NASA/TM—2010-216263

Material Properties of Three Candidate Elastomers for Space Seals Applications

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May 2010

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Prepared under Contract NNC08CA35C
Prepared under Cooperative Agreement NNC04AA73A

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Space Administration

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Acknowledgments

The authors wish to acknowledge the Parker Hannifin Corporation's Composite Sealing Systems Division (San Diego, CA) and Esterline Kirkhill for supplying the test articles used in this study. Furthermore, the work of OCM Test Laboratories for the elastomer outgas testing, Akron Rubber Development Laboratory for compression set testing, Axel Rubber Products for mechanical material properties testing, Porous Materials Inc. and Mocon Testing Service for material permeability characteristics, and Data Point Labs for the glass transition temperature testing is acknowledged. The financial support of NASA Glenn Research Center is also recognized as portions of this work were completed under NASA Cooperative Agreement NNC04AA73A and NASA Contract NNC08CA35C.

Level of Review: This material has been technically reviewed by technical management.

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Abstract

A next-generation docking system is being developed by the National Aeronautics and Space Administration (NASA) to support Constellation Space Exploration Missions to low Earth orbit (LEO), to the Moon, and to Mars. A number of investigations were carried out to quantify the properties of candidate elastomer materials for use in the main interface seal of the Low Impact Docking System (LIDS). This seal forms the gas pressure seal between two mating spacecraft. Three candidate silicone elastomer compounds were examined: Esterline ELA–SA–401, Parker Hannifin S0383–70, and Parker Hannifin S0899–50. All three materials were characterized as low-outgassing compounds, per ASTM E595, so as to minimize the contamination of optical and solar array systems. Important seal properties such as outgas levels, durometer, tensile strength, elongation to failure, glass transition temperature, permeability, compression set, Yeoh strain energy coefficients, coefficients of friction, coefficients of thermal expansion, thermal conductivity and diffusivity were measured and are reported herein.

Introduction

The Low Impact Docking System (LIDS) (Ref. 1) is a next generation mating system currently being developed by the National Aeronautics and Space Administration (NASA). The LIDS is being designed to operate in various space environments, including low Earth orbit (LEO), the Moon, and Mars. The system is being considered as an improvement over previous and current docking mechanisms used for the human exploration of space. It eliminates the need for high-velocity docking, provides a standard interface that is easily reconfigurable, and supports a wide range of mating operations (Ref. 2).

The current design of the LIDS-to-LIDS interface employs two functionally different halves of LIDS. One of the two mating LIDS halves will be an active docking system while the other will remain passive. The active half contains a gas pressure seal, referred to as the main interface seal, and is shown in Figure 1. This seal is critical as it confines breathable air inside the mated vehicles during the mission. Any volume of gas that is lost past this seal must be replaced, consuming valuable resources.

When undocked, the LIDS main interface seal will be exposed to various space elements, including atomic oxygen (AO), ultraviolet (UV) and particle radiation, and micrometeoroids and orbital debris (MMOD) as no protective cover is planned for the LIDS at this time. Prediction and prevention of the negative space environment effects on the seal materials is part of the ongoing research (Ref. 3). In addition, the LIDS operating environment includes a range of temperatures to which the system may be exposed while performing NASA Constellation missions. The temperature range of the LIDS severely

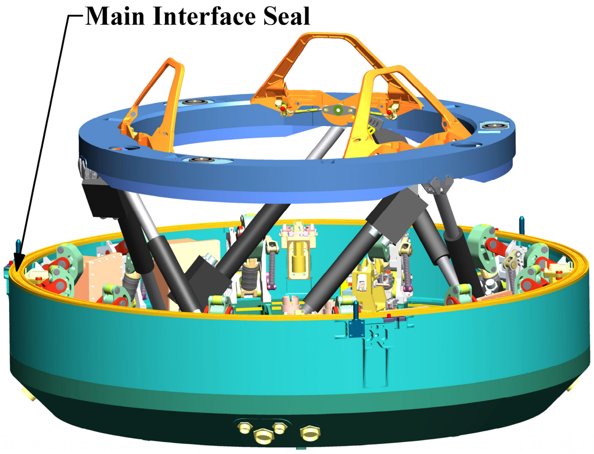

Figure 1.—Illustration of the LIDS.

limits the types of materials that may be used to form the main interface seal. Silicone rubber is the only class of elastomers that is commonly molded into seals, can be cycled repeatedly, and has an operating temperature that encompasses expected LIDS exposure temperatures (–75 to 125 °C).

NASA requires that all materials used for external spacecraft structures exhibit low-outgassing characteristics, namely minimal volatility, total mass loss (TML) less than 1.0 percent and collected volatile condensable materials (CVCM) less than 0.1 percent (Ref. 4). These specifications are enforced to minimize the possibility of contaminating important components or assemblies (e.g., optical instruments and solar arrays) with products liberated from the external spacecraft structures when exposed to vacuum pressure. A limited number of silicone elastomers meet the low-outgas standards.

LIDS is expected to undergo numerous docking and undocking operations. Therefore, to predict the geometry and behavior of the seal molded from the candidate compounds subsequent to many mating and demating cycles, the elastomer's compression set characteristics over a range of temperatures were evaluated. Measured compression set values are expected to provide information about the seal elastomer compound's ability to retain its elastic properties after prolonged compression. The compression set measurements can be used during the seal design phase to ensure that a proper level of seal compression will occur even after the compression set has taken place.

Due to their importance, the chosen mechanical properties of the three candidate silicone elastomer compounds have been outlined here. Materials of three different durometer values were chosen and their hardness values were measured to aid in predicting their possible reaction to the MMOD impacts. The tensile strength and elongation to failure values of the three compounds were measured to ensure that the elastomer will not be damaged during repeated docking and undocking procedures or tear when demated under a high level of adhesion between the elastomer and its mating counterpart. Any damage to the seal, including tearing or pitting, would render the seal unusable for the next mating cycle. The brittle point, brittleness, and glass transition temperature properties were tested to determine the elastomer's usability across the seal's expected operating temperature range (–50 to 50 °C). To identify and prevent possible repercussions from the differences in coefficient of thermal expansion (CTE) between the silicone elastomer and its aluminum retainer ring, the CTE values of the three compounds were measured at three different temperatures. It was observed in previous work (Ref. 5) that at elevated temperatures the difference in CTE values between the S0383–70 and the aluminum retainer ring caused an increase in the force required to fully compress the seals.

In the development phase of the LIDS main interface seal, fabrication of multiple verisons of seal test specimens was considered to be too expensive and time consuming. In addition, testing of various seal designs across the range of operating conditions in a timely manner was also considered to be a challenge. To overcome these obstacles, computational models of the nonlinear mechanics of engineered seal components were completed. To confirm validity of the computational model, certain material properties were measured. These properties included the specific gravity, constants for the Yeoh strain energy function, static and dynamic coefficients of friction, and bulk properties, many of them at temperatures from –50 to 50 °C.

In addition, permeability tests were performed on the three compounds to determine how much gas could leak through the seal material if it was to be used in the interface. Two gas mediums were tested, namely air and helium, to simulate possible operating conditions. These tests were also run at three different temperatures to encompass the expected thermal environments.

The objective of this work was to summarize the properties of three silicone elastomer compounds currently being evaluated as candidate space seal materials. The applicability of these compounds and their responses to the various space environments have been evaluated in other papers (Ref. 3).

Properties

The material properties of three candidate elastomer compounds were investigated. The compounds were supplied by two manufacturers: Esterline (ELA–SA–401) and Parker Hannifin (S0383–70 and S0899–50).

The three elastomers were tested, per ASTM E595, to quantify the TML and CVCM levels. For use aboard spacecraft, NASA requires the TML and CVCM levels to be below the required limits of 1.0 and 0.1 percent, respectively. The test specimens were molded into either of two configurations: 0.21 in. thick sheet or o-ring form. The outgas test results,shown in Table 1, reveal that all three materials met the outgassing requirements. The presented TML and CVCM values for S0383–70 and ELA–SA–401 were averaged from a number of outgas tests performed on materials from various batches. In the case of a S0899–50 compound, a single batch was tested and was procured in a low-outgassing formulation. It should be noted that the compound supplied by Esterline was initially referred to as XELA–SA–401 and subsequently renamed ELA–SA–401.

TABLE 1.—OUTGAS TESTING VALUES FOR THE
CANDIDATE SILICONE ELASTOMER COMPOUNDS

	S0383–70		S0899–50		ELA–SA–401	
	Sheet	o-ring	Sheet	o-ring	Sheet	o-ring
TML, percent						
Average	0.201	0.128	0.320	0.170	0.110	0.105
Standard deviation	0.052	0.077	-------	-------	0.025	0.049
CVCM, percent						
Average	0.080	0.054	0.080	0.050	0.076	0.052
Standard deviation	0.013	0.027	-------	-------	0.025	0.032

To understand the differences between the three candidate elastomer compounds, their general mechanical properties were evaluated. The results are shown in Table 2 along with the particular ASTM standard (Refs. 8 to 13) to which each test complied. It should be noted that the values presented for the S0383–70 compound represent an average over numerous batches.

In addition, the compression set values at a range of test temperatures were evaluated. The tests performed at low temperatures (–50, –25, and 0 °C) followed the guidelines of the ASTM D1229–03 standard (Ref. 14). After the solid button specimens were held unlubricated at 25 percent compression for 70 hr, the compression set was immediately measured upon release. The specimens were then allowed to recover in air at the test temperature for 30 min and the measurement was repeated. The obtained values are shown in Figure 2. Moreover, the compression set test results at –50 °C test temperature with 25 percent compression and various dwell times for ELA–SA–401 and S0383–70 compounds are shown in Figure 3.

TABLE 2.—SUMMARY OF THE GENERAL MATERIAL PROPERTIES OF CANDIDATE COMPOUNDS

Property	Standard	S0383–70	S0899–50	ELA–SA–401
Hardness, Durometer A	*ASTM D2240*	66	50	38
Tensile strength, psi	*ASTM D412*	1163	1106	1050
Elongation, percent	*ASTM D412*	265	532	625
Tear strength, psi	*ASTM D624 B*	-------	-------	65
Specific gravity	*ASTM D297*	1.28	1.18	1.13
Brittle Point, °F	*ASTM D2137*	-------	-------	–177
Modulus at 100 psi	----------------	593	128	-------
Brittleness 3 min. –120 °F	*ASTM D2137 A*	Pass	-------	-------
Glass transition temperature, °C	*ASTM D5279-01*	–110	–110	–110

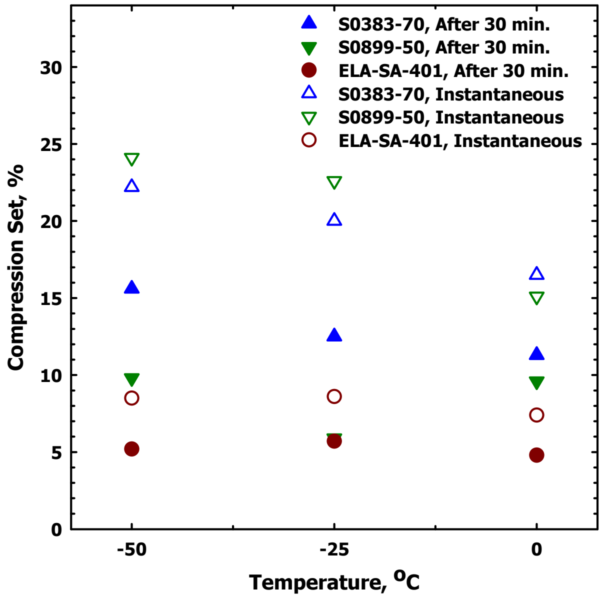

Figure 2.—Compression set values of three candidate elastomer compounds at low test temperatures with two recovery times and 70 hr dwell time.

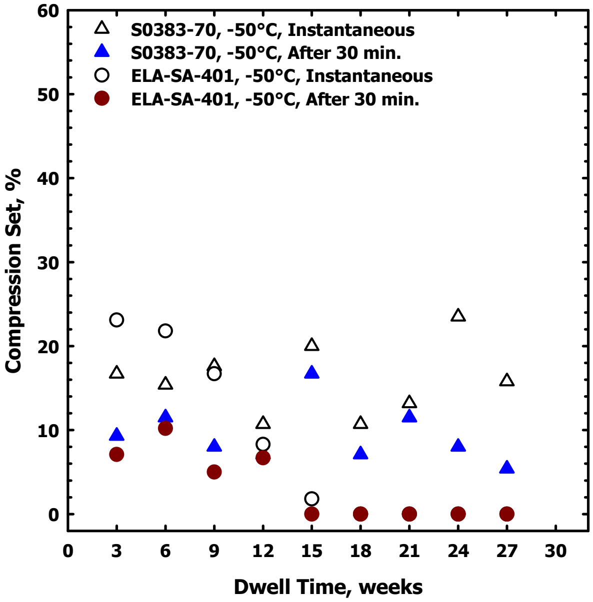

Figure 3.—Compression set values of two candidate elastomer compounds at refrigerated test temperature with two recovery times.

The room and elevated temperature compression set tests complied with the ASTM D395–03 standard, method B (Ref. 15). The solid buttons were compressed 25 percent and aged at the given test temperature for 70 hr. Subsequently, the specimens were permitted to recover 30 min prior to post-test measurements. The low, room, and elevated temperature results after the 30 min recovery period are shown in Figure 4. Additionally, at four of the temperatures, namely –50, 23, 50, and 125 °C, compression set values for a number of dwell times were obtained for ELA–SA–401 and S0383–70 compounds. These values, measured 30 min after release to accommodate recovery, are presented in Figure 5.

The compression set tests at four of the temperatures with 70 hr dwell time considered in Figures 2 and 4, namely at –50, 25, 50, and 125 °C, were repeated. The resulting compression set values were found to be significantly different in some cases, see Figure 6. All of the tests were performed at the same accredited laboratory under the same conditions. Therefore, the differences in the observed values are assumed to have resulted from testing different material batches, which was considered during the design phase of LIDS main interface seal.

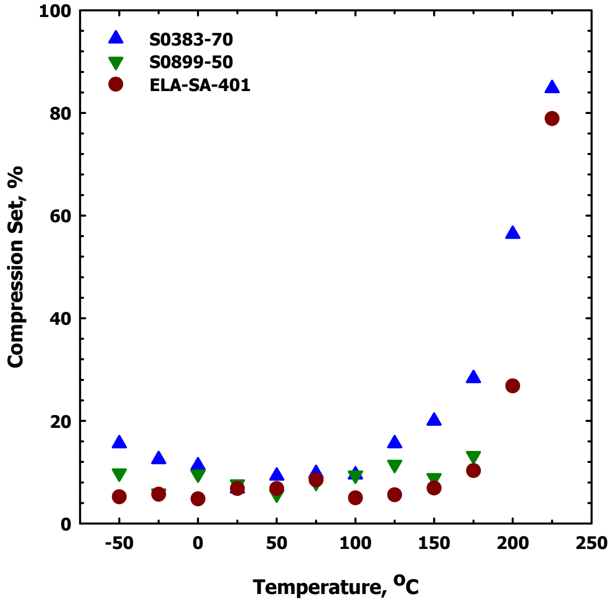

Figure 4.—Compression set values of three candidate elastomer compounds at low, room and elevated temperatures with 70 hr dwell time.

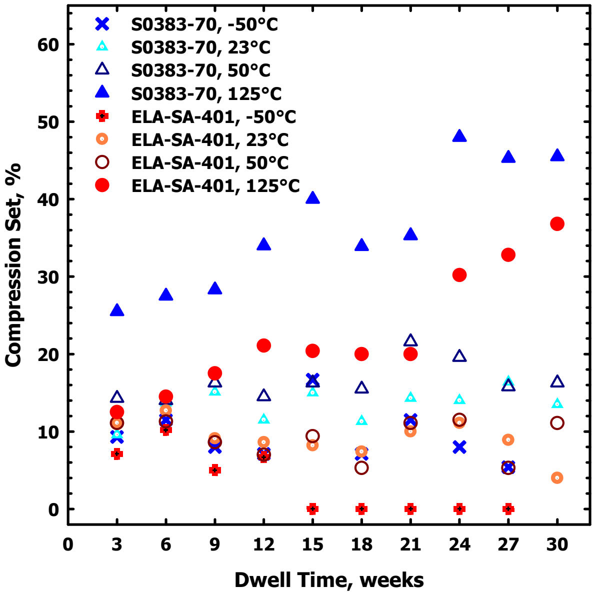

Figure 5.—Compression set values of two candidate elastomer compounds at low, room and elevated temperatures.

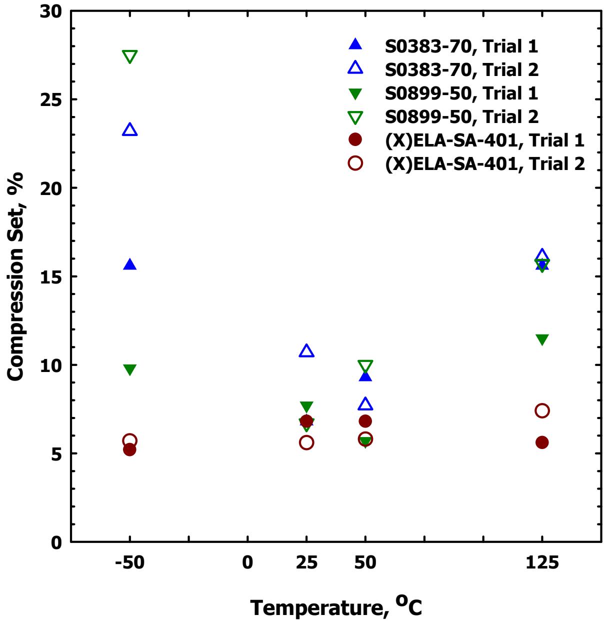

Figure 6.—Differences in compression set measurements of the three candidate compounds with 70 hr dwell time.

Permeablity diffusion coefficients of two candidate elastomers, S0383–70 and ELA–SA–401, were tested with helium gas at standard conditions. The results are shown in Table 3. As presented, the S0383–70 compound exhibited the least diffusion permeablity thus suggesting that less gas would leak through a seal made from that material. Additionally, the permeation transmission rate of the candidate S0383–70 elastomer of two thicknesses was tested with two gases: air and helium, and at three temperatures: –12, 23, and 50 °C. The results are shown in Table 4.

Tables 5 to 8 present additional material properties that were measured for use in numerical modeling of the candidate seal materials.

TABLE 3.—PERMEABILITY DIFFUSION COEFFICIENTS OF TWO CANDIDATE MATERIALS

	Diffusion Permeability, scc*cm/min/cm^2	
Material	Trial 1	Trial 2
S0383–70	2.1879E-04	2.6432E-04
ELA–SA–401	4.8076E-04	4.6034E-04

TABLE 4.—TRANSMISSION RATE THROUGH PERMEATION OF S0383–70 ELASTOMER COMPOUND SAMPLES

Sample thickness, inch	Test temperature, °C	Air transmission rate, cc/(m^2*day)		Helium transmission rate, cc/(m^2*day)	
		Sample 1	Sample 2	Sample 1	Sample 2
0.21	50	2664	2555	4632	4581
	23	1944	1887	2337	2238
	–12	1177	1165	915	879
0.08	50	8705	8133	13380	13150
	23	5981	5551	7862	7748
	–12	3142	2946	3084	3076

TABLE 5.—CONSTANTS FOR THE YEOH STRAIN ENERGY FUNCTION (REF. 16) AT DIFFERENT TEMPERATURES (c_1 in MPa, d_1 in MPa^{-1})

Material	Temperature, °C	c_1	c_2	c_3	d_1	d_2	d_3
S0383–70	–50	0.6494	–0.3435	0.4189	0.00092	1.51E-05	–4.56E-07
	23	0.4877	–0.1630	0.1368	0.00125	2.51E-05	–1.71E-06
	50	0.5128	–0.1766	0.1395	0.00121	4.99E-05	–9.22E-06
	125	0.7563	–1.2003	8.4267	0.00153	4.97E-05	–1.08E-05
S0899–50	–50	0.2839	–0.0735	0.0385	0.00114	2.51E-05	–1.44E-06
	23	0.2693	–0.0644	0.0278	0.00112	8.38E-05	6.43E-06
	50	0.2505	–0.0391	0.0157	0.00138	3.52E-05	–2.97E-06
	125	0.2668	–0.0491	0.0185	0.00162	4.70E-05	–6.93E-06
ELA–SA–401	–50	0.1760	–0.0446	0.0347	0.00111	2.69E-05	–1.65E-06
	23	0.1631	–0.0282	0.0174	0.00114	4.34E-05	–7.29E-06
	50	0.1696	–0.0277	0.0173	0.00091	–2.55E-04	1.32E-06
	125	0.1975	–0.0301	0.0199	0.00159	3.47E-05	–3.30E-06

TABLE 6.—STATIC AND DYNAMIC COEFFICIENTS OF FRICTION (SAME MATERIAL) AT DIFFERENT TEMPERATURES

Temperature, °C	Normal pressure, kPa	S0383–70		S0899–50		ELA–SA–401	
		Static	Dynamic	Static	Dynamic	Static	Dynamic
–50	14	1.74	0.93	1.92	0.99	2.90	2.26
	70	1.39	1.10	1.35	0.96	2.16	2.01
	700	0.85	0.75	0.80	0.61	0.85	0.82
23	14	1.04	0.73	1.78	0.78	2.43	2.15
	70	0.76	0.67	1.25	0.73	1.72	1.57
	700	0.64	0.56	0.53	0.37	0.54	0.52
50	14	1.10	0.73	1.64	0.80	3.88	3.62
	70	0.85	0.76	1.16	0.82	2.04	1.71
	700	0.61	0.59	0.67	0.48	0.50	0.49
125	14	0.85	0.63	1.25	0.87	2.04	1.66
	70	0.68	0.62	0.96	0.77	1.54	1.36
	700	0.47	0.44	0.51	0.43	0.43	0.41

TABLE 7.—COEFFICIENT OF THERMAL EXPANSION AT DIFFERENT TEMPERATURES

	°C$^{-1}\times10^{-6}$		
Material	–50 °C	23 °C	50 °C
S0383–70	371	355	348
S0899–50	317	330	321
ELA–SA–401	430	389	374

TABLE 8.—BULK PROPERTIES AT 23 °C

Material	Thermal conductivity, κ, W/mK	Thermal diffusivity, α, mm^2/s	Heat capacity, c, MJ/m^{3}K	Density, ρ (g/cm^3)
S0383–70	0.334	0.237	1.41	1.24
S0899–50	0.332	0.229	1.45	1.13
ELA–SA–401	0.241	0.161	1.50	1.17

Summary

NASA is currently developing a Low Impact Docking System in support of future Constellation missions. Three elastomer compounds (S0383–70, S0899–50, and ELA–SA–401) were considered herein as candidate materials for the LIDS main interface seal meant to prevent breathable air from escaping into the vacuum. The important thermo-mechanical and chemical property characteristics of these silicone compounds were presented here, including outgas levels, durometer, tensile strength, elongation to failure, glass transition temperature, diffusion permeability, Yeoh strain energy coefficients, coefficients of friction, coefficient of thermal expansion, thermal conductivity and diffusivity. These properties were measured in support of next-generation seal designs and numerical modeling activities.

All three candidate materials were found to meet the low-outgas requirements enforced by NASA. In addition, the compression set values of the materials were found to increase significantly with test temperature, for the samples tested above refrigerated temperatures, and increase with decreasing temperature for samples tested below 0 °C. The increase of compression set with dwell time was also considered. No significant change was observed for samples tested at the room and refrigerated temperatures over time; however, an increasing trend in compression set values with dwell time was noted for the materials tested at the 125 °C.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 01-05-2010	**2. REPORT TYPE** Technical Memorandum	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE
Material Properties of Three Candidate Elastomers for Space Seals Applications

5a. CONTRACT NUMBER
NNC08CA35C

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bastrzyk, Marta, B.; Daniels, Christopher, C.; Oswald, Jay, J.; Dunlap, Patrick, H., Jr.; Steinetz, Bruce, M.

5d. PROJECT NUMBER
NNC04AA73A

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 644423.06.31.04.01.03.22

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17249

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2010-216263

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Categories: 27 and 37
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A next-generation docking system is being developed by the National Aeronautics and Space Administration (NASA) to support Constellation Space Exploration Missions to low Earth orbit (LEO), to the Moon, and to Mars. A number of investigations were carried out to quantify the properties of candidate elastomer materials for use in the main interface seal of the Low Impact Docking System (LIDS). This seal forms the gas pressure seal between two mating spacecraft. Three candidate silicone elastomer compounds were examined: Esterline ELA-SA-401, Parker Hannifin S0383-70, and Parker Hannifin S0899-50. All three materials were characterized as low-outgassing compounds, per ASTM E595, so as to minimize the contamination of optical and solar array systems. Important seal properties such as outgas levels, durometer, tensile strength, elongation to failure, glass transition temperature, permeability, compression set, Yeoh strain energy coefficients, coefficients of friction, coefficients of thermal expansion, thermal conductivity and diffusivity were measured and are reported herein.

15. SUBJECT TERMS
Elastomers; Seal; Outgassing; Compression set; Permeation; Low impact docking system

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	14	**19b. TELEPHONE NUMBER** *(include area code)* 443-757-5802