Instantaneous Self-Sealing of Heterogeneous Hose Systems from Ballistic Impacts

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Abstract

The instantaneous self-sealing performance of homogeneous and heterogeneous elastomer systems confining a pressurized liquid payload were studied. The primary research focused on the selected elastomers ability to "snap back" to its original position after a complete penetration occurs. The specific self-sealing configuration studied was for a cylindrical hose system exposed to both incident and exit complete penetration from a 0.50 caliber ogive projectile. Separate self-sealant studies were performed to investigate both homogeneous and heterogeneous elastomer systems. All homogeneous elastomer systems studied incorporated polyureas only. Composite elastomer systems incorporated polyureas as outer hose claddings and natural/synthetic rubbers as inner liners.

Varied physical properties of the selected elastomers were correlated to their ability to prevent leakage from a pressurized working fluid after a complete ballistic penetration. Physical properties including ultimate stress and strain, modulus and glass phase transition were correlated to their ability to self-seal under ambient temperatures. For heterogeneous elastomer systems, low modulus high elongation materials were studied for their ability to support plugging of the outer elastomer cladding penetration cavities.

Introduction

Since World War I the application of self-sealing was introduced to prevent fuel loss where fuel storage containers punctured by bullets/fragments could lead to catastrophic failure through both fire and loss of fuel[1]. The initial self-sealing technology incorporated two outer layers that were resistant to the fuels sandwiching a polymer that expands when exposed to fossil fuels[2]. Recent developments in new fuels may require that self-sealing systems cannot rely on reactivity with the fuel system to enable material expansion. New designs require two-part reactants separated by a membrane which enables mixing when a perforation occurs, without exposure to fuels[3]. Both the increased complexity and size may create additional issues for fuel storage systems.

In addition to fuel tank self-sealant technologies, a similar issue exists for fuel hose systems. The developed technologies for the fuel tank systems can be applied to the fuel hose applications but an increased risk of the fuel line blockage exists[2]. Current fuel lines can incorporate existing self-sealant technologies but the internal throughput diameter size must be increased to address the internal expansion from a self-sealing reaction.

An alternative approach to the development of self-sealing hoses is the "snap back" effect[4,5]. The "snap back" effect depends on the physical properties of elastomeric materials to enable complete penetration with minimal damage to the elastomers followed by closure[4]. The "snap back" effect is directly related to dynamic behavior of certain elastomers that experience an increase in yield strength while maintaining elongations of typically 150% or greater[5].

To achieve instantaneous self-sealing performance incorporating the “snap back” effect, selected polyureas were studied. Polyureas are elastomeric co-polymers formed between the reaction of an amine (NH_2 group) and isocyanate. The elastomer behavior occurs from the alternating flexible polyether segments combined with hard urea segments within the polymer chain[6,7]. Key attributes of polyureas include high strength (> 6000 psi) and high elongation (>650%)[8].

Variants on the polyurea can be formed through variations in the amine group as well as variation in ratios of the amine group to isocyanate where an increase in isocyanate produces harder and more brittle polyurea systems[9].

Heterogeneous self-sealant hose systems were additionally studied where soft low modulus high elongation materials serving as an inner liner were investigated for improved self-sealing performance. The inner liners, during ballistic penetration, can support a different material response where a more compliant material supports penetration cavity plugging. Within this study only physical properties including stress/strain behavior and glass phase transition temperatures (T_g) were correlated to self-sealing performance.

The understanding of T_g is very critical for each material studied as the response to ballistic impacts can vary from a rubbery state to a more glassy state where additional damage is observed due to brittle fracture and shear plugging[10]. In addition, for applications where self-sealing performance is required at lower temperatures, the T_g of the materials used must be below these temperatures.

Experimental

Experimental studies were performed in three phases. The initial phase studied single entrance penetrations of varied polyurea materials formed into a 0.95 cm thickness layer and internally pressurized with a working fluid. Polymers capable of successfully self-sealing a complete penetration were further studied in a hose configuration.

Self-sealant performance, within a hose configuration, incorporated an external hose diameter of 3.5 cm and an internal diameter of 1.27 cm including both homogeneous and heterogeneous systems. The homogeneous hose assemblies incorporated selected polyurea elastomers from the initial single wall screening. For heterogeneous hose studies an inner natural/synthetic rubber served as an inner liner with an inside diameter of 1.27 cm and varied wall thickness encapsulated within a polyurea elastomers from the initial phase.

All ballistic penetration studies were performed using 0.50 caliber Browning machine gun (BMG) ball rounds with a nominal incident velocity of 488 m/s[11]. All projectiles were launched using a smooth bore 2.54 cm barrel inside diameter light gas gun[12]. Polycarbonate serrated self-discarding sabots were used to launch the 0.50 caliber bullets. A Shimadzu HPV-X2 high-speed video camera[13] was used to determine both the projectile incident yaw/velocity and quantify instantaneous self-sealing performance.

Within the initial phase a total of 12 selected polyureas, incorporating varied physical properties (modulus, elastic limit, ultimate stress and strain and T_g), were studied. Elastomer targets were constructed using a 10 cm ID PVC tubing and an alignment tool to integrate molds to a 7.62 cm NPT male coupler (figure 1). Based on the type of polyurea used, applying the polymer included both high- and low-pressure spray as well as pour fabrication methods. All targets were force cured over a 24-hour period at 71°C.

Prior to each test, water was filled within the reservoir chamber backing the polymer layers and an external air hose regulated to 276 kPa was connected and air pressure applied. A mild solid steel cylinder was placed behind the self-sealant target, within the pressurized fluid chamber, to arrest the projectile after complete penetration through the self-sealing target. Once the target was filled, pressurized, and leak checked, the self-sealant test was performed.

Figure 1. Single wall self-sealing studies test configuration. Each of the 12 selected elastomers were bonded to a 7.62 cm NPT coupler and mounted to the pressurized tank system presented.

Within the second phase, homogeneous self-sealing hose studies were performed using 5 different elastomers. Elastomers selected for the homogeneous hose studies included successful self-sealing materials from the initial phase. Three of the homogeneous elastomers were based on polythiourea[14] with varied crosslinking to enable variations physical properties. Polythiourea is chemically very similar to a polyurea with the replacement of the termination atom from oxygen to sulfur. The sulfur atom enables a high chemical resistance to many chemicals including fuels[15]. The remaining two elastomers selected were polyureas (Dragonshield and HM-VK)[15]. Both polyureas selected demonstrate high tensile strength and elongation as well as a low T_g. Initial studies did not consider T_g as a performance requirement but for lower temperature applications the T_g must be lower than the testing temperature by at least 10℃ to avoid brittle failure during high strain rate impacts.

Homogeneous and heterogeneous self-sealing hose targets were similarly fabricated through both spray and pour mold applications followed by a force cure. Each target hose constructed was an overall length of 20 cm. Heterogenous hose systems incorporated primarily PTU 300 as an outer cladding encapsulating an inner rubber hose with wall thicknesses varying from 0.16 to 0.32 cm. All hose ends, of the target assemblies, prior to the force cure, were tapped to receive 0.625 cm NPT nipple (upper end) and 1.27 cm 5.12 threads/cm (lower end). Both fittings were inserted and sealed with HM-VK polyurea before force curing.

The hose target mounting system incorporated two 3.8 cm U-bolts to mount each target (figure 2). Each hose target was mounted nominally 1 meter from the gun muzzle to enable sabot separation. Similar to initial single elastomer wall studies, water, serving as a working fluid, was also filled and pressurized to 276 kPa prior to testing.

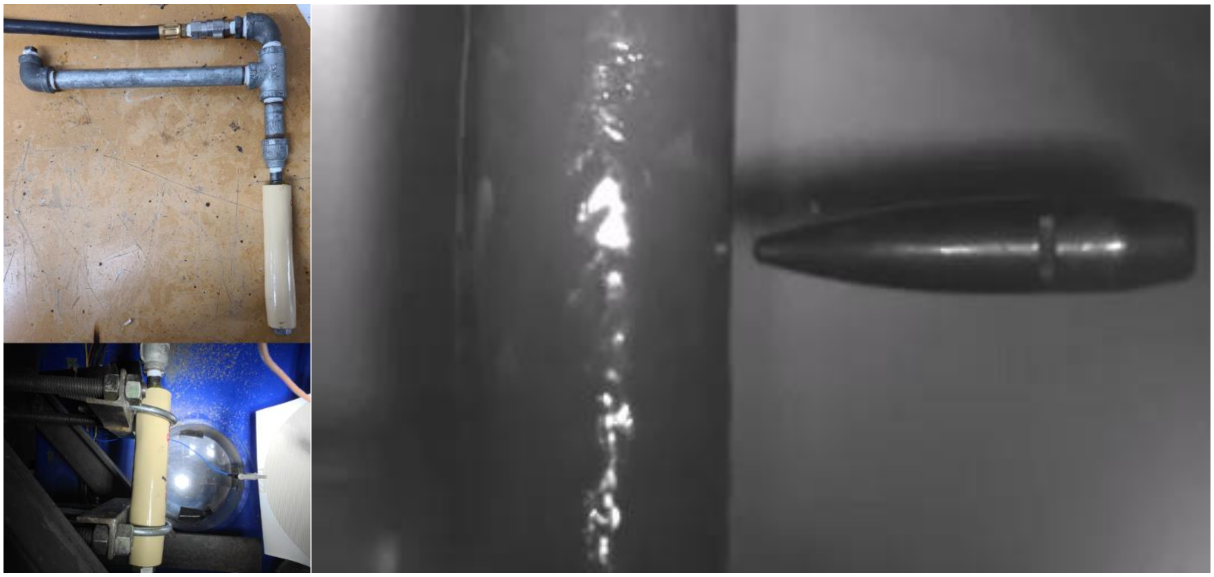


Figure 2. Self-sealing hose system test fixture. For both homogeneous and heterogeneous self-sealing studies. The mounting system enables alignment of the hose center to the flight path of the projectile.

Self-sealant performance was performed within 3 minutes after the ballistic impact. A score chart (figure 3) was used to classify both the entrance and exit hole leakage on a scale from 0 – 10. A score of zero represents complete failure to ten where no leakage was observed.

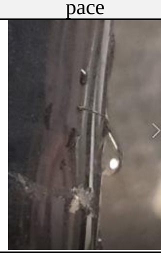
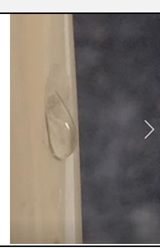
0	1	2	3	4	5
Complete failure / spraying Water	Strong stream of water detached from the hose	Weak stream of water detached from the hose	Water creates an arch and then reconnects with hose	Continuous strong stream remaining in contact with hose	Continuous weak stream remaining in contact with hose
					
6	7	8	9	10	
Constant individual drops of water at a fast pace	Constant individual drops of water at a slow pace	Drops form but do not drip within 5 sec of forming	Drops form but do not drip within 1 min of forming	Complete seal	
					

Figure 3. Quantitative scoring of the self-sealing performance used to quantify sealing performance on both projectile entrance and exit perforations external to the hose system.

In parallel to the ballistic self-seal studies, physical properties for each elastomer were measured through tensile studies. During hose construction, free films for each elastomer were made, cured and cut into ASTM D 412 “die-C” tensile samples. Using an Instron (model 1000), physical properties including: modulus, elastic limit and stress/strain values were measured. All tensile tests were performed at a strain rate of 0.86 cm/min.

T_g measurements were performed using Differential Scanning Calorimetry (DSC). T_g measurements enable an understanding of the transition from the rubbery state to a harder glassy state as the temperature is decreased. A TA Instruments model Q100 was used to determine the T_g temperatures for the selected elastomers. All T_g measurements were cycled between -140°C and 140°C using a temperature rate of 10°C/min. The samples were held at -140°C for 10 minutes and 140°C for 1 minute isothermally.

Experimental Results

Single Layer Self-Sealant Studies

Within the initial screening, 12 elastomer targets (table 1) were screened for instantaneous closure. Materials supporting self-sealing behavior were further studies as cladding components of a self-sealant hose system.

Table 1. Initial single wall self-sealing elastomer physical property measurements of stress/strain properties. All Data is averaged over three separate tests. All polymers were manufactured by Specialty Products Incorporated.

Elastomer	Elastic Modulus (kPa)	Ultimate Stress (MPa)	Ultimate Strain (%)
PTU 300	2428	30.50	172
Hard Cap 100	5563	24.42	17
HFM 27	3569	29.21	226
PTU	2234	24.88	119
HM-VK	588	22.09	342
Dragonshield	2866	41.85	441
EF 1.0 Pour	68	13.30	483
EF 1.0 Spray	13	6.96	482
EPL9 Pour	405	18.38	357
EPL9 Spray	21	9.45	353
Aqua Seal Pour	92	12.23	445
Aqua Seal Spray	12	6.85	423

Figure 4 presents the stress/strain curves of the 12 different polymer targets in the initial single wall self-sealant studies. The bold lines within figure 4 represent polymers that successfully self-sealed. Correlation of stress/strain curve characteristics to self-sealing performance were found to depend on: continuous strain hardening, elastic limit and ultimate elongation. Materials including Hard Cap 100 having a large elastic limit (29.5 MPa) but a low strain (21%) and EPL 9 having a low elastic limit (2.6 MPa) but a high elongation (350%) failed to enable self-sealing performance. Successful self-sealing performance was observed in materials having a minimum elastic limit of 7 MPa and a minimum elongation of 100%. HFM 27 polyurea physical properties supported self-sealant performance but leakage occurred. The initial drop beyond the elastic limit, in the stress/strain curve, for HFM 27, suggests a limited chain failure. This chain failure may weaken the polymers ability to “snap back” after penetration.

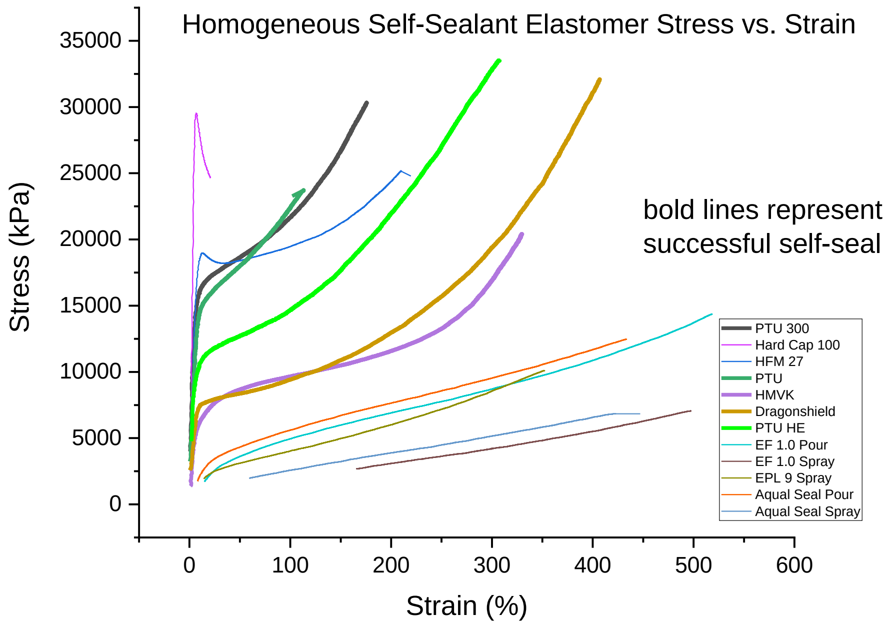


Figure 4. Selected initial phase elastomer cladding candidates presented stress vs. strain response for the initial 12 materials. Correlation of physical properties to self-sealing performance (table 2) suggests a dependence on continuous strain hardening, elastic limit and elongation. A total of five elastomers enabled a self-sealing performance of 8 or greater. The five elastomers were further studied within the homogeneous self-sealant studies.

Table 2. Initial single wall polymer self-sealing performance scoring of the initial 12 materials

Elastomer	Self-Seal
PTU 300	9
Hard Cap 100	0
HFM27	7
PTU	8
HM-VK	10
Dragonshield	9
PTU HE	9
EF 1.0 Pour	0
EF 1.0 Spray	0
EPL9 Spray	0
Aqua Seal Pour	0
Aqua Seal Spray	0

Homogeneous Hose Self-Sealant

Homogeneous hose studies incorporated the five identified elastomers from the initial 12 polymers screened in the single wall studies (PTU 300, PTU, PTU HE, Dragonshield and HM-VK). For each elastomer, a series of three tests were performed including: T_g, stress/strain properties and self-sealing performance.

The majority of the elastomers incorporated within the homogeneous self-sealant hose studies exhibited a fairly low $T_g < -50°C$ whereas both PTU and PTU 300 exhibited a higher T_g. The lower T_g's supporting material response in the rubbery phase (Dragonshield, HM-VK and PTU-HE) and higher T_g (PTU and PTU 300) supporting a more glassy" response. Higher T_g elastomers resist more material flow during impact but exhibit shear plug damage and increased cracking within the penetration cavity. It is currently not well understood what the role of T_g has in the self-sealing behavior.

Table 3. Homogeneous self-sealant hose elastomer studies measured T_g values

Elastomer	**T_g (°C)**
HM-VK	-73.3
PTU 300	-34.2
PTU	-26.3
PTU HE	-54.6
Dragonshield	-57.3

Similar to the initial single layer studies "as sprayed/poured" free films of the five different homogeneous elastomer cladding materials enabled tensile stress/strain physical properties of the five materials. Clear differences in ultimate stress and strain, as well as elastic limit/modulus, were observed between the five elastomers (table 4, figure 5). Large variations in elastic modulus, ultimate stress/strain and elastic limit exist but each enabled self-sealing performance within the initial studies.

Table 4. Tensile strength measurements of the five selected elastomers incorporated within the homogeneous self-sealing hose studies. The tensile measurements represent the as tested material, fabricated during hose construction. Only HM-VK tensile properties varied significantly from manufacturers published technical data and initial screening measurments. All data is averaged over three separate runs.

Elastomer	**Elastic Modulus (kPa)**	**Ultimate Stress (MPa)**	**Ultimate Strain (%)**
PTU	1386	22.87	106
PTU 300	2034	24.13	143
PTU HE	1891	33.17	292
Dragonshield	2866	41.85	441
HM-VK	588	22.09	342

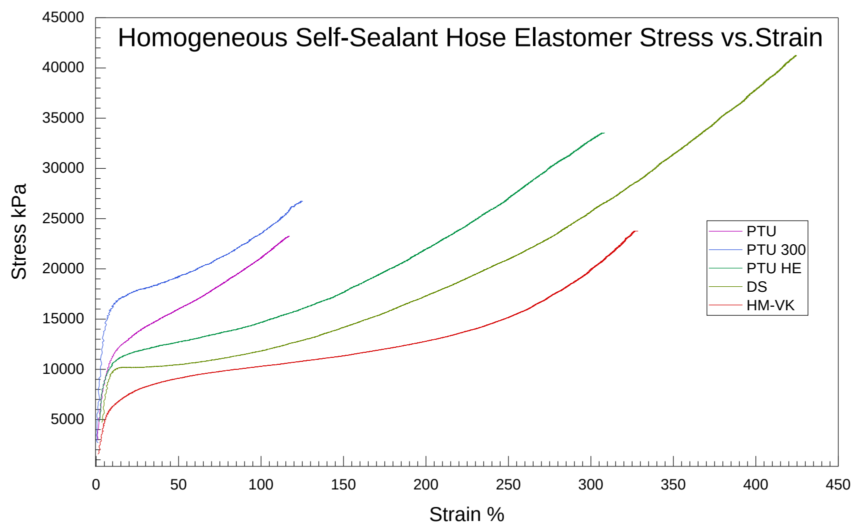


Figure 5. Five different elastomers incorporated within the homogeneous self-sealant hose study.

All self-sealing performance scoring was performed using an internal water under pressure (276 kPa). Both the incident and exit perforations were scored separately. Typically, it was found more difficult to enable self-sealing of the exit pathway in comparison to the entrance. All of the homogeneous hose systems performed nearly the same. None of the hose systems enabled a complete self-seal solution (table 5). The best performance for the entrance penetration cavity was a slow continuous drip (7) whereas the best exit cavity seal was a fast-continuous drip (6).

Table 5. Self-sealant performance of homogeneous self-sealing hoses pressurized to 276 kPa 5 minutes after penetration.

	Internal Pressure 276 kPa	
Elastomer	**in**	**out**
PTU 300	7	5
PTU	6	5
PTU HE	6	6
HM-VK	5	4
Dragonshield	6	6

Figure 6 presents posttest images of the five homogeneous hose systems studied. Images include entrance and exit penetration cavities as well as cross section and bi-section of the penetration cavity. Key observations include an increased crack propagation within the two higher T_g elastomers (PTU, PTU 300). Within the lower glass phase transition temperatures, the cavities appeared to close in further than the higher T_g samples. As much of the cavity assessment was dependent on the bisectional cut minimal correlations can be made regarding post impact penetration cavity assessments.

Based on the studies of homogeneous self-sealing hoses, for the dimensions studied, none of the five materials enabled adequate self-sealing performance. A possible solution is through the incorporation of a low strength, compliant inner liner within the hose system.

Figure 6. Side and cross-sectional posttest images of the five homogeneous self-sealant hose tests Note the external cracking on both PTU and PTU 300 having a higher T_g.

Heterogeneous Self-Sealing Hose Systems

Further investigations were performed to incorporate an inner hose system within four selected elastomers serving as claddings from the homogeneous self-sealing hose studies. The selected elastomers served as outer claddings for the heterogeneous self-sealing hose systems which included: Dragonshield, PTU, PTU 300 and PTU HE. Initial inner liner hose screening will only be tested using PTU 300 but the highest performing inner liner will be further tested using all four of the cladding materials.

Inner hose systems included high elongation, low modulus natural and synthetic rubbers. No chemical resistance criteria was placed on the Inner hose systems, the only variables investigated were physical properties, T_g and hose wall thickness.

The inner hose system is hypothesized to support plugging of both entrance and exit holes of the outer cladding hose after perforation. Ideal hose lining materials incorporate a low modulus (both elastic and plastic regions) and ultimate stress as well as a low T_g to maintain physical properties within the rubbery state for a range of negative temperatures. Table 6 and figure 7 present the measured physical properties of the selected inner rubber hose systems.

Self-sealing performance of the heterogeneous hose systems demonstrated higher levels of self-sealing performance (for select inner liners) compared to the homogeneous self-sealing hoses. Through the incorporation of both latex and Santoprene® inner hose liners with PTU 300 as the outer cladding, both heterogeneous hose systems enabled complete self-sealing.

Within the heterogeneous self-sealing study, with the exception of Viton®, the self-sealant performance either remained the same or improved. In the case of Viton® the performance decreased. The decrease is attributed to the higher T_g where under a higher strain-rate impact, the hose transitions to a brittle state. Under a brittle state, material within the penetration cavity tends to shear plug as opposed to flexing. The bisectional image within figure 9 of Viton® exhibits a higher level of liner material transferred into the cladding component preventing any self-sealing performance from the Viton® hose.

Table 6. Inner hose liner measured physical properties.

Elastomer	Elastic Modulus (kPa)	Ultimate Stress (MPa)	Ultimate Strain (%)	Modulus (250%) (kPa)
Tygon®	56	11.73	245	38.2
Latex	24	20.07	607	4.3
Gum Rubber	11	6.39	326	19.1
HT Silicone (D50A)	7	6.18	504	5.8
HT Silicone (D70A)	58	7.93	240	34.8
Viton®	55	7.69	185	N/A
Santoprene®	33	4.73	340	9.4

Table 7. Measured inner rubber hose glass phase transition temperatures

Elastomer	**T_g (°C)**
Tygon*	(1) -49.8°C, (2) -22.7°C
Latex	-62.6°C
Gum Rubber	-61.7°C
HT Silicone D50A	-126.1°C
HT Silicone D70A	-127.1°C
Viton	-19.7°C
Santoprene*	(1) -66.8°C, (2) -52.7°C

* Two T_g values were observed for both Tygon and Santoprene

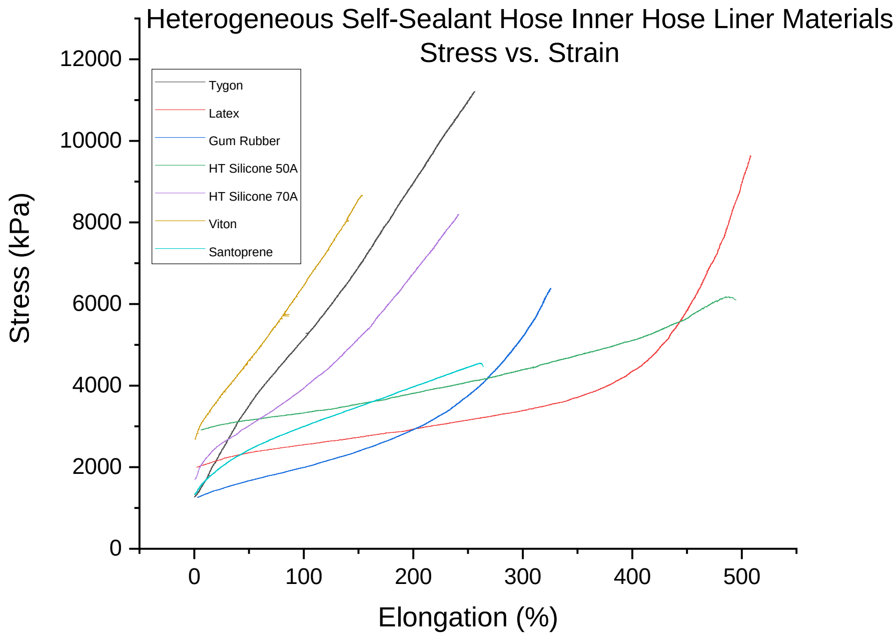


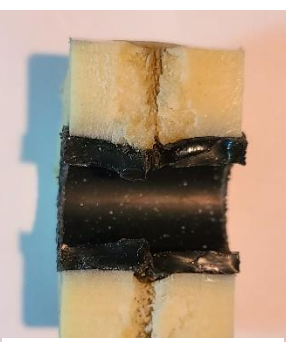
Figure 7. Stress/strain curves of the inner liner hose systems incorporated within the heterogeneous self-sealing hose studies.

Tables 6 and 7 present the physical and T_g properties of the seven different elastomers incorporated as inner liner materials for the heterogeneous self-sealing hose system. Figure 7 presents the stress/strain curves for the seven elastomers. Through comparison of table 8 with figure 7 a correlation can be made between the modulus of the inner liner elastomers at 250% elongation and the self-sealing performance. Modulus values of the inner liner under 10 kPa enabled a self-sealant performance, whereas inner liner hoses with higher modulus did not improve the self-sealing capability of the outer cladding material.

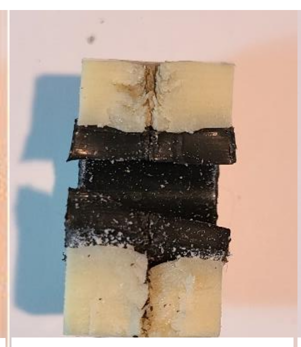
Figure 8 presents bisectional images of the heterogeneous hose systems. A key general observation is the inner liner material typically shows decreased penetration cavity damage in comparison to the outer cladding materials. The only variance as mention previously is the Viton® inner hose that transitions to a brittle state under high strain rate.

Table 8. Heterogeneous hose self-sealing performance score

Test	Material	Inner Hose		Polymer Coating	Self-Sealing Performance	
		Inner Dia	**Outer Dia**		**in**	**out**
1	Latex	0.50	0.63	PTU 300	5	5
2	Latex	0.50	0.75	PTU 300	10	10
3	High-temp Silicone Durometer 50A	0.50	0.63	PTU 300	6	6
4	High-temp Silicone Durometer 50A	0.50	0.75	PTU 300	7	10
5	High-temp Silicone Durometer 70A	0.50	0.63	PTU 300	5	5
6	High-temp Silicone Durometer 70A	0.50	0.75	PTU 300	5	5
7	Gum Rubber	0.50	0.75	PTU 300	7	6
8	Santoprene®	0.50	0.63	PTU 300	10	10
9a	Santoprene®	0.50	0.75	PTU 300	8	8
9b	Santoprene®	0.50	0.75	Dragonshield	10	7
9c	Santoprene®	0.50	0.75	PTU HE	8	8
9d	Santoprene®	0.50	0.75	PTU	7	7
10	Tygon®	0.50	0.63	PTU 300	5	5
11	Tygon®	0.50	0.75	PTU 300	7	5
12	Viton®	0.50	0.75	PTU 300	0	0
13	Viton®	0.50	0.75	PTU 300	2	2


PTU 300/0.63” Latex


PTU 300/0.75” Latex


PTU 300/0.63” HT Si 50A

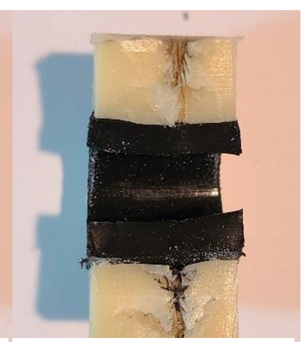

PTU 300/0.75” HT Si 50A

Figure 8. Posttest images of the heterogeneous self-sealant hose systems.

Conclusions

A self-sealant hose incorporating an outer elastomer cladding and an inner soft rubber liner, with a working fluid (water) pressurized to 276 kPa, was successful in enabling a complete self-seal from an incident 0.50 caliber ogive ball round incident at 488 m/s. Performance characteristics for the outer cladding elastomers required a minimum elongation of 100% and minimum elastic limit of 7 MPa. Within the five cladding elastomers that met the minimum criteria, each cladding performed comparable to each other. Inner soft rubber liners supporting complete self-sealing require a low modulus (10 kPa @ 250% elongation) and high elongation.

Homogeneous self-sealing hose systems, using only the outer cladding material, could not enable full self-sealing performance. Penetration cavities formed within the cladding material which enabled some of the working fluid to escape. The application of the soft inner rubber liner exhibits a reduced penetration cavity. The incorporation of heterogeneous hose system enables complete self-seal

For self-sealant hose systems that require operation at low temperatures, the T_g value must be addressed. For self-sealing hose systems having a high T_g the high strain rate from the ballistic impact can shift the elastomer into the glassy state. Within the glassy state the compliancy of the elastomer is reduced and penetration mode of failure shifts to "shear plugging". Within "shear plugging" material is removed from the penetration cavity and greatly reducing self-sealing performance. Many elastomers support both low T_g (silicone rubber -128°C) and characteristic physical properties to support self-sealing performance.

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Notes

The authors declare no competing financial interests.

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