# Unusual Design Influences a Building's Biocolonization Pattern and Complicates Remediation

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***Abstract*— The Smithsonian Institution's National Museum of the American Indian (NMAI) opened its doors for the first time to the public on September 21, 2004. Designed by Douglas Cardinal, the building stands out from other museums on the National Mall in Washington, D.C., because of its curvilinear shape and the yellow-golden color of its stone, which are intended to recall cliff dwellings of the American Southwest. Biocolonization on the stonework, a consequence of both the building's design and the stone's porosity and facture, has resulted in five cleaning campaigns over the 13 years since the building's inauguration. Such frequent cleaning, three times with the same biocide, is both expensive and potentially self-defeating. Microorganisms tend to become resistant to biocides, and/or new organisms may develop that are even more aggressive. Since a pristine building is preferred by its stakeholders, alternative approaches are being explored to prevent biocolonization. Any alteration of the building's architecture has been rejected, and pressurized water washing is considered inadvisable as an alternative to biocidal cleaning. Good results reported for inhibition of biocolonization by zinc strips led to their testing on a Kasota limestone block, which proved very effective, and in February 2012 zinc strips were installed in two locations on the NMAI building. After several years the blocks showed localized reduction of biocolonization, but the strips have not yet been proven effective in reducing biocolonization on the building's façade. Installation of zinc sheets to cover top capstone surfaces, both horizontal and outward sloping, is in the process of implementation on two test areas. The non-uniform flow of water over the irregular surfaces on the façade below, however, is likely to result in incomplete inhibition of biocolonization by the zinc. Moreover, randomly projecting blocks scattered across the facade cannot be protected by zinc strips without interfering with the building's appearance. Alternative biocides and methods of inhibition are also being considered. These include incorporation of zinc compounds in hydraulic lime parging on capstones, a technique that might be used on window sills and capstones that are not visible from the ground; it should inhibit biocolonization on these surfaces and possibly on the façade below them.***

***Keywords*— *National Museum of the American Indian; Canadian Museum of History; dolomitic limestone; biocolonization; cleaning; biocides; zinc strips***

## I. INTRODUCTION

The Smithsonian Institution's National Museum of the American Indian (NMAI) opened its doors for the first time to the public on September 21, 2004. Designed by the native architect Douglas Cardinal, the building stands out from other museums on the National Mall in Washington, D.C., because of its curvilinear shape and the yellow-golden color of its stone cladding, which are intended to recall cliff dwellings of the American Southwest. Since construction, the dolomitic stone has undergone rapid biocolonization, identified as consisting mainly of cyanobacteria (blue-green algae) [1-5]. Because the building is prominently located facing the U.S. Capitol and a pristine appearance is preferred by its stakeholders, this has led to five cleaning campaigns over the 13 years since its completion. Reduction of the biocolonization over the long term presents many difficulties given the architectural design of the building. This paper describes the occurrence of biocolonization on the building, compares it to a similar building in Canada also designed by Cardinal, and discusses alternative solutions to periodic cleaning.

## II. CARDINAL'S ARCHITECTURE AND STONE CLADDING

Natural stone is fundamental to the design concept of the NMAI building [6]. Covering most of the façade are curved "split-face" blocks made by hydraulic chisels, which contribute to the appearance of a natural stone formation because of their irregular surfaces. High-relief areas on these blocks project from the façade, making them susceptible to biocolonization. Use of the hydraulic chisels also created subsurface cracks that retain water and have led to exfoliation of flakes in areas where the flow of water is greatest. "Tapestry"-finish blocks used for sills, window surrounds, and capstones were sawn and then sandblasted to remove the saw marks for a smooth natural-looking finish. "Roughback" stones are highly decorative blocks at ground level. Their surfaces, which correspond to the naturally weathered horizontal surfaces of quarry beds, are textured by fossil traces and colored by iron deposits in rusty hues ranging from yellow to red to dark brown. Since these blocks are face bedded, they are particularly delicate and susceptible to exfoliation.

Stone cladding on the exterior of the NMAI building was obtained from Vetter Stone's quarries in Kasota, Minnesota [7]. From Ordovician-age Oneota Dolomite strata found in southeastern Minnesota, the stone is known in the building trade as Kasota, Mankato, or Minnesota limestone. It is classified by geologists as a calcitic dolomite because of the relative percentages of calcium and magnesium. Its color results mainly from the presence of iron-bearing minerals, nearly 1% by weight expressed as iron III oxide ($Fe_2O_3$). The acid-insoluble fraction, averaging 15% for three samples, contains quartz, feldspars, and clays. Thin sections show a grain-supported structure with voids between dolomite crystals partly filled with fine-grained cement, mainly micritic calcite with occasional particles of K feldspar and quartz. The calcite is expected to weather out before the dolomite. Apparent porosity for two samples averaged 5% by weight and open porosity 12% by volume. Water absorption and drying curves for test cubes showed that drying the stone in laboratory conditions takes at least four times longer than absorption. Porosity is non-homogeneous because of a wide variety of pore sizes, and imaging showed irregular connections between pores. Water will be retained by capillary pores, the largest of which measure only about 0.1 mm in linear dimension, and by long flat pores. These characteristics contribute to the susceptibility of the stone to biocolonization, especially the porosity and water absorption and retention. Other buildings on the National Mall are constructed of low porosity stones — granite, marble, and Holston Limestone (with 0.31% open porosity by volume) — and exhibit relatively little biocolonization. On the other hand, nearby office buildings constructed of Salem Limestone with open porosity slightly higher than Kasota limestone display considerable biocolonization.

Douglas Cardinal's similar design for the Canadian Museum of History (CMH) provides an interesting comparison to the NMAI building. Originally called the Canadian Museum of Civilization and located in Gatineau, Quebec, it faces the Canadian seat of government (Parliament) across the Ottawa River in the capitol Ottawa. Completed in 1989, fifteen years earlier than the NMAI building, the huge CMH building is clad with Tyndall limestone from Garson, Manitoba, about 49 km from Winnipeg, and the stone is also an Ordovician dolomite [8]. The Tyndall limestone is variegated in color, with prominent dark gray dolomitic fossil traces in a light gray calcitic matrix. As expected, calcite portions weather out first, as can be seen on CMH blocks over which fountain water flows. The Tyndall limestone is somewhat less porous than Kasota limestone based on average proportional increases in weights for pairs of cubes (2.5 cm on a side) of the two limestones following 24 hours of total water immersion.

## III. PATTERNS OF BIOCOLONIZATION ON THE NMAI AND CMH BUILDINGS

The NMAI building's non-traditional design enhances biocolonization on its stonework, which occurs where rain falls on the building or flows over it and manifests as both localized dark spots and streaks [9]. The dark color is provided by *Gloeocapsa* cyanobacteria, which develop dark sheaths for protection from ultraviolet radiation [10]. In the absence of an overhanging cornice protecting the façade from rainwater, portions of the split-face blocks that project randomly from the facade are wetted during rainfall and subsequently darkened by microorganisms. Disfiguring streaks (also known as *Tintenstriche*) occur mainly below balconies topped by tapestry-finish capstones that shed large amounts of water onto the façade from downward sloping top surfaces. Recessed silicone caulk between the capstones also channels and concentrates water flow to produce streaks below the joints (figs. 1, 2). Water repellency of the caulk and adjacent stonework into which the silicone oils bled no doubt contribute to the channeling. In addition, a damp-proof membrane below the capstones makes the capstones reservoirs for water and microorganisms, which can be picked up by rainwater as it flows over them and down the facade. The handsome highly colored roughback blocks at the base of the building are also subjected to wetting because, *a priori*, their flat bedding surfaces cannot conform to the building's curves. In some locations irregular wind patterns around the curvilinear building and vegetation close the building increase biocolonization by slowing the drying of stone after rainfall and creating damp microclimates respectively.

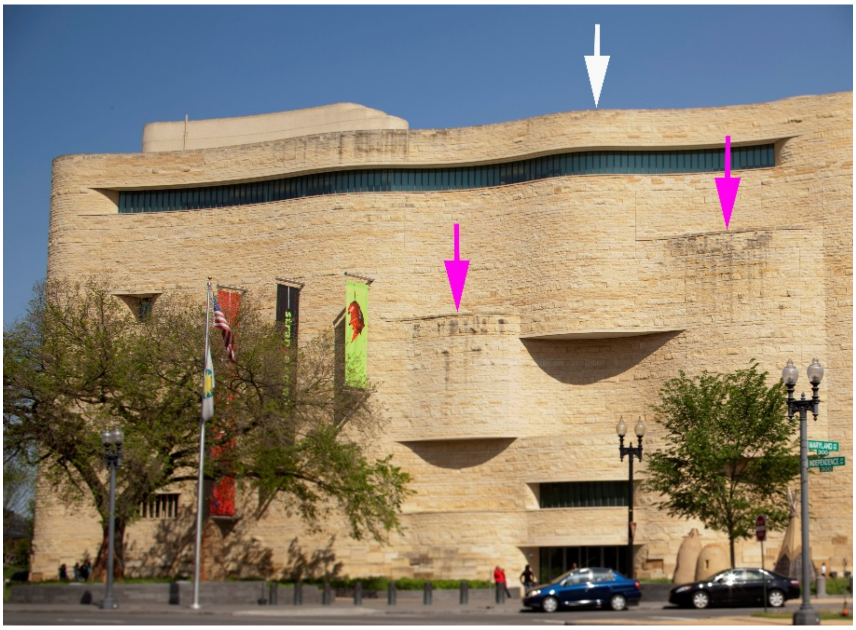

Fig. 1. NMAI, south facade. The white arrow indicates stonework at the roofline that protects balconies below from biocolonization; pink arrows indicate darkened stone on balconies unprotected by stonework above (M. Wachowiak and E. Webb, April 22, 2010).

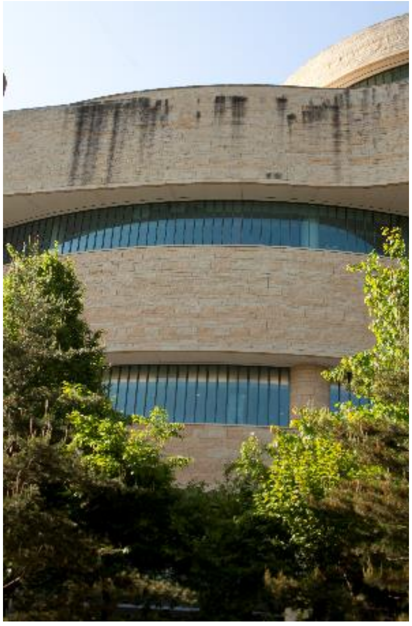

Fig. 2. NMAI, north façade. Sloping capstones contributed to severe black streaking from biocolonization below the Inouye Terrace just six years after the building opened (M. Wachowiak and E. Webb, April 22, 2010).

Similar design and facture of the CMH has also resulted in biocolonization on blocks that project from the façade (figs. 3, 4), but the especially disfiguring streaks on the NMAI building are less common on the CMH. This is probably because the CMH building does not have sloping capstones, and its capstones shed less water as a result. The caulk in narrow joints between capstones and adjacent stonework also show no evidence of water repellency to contribute to the channeling of water. Finally, the CMH capstones have slightly different detailing: an air gap of about 1 cm below capstones on CMH is created by rubber bumpers, which separate them from masonry below topped by a damp-proof membrane. Hence, the capstones should retain less moisture and probably do not send microbe-laden water to the same extent onto the façade.

Biocolonization seems to have occurred far more quickly on the NMAI building than on the CMH building. In contrast to the five cleanings of the NMAI building over 13 years, no records have been found of any previous cleaning over the past nearly 30 years before pressurized steam cleaning being completed this year (2017).[1] That the building has not been previously cleaned is confirmed by the lack of severity of black deposits visible only from the roof, which are unlikely to ever have been cleaned (fig. 4). The lower porosity of the Tyndall limestone almost certainly plays a role in the slower biocolonization of the CMH building. In addition, the difference in biocolonization may be attributed to distinct climatic conditions. Washington has averaged 106 cm annual precipitation and 38 cm snowfall since NMAI's construction.[2] Ottawa averages only about 10% less precipitation at 94 cm but has more than six times the amount of snowfall at 236 cm.[3] Washington is also warmer and more humid than Ottawa.

## IV. CLEANING

Localized cleaning to remove black deposits began on the NMAI building as early as 2006, just two years after the building was completed [11]. The first major cleaning of disfigured areas was implemented by a contractor in the spring of 2011: application of the quaternary ammonium biocide D/2 (manufactured for Cathedral Stone), followed by scrubbing with plastic brushes and rinsing with water at ordinary pressure. The same method was employed by the same contractor on a terrace in the spring of 2014, using D/2 (manufactured for D/2 Biological Solutions, Inc.) just before its dedication in honor of Senator Daniel K. Inouye.

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[1] Alain Proulx, who has been at CMH for 10 years, reported that the contractor is employing 170º C water at about 35 mPa pressure; personal communication, May 17, 2017. Genivar, "Investigation and report: Tyndall stone cleaning, The Canadian Museum of Civilization," unpublished report, October 5, 2012.

[2] National Climate Data Center, www.weather.gov/media/lwx/climate/dcaprecip.pdf and www.weather.gov/media/lwx/climate/dcasnow.pdf.

[3] Statistics Canada, www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/phys08a-eng.htm.

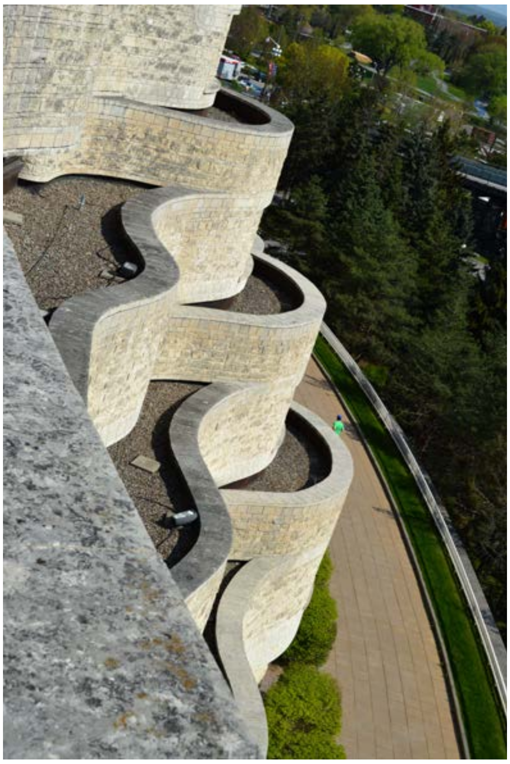

Fig. 3. CMH. Balconies exhibit dark spots on projecting stones. Biocolonization can be seen on the capstone in the foreground at left (May 17, 2017).

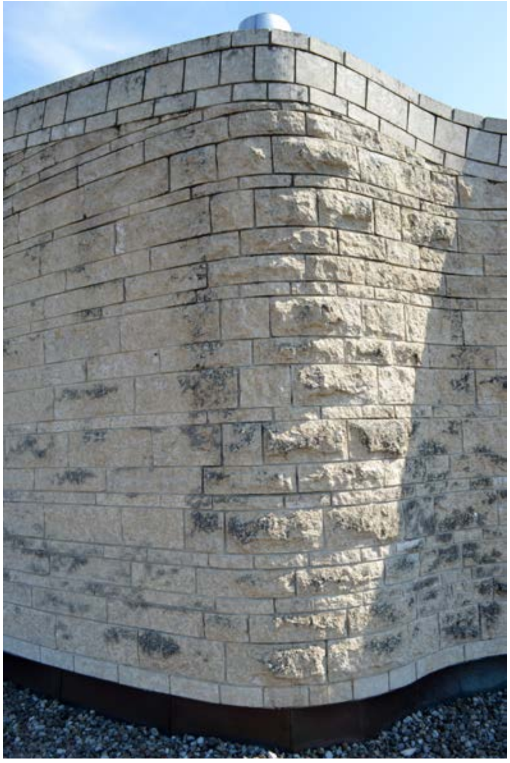

Fig. 4. CMH. Stonework on the roof of the curatorial building shows scattered biocolonization on high relief areas nearly 30 years after the building opened. Since it cannot be seen from the ground (or Parliament), it is unlikely to have ever been cleaned (May 17, 2017).

A Minolta CR300 Chroma Meter was used to measure changes in coloration on terrace capstones from just before the 2014 cleaning and every six months over the following two-and-a half years. Blocks were selected for measurement to represent a range of textures and porosity, which are reflected in a range of L* values (black to white) for the biocolonized blocks before cleaning; at maximum brightness, in contrast, the L* values show remarkable consistency for the different blocks (Table 1). It is noteworthy that the L* values do not show maximum brightness instantaneously; rather, they show it occurring two-and-a-half years after application of the biocide. The ΔE* values (overall color change between successive readings) show diminishing change up to about two years, then slight increases. This suggests that recolonization was beginning but not yet visible, since ΔE*values greater than 3 are considered necessary for the human eye to detect a difference. At this rate, it is estimated that biocidal reapplication will become desirable approximately every five years.

By 2016, five years after the first major cleaning, the building had become fairly disfigured by biocolonization. The rate of recolonization may have been increased because horizontal surfaces of capstones were not cleaned during the 2011 campaign and thus served as reservoirs for rapid growth of the cyanobacteria on the facade. In any case, comparison of photographs indicates that less darkening occurred over the five-year period from 2011 to 2016 than over the previous eight-year period from the opening of the building to its first major cleaning. In December 2016 the most comprehensive cleaning to date was done in anticipation of the January 2017 presidential inauguration. Specifications implemented by a different contractor called for application of the D/2 manufactured for D/2 Biological Solutions followed by pressurized water washing. Use of highly pressurized water washing alone was observed on a weekend when no supervision of workmen was apparent.[4]

[4] The Smithsonian must often take the lowest bid when contracting work.

*Table 1. Average of 50 random colorimetric measurements on Inouye Terrace capstones expressed as ΔE*, the overall change in color for two successive measurements where a lower number indicates that color change is less (values of ΔE* ≥ 3 are necessary for the human eye to detect a difference); and L*, the amount from dark (0) to light (100).*

| **Date** | **Time relative to the May 2014 cleaning** | **Block #3** | | **Block #8** | | **Block #24** | |
|---|---|---|---|---|---|---|---|
| | | ***ΔE**** | ***L**** | ***ΔE**** | ***L**** | ***ΔE**** | ***L**** |
| March 2014 | just prior to cleaning | - | 40.95 | - | 51.25 | - | 50.51 |
| Oct. 2014 | ½ year after cleaning | 27.59 | 65.54 | 15.43 | 66.65 | 14.66 | 63.76 |
| May 2015 | 1 yr. after cleaning | 0.69 | 66.19 | 1.42 | 67.99 | 3.27 | 66.68 |
| Sept. 2015 | 1½ yr. after cleaning | 0.87 | 66.43 | 0.93 | 68.41 | 1.43 | 67.78 |
| April 2016 | 2 yrs. after cleaning | 1.27 | 66.07 | 0.77 | 67.88 | 0.44 | 67.85 |
| Oct. 2016 | 2½ yrs. after cleaning | 1.04 | 67.05 | 1.06 | 68.90 | 0.80 | 68.59 |

Pressurized water washing is generally considered ill-advised as a method of ameliorating biocolonization, since it drives microorganisms into stone, and the large amounts of water received by stone may contribute further to biocolonization. In addition, excessive water pressure may lead to mechanical damage, which is almost certainly responsible for some of the significant detritus of stone particles and flakes around the building after the December 2016 cleaning and enhanced by freeze-thaw cycling that occurred when the temperature fell below freezing at night. The practice of using pressurized water during window washing to remove residues that include guano is nevertheless expected to continue, as occurred in late 2014.

Cleaning of NMAI stonework is expensive, both because it is labor intensive and requires use of a lift at least 34 meters high to reach the top of the nearly 40-meter-high building. Moreover, use of the same biocide is self-defeating in the long run. Microorganisms tend to become resistant, and new organisms may develop that are even more aggressive [12]. Although the building is supposed to represent the equilibrium of man with nature, its stakeholders prefer a pristine building, which has resulted in exploration of alternative approaches to prevent biocolonization.

## V. ALTERNATIVE METHODS

Architectural features of the NMAI building are responsible for much of its biocolonization, and possible modifications to reduce biocolonization were explored, such as replacement of sloping capstones with flat ones. However, such architectural changes would be both major expenses and unacceptable to the museum.

Good results reported for inhibition of biocolonization by installation of zinc strips on the gabled roof of the granite Stanford Mausoleum at Stanford University [13, 14] and on Indiana limestone capstones of the Holocaust Museum in Washington, D.C. (fig. 5), led to testing of zinc strips on two Kasota limestone blocks, which proved very effective (fig. 6). Theoretically, zinc ions dissolved in rainwater inhibit biocolonization where the water washes over stonework. Zinc test strips were installed in two locations on the NMAI building in February 2012. After several years they showed localized reduction of biocolonization but have not yet been proven effective in reducing biocolonization on the building's façade because of problems with the test methodology. For an area on the Inouye Terrace shown in Fig. 7, the test period was insufficient because of premature cleaning with the biocide D/2 just two-and-a-half years later in 2014 and then again in 2016. The visibility of the strips on the terrace, which is used both for receptions and by staff, also makes them unacceptable to the museum for further installation there. In the second area where zinc strips were installed atop ledges of roughback blocks, the strips appear to have been only partially effective, mainly because water washes unevenly over the highly textured blocks but also because the strips were placed where they receive less rainfall at the back of the ledges in order to prevent them from being visible. As another test, installation of zinc sheets is scheduled to cover capstones on a sloping balcony and at the top of the building, where they are likely to be most effective. The non-uniform flow of water over the façade's irregular surfaces is likely to result in incomplete inhibition of biocolonization below the capstones, however, since the successful use of metallic zinc in preventing biocolonization relies on the even flow of water down a building's flat ashlar walls, like those of the Holocaust Museum and Stanford Mausoleum. Use of zinc is precluded in other areas; in particular, zinc strips cannot be installed to protect randomly projecting blocks scattered across the facade without interfering with the building's appearance.

Fig. 5. U.S. National Holocaust Museum (1993). By 2000, the building's Salem Limestone had become disfigured by biocolonization. Following cleaning of the building in 2010, zinc strips installed near the edge of the roof have largely eliminated the problem on flat portions of the façade (June 2, 2017).

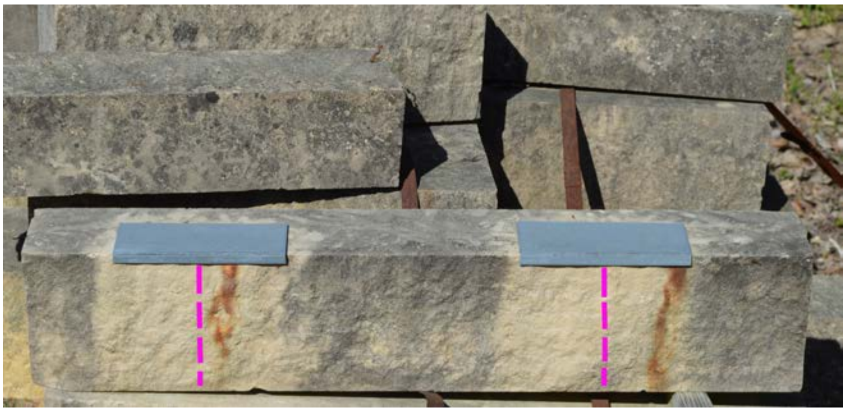

Fig. 6. The center of this Kasota limestone block between pink dashes was cleaned with D/2 in 20011, and zinc sheets were installed to span both the cleaned and uncleaned outer areas. More than four years later, both cleaned and uncleaned areas were clean where they had been washed by rainwater that ran over the sheets, while the central cleaned area between the sheets recolonized. Iron stains are from bands that held the blocks on a skid (April 20, 2016).

A related method of inhibition being tested on the NMAI building is incorporation of zinc compounds in hydraulic lime parging placed atop five heavily biocolonized capstones on the loading dock wall. Over time the parging itself will eliminate biocolonization on the stone by preventing the sunlight required by the cyanobacteria from reaching it. In addition, the zinc ions should inhibit biocolonization on the parged surfaces and possibly over the long term on vertical façade surfaces below the sloping capstones, where the zinc ions should gradually be carried by rainwater [15, 16]. If successful, the parging might be a suitable alternative for sills and capstones that are not visible from the ground.

Several other cleaning approaches using products that have biocidal effects were tested on the building's loading dock capstones in November 2015. These included application of a zinc citrate solution and "Mélange d'Angkor" [5, 17] in comparison to quaternary ammonium compounds. The test period was insufficient, however, since the test areas were cleaned only a year-and-a-half later in December 2016.

Protective products such as photocatalytical nano-$TiO_2$ coatings and water-repellents are being considered for testing, but both have drawbacks. They must be applied to clean surfaces, thus requiring both the expense of cleaning and application of the product after stone surfaces have dried. The $TiO_2$ photocatalytic products, which decompose organic molecules and are "self-cleaning," show promise but require specific light wavelengths and intensity to be effective. As a result, they may not be successful where the building is in shadow; moreover, they are expected to last only about five years [18]. Water repellents are not suitable for application to the split-face blocks that cover most of the façade, because they weather unevenly on the rough surfaces, resulting in an unattractive pattern of light and dark coloration during and after rain events. They would best be limited to top surfaces of capstones in order to reduce the amount of water they retain, but application would have to be extremely careful to avoid drips on the façade and differences in coloration from rainfall; this care would increase the cost of application. Finally, recolonization has been found to recur within five years of the application of water repellents [19].

## VI. DISCUSSION AND CONCLUSIONS

For the most part, biocolonization on the NMAI building does not represent a threat to the strength of the stone cladding, which is approximately 10 cm thick; rather, negative aesthetic perception of biocolonization is the issue in spite of the fact that the building is meant to represent the equilibrium of man with nature. A pristine building is preferred by its stakeholders today, but perhaps some biocolonization on the building may eventually be accepted as natural.

Other problems include the practice of selecting contactors to work on the building based on cost, since it can lead to damage. A serious threat to the stonework over the long term is also posed by soluble salts from de-icing compounds, which are beginning to be visible on blocks where paving abuts the base of the building and are a particular threat to the delicate roughback blocks. The amount of snow and ice in Ottawa is much greater, but replacement of many badly salt-damaged blocks at the base of the CMH building with

Fig. 7. NMAI, Inouye Terrace. Two years after installation, zinc strips had eliminated biocolonization on outer edges of capstones (March 31, 2014), but their effectiveness on the façade below was indeterminate because of cleaning the following month (and again in 2016). Biocolonization is also absent below the lightning rod from dissolution of copper and near joints where the stone was made water repellent by silicone caulk.

Fig. 8. NMAI, loading dock wall. Hydraulic lime parging containing zinc compounds was applied to the uncleaned pair of capstones on either side of the untreated, dark-colored "control" block at the center less than a year before this photograph was taken on June 6, 2017. The coloration of the parging could be adjusted to better match the stone. The west facade in the background was cleaned in December 2016.

cast-concrete blocks is a likely precursor of what may eventually be required on the NMAI building if the use of deicing salts is continued.

The estimated durability of two solutions proposed for reducing biocolonization on the NMAI building is about five years, so that consideration must be given to repeatability and cost. First, a quaternary ammonium biocide has proven successful in eliminating biocolonization on the NMAI building, but it has the disadvantages that repeated application is expensive and organisms may become resistant. A second possibility — application of a nano-photocatalytic $TiO_2$ coating planned for testing in the near future — is expected to be more expensive, in part because of the cleaning required before application. In addition, little is known yet about retreatability when a $TiO_2$ coating begins to fail after about five years. Covering of capstones with zinc sheets has the potential to achieve long lasting results, but when tests are evaluated several years in the future the inhibition of biocolonization on the façade is likely to be found ineffective where water flowing over the zinc-covered capstones does not reach stonework on account of its irregular surface. For aesthetic reasons, moreover, installation of zinc sheets would be limited to capstones at the roofline and on terraces that are not visible from public areas.

The key problems of the National Museum of the American Indian stem from the choice of its building design. Unusual designs like that of this building require special maintenance and developing appropriate and acceptable maintenance programs takes time.


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