Effect of Varying Urethane Thickness on Valves

F.C. Yu, J. Podczerviensky, S. Ehrlich and L. Levine

ALine, Inc., 19500 S. Rancho Way, Ste. 107 Rancho Dominguez, CA 90220; info@alineinc.com

ABSTRACT

On-board pneumatic valves produced with laminate fabrication processes provide a cost effective way to perform metering mixing and gating of fluid movement in Lab on a chip devices. These valves can be used in multiplexed molecular- or immunoassays where successive reagent additions and/or washes are needed. The laminate valve assembly, produced in a batch fabrication process, is combined with an injection molded component that contains the reagent reservoirs, along with either an optical or electroactive sensor for detection, enabling complete sample to answer performance. To meet the cost and performance requirements for single use devices, the valves must be easy to produce in volume with performance characteristics that are tolerant to a range of pressures, channel geometries and fluid processing requirements while being ammenable to volume production. This paper investigates the geometry required to match the functional performance of our pneumatically actuated diaphragm valves using a .001” urethane vs .002” and .004” thick urethane. Also of interest is the viability of the spike and hold method of closing valves using the standard valve geometry.

1. INTRODUCTION

Lab on a Chip devices must perform all the steps of an assay using a fluid circuit to meter, mix, vent, wash and enable quantitative detection at the sensor. For point of care applications, this means the cost of manufacture must be low, and the performance robust enough to tolerate a range of conditions that would be encountered in the field. The complex fluid movements required for a multistep immunoassay present a conundrum in the development of an inexpensive single use disposable: to maintain low costs, the device itself must be as simple as possible, yet it must be able to perform quantitative assays that require precise metering and thorough mixing, with multiple reagent additions and washes. The desire then is to have as simple a device as possible that is able to robustly perform complex fluid movement with good precision. While injection molded devices would appear at first blush to offer a ready solution to meet these requirements, the reality is that the precision required of the molded part drives up both the development and manufacturing cost, and results in a device that is less tolerant of manufacturing process variability; a result of having to use heat in the process of molding as well as bonding components together. Heat induces stress in plastics and increases the functional variability of the device to levels that cause them to perform no better than lateral flow devices, but at a cost of manufacture that is much higher.

Laminate stacks of polymer films and sheets that are bonded with pressure sensitive adhesives offer a cost effective solution in providing complex fluid movements with, for example, 2% variability in pumped volume [1] using simple stacks of materials that have known thickness tolerances. With designs that incorporate the appropriate design rules, low cost, robust fluid circuits with on board valves, vents, and pumps have been developed with repeatable performance over tens of thousands of devices.

A key feature in the success of our devices is the data we have collected on the performance characteristics of our valves and pumps over a range of plausible conditions and geometries, and then provide optimal operating conditions that can be designed into the product. To further our earlier work we report here on the operating parameters and geometry for our valves using a variety of thicknesses of urethane materials. The advantage of thicker materials is ease of processing in roll to roll manufacturing, and reduce gas permeability.

2. MATERIALS AND METHODS

This paper explores the possibility of the use of thicker urethane in our valves, using polymer laminate technologies (PLT). Test devices were constructed using PET (polyethylene ester terphthalate) and acrylic (polymethyl methacrylate). PET can be obtained in thicknesses or 12.5 to 250 microns, with a variability of +/- 10%. The acrylic usually ranges from 1 to 1.5 mm thick (+/- 10%). The bonding materials consisted of silicone and solvent acrylic based pressure sensitive adhesives. These adhesives are transparent and biocompatible with thicknesses of 25 and 50 microns (+/- 5%)

2.1 Device Fabrication

The devices were built in a batch based, modular approach, that could be separated into sub-assemblies for the critical components of the device. The sub-assemblies for this device include the acrylic manifold layer, the valve layer, and the channel layer. Sub-assemblies allow
for easy in-process quality checks before the final assembly.

These different device layers are composed of plastic substrates, such as PET and PMMA, which are cut on a CO₂ laser and then cleaned with isopropyl alcohol. The cut and cleaned layers are then aligned using pin fixtures and bonded together using pressure sensitive or thermal bonded adhesives. To increase the bonding strength between materials, an atmospheric argon plasma stream can be used to treat the materials before bonding. After the sub-assemblies are built and undergo QC, they are laminated together with pressure and heat and then cut out from the sheet using the laser.

2.2 Structure of the Pneumatic Valves

The current valves use a 0.001” urethane membrane, which is difficult to handle during production and is gas permeable. A thicker membrane improves handling, and reduces gas permeability, but could also impact valve functional performance at the pressures that are routinely used.

A cross sectional view of the valve is shown in Figure 1. The pneumatic valves are positioned above the channel layer. Between the valve and the channel layers are vias, or through-holes. The channels end at the via, requiring liquid to flow through the via and into the valve seat in order to reconnect through a second via with the channel. These valves are normally open, so that when there is no pressure applied to the valve membrane, the fluid is allowed to travel into the valve seats through the central via toward the via at a distal location, Figure 1a. When pressure is applied, however, the actuated valves stop fluid flow by blocking the through holes over the channel ends, Figure 1b.

2.3 Test Platform

Increasing urethane thickness has an impact on its mechanical properties and demands higher pressures for actuation. In order to compensate for added stiffness, the valve-seat area was enlarged to alleviate pressure requirements. A fluid reservoir, containing dyed water, was pressurized using regulated house-compressed air.

![Figure 1: Valve Schematic](image1.png)

**Figure 1a Diagram of an Open Valve [2]**

**Figure 1b Diagram of a Closed Valve [2]**

The reservoir was then connected to the test device with tubing and a valve was fitted over the connecting tubing to control the fluid between reservoir and test device. A schematic of the test bench can be seen in Figure 2. Each test device, as shown in Figure 3, contains eight fluid channels, and 5 valve-governing (air) channels; each channel has five valves. Starting with the standard valve size, the area of the following valves was incremented by 15%, making the last valve 60% larger. It can be appreciated that each air channel controls all valves of the same scale. There were three devices made, one for each thickness of urethane: 0.001”, 0.002”, and 0.004”.

Metering channels were fabricated with a height of 0.007” and a width of 0.020” to measure the leak rate of the valves. The divisions engraved into the channels are separated by 1mm which represent a volume of 0.0889µL per unit length. The resolution of measurements is 0.022µL or a distance of 0.25 mm, as a Femtoscope MZ7 is used to view the channels during data collection. Hose barbs were glued into the inlet and outlet of each of the channels in both the test device and metered channels. The test device outlet was then connected to a metered channel inlet using soft tubing.
Air pressure was provided by the facility’s compressor and regulated using pressure gauges. The in-house developed ALine ADEPT platform uses regulated air pressure to control up to eight air outlets. The ADEPT consists of on-board air regulators and pressure sensors and has the ability to control valves both manually and through software. One of ADEPT’s outputs was connected to the valve-governing channel in the test device that will be manually actuated.

The procedure for measuring leak rates for each valve is as follows. With all valves open, channels are filled with pressure-driven flow. The liquid first enters the test device and the metering channel second. When liquid enters the measuring scale, one air channel is actuated through the ADEPT. This closes only one valve per channel, the one that is being tested. The initial position of the liquid column is recorded. After a given amount of time has passed the position of the liquid column is again recorded; the collected data is used to calculate leak rate. The channels are dried between each test using 5psi air.

An initial fluid displacement of 0.040-0.120" after the valve closure was observed in the metered channels. This displacement was disregarded in the leak rate measurement because the fluid displacement roughly correlates to the volume of the valve; therefore when the valve is actuated any fluid within the valve is pushed through to the channel. Leak rates were recorded over the course of 10 minutes to allow the fluid time to travel 0.040-0.080". These tests are repeated for each of the valve geometries and thicknesses of urethane.

2.4 Leak Rate vs. Applied Pressure with Various Urethane Thicknesses

On previous work, we developed a rule of thumb that demonstrates that air pressure that is five times greater than fluid pressure is enough to produce leak rates below 0.1µL/min. The experiments were designed to allow a direct comparison of the thicker urethane membrane with the standard .001” urethane for the same valve geometry, with standard fluid and pneumatic actuation pressures.

The stiffness of a material is proportional to a power of its thickness. It is expected that thicker-urethane valves will require more pneumatic pressure than their standard-thickness cousins, to successfully stop flow. Leak rates were measured, with the previously described protocol, for three thicknesses, using different fluid and pneumatic pressures. Such parameters are summarized in Table 1.

This experiment will determine the optimal pressure needed to close the standard valve footprint with 0.002” and 0.004” urethane at a fluid pressure of 1 and 3 psi. The valves were pneumatically actuated with pressures between 5-25 psi with a 5psi increment.

In addition to testing the current valves with the different urethane thicknesses, we evaluated the leak rate for different valve footprints.
2.5 Leak Rate vs. applied pressure for different valve scales

For the 0.002” and 0.004” urethane, valve footprint was increased by 15% with the largest footprint being 160% the size of the standard design. The leak rates for each of these valves were tested at a fluid pressure of 1 and 3 psi with valve pneumatic pressures between 5-25 psi.

<table>
<thead>
<tr>
<th>Urethane thickness</th>
<th>Valve scales tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001”</td>
<td>1.00</td>
</tr>
<tr>
<td>0.002”</td>
<td>1.00, 1.15, 1.30, 1.45, 1.60</td>
</tr>
<tr>
<td>0.004”</td>
<td>1.00, 1.15, 1.30, 1.45, 1.60</td>
</tr>
</tbody>
</table>

Table 1 Urethane Thicknesses and tested Valve Geometries

The goal of this matrix of experiments is to provide a new set of design rules and operating pressure ranges for each urethane thickness and valve geometry. The user will then be able to choose geometries and operating parameters that best suit their application.

2.6 Spike and Hold Experiments

Also of interest is the use of the spike and hold method of closing valves. The spike and hold experiment consists of using an initial spike of pressure to close the valve followed by a reduction of pressure to hold the valve closed. This method has the advantage of maintaining valve closure at a lower pressure than the magnitude required to initially stop fluid. This minimizes delamination, and reduces gas permeability rates through the urethane, especially in experiments where the valves are held closed over a long period of time.

The standard valve geometry with the 0.001” and 0.002” urethane were used to test spike and hold. The valves were tested with a fluid pressure between 1-5psi, spike pressures between 5-25psi, and hold pressures between 1-20psi, as seen in Table 2. Recording the leak rate of the spike and hold method was done similar to the previous experiment, the fluid flowed into the metered channel, and then the standard pressure to close the valve was applied. The initial pressure was held between 1-3 seconds, until fluid movement stopped. The pressure was then lowered to the hold pressure and the leak rate was
measured after 10 minutes. This test was repeated for various hold pressures over a range of 1-20 psi or until liquid started flowing again.

Table 2: Tested Hold Pressures for various spike and fluid Pressures.

<table>
<thead>
<tr>
<th>Fluid Pressure (psi)</th>
<th>Spike Pressure (psi)</th>
<th>Tested Hold Pressures (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>4  3  2  1</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>8  6  4  2</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>10 8  6  5  3</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>15 10 8  6  4</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>20 15 10 8  5</td>
</tr>
</tbody>
</table>

3 RESULTS

The standard valve configuration comfortably achieved low leak rates, which was not the case for devices fabricated with thicker urethane membranes. Leak rates for the 0.001” urethane valves were lower than 0.05µL/min on all performed experiments; i.e. for both liquid pressures, and through the whole range of pneumatic valve pressures tested. Performance of devices with thicker urethane layers is less robust with respect to both liquid and valve pressure.

3.2 Effect of Urethane Layer Thickness on Leak Rates

At a liquid pressure of 1psi, 0.002” urethane valves have leak rates under 0.1µl/min, on the three valve pressures tested. Valves featuring the thicker 0.004” membrane needed a valve pressure of 15 psi to close the standard scale valve and therefore could not stop fluid pressures of 1 psi at the standard pneumatic pressure of 5 psi.

The behaviour of valves fabricated with various thickness membranes is shown in Figure 5.a. For a liquid of given pressure, 3psi in this case, leak rates decrease when using higher valve pressures. It was also observed that thicker membranes need higher valve pressures to achieve the low leak rate values that can be obtained with thinner urethane valves. Low pneumatic pressures not only represent high leak rates for thick urethane valves, but also high variability. 0.004” urethane valves operating at 5psi have a deviation of 46%. The standard deviation of leak rates measurements is lowest for the 0.001” valves, increases for 0.002”, and is the highest for devices using 0.004” urethane. Nonetheless, all tested valves achieve leak rates lower than 0.05µL/min as shown in figure 5.b. Even considering high variabilities on devices with thick urethane layers, leak rates remain well under 0.1µL/min.

3.3 Effect of Scaling Valve Area on Leak Rates

Modifying the scale (valve’s footprint), of a valve should help relieve pressure requirements. Results obtained from testing five different scales at a liquid pressure of 3psi and air pressure of 5psi are shown in figure 5.c. The 0.002” urethane’s performance is fairly uniform across all valve scales. The performance of 0.004” urethane, on the other hand, greatly improves as the valve footprint increases. For example, consider the device fabricated with 0.004” urethane. Tests with the standard scale produce leak rates of 34ul/min; when valve area is 45% larger leak rate is reduced to 0.67µL/min. This performance is now on the range of that achieved by 0.001” and 0.002”-urethane devices.

As expected, valves with larger areas need less pressure to seal the channel. Both devices fabricated with non-standard urethane thickness show the same behaviour when scale increases.

Figure 5a: Hold pressures that maintain <0.1ul/min leak rates vs. spike pressure

Figure 5b: Leak rate vs hold pressure with spike-hold method (fluid pressure=3psi, spike=15psi)
3.4 Spike and Hold Experiments

The Spike and hold experiments, Figure 5.a, revealed that a hold pressure of half the spike pressure is adequate to keep the leak rate below 0.1 µL/min. Lower hold pressures could also maintain the accepted leak rates. The only time leak rates above 0.1 µL/min were observed occurred when the hold pressure equaled the fluid pressures; all other tested hold pressures were successful in holding the valve closed for both the 0.001” and 0.002” urethane. Performance of spike and hold seems to peak at twice the fluid pressure, Figure 5.b, and then remain consistent with increasing hold pressures. The 0.004” urethane was not tested for the spike and hold method of closing valves.

Table 3 Tested Hold Pressures for fluid and spike pressures. Grayed boxes indicate the hold pressures that did not close the valves effectively.

<table>
<thead>
<tr>
<th>Fluid Pressure (psi)</th>
<th>Spike Pressure (psi)</th>
<th>Tested Hold Pressures (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>4 3 2 1</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>8 6 4 2</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>10 8 6 5 3</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>15 10 8 6 4</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>20 15 10 8 5</td>
</tr>
</tbody>
</table>

4 DISCUSSION

4.2 Leak Rate dependence on Urethane Thickness and Valve Area

In a standard valve, a valve pressure of five times the fluid pressure can adequately close the valve and stop fluid flow with a leak rate of less than 0.1 µL/min. The 0.002” urethane could achieve these conditions with the standard valve scale and pressure.

Both the 0.002” and 0.004” urethane displayed comparable performance to the standard valve and preserve the rule of thumb that says five times the fluid pressure equals the pneumatic pressure to close the valve. The data suggests that a valve scale of 1 and a valve scale of 1.45 with membrane thicknesses of 0.002” and 0.004”, respectively, would give comparable performances to the standard valve of a leak rate of less than 0.1 µL/min. Smaller valve footprints could be used with 0.004” urethane if the valve pressures were significantly increased. The standard valve footprint with 0.004” urethane, for example, could maintain leak rates of less than 0.1 µL/min as long as the valve pressure is greater than 15 psi. Table 4 summarizes the recommended valve pressures for each thickness of urethane and valve footprints.

Table 4 Recommended Valve Pressures for optimal valve footprints and each thickness of urethane.

<table>
<thead>
<tr>
<th>Urethane thickness</th>
<th>Valve Scale</th>
<th>Fluid Pressure (psi)</th>
<th>Recommended Valve pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001”</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>0.002”</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>0.004”</td>
<td>1</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>1.45</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>15</td>
</tr>
</tbody>
</table>

4.3 Hold Pressure Requirements for Given Fluid and Spike Pressures

The spike and hold experiments were conducted over the standard valve footprint with the 0.001” and 0.002” urethane. They revealed that the valves could safely maintain a leak rate of less than 0.1 µL/min with both the 0.001” and 0.002” urethane when the hold pressure equals half the spike pressure. Hold pressures, however, could go as low as two times the fluid pressure or lower, Table 3.

The initial fluid flow after the valve closure was not seen in our previous valve paper[2]. This initial flow can be accounted for by the fact that in the initial paper used tubing with an inner diameter of 0.5 mm, area of 0.2 mm², to measure the leak rate of the valves. The current experiment increased the resolution of measurement because the current area of measurement was 0.089 mm². Smaller volumes of flow could be seen more easily, such as the initial displacement of fluid when the valve was closed. This initial displacement was disregarded in our leak rate measurements because the displaced fluid roughly correlates with the volume of the valve.

5 CONCLUSIONS

Comparable performance can be achieved with all material thicknesses with the right choice of operating conditions and/or change in valve footprint. The 0.002” membrane performed comparably to the standard valve whereas the 0.004” membrane performed best with the valve seat area scaled up by 45%. The use of a variety of thickness of urethane is possible, broadening the range of operating parameters for lab on a Chip devices.
Application of the close pressure ("spike"), followed by a reduction in the pressure by half, does not alter the valve leak rate (less than 0.1µL/min.). This actuation routine broadens the use of these valves for applications where the valves are pressurized for a long period of time and when high pressures are needed to initially stop fluid.

REFERENCES