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Refinement of Propellant Strand Burning Method to Suit Aluminised Composite Rocket Propellant

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ABSTRACT

An epoxy coating was trialled as an inhibitor for composite rocket propellant strands burned in a Crawford–style bomb. The epoxy coating performed at least as well as the traditional paint coating and produced a virtually identical burn rate law. Burn rate results for epoxy coated strands were insensitive to strand preparation technique such as bevelling of the strand and de-dusting, thus demonstrating a robust inhibitor system. Acceptable robustness of the epoxy coating was demonstrated when applied to aluminised composite rocket propellant with no spurious results recorded. Accuracy and precision of results for all four batches of aluminised composite propellant were acceptable and at least as precise as historical results obtained with non-aluminised propellant inhibited with paint. A couple of methods for reducing effort while maintaining sufficient accuracy of burn rate data were demonstrated. A single coating of epoxy as opposed to two provided sufficient inhibition and could almost halve combined preparation and coating time. Burning as little as 6 strands, one at each pressure across the range of interest, can provide a sufficiently accurate burn rate law during the early stages of propellant development.

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Refinement of Propellant Strand Preparation and Burning to Suit Aluminised Composite Rocket Propellant

Executive Summary

Linear propellant burn rate determination from strands has been practised at DSTO for many decades. The current practice is to machine square cross-section strands from a block of propellant that are then inhibited along the longitudinal faces with a low flammability coating. Strands are burned vertically in a Crawford-style vessel pressurised with nitrogen over a range of pressures up to a maximum of 20 MPa to determine the pressure dependence of propellant burn rate.

The traditional house paint-based strand inhibitor does not have the robustness required for the aggressive burn of an aluminised composite rocket propellant. Furthermore, the paint-based coating is prone to cracking which can open a path for the flame to travel down the side of the strand producing spurious results. A two-part epoxy-based inhibitor by the name of R180/H180 was successfully trialled as a replacement for the current paint-based coating.

Initially the epoxy coating was trialled alongside the paint coating with a non-aluminised propellant to compare accuracy and precision of results. The epoxy coating performed at least as well as the paint coating in terms of precision and produced a virtually identical burn rate law. Burn rate results for epoxy coated strands were insensitive to strand preparation technique such as bevelling of the strand and de-dusting, thus demonstrating a robust inhibitor system.

Acceptable robustness of the epoxy coating was demonstrated when applied to aluminised composite rocket propellant with no spurious results recorded. The accuracy and precision of results for all four batches of aluminised composite propellant was acceptable and at least as precise as historical results obtained with non-aluminised propellant inhibited with paint. Of the 110 strands burned with an R180/H180 epoxy inhibitor coating, there were no wildly spurious results as experienced with painted strands and the largest standard deviation for a triplet was 0.24 $mm \cdot s^{-1}$.

A couple of methods for reducing effort while maintaining sufficient accuracy of burn rate data were demonstrated. A single coating of epoxy as opposed to two provided sufficient inhibition and could almost halve preparation and coating time. Burning as little as 6 strands, one at each pressure across the range of interest, can provide a sufficiently accurate burn rate law during the early stages of propellant development.

Contents

Abbreviations

AP	Ammonium perchlorate
AS	Ammonium sulfate
ATK	Alliant Techsystems Inc
atm	Atmosphere
C/F	Coarse/fine ratio
CV	Coefficient of variation
DOA	Di-octyl adipate
EI	Explosives Instruction
IPDI	Isophorone diisocyanate
NATO	North Atlantic Treaty Organization
NCO/OH	Isocyanate/hydroxyl ratio
P	Pressure
STANAG	NATO abbreviation for Standardization Agreement
T	Temperature
TPB	Triphenyl bismuth

Nomenclature

Symbol	Description	Units
a	Burn rate coefficient	$mm \cdot s^{-1} \cdot P^{-1}$
I_{SP}	Specific impulse	s
I_{VAC}	Vacuum specific impulse	s
n	Pressure exponent	-
P	Pressure	MPa
r	Burn rate	$mm \cdot s^{-1}$
R^2	Coefficient of determination	-
ρ	Density	$g \cdot cm^{-3}$
π_k	Temperature sensitivity of pressure	$\% \cdot {}^{o}K^{-1}$

1. Introduction

Linear propellant burn rate determination from strands has been practised at the DSTO for many decades. The current practice is to machine square cross-section strands from a block of propellant that are then inhibited along the longitudinal faces with a low flammability coating to ensure a cigarette-type linear burn. Strands are drilled to accept an igniter and two timing (fuse) wires at set locations before being secured to a firing head and placed vertically in a Crawford-style vessel pressurised to a maximum of 20 MPa (low pressure strand burner). Burn rate at various pressures is determined under an atmosphere of nitrogen at temperatures ranging from -60 to +60°C. The burn rate dependence on pressure is generally described with the power law relationship of Equation 1 and is calculated from discrete burn rates at each pressure. Strands are ignited with a nickel-chromium (nichrome) wire with burn time measured via timing wires which fuse thus breaking electrical conductivity to start and stop the timer.

$$r = aP^n \tag{1}$$

Accuracy and repeatability of the method is highly dependant on a disciplined approach to the handling and preparation of strands, as demonstrated by many authors [1-3]. Strand preparation, choice of inhibitor coating and inhibitor application technique have proven to be critical factors in the accuracy and precision of burn rate results obtained from strands. In a DSTO (then WSRL) report published in 1985 by Kempson, et al. [1], a polyvinyl chloride/acetate copolymer solution in dichloromethane inhibitor was replaced with a water-based paint. Reasons for the change included variation in burn rate with number of coats applied and the elapsed time between coating and burning, contamination of the inhibitor with propellant leachate and the health effects of dichloromethane exposure. Kempson, et al. identified Wattyl GP24 Colourmaster as a suitable acrylic (latex) based paint diluted with water (60 %v/v paint). They achieved satisfactory accuracy and precision with both cast double base and composite propellant, though the composite propellant was non-aluminised. They also found that burn rate results were not affected by thickness of the coating or elapsed time between coating and burning. Burn rates obtained with the paint inhibited strands were also closer to those obtained from motor firings.

In recent years, very few propellants have been assessed for burn rate in this facility and as a consequence the technical expertise has been largely lost from the group. In addition to the recent lack of practice is the fact that the original paint used to inhibit strands has been discontinued by the manufacturer. This has meant that the closest alternative product was sourced and required the refinement of the inhibition method in 2003 by Hart and Pietrobon [3]. Some of the critical factors for the paint were identified as pigment content, type of antifoaming agent and product viscosity. Their work greatly improved reproducibility of the strand burning method but little work has been performed since.

A further consideration is that historically, most of the propellant formulations tested in the low pressure strand burning facility have been either cast double base or non-aluminised composite propellant. Aluminised composite propellant burns much more vigorously and with a higher flame temperature. This can create a more aggressive

environment within the firing chamber and produces a large mass of hot aluminium oxide. Those hot particles carry significant thermal energy and are free to migrate throughout the chamber with the potential to cause measurement anomalies.

This report describes an initial attempt to gather reproducible burn rate results for an aluminised HTPB/AP composite propellant in the low pressure Crawford-style strand burner with the existing paint inhibitor. It then details the effort to improve reproducibility and accuracy of the method. Finally, the report details the development of improved methods for preparation and inhibition of strands leading to accurate and reproducible burn rate data for aluminised composite rocket propellant.

2. Experimental

2.1 Propellant Formulation

The aluminised composite propellant assessed in this report was based on a binder composed of hydroxy-terminated polybutadiene (HTPB) cross-linked with isophorone diisocyanate (IPDI). The formulation is a highly aluminised one containing 18 wt% aluminium (Al) and ammonium perchlorate as oxidant. To achieve the desired burn rate, 0.2 to 0.5 wt% iron oxide was specified as a burn rate catalyst while dioctyl adipate (DOA) was chosen as plasticiser. Other minor ingredients included 2,2-methylenebis(4-methyl-6-tertbutylphenol) (AO 2246) as antioxidant and triphenyl bismuth (TPB) as cure-rate catalyst to achieve a satisfactory pot-life.

Various propellant batches with slightly different formulations were manufactured in either a 1 pint or 2 gallon planetary mixer (refer to Appendix A for the specific formulations). Propellant was poured into Teflon coated moulds, degassed under vacuum and vibration, and cured in an oven at 60^{o}C for 7 days.

A non-aluminised, non-plasticised HTPB/AP composite propellant (batch P0085) manufactured in 2002 was used as a control during the diagnostic exercise to determine whether the erratic burn rate results were due to a system problem or whether the problem was related to the aluminised formulation. P0085 contained all of the ingredients in the aluminised propellant except for DOA (plasticiser), Al, the bonding agent (HX-752) and cure rate catalyst (TPB). The strands had been inhibited with a paint-based inhibitor and stored in a magazine without temperature or humidity control for several years. Later inhibitor comparisons were performed with a batch (P0192) of non-aluminised composite propellant detailed in Appendix A. That formulation is similar to P0085 but with 3 wt% plasticiser (DOA) and a small quantity of TPB.

2.2 Preparation and Burning of Strands

Following removal from the mould, propellant was machined by bandsaw into 5 X 5 X 170 mm long strands. Strands were then chamfered to remove sharp edges thereby improving inhibitor coverage, loose propellant was removed with a soft brush (dedusting) and the strands were inhibited with paint diluted by water. The paint was a Super Flat acrylic, deep tint base (Line 500) supplied by Solver Paints. Strands were dipped in the paint with

the excess allowed to run from strands during the drying period. Four coats of paint were applied with an appropriate drying period between each coat. Following a final curing period of at least 48 hours the strands were drilled to accommodate firing and timing wires.

A nichrome ignition wire was threaded through the top hole while solder-based fuse wire was threaded through the start and stop holes 127 mm apart (Figure 1). Strands were placed on one of four firing heads and were held in position by a thumb screw against a backstop. Firing and timing wires were loosely wrapped around the respective terminals and clamped in place. Excess wire was removed with wire cutters.

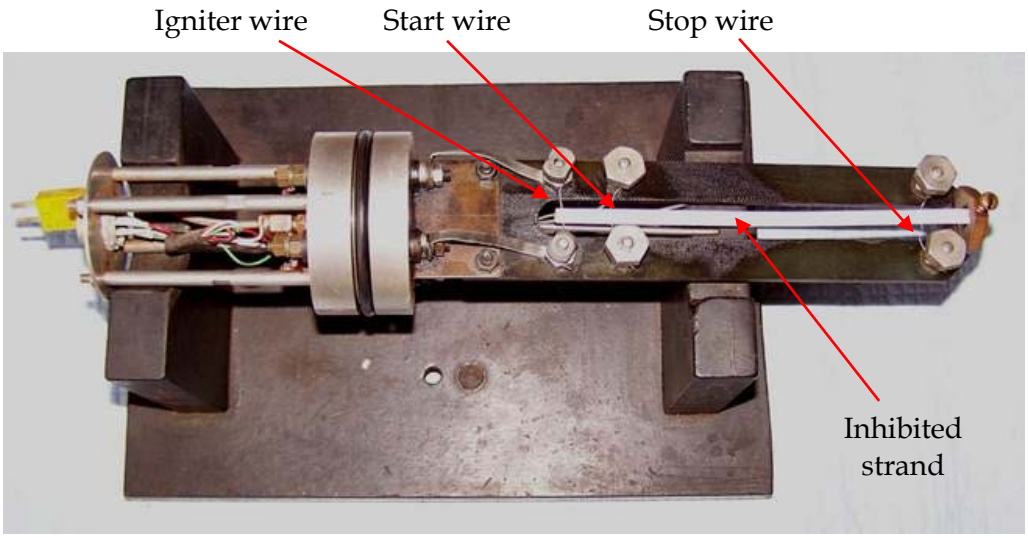

Figure 1: Crawford-style strand burning head with a strand ready for firing. Note the ignition wire (left) and start and stop timing wires. Thumb screw to stabilise the strand is on the far right.

The loaded firing head was placed into the Crawford bomb and pressurised with nitrogen to the specified pressure. Once pressure and temperature were stable at the required set-point, the strand was ignited. A timing system based on electrical continuity was used to determine burn time. Linear burn rate was calculated from the burn time and distance between fuse wires.

Poor initial results led to the use of a second inhibition method used in the past for particularly aggressive propellant. This method involved the coating of strands of propellant with a two-part epoxy polymer. Strands were dipped into a bath of epoxy polymer in a similar fashion to the paint system but only one coating is normally applied. The limited number of available strands meant that some were coated with epoxy directly over the top of the paint layer. Others had an epoxy coating applied to the bare propellant surface.

Stocks of the two-part epoxy material previously used was estimated to be greater than 10 years old, and therefore may have degraded, and was also likely to have been discontinued by the manufacturer. A new source of epoxy was therefore sought. An epoxy product called Polysciences Epon 828 combined with HXSMP 572 curing agent, supplied by Jomar Bioscience, was utilised first. However, the viscosity and pot life of this

combination proved to be unsuitable and a different epoxy combination was sought. A product called R180 (epoxy pre-polymer) and H180 (epoxy hardener) were purchased from Adelaide Moulding & Casting Supplies. This material had a much lower viscosity of 50 - 100 cP and a pot life of 15 - 65 mins at 20°C when mixed at a volume ratio of 5 to 1.

3. Results and Discussion

3.1 Initial Strand Burn Results

The aluminised composite rocket propellant formulation under assessment had an estimated burn rate of between 10 and 15 mm·s^{-1} at 6.89 MPa and a pressure exponent of between 0.4 and 0.5. Propellant batch P0176 had a burn rate catalyst level of 0.2 wt% which is on the low end in terms of additive level and should have produced a burn rate of 11-12 mm·s^{-1} at 6.89 MPa. Based on a burn rate of 12 mm·s^{-1} at 6.89 MPa and a pressure exponent of 0.45, the nominal burn rate at 2, 4 and 6 MPa should be 6.87, 9.39 and 11.27 mm·s^{-1}, respectively.

Table 1: *Low pressure strand burn results for P0176 coated with paint and burnt on 10/7/11*

Pressure (MPa)	Burn Time (s)	Burn Rate (mm·s^{-1})	Firing head	Comments
2	11.86	10.71	2	
2	16.71	7.60	6	
4	3.55	35.77	3	
4	6.27	20.26	2	
4	5.96	21.31	3	
6	-	-	6	Timer did not function
6	0.48	264.58	2	
6	7.16	17.74	6	Wrapped in fibre tape
6	3.83	33.16	3	Wrapped in fibre tape

Possibly with the exception of the second burn rate test at 2 MPa, burn rate results for painted P0176 were clearly far from accurate, nor were they precise (Table 1). All burn rates were too high, most by a factor of two or more and results were extremely variable. Initial concerns centred on the possibility of a flame front flashing down the outside of the strand due to poor or inconsistent coating. Fibre tape was therefore applied to two strands in an attempt to reduce the possibility of a flame front down the outer length of the strand. This method has been employed in the past with some success but clearly it did not greatly improve the results here. Suspicions were raised over the reliability of the timing system due to one occasion where the timer failed to function (timer did not start) and one where the burn time was less than one second.

A review of past test results for aluminised propellant indicated that a more robust inhibitor was necessary to achieve satisfactory results. The chosen inhibitor was a two-part epoxy coating applied in a similar fashion to the paint but requiring only one coat. However, the available inventory of epoxy was more than 10 years old and the material is now obsolete. Identification of a suitable epoxy coating was investigated by reviewing the available open source literature for linear burn rate determination of energetic materials

(propellant or explosives). A candidate coating was identified from the literature that was locally available.

3.2 Epon 828 Coated Strands

3.2.1 Epoxy Coating Process

Several authors used two-part epoxy products (epoxy resin cross-linked with an amine-based curing agent) to inhibit the outer surface of energetic materials (energetics) but rarely were the specific products identified. Maienschein et al. [4] inhibited strands of HMX-based explosives with Epon 828 cured with Versamid 140. A local suppler of both products was identified (Table 2) and the vital specifications are summarised in Table 3.

Table 2: *Epoxy coating suppliers*

Product	Supplier
Epon 828	Jomar Bioscience 15 Maesbury Street, Kensington South Australia 5068
Versamid 140	Cognis Australia 4 Saligna Drive Tullamarine, VIC, 3043
HXSMP 572	Jomar Bioscience 15 Maesbury Street, Kensington South Australia 5068

Table 3: *Epoxy coating product specifications*

Product	Viscosity (Pa.s)	Mixing Ratio (Parts per 100)	Pot-life (h @ 25°C)	Optimum Cure (h)
Epon 828	110-150	-	-	-
Versamid 140	0.3-0.6	50	2	6 @ room T
HXSMP 572	1.5	20	0.25	8 @ room T

Versamid 140 was not easily obtainable, this necessitated the procurement of an alternative product (HXSMP 572) which was recommended by the manufacturer of Epon 828. HXSMP 572 has a lower mixing ratio but a much higher viscosity than Versamid 140. In addition, it has a much shorter pot-life. Despite those less than ideal features, HXSMP 572 was used as the cross-linking agent at a mixing ratio of 22 parts in 100 (of Epon 828). The mixture of resin and curative was poured into a dipping bath as for the paint system and 6 strands were lowered into the bath at a time then suspended to drain off excess coating. Unfortunately, the viscosity of the epoxy was such that the excess needed to be manually removed by scraping the strands on the edges of the bath as they were removed. This effectively resulted in a very uneven coating with a thin layer on some faces and a very thick layer on others. In addition, the thickness of the coating was much greater at the bottom of the strand than at the top.

The intent was to coat 24 strands of each of the four representative batches of propellant. However, the relatively short pot-life combined with difficulties associated with the coating process meant that the resin cured before all strands could be coated (Table 4). Two batches (P0175 and P0176) were already coated with paint while the other two had not received a coating prior to the epoxy layer.

Table 4: *Strands coated with Epon 828 and HXSMP 572*

Batch number	Under Coat	Number Coated
P0175	Paint	24
P0176	Paint	24
P0177	None	12
P0178	None	3

3.2.2 Strand Burn Results

Following the poor initial results with painted strands, the focus was on producing consistent and accurate results, therefore the same batch number of propellant was burned at low pressures of 6 and 8 MPa (Table 5). Two very fast burn rates and two rates close to the expected value were recorded at 6 MPa. This was followed by a very fast burn (1.47 s) at 8 MPa. It should be noted that even though the timing system displayed a burn time of less than 2 s, both pressure and temperature were still rising, indicating that the propellant had not been completely consumed at that stage.

Table 5: *Low pressure strand burn results for P0 176 coated with paint and epoxy burnt on 8/11/11*

Pressure (MPa)	Burn Time (s)	Burn Rate ($mm \cdot s^{-1}$)	Firing head	Comments
6	0.28	453.6	6	Stop wire broke
6	9.59	13.24	2	
6	1.72	73.84	3	
6	10.09	12.59	6	
8	1.47	86.39	3	
8	0.18	705.6	2	Ensured that grips on lower fuse wire were tight
8	3.68	34.51	6	Strand taped at mid-point to stabilise it
8	4.84	26.24	2	Strand taped at mid-point to stabilise it
8	1.05	120.95	3	Strand taped closer to the stop wire improve stability
0.1 (open air)	83.59	1.52	6	Poor surface coating of epoxy
8	10.26	12.38	2	Tape applied to stop wire to provide a shroud

At this point it was suspected that the very fast burn times were due to loose nuts on the stop wire causing an electrical circuit breakage and therefore prematurely triggering the timer. Greater rigor was exercised when tightening timing wires from that test onwards by ensuring that fuse wires were not in longitudinal tension and nuts were tightened with a

spanner. The next test produced a 0.18 s burn time (Table 5). Greater slack was provided in the bottom stop wire and strands were taped to the backing card to limit movement during combustion in an attempt to ensure that the stop wire was not being broken prematurely by mechanical force (thrust). The following tests at 8 MPa failed to produce more consistent results or burn times closer to theoretical.

A timing system problem that may explain the extremely fast burn times of fractions of a second could not be ruled out, nor could a phenomenon related to the severe environment that exists in the vessel during propellant burning at high pressures. An example of such a phenomenon is the premature fusing of the timing wires by hot alumina particles or a segment of burning strand contacting the stop wire. Therefore, it was decided to burn a strand in open air and to record vision of the burn to try to rule out a timing system issue and possibly identify any anomalies during the burn that may cause the stop wire to prematurely fuse. The burn time was 83.59 s and no anomalies were identified to explain the shorter burn times at high pressure. A final specimen for 8/11/11 was burned at 8 MPa and included a shroud of Teflon tape over the stop wire to shield it from falling hot propellant fragments or hot aluminium oxide. The recorded burn rate was close to theoretical at 12.38 $mm{\cdot}s^{-1}$.

The encouraging last result on 8/11/11 prompted the duplication of those conditions for two further strands at 8 MPa on 9/11/11 (Table 6). Unfortunately, the burn rate was much higher than the strand burned on the previous day but the two results were at least concordant. A strand was therefore burned at 10 MPa under the same conditions but resulted in a very short burn time again, indicating that the earlier problems had not been resolved.

Table 6: *Low pressure strand burn results for P01176 coated with paint and epoxy burnt on 9/11/11*

Pressure (MPa)	Burn Time (s)	Burn Rate ($mm{\cdot}s^{-1}$)	Firing head	Coating	Comments
8	6.02	21.10	5	Paint + epoxy	Stop wires shrouded with tape
8	5.88	21.60	6	Paint only	Stop wires shrouded with tape
10	1.8	70.56	5	Paint + epoxy	Stop wires shrouded with tape

To further distinguish the two issues (the timing system malfunction or the aggressive combustion character of aluminised propellant was causing timing system problems), a non-aluminised propellant was burned as a comparison (refer Appendix A for the formulation). Batch number P0085 was produced on 1/8/2002 and was already inhibited with paint. The first result at 4 MPa was a burn rate close to that determined in 2002 (10.17 $mm{\cdot}s^{-1}$ and 11.09 $mm{\cdot}s^{-1}$, respectively). The second result was an obviously anomalous burn rate of 43.05 $mm{\cdot}s^{-1}$ (Table 7). In an attempt to reduce the possibility that the timing stop wire was fusing prematurely, the fuse wires were changed to tin coated copper wires that had been used successfully in the past. The next three results were similar to the first and within the expected variation for this method.

Table 7: *Low pressure strand burn results for P0085 coated with paint burnt on 9/11/11. # - switched to tin coated copper fuse wires from this time on*

Pressure (MPa)	Burn Time (s)	Burn Rate ($mm \cdot s^{-1}$)	Firing head	Coating	Comments
4	12.49	10.17	3	Paint only	
4	2.95	43.05	2	Paint only	
4	12.45	10.20	5	Paint only	# Tin coated copper fuse wires
4	11.12	11.42	6	Paint only	
4	11.78	10.78	2	Paint only	
4	12.29	10.33	6	Paint only	
4	12.23	10.38	2	Paint only	

From the above, tin coated copper timing wires were seen as a potential solution to the premature fusion of stop wires in the case of aluminised propellants and were therefore used for all further strand burn tests. However, three subsequent tests of aluminised propellant at 6 MPa (Table 8) demonstrated that tin plated copper wires did not solve the problems and put the suspicion back onto the timing system. A further 2 strands of P0085 were burned to again rule out timing system issues and produced very similar results to the earlier ones at 10.33 and 10.38 $mm \cdot s^{-1}$ (last two results in Table 7).

To test the hypothesis that the high pressure and therefore, aggressive conditions within the strand vessel were the cause of anomalous results, P0176 strands were burned in the vessel but at ambient pressure (last four results in Table 8). The result was long burn times and very low burn rates as expected however, the results were inconsistent.

Table 8: *Low pressure strand burn results for P0176 coated with paint and epoxy burnt on 9/11/11. # - switched to tin coated copper fuse wires from this time on*

Pressure (MPa)	Burn Time (s)	Burn Rate ($mm \cdot s^{-1}$)	Firing head	Coating	Comments
6	-	-	3	Paint + epoxy	# No ignition, flickering stop/start lights on the control panel
6	-	-	3	Paint + epoxy	No ignition, flickering stop/start lights on the control panel
6	2.75	46.18	5	Paint + epoxy	
Ambient	43.31	2.93	5	Paint only	
Ambient	71.06	1.79	6	Paint only	Stop light off after pressure began to fall
Ambient	45.47	2.79	2	Paint only	
Ambient	31.24	4.07	5	Paint only	

Work on the following day (10/11/11) centred on protecting the stop wire from extraneous material and/or heat that may cause it to fuse prematurely (Table 9). To that

end, the timing stop wire was covered with glass cloth tape and attention was directed at ensuring that the stop wire was secured correctly, that is, not too tight and not too loose. It may be argued that the results were slightly better and more consistent but they were still far from ideal. The following 3 strands also had glass cloth tape applied to the whole length of the strand, in addition to the paint and epoxy inhibitor layer. However, the results show that the use of tape did not improve reproducibility (last 3 results of Table 9).

Table 9: *Low pressure strand burn results for P0176 coated with paint and epoxy burnt on 10/11/11.*

Pressure (MPa)	Burn Time (s)	Burn Rate ($mm \cdot s^{-1}$)	Firing head	Coating	Comments
6	0.41	309.8	6	Paint + epoxy	Stop wire covered with tape. Stop wire retaining nut loose.
6	3.62	35.08	2	Paint + epoxy	Stop wire covered with tape.
6	8.63	14.72	5	Paint + epoxy	Stop wire covered with tape plus tape applied to whole length of strand.
6	7.15	17.76	6	Paint + epoxy	Stop wire covered with tape plus tape applied to whole length of strand.
6	3.91	32.48		Paint + epoxy	Stop wire covered with tape plus tape applied to whole length of strand. Stop wire retaining nut loose.
6	9.09	13.97		Paint + epoxy	Stop wire covered with tape plus tape applied to whole length of strand. Nuts tightened well.

A change to propellant batch number P0175 was required once stocks of inhibited P0176 were exhausted. P0175 had a higher iron oxide content and therefore was expected to have a higher burn rate. Strands were also first coated with paint and then a layer of epoxy over the top. The first four strands (Table 10) had cloth tape applied to the top and bottom timing wires and the entire length of the strand. Results were a mixture of very short burn times and generally erratic results.

Table 10: *Low pressure strand burn results for P0175 coated with paint and epoxy burnt on 10/11/11*

Pressure (MPa)	Burn Time (s)	Burn Rate ($mm{\cdot}s^{-1}$)	Firing head	Coating	Comments
6	-	-	2	Paint + epoxy	Stop wire covered with tape plus tape applied to whole length of strand. No time recorded
6	8.21	15.47	5	Paint + epoxy	Stop wire covered with tape plus tape applied to whole length of strand.
6	-	-	2	Paint + epoxy	Stop wire covered with tape plus tape applied to whole length of strand. No time recorded
6	32.89	3.86	6	Paint + epoxy	Stop wire covered with tape plus tape applied to whole length of strand.
6	10.74	11.82	6	Paint + epoxy	Stop wire covered with tape only
6	10.69	11.88	5	Paint + epoxy	Stop wire covered with tape only
6	11.33	11.21	6	Paint + epoxy	Stop wire covered with tape only

The final three strands did not have tape applied to the length of the strand (Table 10). Burn rates for those three strands were consistent and in approximate agreement with the expected burn rate. Based on those good results, a further three strands were tested on the following day at 10 MPa under similar conditions, that is, protection of stop wires with tape (Table 11). However, with the exception of the first strand, erratic results were again observed.

Table 11: *Low pressure strand burn results for P0175 coated with paint and epoxy burnt on 11/11/11*

Pressure (MPa)	Burn Time (s)	Burn Rate ($mm{\cdot}s^{-1}$)	Firing head	Coating	Comments
10	9.63	13.19	6	Paint + epoxy	Stop wire covered with tape + shroud over stop wire
10	0.90	141.1	5	Paint + epoxy	Stop wire covered with tape + shroud over stop wire
10	2.16	58.80	6	Paint + epoxy	Stop wire covered with tape + shroud over stop wire + tape down length of strand

At this stage the hypothesis was that the original paint inhibitor coating was not able to prevent a flash of flame or hot gas reaching the stop wire before the main flame front. The high viscosity of the epoxy meant that it did not flow into existing cracks or imperfections in the paint surface. The outer epoxy layer was therefore not able to prevent the flame front from running down the length of the strand since it sat on top of the paint layer(s). Paint used to inhibit these strands was tested extensively by Hart et al. [3] but only on non-aluminised composite propellant. Hart et al. also found that age of the paint had a significant effect on viscosity and therefore it's ability to cover the strand effectively. It was necessary to dilute the paint to achieve the correct viscosity. Another contributing factor may have been the method of preparation of strands since they were fully machined on a bandsaw whereas historically they were machined into sheets then finally cut into strands with a sharp knife. The level of residual dust on strand surfaces may have also contributed to a poor coverage or adhesion of paint inhibitor. This may be a factor because the strands are chamfered by sanding the edges which generates and deposits dust on the strand surfaces.

3.3 R180/H180 Epoxy Coating

3.3.1 Epoxy Coating Process

An alternative epoxy resin with lower viscosity and a longer pot-life than that of Epon 828/HXSMP 572 was sought to improve the epoxy coating process and quality of inhibited strands. Epoxy resin R180 was identified and was combined with a slow curing hardener, H180 (Table 12 and 13). H180 was used as a cross-linking agent at a mixing ratio of 20 parts to 100 parts of R180. A mixture of resin and curative was poured into a dipping bath as for the paint system and 3 strands were lowered into the bath at a time and then suspended from a rack to drain. Excess epoxy was allowed to run from strands onto a drip tray with a cure time of at least 24 hours. Strands were then inverted and a second coating was applied as for the first, resulting in fully coated strands.

Table 12: *Epoxy coating supplier*

Product	Supplier
R180 Resin H180 Hardener	Adelaide Moulding and Casting Supplies 735b Marion Road, Ascot Park South Australia 5043

Table 13: *Epoxy coating product specifications*

Product	Viscosity (Pa·s)	Mixing Ratio (Parts per 100)	Pot-life (h @ 25°C)	Optimum Cure (h)
R180 Resin		-	-	-
H180 Hardener	0.05-0.1	16	0.5 - 1	6 @ room T

In an attempt to improve surface preparation of strands and therefore bond between epoxy resin and propellant, six strands were sanded with 240 grit sandpaper. The already chamfered edges and machined surfaces were lightly sanded then dedusted by wiping the strands with lint-free paper towel. This is in contrast to the usual chamfering process with

40 grit sand paper. A greatly reduced surface roughness resulted and loose material present on strands was removed with a soft brush in the usual manner. Six strands were treated in the aforementioned way while 6 other strands that had gone through the standard chamfering process were coated with R180/H180 epoxy with the intention of comparing results to determine the impact of surface preparation on burn rate consistency. All 12 strands were from batch P0177 and were chamfered only, without any form of pre-coating (no paint).

3.3.2 Strand Burn Results

A significant improvement in consistency of burn rate at a fixed pressure is evident from the results presented in Table 14. Furthermore, there does not appear to be a significant difference in precision afforded by the sanding step in addition to a chamfering step, as indicated by standard deviations of three results at each pressure. This provides a clear indication that the paint layer was not able to prevent a flame running down the outside surface of propellant strands, prematurely triggering a stop signal. Some level of robustness is also evident from the lack of sensitivity to surface roughness.

Table 14: *Low pressure strand burn results for P0177 coated with epoxy and burned on 26/3/12*

Pressure (MPa)	Burn Time (s)	Burn Rate ($mm \cdot s^{-1}$)	Firing head	Preparation	Average Burn Rate ($mm.s^{-1}$)	Standard Deviation ($mm.s^{-1}$)
6	15.16	8.38	6	Chamfered and sanded	8.32	0.05
6	15.30	8.30	5			
6	15.33	8.28	2			
8	13.86	9.16	6	Chamfered and sanded	9.18	0.10
8	13.67	9.29	5			
8	13.97	9.09	2			
10	12.87	9.87	6	Chamfered only	9.83	0.03
10	12.93	9.82	5			
10	12.94	9.81	2			
12	12.27	10.35	6	Chamfered only	10.40	0.07
12	12.12	10.48	5			
12	12.23	10.38	2			

The initial strand burn results recorded over the pressure range of 6 to 12 MPa are plotted in Figure 2 and have a high degree of fit to the predicted power law relationship of burn rate with pressure.

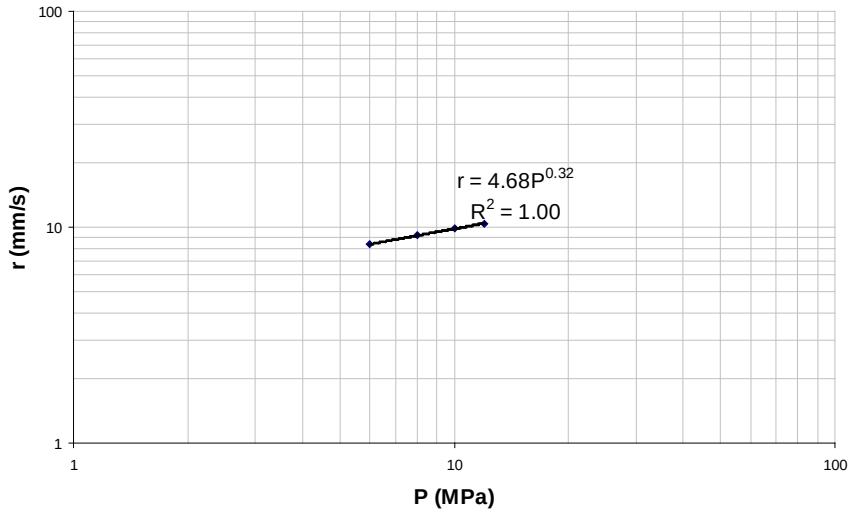

Figure 2: Low pressure strand burn results for P0177 coated with epoxy. A trend line based on the expected power law relationship between burn rate and pressure is included.

Based on these encouraging initial results, the remainder of available strands for batch P0177 and 30 each of three other batches with varying ballistic additive content (and therefore burn rates) were coated with R180/H180. Sanding and dedusting of these strands was not as rigorous as for the initial 12. Results for the four different batches burned over a pressure range of 4 to 20 MPa are presented in Tables B-1 to B-4, Appendix B and in graphical form in Figure 3.

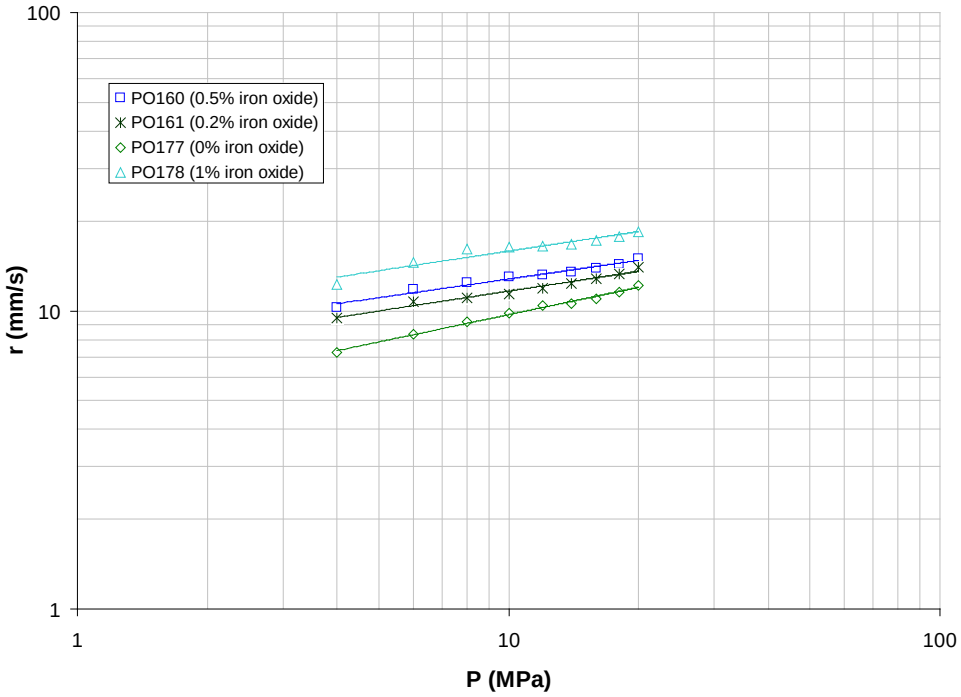

Figure 3: Low pressure strand burn results for four different formulations of aluminised composite rocket propellant coated with epoxy

Accuracy and precision of results for all four batches of aluminised composite rocket propellant was acceptable and at least as precise as historical results obtained with non-aluminised propellant inhibited with paint. The contrast to results obtained with painted or painted and epoxy coated strands in sections 3.1 and 3.2 is stark. Of the 110 strands burned with an R180/H180 epoxy inhibitor coating, there were no wildly spurious results as experienced with painted strands and the largest standard deviation for a triplet was 0.24 $mm{\cdot}s^{-1}$.

Additionally, the coating process is quicker, easier and therefore less susceptible to error or variability. The epoxy method requires only two coats with a 24 h cure between coats whereas the paint method requires 4 coats with a 24 h drying period between each. The paint method also requires dilution of the paint with water and confirmation of final viscosity to account for product (paint) variability.

3.4 Comparison of Paint and Epoxy Coated Non-Aluminised Propellant

In order to compare accuracy of burn rate results obtained using both inhibitors, a single batch of non-aluminised propellant was manufactured and machined, then split into two equal portions. One portion was coated as per Explosives Instruction EI 253 (Appendix C contains an abridged version) with the paint system while the other portion was coated as outlined in section 3.3 with R180/H180 epoxy. The remainder of the strand burning operation was identical to facilitate a direct comparison of burn rates obtained.

3.4.1 Sensitivity to Strand Preparation Technique

Since results of this work will form the basis for a revised EI covering coating of aluminised composite rocket propellant strands with the new epoxy coating, a sensitivity study was conducted to determine optimal strand preparation parameters. Factors such as the existence of bevelled edges on strands, dedusting and the number of coatings were studied by burning six strands of each at 10 MPa, at the conditions listed below.

- Control – dedusted, large bevel, two coatings
- 1 Coating only, dedusted, large bevel
- 2 Coatings, large bevel, not dedusted
- 2 Coatings, dedusted, no bevel
- 2 Coatings, large bevel, dedusted, top layer
- 2 Coatings, large bevel, dedusted, bottom layer
- 2 Coatings, large bevel, dedusted, second to bottom layer

Control strands constituted dedusted strands with a large bevel and two coatings of epoxy. A statistical analysis was performed to identify significant differences. The final two scenarios above are designed to determine whether a material difference in burn rate is present for strands that originate from the top or bottom of a propellant slab. As the cross-linking process occurs over a finite period of time and rocket propellant is a slurry, settling of solids may occur, this may have an effect on propellant burn rate.

Results for each of the scenarios above reveal only minor differences in burn rate with the exception of the bottom layer, which had a significantly higher burn rate than the control

and all other data sets (Table 15). This is due to the aforementioned settling of solids to create a solids-rich layer at the bottom of the propellant block. The second to bottom layer was assessed and it had a very similar rate to that of the control. This confirms that the solids-rich layer only extends 5 to 10 mm from the lower surface of the casting. A corresponding binder-rich (solids poor) layer on the surface of the block is expected to result in significantly lower burn rates. However, this was not the case here because the block was machined into sheets from the bottom surface up and as the very top layer was less than 5 mm thick, it was discarded.

Table 15: *Low pressure strand burn results at 10 MPa for a non-aluminised propellant coated with epoxy and comparing strand preparation parameters. Results are an average of 6 replicates except for bottom layer which is an average of five.*

Preparation	Average Burn Rate ($mm \cdot s^{-1}$)	Standard Deviation	Relative Standard Deviation (%)
Control	8.72	0.02	0.25
Single Coating	8.63	0.05	0.53
Not Dedusted	8.73	0.17	1.92
No Bevel	8.64	0.18	2.05
Top Layer	8.63	0.04	0.46
Bottom Layer	11.01	0.14	1.30
Second Bottom Layer	8.79	0.09	0.97

Dedusting and a bevel may offer some benefit in terms of within dataset variance as indicated by a slightly higher relative standard deviations for those parameters but average results were not significantly different from the rest. Overall, the strand preparation technique displayed considerable robustness and was insensitive to the parameters tested. These results confirm the earlier indicated robustness mentioned in section 3.3.2.

Of the parameters tested, the one that could result in a significant productivity improvement without compromising on accuracy or precision is the number of coatings. The two-part epoxy coating chosen has a relatively high viscosity which produces a relatively thick coating. Care to ensure that strands receive an even coating should obviate the need for a second coating since the relative standard deviation remained low for strands coated with only a single layer.

3.4.2 Burn Rate Comparison – Epoxy and Paint Coatings

A single block of non-aluminised propellant was machined into 10 layers with 7 or 8 strands cut from each layer. Each layer was labelled from 1 to 10 to identify the position in the block with 1 being the bottom. Half the strands from each layer were coated with paint and half with epoxy. Strands were burned in triplicate at pressures from 4 MPa to 18 MPa at 2 MPa intervals. Strands were chosen from the top layer for the lowest pressure such that as pressure increased, strands were burned from the top layer down. This regime was repeated for the painted strands so that any slight differences in burn rate due to position within the block were normalised. In addition, the actual pressures that the two sets of strands were burned at were matched as far as possible to ensure that no bias was introduced due to starting pressure. Complete results for the two datasets are located in

Appendix B2, Tables B5 and B6 and are summarised in Table 16 and by the two burn rate curves in Figure 4.

Table 16: *Low pressure strand burn results for paint and epoxy coated non-aluminised propellant*

	Paint		Epoxy	
Pressure (MPa)	**Average Burn Rate ($mm.s^{-1}$)**	**Standard Deviation ($mm.s^{-1}$)**	**Average Burn Rate ($mm.s^{-1}$)**	**Standard Deviation ($mm.s^{-1}$)**
4.1	6.44	0.50	6.16	0.06
6.1	7.07	0.09	6.97	0.02
8.0	8.60	1.55	7.75	0.08
10.0	8.68	0.10	8.79	0.03
12.0	9.13	0.21	9.76	0.50
14.0	10.08	0.17	10.13	0.09
16.0	10.62	0.04	10.90	0.50
18.0	11.39	0.05	11.80	0.08

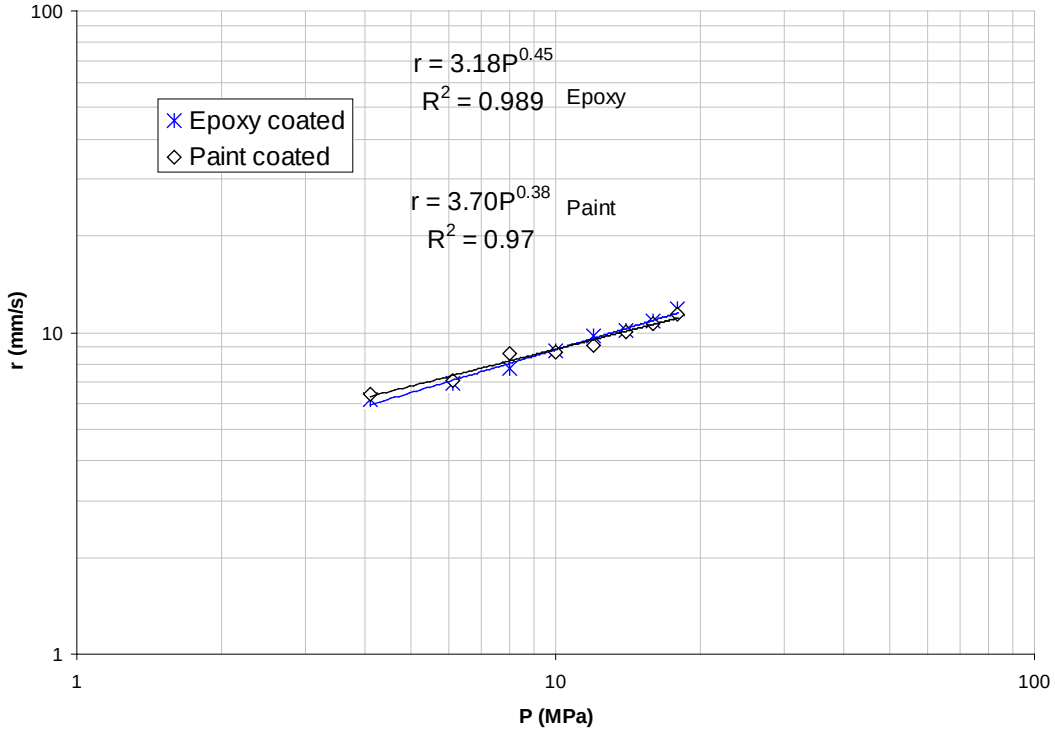

Figure 4: Low pressure strand burn results comparing non-aluminised propellant coated with epoxy and paint. Trend lines based on the expected power law relationship between burn rate and pressure are included

Results are similar but a distinct difference in slope (burn rate sensitivity to pressure) is evident with paint inhibited strands having an exponent of 0.445 whereas the value for epoxy coated strands was 0.380. It should be noted that within the dataset for the paint inhibited strands two values were more than 2 seconds faster in terms of burn time than the other replicates (4.09 MPa and 8.01 MPa). Inspection of the strand following

combustion revealed splits in the paint coating (paint shell) for a significant length of each strand (Figure 5). It is thought that either the paint coating was flawed or the internal pressure created by the burning propellant caused the coating split. This would allow the flame to run down the longitudinal faces of the strand resulting in an artificial elevation of the burn rate.

Figure 5: Burned strands showing splits in the coating – 4.09 MPa (top) and 8.01 MPa

To provide a fair comparison, the two suspect results were repeated with paint inhibited strands that did not show obvious signs of a flawed coating. The results are contained in Appendix B2, Table B7 and are summarised in Table 17 and Figure 6. The two curves are now more closely matched in terms of the burn rate coefficient and burn rate pressure exponent and are expected to be within the precision of the method.

Provided that the coating is adequate and without flaws, the actual substance of the coating has little bearing on burn rate results but the paint coating did demonstrate a propensity to produce a flawed coating whereas an epoxy coating did not cause anomalous results due to flaws in the coating. This demonstrates a clear advantage for the epoxy system over a paint system.

Table 17: *Low pressure strand burn results for paint and epoxy coated non-aluminised propellant including the two repeated values*

	Paint		Epoxy	
Pressure (MPa)	**Average Burn Rate ($mm.s^{-1}$)**	**Standard Deviation ($mm.s^{-1}$)**	**Average Burn Rate ($mm.s^{-1}$)**	**Standard Deviation ($mm.s^{-1}$)**
4.1	6.09	0.10	6.16	0.06
6.1	7.07	0.09	6.97	0.02
8.0	7.75	0.16	7.75	0.08
10.0	8.68	0.10	8.79	0.03
12.0	9.13	0.21	9.76	0.50
14.0	10.08	0.17	10.13	0.09
16.0	10.62	0.04	10.90	0.50
18.0	11.39	0.05	11.80	0.08

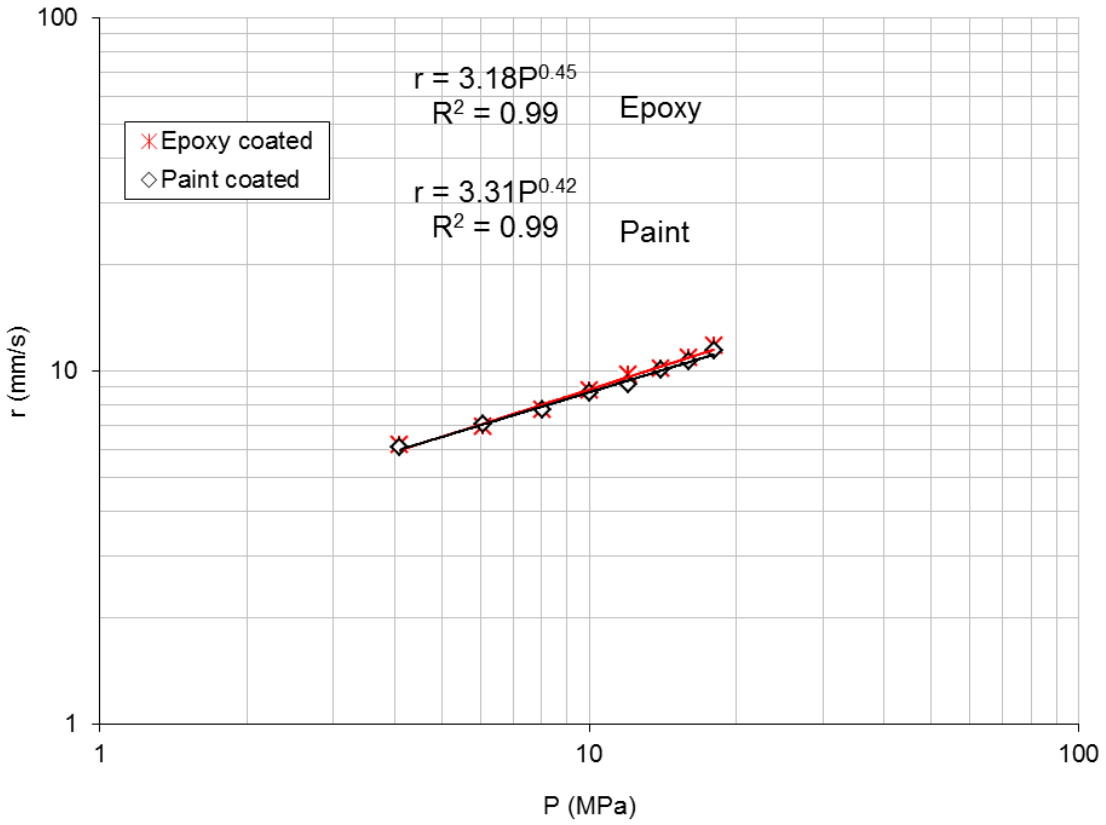

Figure 6: Low pressure strand burn results comparing non-aluminised propellant coated with epoxy and paint. The results are identical to those in Fig. 5 but with two repeat values for the paint inhibited dataset. Trend lines based on the expected power law relationship between burn rate and pressure are included.

3.5 Effect of Number of Replicates on Burn Rate Results

Burning strands in triplicate is not always feasible during the early stages of propellant development. The general practice of beginning small and scaling up as knowledge of the ingredients and propellant grows may mandate the production of only a small number of strands per batch. Another factor may be ingredient quantities which could be limited in the case of new or experimental ingredients. The most recent practice at DSTO has been to measure in duplicate at each pressure with a third burned if the variance between replicates is too high. In addition, a highly accurate burn rate in the early stages of propellant development may not be necessary. Often only coarse changes to propellant ballistic performance are attempted at smaller mixing scales which can be followed with more accurate measurements after down-selecting from a few candidate formulations.

There are obvious productivity gains to be made if only a single strand is burned at each pressure over the range of interest. Another productivity benefit of a single strand at each pressure is that the operator is not required to precisely adjust the pressure of the

triplicates to ensure that the starting value is within a certain margin for a valid statistical comparison of replicates. This results in significant savings in terms of time and effort finely adjusting pressure. The operator can simply adjust pressure to a value within 0.5 MPa of the target value and wait for the value to stabilise before firing. The actual pressure and burn rate is then plotted for values measured across the pressure range and given an acceptable coefficient of determination (R^2), a burn rate law can be calculated. Results for burn rate of 6 painted strands burned at pressures ranging from 5.30 MPa to 17.91 MPa are listed in Table 18. A comparison of the burn rate law determined from those six strands and the 24 strands appearing in Table B7 is depicted in Figure 7.

Table 18: *Low pressure strand burn results for a single strand at 6 different pressures across the range*

Pressure (MPa)	**Burn Time (s)**	**Average Burn Rate ($mm \cdot s^{-1}$)**
5.30	18.51	6.86
7.01	17.24	7.37
8.79	15.67	8.10
11.75	14.46	8.78
15.19	12.12	10.48
17.91	10.90	11.65

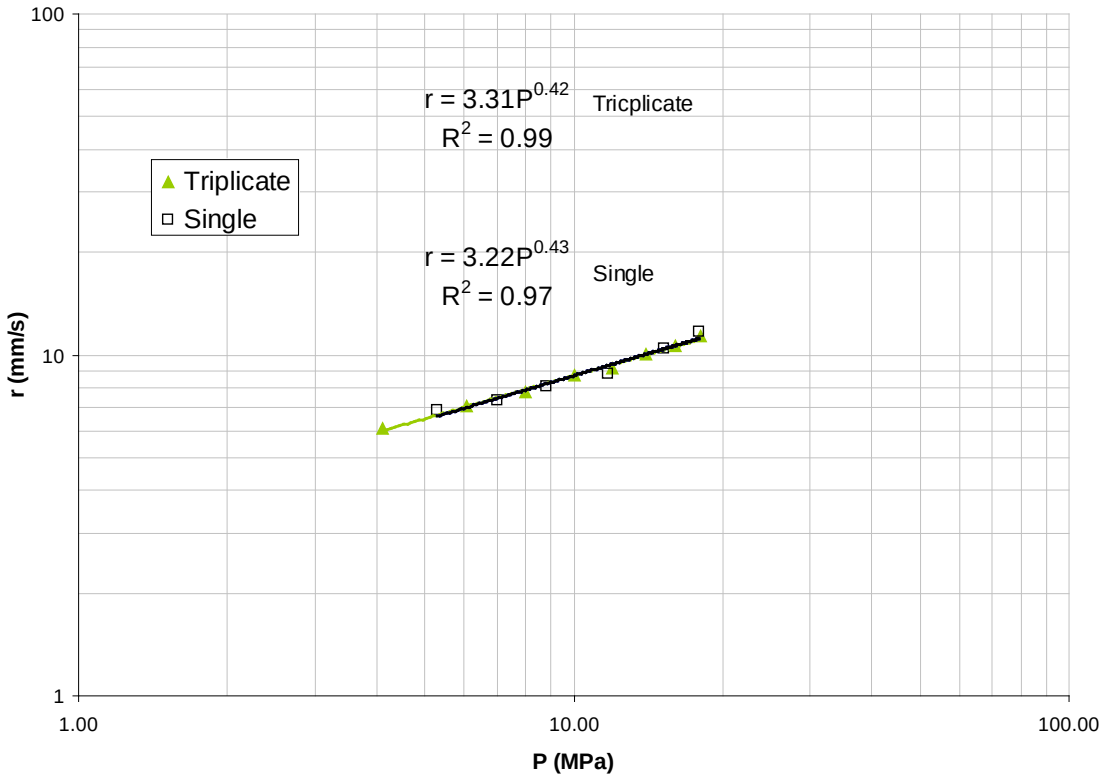

Figure 7: Low pressure strand burn results for non-aluminised propellant coated with paint comparing results in triplicate with single values at each pressure. Trend lines based on the expected power law relationship between burn rate and pressure are included.

As one may expect, the R^2 value for the single strand dataset is lower than for the triplicate set but is still very acceptable at > 0.96. The value for burn rate coefficient (a) is also quite close and differs by less than 0.1. Burn rate pressure sensitivity is slightly higher in the case of the single strand dataset and is 0.11 greater than for the triplicate set. Overall, the two results are quite close and would certainly be acceptable as a 'first look' at the burn rate law and would provide the accuracy to facilitate a comparison between different formulations. The comparable results are despite the fact that the single strand at each pressure dataset was collected over a narrower pressure band. A cautionary note is that the abbreviated test regime may not be suitable for propellant formulations that do not conform to the traditional power law relationship between pressure and burn rate. Where it is expected that there is a significant slope break or a plateau, the more precise method should be chosen.

4. Conclusions

The traditional house paint based strand inhibitor does not have the robustness required for the aggressive burn of an aluminised composite rocket propellant. Furthermore, the paint-based coating is prone to cracking which can open a path for the flame to travel down the side of the strand producing spurious results. Preparation time for the paint-based system is also quite long since a total of four coats are required with a drying period of 24 hours between coats. A two-part epoxy based inhibitor by the name of R180/H180 was successfully trialled as a replacement for the current paint-based coating.

An epoxy coating was trialled alongside the paint coating with a non-aluminised propellant to compare accuracy and precision of results. The epoxy coating performed at least as well as the paint coating and produced a virtually identical burn rate law. Burn rate results for epoxy coated strands were insensitive to strand preparation technique such as bevelling of the strand and de-dusting, thus demonstrating a robust inhibitor system.

Acceptable robustness of the epoxy coating was demonstrated when applied to aluminised composite rocket propellant with no spurious results recorded. The accuracy and precision of results for all four batches of propellant was acceptable and at least as precise as historical results obtained with non-aluminised propellant inhibited with paint. Of the 110 strands burned with an R180/H180 epoxy inhibitor coating, there were no wildly spurious results as experienced with painted strands and the largest standard deviation for a triplet was 0.24 $mm \cdot s^{-1}$.

A couple of methods for reducing effort while maintaining sufficient accuracy of burn rate data were demonstrated. A single coating of epoxy as opposed to two provided sufficient inhibition and could almost halve the preparation and coating time. Burning as little as 6 strands, one at each pressure across the range of interest, can provide a sufficiently accurate burn rate law during the early stages of propellant development.

It is recommended that the R180/H180 two-part epoxy coating system be adopted as the standard inhibitor for composite rocket propellant strand burning. A method involving a single coating of epoxy should be outlined in the relevant Explosive Instruction.

Furthermore, tine coated copper wires should be used as fuse wires as a replacement for solder containing lead.

5. Acknowledgements

The authors wish to thank Mr Tony Ferschl for his assistance with propellant machining and strand preparation.

6. References

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3. Hart, A.H. and R. Pietrobon, *Improved Strand Burn Rate Reproducibility Using a New Preparation Methodology for Paint-Based Inhibitors*. 2003, DSTO-TN-0513.
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Appendix A: Propellant Formulation

A.1. Propellant Composition

Table A1: Composition of propellant batches in wt%.

Batch Number	P0085	P0160	P0161	P0175	P0176	P0177	P0178	P0192
HTPB	13.70	8.72	8.72	8.85	8.85	8.85	6.08	13.28
DOA	0	3	3	3	3	3	6	2.9
AO2246	0.15	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Fe_2O_3	0.5	0.5	0.2	0.5	0.2	0	0.5	0
Aluminium	0	18	18	18	18	18	18	0
AP (Coarse)	65.1	51.5	51.5	51.5	51.6	51.75	40.8	49.5
AP (Fine)	19.4	17	17.3	17	17.2	17.25	27.2	33
IPDI	1.15	0.88	0.88	0.75	0.75	0.75	0.52	1.22
HX-572	0	0.3	0.3	0.3	0.3	0.3	0.3	0
TPB	0	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025

Appendix B: Propellant Burn Rate Results

B.1. Aluminised Propellant Coated with R180/H180 Epoxy

Table B-1: *Low pressure strand burn results for P0160 coated with epoxy R180/H180.*

Pressure (MPa)	Burn Time (s)	Burn Rate ($mm \cdot s^{-1}$)	Average Burn Rate ($mm \cdot s^{-1}$)	Standard Deviation ($mm \cdot s^{-1}$)
4	12.38	10.26	10.24	0.10
4	12.29	10.33		
4	12.54	10.13		
6	10.67	11.90	11.79	0.13
6	10.90	11.65		
6	10.66	11.91		
6	10.85	11.71		
8	10.12	12.55	12.48	0.06
8	10.21	12.44		
8	10.21	12.44		
10	9.77	13.00	13.01	0.05
10	9.79	12.97		
10	9.72	13.07		
12	9.51	13.35	13.23	0.12
12	9.67	13.13		
12	9.63	13.19		
14	9.40	13.51	13.44	0.07
14	9.44	13.45		
14	9.50	13.37		
16	9.19	13.82	13.92	0.15
16	9.17	13.85		
16	9.01	14.10		
18	8.94	14.21	14.31	0.10
18	8.88	14.30		
18	8.81	14.42		
20	8.48	14.98	14.93	0.04
20	8.52	14.91		
20	8.52	14.91		

Table B-2: *Low pressure strand burn results for P0161 coated with epoxy R180/H180.*

Pressure (MPa)	Burn Time (s)	Burn Rate ($mm \cdot s^{-1}$)	Average Burn Rate ($mm \cdot s^{-1}$)	Standard Deviation ($mm \cdot s^{-1}$)
4	13.51	9.40	9.44	0.04
4	13.40	9.48		
4	13.44	9.45		
6	11.67	10.88	10.77	0.10
6	11.84	10.73		
6	11.88	1069		
8	11.45	11.09	11.08	0.03
8	11.50	11.04		
8	11.43	11.11		
10	11.08	11.46	11.42	0.09
10	11.24	11.30		
10	11.05	11.49		
10	11.12	11.42		
12	10.72	11.85	11.91	0.06
12	10.62	11.96		
12	10.65	11.92		
14	10.36	12.26	12.32	0.06
14	10.26	12.38		
14	10.30	12.33		
16	9.99	12.71	12.77	0.13
16	9.83	12.92		
16	10.02	12.67		
18	9.49	13.38	13.32	0.10
18	9.62	13.20		
18	9.50	13.37		
20	9.08	13.99	14.01	0.04
20	9.08	13.99		
20	9.03	14.06		

Table B-3: *Low pressure strand burn results for P0177 coated with epoxy R180/H180.*

Pressure (MPa)	Burn Time (s)	Burn Rate ($mm \cdot s^{-1}$)	Average Burn Rate ($mm \cdot s^{-1}$)	Standard Deviation ($mm \cdot s^{-1}$)
4	17.33	7.33	7.28	0.06
4	17.62	7.21		
4	17.42	7.29		
6	15.16	8.38	8.32	0.05
6	15.30	8.30		
6	15.33	8.28		
8	13.86	9.16	9.18	0.10
8	13.67	9.29		
8	13.97	9.09		
10	12.87	9.87	9.83	0.03
10	12.93	9.82		
10	12.94	9.81		
12	12.27	10.35	10.40	0.07
12	12.12	10.48		
12	12.23	10.38		
14	12.07	10.52	10.56	0.05
14	12.06	10.53		
14	11.96	10.62		
16	11.53	11.01	10.99	0.09
16	11.66	10.89		
16	11.48	11.06		
18	11.03	11.51	11.52	0.01
18	11.02	11.52		
18	11.03	11.51		
20	10.46	12.14	12.17	0.04
20	10.39	12.22		
20	10.45	12.15		

Table B-4: *Low pressure strand burn results for P0178 coated with epoxy R180/H180.*

Pressure (MPa)	Burn Time (s)	Burn Rate ($mm \cdot s^{-1}$)	Average Burn Rate ($mm \cdot s^{-1}$)	Standard Deviation ($mm \cdot s^{-1}$)
4	10.25	12.39	12.26	0.14
4	10.48	12.12		
4	10.36	12.26		
6	8.71	14.58	14.51	0.21
6	8.90	14.27		
6	8.66	14.67		
8	7.81	16.26	16.11	0.16
8	7.87	16.14		
8	7.97	15.93		
10	7.65	16.60	16.33	0.24
10	7.81	16.14		
10	7.87	15.93		
12	7.70	16.49	16.45	0.04
12	7.74	16.41		
12	7.72	16.45		
14	7.59	16.73	16.74	0.03
14	7.60	16.71		
14	7.57	16.78		
16	7.38	17.21	17.20	0.04
16	7.40	17.16		
16	7.37	17.23		
18	7.16	17.74	17.75	0.08
18	7.18	17.69		
18	7.12	17.84		
20	6.93	18.33	18.42	0.18
20	6.94	18.30		
20	6.82	18.62		

B.2. Non-Aluminised Propellant Coated with R180/H180 Epoxy

Table B-5: *Low pressure strand burn results for P0192 coated with epoxy R180/H180.*

Pressure (MPa)	Layer	Burn Time (s)	Burn Rate ($mm \cdot s^{-1}$)	Average Burn Rate ($mm \cdot s^{-1}$)	Standard Deviation ($mm \cdot s^{-1}$)
4.10	10	20.72	6.13	6.16	0.06
4.14	10	20.73	6.13		
4.09	10	20.40	6.23		
6.10	4	18.16	6.99	6.97	0.02
6.07	9	18.20	6.98		
6.09	9	18.27	6.95		
8.01	9	16.30	7.79	7.75	0.08
8.00	8	16.60	7.65		
8.04	8	16.29	7.80		
10.00	8	14.40	8.82	8.79	0.03
10.00	8	14.44	8.80		
10.03	7	14.49	8.76		
12.02	7	13.30	9.55	9.76	0.50
12.00	7	13.50	9.41		
12.00	7	12.31	10.32		
14.00	6	12.60	10.08	10.13	0.09
14.00	6	12.40	10.24		
14.00	6	12.60	10.08		
16.00	5	12.17	10.44	10.90	0.50
16.00	5	11.72	10.84		
16.00	5	11.11	11.43		
18.00	5	10.68	11.89	11.80	0.08
18.00	4	10.78	11.78		
18.00	4	10.83	11.73		

Table B-6: *Low pressure strand burn results for P0192 coated with paint.*

Pressure (MPa)	Layer	Burn Time (s)	Burn Rate ($mm \cdot s^{-1}$)	Average Burn Rate ($mm \cdot s^{-1}$)	Standard Deviation ($mm \cdot s^{-1}$)
4.09	10	20.57	6.17	6.44	0.50
4.09	10	18.08*	7.02		
4.14	10	20.71	6.13		
6.10	10	17.71	7.17	7.07	0.09
6.07	9	18.07	7.03		
6.09	9	18.14	7.00		
8.04	9	16.17	7.85	8.60	1.55
8.00	9	16.78	7.57		
8.01	8	12.23*	10.38		
10.01	8	14.44	8.80	8.68	0.10
10.01	7	14.74	8.62		
10.00	7	14.72	8.63		
12.00	7	13.56	9.37	9.13	0.21
12.00	6	14.16	8.97		
12.00	6	14.01	9.06		
14.00	6	12.73	9.98	10.08	0.17
14.00	6	12.36	10.28		
14.00	5	12.73	9.98		
16.00	5	12.01	10.57	10.62	0.04
16.00	4	11.95	10.63		
16.00	4	11.93	10.65		
18.00	4	11.12	11.42	11.39	0.05
18.00	3	11.20	11.34		
18.00	3	11.12	11.42		

* Suspect results – split inhibitor coating

Table B-7: *Low pressure strand burn results for P0192 coated with paint and including two repeat values.*

Pressure (MPa)	Layer	Burn Time (s)	Burn Rate ($mm \cdot s^{-1}$)	Average Burn Rate ($mm \cdot s^{-1}$)	Standard Deviation ($mm \cdot s^{-1}$)
4.09	10	20.57	6.17	6.09	0.10
4.09	10	21.25*	5.98		
4.14	10	20.71	6.13		
6.10	10	17.71	7.17	7.07	0.09
6.07	9	18.07	7.03		
6.09	9	18.14	7.00		
8.04	9	16.17	7.85	7.75	0.16
8.00	9	16.78	7.57		
8.00	8	16.22*	7.83		
10.01	8	14.44	8.80	8.68	0.10
10.01	7	14.74	8.62		
10.00	7	14.72	8.63		
12.00	7	13.56	9.37	9.13	0.21
12.00	6	14.16	8.97		
12.00	6	14.01	9.06		
14.00	6	12.73	9.98	10.08	0.17
14.00	6	12.36	10.28		
14.00	5	12.73	9.98		
16.00	5	12.01	10.57	10.62	0.04
16.00	4	11.95	10.63		
16.00	4	11.93	10.65		
18.00	4	11.12	11.42	11.39	0.05
18.00	3	11.20	11.34		
18.00	3	11.12	11.42		

* Repeated values

Appendix C: Paint Coating Process

C.1. Excerpt from EI 253

8.5 Application of Paint Inhibitor

8.5.1 Switch on the fume hood and prepare a 70% dilution of inhibitor paint as per instructions of document 3.5. Pour the paint inhibitor solution into a brass dipping tank, filling it to about 20 mm under the lip. This prevents overflow when dipping. Place a piece of paper or aluminium foil on the drip tray of the drying stand to catch any drips and thus facilitate cleaning and disposal.

8.5.2 Attach several strands to the brass batten by means of the clips and record the batch or cast number on the batten.

8.5.3 Dip the strands into the dipping tank for 5 to 10 seconds and ensure they are wetted with inhibitor up to the clips. Ensure that the strands do not touch the base or edges of the tank nor each other.

8.5.4 Remove the batten from the tank, place it on the drying stand and allow the strands to dry. Ensure that the strands are suspended vertically and do not touch one another or the base of the drying stand. It may be necessary to touch up bare areas of the first coat. This can be done with the small paint brush. Keep the tank covered when it is not in use.

8.5.5 Allow the strands to dry for at least 60 minutes before applying the next coat.

8.5.6 Repeat instructions 8.5.2 to 8.5.5 to achieve the required number of coats specified on the request sheet (usually four). To produce as even a coating as possible, it is recommended that the strands be inverted with alternate coatings.

8.5.7 Enter any details and comments in the inhibition record book (eg the time when coatings were applied, any difficulties due to the propellant formulation, etc) and request sheet.

8.5.8 Strands must be burned as soon as practical after inhibition as this will minimise any affects on the propellant.

8.5.9 The paint inhibitor solution may be used for up to a week after preparation as long as it is stored in a sealed glass container at the end of each day. Clean the dipping tank and battens with water at the days end.

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19. ABSTRACT

An epoxy coating was trialled as an inhibitor for composite rocket propellant strands burned in a Crawford–style bomb. The epoxy coating performed at least as well as the traditional paint coating and produced a virtually identical burn rate law. Burn rate results for epoxy coated strands were insensitive to strand preparation technique such as bevelling of the strand and de-dusting, thus demonstrating a robust inhibitor system. Acceptable robustness of the epoxy coating was demonstrated when applied to aluminised composite rocket propellant with no spurious results recorded. Accuracy and precision of results for all four batches of aluminised composite propellant were acceptable and at least as precise as historical results obtained with non-aluminised propellant inhibited with paint. A couple of methods for reducing effort while maintaining sufficient accuracy of burn rate data were demonstrated. A single coating of epoxy as opposed to two provided sufficient inhibition and could almost halve combined preparation and coating time. Burning as little as 6 strands, one at each pressure across the range of interest, can provide a sufficiently accurate burn rate law during the early stages of propellant development.