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METALS

Conserving church bells: Answering for whom the bells toll

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Abstract
Bronze bells were of critical importance for Spanish-American colonial churches. While many are now merely decorative, the bells at San Xavier del Bac, a living church located in the desert on the Tohono O'odham Nation in Arizona, remain a communication device for the local community. Under the authority of the nonprofit Patronato San Xavier, conservators collaboratively treated four bronze bells to ensure their cultural continuity and sustainability. The first bell was removed for study and treatment off-site in a laboratory as it is not rung. The other three were treated individually in situ using materials and methods developed through testing. This paper discusses the methodology and techniques used to establish protocols for the appropriate treatment and maintenance of bronze bells. The project required special coordination due to the pandemic and ongoing collaboration with the village bell ringers, iron workers, and colleague conservators. Preserving the function of sound was most important.

INTRODUCTION

Mission bells once served as a community timepiece: they called the faithful to mass, provided warning of danger, and were rung for devotions, funerals, weddings, and festival feast days. Many bells had life histories and itineraries of travel (Thomas 2017, 397). Today, the bronze bells at Mission San Xavier del Bac are rung, but not at the direction of the priests. Rather, they are the responsibility of bell ringers of the village of Wa:k, located south of Tucson in the San Xavier District of the Tohono O'odham Nation, in a region long known as the Pimería Alta. Presently, three of the Mission's bronze bells are rung in patterns that communicate meaning to the village, mostly to announce deaths within the community. They also ring to joyously celebrate the feast days of the Mission's patron saints: Saint Francis Xavier and Saint Francis of Assisi. The fourth bell hangs separately on a nearby mortuary chapel and is not rung.

Missionary activity at San Xavier began in 1692 after Jesuit priest Father Eusebio Francisco Kino was invited by the tribe to establish the mission. The current structure was built under Franciscan administration, following the Jesuits' expulsion in 1767. Begun in 1783, by 1790 historical accounts indicate that the richly decorated interior included elaborate paintings, statues of religious figures, and ornaments. It is unclear how and when the bells were added, although they appear in the earliest photographs of the mission. Apart from a brief period in the early 19th century, the mission has functioned continuously as an active church.

In 1978, the nonprofit Patronato San Xavier was founded to support preservation of the mission. Today, the organization funds and directs ethical conservation, conducts scientific research, and interprets the significance of Mission San Xavier. In addition to being an active Catholic church, San Xavier is a National Historic Landmark, hosts a museum, and attracts more than 200,000 visitors annually. With input from professional conservators, the organization recently developed a Conservation Management Plan that highlights the range of cultural, spiritual, and historical values associated with the site. Balancing traditional use and spiritual practice with informed and sustainable conservation is the primary focus of the plan.

DOCUMENTATION AND METHODS OF STUDY

Mission bells may have genealogies or life histories. Some began their lives in European foundries, and many have moved numerous times throughout their life span. The Kings of Spain typically provided colonial missions with vestments, ornaments, chalices, and a mission bell (Bolton 1932, 53). Other bells were crafted on-site by friars using printed instruction manuals. Sometimes craftsmen would inscribe their name and the casting date on the bell, or the name of the mission where the bell would hang. Bells could be consecrated through baptism and naming, thus acquiring an individual identity. Mahar (2013) writes that "the church bell was a full-fledged member of the community, reflecting a power that blurred the lines between person and thing."

Bronze bells are said to resonate best with a 78% copper (Cu)-22% tin (Sn) mix. Using electrochemical impedance spectroscopy (EIS), Contreras-Vargas et al. (2016) determined that fragments from two bells dating to around 1810 had compositions of 90%–94% Cu, 5%–8% Sn, and 1%–2% lead (Pb) nodules. Ramos et al. (1992, 783) observed that the higher copper content reduced mechanical strength and increased cracking. This may be because tin (cassiterite) deposits in Mexico are rare and come mostly from the Zacatecas region (Hosler 1994, 22).

Jesuit priests were encouraged to mine for precious metals. Molina Alvarez (2007, 24) reports that the techniques of bell founding were rigorously kept secret by foundries as well as religious orders that had specialized bell ringers. Ives (1963, 19–20) reports the existence of a foundry that operated from 1790 to 1850 where a bell was said to have been cast in an adobe mold. He describes the troubles that could occur with casting: "… if the adobe did not contain enough clay, the mould disintegrated, releasing the hot metal all over the place; if the adobe was too moist, the mould exploded." He also explains that the Kino Mission documents "… only reference requests [for bells] to be sent from the south." Observation confirms that many bronze bells in the region are prone to breakage due to poor material selection and/or inadequate manufacturing techniques. Giffords (2007, 212) found that mission bells cast in the Pimería Alta were not known to be tuned by trimming or significantly finished after casting.

Many mission bells cast prior to 1863 have a junction at the rim or top of the sound bow that has a pronounced angle rather than a gentle curve. Bells cast in Zacatecas in the late 18th century also have the characteristic squared lip, diamond cross, and modified Roman letters (Imwalle 2017, 28). Imwalle (2017, 31) also noted that most clappers have a ring for attaching a rope, which suggests that the bells were stationary so the clapper would strike directly when pulled. The profiles, inscription letters, cross ornament, and clappers of the Mission San Xavier bells match this description.

CONDITION OF THE BELLS

A loose bell clapper was the impetus for this conservation project. Regular use of the bells at San Xavier has created problematic patterns of wear, damage, and surface alteration. Surface cracks and deformations suggest inferior casting and melting techniques, indicating that obtaining high-purity metal materials was difficult. Inadequate hanging methods and poor clapper repairs have also impacted the condition of the bells. It was observed that two bells mounted close together struck one another and the masonry walls during ringing, thus raising the concern for potential serious cracking. While surface corrosion was not observed to be extensive, iron oxide staining runoffs from their iron chain as well as considerable dust and bird debris were present.

Before beginning any conservation work on the bells, a meeting with the bell ringers was held in 2019. They shared that the bells are the responsibility of the village and are rung mostly for funerals and on two feast days. Some bell ringers bless the bells and themselves before ringing them. At Mission San Xavier, the copper alloy bells do not ring for mass or toll; rather, this function is performed by a large iron Blymyer bell in the same tower that is rung with a rope at the discretion of the priests. Lira and Peñuelas (2019) wrote that "in order to understand and preserve bells according to their symbolic function: [it is necessary to understand] their sound, the way they are rung and the reasons for doing so." Our observations also confirm this.

Bells do deteriorate in the arid American Southwest, subject to the effects of temperature extremes, blowing dust and sand, and monsoon wind and rains. The bell ringers agreed to a conservation study and treatment that would lead to a maintenance plan. Their concerns were: (i) that the treatment time would disrupt bell-ringing needs, (ii) that the clappers be wrapped so the bells did not ring during treatment, and (iii) that the treatment would not alter the sound of the bell.

A joint proposal for study and treatment was thus outlined. Developing appropriate solutions for cleaning the bells' bronze surfaces and their iron clappers required testing, and determining the appropriate level of cleaning desired required discussions. Once tested, the products and methods were modified to in situ treatment applications.

As Contreras-Vargas et al. (2016, 255) note, "Communicating the decision-making process with the stakeholders is central since the main aspect in this case is preserving the relationship of the community with their heritage." The idea for a new hanging method that would prevent the bells from hitting each other or the masonry walls was also approved. A follow-up meeting was held with the village iron workers to design, construct, coat, and install new hanging devices for each of the four bronze bells.

ALLOY ANALYSIS USING PXRF

A portable X-ray fluorescence (XRF) instrument proved useful for compositional study as the measurements could be taken in situ. Zlateva (2017) and Edwards et al. (2019) refer to its utility prior to further analysis and note that metal analysis without patina crusts affords better accuracy of metal homogeneity and production technique. Common surface corrosion products on bronzes consist of copper carbonates, oxides, and chlorides. Chemical spot testing confirmed the presence of carbonates and that chlorides were minimal. Because corrosion crust removal was not part of the conservation plan, pXRF readings were only taken for the purpose of documentation and basic alloy comparison among the bells (Table 1). The four bronze bells are only slightly different in shape and composition, and this results in varying acoustic quality:

Table 1. Portable XRF test results

pXRF READINGS (%) Olympus Innov-X Spectrometer Delta Analyzer, Environmental DS-4000cc, 90 Sec, Alloy Mode. The percent is based on the average of three readings.			
Element	**Cu**	**Sn**	**Impurities**
San Xavier Bell **30 cm (H) × 28 cm (D)**	**90.08**	**2.66**	**7.26** **(3.04 Pb)**
San Pedro Bell **40 cm (H) × 44 cm (D)**	**85.41**	**12.07**	**2.52**
San Juan de Bautista Bell **44.5 cm (H) × 44 cm (D)**	**88.34**	**9.44**	**2.22**
San Augustin Bell **54.5 cm (H) × 55.5 cm (D)**	**85.05**	**10.96**	**3.99**

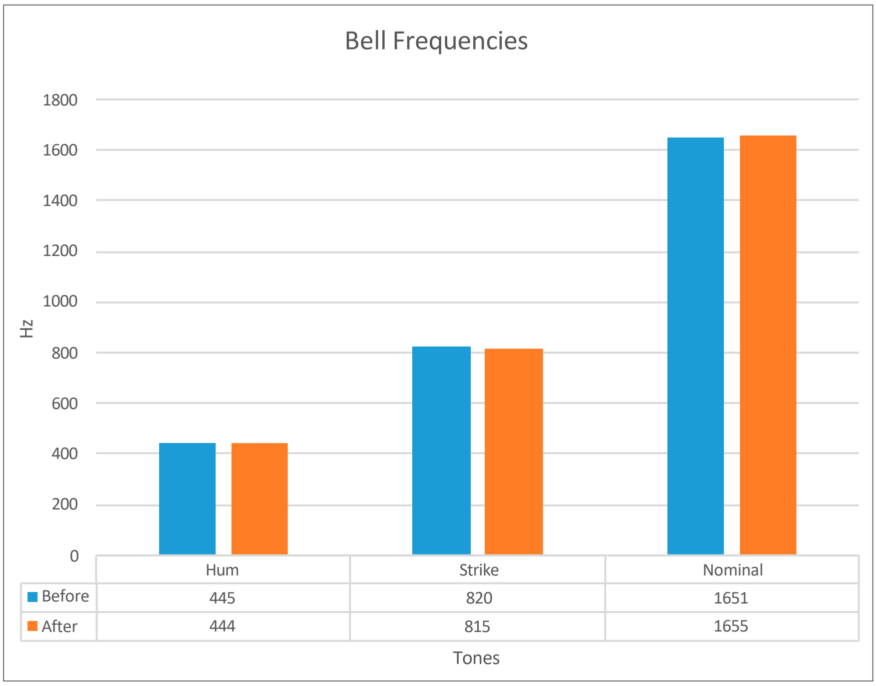
- The San Xavier bell is the highest in copper, lowest in tin, and highest in impurities. Notable is lead at 3.04%. The addition of lead at 4% is known to increase sound vibrations and shape distortions. This bell is believed to have been cast on-site, has numerous distortions/cracks, and produces a more somber sound. For modern bell metal, Cekus and Nadolski (2021, 532) advise that impurities should not exceed 2% for a bell to produce a quality sound.
- The San Pedro bell is the highest in tin. A higher tin content increases the rigidity of the metal and subsequently the bell's resonance. The bell ringers admire the sound of this bell.
- The San Juan de Bautista bell is in the middle range of alloy composition compared to the other bells. Duell (1919, 35) reports that it may be one of nine that were made by an old Peruvian bell-maker. The San Juan and San Pedro bells are most commonly rung together.
- The San Augustín bell is also in the middle range of alloy composition, but notably with more impurities. It originally hung at the Tucson Presidio, which dates to 1775, and is date-marked 17--. Lead was detected where three gunshots have indented the surface. This bell now hangs in the mortuary chapel and is not rung.

SOUND CAPTURE

A number of factors impact bell sound: the composition of metal alloys, the bell's shape and thickness, the form and composition of the clapper, and the manner in which the bell is rung. Bells generally have a fixed pitch and do not go out of tune. They are said to produce a complex sound composed of the nominal note and a series of harmonics that are produced at different points in the bell's profile and are closely linked to the various diameters. Ramos et al. (1992) used recorded frequencies for acoustic studies when repairing a crack in a similar 17th-century mission bell.

The sound of the San Augustín bell was videorecorded as it was struck in the conservation laboratory of the Arizona State Museum, before and after conservation treatment, using a cell phone . The bell was hung from a wooden frame and its clapper was held to the inner edge of the sound bow, then released and allowed to swing and strike the other side. Five recordings were taken both before and after treatment. The recordings were converted from MP4 to MP3 audio files and put through the Wavanal bell analysis program (used for tuning), which detects different overtones in a recording and can give the frequencies that comprise the sound of a bell. A comparison of the before and after recordings indicated good consistency and minimal change in the frequencies of the different overtones (Table 2).

Table 2. Sound frequency results



COATING STUDY

Selecting a coating system for the copper alloy bells at San Xavier was the catalyst for a formal review of materials and techniques, potential options, and eliminations. Our goals required that the coating selected be:

- A barrier between the environment and the metal substrate that is stable.
- Able to perform within a wide range of temperatures, light exposure, abrasive substances (particulate), pollution, and weather conditions (heavy rain and dust storms).
- Tolerant of the functional aspect of ringing when the clapper strikes the interior sound bow and not adversely affect the sound.
- Renewable by trained preventive specialists and/or the bell ringers.

Over the last forty years, coatings for the preservation of metal fine arts or historical objects such as sculptures, historical plaques, and monuments in the outdoors have consisted of variations of three systems: (1) the application or reapplication of a painted or polychromed surface, based on the original creation and controlled by the artist's choice of color or colors; (2) the use of a clear coating (lacquer) or a conservation resin such as Paraloid B-48N or Incralac (a modified Paraloid B-44 resin in solvents with benzotriazole corrosion inhibiter and a UV absorber), or Permalac (an acrylic resin spray containing Paraloid B-48N); (3) varied mixtures of waxes (microcrystalline, natural, or modified) with or without benzotriazole and sometimes with PolyWax 2000 polyethylene.

A metal sheet of 510 phosphor bronze (89%–90% Cu, 10%–11% Sn, and 0.01%–0.35% P) was cut into 12 individual coupons, number stamped into the center top rear as an identifier, cleaned, and photographed. A range of coatings were prepared and applied to the metal coupons (Table 3).

Table 3. Coating test results

Panel	Test Coupon	Application	Solvent	Buff	Change Rank
1	no coating / control				
2	no coating				1
3	Butchers Bowling Alley cold wax	brush	VM&P Naptha	buffed	7
4	Behlen Blue Label cold wax	brush 2X	VM&P Naptha	buffed	6
5	Goldens MSA Varnish (gloss)	brush 2X	MSA 1:1		5
6	K-C Wax: Kinco 478-J (30%) + 278-E (20%)	brush 2X	VM&P Naptha		4
7	Incralac	brush 2X	Toluene & alcohol		2
8	Permalac (Satin)	spray 2X			9
9	Permalac (Matt)	spray 2X			10
10	K-C Wax: Kinco 478-J (30%) + 278-E (20%)	brush + propane torch	VM&P Naptha	buffed	8
11	Acryloid B-48N	brush 2X	Toluene 1:1		3
12	K-C Wax: Kinco 478-J (30%) + 278-E (20%)	brush + propane torch	VM&P Naptha		11
	after cooling: Behlen cold wax	brush	VM&P Naptha	buffed	

The coupons were hung under accelerated aging conditions in a closed environmental chamber at the University of Arizona. The test samples were exposed to temperatures from –30°C to 85°C, relative humidity of 20%–95%, and average solar irradiance at 1000 W/m^2. The test plan was to replicate extreme weather conditions in Tucson during May/June, which can include temperatures of 20°C to 38°C, 13% humidity, and solar irradiance ultraviolet index (UVI) intensity values of 4.0 (moderate) to 6.2 (high). Over a period of months, the coupons were exposed to 9.8 equivalent test "days" with lamps on and off.

Careful examination indicated that there were visible changes to the coupons, which could be ranked from more to less changes as 2, 7, and 11, then 6, 5, 4, and 3, 10, 8, 9, 12. Microscope examination indicated that no changes occurred in the quality or amount of coating remaining on the test samples. Based on performance and microscopic appearance, wax mixture #12 was the coating selected for all the San Xavier bronze bells.

BELL TREATMENT PROTOCOL

- Clean from the top down with dry brushes to remove loose dust and particulates from the surfaces.
- Rinse from the top down with distilled water from a sprayer.
- Wash with a dilute aqueous solution (0.2%) of Orvus (sodium lauryl sulfate) and brush to remove dirt and bird guano from the surfaces.
- Rinse from the top down with distilled water from a sprayer.
- Prepare a heated aqueous 5% solution of sodium [hexa]metaphosphate, also known as Calgon, and apply with stiff nonmetal brushes as needed to reduce areas of corrosion. As a cation, the solution creates a dispersion of calcium and magnesium salts by breaking down and complexing them to form soluble salts that may be dispersed into a general solution. After testing several solution mixtures of acids and gels, this method was selected because it was manually more controllable and safer.

- Rinse from the top down with distilled water from a sprayer.
- Dry surfaces with a clean, soft cloth.
- Warm a small section of the interior surface using a propane torch (15–20 cm^2 at 74°C) and brush the wax mixture in VM&P naphtha onto this surface. Continue heating and applying the wax mixture on the interior until evenly coated. Hot-wax the exterior surfaces of the bell following the same heat and wax procedure.
- When cooled, apply a single brush coat of Mohawk Blue Label Paste Wax to all surfaces. Behlen wax (a blend of carnauba waxes and gum spirits) was originally used on the bells because it had a successful history on bronze sculpture in this climatic region since 2012. However, as of June 2019, Behlen wax products transitioned to the Mohawk Finishing Products label. Mohawk Blue Label Paste Wax is easily available and has become the coating used for maintenance.
- When dry, buff the bell surfaces using a soft natural fiber brush (a shoe polishing brush) and clean cotton cloths (Figures 1–4).

Figure 1. San Pedro bell: (a) before treatment, (b) during cold waxing, (c) after treatment

Figure 2. San Juan de Bautista bell: (a) before treatment, (b) testing hanging device, (c) washing, (d) after treatment

Figure 3. San Xavier bell: (a) before treatment, (b) washing, (c) hot waxing, (d) after treatment

Figure 4. San Augustín bell: (a) before treatment, (b) during cleaning, (c) brush detail, (d) after treatment

BELL HANGING SYSTEM

Early photographs show that the bells have been hung by a single-chain device since at least the mid-19th century. This resulted in one bell swinging and hitting the adjacent masonry and two bells that shared a beam hitting each other. The original wood endured harsh environmental conditions, with repeated coatings of boiled linseed oil resulting in visible damage from UV exposure, accumulated dust, mold, and air pollutants. Conservator Luke Addington utilized the modular cleaning program (MCP) to develop a formula to reduce old coatings and stains, protect the beams from further deterioration, and prepare them for the new hanging devices.

After reviewing images of other mission bells, visiting many churches, and discussing options with the Wa:k village bell ringers and iron workers, the decision was made to use metal U-bolts for hanging. The Council for the Care of Churches (1993, 12) suggests that when there are fewer than six canons and no holes through the crown, U-bolts can be used. Metal U-bolts are able to withstand the dynamic forces of a ringing bell and distribute the weight of the bell across the support beam rather than at one point. The Wa:k village iron workers created custom U-bolts and associated fixtures for each bell using 5/8-inch (1.6 cm) iron rods for the U-bolts, and 1/8-inch-thick (0.3 cm) metal plates for the top of the hanging beam. Prior to installation, Evapo-Rust was used to remove surface rust from the metal pieces, which were then sprayed with Rust-oleum Rust Reformer paint and brush-painted with black urethane alkyd paint. Black silicone sheets were placed between the metal plates and the wood to serve as a barrier.

PREVENTIVE MAINTENANCE

A conservation maintenance plan was devised and initiated during the bell conservation project to provide a framework for the care and management of Mission San Xavier based on associated values and physical needs. The plan considers the historical, spiritual, and archaeological significance of the Mission along with its contemporary context of place and community. A chronology and conservation history were created based on historic images, records, and reports. Vulnerabilities and priorities were also identified. A preventive maintenance program has since been started to monitor the bells and identify the frequency of routine preventive action.

CONCLUSION

This treatment was an opportunity for conservators to understand the condition of the bells and marvel at their sound. The metal composition and manufacturing technology, including the flaws and signs of aging from over 200 years of outdoor exposure and regular use, are the details from which we can learn more. These bells, and especially their sound, are of great importance to the Tohono O'odham people of Wa:k and their cultural traditions. Sounding separately or in clusters of sound, they inform the sense of community while evoking individual emotions.

ACKNOWLEDGMENTS

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MATERIALS LIST

Behlen Blue Label paste Wax
H. Behlen & Bro. Hudson, NC 28638 USA, now Mohawk Finishing Products, 1565 East Kent Ave N, Vancouver, BC V5P 4Y7, Canada

Black silicone sheet
RubberCal, 18424 Mt. Langley St. Fountain Valley CA 92708, USA

Bronze 501 sheet
McMaster-Carr P.O. Box 740100 Atlanta, GA 30374-0100, USA

Butchers Bowling Alley Wax
https://store.bwccompany.com/

Evapo-Rust: 800 Enterprise Road, Suite 101, Horsham, PA 19044, USA

Incralac
Talas 330 Morgan Ave., Brooklyn, NY11211, USA

Microcrystalline wax (478J & 278E)
The Kindt-Collins Company LLC, 12651 Elmwood Ave., Cleveland, OH 44111, USA

Permalac
Peacock Laboratories, Inc. 1901 S. 54th Street, Philadelphia, PA 19143, USA

Olympus Innov-X spectrometer Delta Analyzer Environmental DS-4000cc
Evident (formerly Olympus Scientific Solutions), Waltham, MA, USA

Orvus WA paste
Proctor & Gamble Professional, 2 P&G Plaza, Cincinnati, OH 45202, USA

Sodium [hexa]metaphosphate
Aldrich Lot #BCBV8565, Sigma-Aldrich St. Louis, MO USA

Wavanal bell analysis program
https://www.are.na/block/15419212

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