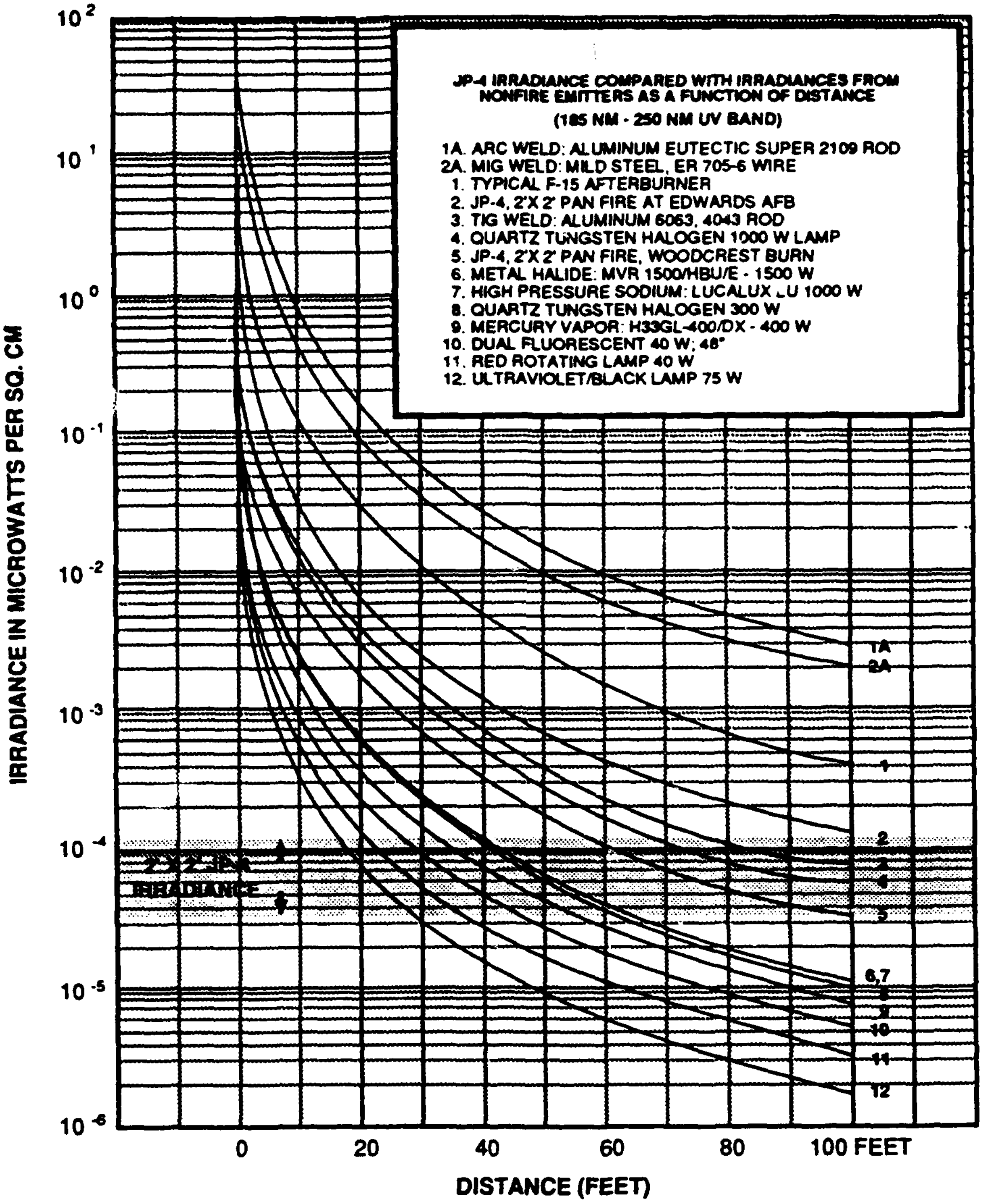

Figure 4. JP-4 Irradiance (185 NM - 250 NM UV Band)

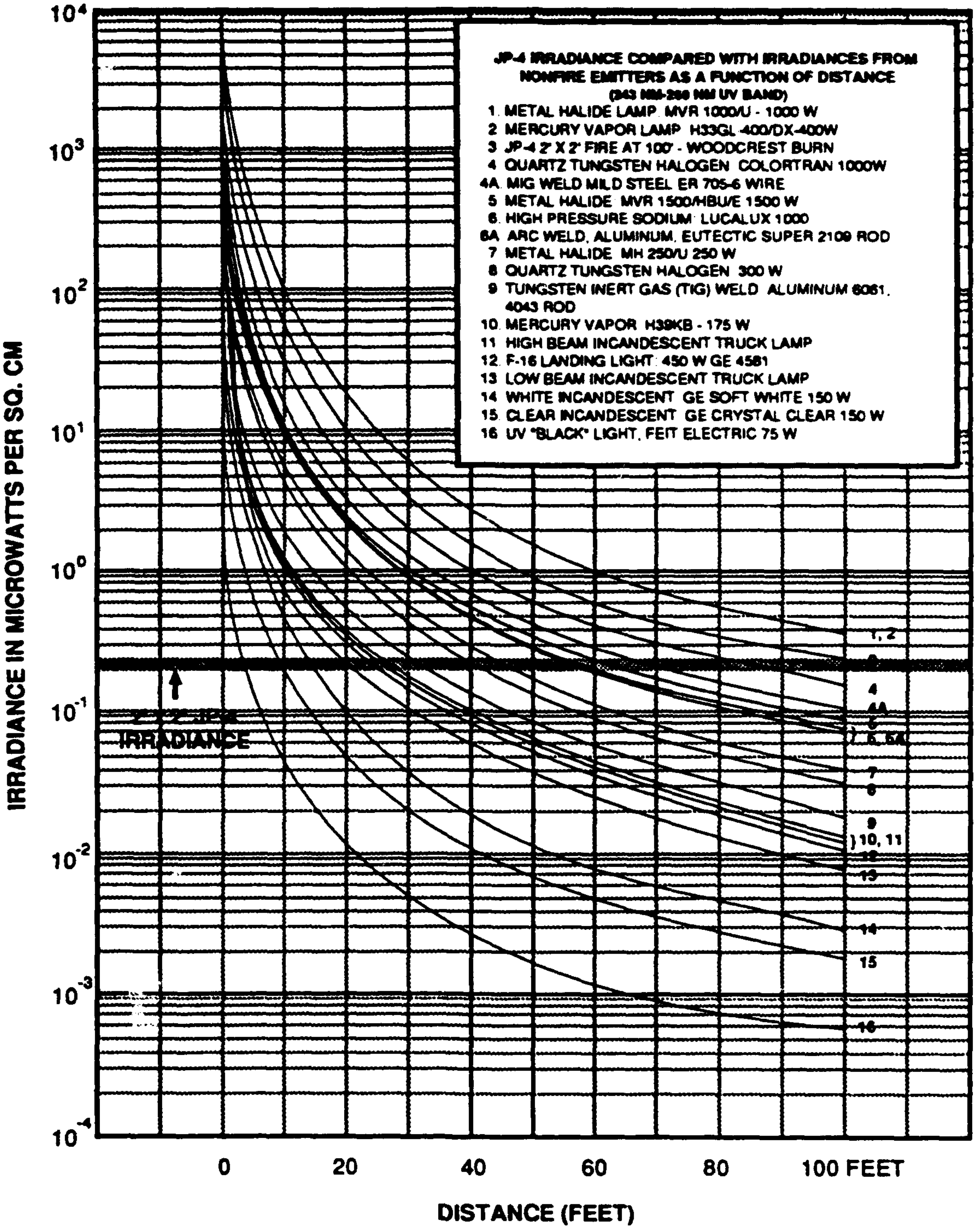

Figure 5. JP-4 Irradiance (243 NM - 269 NM UV Band)

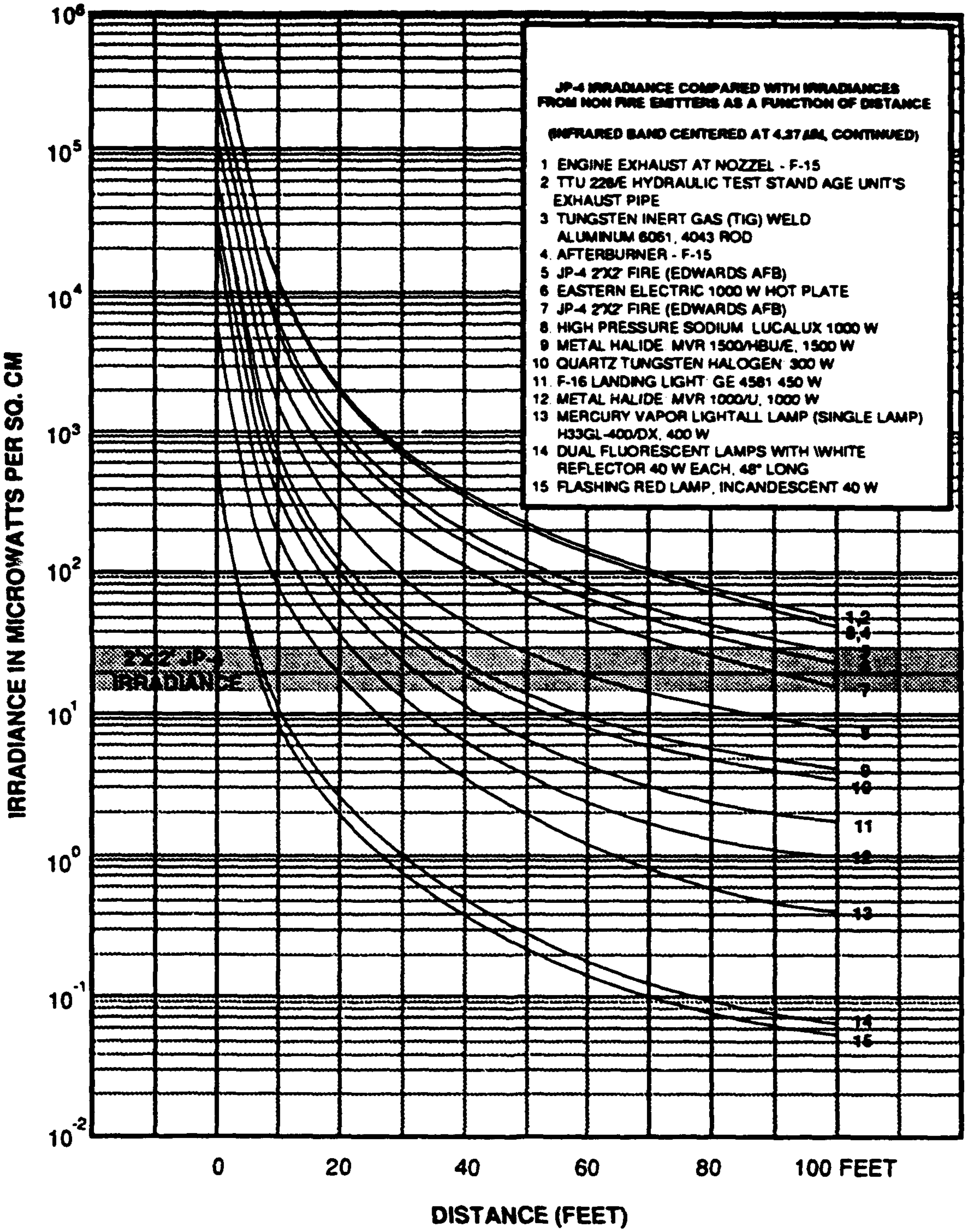

Figure 6. JP-4 Irradiance (Infrared Band Centered at 4.37 μV)

The standard JP-4 fire detection criterion is used here because the detectors used for ammunition/pyrotechnic fire detection are normally based upon these measurement specifications/ standards, although altered to some degree to decrease the time of response to tens of milliseconds. Note also that the spectralirradiances of emission properties in both UV and IR from pyrotechnic material combustion/explosion are not known. Such information is almost a necessity in designing specificity into a detector's mode of operation, wavelength bands, and response time.

With the horizontal straight lines serving as the detection criteria to be satisfied, all curves that extend above these lines show irradiance values that could trigger false alarms (again assuming a 2 foot x 2 foot JP-4 fire at 100°). This is true over the range of distances where each curve goes above the detection criterion. If the detection criteria differ as to the fire type, size, and distance, a separate horizontal irradiance line would have to be determined for each. This needs to be accomplished for Army munitions applications to establish a scientific basis for maximizing a detector's performance and minimizing its susceptibility to false alarms.

For the distances where the curves are below the detection criterion, however, each radiation source individually would not have sufficient irradiance to trigger a false alarm. By superimposing additively the irradiances of two or more sources at such distances, it is possible to obtain a combined irradiance that may trigger a false alarm. Such combinations could be estimated from the curves.

Study across all curves of the three bands shows that the steepest rolloff is within about the first 20 feet. Thereafter the rolloff of irradiance with distance is more and more gradual.

Hence, it was shown that:

1. individual radiation sources can trigger a false alarm within the distance over which their irradiance exceeds the detection threshold criterion;

2. individual radiation sources cannot trigger a false alarm for distances where their irradiance is below the detection criterion;

3. a combination of radiation sources of the kind in (2) above can be combined to trigger a false alarm.

Eight commercially available detectors, including UV, IR, and UV/IR types, were used in tests to determine the effects of the potential false alarm sources listed in Table 1. The detectors tested were set by the manufacturers to the following fire threshold: 2-foot x 2-foot JP-4 pan fire at 100 feet within 5 seconds of the fire attaining full size. This is a standard Army Corps of Engineers and Air Force specification (Air Force Requirement AFR 88-15, Criteria And Standards For Air Force Construction, January 1986) for fire detectors in hangars and shelters, although some other more sophisticated "system" performance specifications call for different sizes at different distances. It was found that the "fire detection threshold" of each detector differed somewhat against the same sources (butane flame and propane flame) at the same distance.

The test procedures followed the following format:

Test 1: The radiation sources (s) and detectors are separated at various distances. At each selected distance, after 30 minutes of radiation source operation, the detector is subjected to an "on-off" switching rate of 1 second on and 1 second off, 5 consecutive times. The detector is then left on and the radiation source (s) switched on and off five times at 1-minute intervals, if applicable/allowable by the nature of the source.

Test 2: Each radiation source, at its respective distance from the detector, is then chopped at the following rates with a chopper fan located about 10 inches from the face of the detector: (1) 2 Hz; (2) 10 Hz; and (3) optionally 5 Hz.

Test 3: If applicable, the glass lens cover plate is removed, and Test 2 is repeated.

Test 4: If applicable, the glass lens cover plate is removed, and Test 1 is repeated at its respective distance.

Comparing the chopped data with unchopped data, it was evident that the straight flux from either AC or DC operated light sources is not sufficient, in general, to trigger all detectors. However, where the source flux is chopped, all the detectors are triggered to false alarm. Response of the detectors, at least those used in these tests, is therefore controlled by the particular frequency response "window" designed into the detector and, of course, the value of the spectral irradiance of the nonfire source in the wavelength band of interest. As stated earlier, however, use of flicker as a detection criterion, may not be advantageous in pyrotechnic material fire detection because it would slow down the overall detection time.

It was also found that there is a pronounced effect on detectors to alarm when the lamp's glass cover plate is removed or cracked/broken. The implication is that radiation in the 200 nm UV band is not reduced greatly by the protective window, but rather by the outer bulb of the lamp itself, if it has one. If the outer bulb, however, were to crack or rupture, the UV radiation emanating from the lamp would be much greater than normal. Such circumstances, where a small hole or crack occurs in the outer bulb, could enhance the probability of a false alarm event. We were unable in this brief study to find documentation whether such events have been reported in Army munitions plants.

A complete review of the test results which describe in detail the false alarm responses of the eight detectors to a large variety of sources, either singly or in combination, at various distances, chopped at various frequencies, can be found in Final Report: "Characteristics of Optical Fire Detector False Alarm Sources and Qualification Test Procedures to Prove Immunity," Contract No. F08635-91-C-0129, CEL-TR-92-62, Sponsor HQ AFCESA/RACF, Tyndall AFB, October 8, 1992, Goedeke, A.D., and H. G. Gross, Donmar Ltd., Newport Beach, CA. In general, most of the detectors could be fooled into false alarming with the presence of most of the UV and IR sources tested, even at relatively large separation distances.

H. EXAMPLES OF POTENTIAL FALSE ALARMS DUE TO THE PRESENCE OF MULTIPLE NONFIRE SOURCES OF UV AND IR RADIATION

1. Simple Two-Source Test

Analysis showed that the potential of false alarms is much greater when two or more UV and/or IR radiation emitters are present in the FOV of a detector and that the sources have enough radiance in the detector's operating spectral bands to equal or exceed the fire detection threshold irradiances at the distance of the detector. A standard 300 watt Quartz Tungsten Halogen (QTH) work lamp, with its glass cover plate on, has an irradiance in the 185 nm to 250 nm band at about 30 feet distance which is equivalent to a 2 foot x 2 foot JP-4 pan fire at 100 feet in the same spectral band. This means that this lamp alone, located at 1 - 30 feet from the detector, may satisfy the UV irradiance threshold value required by a fire detector to alarm (in this case to a 2' x 2' JP-4 fire at 100' or less), provided other factors (e.g. flicker), if any, are also satisfied.

If the detector is a multiwavelength detector, also requiring satisfaction of a 4.4 μm band IR threshold, this same lamp projects an irradiance out to about 30 feet that equals or exceeds that emanating from the 2-foot x 2-foot JP-4 pan fire at

100 feet. Therefore, a single source may satisfy dual wavelength detection requirements, at least as far as the irradiance values are concerned.

Again, other factors have been built into most detectors today that add features such as "flicker", ratioing, or intensity "spikes". These "other" factors can also be duplicated and are not "fool proof." For example, the chopping effect , at low frequencies, can be duplicated by several people walking in front of a source, a person waving his arms, an irregularly shaped vehicle or mobile platform being moved between the detector and source, a fan, or the chopping effect inherent in certain light sources when they are in start, restart, or failure modes. In some cases, the chopping effect, or flicker frequency requirement built into the detector's response logic, has a narrow frequency window. As an example, it will not alarm unless the frequency is 10 Hz or more, while another detector will respond if the frequency is anywhere between 1 Hz and 20 Hz.

If a detector did not require chopping or some other effect, the detector would assuredly false alarm if its spectral irradiance threshold(s) were satisfied. If the detector required the additional factor of "flicker" (1-20 Hz UV and/or IR signal variation, or other factors) to be satisfied, then the detector should not "go-off" to this simple light source, unless all requirements, including spectral irradiance and flicker and other factors, were satisfied.

A possible scenario may be a facility which contains a hot body, such as a vehicle's exhaust, lamp, or a heater, and a light source such as a 300 watt incandescent Quartz Tungsten Halogen lamp (lamp/light source is mentioned twice because one lamp alone may satisfy both UV <u>and</u> IR emission requirements to false alarm). Both types of sources, hot bodies and 300 W QTH lamps, are found routinely in military facilities. Assume that both sources are in the field-of-view of the detector.

Assume the hot body has a temperature of about 670° C (1238° F).and is located some 20 feet from the detector. The irradiance of this "hot body" in the 4.4 micrometer band is such as to exceed the irradiance from a 2 foot x 2 foot JP-4 pan fire as far away as 100 feet. We use a standard 1000 W hot plate for this test. A single element hot plate at full power will reach about 670° F, the average temperature of an exposed exhaust pipe on a ground equipment item. Also, its areal extent is about half of that of the vehicle's exhaust surface. At 10 feet distance, this hot plate has about the same irradiance in the 4.4 micrometer band as does the 1238° F exhaust pipe at 15-20 feet.

Also, assume the Quartz Tungsten Halogen lamp may be without its glass cover plate, and is 10 feet away from the detector. Broken, cracked, or absent cover plates on lamp fixtures in some military facilities is not rare.

To test whether different types of detectors would alarm to the simultaneous presence of these two simple nonfire radiation sources, located at distances from the detectors which emulate practical situations, the following test was conducted using an array of 8 commercial fire detectors, two types of which have been used in Army munitions fire detection applications.

Step 1. The first step in the sample procedure is to located the detector 10 feet from the sources; turn on the detector and let it warm up for a few minutes to verify that it is working properly. After 10 minutes, turn-on the 1000 watt hot plate at maximum. After 10 minutes at maximum temperature, observe the response of the detectors.

Step 2. The second step is to "chop" the IR-emitted radiation from the hot plate with a "chopper blade" apparatus such as a fan-wheel device at speeds of 1 Hz to 10 Hz and above. This duplicates several people walking in between the hot plate and detector, a floor fan, an irregularly shaped vehicle passing through the FOV, or a person waving his arm in front of either the detector or hot plate. Observe the response of the detectors.

Step 3. The third step is to remove the hot plate or let it cool down to room temperature and then turn on the Quartz Tungsten Halogen lamp with the glass cover plate on. Observe the response of the detectors. After 15 minutes turn lamp on and off at 10 second intervals, 5 times. Observe the response of the detectors.

Step 4. The fourth step is to chop the radiation from the lamp by the same means as above, either by waving an object back and forth through the FOV close to the lamp or with the use of a fan by just spinning the fan blade by hand.

Step 5. The fifth step is to turn the hot plate back on and let it reach maximum temperature. Ten minutes after it has reached maximum temperature, turn on the lamp. Observe the response of the detectors over the next 10 minutes.

Step 6. The sixth step is to chop the hot plate's emission with the lamp remaining on and not chopped. Observe the response of the detectors. Turn off the lamp. While the hot plate is being chopped, switch on the lamp. Observe the response of the detectors.

Step 7. The seventh step is to stop chopping the hot plate and chop only the lamp. Observe the response of the detectors.

Step 8. The eighth step is to chop both sources near the detector so that the entire FOV is chopped. Observe the response of the detectors.

Step 9. A ninth step was carried out which amounted to repeating steps 1-8 with the Quartz Tungsten Halogen glass plate cover removed.

Table 2 summarizes the response of the different detectors to these nine steps. Note that the response for steps 1-8 are given first in the table as "Y" or "N" (yes or no response), followed by another "Y" or "N" designating the response to step 9 when the lamp glass cover plate is removed. Light fixtures without glass cover plates are not uncommon in many military facilities, as are also cracked or broken lens cover plates.

What occurs is as follows:

In Step 1 no responses are observed, implying that its irradiance at 10 feet distance is either less than that from a 2-foot x 2-foot JP-4 pan fire at 100 feet, and/or all other detection criteria, such as flicker/chopping, are not satisfied.

In Step 2, detectors B and D go off to both glass cover plate-on and glass cover plate-off conditions, both detectors being IR detectors. This implies that the irradiance in the IR is equivalent to that from a 2-foot x 2-foot JP-4 pan fire at 100 feet and that, indeed, chopping is a requirement of these IR detectors. Other detectors did not go off because no UV was present.

In Step 3, no detectors alarm when the glass cover plate is on, indicating that the UV irradiance is either insufficient and/or other conditions such as chopping have not been met. But with the glass plate removed, detectors C and E alarm when the lamp is turned on, and detectors C, E, and G alarm when the lamp is switched on and off consecutively. Detector C is a UV-only detector and E and G are dual UV/IR units, indicating that the IR from the lamp is equivalent to that from a 2-foot x 2-foot JP-4 pan fire at 100 feet.

In Step 4, only detector G goes off when the glass cover plate is on and the radiation chopped. This same detector also alarmed in Step 3 above without chopping and without the glass plate cover. This indicates that the chopping effect is not very important to this detector. Detectors A, C, and E alarm without the glass plate on the lamp. Detectors A and E therefore have IR thresholds that are satisfied by the lamp.

In Step 5, detectors C and G are the only ones to alarm with the glass plate on. Without the cover plate, detectors C, E, and G respond.

In Step 6, detectors B, C, D, and G alarm with the glass cover plate on. Without the cover plate, detectors A, B, C, D, G, and H go off. This indicates the importance of IR chopping to these detectors.

In Step 7, no detectors go off with the cover plate on. However, without the cover plate, detectors A, C, E, and G go off.

In Step 8, detectors B, C, D, and G go off with the glass plate on. All detectors except F go off when the glass cover plate is removed.

Table 2

False Alarm Response Due to Presence of Hot Body and 300 W Quartz Tungsten Halogen Lamp

	(N=NO; Y=YES)					DETECTORS			
TEST #	SOURCE & CONDITION	A UV/IR	B IR	C UV	D IR	E UV/IR	F UV/IR	G UV/IR	H UV/IR
1	HOT PLATE-ALONE	NN	NN	NN	NN	NN	NN	NN	NN
2	HOT PLATE CHOPPED	NN	YY	NN	YY	NN	NN	NN	NN
3	QTH LAMP-ALONE NO HOT PLATE	NN	NN	NN	NN	NN	NN	NY	NN
4	QTH LAMP-CHOPPED NO HOT PLATE	NY	NN	NY	NN	NY	NN	YY	NN
5	HOT PLATE + QTH LAMP: UNCHOPPED	NN	NN	YY	NN	NY	NN	YY	NN
6	HOT PLATE CHOPPED AND QTH LAMP UNCHOPPED	NY	YY	YY	YY	NN	NN	YY	NY
7	HOT PLATE UNCHOPPED AND QTH LAMP CHOPPED	NY	NN	NY	NN	NY	NN	NY	NN
8	BOTH HOT PLATE AND QTH LAMP CHOPPED	NY	YY	YY	YY	NY	NN	YY	NY

The results of Step 9 indicate that either an additional amount of UV in the 185-250 nm band must be present, and/or shorter wavelength UV, previously absorbed by the glass plate, may be present that has higher ionization efficiency of the UV tube's gas fill. Lamp fixtures such as the one used here are sometimes found with cracked or broken lenses, or without the entire glass cover plate.

The overall results indicate the importance of detecting flicker/chopping of the IR and UV emissions. Although chopping may not be an important factor for some detectors, and not a factor at all for others, it still affects the various mechanisms of all the detectors used herein.

Analysis of this table demonstrates the various requirements, in addition to sufficient energy flux in different spectral bands, to cause a detector to alarm. It is apparent from steps 1 and 2 that the IR-only detectors employed here require some form of chopping along with sufficient spectral irradiance to alarm. Also, Steps 3 and 4 show that the UV-only detector does not require chopping of the UV radiation source, as it will go off without the glass plate cover with or without chopping.

These tests were repeated several times to determine consistency of detector response. The only variation in the repeated tests was a slight change in the frequency of the chopper wheel device. It was observed that this small change, in some cases, affected a detector's response.

It appears that, in general, the 300-watt Quartz Tungsten Halogen lamp with its glass fixture plate on meets, or is slightly less, than the average detector's specific spectral irradiance requirements at 10 feet distance in the UV band(s) of interest, and certainly meets or exceeds these requirements when the glass cover plate is removed/broken. It must be remembered, however, that in these tests with the chopper operating the energy flux incident upon the detector was reduced by 50%. The relative distance then of the source from the detector was much larger than the 10 feet used here. Also, the internal electronics of the detector also has an effect upon the relative distance of the source.

The irradiance of the lamp without the cover plates was measured to be about 5.04×10^{-2} microwatts/cm^2 at 22 inches distance. This equates to an irradiance in the 200 nm band of about 1.69×10^{-3} microwatts/cm^2 at 10 feet distance, the distance used in these procedure tests. This lamp source, if located 34 feet from the detector, without its glass cover plate, would therefore have the same irradiance in this spectral band as a 2-foot x 2-foot JP-4 pan fire at 100 feet. This shows the large difference in irradiance-effective distance when an incandescent or HID lamp fixture is without its glass cover or if the cover is cracked or broken.

As pointed out above, the chopping effect imposed in these tests reduced the irradiance of UV and IR, respectively, by as much as 50%. This implies that the actual irradiance levels during chopping can be correlated with the same sources located at much greater distance than the 10 feet used in the tests.

It can therefore be concluded from this simple procedure that optical fire detectors, in general, can be fooled by the presence of certain nonfire types of sources of UV and IR, and especially if other factors are present such as objects of motion that may effectually "chop" (disrupt) the UV and/or IR signals at a frequency between 1 Hz and 20 Hz.

It would be prudent to determine the spectral irradiances of the many types of possible false alarm sources that may exist in the vicinity of, or in the approximate field-of-view of, the fire detection system. It would also be prudent to require qualification performance testing on detectors being considered for acquisition before the detectors are acquired and installed. The detectors should be immune to any scenario that includes the presence of one or more of the possible sources of UV, IR, and visible radiation.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

This study was limited in time and in scope, but there were significant observations made regarding pyrotechnic/ammunition materials fire protection systems. Several major observations were made which led to the conclusions stated earlier, which form the basis of the following recommendations.

A. GENERAL OBSERVATIONS

The current fire detection and suppression technologies being applied in Army ammunition/propellant-related facilities should be thoroughly reviewed with respect to the threat, required reliability, desired performance criteria, and overall mission success goals. The fire/explosion threat needs definition in terms of the system performance requirements to quell the threat before any loss of resources or life occurs. The basic parameters are known through the use of fast video data and during past experiments and field tests. It can safely be stated that test results indicate a need for faster and more reliable fire detection and suppression approaches. Current systems are, in general, satisfactory for some pyrotechnic fire events, but lack the necessary speed and effectiveness for other events. Reliability is also an apparent problem in that false alarms/false dumps continue to occur, although they have not been thoroughly documented or their causes determined in detail.

In other words, there is a lack of scientific information pertaining to the nature and properties of the fire/explosion events, as well as to the reasons for false alarms. Use of deluge water suppression and single band UV detectors should be more thoroughly reviewed in terms of their operational characteristics, performance, and reliability. New technology approaches to these problems should also be reviewed and analyzed with respect to the application requirements, and compared to existing, but older, technology. Selected new technology systems, specifically designed to maximize effectiveness, should then be tested against real fire/explosion events.

It was also apparent from the study that formal guidance is lacking for Hazard Class 1.3 protective features compared to the information for Class 1.1 protective features (TM 5-1300, "Structures to Resist the Effects of accidental Explosions [Tri-Service Manual]).

B. RECOMMENDATIONS

From such a study and tests conclusion can be drawn regarding the best potential approaches to solve the problems. This would include fire detection and suppression system options that should be tested against to select the optimum approach. Once selected, the approach should be developed in hardware and tested in operational environments. The following are the specific recommendations.

1. A review should be made of past reports of fire events and false alarm events. Efforts should be made to determine their nature, cause, and impact, both financially and operationally. It was found in this study that such information is scarce although it is generally known in the industry that such events have occurred.

2. Determine the problems associated with currently installed detectors. This will involve travel to several sites and discussions with facility personnel. Records, if any, would be obtained regarding past history of fire events and detector response. False alarm reports, if they exist, would also be analyzed. Field tests would be performed on several selected existing detection/suppression systems to measure response times.

3. It is necessary to determine the UV, visible, and IR spectral irradiances (in several bands) of various pyrotechnic material fires/explosions. This would be accomplished by obtaining any existing reports or data and experimentally measuring spectral emissions during burns of the pyrotechnic/ordnance materials. No spectral data appear to exist in the available literature that definitize the spectral emission properties. Knowing the wavelength regions where maximum emissions occur during ordnance material burns will dictate the optimum spectral bands where the detector should operate. The effort would also determine what sources of UV/IR/visible may cause false alarms.

This experimental effort would involve field burn tests of several selected materials. Spectrometer data would be obtained in selected bands and irradiances determined. The tests require some safety precautions, as the optical instrumentation will have to be located close enough to the ignition source to be able to maintain the image in the total field of view. The equipment will have to be rented or purchased. Two spectrometers would be required: (1) UV through visible (185 nm - 900 nm); and (2) near IR (1-5μm). Also, a multichannel data recorder interfaced to a CCD would be necessary because of the short time duration of the event.

During this task, it would also be necessary to measure the emission characteristics from objects/phenomena that are not ordnance fire related. This would include several possible false alarm sources.

4. The data obtained should be used to determine the detection and false alarm immunity characteristics of present day detectors used for munitions fire detection. This would require the acquisition of detectors presently in use for such applications, as

well as detectors that should be evaluated for such applications, such as the machine vision detector.

5. Tests should then be conducted in the lab on the response characteristics of each detector to nonfire source. Lab fixtures and test configurations would be built. False alarm sources would be mounted in appropriate lab fixtures.

Detector responses to pyrotechnic/ordnance fire events should be conducted at a "safe" facility, such as at Crane, IN. If possible, simulations could be used of the emissions from the events. For machine vision, video fire data should also be used.

6. A concept design should then be developed for an optimized detection system.

7. The next recommendation would be to design, develop, configure and test an optimized detection system.

8. Acquire, install and test a complete advance technology fire detection and suppression system. During the tests, test the performance of the machine vision detector vs. other detection morphologies. This includes modifications to the machine vision detection mode to be applicable to "fast response" as well as semi-fast response to certain events.

9. Prepare a final report that is a specification for both an optimized system and a future generation/advanced system. Include in final report a design handbook to provide general design information on optimization.

10. Proceed with the optimization of current systems, including deluge subsystems. The latter subsystems require special engineering and technical knowledge and should only be further developed/augmented by recognized, experienced professionals with demonstrated expertise in this area. The AMCCOM Safety Office should be an integral part of this effort, as they are recognized as the center of expertise on deluge systems.

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