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# Rolled Dielectric Polymer Actuators

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*Contract Number: W7707-052935/001/HAL*

*Contract Scientific Authority: J. Szabo, Ph.D. (902) 427-3427*

**Defence R&D Canada – Atlantic**

Contract Report
DRDC Atlantic CR 2006-085
May 2006

Canada

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## Defence R&D Canada – Atlantic

## Contract Report

DRDC Atlantic CR 2006-085

May 2006

Author

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Approved by

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# Abstract

In this program we continued the previous work on the fabrication of dielectric actuators. When compliant electrodes applied to an elastomeric dielectric film in a dielectric actuator are charged, the electrodes attract, compressing the film and causing it to move in a direction perpendicular to the applied force. The geometry of the actuator was a long strip consisting of alternating dielectric and electrode layers, rolled up and electrically terminated to form the final device.

In our previous work two main obstacles were encountered: conductivity through the middle dielectric layer and the ability to electrically terminate the device. By using silicone for the dielectric layer and a formulation based on carbon black milled with thermoplastic polyurethane as the electrode, termination of the device was reliable and consistent. However, conductivity through the middle dielectric layer is still an issue. Three actuators with nominal thickness of 200, 300, and 400 µm that did not conduct through the middle layer were produced and submitted to the Scientific Authority. These could not be produced reliably however. We suspect that this inconsistency is related to the spray process used to fabricate the actuators. Further work should concentrate on improvements to the process for fabrication of actuators.

# Résumé

Le présent rapport décrit la suite du travail portant sur la fabrication d’actionneurs diélectriques. Lorsque des électrodes élastiques appliquées à un film diélectrique élastomère dans un actionneur diélectrique sont chargées, elles s’attirent, ce qui comprime le film et le déplace dans une direction perpendiculaire à la force appliquée. La géométrie de l’actionneur comprend une longue bande constituée de couches alternées de diélectrique et d’électrode, enroulées et connectées électriquement de façon à former le dispositif de réglage final.

Dans nos recherches antérieures, nous avons rencontré deux obstacles principaux : la conductivité au travers de la couche diélectrique médiane et la difficulté à connecter électriquement le dispositif. Grâce à l’utilisation de silicone pour la couche diélectrique et une formulation basée sur le noir de carbone broyé avec du polyuréthanne thermoplastique comme électrode, la connexion du dispositif était fiable et reproductible. Cependant, la conductivité au travers de la couche diélectrique médiane pose toujours problème. Trois actionneurs d’une épaisseur nominale de 200, de 300 et de 400 µm qui ne conduisaient pas le courant à travers la couche centrale ont été produit et soumis au responsable scientifique. Cependant, leur production n’était pas fiable. Nous soupçonnons que ce manque de reproductibilité est lié au procédé de pulvérisation utilisé pour fabriquer les actionneurs. Des recherches futures devraient se concentrer sur des améliorations du procédé de fabrication des actionneurs.

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# Executive summary

Background

The dielectric actuators investigated in this work are capacitors in which both the dielectric and conductive layer are elastomeric. The charges on the opposite electrodes attract, resulting in compression of the dielectric and therefore elongation in the direction perpendicular to the force. In this project the feasibility of producing dielectric actuators in the form of a long strip which is subsequently rolled to form a cylinder was investigated. The anticipated advantage of this approach is the ability to form large elastomeric actuators consisting of very thin layers.

In a previously completed TIF program, the focus was mainly on a polyurethane dielectric. The two main problems that were not resolved in that program were electrical termination of the actuators and excessive conductivity across the dielectric layer.

The program described in this report is a continuation of the previous work with the main objective of overcoming the problems encountered previously and producing working actuators.

Results

The approach taken in this program was to investigate a silicone elastomer as the dielectric and to evaluate different electrodes formulated using silicone, polyurethane, and brushed graphite. The effect of dielectric thickness was also investigated by producing actuators with a dielectric thickness in the range 150 to 400 µm.

Using a polyurethane-based electrode formulation in combination with a silicone dielectric resulted in a reliable termination of the actuators. The thickness of the dielectric had the expected effect on capacitance, with capacitance being inversely proportional to the thickness. Capacitance of rolled actuators was double that of lay-flat actuators.

Several actuators were produced with electrical readings as expected (e.g. capacitance from 8 nF for a 400 µm dielectric to 15 nF for a 200 µm dielectric with resistance through the dielectric layer greater than 32 MΩ), but other actuators of similar configuration showed considerable conductivity across the dielectric (resistance in the 50 kΩ range). The issue of conductivity across the dielectric layer was not fully resolved. While there was not a consistent relationship between dielectric thickness and conductivity through it, the actuators produced with thicker dielectric layers tended to be of higher resistance.

Significance

Rolled dielectric actuators are considered to have potential applications in active/ passive vibration isolation, especially for the reduction of the acoustic signature of ships. There is a similar potential application in vibration isolation of land vehicles.

Future Plans

In this and the previous program, processes and formulations for the fabrication of rolled dielectric actuators were developed. The major unit operations are preparation of the actuator in the lay-flat position, rolling and termination. It was demonstrated that using a silicone elastomer as the dielectric and a sprayed polyurethane-based electrode formulation, effective electrical termination may be achieved. Several actuators were produced with the expected capacitance/ resistance characteristics, but these actuators could not be produced reproducibly, with conductivity across the dielectric layer varying in actuators produced under nominally identical conditions. This indicates that the process used to form these actuators is not reliable and needs further improvement.

The next phase of this work should be directed towards improving the process for the formation of actuators followed by characterisation of these actuators.

Massey, J.. 2006. Rolled Dielectric Polymer Actuators. DRDC Atlantic CR 2006-085. Bodycote Materials Testing Canada.

# Sommaire

Introduction

Les actionneurs diélectriques étudiés sont des condensateurs dans lesquels tant la couche diélectrique que la couche conductrice sont élastomères. Les charges appliquées aux électrodes opposées s'attirent, ce qui comprime le diélectrique et cause l'allongement dans la direction perpendiculaire à celle de la force. Dans ce projet, on a étudié la faisabilité de produire des actionneurs diélectriques sous la forme d'une longue bande enroulée par la suite pour former un cylindre. L'avantage anticipé de cette méthode est la possibilité de former de grands actionneurs élastomères constitués de couches très minces.

Dans le programme FIT antérieur terminé, l'accent était mis sur un diélectrique en polyuréthanne. Les deux problèmes principaux qui n'ont pas été résolus dans le cadre de ce programme étaient la connexion électrique des actionneurs et une conductivité excessive au travers de la couche diélectrique.

Le programme décrit dans le présent rapport était la suite du travail antérieur et avait pour objectif principal de surmonter les problèmes rencontrés auparavant et de produire des actionneurs fonctionnels.

Résultats

La méthode suivie dans ce programme consistait à étudier un élastomère de silicone utilisé comme diélectrique et à évaluer différentes électrodes formulées à l'aide de silicone, de polyuréthanne et de graphite brossé. Nous avons également étudié l'effet de l'épaisseur du diélectrique en produisant des actionneurs avec un diélectrique d'une épaisseur de l'ordre de 150 à 400 µm.

L'utilisation d'une formulation des électrodes à base de polyuréthanne conjointement avec un diélectrique de silicone a donné lieu à une connexion fiable des actionneurs. L'épaisseur du diélectrique avait l'effet prévu sur la capacité : celle-ci était inversement proportionnelle à l'épaisseur. La capacité des actionneurs enroulés était égale au double de celle des actionneurs à plat.

Nous avons produit plusieurs actionneurs avec des valeurs électriques conformes aux prévisions (p. ex., la capacité variait de 8 nF pour un diélectrique de 400 µm à 15 nF pour un diélectrique de 200 µm avec une résistance de la couche diélectrique supérieure à 32 MΩ), mais d'autres actionneurs de configuration semblable présentaient une conductivité considérable au travers du diélectrique (résistance de l'ordre de 50 kΩ). Le problème de la conductivité au travers de la couche diélectrique n'a pas été complètement réglé. Bien qu'il n'y ait pas de rapport cohérent entre l'épaisseur du diélectrique et la conductivité au travers du diélectrique, les actionneurs produits avec des couches diélectriques plus épaisses tendaient à avoir une plus grande résistance.

Portée

Les actionneurs diélectriques enroulés sont supposés avoir des applications potentielles en isolement actif/passif des vibrations, notamment aux fins de la réduction de la signature acoustique de navires. Il y a une application potentielle semblable dans l’isolement des vibrations de véhicules terrestres.

Recherches futures

Au cours de ce programme et du programme antérieur, on a mis au point des procédés et des formulations pour la fabrication d’actionneurs diélectriques enroulés. Les opérations unitaires principales sont la préparation de l’actionneur à plat, l’enroulement et la connexion. Il a été démontré que l’utilisation d’un élastomère de silicone en tant que diélectrique et d’une formulation à base de polyuréthanne pulvérisé pour l’électrode permet de réaliser une connexion électrique efficace. Nous avons produit plusieurs actionneurs avec les caractéristiques de capacité/résistance prévues, mais ces actionneurs n’étaient pas reproductibles, la conductivité au travers de la couche diélectrique variant parmi des actionneurs produits dans des conditions nominalement identiques. Cela indique que le procédé utilisé pour former ces actionneurs n’est pas fiable et a besoin d’améliorations.

La prochaine étape de ce projet devrait être orientée vers l’amélioration du procédé de formation des actionneurs suivi de la caractérisation de ces actionneurs.

Massey, J. 2006. Rolled Dielectric Polymer Actuators. DRDC Atlantic CR 2006- 085. Bodycote Materials Testing Canada.

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# 1. Introduction

Dielectric actuators, also referred to as Maxwell's actuators, are capacitors in which both the dielectric and the conductive layer are elastomeric. The charges on the opposite electrodes attract one another resulting in compression of the dielectric and therefore elongation in the direction perpendicular to the force.

Bodycote Materials Testing Canada Inc. recently completed a TIF-supported program that focused on fabricating dielectric actuators for active vibration damping. Since, for marine engine applications large size actuators would be required, we developed a concept for a "rolled" actuator - a long, flat, rectangular actuator which, when rolled, forms a cylindrical actuator.

The program consisted of the following components:

- development of material formulations for the dielectric and conductive electrode;
- development of equipment and processes for fabrication of lay-flat actuators;
- conversion of lay-flat actuators into rolled form; and
- development of electrical termination.

The steps in that program are described in detail in our previous reports [1-7]. We worked with two dielectric materials, a thermosetting polyurethane and silicone, and two electrode types, sprayed thermoplastic polyurethanes with conductive carbon and brushed graphite. The issues, which we encountered, are summarised in the table below:

***Table 1.*** *Previous Issues with rolled actuators*

| | **SPRAYED ELECTRODE** | **BRUSHED ELECTRODE** |
|---|---|---|
| **POLYURETHANE DIELECTRIC** | Considerable conductivity across the dielectric layers | No termination |
| **SILICONE** | Not evaluated | Unreliable termination |

There are two major remaining issues - conductivity through the dielectric layers and reliable electrical termination.

An additional issue has been observed when working with silicone - poor shelf life stability when formulated with toluene for spraying. This issue was eventually dealt with by producing solutions just before spraying. After consultation with the supplier of this silicone (Wacker), we concluded that a trace amount of sulphur present in the toluene might be enough to poison the platinum catalyst used in this particular silicone.

In the work conducted by DRDC, a further issue of cure inhibition by conductive graphite filler was also observed. The reason for this inhibition is not known, but we can speculate that it is a similar effect of trace elements present in graphite poisoning the platinum catalyst.

# 2. Material Development

## 2.1 Dielectric Silicone

To avoid what was believed to be inhibition of the platinum catalyst in Elastosil RT 601 silicone resin (Wacker) by sulphur in toluene, we sourced peroxide-cure and moisture-cure alternatives to this material.

The peroxide-cure systems were SE6035 and SE6075 from GE Silicones. We evaluated the solubility of each of these resins in toluene, VM&P naphtha (petroleum spirit), OS-10 silicone fluid (Dow Corning), hexane, THF, and cyclohexane at a level of 20% by weight at room temperature. None of the solvents were able to dissolve either resin at this level. The SE6035 in toluene came the closest to forming a solution. The solubility of the two resins was then evaluated in toluene, petroleum spirits, OS-10 silicone fluid, carbon tetrachloride, dichloromethane, chloroform and butyl acetate at a level of 10% by weight. Suitable solubility was observed only for SE6035 in toluene and butyl acetate. A *ca* 10% solution of SE6035 in toluene was successfully milled with carbon black to evaluate cure and conductivity (see below).

Thin films of SE6035 were cast from toluene solutions containing different organic peroxides to evaluate the cure of these systems. Benzoyl peroxide, lauroyl peroxide, dicumyl peroxide, methyl ethyl ketone peroxide, and bis(2,4-dichlorobenzoyl peroxide) were evaluated at loadings of 2-5% and three temperatures, 65ºC, 100ºC and 150ºC. The only system that cured was the one with bis(2,4-dichlorobenzoyl peroxide) at 150ºC. We attempted to lower the cure temperature to 65ºC, the maximum temperature that the spray apparatus can reach, by incorporating metal driers. Driers are organometallic salts commonly used in the paint industry and are accelerators for the peroxide. By using Nuodex cobalt and Nuxtra zirconium we were able to lower the cure temperature to 75ºC.

The moisture cure systems, 3-1765 and 3-1965 from Dow Corning, are claimed to have very rapid cure cycles (~2 minutes @ 60ºC). While these resins would work well as the dielectric layer, they would not allow formulation into the electrode since the rapid moisture cure would make pigment incorporation difficult if not impossible.

The cure potential of Elastosil RT 601 silicone was re-evaluated in three solvents, toluene, petroleum spirits and OS-10 silicone fluid. The two-component silicone solutions were freshly prepared before spraying. All three films cured as expected without issue. Dielectric breakdown measurements were performed and the results are summarised below:

***Table 2.*** *Results of Dielectric Breakdown Testing*

| BREAKDOWN STRENGTH* (KV/MM) | SPRAYED FROM TOLUENE | SPRAYED FROM PETROLEUM SPIRITS | SPRAYED FROM OS-10 |
|---|---|---|---|
| Average | 50 | 30 | 43 |
| Standard deviation | 15 | 16 | 26 |
| Min. | 22 | 11 | 7 |
| Max. | 75 | 61 | 84 |

*Measured as described in DRDC Atlantic CR 2003-064, Reference 3.

In addition, the film capacitance was found to be the same for all three, with a nominal capacitance of 0.3 nF using the same set-up as for dielectric breakdown measurements. RTV12 from GE Silicones was also evaluated for use as the dielectric layer and as the binder for the electrode layer. This resin is a two-component silicone with a tin-based catalyst. The product data sheet claims a gel time of 30 minutes at 85ºC and 100 minutes at 25ºC. Durometer hardness after 3 days is 18 Shore A. However, initial observations suggested that cure requires a longer time or a higher temperature than that claimed in the data sheet. A film sprayed with the spray apparatus required three cure cycles to produce a tack-free film. The film was very soft and could not be removed from a glass plate treated with soap.

It consultation with the Scientific Authority it was decided to continue using RT 601 from Wacker sprayed using toluene as the dielectric layer of the actuators.

## 2.2 Sprayed Electrode Formulation

Electrode formulations were prepared with both carbon black and graphite in Elastosil RT 601 at a range of levels. Films were checked for cure:

***Table 3***. *Summary of Formulation and Cure*

| FILLER | LEVEL (PHR) | CURE |
|---|---|---|
| Carbon black | 60.0 | No – film smeared |
|  | 30.0 | No – film smeared |
|  | 25.0 | No – film smeared |
| Graphite | 60.0 | Yes |
|  | 28.9 | Yes |
|  | 15.0 | Yes |

It would appear that some component of the carbon black pigment (perhaps sulphur) inhibited cure. The graphite did not exhibit the same effect, showing good cure initially and after one week. Unfortunately, it was observed in the previous phase of the project that films containing graphite do not conduct to the same degree as those with carbon black. The films described in Table 3 filled with graphite displayed negligible conductivity.

We then investigated electrode formulations based on SE6035 and RTV12. We incorporated carbon black in SE6035 by ball milling and were able to cure the electrode at 75ºC. The conductivity of a 10 µm thick film was *ca* 2 kΩ/square with a 30% loading of carbon black.

We were able to mill carbon black in RTV12 using a dispersant (Disperbyk 163). We found previously that the cure profile of RTV12 did not correlate well with the product literature. Therefore, to facilitate cure, we added an additional tin-based catalyst, FASCAT 4200 from Arkema. The formulation cured in less than an hour at 65ºC. The conductivity of a 25 µm thick film was *ca* 4 kΩ/square with a 30% loading of carbon black.

We chose to formulate the silicone electrode with RTV12 and carbon black dispersed with Disperbyk 163 since adding FASCAT 4200 lowered the cure temperature to within the temperature reached by our spray apparatus. Using SE6035 would have required modification of the spray apparatus to raise the cure temperature by 10ºC. Carbon black loading levels of 20, 30 and 35% were evaluated. A loading of 20% carbon black yielded an insulating film while a loading of 35% produced a crumbly film. A loading of 30% showed appreciable conductivity with reasonable film qualities.

When the formulation was diluted to 20% solids so that it could be sprayed, the carbon black agglomerated. Adding more dispersant stabilised the carbon black such that the electrode formulation could be sprayed. However, when the electrode was evaluated (actuator 06-05-10481-64) it had no detrimental effects on the device but the dielectric layer still displayed appreciable conductivity. No further work to refine the electrode formulation was carried out.

# 3. Actuator Production

Actuators were produced using the spray apparatus as reported in DRDC Atlantic CR 2003-227 [2]. The methodology used for actuator production was previously reported in DRDC Atlantic CR 2005-076 [6] and DRDC Atlantic CR 2004-195 [4]. To facilitate characterisation of the actuator in the lay-flat configuration, exposed electrodes were left on either side of the actuator along its entire length. These were trimmed before the actuator was rolled. Also, electrode tabs were incorporated at one end of the actuator to allow for a second means of terminating the device. Since the tabs were so thin, they needed to be reinforced. A tulle-like fabric (Sefar 7-105/52) that would not constrain the movement of the actuator where it overlapped the active area was used. The following table summarises the actuators produced by the spray process during this program.

***Table 4.*** *Summary of Actuators Produced*

| SAMPLE ID | INTENDED DIELECTRIC THICKNESS | DIELECTRIC MATERIAL | ELECTRODE MATERIAL | LAYERS | NUMBER OF PASSES | MEASURED THICKNESS |
|---|---|---|---|---|---|---|
| 05-05-10320-104<br>actuator 1<br>with tabs | 100 µm | Silicone<br>RT601 from Wacker | Graphite<br>Timrex KS6 | ***Base dielectric*** | 6 | 42 µm |
| | | | | ***1st electrode*** | 3 polished coats | N/A |
| | | | | ***Central dielectric*** | 12 | 77 µm |
| | | | | ***2nd electrode*** | 3 polished coats | N/A |
| | | | | ***Top dielectric*** | 6 | N/A |
| 05-05-10320-122<br>actuator 2<br>with tabs | 100 µm | Silicone<br>RT601 from Wacker | Graphite<br>Timrex KS6 | ***Base dielectric*** | 8 | 35-50 µm |
| | | | | ***1st electrode*** | 3 polished coats | N/A |
| | | | | ***Central dielectric*** | 16 | 113 µm |
| | | | | ***2nd electrode*** | 3 polished coats | N/A |
| | | | | ***Top dielectric*** | 8 | 53 µm |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| 05-05-10320-152<br>actuator 3<br>with tabs | 100 µm | Silicone<br>RT601 from Wacker | Carbon black/Pellethane | ***Base dielectric*** | 8 | 66 µm |
|  |  |  |  | ***1st electrode*** | 2 | 8 µm |
|  |  |  |  | ***Central dielectric*** | 8 | 60 µm |
|  |  |  |  |  | 8 | 78 µm |
|  |  |  |  | ***2nd electrode*** | 2 | 5 µm |
|  |  |  |  | ***Top dielectric*** | 8 | 62 µm |
| 06-05-10320-180<br>actuator 4<br>with tabs | 400 µm | Silicone<br>RT601 from Wacker | Carbon black/Pellethane | ***Base dielectric*** | 14 | 121 µm |
|  |  |  |  |  | 14 | 110 µm |
|  |  |  |  | ***1st electrode*** | 2 | 0 µm |
|  |  |  |  |  | 2 | 8 µm |
|  |  |  |  | ***Central dielectric*** | 14 | 115 µm |
|  |  |  |  |  | 14 | 111 µm |
|  |  |  |  |  | 14 | 106 µm |
|  |  |  |  |  | 14 | 116 µm |
|  |  |  |  | ***2nd electrode*** | 2 | 7 µm |
|  |  |  |  | ***Top dielectric*** | 14 | 144 µm |
|  |  |  |  |  | 14 | 135 µm |
| 06-05-10320-197<br>actuator 5<br>with tabs | 200 µm | Silicone<br>RT601 from Wacker | Carbon black/Pellethane | ***Base dielectric*** | 14 | 103 µm |
|  |  |  |  | ***1st electrode*** | 2 | 4 µm |
|  |  |  |  | ***Central dielectric*** | 14 | 111 µm |
|  |  |  |  |  | 14 | N/A |
|  |  |  |  | ***2nd electrode*** | 22 | 11 µm |
|  |  |  |  | ***Top dielectric*** | 14 | 122 µm |

| | | | | | | |
|---|---|---|---|---|---|---|
| 06-05-10320-12<br>actuator 6<br>with tabs | 150 µm | Silicone<br>RT601 from Wacker | Carbon black/Pellethane | ***Base dielectric*** | 10 | 75 µm |
| | | | | ***1st electrode*** | 2 | 4 µm |
| | | | | ***Central dielectric*** | 10 | 77 µm |
| | | | | | 10 | 83 |
| | | | | ***2nd electrode*** | 2 | 5 µm |
| | | | | ***Top dielectric*** | 10 | 84 µm |
| 06-05-10481-36<br>actuator 7<br>with tabs | 300 µm | Silicone<br>RT601 from Wacker | Carbon black/Pellethane | ***Base dielectric*** | 10 | 76 µm |
| | | | | | 10 | N/A |
| | | | | ***1st electrode*** | 2 | 2 µm |
| | | | | ***Central dielectric*** | 14 | 107 µm |
| | | | | | 14 | 111 µm |
| | | | | | 14 | 93 µm |
| | | | | ***2nd electrode*** | 2 | 4 µm |
| | | | | ***Top dielectric*** | 10 | 91 µm |
| | | | | | 10 | 91 µm |
| 06-05-10481-64<br>actuator 8<br>no tabs | 200 µm | Silicone<br>RTV 601 from Wacker | Carbon black/RTV 12<br>(silicone from GE Silicones) | ***Base dielectric*** | 14 | 100 µm |
| | | | | ***1st electrode*** | 2 | 9 µm |
| | | | | | 2 | 8 µm |
| | | | | ***Central dielectric*** | 14 | 106 µm |
| | | | | | 14 | 102 µm |
| | | | | ***2nd electrode*** | 4 | 25 µm |
| | | | | ***Top dielectric*** | 14 | 120 µm |

| | | | | | | |
|---|---|---|---|---|---|---|
| 06-05-10481-82<br>actuator 9<br>no tabs | 200 µm | Silicone<br>RT601 from Wacker | Carbon black/Pellethane | ***Base dielectric*** | 14 | 103 µm |
| | | | | ***1st electrode*** | 2 | 4 µm |
| | | | | | 2 | 5 µm |
| | | | | ***Central dielectric*** | 14 | 112 µm |
| | | | | | 14 | 113 µm |
| | | | | ***2nd electrode*** | 4 | 7 µm |
| | | | | ***Top dielectric*** | 14 | 107 µm |
| 06-05-10481-106<br>actuator 10<br>no tabs | 200 µm | Silicone<br>RT601 from Wacker | Carbon black/Pellethane | ***Base dielectric*** | 14 | 112 µm |
| | | | | ***1st electrode*** | 2 | 7 µm |
| | | | | ***Central dielectric*** | 14 | 103 µm |
| | | | | | 14 | 114 µm |
| | | | | ***2nd electrode*** | 2 | 7 µm |
| | | | | ***Top dielectric*** | 14 | 130 µm |
| 06-05-10581-127<br>actuator 11<br>no tabs | 350 µm | Silicone<br>RT601 from Wacker | Carbon black/Pellethane | ***Base dielectric*** | 12 | 88 µm |
| | | | | | 12 | 90 µm |
| | | | | ***1st Electrode*** | 2 | 6 µm |
| | | | | ***Central dielectric*** | 16 | 122 µm |
| | | | | | 16 | 120 µm |
| | | | | | 16 | N/A |
| | | | | ***2nd electrode*** | 2 | 5 µm |
| | | | | ***Top dielectric*** | 12 | 118 µm |
| | | | | | 12 | 99 µm |

One additional actuator was produced by a drawdown process to determine if this method would be an improvement to the spray process. Unfortunately, it had very poor performance with significant conductivity through the middle dielectric layer

## 3.1 Detailed Electrical Measurements of the Actuators in the Lay-Flat Configuration

For each electrode layer in the actuator, the resistance was measured at various locations and configurations along the whole actuator. The capacitance and resistance of the middle dielectric layer in the lay-flat configuration was also measured in various locations and configurations. In addition, the capacitance was measured as a function of frequency along the entire length using the exposed electrodes. The following figure is intended to allow the reader to reference where the measurements were made:

***Figure 1.*** *Reference Diagram for electrical measurements*

Measurements were made with a multimeter (MII B04933) and capacitance meter (MII B06826,for reference only). Measurements as a function of frequency were made with an HP LF impedance analyser (MII A07466, for reference only).

### 3.1.1 05-05-10320-104

This actuator consisted of a 100 µm thick middle dielectric layer with a graphite electrode.

***Table 5.*** *First graphite electrode.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.480 KΩ |
| From end to end | 131.3 KΩ |
| Hepa end of actuator | 9.25 KΩ/square |
| Middle | 10.15 KΩ/square |
| Heater end | 12.15 KΩ/square |

***Table 6**.  Second graphite electrode.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.942 KΩ |
| From end to end | 419 KΩ |
| Hepa end of actuator | 14.30 KΩ/square |
| Middle | 15.30 KΩ/square |
| Heater end | 13.40 KΩ/square |

***Table 7.**  Between electrodes in the lay-flat position before topcoating.*

| | |
|---|---|
| Across electrode tabs, pushing with full force | 686 KΩ |
| | 15.70 nf |
| Side to side resistance, full weight on each strip | 36.10 KΩ |
| | 9.56 nf |

***Table 8**.  After Topcoating.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 55.7 KΩ |
| | 10.80 nf |
| Across tabs | >32,000 KΩ |
| | 0.186 nf |

### 3.1.2 05-05-10320-122

This actuator consisted of a 100 µm thick middle dielectric layer with a graphite electrode.

***Table 9.**  First graphite layer.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.604 KΩ |
| From end to end | 306 KΩ |
| Hepa end of actuator | 14.02 KΩ/square |
| Between Hepa end and middle | 14.81 KΩ/square |
| Middle | 15.43 KΩ/square |
| Between middle and heater end | 8.61 KΩ/square |
| Heater end | 10.87 KΩ/square |

***Table 10.** Second graphite layer.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.507 KΩ |
| From end to end | 127.5 KΩ |
| Hepa end of actuator | 11.80 KΩ/square |
| Between Hepa end and middle | 8.07 KΩ/square |
| Middle | 8.52 KΩ/square |
| Between middle and heater end | 14.05 KΩ/square |
| Heater end | 11.95 KΩ/square |

***Table 11.** Between electrodes in the lay-flat position before topcoating.*

| | |
|---|---|
| Across electrode tabs | 231.3 KΩ |
| | 0.313 nf |
| Side to side resistance, full weight on each strip. | 75.0 KΩ |
| | 11.46 nf |

| BETWEEN | RESISTANCE | CAPACITANCE |
|---|---|---|
| 1&4 | 174.5 KΩ | 0.40 nf |
| 2&3 | 431 KΩ | 1.29 nf |
| 1&2 | 456 KΩ | 1.78 nf |
| 3&4 | 77.7 KΩ | 0.74 nf |
| 1&3 | 128.4 KΩ | NA |
| 2&4 | 468 KΩ | NA |
| 4&5 | 106.5 KΩ | NA |

***Table 12.** After Topcoating.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 152.5 KΩ |
| | 12.66 nf |
| Across tabs | 228.6 KΩ |
| | 0.08 nf |

| BETWEEN | RESISTANCE | CAPACITANCE |
|---|---|---|
| 1&4 | 637 KΩ | 0.52 nf |

|  |  |  |
|---|---|---|
| 2&3 | 668 KΩ | 0.57 nf |
| 1&2 | 1102 KΩ | 1.89 nf |
| 3&4 | 144.2 KΩ | 0.99 nf |
| 1&3 | 553 KΩ | NA |
| 2&4 | 585 KΩ | NA |
| 4&5 | 127.1 KΩ | NA |
| 3&6 | 65.8 KΩ | NA |

***Table 13**. Conductance and Capacitance as a function of frequency.*

| FREQUENCY IN KHZ | CAPACITANCE | CONDUCTANCE |
|---|---|---|
| 0.005 | -0.047 µf | 5.81 µS |
| 0.100 | 14.18 nf | 6.34 µS |
| 0.250 | 14.39 nf | 7.25 µS |
| 0.500 | 14.26 nf | 10.63 µS |
| 1.000 | 13.81 nf | 23.50 µS |
| 2.500 | 11.47 nf | 0.909 mS |
| 5.000 | 7.59 nf | 0.208 mS |
| 7.500 | 5.272 nf | 0.287 mS |
| 10.00 | 3.946 nf | 0.338 mS |
| 25.00 | 1.606 nf | 0.480 mS |
| 50.00 | 0.855 nf | 0.605 mS |
| 100.0 | 0.391 nf | 0.768 mS |
| 250.0 | 0.034 nf | 0.916 mS |
| 500.0 | -0.076 nf | 0.777 mS |
| 1000 | -161.9 nf | -0.532 mS |
| 2500 | 0.643 nf | -0.918 mS |
| 3000 | 0.531 nf | 0.908 mS |
| 5000 | 0.528 nf | 4.31 mS |

| | | |
|---|---|---|
| 7500 | 1.077 nf | 40.43 mS |
| 10000 | -0.884 nf | 6.76 Ω |
| 11000 | -0.491 nf | 5.51 Ω |
| 12000 | -0.328 nf | 3.75 Ω |
| 13000 | -0.232 nf | 1.42 Ω |

***Table 14.*** *Measurements taken between 1&2 and 3&4.*

| POSITION | RESISTANCE | CAPACITANCE |
|---|---|---|
| ~ 1 foot from Hepa end | 270.6 KΩ | 2.36 nf |
| ~ 2 feet from Hepa end | 393.0 KΩ | 3.56 nf |
| Middle | 535.0 KΩ | 4.06 nf |
| ~ 2 feet from heater end | 659.0 KΩ | 3.64 nf |
| ~ 1 foot from heater end | 856.0 KΩ | 3.81 nf |

***Table 15.*** *After cutting out 0.125" strip between tabs and the rest of the actuator, measurements taken between 1&2 and 3&4.*

| POSITION | RESISTANCE |
|---|---|
| ~ 1 foot from Hepa end | 508 KΩ |
| ~ 2 feet from Hepa end | 572 KΩ |
| Middle | 641 KΩ |
| ~ 2 feet from heater end | 715 KΩ |
| ~ 1 foot from heater end | 950 KΩ |

***Table 16.*** *Cured for 40 minutes and checked hot.*

| POSITION | RESISTANCE |
|---|---|
| ~ 1 foot from Hepa end | 506 KΩ |
| ~ 2 feet from Hepa end | 592 KΩ |
| Middle | 659 KΩ |
| ~ 2 feet from heater end | 981 KΩ |
| ~ 1 foot from heater end | 1326 KΩ |

***Table 17.*** *Cut 2nd strip 8" away from the 1st strip and after cooling down.*

| POSITION | RESISTANCE |
|---|---|
| ~ 1 foot from Hepa end | 1726 KΩ |
| ~ 2 feet from Hepa end | 1621 KΩ |
| Middle | 1296 KΩ |
| ~ 2 feet from heater end | 1217 KΩ |
| ~ 1 foot from heater end | 1383 KΩ |

### 3.1.3 05-05-10320-152

This actuator consisted of a 100 µm thick middle dielectric layer with a carbon black/Pellethane electrode.

***Table 18.*** *First electrode layer.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.590 KΩ |
| From end to end | 498 KΩ |
| Hepa end of actuator | 6.86 KΩ/square |
| Between Hepa end and middle | 11.84 KΩ/square |
| Middle | 12.93 KΩ/square |
| Between middle and heater end | 12.63 KΩ/square |
| Heater end | 17.29 KΩ/square |

***Table 19.*** *Second electrode layer.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.781 KΩ |
| From end to end | 378 KΩ |
| Hepa end of actuator | 14.02 KΩ/square |
| Between Hepa end and middle | 15.88 KΩ/square |
| Middle | 13.57 KΩ/square |
| Between middle and heater end | 17.33 KΩ/square |
| Heater end | 24.47 KΩ/square |

***Table 20.*** *Between Electrodes after Topcoating*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 21.33 KΩ |
| | 4.43 nf |
| Across tabs | 106.7 KΩ |
| | -0.042 nf |

| BETWEEN | RESISTANCE | CAPACITANCE |
|---|---|---|
| 1&4 | 459 KΩ | 0.11 nf |
| 2&3 | 448 KΩ | 0.09 nf |
| 1&2 | 401 KΩ | 0.83 nf |
| 3&4 | 44.2 KΩ | -0.47 nf |
| 1&3 | 449 KΩ | NA |
| 2&4 | 450 KΩ | NA |

***Table 21.*** *Measurements taken side to side between 1&2 and 3&4.*

| POSITION | RESISTANCE | CAPACITANCE |
|---|---|---|
| Hepa end | 43.6 KΩ | -0.46 nf |
| Between Hepa end and middle | 120.5 KΩ | 0.72 nf |
| Middle | 153.4 KΩ | 1.59 nf |
| Between middle and heater end | 261.3 KΩ | 2.20 nf |
| Heater end | 359 KΩ | 0.81 nf |

***Table 22****. Conductance and Capacitance as a function of frequency***.**

| FREQUENCY IN KHZ | CAPACITANCE | CONDUCTANCE |
|---|---|---|
| 0.005 | -0.005 µf | 48.75 µS |
| 0.100 | 11.89 nf | 48.15 µS |
| 0.250 | 11.96 nf | 49.43 µS |
| 0.500 | 11.93 nf | 50.27 µS |
| 1.000 | 11.82 nf | 55.84 µS |
| 2.500 | 11.18 nf | 0.091 mS |
| 5.000 | 9.50 nf | 0.190 mS |

| | | |
|---|---|---|
| 7.500 | 7.723 nf | 0.297 mS |
| 10.00 | 6.254 nf | 0.392 mS |
| 25.00 | 2.297 nf | 0.677 mS |
| 50.00 | 0.983 nf | 0.806 mS |
| 100.0 | 0.350 nf | 0.951 mS |
| 250.0 | 0.0.48 nf | 1.057 mS |
| 500.0 | -0.289 nf | 0.851 mS |
| 1000 | -0.191 nf | -0.399 mS |
| 2500 | 0.628 nf | 0.059 mS |
| 3000 | 0.529 nf | 1.426 mS |
| 5000 | 0.525 nf | 5.19 mS |
| 7500 | 0.927 nf | 41.63 mS |
| 10000 | UCL nf | _.__ Ω |
| 11000 | -0.529 nf | 3.73 Ω |
| 12000 | -0.328 nf | 4.70 Ω |
| 13000 | UCL nf | _.__ Ω |

### 3.1.4 06-05-10320-180

This actuator consisted of a 400 µm thick middle dielectric layer with a carbon black/Pellethane electrode.

***Table 23.*** *First electrode layer.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.357 KΩ |
| From end to end | 356 KΩ |
| Hepa end of actuator | 10.44 KΩ/square |
| Between Hepa end and middle | 10.78 KΩ/square |
| Middle | 8.07 KΩ/square |
| Between middle and heater end | 8.89 KΩ/square |
| Heater end | 17.04 KΩ/square |

***Table 24**. Second electrode layer.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.604 KΩ |
| From end to end | 398 KΩ |
| Hepa end of actuator | 11.32 KΩ/square |
| Between Hepa end and middle | 11.54 KΩ/square |
| Middle | 11.60 KΩ/square |
| Between middle and heater end | 11.59 KΩ/square |
| Heater end | 15.27 KΩ/square |

***Table 25.** Between the Electrodes after Topcoating.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | >32,000 KΩ |
| | 4.54 nf |
| Across tabs | >32,000 KΩ |
| | 4.23 nf |

| BETWEEN | RESISTANCE | CAPACITANCE |
|---|---|---|
| 1&4 | >32,000 KΩ | 2.06 nf |
| 2&3 | >32,000 KΩ | 1.86 nf |
| 1&2 | >32,000 KΩ | 1.54 nf |
| 3&4 | >32,000 KΩ | 1.61 nf |
| 1&3 | 466 KΩ | NA |
| 2&4 | 428 KΩ | NA |

***Table 26.** Measurements taken side to side between 1&2 and 3&4.*

| POSITION | RESISTANCE | CAPACITANCE |
|---|---|---|
| Hepa end | >32,000 KΩ | 1.561 nf |
| Between Hepa end and middle | >32,000 KΩ | 2.73 nf |
| Middle | >32,000 KΩ | 3.47 nf |
| Between middle and heater end | >32,000 KΩ | 2.58 nf |
| Heater end | >32,000 KΩ | 1.54 nf |

***Table 27.*** *Conductance and Capacitance as a function of frequency.*

| FREQUENCY IN KHZ | CAPACITANCE | CONDUCTANCE |
|---|---|---|
| 0.005 | -0.12 µf | -0.05 µS |
| 0.100 | 4.13 nf | 0.01 µS |
| 0.250 | 4.16 nf | 0.05 µS |
| 0.500 | 4.19 nf | 0.21 µS |
| 1.000 | 4.186 nf | 0.74 µS |
| 2.500 | 4.168 nf | 4.65 µS |
| 5.000 | 4.081 nf | 17.92 µS |
| 7.500 | 3.959 nf | 0.0383 mS |
| 10.00 | 3.795 nf | 0.0651 mS |
| 25.00 | 2.809 nf | 0.2425 mS |
| 50.00 | 1.884 nf | 0.4723 mS |
| 100.0 | 1.1795 nf | 0.6523 mS |
| 250.0 | 0.683 nf | 1.256 mS |
| 500.0 | 0.376 nf | 1.537 mS |
| 1000 | 0.2775 nf | 1.063 mS |
| 2500 | 0.4887 nf | 1.110 mS |
| 3000 | 0.4900 nf | 2.407 mS |
| 5000 | 0.528 nf | 5.95 mS |
| 7500 | 0.8141 nf | 40.43 mS |
| 10000 | -.6776 nf | 24.58 mS |
| 11000 | -0.4586 nf | 9.67 mS |
| 12000 | -0.3198 nf | 4.26 mS |
| 13000 | -0.2326 nf | 1.80 mS |

After rolling and terminating the actuator

Resistance >32,000 KΩ

Capacitance 7.97 nF

### 3.1.5 06-05-10320-197

This actuator consisted of a 200 µm thick middle dielectric layer with a carbon black/Pellethane electrode.

***Table 28.*** *First electrode layer.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.776 KΩ |
| From end to end | 500 KΩ |
| Hepa end of actuator | 14.46 KΩ/square |
| Between Hepa end and middle | 13.92 KΩ/square |
| Middle | 14.18 KΩ/square |
| Between middle and heater end | 12.63 KΩ/square |
| Heater end | 19.22 KΩ/square |

***Table 29.*** *Second electrode layer*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.526 KΩ |
| From end to end | 366 KΩ |
| Hepa end of actuator | 9.87 KΩ/square |
| Between Hepa end and middle | 10.24 KΩ/square |
| Middle | 9.68 KΩ/square |
| Between middle and heater end | 9.47 KΩ/square |
| Heater end | 15.06 KΩ/square |

***Table 30.*** *Across the dielectric after topcoating.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | >32,000 KΩ |
| Side to side capacitance, full weight on each strip | 8.38 nf |
| Across tabs resistance | >32,000 KΩ |
| Across tabs capacitance | 1.75 nf |

| BETWEEN | RESISTANCE | CAPACITANCE |
|---|---|---|
| 1&4 | >32,000 KΩ | 1.78 nf |
| 2&3 | >32,000 KΩ | 1.55 nf |

| | | |
|---|---|---|
| 1&2 | >32,000 KΩ | 1.76 nf |
| 3&4 | >32,000 KΩ | 1.96 nf |
| 1&3 | 431 KΩ | NA |
| 2&4 | 681 KΩ | NA |

***Table 31.*** *Measurements taken side to side between 1&2 and 3&4.*

| **Position** | **Resistance** | **Capacitance** |
|---|---|---|
| Hepa end | >32,000 KΩ | 1.96nf |
| Between Hepa end and middle | >32,000 KΩ | 3.32 nf |
| Middle | >32,000 KΩ | 4.05 nf |
| Between middle and heater end | >32,000 KΩ | 3.89 nf |
| Heater end | >32,000 KΩ | 1.77nf |

***Table 32****. Conductance and Capacitance as a function of frequency.*

| **FREQUENCY IN KHZ** | **CAPACITANCE** | **CONDUCTANCE** |
|---|---|---|
| 0.005 | 0.004 µf | -0.25 µS |
| 0.100 | 7.91 nf | 0.05 µS |
| 0.250 | 7.96 nf | 0.21 µS |
| 0.500 | 7.97 nf | 0.85 µS |
| 1.000 | 7.932 nf | 3.27 µS |
| 2.500 | 7.715 nf | 18.89 µS |
| 5.000 | 7.11 nf | 0.0681 mS |
| 7.500 | 6.334 nf | 0.1292 mS |
| 10.00 | 5.593 nf | 0.1913 mS |
| 25.00 | 3.078 nf | 0.4633 mS |
| 50.00 | 1.733 nf | 0.7031 mS |
| 100.0 | 0.9603 nf | 0.8329 mS |
| 250.0 | 0.534 nf | 1.272 mS |
| 500.0 | 0.315 nf | 1.368 mS |
| 1000 | 0.2736 nf | 0.781 mS |

| | | |
|---|---|---|
| 2500 | 0.5011 nf | 1.047 mS |
| 3000 | 0.5038 nf | 2.173 mS |
| 5000 | 0.579 nf | 5.84 mS |
| 7500 | 0.8884 nf | 56.14 mS |
| 10000 | -0.6312 nf | 15.80 mS |
| 11000 | -0.4159 nf | 6.18 mS |
| 12000 | -0.2912 nf | 2.55 mS |
| 13000 | -0.2129 nf | 0.82 mS |

After rolling and terminating the actuator

| | |
|---|---|
| Resistance | > 32,000 KΩ |
| Capacitance | 15.93 nF |

### 3.1.6 06-05-10320-12

This actuator consisted of a 150 µm thick middle dielectric layer with a carbon black/Pellethane electrode.

***Table 33.*** *First electrode layer.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 1.102 KΩ |
| From end to end | 596 KΩ |
| Hepa end of actuator | 17.19 KΩ/square |
| Between Hepa end and middle | 15.96 KΩ/square |
| Middle | 16.92 KΩ/square |
| Between middle and heater end | 19.31 KΩ/square |
| Heater end | 21.88 KΩ/square |

***Table 34.*** *Second electrode layer.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.798 KΩ |
| From end to end | 445 KΩ |
| Hepa end of actuator | 15.28 KΩ/square |

| | |
|---|---|
| Between Hepa end and middle | 12.29 KΩ/square |
| Middle | 15.18 KΩ/square |
| Between middle and heater end | 13.20 KΩ/square |
| Heater end | 17.13 KΩ/square |

***Table 35.** Across the dielectric layer after topcoating.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 64.9 KΩ |
| | 7.42 nf |
| Across tabs | 159.5 KΩ |
| | 1.15 nf |

| BETWEEN | RESISTANCE | CAPACITANCE |
|---|---|---|
| 1&4 | 637 KΩ | 0.056 nf |
| 2&3 | 839 KΩ | 0.52 nf |
| 1&2 | 1369 KΩ | 1.51 nf |
| 3&4 | 110.8 KΩ | 0.33 nf |
| 1&3 | 587 KΩ | NA |
| 2&4 | 814 KΩ | NA |

***Table 36**. Measurements taken side to side between 1&2 and 3&4.*

| POSITION | RESISTANCE | CAPACITANCE |
|---|---|---|
| Hepa end | 118.9 KΩ | 0.28 nf |
| Between Hepa end and middle | 288 KΩ | 1.99 nf |
| Middle | 607 KΩ | 3.07 nf |
| Between middle and heater end | 966 KΩ | 3.50 nf |
| Heater end | 1395 KΩ | 1.41 nf |

***Table 37.** Conductance and Capacitance as a function of frequency.*

| FREQUENCY IN KHZ | CAPACITANCE | CONDUCTANCE |
|---|---|---|
| 0.005 | -0.023 µf | 15.02 µS |
| 0.100 | 10.37 nf | 15.36 µS |
| 0.250 | 10.43 nf | 15.69 µS |

| | | |
|---|---|---|
| 0.500 | 10.39 nf | 17.22 µS |
| 1.000 | 10.234 nf | 23.34 µS |
| 2.500 | 9.35 nf | 0.0605 mS |
| 5.000 | 7.34 nf | 0.1467 mS |
| 7.500 | 5.730 nf | 2.249 mS |
| 10.00 | 4.574 nf | 0.2823 mS |
| 25.00 | 1.938 nf | 0.4702 mS |
| 50.00 | 1.053 nf | 0.5916 mS |
| 100.0 | 0.6334 nf | 0.6025 mS |
| 250.0 | 0.4219 nf | 0.9208 mS |
| 500.0 | 0.2775 nf | 0.9273 mS |
| 1000 | 0.2677 nf | 0.291 mS |
| 2500 | 0.5113 nf | 0.164 mS |
| 3000 | 0.5176 nf | 1.466 mS |
| 5000 | 0.591 nf | 4.57 mS |
| 7500 | 1.1186 nf | 55.46 mS |
| 10000 | -0.6723 nf | 14.33 mS |
| 11000 | -0.4298 nf | 5.27 mS |
| 12000 | -0.2977 nf | 2.00 mS |
| 13000 | -0.2167 nf | 0.46 mS |

### 3.1.7 06-05-10481-36

This actuator consisted of a 300 µm thick middle dielectric layer with a carbon black/Pellethane electrode.

***Table 38.*** *First electrode layer*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.601 KΩ |
| From end to end | 447 KΩ |
| Hepa end of actuator | 11.60 KΩ/square |

| | |
|---|---|
| Between Hepa end and middle | 13.43 KΩ/square |
| Middle | 11.76 KΩ/square |
| Between middle and heater end | 11.03 KΩ/square |
| Heater end | 17.73 KΩ/square |

***Table 39.** Second electrode layer*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.697 KΩ |
| From end to end | 419 KΩ |
| Hepa end of actuator | 10.02 KΩ/square |
| Between Hepa end and middle | 11.27 KΩ/square |
| Middle | 11.73 KΩ/square |
| Between middle and heater end | 10.73 KΩ/square |
| Heater end | 16.93 KΩ/square |

***Table 40.** Across the dielectric after topcoating*

| | |
|---|---|
| Side to side resistance, full weight on each strip | >32,000 KΩ |
| | 6.11 nf |
| Across tabs | >32,000 KΩ |
| | 5.06 nf |

| BETWEEN | RESISTANCE | CAPACITANCE |
|---|---|---|
| 1&4 | >32,000 KΩ | 1.48 nf |
| 2&3 | >32,000 KΩ | 1.60 nf |
| 1&2 | >32,000 KΩ | 1.62 nf |
| 3&4 | >32,000 KΩ | 1.61 nf |
| 1&3 | 514 KΩ | NA |
| 2&4 | 595 KΩ | NA |

***Table 41.** Measurements taken side to side between 1&2 and 3&4.*

| POSITION | RESISTANCE | CAPACITANCE |
|---|---|---|
| Hepa end | >32,000 KΩ | 1.62 nf |
| Between Hepa end and middle | >32,000 KΩ | 2.64 nf |

| | | |
|---|---|---|
| Middle | >32,000 KΩ | 3.41 nf |
| Between middle and heater end | >32,000 KΩ | 3.16 nf |
| Heater end | >32,000 KΩ | 1.63 nf |

***Table 42.*** *Conductance and Capacitance as a function of frequency.*

| FREQUENCY IN KHZ | CAPACITANCE | CONDUCTANCE |
|---|---|---|
| 0.005 | 0.005 µf | 0.14 µS |
| 0.100 | 5.63 nf | 0.03 µS |
| 0.250 | 5.67 nf | 0.13 µS |
| 0.500 | 5.69 nf | 0.51 µS |
| 1.000 | 5.661 nf | 2.10 µS |
| 2.500 | 5.515 nf | 12.87 µS |
| 5.000 | 5.11 nf | 0.0453 mS |
| 7.500 | 4.608 nf | 0.0865 mS |
| 10.00 | 4.113 nf | 0.1296 mS |
| 25.00 | 2.393 nf | 0.3116 mS |
| 50.00 | 1.551 nf | 0.4825 mS |
| 100.0 | 0.9897 nf | 0.6131 mS |
| 250.0 | 0.568 nf | 1.129 mS |
| 500.0 | 0.315 nf | 1.266 mS |
| 1000 | 0.2646 nf | 0.552 mS |
| 2500 | 0.4813 nf | 1.944 mS |
| 3000 | 0.4256 nf | 2.383 mS |
| 5000 | 0.561 nf | 5.58 mS |
| 7500 | 0.8971 nf | 43.87 mS |
| 10000 | -0.6796 nf | 20.97 mS |
| 11000 | -0.4480 nf | 8.07 mS |
| 12000 | -0.3111 nf | 3.44 mS |
| 13000 | -0.2262 nf | 1.31 mS |

After rolling and terminating the actuator

| | |
|---|---|
| Resistance | >32,000 KΩ |
| Capacitance | 10.99 nF |

### 3.1.8 06-05-10481-64

This actuator consisted of a 200 µm thick middle dielectric layer with a carbon black/RTV12 (silicone) electrode.

***Table 43.*** *First electrode layer, first application.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 2.150 KΩ |
| From end to end | 2802 KΩ |
| Hepa end of actuator | 51.8 KΩ/square |
| Between Hepa end and middle | 94.3 KΩ/square |
| Middle | 90.2 KΩ/square |
| Between middle and heater end | 61.1 KΩ/square |
| Heater end | 99.9 KΩ/square |

***Table 44.*** *First electrode layer, second application.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 1.087 KΩ |
| From end to end | 1386 KΩ |
| Hepa end of actuator | 25.74 KΩ/square |
| Between Hepa end and middle | 37.0 KΩ/square |
| Middle | 45.9 KΩ/square |
| Between middle and heater end | 27.45 KΩ/square |
| Heater end | 47.1 KΩ/square |

***Table 45.*** *Second electrode layer*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.645 KΩ |
| From end to end | 863 KΩ |
| Hepa end of actuator | 29.72 KΩ/square |
| Between Hepa end and middle | 21.59 KΩ/square |

| | |
|---|---|
| Middle | 27.18 KΩ/square |
| Between middle and heater end | 33.9 KΩ/square |
| Heater end | 25.96 KΩ/square |

***Table 46.*** *Across the dielectric after topcoating.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 1289 KΩ |
| | 7.66 nf |

| BETWEEN | RESISTANCE | CAPACITANCE |
|---|---|---|
| 1&4 | 2912 KΩ | 0.13 nf |
| 2&3 | 3050 KΩ | 0.14nf |
| 1&2 | 1746 KΩ | 0.38 nf |
| 3&4 | 3390 KΩ | 0.75 nf |
| 1&3 | 2493 KΩ | NA |
| 2&4 | 2437 KΩ | NA |

***Table 47.*** *Measurements taken side to side between 1&2 and 3&4.*

| POSITION | RESISTANCE | CAPACITANCE |
|---|---|---|
| Hepa end | 3440 KΩ | 0.75 nf |
| Between Hepa end and middle | 2715 KΩ | 1.48 nf |
| Middle | 1857 KΩ | 1.17 nf |
| Between middle and heater end | 1359 KΩ | 1.15 nf |
| Heater end | 1706 KΩ | 0.41 nf |

***Table 48.*** *Conductance and Capacitance as a function of frequency*

| FREQUENCY IN KHZ | CAPACITANCE | CONDUCTANCE |
|---|---|---|
| 0.005 | 0.003 µf | 1.84 µS |
| 0.100 | 7.58 nf | 1.85 µS |
| 0.250 | 7.62 nf | 2.29 µS |
| 0.500 | 7.57 nf | 3.95 µS |
| 1.000 | 7.372 nf | 10.12 µS |
| 2.500 | 6.301 nf | 45.28 µS |

| | | |
|---|---|---|
| 5.000 | 4.30 nf | 0.1151 mS |
| 7.500 | 2.913 nf | 0.1671 mS |
| 10.00 | 2.046 nf | 0.2013 mS |
| 25.00 | 0.480 nf | 0.2634 mS |
| 50.00 | 0.170 nf | 0.2686 mS |
| 100.0 | 0.1125 nf | 0.1332 mS |
| 250.0 | 0.2363 nf | 0.1952 mS |
| 500.0 | 0.2210 nf | 0.0916 mS |
| 1000 | 0.2418 nf | -0.396 mS |
| 2500 | 0.4684 nf | -1.348 mS |
| 3000 | 0.4956 nf | -0.135 mS |
| 5000 | 0.546 nf | 1.63 mS |
| 7500 | 1.2849 nf | 23.91 mS |
| 10000 | -0.8979 nf | 16.65 mS |
| 11000 | -0.5127 nf | 4.85 mS |
| 12000 | -0.3375 nf | 1.51 mS |
| 13000 | -0.2392 nf | 0.08 mS |

### 3.1.9 06-05-10481-82

This actuator consisted of a 200 µm thick middle dielectric layer with a carbon black/Pellethane electrode.

***Table 49**. First electrode layer*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.277 KΩ |
| From end to end | 203 KΩ |
| Hepa end of actuator | 6.98 KΩ/square |
| Between Hepa end and middle | 7.89 KΩ/square |
| Middle | 6.27 KΩ/square |
| Between middle and heater end | 7.07 KΩ/square |

| | |
|---|---|
| Heater end | 7.65 KΩ/square |

***Table 50.*** *Second electrode layer*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.184 KΩ |
| From end to end | 115 KΩ |
| Hepa end of actuator | 6.30 KΩ/square |
| Between Hepa end and middle | 3.52 KΩ/square |
| Middle | 3.27 KΩ/square |
| Between middle and heater end | 3.28 KΩ/square |
| Heater end | 5.55 KΩ/square |

***Table 51**. Across the dielectric layer after topcoating**.***

| | |
|---|---|
| Side to side resistance, full weight on each strip | 158.6 KΩ |
| | 5.87 nf |

| BETWEEN | RESISTANCE | CAPACITANCE |
|---|---|---|
| 1&4 | 226.5 KΩ | 0.94 nf |
| 2&3 | 316 KΩ | 1.82 nf |
| 1&2 | 413 KΩ | 1.99 nf |
| 3&4 | 124.8 KΩ | 0.72 nf |
| 1&3 | 135.3 KΩ | NA |
| 2&4 | 271.2 KΩ | NA |

***Table 52**. Measurements taken side to side between 1&2 and 3&4.*

| POSITION | RESISTANCE | CAPACITANCE |
|---|---|---|
| Hepa end | 121.6 KΩ | 0.72 nf |
| Between Hepa end and middle | 128.9 KΩ | 2.48 nf |
| Middle | 200.1 KΩ | 3.92 nf |
| Between middle and heater end | 306 KΩ | 3.81 nf |
| Heater end | 410 KΩ | 1.95 nf |

***Table 53.*** *Conductance and Capacitance as a function of frequency.*

| FREQUENCY IN KHZ | CAPACITANCE | CONDUCTANCE |
|---|---|---|
| 0.005 | -0.013µf | 12.73 µS |

| | | |
|---|---|---|
| 0.100 | 7.52 nf | 12.99 µS |
| 0.250 | 7.57nf | 13.15 µS |
| 0.500 | 7.59 nf | 13.35 µS |
| 1.000 | 7.586 nf | 14.04 µS |
| 2.500 | 7.571 nf | 19.07 µS |
| 5.000 | 7.48 nf | 0.0379 mS |
| 7.500 | 7.348 nf | 0.0673 mS |
| 10.00 | 7.174 nf | 0.1061 mS |
| 25.00 | 5.796 nf | 0.4329 mS |
| 50.00 | 4.  03 nf | 0.972 mS |
| 100.0 | 2.341 nf | 1.533 mS |
| 250.0 | 1.158 nf | 2.553 mS |
| 500.0 | 0.648 nf | 3.173 mS |
| 1000 | 0.4269 nf | 3.073 mS |
| 2500 | 0.5377 nf | 5.713 mS |
| 3000 | 0.4806 nf | 6.729 mS |
| 5000 | 0.544 nf | 14.14 mS |
| 7500 | 0.0622 nf | 51.17 mS |
| 10000 | -0.4565 nf | 15.24 mS |
| 11000 | -0.3399 nf | 7.66 mS |
| 12000 | -0.253 nf | 3.94 mS |
| 13000 | -0.1911 nf | 1.91 mS |

### 3.1.10 06-05-10481-106

This actuator consisted of a 200 µm thick middle dielectric layer with a carbon black/Pellethane electrode.

***Table 54**. First electrode layer.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.435 KΩ |

| | |
|---|---|
| From end to end | 355 KΩ |
| Hepa end of actuator | 16.21 KΩ/square |
| Between Hepa end and middle | 14.15 KΩ/square |
| Middle | 12.80 KΩ/square |
| Between middle and heater end | 12.97 KΩ/square |
| Heater end | 19.41 KΩ/square |

***Table 55***. *Second electrode layer*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 1.072 KΩ |
| From end to end | 511 KΩ |
| Hepa end of actuator | 22.53 KΩ/square |
| Between Hepa end and middle | 16.89 KΩ/square |
| Middle | 17.54 KΩ/square |
| Between middle and heater end | 16.44 KΩ/square |
| Heater end | 49.8 KΩ/square |

***Table 56.*** *Across dielectric after topcoating*

| | |
|---|---|
| Side to side resistance, full weight on each strip. | 65.4 KΩ |
| | 4.65 nf |

| BETWEEN | RESISTANCE | CAPACITANCE |
|---|---|---|
| 1&4 | 549 KΩ | 0.24 nf |
| 2&3 | 450 KΩ | 0.20 nf |
| 1&2 | 527 KΩ | 0.66 nf |
| 3&4 | 327 KΩ | 0.61 nf |
| 1&3 | 575 KΩ | NA |
| 2&4 | 396 KΩ | NA |

***Table 57. Measurements taken side to side between 1&2 and 3&4.***

| POSITION | RESISTANCE | CAPACITANCE |
|---|---|---|
| Hepa end | 328 KΩ | 0.57 nf |
| Between Hepa end and middle | 106.2 KΩ | 1.71 nf |

| | | |
|---|---|---|
| Middle | 182.2 KΩ | 1.12 nf |
| Between middle and heater end | 120.3 KΩ | 1.76 nf |
| Heater end | 497 KΩ | 0.63 nf |

***Table 58.*** *Conductance and Capacitance as a function of frequency.*

| FREQUENCY IN KHZ | CAPACITANCE | CONDUCTANCE |
|---|---|---|
| 0.005 | -0.016 µf | 16.89 µS |
| 0.100 | 7.36 nf | 17.37 µS |
| 0.250 | 7.45 nf | 17.46 µS |
| 0.500 | 7.45 nf | 18.05 µS |
| 1.000 | 7.414 nf | 20.29 µS |
| 2.500 | 7.204 nf | 35.52 µS |
| 5.000 | 6.60 nf | 0.823 mS |
| 7.500 | 5.872 nf | 0.1410 mS |
| 10.00 | 5.170 nf | 0.2004 mS |
| 25.00 | 2.736 nf | 0.4473 mS |
| 50.00 | 1.564 nf | 0.6413 mS |
| 100.0 | 0.9202 nf | 0.7461 mS |
| 250.0 | 0.554 nf | 1.196 mS |
| 500.0 | 0.323 nf | 1.316 mS |
| 1000 | 0.2946 nf | 0.652 mS |
| 2500 | 0.4993 nf | 1.891 mS |
| 3000 | 0.4550 nf | 2.539 mS |
| 5000 | 0.591 nf | 5.85 mS |
| 7500 | 0.9145 nf | 51.43 mS |
| 10000 | -0.6571 nf | 17.86 mS |
| 11000 | -0.4321 nf | 7.00 mS |
| 12000 | -0.3015 nf | 2.97 mS |
| 13000 | -0.2201 nf | 1.08 mS |

### 3.1.11 06-05-10581-127

This actuator consisted of a 350 µm thick middle dielectric layer with a carbon black/Pellethane electrode.

***Table 59.*** *First electrode layer.*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 1.299 KΩ |
| From end to end | 526 KΩ |
| Hepa end of actuator | 14.79 KΩ/square |
| Between Hepa end and middle | 13.66 KΩ/square |
| Middle | 12.62 KΩ/square |
| Between middle and heater end | 20.27 KΩ/square |
| Heater end | 28.95 KΩ/square |

***Table 60.*** *Second electrode layer*

| | |
|---|---|
| Side to side resistance, full weight on each strip | 0.588 KΩ |
| From end to end | 479 KΩ |
| Hepa end of actuator | 10.34 KΩ/square |
| Between Hepa end and middle | 10.39 KΩ/square |
| Middle | 14.31 KΩ/square |
| Between middle and heater end | 11.55 KΩ/square |
| Heater end | 20.69 KΩ/square |

***Table 61****.* *Across dielectric after topcoating*

| | |
|---|---|
| Side to side resistance, full weight on each strip | >32,000 KΩ |
| | 4.71 nf |

| **BETWEEN** | **RESISTANCE** | **CAPACITANCE** |
|---|---|---|
| 1&4 | >32,000 KΩ | 1.39 nf |
| 2&3 | >32,000 KΩ | 1.41 nf |
| 1&2 | >32,000 KΩ | 1.33 nf |
| 3&4 | >32,000 KΩ | 1.47 nf |
| 1&3 | 617 KΩ | NA |

| | | |
|---|---|---|
| 2&4 | 540 KΩ | NA |

***Table 62.*** *Measurements taken side to side between 1&2 and 3&4.*

| POSITION | RESISTANCE | CAPACITANCE |
|---|---|---|
| Hepa end | >32,000 KΩ | 1.47 nf |
| Between Hepa end and middle | >32,000 KΩ | 2.49 nf |
| Middle | >32,000 KΩ | 3.11 nf |
| Between middle and heater end | >32,000 KΩ | 2.72 nf |
| Heater end | >32,000 KΩ | 1.34 nf |

***Table 63.*** *Conductance and Capacitance as a function of frequency.*

| FREQUENCY IN KHZ | CAPACITANCE | CONDUCTANCE |
|---|---|---|
| 0.005 | -0.016 µf | -0.15 µS |
| 0.100 | 4.26 nf | 0.02 µS |
| 0.250 | 4.33 nf | 0.13 µS |
| 0.500 | 4.34 nf | 0.46 µS |
| 1.000 | 4.325 nf | 1.67 µS |
| 2.500 | 4.202 nf | 9.88 µS |
| 5.000 | 3.861 nf | 33.98 µS |
| 7.500 | 3.493 nf | 0.0631 mS |
| 10.00 | 3.156 nf | 0.0936 mS |
| 25.00 | 1.942 nf | 0.2207 mS |
| 50.00 | 1.366 nf | 0.3448 mS |
| 100.0 | 0.9564 nf | 0.4525 mS |
| 250.0 | 0.594 nf | 0.980 mS |
| 500.0 | 0.333 nf | 1.155 mS |
| 1000 | 0.2863 nf | 0.348 mS |
| 2500 | 0.4533 nf | 1.746 mS |
| 3000 | 0.4321 nf | 1.715 mS |
| 5000 | 0.563 nf | 5.37 mS |

| | | |
|---|---|---|
| 7500 | 0.9184 nf | 43.06 mS |
| 10000 | -0.6929 nf | 21.81 mS |
| 11000 | -0.4543 nf | 8.31 mS |
| 12000 | -0.3146 nf | 3.56 mS |
| 13000 | -0.2286 nf | 1.42 mS |

After rolling and terminating the actuator

| | |
|---|---|
| Resistance | 61.6 KΩ |
| Capacitance | 1.93 nF |

## 3.2 Summary of Electrical Properties of Actuators Produced

The following table summarizes the electrical properties of the actuators. The values of resistance (R) and capacitance (C) used for the lay flat geometry correspond to the final dielectric topcoat with the "side to side resistance, full weight on each strip" , as in Table 61.

***Table 64.*** *Summary of Electrical Properties*

| ACTUATOR ID | DIELECTRIC | | ELECTRODE | LAY FLAT | | ROLLED | |
|---|---|---|---|---|---|---|---|
| | *Type* | *Nominal Thickness ($\mu$m)* | *Type* | *R (k$\Omega$)* | *C (nF)* | *R (k$\Omega$)* | *C (nF)* |
| 05-05-10320-104 | Silicone | 100 | Graphite | 55.7 | 10.8 | N/A | N/A |
| 05-05-10320-122 | Silicone | 100 | Graphite | 152.5 | 12.66 | N/A | N/A |
| 05-05-10320-152 | Silicone | 100 | Carbon black/pellethane | 21.33 | 4.43 | N/A | N/A |
| 06-05-10320-180 | Silicone | 400 | Carbon black/pellethane | >32,000 | 4.54 | >32,000 | 7.97 |
| 06-05-10320-197 | Silicone | 200 | Carbon black/pellethane | >32,000 | 8.34 | >32,000 | 15.93 |
| 06-05-10320-12 | Silicone | 150 | Carbon black/pellethane | 64.9 | 7.42 | N/A | N/A |
| 06-05-10481-36 | Silicone | 300 | Carbon black/pellethane | >32,000 | 6.11 | >32,000 | 10.99 |
| 06-05-10481-64 | Silicone | 200 | Carbon black/RTV12 | 1289 | 7.66 | N/A | N/A |
| 06-05-10481-82 | Silicone | 200 | Carbon black/pellethane | 158.6 | 5.87 | N/A | N/A |
| 06-05-10481-106 | Silicone | 200 | Carbon black/pellethane | 65.4 | 4.65 | N/A | N/A |
| 06-05-10581-127 | Silicone | 350 | Carbon black/pellethane | >32,000 | 4.71 | 61.6 | 1.93 |

# 4. Conclusions

In our previous work on dielectric actuators, two main problems were encountered: the ability to terminate the device and conductivity through the middle dielectric layer. In this project, termination of the final device was not an issue but the problem of conductivity through the central dielectric remained. Three actuators with nominal thickness of 200, 300, and 400 µm that did not conduct through the middle layer were produced and submitted to the Scientific Authority. These could not be produced reliably however. We suspect that this inconsistency is related to the spray process used to fabricate the actuators. Further work should concentrate on improvements to the process for fabrication of actuators.

# 5. References

[1] Massey, Jason (2003), Fabrication of Dielectric Polymer Actuators: Formulation of Polyurethane Elastomers, (Contactor Report 2003-226), Defence R&D Canada - Atlantic.

[2] Massey, Jason (2003), Fabrication of Dielectric Polymer Actuators: Design, Construction, and Debugging of the Actuator Fabrication Device, (Contactor Report 2003-227), Defence R&D Canada - Atlantic.

[3] Massey, Jason (2003), Filled Elastomer Films for Actuator Applications, (Contactor Report 2003-064), Defence R&D Canada - Atlantic.

[4] Leidner, Jacob (2004), Fabrication of Dielectric Polymer Actuators: Assembly of Rolled Actuators Part I, (Contractor Report 2004-195), Defence R&D Canada - Atlantic.

[5] Massey, Jason (2004), Fabrication of Dielectric Polymer Actuators: Formulation of a Compliant Electrode, (Contactor Report 2004-050), Defence R&D Canada - Atlantic.

[6] Leidner, Jacob (2005), Fabrication of Dielectric Polymer Actuators: Assembly of Rolled Actuators Part II, (Contractor Report 2005-076), Defence R&D Canada - Atlantic.

[7] Jaklewicz, Magda (2005), Fabrication of Dielectric Polymer Actuators: Fibre Actuators, (Contractor Report 2004-109), Defence R&D Canada - Atlantic.

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In this program we continued the previous work on the fabrication of dielectric actuators. When compliant electrodes applied to an elastomeric dielectric film in a dielectric actuator are charged, the electrodes attract, compressing the film and causing it to move in a direction perpendicular to the applied force. The geometry of the actuator was a long strip consisting of alternating dielectric and electrode layers, rolled up and electrically terminated to form the final device.

In our previous work two main obstacles were encountered: conductivity through the middle dielectric layer and the ability to electrically terminate the device. By using silicone for the dielectric layer and a formulation based on carbon black milled with thermoplastic polyurethane as the electrode, termination of the device was reliable and consistent. However, conductivity through the middle dielectric layer is still an issue. Three actuators with nominal thickness of 200, 300, and 400 µm that did not conduct through the middle layer were produced and submitted to the Scientific Authority. These could not be produced reliably however. We suspect that this inconsistency is related to the spray process used to fabricate the actuators. Further work should concentrate on improvements to the process for fabrication of actuators.

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