

HYDROGEN PEROXIDE - FROM BRIDESMAID TO BRIDE

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ABSTRACT

The criticisms raised by John Clark concerning the use of hydrogen peroxide as a future rocket propellant are revisited. These criticisms focus on five important issues associated with detonation hazards, consequences of contamination, stability in storage, difficulties with ignition and problems associated with its freezing point. Each of these criticisms is questioned in the light of present experience and knowledge. The overall conclusion drawn is that Clark's assessment of peroxide was unfair and that many of peroxide's apparently undesirable attributes are shared with other propellants that are in common usage.

1. INTRODUCTION

THAT there may be a need to abandon dinitrogen tetroxide and the various hydrazine-based fuels on grounds of toxicity presents a significant challenge to those in the research community who are engaged in finding suitable, replacement propellants. The challenge is significant for a number of reasons. Firstly, this propellant combination has a very high specific impulse. Secondly, these propellants store well both on the ground and in the space environment. This is particularly important for long-duration missions culminating in critical manoeuvres. Thirdly, the combination is hypergolic and so ignition is almost guaranteed. Largely because of these attributes, it was this mix of hydrazine and dinitrogen tetroxide that was chosen for the Apollo Moon landings and for the homeward return of the Command Module from Lunar orbit.

It seems likely that if hydrazine were ever to be abandoned on the specific grounds of its carcinogenicity then most likely its hypergol partner, dinitrogen tetroxide, would similarly be abandoned. This paper explores the reasons why so many practitioners in the propellant business are guarded in their assessment of hydrogen peroxide as a viable oxidiser to replace dinitrogen tetroxide. This caution is viewed with considerable frustration by many experts in the

hydrogen peroxide research community despite the fact that hydrogen peroxide (peroxide) is an industrial chemical with a world-wide production exceeding 2 million tonnes per year. It is used as a clean ('green') oxidizer for the bleaching of paper and textiles, as an agent for water treatment and as an oxidising intermediate in the chemical and detergent industry. In high concentrations it has a long and proven history for both propulsion and gas generation applications and has been used in Russian (former Soviet Union) rocket programmes for both space and military applications for over 40 years. Despite this heritage, hydrogen peroxide is viewed with caution by practitioners in the rocket engine community. The caution stems from criticisms that are often levelled against peroxide, which in truth have their origins not in direct experience of the material but rather in historical anecdotes.

One such potent anecdote, which will be the focus for much of the present paper, is the section on hydrogen peroxide in John Clark's seminal work published in 1972¹. His view of peroxide, somewhat loosely paraphrased as "*..... always the bridesmaid; never the bride*", seems to have developed a certain inertia within the rocket community that still remains thirty five years after the publication. Of course, there can be no doubt at all that Clark was a propellant chemist of great distinction and a strong case would have to be made to query any conclusions drawn by a man of such immense knowledge and experience. Nevertheless, it is the intention in this paper to query every single criticism made against hydrogen peroxide by Clark and examine the context in which they were levelled. In so doing, it is hoped that hydrogen peroxide's latent potential will be embraced by the research community and its associated funding agencies.

The next section of the paper addresses all of the 5 major criticisms made by Clark. Each one will be described and challenged. Section III cites some successes and explores the future prospects for hydrogen peroxide as a future oxidiser. Some conclusions are drawn in Section IV.

2. JOHN CLARK'S CRITICISMS

A close reading of Clark¹ leads to a list of five major criticisms of hydrogen peroxide (referred to hereafter as simply 'peroxide'). The following is a list of these criticisms, presented here in the order of importance as perceived by the authors of this paper:

- peroxide and fuel mixtures can detonate
- peroxide could explode if exposed to gross contamination
- peroxide is not stable and is dangerous in storage
- peroxide has ignition problems and is hypergolic only with hydrazine
- peroxide has an undesirably high freezing point

These claims will now be examined.

2.1 Detonation Risk

The prospect of dealing with any kind of detonation event has a certain psychological impact on the minds of those responsible for policy and procedures in the rocket community. This, of course, is an entirely natural stance to take. However, in the case of Clark's claim about the detonation hazard of peroxide, it seems that this psychological impact has been so great that readers of Clark have failed to notice the context in which the claim was made.

Clark describes an experiment in which jet fuel was poured onto a pool of peroxide and then ignited. As the fuel burned away (consuming atmospheric oxygen since such fuel floats on peroxide) the peroxide gradually warmed and subsequently boiled. At this point the peroxide began to decompose and oxygen from beneath the mixture fed the flames. The mixture was then seen to detonate "*.....with absolutely shattering violence*".

Clark was actually commenting on the idea that the US Navy, at one time in the post-war years, was interested in fitting some of its carrier-borne fighters with peroxide tanks. If a pilot needed to accelerate away from danger he would simply activate an auxiliary rocket motor that used peroxide as its oxidiser. If this concept was to be pursued then it was essential to study the implications for storing peroxide onboard the carrier fleet. This led to a number of tests, including the one cited above.

Now most good rocket propellants, if they are forced together and then ignited, will most likely create something of a spectacle. Clark adds weight to his criticism of peroxide by describing how a pool of hydrazine (of the unsymmetrical dimethyl variety) and

acid (presumed to be nitric acid) merely flared but did not explode. This is attributed by Clark to the materials being forced apart, presumably by gaseous evolution, rather than being intimately mixed. To the researcher these observations put the hydrazine-based propellants in the category of 'relatively safe to use' and the peroxide in the category of 'extremely hazardous to use'.

Notice that Clark does not describe what would have happened if the hydrazine and NTO propellants had accidentally mixed in a closed environment. In such conditions one can be confident that the outcome would be the same as jet fuel and peroxide, with the one important exception that this latter mixture is definitely not hypergolic and would therefore require an ignition source. Clark's argument here carries weight only in the context of storing jet fuel and peroxide on aircraft carriers where spillage is possible, or in close proximity in storage compounds where an ignition source is possible. In the context of liquid rocket propulsion, it is taken as obvious that the need to keep fuel and oxidiser apart until their mixing in the combustion chamber is paramount, regardless of the choice of propellants.

2.2 Gross Contamination

Clark addresses the issue of gross contamination of peroxide by imagining what would happen if a greasy wrench were inadvertently dropped into a storage tank that is full of the material. Clark does not offer an answer, but on the basis of many investigations involving organic contaminants in hydrogen peroxide, the most likely course of events would be for the peroxide to decompose slowly due to surface contact with the organic matter. As this slow decomposition takes place the concentration of peroxide would decrease - probably to the point where the peroxide would no longer be a source of concern. If the contaminant contained material that is miscible in peroxide then in principle a detonation could occur, but only with a very energetic initiator. In the case of acetone, the contaminant would have to occupy about one third of the tank before detonation could occur following the introduction of an ignition source².

But is it fair to single out peroxide in this way? What would happen if the greasy spanner were to be dropped in liquid oxygen? There are countless reports of similar, accidental contamination occurring with liquid oxygen, which is used widely and routinely in industry. Such events often lead to explosions and fires, and sometimes fatalities. Yet this is never offered as good reason to refrain from using liquid oxygen as a rocket propellant.

The answer to the issue of gross contamination is to have procedures in place to reduce the likelihood of it ever happening. Furthermore, these procedures should

also cover what needs to be done in the event of an incident. But whatever these procedures might be, they would need to address the possibility of a detonation only in the most extreme circumstances. It is the authors' view that such circumstances apply equally to other propellants and that therefore, in this respect, peroxide should not be singled out for special attention.

2.3 Stability and Storage of Peroxide

Clark maintains that peroxide is inherently unstable. Ignoring for the moment any factors associated with the storage conditions, the process that concerns us involves the slow but relentless decomposition of hydrogen peroxide to water and oxygen. The fear here is that at the start of a space mission, the vehicle will be filled with peroxide at high concentration - typically between 90% and 98% - only to discover that later in the mission the concentration will have dropped to a level that would have an adverse effect on the specific impulse.

But by how much would the specific impulse be affected by such a deterioration in the strength of the oxidiser? Using the method of McBride and Gordon³, assuming shifting equilibrium conditions, a chamber pressure of 50 atmospheres and a typical starting concentration of 98%, the vacuum specific impulse is calculated to be 329 seconds using kerosene. If after a period of time the concentration has dropped to 96%, then the specific impulse would drop only very slightly to 327 seconds. This drop in performance of only about 0.5% is small because one of the useful properties of hydrogen peroxide is that the evolved steam has a relatively low molecular mass compared with carbon dioxide. This lower, average molecular mass of the product gases partially compensates for the lower oxygen content in the reactants.

A comprehensive study undertaken at Aerojet Missile and Space Propulsion⁴ has demonstrated that 98% peroxide, stored in outdoor bunkers using standard containers and without cooling, will degrade to approximately 96% concentration in about two years. Such storage conditions are by no means optimal but nevertheless the above data suggest that after two years of operation, a space-craft propulsion or attitude control system, using simple, passivated, aluminium tanks, might suffer a reduction in specific impulse of just 0.5%. This figure probably represents the upper limit for well passivated tanks. It should not be forgotten that the very act of sampling the peroxide during a storage test probably introduces contaminants. Of relevance here is that peroxide drums left untouched for many years have been shown to have had negligible effect on the material. Ventura⁵ has recently reported that 90% peroxide stored for 17 years at ambient conditions in Texas showed a degradation in concentration of just

0.4%. Furthermore, communication with researchers at NAWC (China Lake) has revealed that 98% hydrogen peroxide stored in 2.5 liter nitric acid bottles actually increased in concentration, to 99.5%, over a six month storage cycle in the Mojave Desert. In other words, the rate of evaporation (even in a 'sealed' container) was greater than that of decomposition.

Clark implies that, because peroxide is easily decomposed by accidental contamination, its storage is too problematic. He describes the lengthy process of meticulously pickling and passivating tanks made from the purest aluminium before filling them with peroxide. Then there is the added complication of venting a tank to allow any evolved gases to escape. Finally, if gases are evolved then they are the product of an exothermic decomposition and so the temperature of the peroxide will increase. This warming aids the decomposition and leads eventually to a self-accelerating failure. If the venting arrangements are inadequate then the tank could fail structurally. Clark concludes: *".....many people, myself (particularly) included, tended to look dubiously at peroxide and to pass it by on the other side"*.

When reading Clark's account of experiences with peroxide, the reader must be aware of the era that is being reported. Although this is not cited specifically by Clark, by implication he is reporting investigations that pre-date the end of the second world war, when the quality controls associated with peroxide production were very poor compared with today. The production process improved markedly between the 1940s and the 1960s. As an example, the US Air Force commissioned an investigation into the storage problems of peroxide and the findings were reported by McCormick in 1965⁶. Of particular note is the account of 98% *unstabilised* peroxide stored at 20 deg C in completely sealed one gallon tanks over a period of four weeks. The observed pressure rise was less than one atmosphere - a rise that can easily be catered for by suitable venting arrangements. Another study, not mentioned by Clark, concerned the long-term storage of standard drums of 90% peroxide over a period of three years, during which the drums traveled long distances by freight². This demonstrated that agitating the peroxide did not affect the rate of decomposition, which was recorded, in 1948, as 1% per year.

The response to peroxide's tendency to decompose when in contact with certain (or most) metallic ions was to add stabilisers to the material. More often than not these were in the form of phosphates or stannates. However, Clark's response to this was to comment: *".....but their usefulness was strictly limited; and they made trouble when you wanted to decompose the stuff catalytically"*.

In fact this is not true. The addition of sodium stannate trihydrate actually *aids* the decomposition of peroxide for the particular case of silver-based catalytic beds. This was discovered by the British, who were very active in the 1950s and 1960s in developing propulsion systems using peroxide⁷. They found that there was an optimum stannate content that not only sequestered certain undesired ions in solution but also enhanced the catalytic reaction. This enhancement came about by the stannate's ability gradually to strip away the surface layer of silver, continuously revealing fresh silver catalyst as the engine burn progressed. Too much stannate (>6.5 ppm) would completely remove the silver from its nickel substrate, but the crucial fact is that too little (< 2.5 ppm) would lower the efficiency of the catalyst bed.

Of course, it is well known that phosphate-based stabilisers readily poison a silver catalyst and it is for this reason that a stannate is used. Almost certainly Clark was referring to this although he makes no mention of phosphate poisoning in his book. Instead he leaves the reader with the impression that *all* stabilisers interfere with deliberate attempts to decompose peroxide by catalytic action. Interestingly, it now transpires that even peroxide with very high concentrations of phosphates can be decomposed homogeneously as quickly as the rocket-grade material, which contains small but optimal amounts of stannates⁸.

Although Clark goes on to describe work conducted at NASA's Jet Propulsion Laboratory, using peroxide of high quality manufactured in the US, he does not address specifically the improvements in stability that came as a result. As a consequence the reader is persuaded that peroxide is unstable and dangerous, and therefore has no future. The impression gained by many in the community even today is that Clark's description of peroxide's problems is as true now as it was many decades ago. However, a wider reading of the literature paints a very different picture. For example, the authoritative work on peroxide by Schumb *et al*² states that:

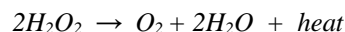
"It has been well established by the work of various investigators that pure hydrogen peroxide of any concentration, in the absence of contaminating catalysts and in a thoroughly clean container of non-catalytic material, is a very stable substance."

The authors² go on to state:

"....in earlier times dosing the hydrogen peroxide with additives was highly favoured as the primary method of preventing its decomposition. The growing realisation of the fact that hydrogen peroxide is not an inherently unstable material and the development of the

electrolytic manufacturing processes, which permitted the production of much purer hydrogen peroxide, altered this early attitude."

In the same reference, the authors remark that the classical decomposition reaction:



does not usually occur without the action of another substance except in the vapour phase at high temperatures. The quality controls associated with modern peroxide production are such that contamination levels of catalytic elements like, lead, iron, manganese, copper and nickel can be held below 40 parts per billion. At such levels it has been shown that the effect of ferric ions as a source of contamination, up to 190 ppb, can be completely quenched by the addition of 2.7 ppm tin (as stannate)⁹. This is now standard practice in the industry.

Quite apart from ill-founded concerns about peroxide's long-term stability, there is a belief within the community that the slightest amount of contamination, perhaps in the form of a single particulate, will bring about the slow but incessant degradation in concentration. This is quite untrue⁶. Simple experimentation demonstrates that a single drop of a ferrous compound, such as ferrous chloride, placed on the surface of a large vessel of stabilised peroxide at high concentration, results in a slight fizz followed by spontaneous quenching. Thereafter no apparent degradation takes place. This quenching takes place in virtue of the adsorptive properties of the stabiliser. As an additional precaution, the fluid could be filtered prior to filling the tank, just like all conventional rocket propellants.

The lesson to be learned is that modern peroxide at 90% or 98% concentration contains such low levels of contaminants that the oxygen loss over a period of years is minimal. The extra effort associated with tank preparation is regarded as quite insignificant compared with the advantages that peroxide offers in terms of bulk density and negligible toxicity. By paying close attention to the storage conditions, including novel materials and temperature, it is conjectured that it will be possible to reduce any performance degradation of a peroxide propulsor to the margins of measurability.

2.4 Hypergolicity

On the subject of peroxide's lack of hypergolicity, Clark asserts that:

"From late 1944 through 1948 they (JPL) worked it out, using 87% to 100% peroxide, and a variety of fuels,

including methanol, kerosene, hydrazine and ethylene diamine. Only the hydrazine was hypergolic with the peroxide; all the other combinations had to be started with a pyrotechnic igniter."

He continues:

"Ignition of a hydrogen peroxide system, particularly one burning gasoline or jet fuel, was always a problem."

Furthermore, on the subject of future research effort in rocket propulsion, his overall conclusion in the last paragraph in his book, is:

"There appears to be little left to do in propellant chemistry, and very few important developments to be anticipated. In short, we propellant chemists have worked ourselves out of a job."

To set this in context, one very good reason why Clark was able to make this assertion concerns the very high reliability and performance of both liquid oxygen, used with either liquid hydrogen or kerosene, and the propellant combination that has precipitated this paper, namely hydrazine and dinitrogen tetroxide. Clark was probably correct in his prediction that these propellants would be in use for many decades; but what about his claim of the uniqueness of peroxide's hypergolicity with hydrazine? Although he does refer to the technique of heterogeneously catalysing the peroxide and then igniting the fuel by spraying it into the hot, evolved oxygen (a technique which he appears to attribute to the (US) Naval Air Rocket Test Station, when in fact it can be traced back to Walter in Germany), this is not an example of liquid-liquid hypergolicity but rather auto-ignition.

Not surprisingly, many fuels have since been found to be hypergolic with peroxide. Of those fuels that do not require an additional catalysing agent, pyrrole and ethanolamine have been found to ignite on contact with peroxide¹⁰. A far greater and more useful choice prevails if one includes fuels to which has been added a catalysing agent. The list includes ethanol or methanol^{10,11} doped with manganese acetate tetrahydrate, ruthenium chloride or sodium iodide, diaminopropane with cupric nitrate¹⁰ and various vinyl ethers¹² and a manganese-promoted diaziridine fuel, named Diran-A¹³. Families of doped fuels have been identified by Purcell *et al*¹², who identified fifty fuels that ignited on contact, and Dobbins¹⁴, who identified the acetylinic 'ECP-dimer', used in conjunction with a carboxylate-amine catalyst, as a potent hypergol.

The view that such doped fuels are not truly hypergolic, but rather *quasi*-hypergolic, is here regarded as

somewhat pedantic. What matters is that when the liquids make contact in a combustion chamber they ignite without the need for an ignition device. In any case, genuinely reactive hypergolic fuels have now been discovered that do not rely on any macroscopic catalytic effect on peroxide¹⁵. The evidence weighs heavily against Clark.

2.5 Peroxide's Freezing Point

The freezing point of hydrogen peroxide propellants ranges from -0.43 deg C for anhydrous peroxide to -10.5 deg C for 90% concentration¹⁶. Clark states that the high freezing point of anhydrous peroxide is a problem for rocket applications and that adding water to lower the freezing point is ".....not a process that appeals to men interested in propulsion!" This claim, written in 1971, certainly seems reasonable for military applications. Mono-methylhydrazine (MMH) and NTO have freezing points of -52 deg C and -11 deg C respectively and so they can be stored for reasonably long periods in cold climates. MON-25, which is a mixture of MMH and 25% nitric oxide, has a much lower freezing point of -55 deg C¹⁷. Attempts to lower the freezing point of peroxide using additives have invariably failed because this can usually only be accomplished at the expense of losing the peroxide's initial stability or rendering the peroxide sensitive to mechanical shock (note, however, the existence of recent patents claiming to alleviate the freezing problem¹⁸). There can be little doubt therefore that peroxide's higher freezing temperature is in principle a cause for concern for certain operational scenarios. But are they pertinent to modern space missions?

For missions involving extended durations with reduced radiative heat from the Sun, it is likely that peroxide would eventually freeze. Note, however, that such a process would most likely be very slow because of peroxide's well-known super-cooling properties. Experience with storing 90% concentration peroxide in cold climates confirms that peroxide does not freeze even in unprotected storage tanks at temperatures below its freezing point². Babinsky *et al*¹⁹ showed that 90% peroxide did not freeze until typically 40 degrees C below its freezing point and that the phase change from liquid to solid was not affected by agitation, dissolved oxygen or rate of cooling. Investigations by Dorsey²⁰ into the similar super-cooling properties of ultra-pure water showed that it was possible to maintain water in the liquid state at temperatures between 15 and 40 degrees below freezing even with prolonged chilling. The factor that governs this super-cooling appears to be the absence of foreign nucleates that are usually responsible for initiating crystallisation. It would seem therefore that occasional drops in temperature onboard a spacecraft would be unlikely to cause a phase change in

peroxide that has been manufactured according to today's stringent quality controls.

Notwithstanding the above observations, any spacecraft could not rely in any deterministic sense on the peroxide remaining liquid when its temperature is very low. Obviously an engine would fail if the peroxide were frozen. Suppose, however, that some of the electrical power collected by the solar panels were diverted to provide a gentle heat flux between the external surface of the peroxide tank and its layer of thermal insulation. This heating could be engineered and controlled using solid-state Peltier elements stacked in such a way as to provide multiple redundancy. Reversing the polarity of these elements would of course cool the peroxide should this be necessary.

Another possibility would be simply to allow the peroxide to freeze. Unlike water, peroxide at high concentrations shrinks in volume by 13% on freezing^{2,6}. For certain missions, involving a prolonged, inactive coast phase, or possibly for missions to the outer planets, allowing the peroxide to freeze would not impose unwanted problems associated with feed-lines or tanks bursting. When the active phase of a mission approaches, a small amount of energy could be used to return the peroxide to its liquid state. By clever design, this energy could even be sourced by the peroxide itself.

Finally, mention should be made of the effect of low temperatures on any tendency for the peroxide to decompose gradually. The Aerojet data cited in Section IIC related to unprotected storage drums at typical average temperatures in California (perhaps 22 deg C). It is well documented that the decomposition rate increases by a factor of about 2.2 for every 10 deg C rise in temperature. Extrapolation suggests that almost anhydrous peroxide at or near freezing temperatures might decompose at such a slow rate that a reduction in specific impulse of merely one part in a thousand would take place over a two-year period. Furthermore, in the solid phase, hydrogen peroxide is not shock-sensitive and is reported to be almost inert². Evidence for the latter claim is associated with the observation that even 0.1 mol/L permanganate solution (normally the most potent of peroxide catalysts) and particles of rust failed to decompose solid peroxide at -55 deg C.

3. MYTHS AND LEGENDS

Much to its embarrassment, the United Kingdom is the only nation to have successfully developed a satellite launcher, to have used it and then to have completely abandoned the capability. That they abandoned the programme was not in any way connected with the fact that the launcher relied on hydrogen peroxide. The programme was scrapped because of the politico-

economic view that the UK would find it cheaper to purchase US Scout launchers for future satellite missions²¹ rather than have its own independent capability.

There are several aspects to the UK's Black Arrow Project that need to be grasped in the context of the present paper. Firstly, the Black Arrow was a three-stage satellite launcher designed and built entirely in the UK and flown successfully from Woomera in Australia in 1971 (Figure 1). The vehicle had three stages, the first two of which used kerosene and 85% peroxide in the mass ratio 8.2:1 for the main propulsion. Of note is the fact that the peroxide had to be transported from the Laporte chemical works in England to Woomera in Australia and this occurred without any mishap or injury. In fact, in a period stretching over a quarter of a century in the UK, up to and including the launches of the Black Arrow rocket, there was not a single instance of any storage tank filled with peroxide ever becoming even warm²². Furthermore, based on wide experience of 85% peroxide applied to eight different rocket engines throughout that era, it was the opinion of the then Chief Designer (Rockets) at Ansty (later to become part of Rolls Royce) that peroxide would suffer only a 1% drop in concentration over a four year period. This slow rate of natural decomposition is almost identical to the rates reported more recently by McPherson⁴.



Figure 1. UK's Black Arrow Satellite Launcher, 1971.
(Courtesy of the Science Museum, London)

Of particular relevance is the fact that the UK chose peroxide for the Black Arrow satellite launcher notwithstanding its loss of the Royal Navy's HMS Sidon in 1955. HMS Sidon sank in Portland Harbour following a malfunction in one of its peroxide-powered torpedoes. A peroxide line ruptured due to a system over-pressure and this allowed the peroxide to make contact with incompatible materials like copper and mild steel (a similar failure is thought to be the cause of the more recent, tragic loss of the Russian submarine, Kursk).

A peroxide leak in a submarine or torpedo is bound to allow peroxide to mix with incompatible materials and for this reason peroxide is viewed with caution at sea. But this argument should not apply to spacecraft. If any type of propellant suffers a significant leak within a spacecraft then its mission is surely jeopardised since from this point on the craft would be unable to manoeuvre. The issue should not be the choice of propellant but rather the means of containing it.

The continued use of peroxide for the Black Arrow project, in the wake of the Sidon disaster, is testimony to the confidence within the UK aerospace industry at the time in using hydrogen peroxide as a rocket propellant. Of note too is the observation that the US used peroxide for the manned X-1 and X-15 missions without mishap throughout the 1950s and early 1960s, culminating in its successful use for attitude control for the manned Mercury spacecraft. The US continued to use peroxide in the LLRV (Lunar Lander Research Vehicle), which was used to train the Apollo commanders prior to the Moon landings. Of relevance here is that Neil Armstrong's LLRV crash shortly before the Apollo 11 flight was not caused by a seized peroxide thruster as is often reported. It was in fact caused by depletion of the helium used to deliver the propellant²³.

4. CONCLUSIONS

If hydrogen peroxide is ever to be used in earnest for future programmes, then three issues need to be addressed:

- the myths about peroxide spread by Clark and others need to be replaced by sound, scientific facts
- the wealth of information concerning recent peroxide research needs to be embraced by policy makers
- the potential for very high specific impulses needs to be investigated more thoroughly.

The 'holy grail' for peroxide research is to find a suitable fuel that, when combined with peroxide, will exceed the

performance of the baseline hydrazine and dinitrogen tetroxide. The ideal, absolute vacuum specific impulse of anhydrous hydrogen peroxide and methanol-based Block 0 at typical conditions is nominally 341 seconds²⁴. This compares with 364 seconds for MMH/NTO. However, if more exotic fuels were to be considered for use with anhydrous peroxide then the potential for improvement would be very significant²⁴. Both quadricyclane²⁵ (C₇H₈) and quadrasilane (SiC₁₂H₁₂) would match the hydrazine performance, while the hybrid fuel, lithium aluminium hexahydride (Li₃AlH₆), would provide a specific impulse of 469 seconds under the same conditions. Of course such potential performance presents some serious technological challenges, but these need not be insurmountable.

It is the opinion of the authors that the time is now ripe for hydrogen peroxide to be shown in a new light - free from the shadows that have beset it since Clark's concerns were first published. These concerns have been shown to be unfair. Furthermore, they were expressed in an era of ignorance concerning hydrazine's latent toxicity.

5. ACKNOWLEDGEMENTS

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