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SUITABILITY OF SILICONE FOR SOFT-ROBOTIC EXPLORATION OF TERRESTRIAL AND EXTRATERRESTRIAL OCEAN WORLDS

This work revisits relevant mechanical and chemical properties of silicone rubber — Ecoflex in this study — to assess its suitability and viability for use in soft-robotic explorer construction and subsequent deployment and as a sealant for communication beacons, sensor pods, and other electronics in extreme planetary liquid environments, such as the depths of Earth's oceans and extraterrestrial ocean worlds. Strain at a range of temperatures, as an indicator for operational durability, was tested under various endpoint clamp forces for several compound ratios. The temperature range at which silicone rubber remains pliable was assessed to determine its deployability. The re-binding property of cured silicone rubber samples with newly curing samples was investigated for its potential for additive manufacturing in soft robotics. Finally, the dissolution resistance, non-polarity, and electrical non-conductivity of silicone rubber were studied to assess its suitability for sealing electronics to be submerged in the salt water of both ocean and saturated salinity, as well as in hydrocarbon liquids.

This work highlights critical aspects of silicone rubber for use in the construction, coating, and deployment of future soft robotic extraterrestrial liquid body explorers: The chosen silicone rubber Ecoflex is an electrically non-conducting sealant and pliable soft robotics material for temperatures above –50 °C, deployable in earthly extreme aqueous environments. Moreover, this work lays the foundation, albeit likely with different (silicone) rubbers/polymers due to much lower temperatures, for the robotic exploration of extraterrestrial liquid environments on ocean worlds, such as the hydrocarbon lakes on Titan and the putative subsurface oceans on Europa, Titan, and Enceladus.

Keywords: *Soft robotics, Communication beacons, Sensor pods, Extreme liquid environments, Ocean worlds, Material/chemical/electrical property testing, Polymers and Plastics.*

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1. INTRODUCTION

Subsurface oceans on planetary bodies known as *ocean worlds*, such as Jupiter's moon Europa (to be visited in April 2030 by NASA's Europa Clipper spacecraft slated to launch in October 2024 [14]) and Saturn's moons Titan and Enceladus, have been postulated based on varying degrees of evidence since the 1980s [11], but there has been no direct confirmation to date through observation let alone in-situ exploration (e.g., [7, 8]). Because these subsurface environments are largely shielded from radiation, and combined with the hypothesized presence of water, they would be prime candidate locales for astrobiological exploration, i.e., the quest for finding extant or fossilized life.

Underwater autonomous vehicles are currently dominated in design by rigid frames [15], which presents an inherent disadvantage in autonomous underwater (or other liquid) exploration due to a limited ability (or lack thereof) to bend through smaller apertures for more ambitious or extensive in-depth exploration. As more research into the development of flexible explorers, such as the PoseiDRONE [1] or the Soft Robotic Fish [10], push the boundaries of soft-robotics as a more effective paradigm for liquid environment exploration, this paper revisits experimentally the suitability of silicone rubber for constructing soft-robotic explorers (e.g., [2—4, 12, 13]), and sealing of associated communication beacons and sensor pods (e.g., [8]) — all in the context of *extreme planetary liquid environments*, such as the depths of Earth's oceans and extraterrestrial ocean worlds. To that effect, the elasticity, resilience at lower temperatures, re-bonding ability, chemical polarity, and electrical conductivity are reexamined.

2. MATERIALS AND METHODS

2.1. Ecoflex Overview. Ecoflex™ 00-30 (referred to as Ecoflex in the following) was chosen as a stand-in for other rubbers/polymers. Ecoflex is a proprietary silicone rubber sold by Smooth-On, Inc. [6], which is made by mixing equal parts of 2 compounds, A and B, by volume or mass because of similar density. Mixing different ratios of A and B results in Ecoflex with increasing elasticity as the percentage of compound A decreases. It cures in approximately 4 hours at room temperature, according to manufacturer instructions. Ecoflex rubber was selected due to known properties ideal for soft robotics, which include, but are not limited to (e.g., [2—4, 12, 13]): (1) resistance to freezing at moderate sub-zero Celsius temperatures, (2) high degree of elasticity and pliability, and (3) ease of casting. In the past, soft robotics applications for Ecoflex rubber range from use in claw machines [16] to a pneumatic robotic fish [20], which provided an additional motivation to investigate it for our purposes: the suitability (re-)assessment of silicone rubber for soft robotic explorers for extreme liquid environments found both on Earth and on extraterrestrial ocean worlds, including its resistance to saltwater and hydrocarbon corrosion as well as extremely low temperatures.

2.2. Strain Testing for Various Temperatures and Compound Ratios. 2.2.1. ***Ecoflex Compound Ratios.*** Ecoflex rectangular prisms (1.25 × 1.00 × 7.50 cm; Figure 1) were cast at three different A:B mixing ratios with 0.01g accuracy: 20 % : 80 %, 50 % : 50 %, and 80 % : 20 %, with four prisms cast from the same batch for each mixing ratio.

2.2.2. ***Strain Testing Setup.*** The Ecoflex prisms were clamped at each longitudinal end, with the edge of each prism aligned with and clamped between optical table post clamps to a force of 5 ± 0.25 N, 10 ± 0.25 N, and 15 ± 0.25 N, measured with a force gauge (Figure 1, *left*). One post was moved (Figure 1, *center* and *right*) using a Velmex stepper motor for continuous and consistent rate of pull (i.e., load rate) of ~3.2 mm/sec (see specification for BiSlide model E50 on page 11 in [18]) until one end slipped out of the clamp grip. The total deformation for the strain was measured from the outer endpoints of the post clamps (yellow lines in Figure 1, *right*). Strain measurements were taken once for each of the four prisms per chosen mixing ratio (section 2.2.1) at each temperature region (section 2.2.3) for each of the three clamp forces.

2.2.3. ***Temperature Conditions.*** Each strain measurement was conducted once per beam at each of the following beam temperature conditions: approximately –5 °C to 0 °C, room temperature ~22.4 °C, and approximately 39 °C to 40 °C. Temperature fluctuations on both extremes were due to the challenge of conducting low and high temperature experiments in

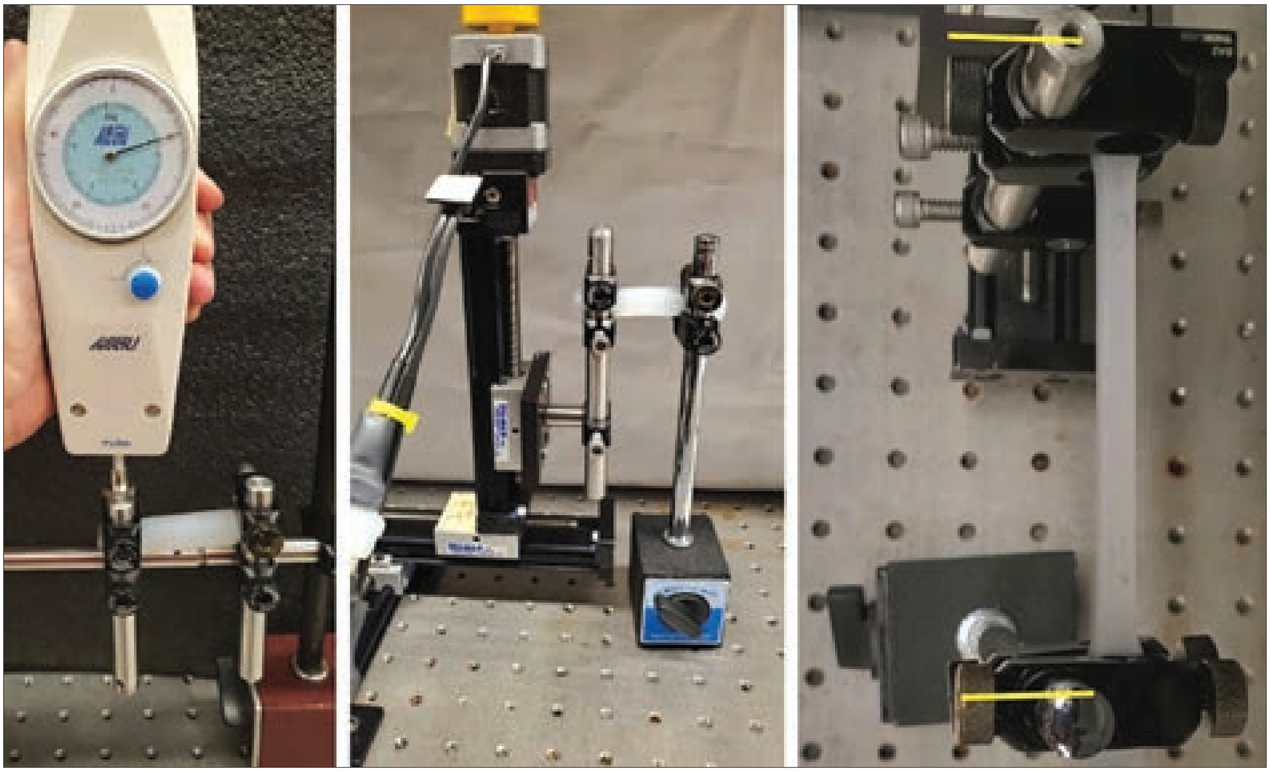

Figure 1. Left: A force gauge is used to compress the Ecoflex prism to correct force, which is then set by screwing post clamps to posts (*center*). All posts are held in place by screws or magnetic bases on an optical table. *Right:* In-progress stretching of Ecoflex prism using lateral stepper motor from a top-down perspective

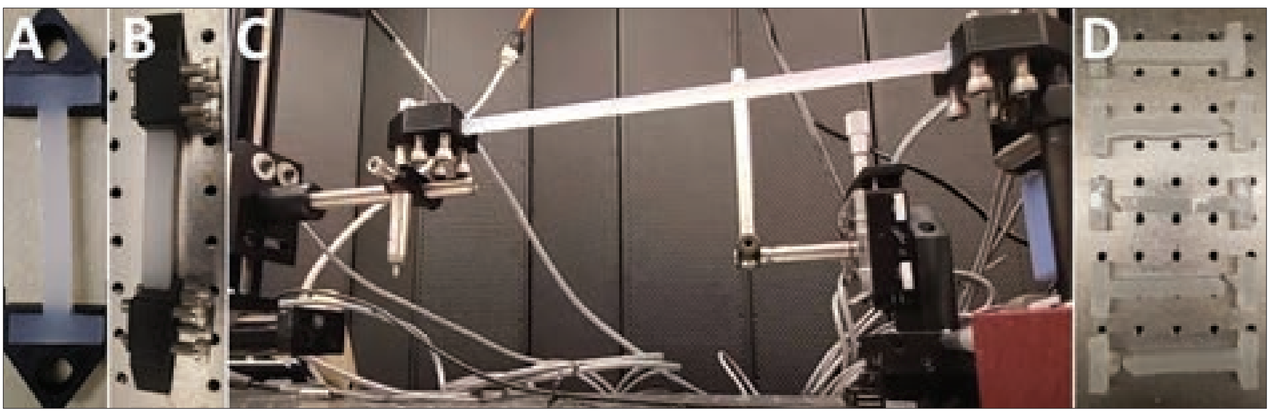

Figure 2. Original I-beam prism in an open (*A*) and threaded 3D-printed clamp (*B*). A magnetic base held one end of the I-beam prism while the other end was pulled longitudinally by a Velmex motor (*C*). The I-beams all broke near the edges (*D*)

a constant temperature environment. Samples were moved from either a freezer or a heated water bath to the testbed and tested immediately. Temperatures for the samples were taken immediately prior to testing using a non-contact infrared temperature sensor.

2.3. Room Temperature Stretching to Failure. A different set of Ecoflex prisms was tested for stretch to breaking point in order to compare to the specification sheet published by Smooth-On, Inc., which claims a breaking elongation of 900 % for this variant

Figure 3. Before and after encapsulation of communication beacon electronics in Ecoflex

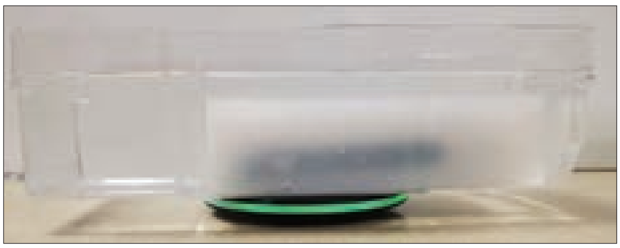

Figure 4. Communication beacon encased in Ecoflex and submerged in the salt water of 3.5 % salinity or saturated salinity at room temperature (~22.4 °C), charged continuously by a wireless charger underneath, communicating to and controllable from a PC via VNC through WiFi

of Ecoflex at room temperature (~23 °C) [6]. This elongation percentage was only tested for the 50 % : 50 % mixture since that is the only one officially supplied on the specification sheet. To that effect, five I-beam prisms were cast, with screw-clamp anchors to hold them at each optical post (Figure 2, *A—C*). The beams were stretched longitudinally using the Velmex stepper motor until completely torn anywhere along the beam (Figure 2, *C* and *D*).

2.4. Very Low Temperature Testing. Ecoflex was tested for its freezing and thawing behavior at low to very low temperatures to simulate environments below water freezing temperature in which a subsurface liquid explorer may be deployed. A total of five prisms of Ecoflex at mixing ratios 10 % : 90 %, 20 % : 80 %, 50 % : 50 %, 80 % : 20 %, and 90 % : 10 % were first placed in a conventional freezer and chilled to –7.5 °C and subsequently returned to room temperature. The same prisms were then placed in a laboratory freezer and kept at –20 °C. After temperature equilibration, they were again returned to room temperature. Next, the same prisms were placed in a –80 °C freezer and later returned to room temperature. Finally, the same prisms were submerged in –196 °C liquid nitrogen and subsequently also returned to room temperature.

2.5. Re-bonding Ability. A shorter piece of cured 50 % : 50 % Ecoflex rubber was placed into a longer mold. The empty spaces on both ends were then filled in with a fresh mix of 50 % : 50 % Ecoflex liquid and allowed to cure within the same day (Figure 7). The same procedure was repeated with increasing time between curing the initial piece and filling the voids up to and including 6 days.

2.6. Dissolution Resistance, Non-Polarity, and Electrical Non-Conductivity. The ***dissolution resistance*** with respect to polar and non-polar liquids was tested by long-term submersion of Ecoflex in water/salt water and mineral oil, respectively, for several weeks.

The ***chemical non-polarity*** of Ecoflex was tested during the Ecoflex compound mixing process using polar/water-soluble food dyes. Once compounds A and B were thoroughly mixed, drops of aqueous food dye were added and mixed in for miscibility testing before curing.

The ***electric non-conductivity*** of Ecoflex was tested by building a small Raspberry Pi-based communication beacon consisting of a Raspberry Pi Zero W, a 5000 mAh power bank, a USB A to micro-USB cable, and a wireless charging receiver coil. The communication beacon electronics were submerged directly into liquid Ecoflex before curing (Figure 3), i.e., the Raspberry Pi had all of its contacts openly exposed, such that any electric conductivity within the Ecoflex would result in immediate short-circuiting and device failure. After the curing process, the power bank was wirelessly charged and turned on.

2.7. Hermeticity. As a final test of resilience as an insulating material, i.e., ***hermeticity***, the communication beacon from Figure 3 was placed in a small tank of water at 3.5 % salinity (weight/weight) to match Earth's ocean salinity (Figure 4) [19], and in a subsequent test at saturated salinity at room temperature (26.3 % weight/weight [17]). In both cases, salt (NaCl) was used. The beacon was connected to a laptop wirelessly via Virtual Network Computing (VNC) using RealVNC and monitored for continuous uptime.

3. STRAIN CALCULATION

Strain calculations were performed using the mechanical strain formula: $\varepsilon = \Delta L / L_i$, i.e., the ratio of change in length of a piece of material as a result of stretching and the original length of that same piece of material. So $\varepsilon = 1$ represents 100 % elongation and $\varepsilon = 0.1$ represents 10 % elongation with respect to the original length, respectively (Figure 5).

4. RESULTS

4.1. Strain Testing Across Multiple Temperatures and Clamp Forces. In general, increased amounts of compound A led to a stiffer Ecoflex (Figure 5), although the difference between 20 % A and 50 % A was less pronounced than the one between 50 % A and 80 % A (Figure 5). Moreover, the strain results appeared to be largely temperature independent (within the measured temperature range) due to the size of the error bars (note: the increasing trendline at 5 N is explained by a single outlier in both 20 % A and 50 % A trials).

4.2. Room Temperature Stretching to Failure. The five I-beam prisms (at 50 % : 50 % mix) were stretched to the breaking point, which occurred at an elongation percent of 553.3 ± 20.5 %. All five prisms broke at a point near the clamping region of the I-beam along the longest axis (Figure 2, *D*).

4.3. Very Low Temperature Testing. The Ecoflex samples did not freeze at either 0 °C or –20 °C across all 5 tested ratios of A : B. All tested ratios froze at –80 °C (Figure 6, *left*). However, this freezing was fully reversible, i.e., all tested ratios returned to pre-freezing pliability once thawed to room temperature. When room temperature samples from all 5 ratios were submerged in –196 °C liquid nitrogen (Figure 6, *center*), the samples froze and shattered (Figure 6, *right*). Moreover, when the samples were removed and allowed to return to room temperature, they shattered into even smaller pieces. All samples, including the smaller pieces, eventually returned to pre-freezing pliability at room temperature.

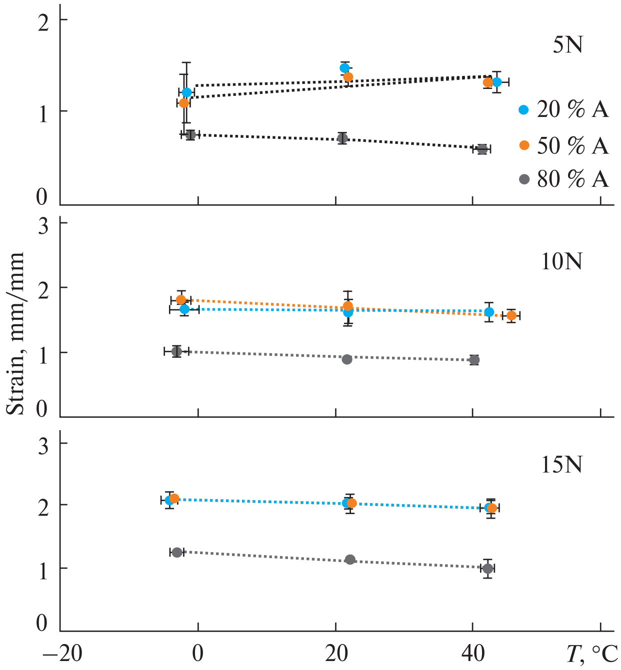

Figure 5. The plot of the measured strain of prisms with different % A compositions at 5N (*top*), 10N (*middle*), and 15N (*bottom*) of clamping force. Dotted lines are the linearly fit trendlines

4.4. Re-bonding Ability. As shown in Figure 7, after new Ecoflex cures adjacent to an already cured piece, the resulting prism is near indistinguishable and does not separate or break off when stressed (i.e., when pulled apart) but rather behaves as if it originated from a single curing session. This illustrates the advantage of using Ecoflex since it allows the construction and encapsulation of soft-robotic, communication beacon, and sensor pod electronic components in an additive manufacturing manner (Figure 3). The re-bonding ability of newly curing to already cured Ecoflex, i.e., at least up to 6 days old samples, was successful (Figure 7).

4.5. Dissolution Resistance, Non-Polarity, and Electrical Non-Conductivity. An important property of the Ecoflex rubber is that it does not interact with polar and non-polar solvents:

• *Dissolution resistance in polar liquids:* Many of the liquids which soft-robotics would explore are known

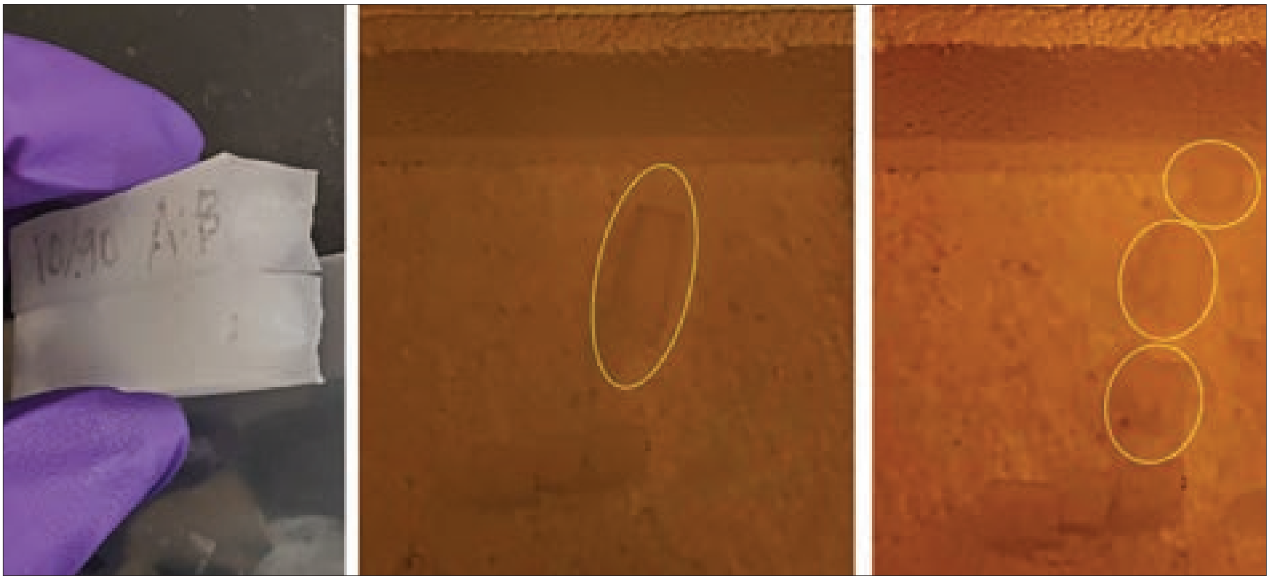

Figure 6. The frozen core of 2 thawing Ecoflex samples can be observed after freezing in a –80 °C freezer (*left*). Before and after (*center* and *right*) of a piece of Ecoflex being frozen in a liquid Nitrogen bath (–196 °C) — note how the sample breaks into 3 smaller pieces. (Note: color corrected for better contrast for *center* and *right* subfigure)

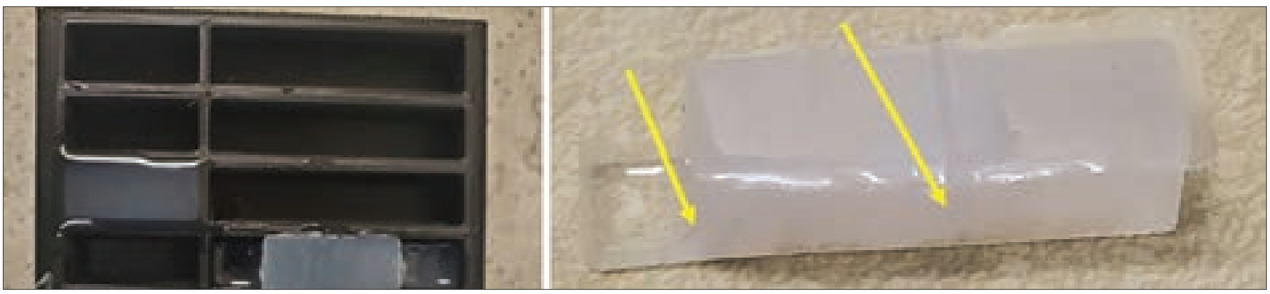

Figure 7. Left: Recasting ends of a prism of Ecoflex rubber: a prism is first cured in the left column of the mold, then placed in a longer mold whose empty spaces to the left and right of the prism are filled with more Ecoflex. *Right:* The interface between already cured and newly cured Ecoflex is indicated by the two yellow arrows

to be polar (such as Earth's own bodies of water), or are suspected to be so on extraterrestrial worlds [11], such as Europa's and Enceladus' putative subsurface oceans. Thus, there is a need for a material that will be resistant to degradation by dissolution. The exposure of cured Ecoflex to water with or without salt at different salinity levels showed no signs of degradation/corrosion through dissolution for at least 21 days (see also section 4.6 below).

• *Dissolution resistance in non-polar liquids:* Since the lakes on Titan's surface are hydrocarbon-based, cured Ecoflex was also exposed to, i.e., soaked in, mineral oil as a stand-in for hydrocarbon liquids and exhibited no degradation/dissolution effects either over a period of at least two months.

• *Pre-cure non-polarity:* In all spots with food dye, the Ecoflex was curing around dye-formed pockets, demonstrating that the material is indeed non-polar during the curing process, i.e., while Ecoflex is still liquid (Figure 8), and, of course, once cured.

• *Non-conductivity:* For soft robotic electronics to operate in a coat of Ecoflex, the rubber would need to encapsulate electronics, such as a Raspberry Pi, without permitting any short-circuiting. Our experiments showed that the Raspberry Pi functioned perfectly, retaining its ability to communicate wirelessly from within a block of solid Ecoflex rubber for approximately 6 hours with a fully charged 5000 mAh power bank.

4.6. Hermeticity. With regards to hermeticity, the ability of the communication beacon to transmit for an extended period of time while underwater (Figure 9) was validated, again for approximately 6 hours, when powered by a fully charged 5000 mAh power bank. Long-term hermeticity in a harsher environment, i.e., saturated salt water, was confirmed by maintaining continuous wireless VNC communication with the beacon (charged wirelessly) for at least 21 days, indicating that Ecoflex did not degrade at all to cause water intrusion. This showcases the potential for Ecoflex as an insulating/encapsulating material in soft robotic lake/ocean explorers and beacons/sensors because of its ability to encapsulate electronics in a soft material while protecting these electronics from short-circuiting in an electrically conductive liquid environment.

5. DISCUSSION & CONCLUSIONS

The silicone rubber Ecoflex 00-30 appears to be an excellent encapsulation option for soft-robotics, communication beacon, and sensor pod applications. Pliability at low temperatures down to at least –20 °C is preserved, more than sufficient for any earthly aqueous exploration missions (see below) and potentially for missions to putative subsurface oceans (if water-based) on extraterrestrial planetary bodies, such as Europa and Enceladus. In particular, for the latter, the presence of a liquid water phase may depend, at least in part, on the concentration of solutes in water (e.g., brines), which can significantly contribute to freezing point depression [5].

For the strain testing, a lower temperature limit of ~–5 °C was chosen, primarily to account for all terrestrial ocean environments: According to the National Oceanic and Atmospheric Administration (NOAA), the lowest ocean temperatures on Earth are about –2 °C [9]. For exploratory operations in extraterrestrial oceans, e.g., on Titan, Europa, and Enceladus, the temperature ranges may/will be well below –5 °C, where Ecoflex^{TM} 00-30 will likely be frozen per the specification sheet published by Smooth-On, Inc., which lists –53°C as the minimum useful

Figure 8. A small sample of Ecoflex with drops of red food dye, whose primary ingredients are water and propylene glycol, i.e., both polar molecules

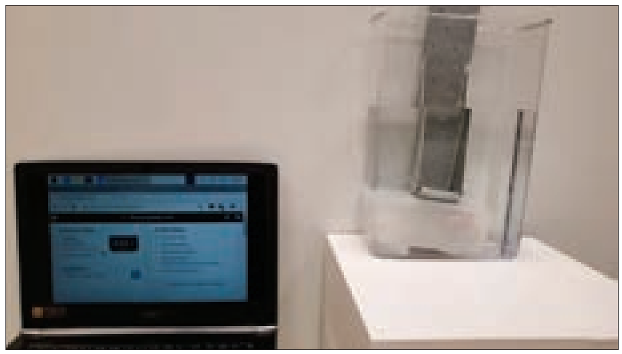

Figure 9. Raspberry Pi unit encased in Ecoflex (Figure 3) and submerged in water, communicating to and controllable from a PC via VNC over WiFi

temperature [6]. However, although not experimentally verified, strain performance similar to the results shown in Figure 5 is expected to be maintained down to around –50° C because of the indicated minimal dependence on temperature.

While prolonged exposure (in our case up to two months) of cured Ecoflex to mineral oil, as a stand-in for hydrocarbon liquids, produced no degradation/dissolution effects, Ecoflex may not be suitable for deployment in Titan's hydrocarbon lakes as their temperature likely is around 94 K (i.e., –179 °C; [11]). In fact, our freezing tests conducted at –80 °C and –196 °C, respectively, confirmed that Ecoflex^{TM} 00-30 is already frozen as expected (see above). Therefore, different (silicone) rubbers or polymers that remain flexible at such low temperatures will have to be used. Notwithstanding the above, Ecoflex, as a stand-in for such (silicone) rubbers or polymers, may pave the way for soft-robotic explorers for extreme planetary liquid environments.

Ecoflex exhibits good elasticity, and despite not being able to replicate the manufacturer-advertised 900 % elongation at breaking point, it was found that even keeping under approximately 550 % elongation still affords soft-robotic explorer flexing and deforming capabilities, both for mobility and accessibility of spaces impossible to reach for a rigid robotic explorer. With this soft-robotic framework in mind, the influence of load frequency, i.e., how often the Ecoflex prisms were stretched within a fixed period of time, on strain was not studied because we do not expect bending/flexing, deforming, and stretching/compressing to occur on a rapid or frequent basis (e.g., at frequencies >1 Hz) during operation of a soft-robotic explorer (or components thereof), let alone during the deployment and/or usage of communication beacons, sensor pods, and other electronics in extreme planetary liquid environments. As such, we were more concerned with strain ability as a function of temperature rather than the cracking susceptibility of Ecoflex as a function of load dynamics, i.e., repetitive application of load on shorter time scales. In our strain test experiments, we repeated the strain experiments on the same Ecoflex prism with minutes in between tests, respectively.

Finally, Ecoflex protects electronics from external, potentially conductive, aqueous, or other liquid environments very effectively while permitting those same electronics to work when directly in contact with, i.e., encased in, Ecoflex. This has been validated by our tests in which the Ecoflex permitted communication with a PC via WiFi both in air and submerged in water, including water at ocean salinity and saturated salinity.

In summary, silicone rubber (Ecoflex^{TM} 00-30 in our case) is a robust yet pliable, easy to use material, which appears to be an excellent candidate for constructing (potentially via additive manufacturing), coating, encasing, and sealing soft robotic explorers and associated communication and sensor components (e.g., [8]) for extreme liquid environments on Earth and extraterrestrial ocean worlds, such as Europa, Titan, and Enceladus.

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COMPETING INTERESTS

The authors report no financial interests in the work presented here.

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США

ПРИДАТНІСТЬ СИЛІКОНОВОЇ ГУМИ М'ЯКОЇ РОБОТОТЕХНІКИ ДЛЯ ДОСЛІДЖЕНЬ ЗЕМНИХ І ПОЗАЗЕМНИХ ОКЕАНСЬКИХ СВІТІВ

У роботі розглядаються відповідні механічні та хімічні властивості силіконової гуми — Ecoflex — для оцінки її придатності та стійкості для використання в створенні та подальшій експлуатації м'яких роботів-дослідників, а також як герметик для комунікаційних маяків, сенсорних блоків та іншої електроніки, що використовується в екстремальних планетарних рідких середовищах, таких як глибини океанів Землі та позаземні океанські світи. Деформація матеріалу в діапазоні температур, як показник довговічності експлуатації, була перевірена під різними кінцевими зусиллями затиску для кількох складових співвідношень. Діапазон температур, при якому силіконова гума залишається гнучкою, оцінювали для визначення її здатності до розгортання. Властивість повторного зв'язування затверділих зразків силіконової гуми з нещодавно затверділими зразками була досліджена на предмет її потенціалу для використання в м'якій робототехніці. Були вивчені стійкість до розчинення, неполярність і електронепровідність силіконової гуми, щоб оцінити її придатність як герметика електроніки для занурення в солону воду океану або інших насичених сольових середовищ, а також у вуглеводневі рідини.

Особливу увагу в роботі приділено критичним аспектам силіконової гуми для використання в конструюванні, покритті та розгортанні майбутніх м'яких роботів-дослідників рідинного інопланетного життя: обрана силіконова гума Ecoflex є електронепровідним герметиком і гнучким м'яким робототехнічним матеріалом для температур вище –50 °C, придатним для розгортання в земних екстремальних водних середовищах. Крім того, ця робота закладає основу, хоча з іншими (силіконовими) каучуками/полімерами через значно нижчі температури, для роботизованого дослідження позаземних рідких середовищ в океанських світах, таких як вуглеводневі озера на Титані та ймовірні підповерхневі океани на Європі, Титані і Енцеладі.

Ключові слова: м'яка робототехніка, маяки зв'язку, сенсорні панелі, екстремально рідкі середовища, океанські світи, тестування хімічних та електричних властивостей матеріалів, полімери та пластмаси.