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REVIEW PAPER

Developments in Pyrotechnics

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ABSTRACT

The application of smoke and various types of smoke bombs/devices developed are narrated. The light output of 51 mm, 81 mm, 120 mm and 120 mm LRM illuminating bombs developed is 2.6, 9.0, 10.8 and 15 lakhs candela, respectively. The IR flares developed for first and second generation anti-tank missile are in regular production. An IR decoy flare is developed for CMDS. Feasibility study on multi-spectral smoke and IR flare compositions is completed. 1W-1A No fire capability EED is developed. Gas generators 1200 cc, 2400 cc, 6000 cc are developed. Accuracy of pyro delay is improved. Laser initiated pyrocartridge is developed. Nano-scale Fe_2O_3 is synthesised and studied. A few toxic ingredients are replaced to march towards green pyrotechnics. Objectives for improved pyrotechnics are included.

Keywords: Pyrotechnics, smokes, illuminants, flares, electro-explosive devices, delays, laser initiation, green pyrotechnics

1. INTRODUCTION

Pyrotechnics from the definition of 'the art of creating fireworks' has evolved into a 'Science and technology of energetic materials' to meet the stringent requirements of Armed Forces. Pyrotechnic formulations are basically physical and heterogeneous mixtures of fuel and oxidizer, belonging to either organic or inorganic classes ingredients or both. Compared to the fairly exact, well-defined science of propellant and explosive technology, there is a lack of theory and understanding factors which influence the kinetics of pyrotechnic reactions. A pyrotechnic composition, when suitably ignited, undergoes the reaction in the absence of atmospheric oxygen and produces special effects like smoke, light, heat, sound, delay, and pressure depending upon the choice of the fuel and the oxidizer.

Pyrotechnic ammunition/device is used to produce terminal effects that are visible, thermal, audible, mechanical or physiological required in offensive or defensive military tactics and during military training. About 70 per cent of ammunition inventory items are pyrotechnic items with any defence service in the world. Major uses of pyrotechnics are:

- Screening and coloured smokes
- Illumination, flare and signal devices
- Incendiary munitions
- Pyrotechnic components
- Weapon training systems
- Battlefield simulation systems
- Police and security products

The design of pyrotechnic ammunition/device is a complex field and requires extensive basic and applied research. The present state-of-the-art of pyrotechnics can best be defined in terms of the experience, ingenuity, and also insight of designers, manufacturers and users.

The High Energy Materials Research Laboratory (HEMRL) is engaged in basic research, design of formulations, processing, pilot batch productionisation, product designing, characterisation, evaluation, establishing proof methods, documentation and transfer of technology to manufacturing sectors. Over the years, a wide range and types of pyrotechnic compositions and pyrotechnic devices have been designed and developed for armament systems and missiles. Many of them are under regular production in ordnance factories/ public sectors/private industries. An overview of pyrotechnics development is presented here covering each area, viz., smokes, illuminating, flares, electro-explosive devices, gas generators, delays, laser initiated pyro devices, nanomaterials and green pyrotechnics along with some aspects of improved pyrotechnics.

2. SMOKE

Smoke, since long, has been employed as a means of concealing battlefield targets. Additionally, incendiary fire causes casualties, material damage and also psychological impact. Smoke has four general uses on battlefield, viz., obscuring, screening, signaling and identifying. Obscuring smoke is placed on an enemy to reduce vision between the target and the observer. Screening smoke is used in friendly operational areas or between friendly units and the enemy. Deceiving smoke is used to mislead the enemy. Identifying/signaling smoke is a form of communication that has multiple uses. Overall, the objective of smoke

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employment is to increase the effectiveness of army operations while reducing the vulnerability of forces.

Dark or black smoke absorbs a large proportion of the light rays striking individual smoke particles. Grayish or white smoke obscures by reflecting or scattering light rays, producing a glare. During bright daylight conditions, less white smoke than black smoke is required to obscure a target. Years of experience with smoke screen technology has shown that white smoke is superior to black smoke for most of the applications. Available white smoke includes white phosphorus and red phosphorus compounds hexachloroethane (HCE) and fog oil (SFG2). Staislaw Cudzilo studied the capability of smoke cloud generated during the combustion process of varied pyrotechnic formulations[1]. The use and application of red phosphorus (RP) pyrotechnic composition for camouflage in the infrared region of radiation has been studied[2].

Development of

- Tear gas grenade,
- HCE-based screening smoke composition for 51 mm and 120 mm mortar bomb,
- Smoke marker for spotting and marking the position for aircraft and helicopter applications,
- Orange smoke for marking the position of training torpedo in sea during recovery and for moored mine,
- HCE-based black colour smoke for hand grenades to defeat MIRA thermal sight and laser range finder,
- Intense red smoke for visual augmentation of PTA tow body from a distance of 5 km,
- White dense smoke for fire-fighting training on a ship,
- Dense yellow smoke for indicating the helipad/drop zones in glacier regions, etc.

Recent developments include red phosphorus (RP) based anti-thermal anti-laser 81 mm smoke grenade for MBT (Fig. 1). Both ground bursting and air bursting below 10 m altitude versions have been demonstrated to Users. Another development is smoke generator for PTA-II for visual observation of target tow body from a distance of > 10 km. (Fig. 2). Many of these are produced in ordnance factories and issued to services against requirements. The effectiveness of smoke screen is observed better when grenade bursts instantaneously on landing/ground. The smoke characteristics of RP-based formulation have been improved using ammonium oxalate regardless of the oxidizer present in the air. An oleoresin based sensory irritating smoke composition which disseminates capsaicinoids as sensory irritant is developed. The hand grenade is effectively used in combating the insurgency operations by Border Security Forces.

The development of multispectral smoke screen for producing an aerosol which is impenetrable in visible, infrared, and millimetric wave range of electromagnetic radiation are underway all over the world[3,4]. Koch[3] disclosed the pyrotechnic smoke screen units for producing an aerosol which is impenetrable in the visible, infrared, and millimeter wave range. Classical camouflage smokes utilises very-near, near, and far-infrared with wavelengths between 0.9 μ and 14μ as well as millimeter wave radar range. Feasibility study on development of multi-spectral smoke composition to cover visual, IR, and millimeter wave bands has been completed.

3. ILLUMINATING CANDLES AND FLARES

The light effect of pyrotechnic composition is utilised in illuminating candles, photoflash cartridges, tracers and signal flares. The long-duration white light from illuminating candle is used for battlefield illumination and short-duration intense white light is suitable for night time aerial photography. The coloured light is utilised for tracers and signal flares. Illuminating compositions[5-7] are basically mixtures of an oxidizing agent and metal fuel. Other materials are added to modify the burn rate radiant output and to increase safety. The HEMRL has developed illuminating compositions based on magnesium powder, sodium nitrate, polyester

Figure 1. 81 mm anti thermal–anti laser smoke grenade.

Figure 2. Smoke generator for PTA.

resin and calcium oxalate. These compositions designated as ME 425 and ME 426 are used in 51mm, 81mm, and 120 mm illuminating bombs. These illuminating compositions have been found to be on par with other illuminating compositions used world wide. All the bombs are produced in Ordnance factories under Transfer of Technology (ToT) from DRDO.

Luminous intensity of the composition is directly related to the diameter of the flare (i.e. burning area of the flare). For a particular composition pressed in containers of various diameters at a given consolidation pressure, the flare of bigger diameter will give more luminous intensity. It is also possible that more area of burning surface will give a longer flame. If the density of the composition is kept constant, the linear burning rate and the efficiency will be unaffected for a particular composition. The candle diameters for 51mm, 81mm,120 mm and 120 mm long range mortar illuminating bombs are 44 mm, 68 mm and 86 mm respectively (Fig. 3). Their light illumination is 2.6, 9.0, 10.8 and 15.0 lakh candela for 35, 35, 45 and 45 s respectively. The most important is the area of illumination at night is 400, 800 and 1200 m diameter respectively producing broad daylight.

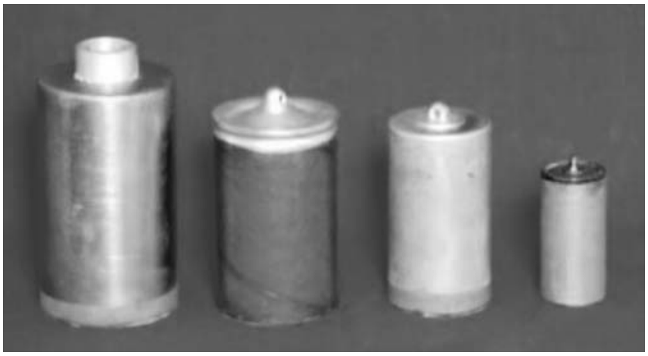

Figure 3. Illuminating candles.

Tracers have dual purpose, to trace the path of the projectile and to destroy the projectile if not functioned after a specified period. To observe a trail at distance, the minimum luminous intensity required from a tracer flame can be calculated theoretically. Tracer for 125 mm Fin stabilised Armoured piercing and discarding sabot (FSAPDS) has been developed by HEMRL that burns for 5 s producing ~ 40 000 cd light intensity.

Infrared (IR) flares can be classified into three classes depending upon their applications-IR tracking flares, IR target flares for training, and IR decoy flares for defensive purposes. Heat-seeking missiles accounted for over 78 per cent of aircraft losses during the Gulf War and as per the current estimation there are over 500,000 man-portable (MANPAD) surface-to-air missiles in the world today, such as the SA-7, SA-14, SA-18 and Stinger. MANPADs are comparatively cheap and easy to operate, and, in today's uncertain world, the need for effective infrared countermeasures has unfortunately never been greater. Accordingly, many of the world's Armed Forces now protect their fixed wing-transport aircraft, helicopters, and fast jets using airborne infra-red countermeasure (AIRCM) expendable decoys.

Military targets such as tanks, warship and aircrafts emit IR radiations significantly in different transmission wavelengths. Therefore these targets can easily be detected and destroyed by IR-guided missiles by sensing the IR radiation without alerting them in advance. For example the main radiation sources on a fighter aircraft are exhaust plume emission at 3-5 μ waveband, thermal radiation of the heated fuselage emits at 8-14 μ and hot tail pipe emits at 2-3 μ. The tail pipe of the jet engine has a typical temperature in the order of 900 K to 1100 K. The exhaust gaseous temperature ranges from 800 K to 1000 K. IR-guided missiles pose the major threat to military aircraft; to counteract these threats, infrared countermeasure system plays a very important role. Infrared flares are pyrotechnic devices, which emit radiations of sufficient intensity in the IR region of the electromagnetic spectrum in addition to the visible radiations. Aircraft for defense against IR-guided missile threats, use infrared decoy flares. When ejected from an aircraft, AIRCM flares are designed to present a more attractive IR signature than that of the target, and thus, seduce or decoy the missile seeker away from the aircraft into tracking the flare. A chemical energy source is used to provide the IR radiation for the flare and may be either pyrotechnic or pyrophoric in nature.

Currently, pyrotechnic IR flares[8,9] come in two types: 'legacy' magnesium-teflon-viton (MTV) decoy which was used for the first time in the Vietnam War, and the dual-spectral flare which is only now entering operational service by USA, Germany, France, and Russia. The MTV flares[10,11] are still effective against the older generation of missile systems. These come in a variety of shapes, formats, sizes, and levels of performance depending on the nation and the service of origin, the aircraft type, and their IR signatures. UK and US flares are, mainly similar in size, form and specification, whereas the French and Russians have designed flares that can only be fired from aircraft of French and Russian origins. Over the years, major improvements have been made in the performance and safety of the MTV decoy, and it is still the most widely used form of flare. HEMRL has developed IR flares for first- and second-generation antitank missile and are regularly produced by Bharat Dynamics Ltd, Hyderabad. An IR decoy flare (Fig.4) is developed for counter measure dispensing system, (CMDS) being adopted for six different types of aircraft and also helicopter fleets.

Dual-spectral flare compositions have been reported by different authors. Partially oxidised carbonaceous fuels together with magnesium have been proposed to prevent soot formation and generate large amounts of carbon dioxide which adds to the radiant emmitance in the 3-5μm waveband. The fuels considered are trioxane, paraformaldehyde, cyanuric chloride etc. As an additional oxidizer, these compositions contain some ammonium perchlorate. The compositions yield spectral ratio $Ø_{2-3/3-5μm}$ equal to 0.76-0.29.

Another attempt to modify the spectral distribution of MTV decoy compositions has been made. The inventors proposed the application of blends of both MTV and

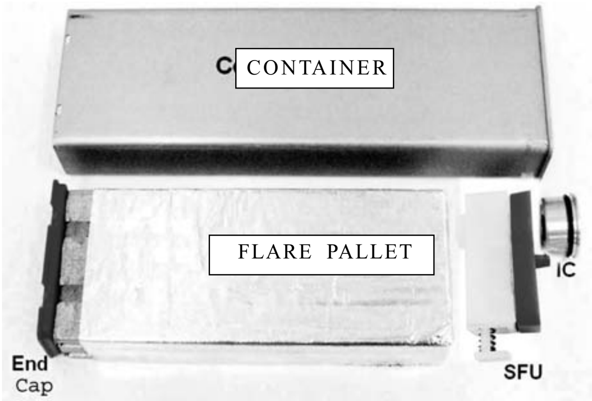

Figure 4. IR flare for CMDS flare pellet.

spectrally adapted composition containing boron, aluminum, hexamine, potassium nitrate and ammonium perchlorate. Both aluminum and boron upon combustion provide selective emitters such as *BO, HBO_2* and Al_2O_3 at 2.5 μ, 5.0 μ and 1.5 μ respectively. The intensity ratio $Ø_{2\text{-}3/3\text{-}5\mu m}$ is equal to 0.56.

Posso[12], *et al.* recently researched in the spectral adaptation problem and addressed the problem of the right H_2O /CO_2 ratio. Posson proposes a series of carbon rich and hydrogen-lean fuels. Callaway[13], *et al.* offered a simple solution to spectral adaptation by proposing common whistle compositions for use in spectrally-adapted decoy flares. These compositions are based on potassium perchlorate and potassium benzoate with viton[4]. Koch[14,15] has developed spectrally balanced compositions based on olefinic and aromatic cyanocarbons as fuels. Other spectrally-balanced compositions are made up similarly as doublebase propellants and contain nitrocellulose (NC), and other esters of nitric acid or nitro compounds oxidizers such as hexanitroethane and nitro compounds and nitramines as high energy fuels.

4. ELECTRO-EXPLOSIVE DEVICES

This class of pyrotechnics includes electrically initiated squibs, primers, pyro-cartridges, igniters, detonators, gas generators, etc. The design choice includes use of conducting composition like lead styphnate mixed with graphite, hot bridgewire, semiconductor-based bridge, exploding bridge wire, thin foil initiator, etc. Development of electro-explosive devices (EEDs) based on hot bridge wire type has competence at HEMRL. A wide range of EEDs have been developed for performing various roles like ignition of solid rocket/missile propellants, ignition of gun propellant, initiation of disruptive explosive train, ignition of pyrotechnic ammunitions/devices, performing mechanical functions like rupturing of a diaphragm, shearing of a cable/ locking pin, actuation of pyro jack, pumping of electrolyte to activate the primary electrical battery, demolition of unexploded ordnances etc. Basically these are one-shot compact devices coupled with very high power-to-weight ratio and high degree of reliability.

The application class includes right from a simple squib used for continuity checking of a firing line to the ammunitions, mines, rockets developed under IGMDP and sophisticated advanced missiles. A wide range of EEDs (Fig. 5) differing in electrical characteristics, safety levels, sizes and output performances has been developed. More than 60 types are regularly produced in ordnance factories after the the smooth technology transfer from HEMRL.

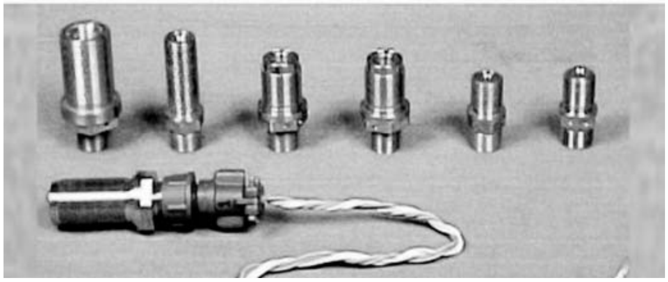

Figure 5. Electro-explosive devices.

With emergence of electronic warfare, the battlefield environment has changed, necessitating higher degree of safety level to prevent unintentional/accidental initiation of EEDs, and in turn, ordnances. Researchers have started working on comparatively insensitive devices free from EMI/EMC, stray electrical currents, etc. Many options have been considered to meet higher degree of safety. In this direction, the existing design of PC 25, PC 50 and PC 100[41] has been modified by choice of bridge wire and formulating new squib composition based on B/KNO_3, $Zr/KClO_4$ and $B/KClO_4$ to provide 1W-1A no fire capability for 5 mins. Development, qualification testing including EMI/EMC and processing of pilot lot has been completed. Pyros have been developed to replace the existing devices in missile applications. Reduction in functioning time from an average value of 15 ms to 3 ms is to be met in future. On similar line, in the absence of any such literature, development of impulse cartridge for[42] CMDS flare, detonator and explosive bolt for LRSAM has been completed successfully and development of semiconductor bridge-based pyro-cartridge and reliability assessment trials are in progress. Gas generators are a special class of pyro devices. Gas generators of 1200 cc and 2400 cc have been developed successfully and are used in activation of a primary battery in missile. Development of gas generators 6000 cc and 14000 cc for advanced missile in final stage of completion.

5. PYROTECHNIC DELAYS

A pyrotechnic delay element is a self-contained pyrotechnic device consisting of an initiator, a delay column and an output charge, assembled in to a specially designed inert housing. Pyrotechnic delays devices are classified as obturated or vented depending upon the design and delay compositions are classified as gasless and slagless depending upon the nature of combustion products. Pyrotechnic delay are smaller, simpler, rugged and cheap compared to mechanical and electronic timers. Pyrotechnic delays are used to perform various roles like providing bore and muzzle safety in ammunition fuzes, aiding in sequential release of payload, providing safety in flight/ trajectory, enabling self-destruction of blind ammunitions, allowing warhead penetration in runway/bunker, etc. Delay time requirement varies from few ms to several seconds. The application ranges from a simple hand-thrown grenade to an advanced canister lunched tactile missile. The main limitation associated with pyrotechnic delay is the accuracy that lies between ± 10 per cent to 20 per cent of mean value over a military operating temperature of - 40º to + 60º. The technology is associated with many factors, both physical and chemical that affects the performance outlined by Wilson and Hancox[16] . Safety, time reproducibility, and ignition transfer are considered important parameters to be met. More than 40 types of delays have been developed meeting the stringent qualitative requirements and most of these are regularly produced in ordnance factories. (Fig. 6) Fifteen types of pyrotechnic delays are under development. Data bank of more than 50 compositions is available for ready reference. The ignition and propagation of an igniferous delay train is considered a complex chemistry[17].

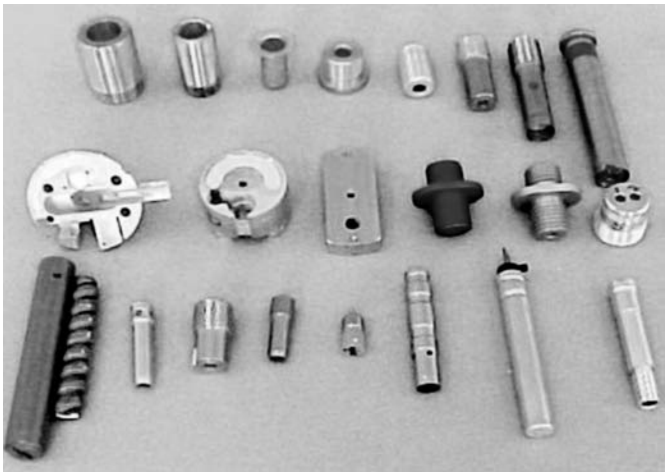

Figure 6. Pyrotechnic delays.

The slow-burning compositions based on tungsten, barium chromate and potassium perchlorate have an inverse burn rate of 16 s/cm maximum. This formulation with an IBR of 12 s/cm when experimented in column diameter of 4 mm, observed failing in propagation. Burning properties of such tungsten based slow compositions have been investigated[18,19]. Basically it is a thermal management or to have a propagation index of greater than one.

An attempt was made to improve the accuracy to pyrotechnic delay for enhancing the effectiveness of a anti-thermal anti-laser smoke grenade. A good success has been achieved by reducing the delay time spread from ± 10 per cent to ± 4 per cent at a given temperature by improving the design in respect of delay tube material and dimensional control. Better accuracy is achieved with brass delay tube compared to aluminium, stainless steel and carbon steel[20].

6. LASER INITIATION OF PYROTECHNICS

Nowadays, the light energy in the form of laser beam is being utilised in civil and military applications[21-25]. Laser ignition of energetic materials like explosives, propellants and pyrotechnics is basically the volumetric absorption of the radiant energy. Laser ignition eliminates the problems associated with electrically-initiated explosive device from accidental initiation by ESD/EMI/EMC. Studies on development of laser devices for pyrotechnic applications, opto-sensitivity characterisation of compositions and design of laser-initiated pyro devices have been highlighted. The study in this advance area began in HEMRL few years ago and a high degree of success has been achieved. Studies carried out on laser-initiation of a series of pyrotechnic compositions, design of laser initiated pyro device (Fig. 7), laser ignition of BEM rocket motor, and development of a compact laser source with 6 point ignition features (Fig. 8) for futuristic defence applications[26-28].

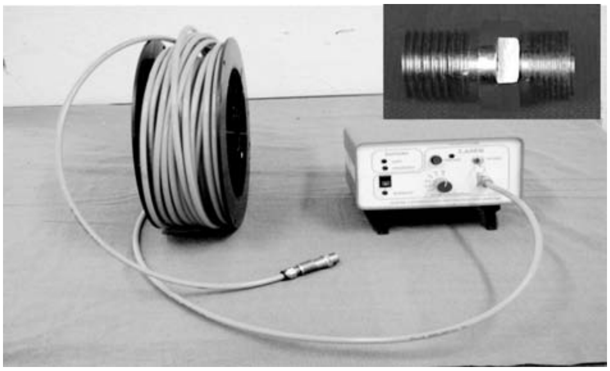

Figure 7. LASER unit with LIPC.

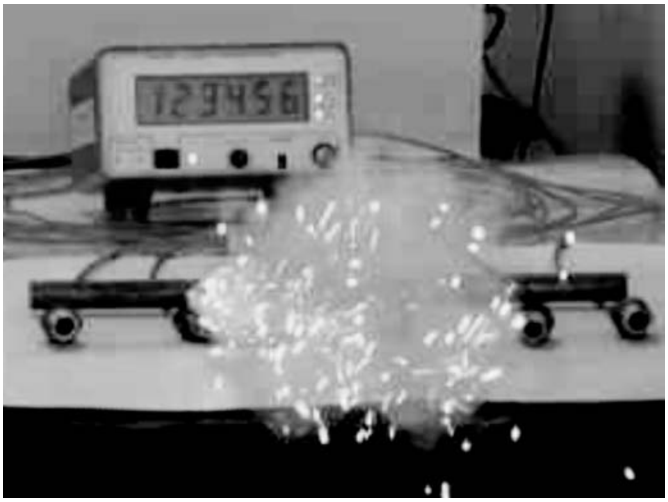

Figure 8. Multi point laser ignition.

Development of dedicated diode laser that can be interfaced with pyro device and a single laser source with branching for simultaneous programmed ignition of a number of pyro devices are currently undergoing.

7. NANO SCALE PYROTECHNICS

Synthesis/manufacturing techniques, characterisation and application of nano-materials are being studied globally since last decade in every sphere of technologies. The application of nano scale (< 100 nm) ingredients is under study in every class of high energy materials, viz., propellants, high explosives and pyrotechnics. The study is carried out on nano scale formulation like Al/MoO_3, $Al/Fe_2O_3/SiO_2$, $Fe_2O_3/SiO_2/R$, $Al/KMnO_4$ [29-33].

Initially nano Fe_2O_3 was studied in delay and priming compositions. Further study is being extended to thermite and IR flare compositions. Ramaswamy[34], *et al*. Nano Fe_2O_3 of particle size 30 nm has been synthesised using sol-gel method and emulsion method. This method has been scaled up to 200 g batch. Metastable intermolecular compositions (MIC's) using nano Al/Fe_2O_3 has been prepared and its physiochemical and thermal properties have been studied. STA analysis showed the decomposition of MIC at 645 °C, whereas the micro thermite did not ignite up to 800 °C. IR flare composition based on MTV and nano *Al* and MTV and carbon nanotube have been experimented and found to burn 2.5 times faster as compared to the conventional system. The optosensitivity of *Zr* and nano iron oxide is studied[35].

8. GREEN PYROTECHNICS

Traditional pyrotechnics are a big source of pollution. Current inventory of pyrotechnic ingredients includes some of the toxic ingredients like lead and barium salts. Recently, efforts of making lead-free electric matches for all kinds of pyrotechnic initiation have increased through the utilisation of nano-scale thermite materials (MICs). High energy density materials like nitrogen-rich compounds serve as potential fuels in combination with less toxic metal ions such as *Cu-II*. Smokeless pyrotechnic composition containing strontium ditetrazolate pentahydrate has been reported. 5-5'-Bistetrazolate (BT) has been found useful in Gas generators. Alkali metal salts of amino azotetrazoles have been found very promising for application in flares[36-38].

A systematic study and processing is undertaken to replace toxic ingredients by non-toxic or comparatively less toxic ones without comprising on processibility, safety and performance effectiveness. To begin with $BaCrO_4$ is replaced by Fe_2O_3 in three types of delay compositions and lead salts by nickel hydrazinium nitrate (*NHN*) and barium ferrocynide (*BFCN*) in detonator and squib compositions, respectively[39-40]. It is a beginning towards a green pyrotechnics.

9. IMPROVED PYROTECHNICS

Safety, reliability and reproducible output performance are becoming of more and more concerned in design of pyrotechnics for modern armament/missile technologies. Caring for the environment is another aspect. In view of meeting future challenges, some of the objectives set for improved pyrotechnics include, design of EEDs with no fire capability of > 1W and 1A for 5 mins duration, development of IR-Illuminating composition, development of multi spectral IR and smoke compositions, replacement of EEDs with LIDs (laser-initiated devices), development of slow burning delay compositions, design of pyro delays with improved accuracy, automation of processes, formulation of compositions with enhanced efficiency and reduced sensitivity level, development of multi-functional formulations, improving the instrumental facilities, studies on nano-scale pyrotechnics, replacement of hygroscopic and toxic ingredients, improving the overall reliability, modelling and studies on reaction kinetics.

10. CONCLUSIONS

An overview of developments in pyrotechnics is presented. Development of hexachloroethane and red phosphorus-based smoke compositions and application of smoke devices are listed. Multispectral smoke and IR compositions are discussed. Illuminating and IR flares are covered. Improvements in sensitivity of electro-explosive devices and accuracy of delay time are presented. Studies on laser initiation of pyrotechnics, green and improved pyrotechnics are highlighted. All the recent development in pyrotechnic have been discussed.

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