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Silicone-Based Membranes as Potential Materials for Dielectric Electroactive Polymer Actuators

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Abstract: This article includes an overview of the materials and a thorough analysis of the methods that are used to produce dielectric electroactive actuator membranes. The paper also presents extensive results from our experimental studies on two types of addition silicone (Silicone Mold Start 15 and Dragon Skin 10M) that are used to manufacture actuators with different active membranes of thicknesses (165 µm and 300 µm, respectively). This study explored in depth the hardware architectures and methodologies for manufacturing the selected actuators. The displacements of the actuators were compared to their responses to two types of voltage excitation: a step response and a sinusoidal signal with an increasing frequency over time. This paper graphically presents the results that we obtained for all devices, with a particular emphasis on the resonance frequencies. When comparing membranes that had the same thickness (165 µm), it was found that the mean amplitude was higher for silicone membranes with lower values for the Young's modulus (DS = 0.57 mm and MS = 0.73 mm). All experiments were repeated for two series of measurements and the results that were obtained in this study demonstrated the successful implementation of the actuator concepts that were made from the new types of silicone, which have not yet been used for production.

Keywords: dielectric electroactive polymer; smart material; silicone membrane; actuator

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1. Introduction

Actuators that are made from intelligent materials are playing increasingly important roles in automation and robotics applications, especially when it is difficult to use classic actuators. One of the most interesting groups of these devices are dielectric electroactive actuators (DEAs), which are highly flexible, light and capable of producing small, fast and precise movements or forces [1,2]. Dielectric electroactive polymer (DEAP) materials are a unique class of materials that are capable of mechanically responding to electric stimuli or storing electrical energy from mechanical deformations in the same way as capacitors [3,4].

DEAP membranes are applied in three types of devices: sensors, generators and actuators. Their application in sensors has been described in a number of studies [5–7]. DEAP membranes allow sensors to sense stretch, displacement and force. The flexibility of sensors is useful for a wide range of applications, such as in biomedical and robotics devices [6,7]. DEAP membranes also allow advanced generators to be built, as presented in [8–10]. Last but not least, there are DEAP actuators, which can produce different kinds of movement. The most popular actuators are ring-shaped actuators with bias (e.g., mass, spring, permanent magnet, pneumatic, etc.) [11–13]. However, other shapes are also popular, such as rectangular and non-uniform actuators [14]. All of the mentioned devices have been extensively developed in scientific laboratories but have also been applied to practical scenarios, for instance in [15–17]. It is possible to apply DEAP actuators in the field of fluid power systems, e.g., as pumps for soft robotics [18].

The crucial aspects of the above devices are the DEAP membranes and their properties. The most common way to produce DEAP materials is to use flexible polymeric membranes with high permittivity, high dielectric breakdown strength, high dielectric constants and low mechanical Young's modulus values with high mechanical strength [19,20]. The relationships between these factors are important features in the design of DEAP membranes. These factors can be controlled by using different types of polymers, such as silicone, acrylate (VHB), polyisoprene (natural) or polyurethane rubbers [21,22] and additive materials (e.g., carbon powder, nanotubes and silver nanowires), or by controlling the thickness of the membranes. It is worth mentioning that decreasing the thickness causes the membranes to become more flexible; however, it also decreases the electric strength. It should be emphasized that the advantages of using polymers for the preparation of DEAP materials include their moderate price, lightness and resistance to corrosion, as well as the ease of processing them to obtain the various required shapes. Acrylic rubbers can produce high voltage-induced strain but, unfortunately, these materials are non-homogeneous due to microgel formation during the cross-linking polymerization process and are characterized by viscoelastic nonlinearities. In turn, this mainly affects the response times of the DEAP materials. Compared to acrylic rubbers, silicone elastomers have lower viscoelasticity, which allows them to work at higher frequencies [23]. In addition, they are susceptible to significant deformations [24] but they also easily return to their original shapes. Silicones are resistant to ultraviolet (UV) irradiation and oxidation and they are chemically and thermally stable. Their mechanical properties remain stable within a wide temperature range, i.e., from $-40\,^{\circ}\mathrm{C}$ to $200\,^{\circ}\mathrm{C}$ [25]. Silicone elastomers are the most frequently used polymeric matrices since they are characterized by fast response times and low (viscoelastic) hysteresis [26].

In general, DEAP actuators are made from flexible membranes with two electrodes. A detailed description of the production process is provided in [3,27]. For scientific purposes, the electrodes can also be produced using carbon grease [28]. Finally, two metal connections are added to provide the electric connection to the external voltage amplifier. The main goal of this work was to show the features of DEAP actuators that were made using a new type of silicone. In this study, commercially available industrial silicone materials were used for the production of dielectric electroactive actuators with different membrane thicknesses and this aspect was found to potentially have further significance for the commercialization of industrial results. The DEAP actuators that were produced had different thicknesses and were experimentally tested to evaluate their properties. The structure of this paper is as follows. First, Section 2 describes the materials and methods that were used to produce and study the DEAP actuators. Next, Section 3 presents the experimental results and discussion. Finally, the conclusions are also presented.

2. Materials and Methods

2.1. Materials

The DEAP actuators that are presented in this work were made from a silicone membrane that had carbon-based electrodes attached to it. The list of silicones that were used is presented in Table 1, together with their properties. As a carbon conductive grease (i.e., a mixture of silicone oil and carbon) was used, which was characterized by the following parameters: a density of $1.1\,\mathrm{g/mL}$, a viscosity of $80.3\,\mathrm{Pa}\cdot\mathrm{s}$ and a resistivity of $63\,\Omega\cdot\mathrm{cm}$. In this work, the silicone membranes were mounted on a rigid poly(methyl methacrylate) PMMA frame (Plexiglass®). The dimensions of the frame and the actuators are shown in Table 2. The final list of materials that were used to build the DEAP actuators was as follows:

- Silicone Mold Start 15 and Dragon Skin 10M (Smooth-On, Inc.);
- Carbon conductive grease (MG Chemicals 846);
- Copper tape;
- Rigid PMMA frame (Plexiglass®).

Table 1. A summary of the silicone parameters.

Parameter	Mold Start 15	Dragon Skin 10M
Modulus	15 Psi	22 Psi
Mixed Viscosity	12,500 cPs	23,000 cPs
Tensile Strength	400 Psi	475 Psi
Specific Gravity	1.18 g/cc	1.07 g/cc
Elongation at Breaks	440 %	1000 %
Shrinkage	<0.001 in./in.	<0.001 in./in.

Table 2. A summary of the PMMA frame dimensions.

Parameter	Dimension
Internal Diameter	70 mm
External Diameter	84 mm
Silicone Membrane Diameter	100 mm

2.2. Methods

The silicone membranes were prepared using two poly-addition silicones: Dragon Skin 10M and Mold Start 15. These types of silicone are formed by a polyaddition chemical reaction. The silicone mixtures were prepared by mixing two silicone components at a weight ratio of 1:1. Then, the silicone mixtures were degassed using a vacuum to avoid any air bubbles and holes forming during the membrane sheet preparation. The silicone membranes were prepared using a 100 µm poly(ethylene terephthalate) (PET) sheet as a support. Firstly, the surface of the casting table (Bevs 1811/3) and the bottom part of the PET sheet were cleaned using ethanol. Then, the PET sheet was placed on the casting table, fixed using the vacuum and the top surface of the PET sheet was cleaned using ethanol. Next, 15 g of the silicone mixtures was applied to the PET sheet using a micrometer adjustable film applicator and then the coating was prepared (Figure 1). The silicone cast layers were left for 24 h in order for the silicone cross-linking to occur and the membranes to be obtained. Finally, two different membrane thicknesses for each silicone type were prepared and used for the preparation of the DEAP actuators. In the remainder of this paper, the names of the silicone membranes are denoted as MS (Mold Start 15) and DS (Dragon Skin 10M), with the measured membrane thickness as a suffix (i.e., 300 µm or 165 µm).

Figure 1. The automatic film applicator (Bevs 1811/3; BEVS Industrial Co., Ltd., Guangzhou, China) that was used to produce the silicone films.

The DEAP actuators were produced using the prepared silicone membranes with the following steps. First, the silicone membranes were applied to a circular rigid PMMA frame. Then, two metal electrodes were glued to the silicone membranes using sticky tape, which enabled the external voltage connection. Finally, the electrodes were connected to each side of the actuators using carbon conductive grease.

The principle of operation of DEAP actuators has been presented in detail in a number of works [4,29,30]. When an external electric charge is applied to the electrodes, the electrostatic attraction between the opposite charges of both electrodes generates electrostatic stress and pressure on the film, thereby causing it to reduce in thickness while expanding in area. Figure 2a,b graphically show how actuator membranes stretch as a result of applied voltage. In this study, we analyzed the voltage to displacement to obtain information about how the DEAP actuators were working.

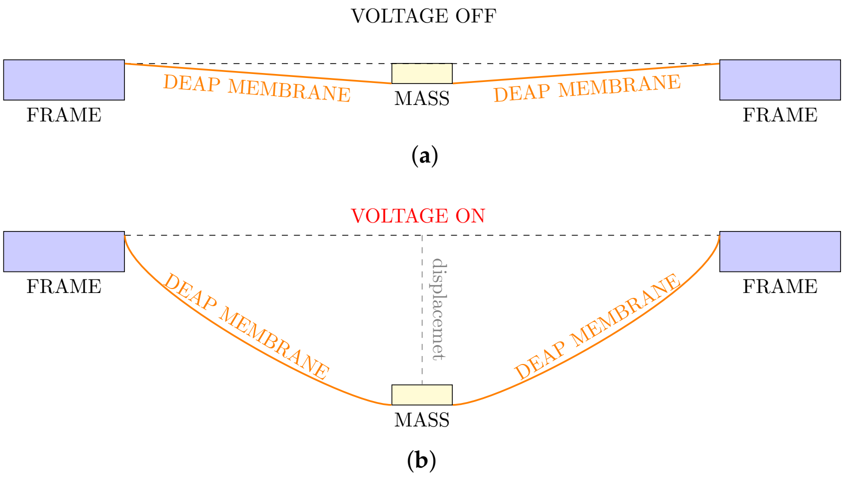

Figure 2. A diagram of a DEAP actuator: (**a**) with the power off (non-deflected state) and (**b**) with the power on (deflected state).

In this study, the DEAP actuators were assembled on a laboratory stand that had an aluminum structure, as shown in Figure 3. The forcing signals were set by a PC using a dedicated measurement card. A detailed description of the hardware architecture can be found in [4], which included a high-voltage amplifier (Trek 10/10B-HS), a laser sensor (Micro Epsilon optoNCDT 1320-10) and a data acquisition board. The DEAP cylinders were loaded with external masses. The voltage was applied as excitation and the distance was measured after a 1 ms sampling time.

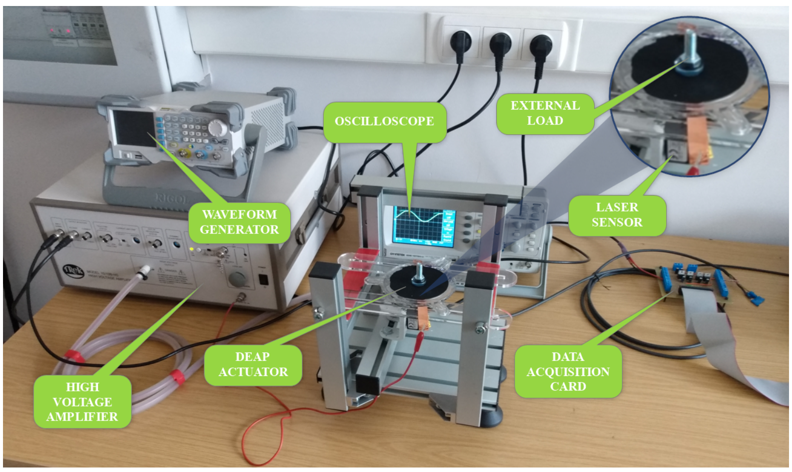

Figure 3. The laboratory setup with a DEAP actuator.

In the first part of the experiment, the capacity of the individual actuators was measured. The results of these measurements are summarized in Table 3. Based on the obtained capacity values, the relative permittivity values ϵ_r for all of the actuators were estimated using Equation (1):

$$\epsilon_r = \frac{C}{C_0} \tag{1}$$

where C is the capacity that was measured using a multimeter (LCR700 SANWA) and $C_0 = \epsilon_0 \frac{d}{S}$ is the capacity of the parallel plate capacitor in a vacuum. In the next stage of the experiment, the DEAP actuators were subjected to two types of voltage excitation: a step response and a sinusoidal signal with increasing frequency over time (chirp signal). The excitation voltage range was experimentally defined so as to avoid causing damage to the actuator diaphragms from overvoltage. Figure 4a shows the step response in the range from 0 kV to 1.5 kV, while Figure 4b shows the initial fragment of the chirp excitation, the definition of which is shown in Equation (2):

$$\begin{aligned} u(t) &= u_c + u_a \sin(2\pi f(t) t) \\ f(t) &= f_0 \cdot \left(\frac{f_1}{f_0}\right)^{\frac{t}{t_1}} \end{aligned} \tag{2}$$

where u_c is the constant voltage and u_a is the voltage amplitude. The displacements that were measured during the chirp excitation were processed using the Butterworth filter with a bass band from 2.5 Hz to 100 Hz. Next, the maximum displacement was calculated from the excitation window, the length of which was equal to the period of the signal (which varied with the chirp signal).

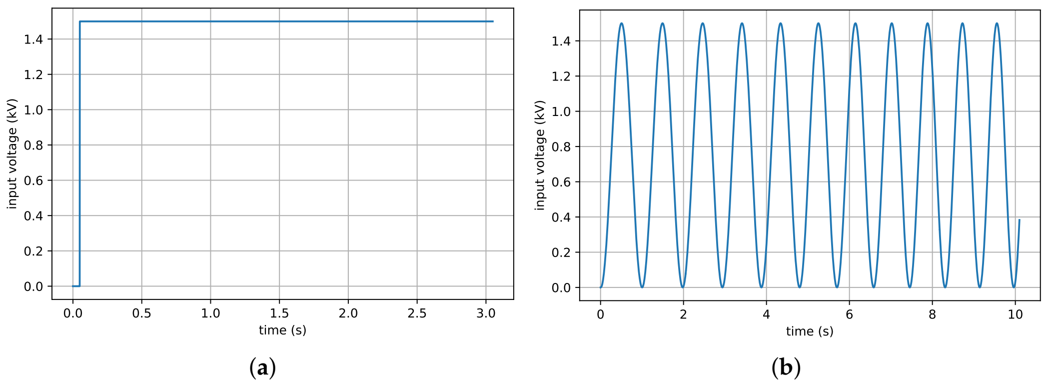

Figure 4. The input voltage that was used to obtain (**a**) the step response and (**b**) the beginning of the chirp excitation.

Table 3. A summary of the capacity and relative permittivity of the actuators.

Silicone	Membrane Thickness	Capacity (pF)	Relative Permittivity (1)
DS	300 µm	392.7	3.40
DS	165 µm	613.4	3.02
MS	300 µm	390.1	3.50
MS	165 µm	691.9	3.36

3. Results and Discussion

Firstly, the capacity of the fabricated actuators was measured, as described in Section 2.2. The results are shown in Table 3. It was found that the capacity strongly depended on the thickness of the actuators. The differences between the two types of silicone were insignificant.

Secondly, the response to the voltage excitation was measured and the results are presented in Figures 5 and 6. The step response in the excitation allowed us to analyze the intensity of the actuator oscillations and their stabilization times. Both types of silicone that were used to make the actuator membranes were tested: Figure 5a,b show the responses of the actuators that were made from Dragon Skin 10M silicone with the two thicknesses (165 µm and 300 µm, respectively); Figure 5c,d present the responses of the actuators that were made from Mold Start 15 silicone with the two thicknesses (165 µm and 300 µm, respectively). The convergence of the measurements for all of the samples (Figure 5a–d) guaranteed the correct course of the experiment. Furthermore, each experiment was conducted twice (denoted as Try 1 and Try 2). It could be seen that the actuators that were made from the thicker silicone were characterized by smaller deflections. Furthermore, the actuator that was made from Dragon Skin 10M silicone (165 µm) responded to greater deflections for the same input voltage and its oscillation damping time was shorter than the Mold Start 15 silicone actuator (165 µm). The reason for the difference in damping time was the higher Young's modulus value of the Dragon Skin 10M silicone.

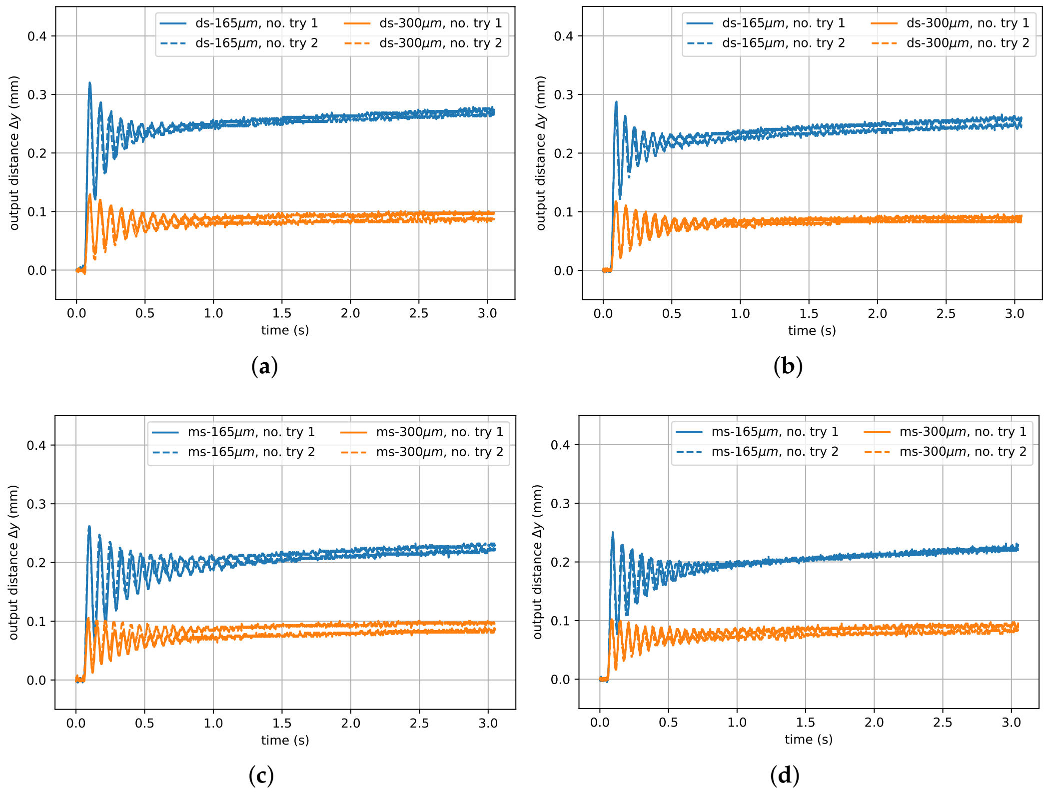

Figure 5. The displacement response of the DEAP actuators to step response excitation: (**a**) DS silicone, sample 1; (**b**) DS silicone, sample 2; (**c**) MS silicone, sample 1; (**d**) MS silicone, sample 2.

In the subsequent measurements, the voltage excitation was a sinusoidal signal that increased in frequency over time, as defined in Equation (2). The experiment was carried out in this to enable an in-depth analysis of the frequency domain of the device operation. Regarding the voltage input, various membrane thicknesses were tested through two series of measurements for each actuator. The aim was to find the resonance frequencies and measure the amplitudes of the individual actuators for a sinusoidal signal with a resonant frequency. The results are presented in Table 4. Figure 6a,c show that for the resonant frequency, the actuators that were made from Mold Start 15 silicone had larger distance amplitudes than the actuators that were made from Dragon Skin 10M. Figure 6b,d show that the actuators that were 165 µm thick deformed slightly less during the second series of measurements than during the first series while the actuators that were 300 µm thick deformed very similarly during both series.

As shown in Table 4, when comparing membranes that had the same thickness, the mean amplitude was higher for silicone membranes with lower Young's modulus values. Further, the decrease in thickness caused an increase in the amplitude of movement. In general, the responses were similar to those from DEAP actuators that have been presented in the literature [4,29]. The step responses consisted of initial oscillations and long relaxation times. The responses to sinusoidal signals also showed resonances around 10 Hz, which were similar the results that have been presented in the literature [4,29].

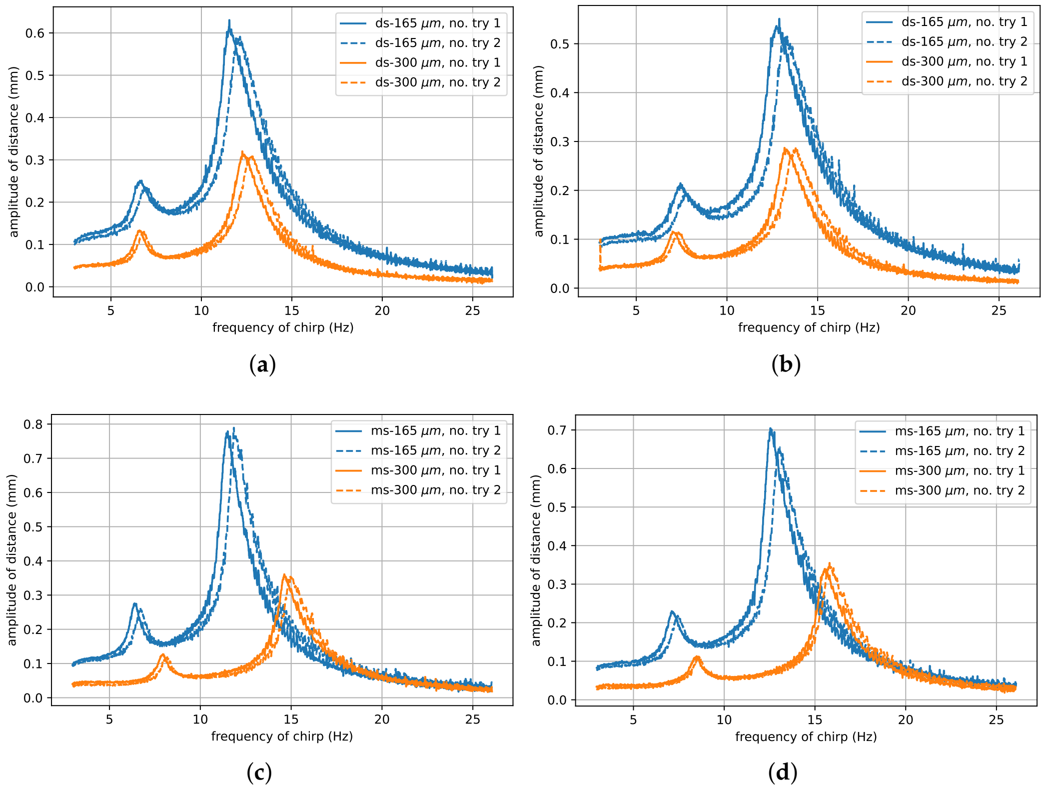

Figure 6. The displacement response of the DEAP actuators to chirp excitation: (**a**) DS silicone, sample 1; (**b**) DS silicone, sample 2; (**c**) MS silicone, sample 1; (**d**) MS silicone, sample 2.

Table 4. A summary of the resonance amplitudes.

Silicone	Mean (mm)	Standard Deviation (mm)
DS 165 µm	0.57	0.04
DS 300 µm	0.30	0.02
MS 165 µm	0.73	0.06
MS 300 µm	0.35	0.01

The DEAP actuators that are presented in this work demonstrated the same kind of responses as the other actuators that have been presented in the literature [12,29]. The frequency characteristics slowly increased to a resonance level that was around a few Hertz, with strong damping effects above that level. The step responses were also similar, but with low damping effects that caused oscillations. Furthermore, the resonance responses of the tested actuators were in the range from 0.4 mm to 0.8 mm, which showed that the actuators could be practically useful. In the future, the influence of additional components that could increase permittivity should be analyzed, as in [31,32].

4. Conclusions

The field of smart materials is developing very dynamically, which has enabled these materials to be adapted for use in sensors and actuators. In this study, two types of silicone that are available within the industry were used to produce dielectric actuators, which were supplemented with carbon electrodes. Precise membranes for dielectric actuators were produced using these types of silicone, which have not yet been presented in the literature. Our experiments were performed with the use of the most modern research equipment and the results were confirmed by two series of measurements. This study could be a starting point for research on the use of dielectric actuators that are made from commonly available materials.

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