

Restoration of Musical Organs: Analysis of Rubber Cloth and Other Historical Materials

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Abstract-- Understanding the relationship between functionality and processing of historical materials is essential in the conservation of cultural artifacts. The lack of well-documented manufacturing techniques during the Second Industrial Revolution creates difficulties replicating modern equivalents of materials or selecting replacements when repairing musical organs. This lack of documentation has contributed to the decline of the cultural, economic, and environmental viability of repairing musical organs. In this work, materials from a century old musical organ were characterized and compared to their modern equivalents through literature review, professional consultation, and materials testing. Structural differences between original and replacement rubber cloths used in the bellows were investigated with electron microscopy. Energy Dispersive Spectroscopy (EDS) and Fourier-Transform Infrared Spectroscopy (FTIR) were used to chemically identify the modern and historical rubber cloth and adhesives. The mechanical properties of the rubber cloths were measured using a permeability chamber. Comparing the analyses of modern and historical materials provides an understanding of the mechanisms responsible for failure. Such an understanding allows for a more informed restoration process such that modern materials and procedures are respectfully substituted in place of their historical counterparts.

I. INTRODUCTION

I.A. Purposes of the Project

The practical purpose of this process is to restore a Beckwith Reed Organ, manufactured approximately in 1908, to a fully playable state. The technical purpose of this project is to pay particular attention to the materials that must be replaced during the installation. For this organ, the materials of interest included the following: rubber cloths and adhesives used to attach the rubber cloths. Other materials used in the organ, include the wooden frame and metal reeds. The wooden frame and metal reeds were subjected to a cleaning process consisting of canned air. Additionally, the rubber cloths had to be replaced due to how worn and torn the rubber cloths had become. The adhesives also had to be replaced due to the rubber cloth needing to be replaced.

In Figure 1, a photograph of the organ in its as-received condition is provided. A photograph of the bond of indemnity is also shown, which indicates that the original warranty was for twenty-five years. Our goal is to provide replacement rubber cloth in the installation that lasts at least twenty-five years. Also shown in Figure 1 are two decals on the face of the organ, which were presumably promotional in nature. One of the decals is marked MCMVII, which is how we date the organ to no earlier than 1907.

During the Second Industrial Revolution demand for organs rapidly grew, allowing for mass production of organs such as the Beckwith reed organ acquired for this experiment. In the early twentieth century, Beckwith reed organs were manufactured and sold as an affordable option to a growing American middle class. During the popularity boom, industries sought to change production techniques to be more economically efficient, but at the cost of performance. The change in production methods were so inconsistent that composition of materials within the organ was highly varied and, in most cases, undocumented [2]. The source and composition of the rubber cloth was also impacted.

Today, the quality of rubber cloth available for organ repair is inferior to that originally used, as evident in the lifespan of the product before failure. While old rubber can last over a century, modern cloths can fail as soon as a decade. This rapid degradation is exacerbated by modern rubber cloth often being unfit for application in bellows. The failures can be investigated in the effectiveness of permeability and the primary degradation mode critical to the fabric's failure. Older samples are prone to cracking and flaking near the edges and folds. Modern samples, however, do not reach the necessary pressure for playability and must be replaced within a few years [2]. Additionally, the recent closure of Laukhuff, the largest and oldest distributor of organ parts, has challenged the economic viability of the organ repair trade.

The adhesive used to bind the rubber cloth to the wooden bellows and frame is also a point of interest. Lacking a known distinction between the current and former glues being used, it was necessary to test and chemically compare the adhesives. The glue used is a commonly used adhesive in instrument manufacturing:

hide glue, manufactured typically from animal protein. It can be produced in varying strengths depending on the application. For example, a weaker glue would be used to join the sides and faceplate of a violin so that, if exposed to humidity, the adhesive would fail before the faceplate cracked [3]. Hide glue also has several advantages over most wood glues. It has a short curing time, meaning clamps are less important. It also does not expand as it cures, which means that pieces will not shift out of place after being glued.

I.B. Challenges in Restoration

The processing and characteristics of objects are widely varied between time periods, locations, and purposes. The organ being investigated was made during 1908. This means that production techniques from 1908 to 1920 must be investigated, and for the rubber cloth in particular, all processing methods from 1870 to 1920 must be investigated. This necessitates that thorough research must be conducted before restoration ever begins. Key to modern preservation and the understanding of historical context is studying and



Figure 1. Top Left: Organ as received. Top Right: Bond of Indemnity stating a twenty-five-year warranty. Bottom Left: A decal commemorating the Jamestown Tercentennial Exposition of 1907. Bottom Right: A decal commemorating the first permanent settlement of English-Speaking People in America Awarded to Beckwith Organ Co.

documenting the material properties of period items. Often there is little or insufficient documentation to reproduce or repair relevant materials. Even if historical documentation exists, the resources and methods needed to recreate the process may not be available, safe, or economically feasible. Mineral fillers such as lead, antimony, and iron were added to rubber cloth for coloring, vulcanization, or increased tensile strength [4]. Thus, original rubber cloth must be handled carefully and many of the production methods would be illegal under modern regulation. An understanding of materials properties and processing allows individuals to identify and design modern techniques and materials to support sustainable and accurate preservation projects.

In organ restoration specifically, there are many approaches with their own limits and goals. When approaching the repair of an organ, several factors may be considered: visual aesthetic, audio quality, mechanical/structural repair, cultural heritage, original versus modern purpose, economic feasibility, and many more. The act of restoration inherently alters the organ and thus acts against at least one factor [5]. Restoration is a constant give and take with any historical object. With organs, there are two main motivations for restoration: aesthetic and utilitarian. This tends to clash with the general ethics and goals of the larger restoration community. Often conservation will focus on maintaining as much of what a historical object once was and all the ways it has been changed by time. Time heavily impacts both utility and aesthetics, making organ repair unique. Organs are also considered to be more of a tool rather than a historical artifact by many, which means that restoring organs rarely focuses on maintaining historical integrity.

Even when there is a lack of period relevant documentation of manufacturing, studying the material properties of an artifact can allow for a deeper understanding of how the artifact was historically made. For most of history, the relationship between material processing, structure, properties, and performance was not completely understood; thus, the details of a production method may have been improperly reported or omitted from any documentation. Due to the focus on economic efficiency, there is also the potential that production methods changed with time to minimize production cost of organs. Different approaches must be taken to have a comprehensive understanding of an individual organ. Historical review may reveal the purpose of an artifact and its intended properties. A microstructural analysis can reveal the actual nature and characteristics of the artifact. With an understanding of both, conservationists can either reinforce a material process or formulate a new one as a substitute which is safer, more economic, or structurally sound. Unseen material failures can also be identified as a proactive means to prevent further deterioration of the object.

The restoration approach in this project focuses on mechanical, rather than visual aesthetic or perfect audio quality. Due to economic and time constraints, this project is centered around learning as much as possible from mechanical restoration. Furthermore, the team working on this project has experience in materials analysis and not instrument restoration. There is potential for future work in further restoration, but to analyze the materials and processing, aesthetics and improved audio quality were secondary. Already a challenging task, the shrinking availability and accuracy of materials necessary to repair organs complicates the task. The complex composition, uniqueness of each organ, and shrinking craft hinder any singular expert to conduct a comprehensive interdisciplinary study.

I.C. Brief History of Reed Organs

Reed organs were most common from the mid-1800s to the early 1900s [2]. Most modern reed organs are based from Alexandre Debain's 1840 patent, and barely changed in general function over their many decades of mass production [6]. During this time, production methods were not well documented. Popularity of reed organs in America began to increase in the late 1800s due to the rise of the middle class caused by the prosperity of the Second Industrial Revolution. The introduction of the transcontinental railroad allowed for businesses like Sears to expand their distribution and sales method. The ideas of novelty and growing wealth were heavily associated with being able to order products previously only available to the wealthy. Reed organs would have been particularly suited to creating an illusion of wealth due to their ornateness and the quality of being both furniture and instrument. During the time organs shifted from a church instrument to a piece of furniture with a wide range of utilities. In Figure 2, we show an advertisement from a 1908 Sears, Roebuck & Company catalog for a Beckwith "Cottage Favorite" Organ for \$33.35 (\$995.99 in 2022 dollars).

As economic circumstances changed with the world wars and American individualism permeating the country, organs grew less popular and the industries supporting organ companies changed. As available materials changed, the quality of rubber cloth declined. Investments in quality improvements became financially unviable with the popularity of pianos far exceeding that of organs. Pianos were easier to both play and produce which led many companies to turn their focus to producing pianos instead of organs.

The organ studied in this project is a Beckwith reed organ dated to have been manufactured between 1908 and 1920. Reed organs were common at the time of production, and production was standardized but not well recorded. Records were also poorly preserved due to business practices and focuses shifting away from organs in the following years. The lack of information on the

materials and processes used makes full restoration difficult, if not impossible. There is little to no way of acquiring or making the materials without a significant budget and more time than allocated to this current project. The purpose of the materials in the organ is easy to understand, but the exact composition and processing are difficult to match. Any changes in processing can cause significant changes in characteristics that drastically affect the quality and playability of the organ.



THE NEW AND IMPROVED BECKWITH COTTAGE FAVORITE ORGAN.
5 years for
 action over
 its lifetime
 No. 46C127 Price, \$33.35

Figure 2. Advertisement from a 1908 Sears, Roebuck & Company catalog for a Beckwith “Cottage Favorite” Organ for \$33.35 (\$995.99 in 2022 dollars) [1].

II. MATERIAL BACKGROUND

While there are many materials used in a reed organ, the most relevant to this restoration project were the rubber cloth, adhesives, and leather. These three materials are all part of the bellows assembly. A schematic of the airflow through the bellows assembly is shown in Figure 3. Photographs of the bellows assembly are shown in Figure 4 and Figure 5.

For the organ to make music, the organist presses down the pedals with their feet. As the pedals are pressed, air is sucked in from the main bellows into the feeder bellows through valve 1, lowering the pressure of the main bellows. As a result, the main bellows contract and sucks air across the reeds creating sound. Also, as the

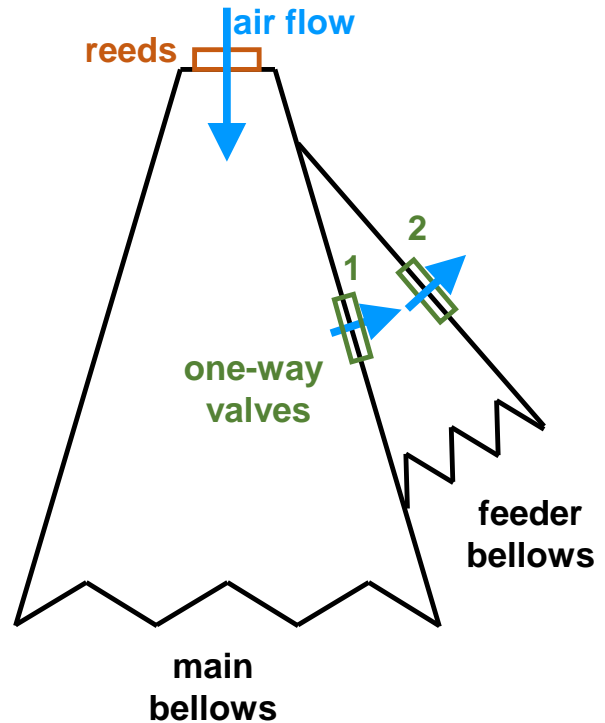


Figure 3. Schematic of air flow in the bellows assembly of a Beckwith pump reed organ.

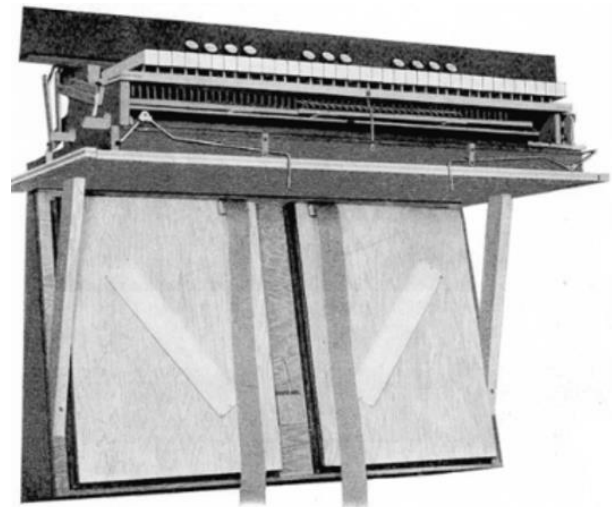


Figure 4. Assembled bellows and action as pictured in the Sears, Roebuck & Company catalog [1].

feeder bellows contract, the air is expelled through valve 2.

The leathers used in the organ ensure proper and tight air flow throughout the multiple mechanisms of the organ. Leather has also historically been used as patchwork to remedy any defects during production. Though leather is still widely used today, methods of

tanning have relied more on artificial and chemical methods over the course of time. The leather industry has also shifted away from serving technical and mechanical functions and towards the fashion industry. This shift has resulted in misleading advertising and noticeable changes in performance, compounding organ restorationists' distrust of modern materials and manufacturing processes [5].

For many centuries, organs exclusively used hide glue of some form. Within a single instrument, components including felt, leather, rubber cloth, metal, and wood were glued together with hide glue. With varying applications and needs, it was common to use an array of differently sourced and specialized hide glues. Hide glues also served as the main laminates for early cardboard and plywood. For restoration, the function and application of hide glues has changed little over time; however, the specialization and number of different glues used within one instrument has been reduced [2]. None the less, the use and expertise of hide glue is still central to organ restoration. In some applications, including as a laminate, hide glue has been phased out for modern adhesives based on economic and functional practicality [2].

During the 1800s, strawboard manufacturing was a common technology and often used for book covers [2]. Due to the easy production of cardboard through laminate layers, strawboard was phased out. When an organ's plywood is heavily damaged, it is simply replaced with

modern plywood. Structurally, plywood from the turn of the century is comparable to today. The current adhesives in producing plywood were developed in the 1930s. Before that, plywood was laminated with hide glue and set with high pressure for extended periods of time, making it more vulnerable to delamination. Wooden furniture from that period is prone to cracks. Lumber was treated to handle cycles of temperature and humidity. As central heating became more common, the constant warm and dry climate sucked moisture out of the wood, resulting in large cracks [7]. Wood for modern furniture is thus treated differently. As an aside, in this project, the three-layer sheet of plywood between the main bellows and the feeder bellows (see Figure 3) had delaminated where the holes were bored for the one-way valve. A repair was made with modern wood glue and a clamp.

The organ contains a number of metal components, as shown in Figure 6. The brass, steel, and other metals used over a century ago are still widely available and used today, but the selection of one metal over the other in historical settings can be ambiguous and difficult to extrapolate. Additionally, methods such as sand-casting iron are not as widely available, more regulated, and nonessential to both utilitarian and aesthetic approaches of restoration [2]. Replicating materials via period accurate methods is often expensive and unsafe according to modern standards. The repairing and replacement of wood is often based on utility and aesthetic rather than historical material accuracy.



Figure 5. Two views of the bellows removed from the organ with the replacement rubber cloth. Left: Side view of the main bellows with the feeder bellows visible to the right side. Right: Front view of the two-feeder bellows attached to the main bellows. The leather strips cover a series of holes bored in the wood that serve as one-way valves, allowing air to flow out of the feeder bellows. Note: In these photographs, the bellows assembly is upside-down of its orientation in the organ. The proper orientation is depicted in Figure 4.

The felts used in modern and historical organs are similar. However, the felt used on the original is often thinner than what is easily accessible. This is due to the decreased variation of felt manufacturing. Because of this reduction, the felt used specifically for restoring organs is no longer widely available. Organ mechanics will use 100% wool felt because felt that includes synthetic fibers frequently damages and scratches moving parts [2].

II.A. Rubber Cloth

The rubber cloth provides a flexible and airtight medium for pumping air with the bellows—the central mechanism which supports the organ’s sound. The

functional demand of the rubber cloth in an organ remains the same as it did one hundred years ago but comparing the modern and historical counterparts reveals major disparities in performance and easily observable characteristics.

Part of the difficulty in determining the composition and processing of rubber stems from conflicting accounts and misconceptions of rubber production. For over seventy years after vulcanization of natural rubber was discovered, rubber nomenclature was barely standardized between users, producers, and chemists, resulting in miscommunication and loss of specific information.

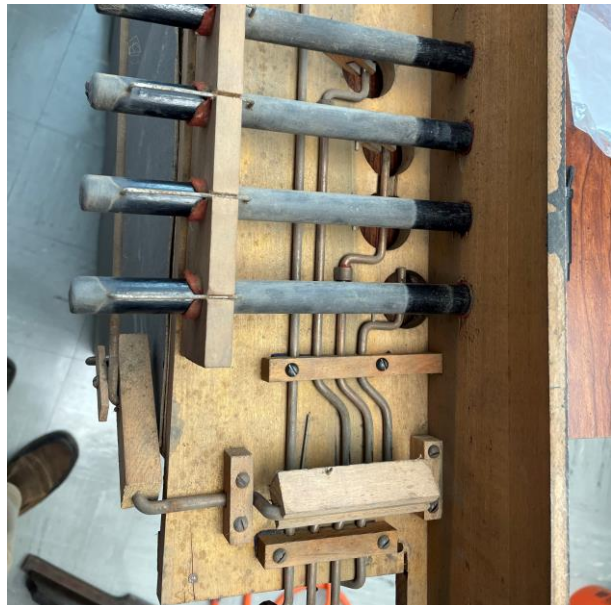


Figure 6. Metal components of the Beckwith reed organ as received and after disassembly of the organ. Top left: a reed. Top right: bellows springs. Bottom left: couplers. Bottom right: stop action.

Commercially sold rubbers were named based on location source, species of source tree, shape, smell, or even color. In terms of color, dying rubbers was relatively standard. Lead was exclusively used for black rubbers and was absent in pale colored samples. When economically reasonable, rubbers containing antimony were dyed red.

In 1915, the rubber industry was dominated by plant-based rubbers with over 50% of the market originating from plantations in south Asia and Brazil [4]. The methods of turning natural latex in to rubber products varied depending on location, but generally followed a process of coagulation, washing out impurities, drying, milling, mixing in additives, calendaring, and vulcanization. Though there were several competing and emerging theories as to how best to create quality rubber, industry experts prescribed to processes dating back to the 1840s, hesitating to standardize any laboratory-based findings.

Universally accepted was the general idea that higher ratios of sulfur and longer heat treatments produced better quality rubbers. At the turn of the century, some common methods called for as high as a three to ten weight ratio of sulfur to crude rubber. Common additives included commercial grade crimson antimony (SbS_3) and litharge (PbO) which were known to carry high amounts of sulfur and were observed to quicken the rate of vulcanization [4]. At the time of production, commercial grades of litharge contained significant amounts of galena (PbS), the primary compound of lead ore [8]. With the first scientific studies on the chemical mechanisms of rubber being published in 1905, industry found testing physical properties of rubber more commercially valuable than understanding the inherent chemical processes during fabrication. Thus, most rubber chemists focused on studying the stress-stretch relationship and methods by which to dye the rubbers. Such an approach resulted in considerable amounts of documentation regarding the smell and shine of rubbers but fails to report the purity, source, and clear identity of additives.

Records also allude to high variation between batches, calling upon the necessity for unique alterations on a batch-to-batch basis. Additionally, there is clear documentation of disdain and lack of faith toward synthetic and laboratory-based rubbers at the turn of the century, citing the growing number of plantations and increasing efficiency in the traditional process [4].

II.B. Materials Selection

While it is important to be as accurate with the historical materials as possible, recreating the exact materials used is not economically feasible. In this case, the materials were selected to be as close as possible to the original functionality rather than exact replicas of historical materials. This was in part because of the economic constraints of the project, but also because of

the skill level of the team working. Furthermore, organs being restored currently are usually restored for playability before aesthetic perfection. Many who work in preservation of cultural artifacts aim for strict material conservation. In doing so, their approach often focuses on individual items rather than the economic sustainability of an entire industry.

Ultimately, the materials used in this restoration project were provided under the guidance of Mr. Brad Rule of B. Rule and Company, New Market, Tennessee. They include contemporary rubber cloth for the main bellows, contemporary rubber cloth for the feeder bellows, hide glue for the adhesive, and chrome tanned sheep skin leather for the leather valves. Photographs of the original and replacement rubber cloths and the replacement leather are shown in Figure 7.

III. TESTING METHODS

Materials characterization was performed to compare new materials used in restoration and the original materials. Historical materials were obtained through the disassembly of a 100-year-old Beckwith reed organ. During the reassembly of the organ, the modern equivalents of rubber cloth and hide glue were substituted as is often standard in modern organ repair. Materials that were substituted were stored for later analysis. The mechanical restoration additionally served to better understand the functionality and application of the materials being studied.

III.A. Fourier Transform Infrared Spectroscopy

To gain insight into the chemical composition of the original and replacement materials, Fourier Transform Infrared Spectroscopy (FTIR) was used. FTIR measures the range of wavelengths that are absorbed or reflected by the material. The light that passes through to reach a sensor creates an absorption spectrum that indicates which chemical functional groups are present in a sample. This helps identify the organic composition of the sample [3]. This technique was used to identify the composition of the original adhesive and confirm that the new glue is similar in composition to the historical glue. FTIR was also used to examine the composition of the original and replacement rubber cloths as well as the new leather. FTIR was performed using a Perkin Elmer (model) at the UT Center for Renewable Carbon (CRC).

FTIR was performed on the cloths and adhesives. Five repetitions were performed on the replacement feeder bellow cloth, the replacement main bellow cloth, the original cloth's interior and exterior sides, the original adhesive, the replacement hide glue, and the replacement leather. A weight of 100 units was kept constant.

III.B. Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) is a method used to visualize the surface of materials by focusing a



Figure 7. Original and replacement fabric components of the Beckwith reed organ. Top left: external side of the original rubber cloth for the main bellows. Deterioration of the cloth, where the rubber layer has been lost, revealing the fabric underneath, is visible. Top right: replacement rubber cloth for main bellows. Bottom left: replacement rubber cloth for feeder bellows; front side is black and back side is white. Bottom right: replacement leather.

beam of electrons into the surface layer of the material. The beam is focused by a series of electromagnets and detected by an x-ray detector, a backscatter detector, and a secondary detector. The x-ray detector identifies elements, and the secondary and backscattered electrons create a topographical map and graphical representation of the atomic weight. SEM was performed using a Phenom Desktop SEM at the UT Department of Materials Science and Engineering (MSE).

III.C. Energy Dispersive X-ray Spectroscopy

Energy Dispersive X-ray Spectroscopy (EDS) is a method used to identify different elements in a material. EDS is limited to identifying some organic elements and all inorganic elements. EDS cannot determine data such as functional groups or material structure. EDS works by shooting a beam of electrons into a sample, causing electrons from the sample to become excited. An inner shell electron is moved to an outer shell, causing an outer shell electron to drop down a level to fill the space. As

the outer shell electron drops to the inner shell, energy is released in a characteristic x-ray. The x-rays have different wavelengths depending on the element they came from, meaning that by detecting the energy of the x-rays, the element can be identified. For this project, EDS was used to identify potential additives in the original rubber cloth, the replacement rubber cloths, and the new leather. EDS was performed using the same equipment as for the SEM listed above.

Both EDS and SEM were performed on the leather, and exterior and interior of the original cloth. Samples of original rubber cloth and modern leather were cut, cleaned, and mounted on sample stages using carbon tape. The samples were loaded into the SEM/EDS and analyzed under a low vacuum and at 15kV. Micrographs were taken using SEM and element identification was performed using EDS.

III.D. Permeability

The ability of the rubber cloth to maintain a pressure difference can be investigated by measuring its permeability. A device to measure permeability was constructed as part of this project. To measure the permeability, a constant flow rate was introduced into the system, and the exiting flow rate was measured; see Figure 8. The permeability was calculated by dividing the exiting flow rate by the area measured.

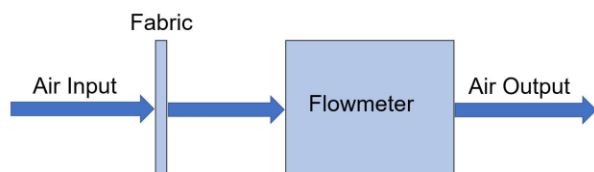


Figure 8. Diagram of permeability measurement apparatus.

IV. RESULTS AND DISCUSSION

IV.A. Fourier Transform Infrared Spectroscopy

In Figure 9, we present the results of the FTIR analysis of the organ materials. According to the FTIR results, the old adhesive and new adhesive are similar in composition. This result is consistent with the idea that the adhesives are based on animal protein, which has not changed since 1907. The old adhesive does show a more pronounced peak at 1072 than the new adhesive, which is due to the presence of aliphatic amines. Aliphatic amines are commonly used in curing epoxy. The presence of significant nitrogen in the sample is consistent with the expectation that both the original and replacement adhesives are based on animal protein.

In Figure 9, the external and internal sides of the original cloth exhibit sulfur-hydrogen stretching at peak 2800. This suggests sulfur crosslinking the backbone of

the cloth. Additionally, there is a peak at 1400 that features a methyl group, and at peak 1000, there is a butadiene group. With the presence of these functional groups, the original cloth was determined to be vulcanized isoprene.

The original rubber cloth and replacement rubber cloth show significant differences. The new cloth shows peaks at 1438 and 950, which indicates the presence of PVC. There is also a peak near 2200, which indicates nitrile, another indicator of PVC. PVC is commonly used to seal textiles that need to be watertight. However, this can be a problem when used to repair organs. Traditionally, galvanized pipes were used to feed air into organ bellows, but increasingly, those pipes have been replaced with PVC [2]. The cement used to join PVC pipes contains various organic solvents (typically, methyl ethyl ketone, cyclohexanone, tetrahydrofuran, and acetone), which dissolve PVC, creating a strong bond between a pipe and a PVC fitting. However, the solvents in the cement have a low vapor pressure. If modern rubber cloth is exposed to PVC cement vapors, the PVC coating on the rubber cloth will be dissolved and the seal of the bellows will be ruined. Therefore, it is essential that any PVC pipe work be completed and the interior space well ventilated before the bellows are replaced.

IV.B. Scanning Electron Microscopy

In Figure 10, we present the results of the SEM analysis of the organ materials. The external and internal sides of the original cloth feature a film like surface such that both sides appear non-porous. The replacement cloth exhibits a tightly woven pattern such that it is much more porous than the original cloth. The leather features a unique surface such that the leather has no porosity.

At the micron scale, the original rubber cloth appears as a continuous film of rubber. However, when viewed at the same scale the replacement rubber cloths for both the main bellows and the feeder bellows show distinct polymer fibers in a woven fabric. The permeability of these cloths is tied to the presence of paths with the lowest resistance to mass transfer. In the original rubber cloth, air would have to find a path through the rubber film. In the replacement, air can move in the gaps between fibers.

IV.C. Energy Dispersive X-ray Spectroscopy

In Figure 10, we present the results of the SEM analysis of the organ materials. Figure A.1., the EDS measurements of the exterior surface of the historical rubber cloth, reports considerable amounts of lead. The high reading is conclusive with period documents which state the extensive and common use of lead compounds for vulcanization. Additionally, the exterior surface was colored black and coincides with the standard practice of dyeing lead containing rubbers black during the early 20th century. Lead was used as an effective catalyst for

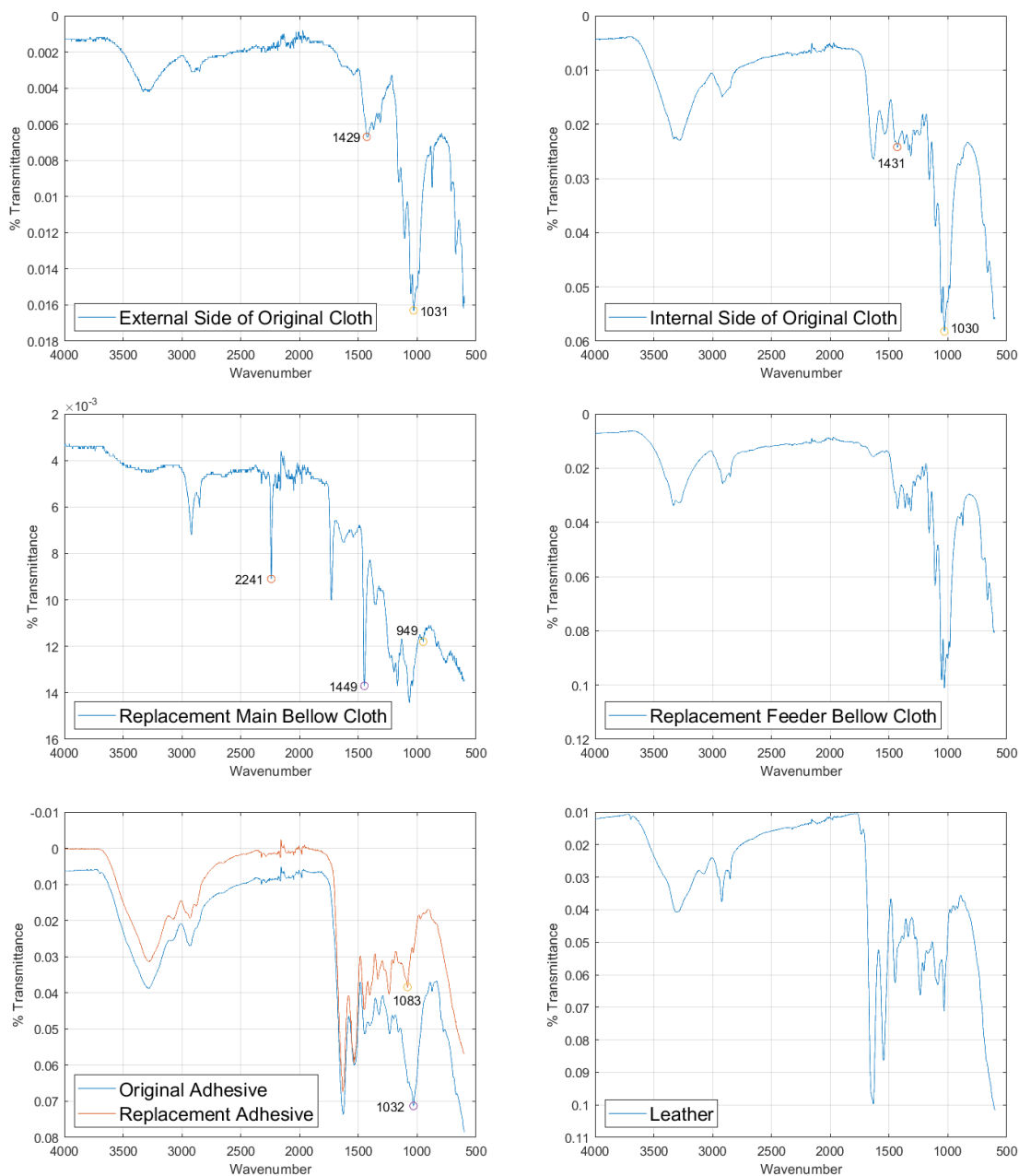


Figure 9. FTIR of organ materials. Top left: exterior of original rubber cloth. Top right: interior of original rubber cloth. Middle left: replacement main bellow rubber cloth. Middle right: replacement feeder bellow cloth. Bottom left: comparison of original and replacement adhesives. Bottom right: replacement leather.

accelerating vulcanization, but it has since been substituted out for zinc oxide [6]. Given the modern understanding of lead, it is not reasonable or effective to reproduce litharge-based rubbers due to environmental, safety, and legal concerns.

The EDS results in Figure A.1. show traces of antimony on the back side of the rubber cloth. Such findings identify the pale substance on the back side of the cloth to be an antimony lased rubber. At first, this was

unexpected as the particles on the back of the cloth did not uniformly cover the cloth and appeared to simply be dirt which had settled over the course of a century. However, returning to literature if rubbers containing antimony occasionally lacked red dye. The pale tone of the rubber and lack of a lead reading in figure A.1. also coincides with the president that black rubbers contained lead. The additional contents of antimony compound the

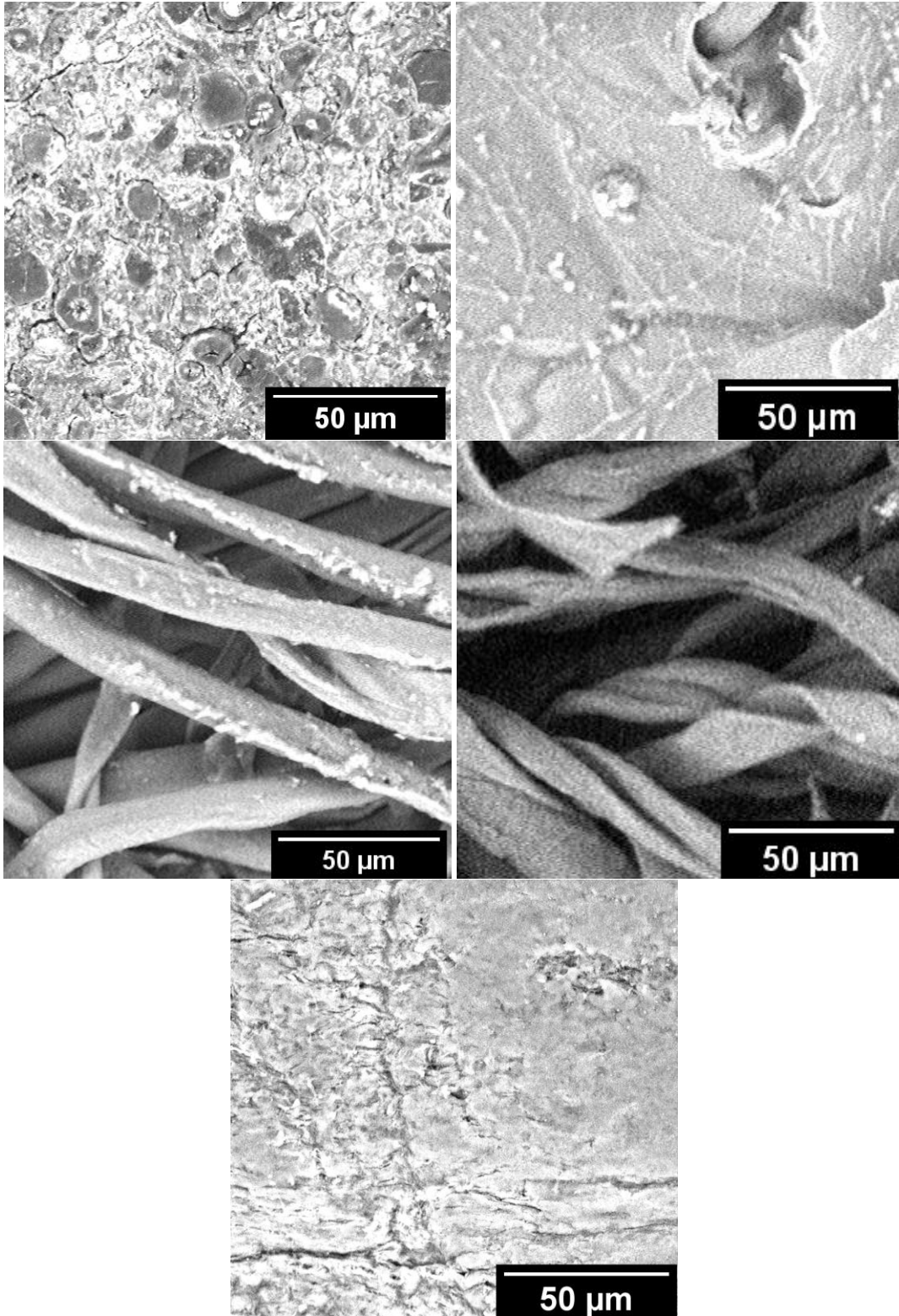


Figure 10. SEM of organ materials. Top left: external side of the original rubber cloth. Top right: the internal side of the original rubber cloth. Middle left: replacement main bellow rubber cloth. Middle right: replacement feeder bellow rubber cloth. Bottom: replacement leather.

impracticality and hazards of reproducing a replacement using historical procedures.

Figure A.1. reports chromium in the leather, confirming that the replacement skins were chrome tanned. It was necessary to conduct EDS because some leathers used in restoration are falsely advertised.

IV.D. Permeability

In Table 1, we report the results of the permeability analysis of the organ materials. Not surprisingly, the original cloth has the highest permeability to air. However, the deterioration of the original rubber cloth visible in Figure 7 suggests that the measured permeability is not representative to the material's original characteristics. The replacement rubber cloth for the feeder bellows has a significantly lower permeability by about a factor of five. The replacement rubber cloth for the main bellow has the lowest permeability for air. The fiber density and morphology shown in Figure 10 supports the data in terms of the replacement main bellow cloth being less permeable than the replacement cloth for the feeder bellows.

The diffusion of air through the solid rubber membrane of the original cloth, shown in Figure 10, would have been more difficult than the woven replacement cloths. Had it not been for the corrosion of the past 100 years, the original rubber cloth was probably less permeable than the newly manufactured replacement cloths.

| Material | Permeability (m/s) |
|---|--------------------|
| Original Rubber Cloth | 0.144 |
| Replacement Feeder Bellow Rubber Cloth | 0.028 |
| Replacement Main Bellow Rubber Cloth | 0.008 |

Table 1. Permeability Measurements.

IV. REFLECTION

This project offered a fascinating look into the world of instrument restoration. Attempting to learn the techniques and skills needed to successfully restore the organ to playability, in addition to research and documentation was time consuming, difficult, and at times chaotic, but overall, extremely rewarding. Working on the organ has shown how many different fields and crafts can be combined with materials science to create a deeper understanding of a single instrument.

While the replacement cloth was found to be 18 times more effective at retaining air than the original cloth, this result is not representative of the original cloth as it would have been when brand new. The original cloth was tested after 100 years of deterioration, while the replacement cloth was essentially new. Additionally, the original cloth was made by pressing sheets of rubber onto cloth, which created a much more solid surface than the

replacement cloth. The replacement cloth was made with woven treated fibers. Most likely, the original cloth would have been less permeable than the replacement when it was new. Furthermore, the original cloth lasts much longer than the replacement cloth. Ideally a new product would be custom made for this application from synthetic rubber pressed onto cloth without the lead and antimony additives.

The replacement cloth contains PVC which allows the cloth to be waterproof. Because of this, it has been found that fumes from PVC glue can cause the cloth to deteriorate. If organs with this type of cloth are used in conjunction with PVC pipes, care must be taken so that the bellows are not exposed to PVC cement fumes.

VI. CONCLUSION

Identification of the differences between the original and replacement materials was successfully accomplished. The original rubber cloth contains toxic lead and antimony additives while the replacement rubber cloth does not. From a structural analysis, we identified why the replacement cloth, composed of woven polymer fibers, does not last a century, as did the original cloth, which was coated with a continuous film of natural rubber. We successfully identified a PVC waterproofing film on the replacement rubber cloth, which provides a cautionary note for repair in organs connected to PVC pipe. Residual PVC cement fumes trapped in the bellows may dissolve and destroy the vinyl coating.

The leather used for repairs appears to be chromium tanned, a synthetic way to tan functional leathers. The original hide glue and the replacement are extremely similar.

Throughout this project an attempt was made to respectfully restore functionality to the organ. However, some concessions to health and safety had to be made, in addition to the time and economic constraints. The bellows in the organ could not be repaired with material exactly like the original because of availability and economic constraints, but also because the high quantity of lead. Despite this, the bellows were successfully restored to a playable state better than the condition in which the organ was received. The replacement material is 18 times more effective (less permeable to air) than the century-old original rubber cloth.

There is much potential for future work in materials analysis of the organ, as well as in restoration work. Identifying the various additives in the rubber cloth and leather can explain some of the properties, but processing is also a vital part of the materials science paradigm. To truly understand the performance of the materials, more work would have to be done on the processing instead of only composition and microstructure. The mechanical restoration is only part of the restoration work that could be done on this organ. However, with the work that has

been done, the organ is in a better state mechanically and produces a better sound. It is safer to play. With the knowledge gained through this project there is a better understanding of how to maintain the organ and to research safer, more effective materials.

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restoration be completed in the time frame of one semester, during which all of the team members were enrolled in a full course load. This restoration in no way reflects their endorsement or that of the associated organizations. We are grateful for their suggestions and cautionary words, which helped us prioritize selected elements of a total restoration and allowed us to have a first opportunity to participate in a hands-on instrument restoration experience.

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APPENDIX

This appendix contains EDS results and photographs of the organ at various points during the restoration.

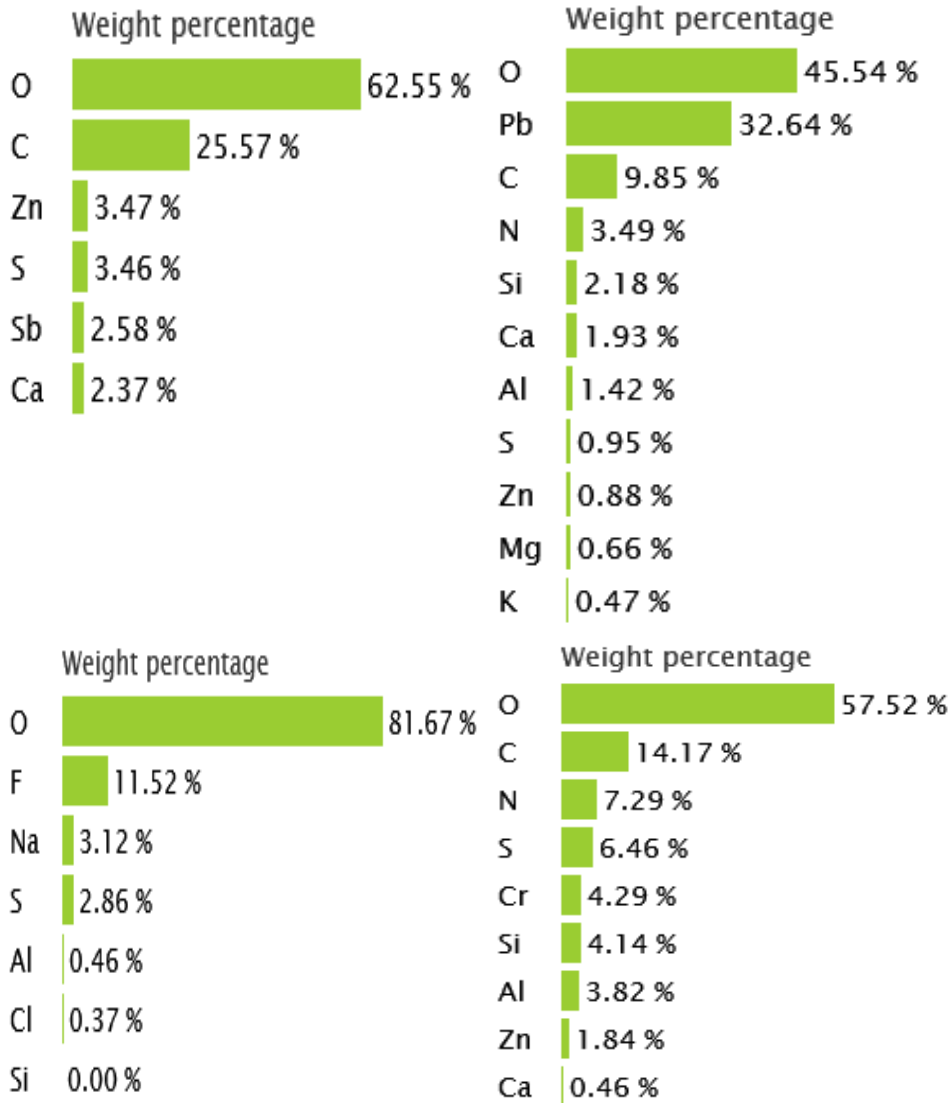


Figure A.1. EDS results of organ materials. Top Left: internal side of original rubber cloth, showing antimony (Sb). Top Right: external side of original rubber cloth, showing lead (Pb). Bottom Left: replacement main bellow rubber cloth. Bottom Right: replacement leather.



Figure A.2. The organ as it was purchased.



Figure A.3. Disassembling the organ. Left, Brad Rule. Right, Matthew Valderrama.



Figure A.4. Attaching replacement cloth to the main bellows.



Figure A.5. Mixing hide glue.



Figure A.6. Lubricating the stickers with crucible graphite.



Figure A.7. Installing soundboard and Vox Humana. Left to right: MacKenzie Camp, Christopher Webb, Matthew Valderrama, Charlotte Buchanan.



Figure A.8. Cleaning Keyboard. Left to right: Christopher Webb, Dr. David Keffer.



Figure A.9. Testing the mechanical functions during reassembly