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Laser Induced Propulsion in Toluene Diisocyanate Based Polyurethane Polymers: Effect of Molecular Weight

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Article Details

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ABSTRACT

The dependence of laser ablation propulsion parameters on both the laser fluence and the molecular weight of toluence diisocyanate based polyurethane polymer is reported in this work. As recoil momentum depends upon the laser supported shockwaves and the mass of ejected particles.A (Q-switched) Nd-YAG laser (5ns pulse duration and max energy 400 mJ) operating at 1064 nm was used to irradiate in the polymer samples for recoil momentum generation at different laser fluence. A contact free method named optical triangulation method was employed for measurement of laser ablation momentum in the samples. The results have shown that the critical propulsion parameters i.e. momentum coupling coefficient and specific impulse vary inversely with molecular weight for each value of fluence. The measurements and calculations depicted that Toluene diisocyanate polymer exhibiting low molecular weight shows better results in terms of performance of critical propulsion parameters at a specific value of fluence. Also, the laser ablation propulsion parameters decrease with decreasing laser fluence. The highest value of Cm (momentum coupling coefficient) is found to be 0.14 mN-s/J at laser fluence 5.79×106 J/m2 for sample with lowest molecular weight i.e. 75 kg/mol. Similarly, Isp (specific impulse) for this sample is found to be 13500 sec.

INTRODUCTION

In laser ablation propulsion (LAP) the energy is transmitted from ground based laser system[1].(LAP) is a scheme in which atoms , ions , molecules and even clusters eject from the surface of the target due to conversion of an initial electronic or vibration photoexcitation into kinetic energy. As a result of which a jet of particles leaves the surface of target along with the laser supported shock waves which provides the recoil momentum is the opposite direction [2].The process agrees well with the momentum conservation law.

Ablative laser propulsion is more advantageous than other schemes in terms of laser propulsion parameters that include momentum coupling coefficient C_m, specific impulse Isp and the thrust T. Accurate and controlled values of Isp (specific impulse) is obtained by accurately selecting the target material i.e the propellant and laser pulse parameters. The momentum of the target depends on interaction of laser beam with matter which is termed as the momentum coupling coefficient [3]

A number of propellants are being investigated for laser ablation propulsion that include metals, polymers etc[4]. The choice of appropriate propellant has been a serious issue so far as the thrust generation is much affected by the thermal, optical and physical properties. Uptill now a lot of work has been done on propellants specifically metals, plastics (Derlin) and polymers including Polyoxymethylene, Glycidyl azide polmer, Polyvinyl chloride etc[3-7]

Polymer have some reported advantages over other propellants that include low cost, easy to manufacture and low threshold ablation [8,9].Moreover the thrust produced by polymers were higher than metals because the decomposition of polymer enhanced the thrust generation. Laser ablation of polymers was reported by Srinivasan and Mayne-Banton in 1982 for the first time [10] that involves photochemical or photothermal processes and depends on various conditions including laser fluence, pulse duration, wavelength and the nature of the polymers [11,12]. Also polymers unlike metals are volume absorbers due to which the laser beam penetrates deeply inside the polymer to liberate enough mass fraction for each pulse to generate momemtum.

Considering the importance of ALP and its performance on the nature of polymer, a series of Toluene diisocyanate polyurethane polymer has been compared and investigated.In our previous study a comparison was made among different types of materials. However it is desireable to investigate the polymer samples so a series of sample was made [4] .The structure of toluene diisocyante is shown in figure 1.In this work, experimental results obtained from the irradiation of target which is fixed on moving ballistic pendulum, in air at STP. Displacement measurements were carried out by a non-contact optical beam triangulation method using the He-Ne laser and a position sensitive detector.

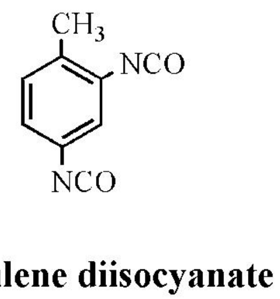

FIGURE. 1 STRUCTURE OF TOLUENE DIISOCYANATE POLYURETHANE POLYMER

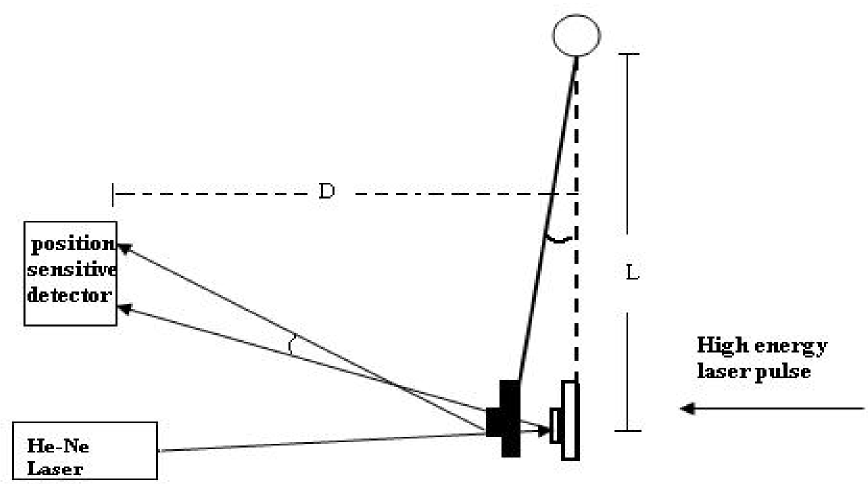

FIGURE. 2 BALLISTIC PENDULUM FOR DISPLACEMENT MEASUREMENT

II. MATHEMATICAL MODEL

Momentum coupling coefficient is one of most important parameter of laser ablation propulsion which depicts the change in momentum of target after laser shot.Mathematically:

$$C_m = m\Delta v / W \qquad (1)$$

Cm is momentum coupling coefficient, where mΔv is the change in momentum of the target material after laser iradiation and W represents energy of each laser pulse.

Also the amount energy required for ablating a fraction of mass is called specific ablation energy

$$Q^* = (W/\Delta m)$$ [13-15]

Specific impulse another important parameter in laser ablation propulsion tells us about amount of ablated mass to required to change the momentum of target.As law of conservation holds for propulsion so dimensionally specific impulse is related to target exhaust velocity as follows:[16]

$$Isp = \mathbf{v_E/g} \qquad (2)$$

Exhaust velocity tell us about the velocity with which ablated mass leaves the surface of target.

$$v_E = \mathbf{C_m} (\mathbf{W}/m_T) \qquad (3)$$

Energy per pulse is represented by W and exhaust velocity of target is represented by v_E. As we are using the optical triangulation so the C_m (momentum coupling coefficient) is calculated by using following formula[13]

$$C_m = (m\mathbf{g}rT/2\pi\mathbf{W}L)(2(1-\cos\theta))^{1/2} \qquad (5)$$

Where m represents mass of thrust stand, g is the gravitational acceleration, r gives the distance from target to suspension point, T is time period , L is the length of target stand , θ is the angular displacement and the energy of single pulse of laser is given by W

Hence thrust can be calculated using

$$T = P \times C_m \qquad (6)$$

Where P is the peak power of incident laser. The ablation efficiency η_{AB} tells us about the conversion of energy of laser beam into exhaust K.E.Its relation with other ablation parameters are

$$\eta_{AB} = W_E/W = \Delta m\psi v_E^2/(2W) = \psi C_m v_E/2 \qquad (7)$$

where $\psi = \langle v_x^2\rangle/(\langle v_x\rangle^2) \geq 1$[17]

W_E is the input electrical power of laser and W is the exhaust power of laser.

TABLE 1: MOLECULAR WEIGHTS OF THE POLYMER SAMPLES

Sample #	Molecular weight (kg/mol)
1	75
2	80
3	85
4	90
5	95

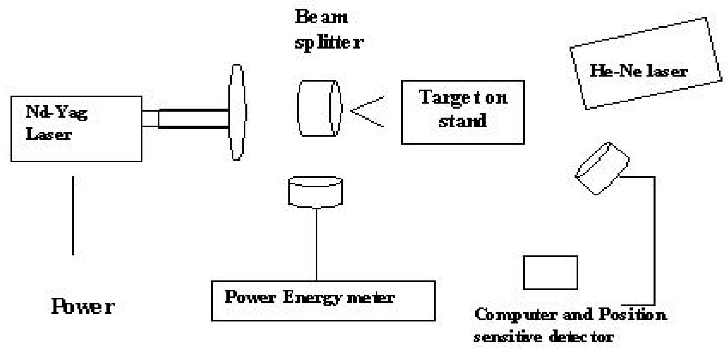

FIGURE 3. BLOCK DIAGRAM OF COMPONENTS' LAYOUT

III. EXPERIMENTAL SETUP

Figure 3 represents the schematic diagram of setup. A Q-switched pulsed Nd-YAG laser (Quantel, France) was operated at wavelength of 1064nm.Irradiation the target material i.e. the toluene diisocyanate based polyurethane polymers was done by pasting target on the pendulum. The molecular weights of synthetic polymers used in this study are listed in table I. The polymer samples were synthesized as follows: The toluene diisocynte was reacted with polymethylsilooxane to form the polyurethane polymer. The samples were prepared by extending the polyurethane prepolymer with series of alkane diols e.g sample 1 was extended with 1,2 ethane diol, sample 2 was extended with 1,3 propane diol, sample 3 was extended with 1,4 butane diol, sample 4 was extended with 1,5 pentane diol and finally sample 5 was extended with 1,6 hexane diol.By increasing the methylene (-CH_2-) unit there is continual increase in the molecular weights(M.wt) of the samples. The method of measurement for laser induced recoil momentum was similar as reported earlier[4].Target was irradiated using pulsed laser beam. Focusing of laser on target was done using Quartz lens. The diameter of focused laser beam used in experiment is 0.15 mm diameter. The laser fluence is varied by varying energy of incident laser using neutral density filters. A reflecting surface was pasted on the opposite side of target for reflection of second laser beam i.e the He-Ne laser which was focused on the that surface. By using setup of He-Ne laser with position sensitive detector a non contact method was used for target displacement. The amount of ablated mass is calculated by irradiating the sample with 500 laser shots and then measured the weight of target before and after laser shots. The amount of mass ablated was calculated using the method reported by Saeed et al.2021 [18]. Experiment was done in air at room temperature.

IV. RESULTS AND DISCUSSION

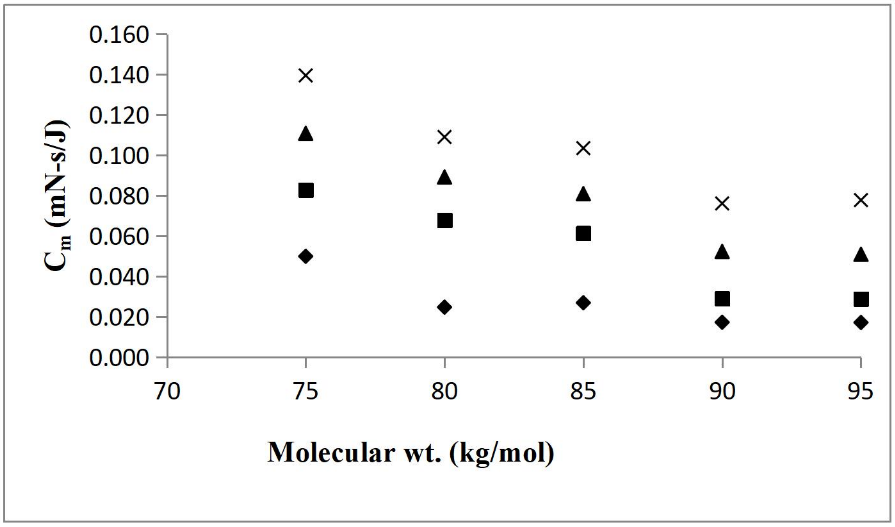

FIGURE 4(A) COUPLING COEFFICIENT C_M AS FUNCTION OF MOLECULAR WEIGHTS AT DIFFERENT LASER FLUENCE (where ♦ 1.02×10^6 J/m^2, ■ 2.60×10^6 J/m^2, ▲ 4.81×10^6 J/m^2 and × 5.79×10^6 J/m^2)

TABLE 2. VALUES OF THE C_M AND ISP AT A HIGHEST LASER FLUENCE I.E. 5.79×10^6 J/M^2

Polymer samples	C_m (mN-s/J)	Isp (sec)	Thrust (N)
1	0.14	13500	2845
2	0.109	10551	2224
3	0.103	10016	2111
4	0.077	7528	1586
5	0.076	7368	1553

The mathematical formulations discussed above have been used to calculate the laser ablation propulsion parameters. Figure 4(a) shows the relationship of momentum coupling coefficient for toluene diisocyante based polyurethane polymer samples having different molecular weights against four laser fluences.The calculated values of Cm indicates the dependence of Cm on the chemical properties of the polymer sample and also on fluence. The error in calculating C_m is found to be 6% by adding errors in quadratures. The sample with low molecular weight has high value of Cm at a particular value of laser energy density (fluence) which shows that lesser the amount of methylene (-CH_2-) unit in this polymer higher is the value of Cm. The reason behind this is that as molecular weight increases the energy consumed for breaking of these bonds also increases, amount of incident energy is consumed in heat conduction which affects the shock waves generation and the evaporation of particles. Hence for low molecular weight sample the absorbed energy is not dissipated and particular amount of shockwaves and plasma generates the high recoil momentum. As a result higher C_m is obtained. Another important reason behind this is that the thermal conductivity increases because of more heat conduction which shortens the thermalization time in samples having large amount of methylene (-CH_2-) group. The calculated results for momentum coupling coefficient of polymer samples at different laser fluence values range from $1.02\times10^6 J/m^2$ to $5.79\times10^6 J/m^2$ at wavelength of 1064nm.The data of momentum coupling coefficients with respect to laser fluence shows the dependence of C_m on different parameters i-e the laser energy, spot area and also on the nature of target used [19].In polymeric material the incident laser energy can penetrate into propellant material deeply and liberate a mass fraction for each incident laser pulse.It was seen that for 1064nm the higher the value of laser fluence the higher the value of Cm.This is due to fact that as when the intensity of incident laser beam increase more plasma is generated along with shockwaves resulting in high C_m. The polymer sample having highest molecular weight (75 kg/mol) has shown better results in terms of C_m as compared to earlier reported work. Previously it has been reported that maximum C_m for Polyoxymethylene (POM) polymer was 100 to 250 µN-s/J when it was irradiated with pulsed CO_2 laser [6].This value is 55.8% less as compared to toluene diisocayanate PU (polyurethane) polymer sample of molecular weight 75 kg/mol studied in present work. Multi-use laser impulse pendulum irradiation with Nd-YAG laser beam for Gray PVC, the maximum C_m was 7.73E-05 N/W [20], 180% lower as compared to sample having molecular wt.75 kg/mol. Polymer doping with IR- dye or carbon nano-particles had resulted in better absorption near IR region.2000 µN/W momentum coupling coefficient was obtained when Glicidyl Azide polymer was doped with IR .The doping of polymers with carbon nano particles gives momentum coupling coefficient in range 120-1170 µN/W [7].Our experimental results of coupling coefficient for polymer samples 1,2,3,4 and 5 at highest value of laser fluence $5.79\times10^6 J/m^2$at 1064 nm are shown in table 2.All samples have highest C_m at this fluence because high fluence governs more plasma resulting in more recoil momentum.Also reported in previous studies the use of Nd-YAG laser at 532nm has resulted in C_m of 5×10^{-5}N/W using metallic samples [21]. The values the coupling coefficient decrease with laser pulses in multiple-pulse propulsion [22]

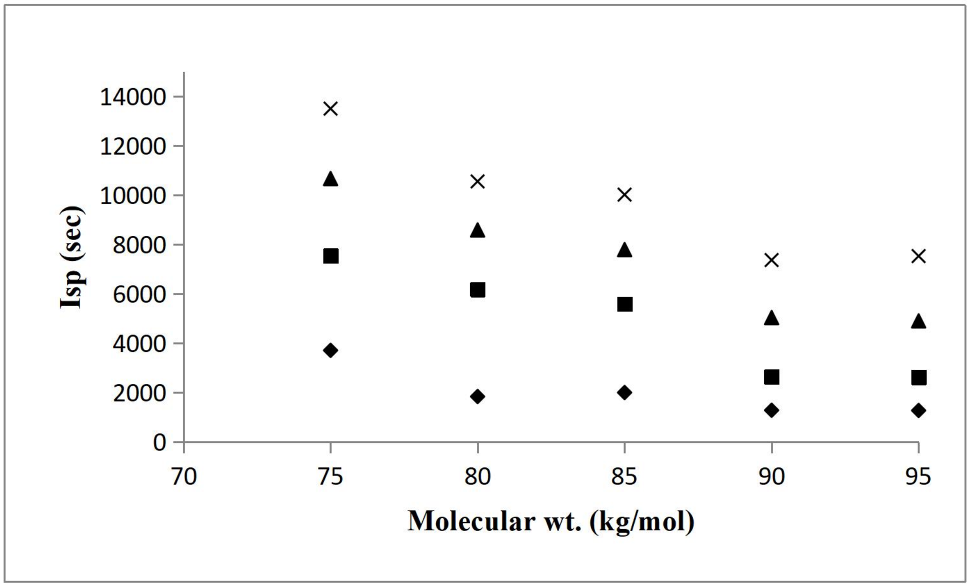

FIG. 4(B) SPECIFIC IMPULSE ISP AS FUNCTION OF MOLECULAR WEIGHTS AT DIFFERENT LASER FLUENCE (where ♦ 1.02×10^6 J/m², ■ 2.60×10^6 J/m², ▲ 4.81×10^6 J/m² and × 5.79×10^6 J/m²)

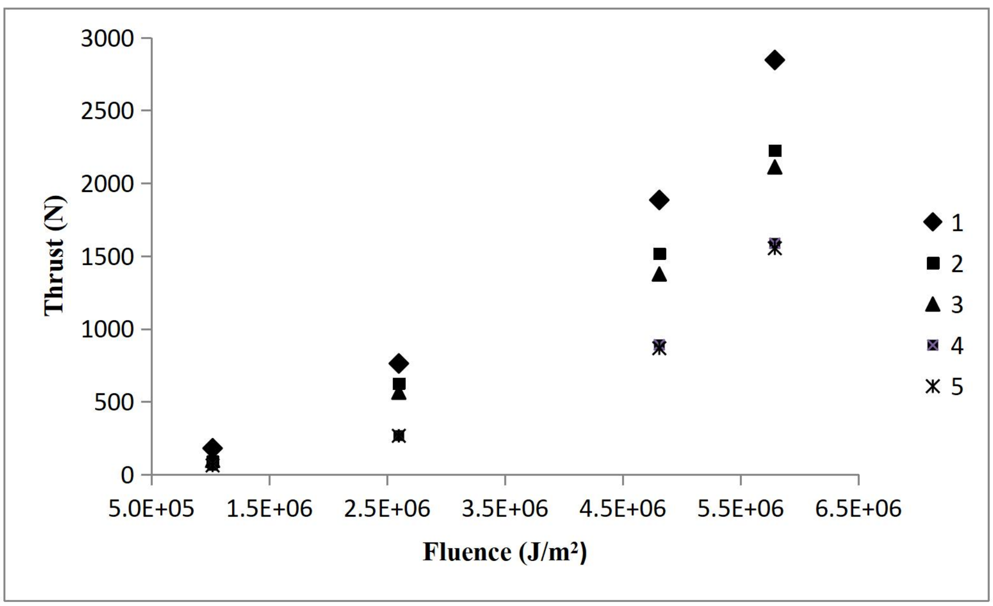

FIG. 4(C) PLOT BETWEEN THRUST AND LASER FLUENCE FOR ALL SAMPLES

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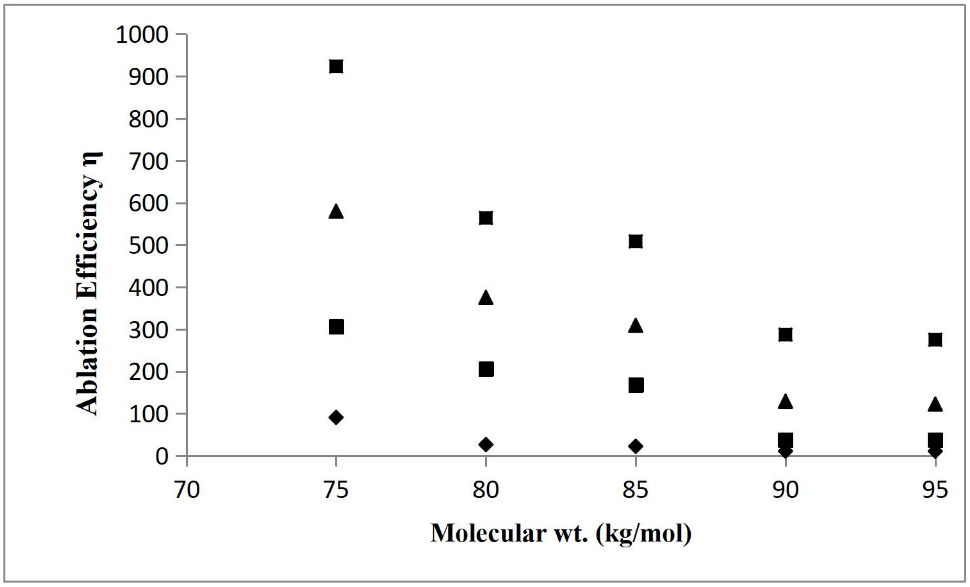

FIG. 4(D) ABLATION EFFICIENCY VERSUS MOLECULAR WEIGHTS AT DIFFERENT LASER FLUENCE (where ♦ 1.02×10^6 J/m², ■ 2.60×10^6 J/m², ▲ 4.81×10^6 J/m² and × 5.79×10^6 J/m²)

If specific impulse is high it means we need less propellant to give a specific amount of momentum. Adding the errors by quadrature the total error in specific impulse values is 12%.From figure 4 (b) it has observed that polymer sample 1 which was extended with 1,4 ethane diol has much high Isp as compared to all other samples. The lower the amount molecular weight the higher will be the value of specific impulse. The reason behind this is that less number of methylene group (-CH_2-) is available in low molecular weight polymer for laser being absorbed.Hence amount of ablated mass is low for low molecular weight sample (sample 1) compared to high molecular weight sample (sample 5).Therfore Isp decreases with increasing molecular weight. This behavior is similar to that observed for metals. The metals which have low atomic weights have higher value of specific impulse [5]. One reason for low specific impulse is that many unionized particles also leaves the surface with ionized particles during ejection[23].Different values of Isp ban be achieved by changing laser fluence on targets. Figure 4 (b) also shows the dependence of Isp on laser. The comparison of our results with previous studies showed that the maximum Isp 100-200 sec was obtained for Polyoxymethylene (POM) polymer when subjected to carbondioxide laser pulses for ablation[6] and when Grey PVC was irradiated by Nd-YAG laser the maximum specific impulse i-e 208 sec was calculated when Grey PVC is ablated using YAG laser using laser impulse pendulum [20]. Similarly, Isp for glycidyl azide polymer (GAP) and polyvinyl chloride (PVC) when doped with carbon nano-particles was found to be 200 to 650 sec respectively[7].The highest value of specific impulse is 13500 sec for polymer sample 1 with lowest molecular weight 75 kg/mol at laser fluence of 5.79×10^6 J/m^2.Isp is the matter of intensity, in another previously reported work Isp of 3000 sec was achieved for ns μLPT [17].Figure 4(c) shows the dependence of laser induced thrust on fluence. As the fluence increases the value of thrust increases for all samples because the mass removal rate changes with the fluence. [24] So, higher values of thrust obtained at higher fluence. Furthermore, the low molecular weight sample 1 gives highest thrust because less energy is absorbed in breaking bonds as number of methylene group is less. Figure 4(d) shows how much propellant is efficient to achieve a thrust. η_{AB} can be 2.3 times higher for the polymer fuels than other fuel materials used so far because chemical energy of the ablating polymers is involved and exothermic reactions takes place [25]

CONCLUSION

It has been concluded from experimental results that propulsion parameters are greatly influence by molecular weight of toluene diisocyanate polyurethane polymer and incident laser fluence at 1064 nm. Polymer samples with low molecular weight having less methylene (-CH_2-) unit showed good results. The highest coupling coefficient and specific impulse is about 0.14mN-s/J and 13500sec and 2845 N respectively for toluence diisocyanate based polyurethane polymer sample having molecular weight 75 kg/mol at fluence of 5.79×10^6 J/m^2.It can be used as efficient propellant where required.

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