

# A Review on Residual Solid Propellant Disposal Methods Using Hazard Risk Index Matrix, Risk Score Matrix, Safety Consequence Analysis and Environmental Impact Analysis

Meikandan M<sup>1</sup>, Nancy Grace N<sup>1</sup>

<sup>1</sup>Department of Mechanical Engineering, VelTech Rangarajan Dr. Sagunthala R&D Institute of Science & Technology, Avadi, Chennai-600062, India

## ABSTRACT

**Introduction:** Solid propellants are high energetic materials used for Launch vehicles and military applications. During solid propellant processing residual propellant generates due to less pot life, machining for insulation lining, scaled and sub scaled trials for mechanical and ballistic properties prediction. A conventional method for disposal of residual propellant is open-air burning; other alternate methods in the literature are incineration, wet air oxidation and molten salt destruction.

**Methods:** Hazard assessment is carried out for the disposal methods both conventional and alternate. Preliminary hazard analysis (PHA), Hazard Risk Index Matrix (HRIM), Risk Score Matrix and as low as reasonably practicable (ALARP) are used to assess the Hazard.

**Results:** Based on the study and calculations Open air burning is having less risk score and medium level safety risk acceptance and tolerable risk which can mitigate. Open-air burning is the safest, efficient and cost-effective way to dispose of the high energetic material but the disadvantage of this method is environmental pollution, high temperature and toxic gases exposure to fire personnel. Based on safety consequences analysis, the 1 gram of solid propellant is found to be 1.308 grams of Trinitrotoluene (TNT) equivalency, and one-time open burning creates 3.822 KPa overpressure on the atmosphere where minimum overpressure to create damage effect is 5 KPa.

**Conclusion:** The environmental impact analysis for disposing of solid propellant gives information about different pollutants, their concentrations in the atmosphere at different altitudes and their impact. Solid propellants are hazard reactive materials they were the one exception under the Resource Conservation and Recovery Act (RCRA) that controls the destruction of hazardous waste.

**Key words:** Disposal methods; Open-air burning; Preliminary hazard analysis; Residual solid propellants; Risk Score Matrix

DOI: <https://doi.org/10.3126/ijosh.v12i3.41375>

Conflicts of interest: None  
Supporting agencies: None

Date of submission: 12.12.2021  
Date of acceptance: 02.03.2022  
Date of publication: 01.07.2022

### Corresponding Author

Meikandan Megaraj,  
Associate Professor, Department of Mechanical Engineering,  
VelTech Rangarajan Dr. Sagunthala R&D Institute of Science  
& Technology,  
Avadi, Chennai-600062, India  
E-mail: [meikandan013@gmail.com](mailto:meikandan013@gmail.com)  
ORCID: <https://orcid.org/0000-0002-6519-0306>

## INTRODUCTION

Solid propellants are high energetic materials used for Launch vehicles and military applications. They produce high-temperature gaseous products.<sup>1</sup> There are several advantages of solid propellants for their use in Launch vehicle and Ballistic missile applications. Some of the advantages of solid propellants in launch vehicle applications include, the high material density of solid propellants leads to high energy density (The energy produced by a unit mass of propellant is called



This journal is licensed under a Creative Commons Attribution-Non Commercial 4.0 International License.

its energy density) needed for producing the required propulsive force, propellants in the onboard rocket are burned in a controlled way (deflagration) to produce the desired thrust, high mass flow rates of gaseous products during launch, resistance to unintended detonation.<sup>2,3</sup> Storage stability with long service lifetimes, simplicity in design, quick response, and reliability related to their chemical stability are some more advantages of solid propellants for both launch vehicles and ballistic missiles.<sup>4,5</sup>

A lot of subscale trials are conducted to fix the is Hydroxy Poly Butadiene (HTPB) percentage due to its long-chain polymer structures the Hydroxide (OH) value changes from batch to batch.<sup>6</sup> To get good mechanical properties for structural integrity during storage and flight the X-value trials are conducted and the samples are tested for the required properties, those samples are generated as residual propellants. Activated copper chromite (ACR) percentage trials are conducted to fix the percentage of Burn rate modifier, to predict the ballistic properties during flight. During the mixing of all raw materials, the curators are added to the premixed propellant slurry 30 min before cast into the case since the pot life (the flowability decreases as time goes beyond this time) of (HTPB)/ Toluene Di-Isocyanides (TDI) based propellant is 3 hrs. Only Free Flowing slurry is casted into the motor case to avoid air voids and pinholes. The flow rate is also fixed for the segment. The high viscous material is discarded as residual propellant since it gets hardened within no time.<sup>7,8</sup>

A solid-propellant consists of several chemical ingredients such as oxidizer, fuel, binder, plasticizer, curing agent, stabilizer, and a cross-linking agent. Ammonium perchlorate (AP), Aluminum (Al), Hydroxy Poly Butadiene (HTPB), Di-octyl Adipate (DOA), Toluene Di-Isocyanides (TDI), Sodium 4-Phenylbutyrate (PBNA), Butanediol and Trimethyl propane and Activated copper chromite (ACR) are the respective ingredients. The specific chemical composition depends on the desired combustion characteristics for a particular mission. Different compositions of chemical ingredients result in different mechanical and ballistic properties, and combustion characteristics, required for specific flight performance of solid rocket motors.<sup>9</sup>

## METHODS

Solid propellants are processed considering all safety measures, the raw materials used are also having

stored energy. Raw materials come under hazard class 1.3, which are shock-sensitive, friction sensitive, and impact sensitive and some of the raw materials are mono propellants they just required ignition sources in any form from a small spark generated by static electricity to friction fire. Every processing facility is designed with a blast wall and traverse to accommodate or to minimize the effect of the explosion outside and the tonnage of explosives to be stored and buildings are constructed with safety distances.<sup>10</sup>

In STEC pamphlet No 18: the Ministry of Defense has given guidelines for the safe disposal of high explosives, propellants, and pyrotechnics. They mentioned these are destroyed by open-air burning since these are bulk high energetic materials.<sup>11</sup>

A question arises why only open-air burning is damaging to human health and the environment. Still in developed countries like the United States, the only hazardous material that is still allowed to be burned in the open for destruction on an industrial scale is explosives. Open Burning and Open Detonation operations are used to destroy excess, obsolete, or unserviceable munitions and Bulk energetic materials like propellants.<sup>12</sup> All other open burning of hazardous materials for destruction has been banned by the Environmental Protection Agency (EPA).<sup>7</sup> The reason for this is, that open burning or detonation was the only safe way to dispose of these materials, and since they are hazardous reactive materials, they were the one exception under the Resource Conservation and Recovery Act (RCRA) that controls the destruction of hazardous waste.<sup>5,13</sup>

## RESULTS

The answer to the above question can be addressed from a safety point of view by finding out the hazards involved in each method. A Hazard present is always a potential risk that harms the target, so based on the Hazard assessment of each method, the safest method with acceptable risk is to be found.<sup>14</sup>

The Hazard/Mishap Severity Categories are shown in Table 1. Hazard/Mishap Probability Level, shown in Table 2. and Hazard Risk Index Matrix are per MIL-STD-882D.

The Risk Assessment Values are determined by multiplying the scores for the Probability and Severity values together.<sup>15,16</sup> The higher the risk assessment, the greater the overall risk for the project. This method

helps balance the weight of severity and probability, as you can see in the following chart that displays the default risk assessment values.<sup>17,18</sup>

The preliminary hazard analysis technique is used to find out the Hazards in each method: The Hazard present is always a potential risk, so finding out them is as best as to control them.<sup>19</sup>

This is the conventional method used worldwide to dispose of the high energetic materials since it is efficient and cost-effective. High energetic materials were placed in open area pits with the quantity not exceeding as per (STEC Pamphlet No: 18) guidelines and ignited from a remote site. The process is simple and inexpensive Electric or burning ignition system is shown in figure 2.1. In general, electric systems are preferable, because they provide better control over the timing of the initiation. In an electric system, an electric current heats a bridge wire, which ignites a primary explosive pyrotechnic, which, in turn, ignites or detonates the material slated to be burned or detonated (Noyes 1996).<sup>20</sup> Preliminary Hazard Analysis of Open-Air Burning system is tabulated in Table 4. If a misfire occurs, personnel are required to wait at least 30 minutes before inspecting the point of initiation. The misfire may be inspected by no more than two personnel, who must follow specific operating procedures.<sup>21</sup>

In the incineration process, pre-treatment of high energetic materials is a must before incineration, the material is fed on the belt conveyor where the metallic element is removed by a metal detector, Particulate form is mixed with water forming an aqueous suspension (Bolejack, Jr. et al).<sup>22</sup> The primary chamber ranges in temperature from 800 °F to 12000 °F and the retention time in the primary chamber, which is varied by changing the rotation speed of the kiln, is approximately 30 minutes.<sup>23,24</sup> Off gases from the primary chamber pass into a secondary combustion chamber (Afterburner), this destroys any residual organics.<sup>25</sup> Gases from the secondary combustion chamber pass into a quench tank where they are cooled from approximately 2000 °C to 200 °C. From the quench tank, gases pass through a Venturi scrubber and a series of baghouse filters, which remove acid gases and particulates before releasing from the stack.<sup>26</sup> The treated product of rotary kiln incineration is ash (or treated soil), which drops from the primary combustion chamber after organic contaminants have been destroyed. This product is routed into a

wet quench or a water spray to re-moisturize it, then transported to an interim storage area pending receipt of chemical analytical results. Preliminary hazard analysis for the Incineration process is carried out by considering equipment-wise hazards and tabulated in table 5.<sup>27,28</sup> There are so many other Hazards are also associated with the Incineration process, if we consider, belt conveyor, stack, pumps, steam generation etc.

Wet air oxidation is a high temperature, high pressure, liquid-phase oxidation process. The technology is used in municipal wastewater treatment, typically for treating dilute solutions of 5 to 10% solids or organic matter. Wet air oxidation also has been tested but not used on a large scale for treating explosives waste.<sup>29</sup> In a typical wet air oxidation system, contaminated slurries are pumped into a heat exchanger, where they are heated to temperatures of 177° C to 300°C, then into a reactor, where they are treated at pressures of 1,000 to 1,800 psi. The Preliminary Hazard Analysis of Wet Air Oxidation method is tabulated in Table 6.

The salt oxidizes the explosive, and organic components in the waste react with oxygen, yielding carbon dioxide, nitrogen, and water. The incineration is accomplished by injecting the hazardous material and air beneath the surface of a pool of molten salts. Typically, sodium carbonate with a small amount (1 to 10%) of sodium sulfate is used as the molten salt, however, other alkali metal carbonates or mixtures of alkali metal carbonates can be employed. Sodium carbonate is used because it reacts instantly with acidic gases to form sodium salts. A small amount of sodium sulfate is used to catalyze the combustion of carbon. Temperatures of the molten salts are usually in the 700° to 1000°C range.<sup>30</sup> As the waste material is oxidized, sodium chloride, sodium phosphate, sodium sulfates, and inorganic ash are accumulated in the molten salt medium. When the dissolved impurities reach 20% by weight of the salt medium, the spent molten salt must be replaced. The salt can either be disposed of or it can be regenerated. Regeneration consists of quenching in water followed by filtration to remove ash. Carbon dioxide is bubbled through the quench solution to precipitate sodium bicarbonate.<sup>9</sup> The solid sodium bicarbonate is filtered and returned to the molten salt furnace. The bicarbonate is converted to carbonate upon heating in the furnace. The principal disadvantage of this process is the high cost and its preliminary Hazard analysis of the Molten Salt Destruction process is been tabulated in Table 7.

**Table 1:** Hazard/Mishap Severity

Description	Category	Value	Impact on Environment, Safety, and Health Result Criteria
Catastrophic	I	4	Human error, environment, design deficiencies, element, subsystem or component failure, or procedural deficiencies may commonly cause death or major system loss.
Critical	II	3	Human error, environment, design deficiencies, element, subsystem or component failure, or procedural deficiencies may commonly cause severe injury or illness
Marginal	III	2	Minor injury or illness or minor system damage such that human error, environment, design deficiencies, subsystem or component failure
Negligible	IV	1	Personnel error, environment, design deficiencies, subsystem or component failure or procedural deficiencies will result in no, or less than minor, illness, injury or system damage.

**Table 2:** Hazard/Mishap Probability Level

Description	Level	Value	Probability Occurrence
Frequent	A	5	Likely to occur often in the life of an item,
Probable	B	4	Will occur several times in the life of an item
Occasional	C	3	Likely to occur sometime in the life of an item,
Remote	D	2	Unlikely but possible to occur in the life of an item,
Improbable	E	1	So unlikely, it can be assumed occurrence may not be experienced,

**Table 3:** Risk Score Matrix



**Table 4:** Preliminary Hazard Analysis of Open-Air Burning system

Ref	System	Hazard element (Causes)	Initiating Mechanism	Accidental event	Effects	Probability	Severity	Hazard Risk Index
CO1	Electric wire ignition system	Bridge wire	Delay in heating	No burning	Process downtime (30 min)	Occasional	Marginal	Medium
CO2	Burning Pits	1. Temperature 2. Toxic gases	Burning of propellant	Exposure	Occupational disease to Fire personnel	Frequent	Critical	High
CO3	Merlon	Non-Explosives like Contaminated Rubber chutes, gloves etc	Mass Explosion	Thrown out Beyond Merlon	Fire Catching in the Surrounding vegetation	Remote	Critical	Medium
CO4	Open burning	Toxic gases	Burning	Exposure	Environmental damage	Frequent	Marginal	Serious

Overall Risk Score: Occasional x Marginal + Frequent x critical + Remote x Critical + Frequent x Marginal  
 = (3 x 1) + (5 x 3) + (2 x 3) + (5 x 1) = 29

**Table 5:** Preliminary Hazard Analysis of Incineration of Waste explosives

Ref	System	Hazard element (Causes)	Initiating Mechanism	Accidental event	Effects	Probability	Severity	Hazard Risk Index
AI1	Wet Grinder	1. Grinding wheels 2. Propellant	1. Over speed 2. Friction	Detonation	1. Fatal 2. Very Serious Injuries 3. High Damage to plants and Premises	Occasional	Catastrophic	High
AI2	Vertical mixer	1. Mixer blades 2. Propellant	Friction generates when oversized particles got stuck in between blades	Detonation	1. Fatal 2. Mixer building will be collapsed 3. High Damage to plants and Premises	Probable	Catastrophic	High
AI3	Rotary Kiln Incinerator	1. High Temp 2. Loss of Containment 3. Hot spots 4. Contaminating drums manually while slurry injection 5. Unburned propellant 6.Noise	Process parameters More Localized heating Incineration of slurries containing explosives causes irregular burning	1. Violent Bursts 2. Dust explosion by ash	1. Fatal 2. High Damage to plants and Premises 3. Process downtime 4. Environmental damage (NOx and PIC pollutants)	Frequent	Catastrophic	High
AI4	After Burner	External Fuel	Ash generation	Localized Dust explosion	Environmental damage	Frequent	Marginal	Serious
AI 5	Wet Scrubber	Residual waste hazardous powder	Corrosion of base	Loss of containment	Soil pollution	Occasional	Marginal	Medium

Overall Risk Score = Occasional x catastrophic + Probable x catastrophic + Frequent x Catastrophic + Frequent x Marginal + Occasional x Marginal  
 = (3x 4) + (4x 4) + (5 x4) +(5 x 1) +(3x 1)  
 = 56

**Table 6:** Preliminary Hazard Analysis of Wet Air Oxidation method

Ref	System	Hazard element (Causes)	Initiating Mechanism	Accidental event	Effects	Probability	Severity	Hazard Risk Index
AW1	Reactor	High temperature (177 to 300° C) High Pressure (1000 to 1800 psi) Corrosive Reaction Mixture.	1. Disruption and fragmentation of the reactor. 2. High Energy radiation	Loss of Containment	1. Trauma wounds 2. Corrosive or toxic propellant aqueous from vessel failure.	Occasional	Critical	Serious
AW2	Heat Exchanger	Temperature	1. Hazardous Material Exposure 2. Cold metal Embrittlement	Fire Explosion Uncontrolled Reactions	1. Very serious Injuries 2. Process downtime 3. Equipment damage	Probable	Catastrophic	High
AW3	Steam Boiler	High Heat High pressure Thermal expansion Thermal contraction Wet Steam Warm up	Deviation from Process Parameters The sudden expansion of components Over pressurization Thermal stress fracturing	Pipe Lines and equipment Rupture Explosions	1. Burns when contact with hot surface 2. Thermal fractures the expansion of water	Frequent	Critical	High
AW4	Separator	1. CO, CO2, NOx PM's gases	Effluent gas	1. Occupational disease 2. Acid Rains	Environmental damage	Frequent	Marginal	Serious

The overall Risk score as per Risk score matrix = Occasional x critical + Probable x catastrophic frequent x critical + frequent x marginal

$$= (3 \times 3) + (4 \times 4) + (5 \times 3) + (5 \times 1) = 45$$

**Table 7:** Preliminary Hazard analysis of the Molten Salt Destruction process

Ref	System	Hazard element (Causes)	Initiating Mechanism	Accidental event	Effects	Probability	Severity	Hazard Risk Index
AM1	Molten salt	Alkali Chemical Sodium Carbonate and Sodium Sulfate	1. Decomposition 2. Process – melting at high temperatures 900 -1100 ° C	Mass loss Effluent Gases SO2 and NO	Environmental damage	Occasional	Critical	Serious
AM2	Cooling Pump	Heat	Salt pump trips	Flow decrease accident, Heat removal function is lost, Fuel salt Temperature Increases further	Explosion	Occasional	Catastrophic	High

AM3	Molten Salt Reactor	1. Propellant 2. High Heat 3. Molten Salt	Deviation from Process Parameters Reactor tubes Blocking Decomposition	Bursts	Explosion	Occasional	Catastrophic	High
AM4	Pipelines, Heat Exchangers, pumps,	Molten Salt	Primary loop is lost	Molten Salt leak accident	Environmental damage	Occasional	Marginal	Medium

The Overall Risk Score = occasional x critical + occasional x catastrophic + occasional x catastrophic + occasional x marginal = (3 x 3) + (3x 4) + (3 x 4) + (3x 1) = 36

**Table 8:** Safety Risk Acceptance levels of individual method

Open Air Burning	Incineration	Wet Air Oxidation	Molten Salt Destruction
Medium	High	Serious	Serious
High	High	High	High
Medium	High	High	High
Serious	Serious	Serious	Medium

**Table 9:** Overall Risk Scores of each individual method

Method	Overall Risk score
Open Air Burning	29
Incineration	56
Wet air Oxidation	45
Molten Salt Destruction	36

**Table 12:** Exhaust gases concentrations of S200 static test at different elevations

Exhaust Gas	At Different Altitudes		
	10 m	300 m	500 m
Al <sub>2</sub> O <sub>3</sub>	0.1 mg/m <sup>3</sup>	0.017 mg/m <sup>3</sup>	0.01 mg/m <sup>3</sup>
HCL	1.4 ppm	-	0.17 ppm
CO	2.35 ppm		0.25 ppm



**Figure 2.1:** Open Air Burning of Solid Propellant

## DISCUSSION

Preliminary hazard analysis is conducted for open-air burning process, incineration process, wet air oxidation and molten salt destruction process, based on safety risk acceptance level criteria risks are tabulated in table 9, Overall risk score of the individual process is tabulated in table 10 and effect of other parameters are tabulated in table 11.<sup>31</sup>

The maximum quantity of propellant to be disposed of at one time in one burning pit as per STEC Guidelines is 500 kg, the safety distance between burning pits is

10 m and transverse is given as 10 m, TNT equivalency is the universal thumb rule to evaluate the safety consequences of different explosives, considered 350 kg of the propellant burned at one time in one pit burn activity accordingly the overpressure produced by 350 kg of propellant burn is determined based on TNT equivalency & its consequences.<sup>32</sup>

TNT equivalency is a way of expressing any type of explosive in terms of its charge weight so that any explosive can be compared to TNT. The idea is based on the knowledge that we have about TNT, whose properties have been widely explored and measured. If we assume that any explosive material has explosive power, this characteristic can be expressed in TNT units of mass<sup>33</sup>. Solid propellants are made up of aluminum and ammonium perchlorate (fuel and oxidizer respectively).

- The heat of combustion of TNT: 4560 J/g
- The heat of combustion of Solid propellant: 5960 J/g
- TNT Equivalency Formula is = Heat of Combustion of Solid propellant / Heat of Combustion of TNT

- This means that for every 1 gram of solid propellant, we will consider 1.308 grams of TNT

A blast is a rapid movement of air or fluid away from a center of outward pressure, as in an explosion. This rapid movement of air determines the damage over many different objects that surround the explosion at a rate that is related to the yield of the explosive. Thus, increasing the amount of the explosive increases the radius of the damage. The blast effect of an explosion is determined by overpressure, which means that there exists a relationship between the explosive and the distance at which an object is going to be affected by the explosion. The overpressure is the rise "from the ambient pressure to a peak incident pressure", or the pressure exceeding the ambient pressure. The gas that the explosion generates moves radially from the source of the explosion toward the perimeter.<sup>4</sup>

The equation governs the overpressure of an explosion is as follows

$$P = 67 \left(\frac{1}{z}\right) + 370 \left(\frac{1}{z}\right)^2 \text{ --- Bracie, Simpson and Baker's equation [6]}$$

$$Z = \frac{Q^{1/3}}{R}$$

Q= Quantity of propellant

R= Distance from explosion source to traverse

Q= 350 kg (As per STEC pamphlet no 18, maximum amount to be disposed)

R= Distance from the explosion traverse to center pit 21 m

$$Z = (350)^{1/3} / 21 = 0.32$$

$$P = 67(1/0.32) + 370(1/0.32)^2$$

$$P = 3822.656 \text{ Pa} \\ = 3.822 \text{ KPa} \\ = 0.037 \text{ Bar}$$

The overpressure due to the burning of 350 kg residual propellant at the disposal bed produces an overpressure of 0.037 bar on the traverse from the center pit. The minimum overpressure to have a damaging effect is 5 KPa. The maximum overpressure to prevent injury to human beings is less than 21 KPa. Hence, the traverse will not get damaged.

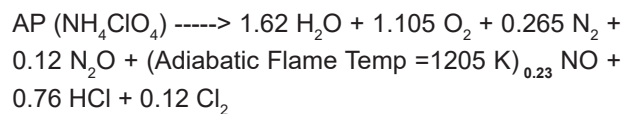
When Solid propellants are burned, they produce high amounts of exhaust gases which are considered as

opposite thrust required for Rocket forward motion, the same way when residual propellants are burned to dispose of produced exhaust gases.<sup>35</sup>

The combustion of AP/ HTPB composite propellant involves an array of intricate physiochemical processes including.<sup>36,37</sup>

- (1) Conductive preheating, decomposition, and phase transition in the condensed phase;
- (2) Multi-stage reactions in the gas phase.

Since the oxidizer and fuel binder are not linked chemically, the combustion characteristics of AP and HTPB are first examined separately.

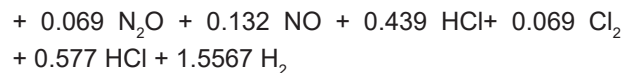
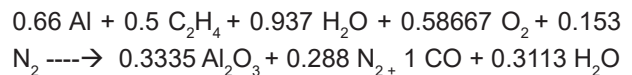
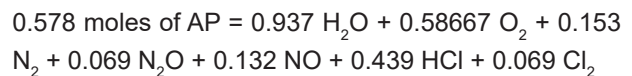


The thermal decomposition of HTPB is assumed to undergo C<sub>2</sub>H<sub>4</sub> and light hydrocarbon species

For 100 g of Propellant 68% AP, 18% Al + 14 % HTPB

In moles 100 g of propellant = 68/117.45

0.578 moles of AP



Total Product moles for 100g of propellant = 4.0665 moles of product gases

Then for 350 kg propellant produces = 14232.75 moles of product gases, in terms of Volume 318.8136 m<sup>3</sup>

The main components of the space shuttle SRM exhaust are

Al<sub>2</sub>O<sub>3</sub> (30% by weight), H<sub>2</sub>O (10%), CO (24%), N<sub>2</sub> (9%), HCl (21%), CO<sub>2</sub> (4%), and H<sub>2</sub>(2%) emitted up to 42 km

1. When the solid motor of the S200 rocket is static test fired, the major exhaust pollutants are Aluminium Oxide (Al<sub>2</sub>O<sub>3</sub>) – 34%, Carbon Monoxide (CO) – 26.6%, and Hydrogen Chloride (HCl) – 20.7%, their concentrations at different elevations is tabulated in table 12.
2. The vapor dispersion of HCl, CO, and particle deposition of Al<sub>2</sub>O<sub>3</sub> was analyzed using the HYSPLIT model at different altitudes.



## CONCLUSION

Based on the preliminary hazard analysis & Risk score calculations, open-air burning is a safer operation with less risk score, this process has a hazard of high temperature and toxic gases to the fire personnel, while they are quenching the burning pits. The reason for following open-air burning worldwide is because this was the only safe way to dispose of bulk energetic materials, and since they are hazardous reactive materials, they were the one exception under the Resource Conservation and Recovery Act (RCRA) that

controls the destruction of hazardous waste. The ozone depletion potential of the alumina emissions ( $\text{Al}_2\text{O}_3$ ) is about 0.03-0.08. Chlorine and particulate emissions from rocket launch vehicles cause complete ozone destruction in the young exhaust plume and potentially lead to a global total ozone loss smaller than 1%, Ozone layer is at 50 km height, the concentrations of the pollutants gradually decrease above 10 m height, wind speeds will increase exponentially above 10 m to disperse the pollutants. Open-air burning can be safer when these pollutants are neutralized before they enter the stratosphere

## REFERENCES

- Mehilal Dhabbe KI, Anjali K, Manoj V, Singh PP, Bhattacharya B. Development of an eco-friendly method to convert life expired composite propellant into liquid fertilizer. *Journal of Hazardous Materials*. 2012; 205–206:89-93.
- Shalini C, Pragnesh N. Solid propellants: AP/HTPB composite propellants. *Arabian Journal of Chemistry*. 2019; 12:2061-68.
- Deluca LT, Galeffi LT. Characterization of HTPB-based solid fuel formulations: Performance, mechanical properties, and pollution. *Acta Astronautica*. 2013; 92: 150-162.
- Robert N. Thermal/Oxidation Processes, Chemical Weapons Destruction Explosive waste. *Unexploded Ordnance Remediation*. 1996;142-52.
- Bolejck J. Incineration process for disposal of waste propellant and explosives. *United States Patent* 1973; 7: 1107-54.
- Brasie WC, Simpson WD. Guidelines for Estimating Damages from Chemical Explosions. symposium on Loss Prevention in the Process Industries. 63<sup>rd</sup> National Aiche Meeting. St. Louis. MO. USA 1968.
- Baker QA, Tang MJ, Scheier EA, Silva GJ. Vapour Cloud Explosion Analysis, *Process Safety Progress*. 1996; 15 (2): 106-9.
- Sergio A, Rosales BS, Polit cnica C. Study for Development of a Blast Layer for The Virtual Range. 2000
- Rajasekhar M, Malapaka Y, Prasad S, Seshagiri V. Exhaust Dispersion Analysis from Large Solid Propellant Rocket Motor Firing Using Hysplit Model Over Satish Dhawan Space Centre. 2014.
- Razionale A, Navarra M, Bartolomeo G, Bubbico R. Safety Assessment of Solid Propellants for Satellites Engines. 2002.
- Elsheikh M. Safety assessment of molten salt reactors in comparison with light water reactors. *Journal for Radiation Research and applied Science* 2013; 6: 63-70.
- Meikandan M, Malarmohan K, Velraj R. Development of superhydrophobic surface through facile dip coating method. *Digest Journal of Nanomaterials and Biostructures*, 2017; 11: 945-51.
- Brady BB, Martin LR, and Lang VI. Effects of Launch Vehicle Emissions in The Stratosphere. *Journal of Spacecraft and Rockets*. 1997.
- Malarmohan K, Meikandan M. Fabrication of a superhydrophobic nanofibres by electrospinning. *Digest Journal of Nanomaterials & Biostructures*; 2018;12 (1): 11-17
- Ganesh Kumar P, Meikandan M, Sakthivadivel D, Vigneswaran VS. Selection of optimum glazing material for solar thermal applications using TOPSIS methodology. *International Journal of Ambient Energy*. 2020; 42; 3: 274-78.
- Danilin MY, Shia RL, Ko MK, Weisenstein DK, and Sze ND. Global Stratospheric Effects of The Alumina Emissions by Solids fueled Rocket Motors. *Journal of Geophysical Research*. 2001; 106: 12: 727-38.
- Deluca LT, and Galeffi LT. Characterization of HTPB-based solid fuel formulations: Performance, mechanical properties, and pollution. *Acta Astronautica* 2013; 92: 150-62.
- Meikandan M, Ganesh Kumar P, Sundarraj M, Yogaraj D. Numerical analysis on heat transfer characteristics of ionic liquids in a tubular heat exchanger. *International Journal of Ambient Energy*. 2018; 41: 8: 911-17.
- Elizabeth R, and Ulrich K. Development of solid propellant for the production of fire suppression aerosols. *Fire Safety Journal*. 2020; 2.
- Gill W, Cruz AA, Donaldson AB, Lim J, Sivathanu Y, Bystrom E, Haug A, Sharp L and Surmick DM. Combustion Diagnosis for Analysis of Solid Propellant Rocket Abort Hazards. *Role of Spectroscopy*. 2014; 66.
- Ashish J, Swaroop G, Balasubramanian K. Effect of Ammonium Perchlorate Particle Size on Flow, Ballistic, and Mechanical Properties of Composite

- Propellant. Nano Materials in Rocket propulsion systems. 2019; 299-312.
22. James A. and Allan R. Wet air oxidation - a treatment means for aqueous Hazardous waste streams. *Journal of Hazardous Materials*. 1985; 12:187-200.
  23. Ka Y, and Pan Y. A new method for ranking potential hazards and risks from wastes. *Journal of Hazardous Materials*. 2019; 365:778-88.
  24. Meikandan M, Sundarraj M, Yogaraj D, Malarmohan K. Experimental and numerical investigation on bare tube cross flow heat exchanger-using COMSOL. *International Journal of Ambient Energy*. 2019; 41:5:500-10.
  25. Kshitiz V. Piping layout for fire sprinkler system: An overview. *International Journal of Engineering and Applied Sciences (IJEAS)*. 2017.
  26. Renuka M, Balaji K, Sakthivadivel D, Meikandan M, Ganesh Kumar P. Selection of optimal glazing material for solar thermal applications using grey relational analysis. *International Journal of Ambient Energy*. 2021; 42: (7): 764-68.
  27. Murray N, Bekki S, Toumi R, and Soares T. On the Uncertainties in Assessing the Atmospheric Effects of Launchers. *Progress in Propulsion Physics*. 2013: 671-88.
  28. Nico H. Recycling and disposal of munitions and explosives. *Waste Management*. 1997; 17:147-50.
  29. Paul M, Christopher L, Santoianni A. Emissions of organic air toxics from open burning: a comprehensive review. *Progress in Energy and Combustion Science*. 2004;30: 1-32.
  30. Viegas RA. A multi-criteria-based hazard and operability analysis for process safety. *Process Safety and Environmental Protection*. 2020; 144: 310-21.
  31. Borcherdin R. An alternative to open burning treatment of solid propellant manufacturing wastes. *Space Propulsion operations*. 1997; 17:135-41.
  32. Rosales BS. Study for Development of a Blast Layer for The Virtual Range. 2000.
  33. Sunghyun C, Chanho P, Jiheon L, Byeongil L, Moona. Finding the best operating condition in a novel process for explosive waste incineration using fluidized bed reactors. *Computers and Chemical Engineering*. 2020; 142.
  34. Voigt C, Schumann U, Graf K, Gottschald K. Impact of Rocket Exhaust Plumes on Atmospheric Composition and Climate - An Overview. *Progress in Propulsion Physics*. 2013;657-70
  35. Weidong C, Piyush T, and Vigor Y. A Model of AP/HTPB Composite Propellant Combustion in Rocket-motor Environments. 2002.
  36. Yi C, Daniel R, Kathryn G, Homeister N G, Marcia A, Howard L, Michael S, Oliver E, Washburn B. Study of Aluminum Particle Combustion in Solid Propellant Plumes Using Digital In-line Holography and Imaging Pyrometry. 2002
  37. Shim Y, Kim J. Successful plant scale production of solid propellant recycling from obsolete ammunition. *Waste Management*. 2016;769-92.