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Moisture Conditions Across Stone Masonry Walls
- A Case Study -

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ABSTRACT

The paper deals with the results of a 12-month monitoring program of massive sandstone masonry walls in a heritage structure in Ottawa. Measurements included temperature, moisture, relative humidity and pressure across the exterior wall system and windows. The purpose of this monitoring program was to determine the source of moisture in the stone masonry walls. The results clearly established that moisture in the walls is primarily from exterior sources (i.e. rain and snow) but that air exfiltration in localized areas is also a contributory factor. The information obtained from this monitoring program has been considered in the design of the restoration program which will be underway shortly.

INTRODUCTION

The Victoria Memorial Museum (VMM), completed in 1910 for the National Museum of Canada, is the largest of the five public stone buildings designed for the national capital by the Department of Public Works then Chief Architect, David Ewart. The VMM is a four-storey structure about 122 m (400 ft) long with widths varying from 20 m to 60 m (66 ft to 197 ft); its architectural style is Tudor Gothic.

A key plan is shown in Fig. 1. The exterior walls are constructed with a combination of dressed and rough sandstone on the outside, backed by an equal

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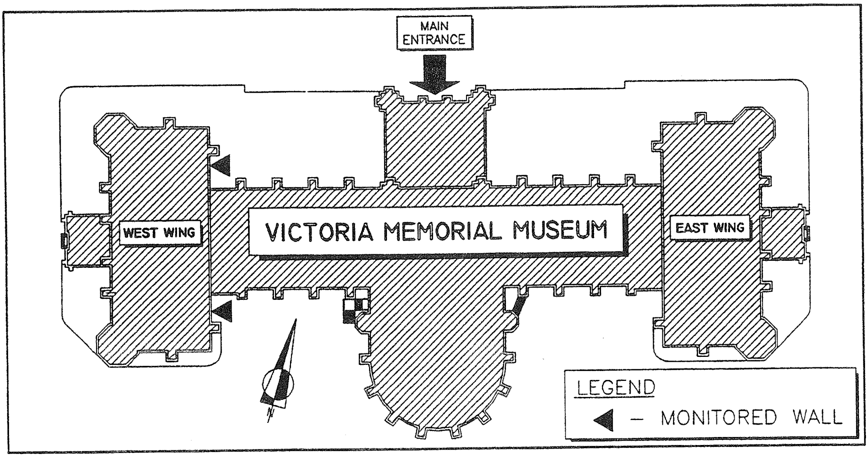

Fig. 1 Key Plan

thickness of limestone. An interior clay tile wall covered with asbestos plaster provides the air barrier. The walls are not insulated. Fig. 2 shows a typical section through the exterior masonry walls.

The original structure included a large central tower at the front of the building. In 1916, the upper portion of this tower was removed to prevent further structural damage due to excessive settlement.

Two types of sandstone face the building exterior: cut and smooth Wallace sandstone from Nova Scotia at windows, doors, parapets, plinth and carved work; local Nepean sandstone for rubble work.

During the building's 80-year service life, its stone masonry walls have developed significant performance problems. Differential foundation settlement has caused major vertical cracks through the masonry walls. The building was erected on about 15 m (49ft) of sensitive compressible marine clay, typical of the clays found in the Ottawa area. Although settlement continues to this day, surveys have shown very small movements of about 0.5 mm/year (0.020 in./year) during the past 20 years.

Currently, the sandstone masonry units (especially those on the upper floors) are spalling. The spalling of the Wallace sandstone is more significant than is the spalling of the Nepean sandstone. The most noticeable Wallace stone spalling occurs at buttresses, at upper level band courses and at the roof turrets. The band course spalling has resulted in the disintegration of the original drip edge. The

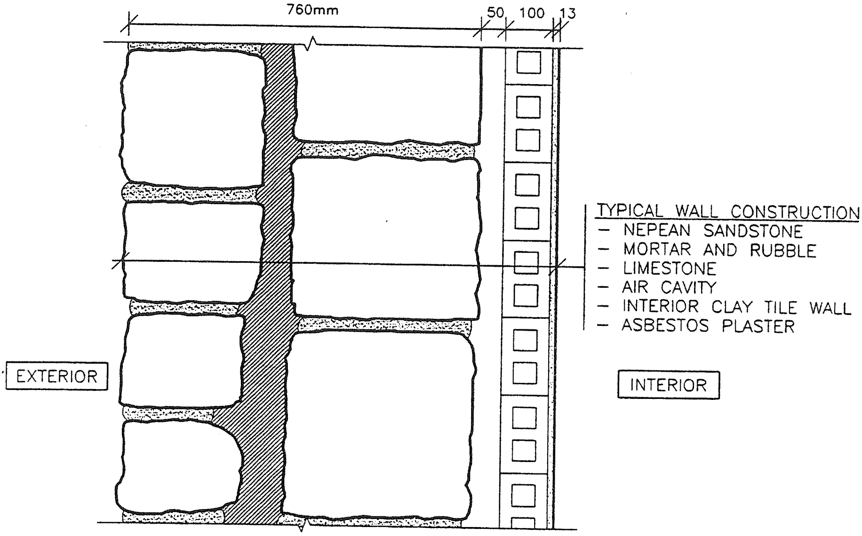

Fig. 2 Typical Wall Section

band courses and buttresses are particularly susceptible to deterioration since more moisture collects on these elements during rainfall and snow melting. Chemical weathering is also more pronounced in these locations due to the increased exposure to acid rain. Efflorescence staining is frequently present at spalling locations.

Backface weathering of the sandstone is taking place to a minor degree, and has been thought to be caused by exfiltration of the high humidity air in the absence of an adequate air and vapour barrier.

Extensive mortar cracking has occurred at the uppermost floor levels. Both the original pointing mortar and the repair mortar, which was applied some 10 to 15 years ago, are cracked. All other wall areas exhibit moderate to fairly extensive mortar cracking and debonding of mortar.

Following a detailed condition survey in 1989, the consultants recommended that major restoration work be carried out on the massive stone masonry walls. As part of the design phase, and to better understand the causes of the stone masonry deterioration, the performance of the walls was monitored for one year between March 1993 and May 1994. This paper summarizes the findings regarding moisture conditions which existed in the massive stone masonry walls during the measurement period, and outlines recommendations which would improve the walls' performance.

INSTRUMENTATION

Instrumentation consisted of thermocouples, electrical resistance moisture sensors, relative humidity transmitters and pressure difference transducers. To install the thermocouples and moisture sensors through the thickness of the stone masonry wall, 75 mm (3 in.) diameter cores were removed from the walls in two locations. Sensors were installed along the length of the cores and the cores were then replaced and sealed at their original locations. The locations of the monitoring stations on the fourth floor of the museum are shown in Fig. 3. In each of these locations, sensors were also installed on the interior and exterior of the museum as well as in the air space between the stone masonry wall and the interior clay tile wall. The type and location of the sensors through the wall are shown in Fig. 4. To assess the pressure differences across the exterior walls over the height of the building, pressure difference transducers were installed both at the fourth floor and at the ground floor level. The data was collected using automatic data loggers.

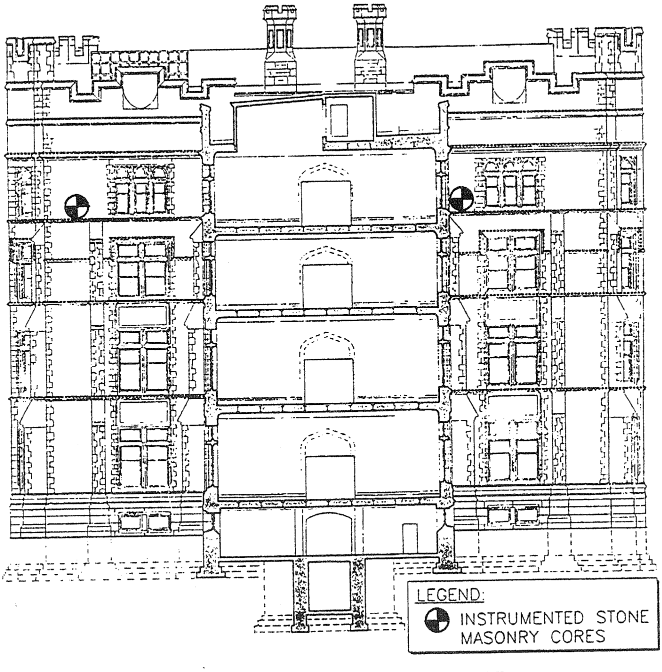

Fig. 3 **East Elevation of West Wing**

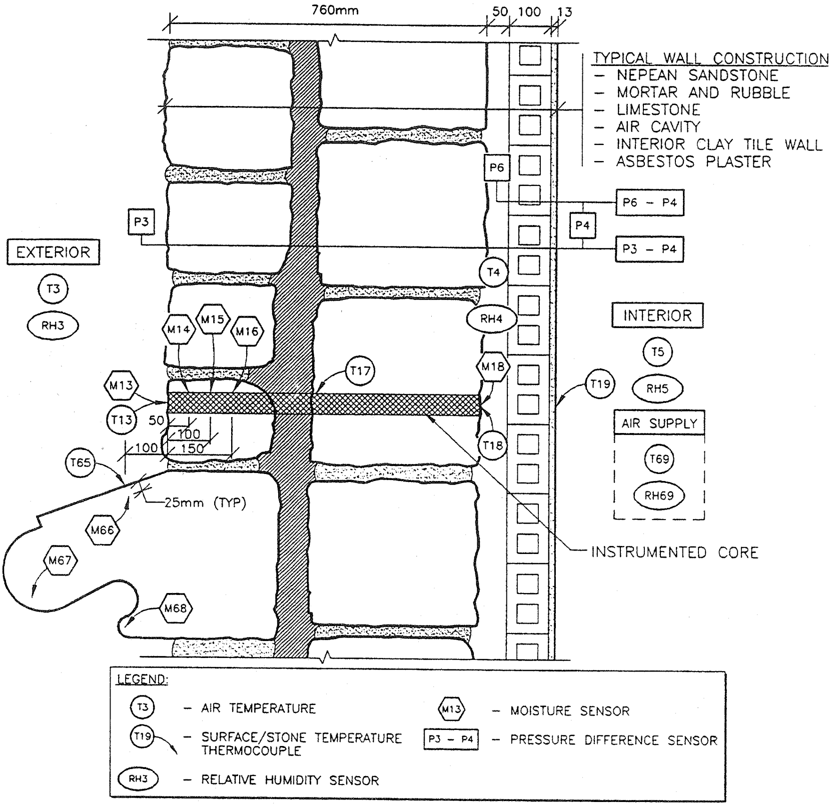

Fig. 4 Instrumentation at Fourth Floor Monitoring Station, North Side

DISCUSSION OF FINDINGS

The monitoring work carried out at the Victoria Memorial Museum provided valuable information about the temperature, the wetness and the air pressure differences across the test walls.

Since exfiltration of moist interior air is potentially detrimental to the building envelope, the climate within the museum is an important factor in the walls' performance. Accordingly, the temperature and relative humidity (RH) within the museum was measured. The measurements showed that the interior air temperature was relatively stable at about 21°C (70°F), but the relative humidity levels fluctuated widely depending on the stability of the weather and the season.

Typically, the interior relative humidity levels were close to the specified levels of 37.5% ± 2.5% in the winter, but in the summer the RH values ranged from 50% to 65%, which is considerably higher than the specified 49.5% ± 2.5%. The relative humidity measurements showed that there is indeed high humidity in the museum throughout the year and that the mechanical systems cannot adequately maintain the interior climate to specified norms.

Pressure differences across the walls were measured to evaluate the potential for air leakage. The pressure difference across the entire wall assembly at the fourth floor ranged between 45 and 65 Pa (0.007 to 0.009 psi). The pressure difference across the clay tile wall was more uniformly at about 40 Pa (0.006 psi). Fig. 5 illustrates the pressure differences during November 1993. The large difference between the two curves and their dissimilar shapes indicates that air leaks across the clay tile wall and that the air cavity is not open to the exterior. The key finding regarding pressure differences is that moist interior air exfiltrates past the air barrier system into the stone masonry walls.

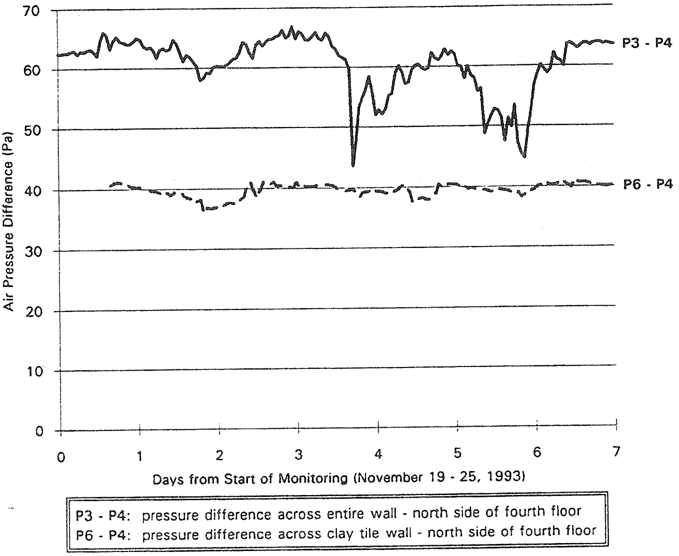

Fig. 5 Fourth Floor Air Pressure Differences

The interior and exterior air temperatures during June 1993 and January 1994 are shown in Figs. 6 and 7. As seen, the interior air temperature is relatively stable at about 21 °C (70°F). The temperature profiles through the masonry walls for extreme summer and winter conditions are shown in Fig. 8. The data review showed that the exterior face of the sandstone masonry experienced about 83

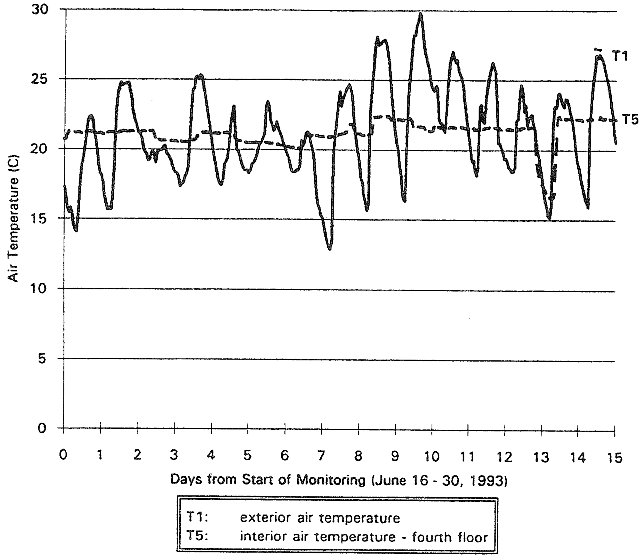

Fig. 6 Air Temperatures During June

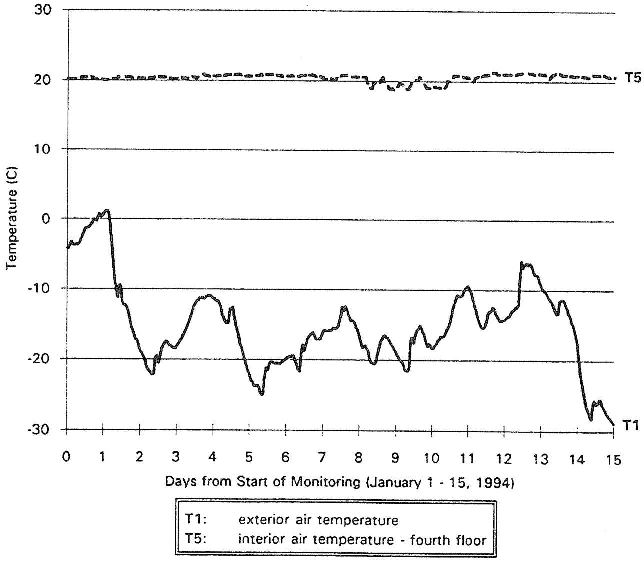

Fig. 7 Air Temperatures During January

freeze/thaw cycles during the winter of 1993/94. Weather data indicates that there are typically about 80 freeze/thaw cycles to be expected in this region during the winter. Therefore, the number of freeze/thaw cycles during 1993/94 was normal, even though the winter of 1993/94 was extremely cold, with long periods of low temperatures. In contrast to the exterior face of the wall, the interior face of the sandstone masonry went through only two freeze/thaw cycles, since it was frozen from December 1993 until March 1994.

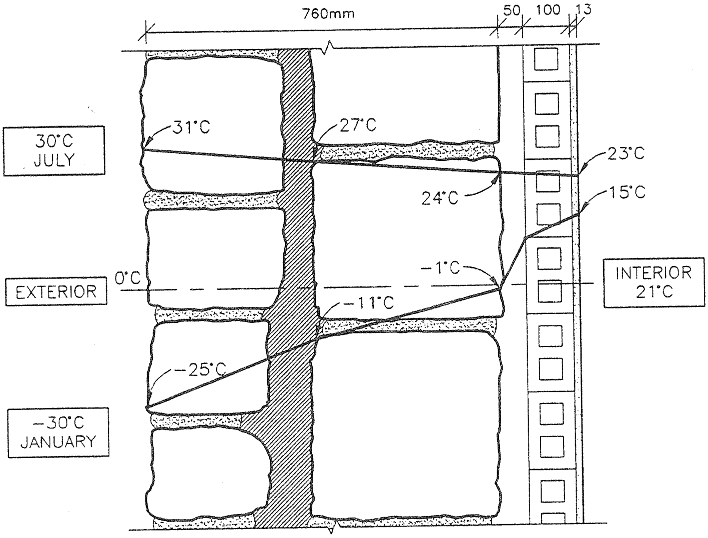

Fig. 8 **Temperature Profile Through Masonry Wall Under Extreme Summer and Winter Conditions**

The temperature profiles through the masonry wall and the dew point temperature for April 1993 and January 1994 are shown for the north side in Figs. 9 and 10, respectively. During spring weather, (Fig. 9), the dew point initially was in the limestone and then it moved into the sandstone. There were several temperature spikes which caused the dew point to move outside the masonry wall for short periods of time. As seen in Fig. 10, the stone masonry wall was frozen through its entire thickness most of the time in January; T18 was at or below 0°C (32°F). The dew point of the cavity air was located at the interior face of the limestone; T18 and DPT4 were at approximately the same temperature. Overall, the incidence of condensation within the masonry walls is as follows:

North Side:

- condensation occurs in the limestone at air temperatures below about 5°C (41°F)
- condensation occurs in the sandstone at air temperatures between about 5°C and 15°C (41°F and 59°F)
- no condensation occurs in the wall at air temperatures above about 15°C (59°F)

South Side:

- condensation occurs in the limestone at air temperatures below about -5°C (23°C)
- condensation occurs in the sandstone at air temperatures between about -5°C and 5°C (23°F and 41°F)
- no condensation occurs in the wall at air temperatures above about 5°C (41°F)

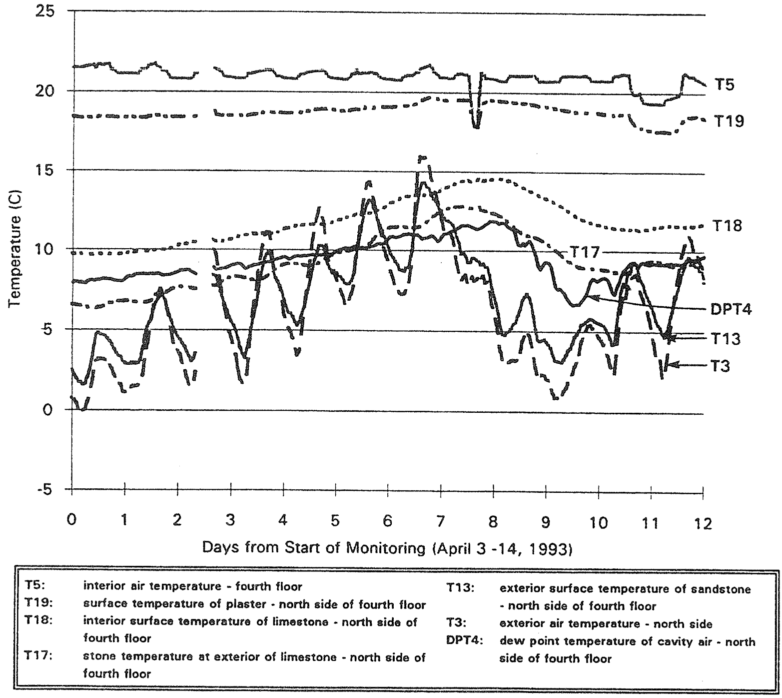

Fig. 9 Temperature Profile Through Stone Masonry Wall in April, North Side

Condensation occurs at higher temperatures on the north side than the south side because there is more moisture in the north cavity than the south cavity. The condition of the air in the cavities was monitored to determine more clearly the source of the cavity moisture. The measurements indicated that the moisture content in the north cavity air is often higher than the moisture content of the interior air or of the supply air. Accordingly, a key source of the moisture in the north cavity is the moist sandstone, air exfiltration contributes moisture to both the north and south cavities.

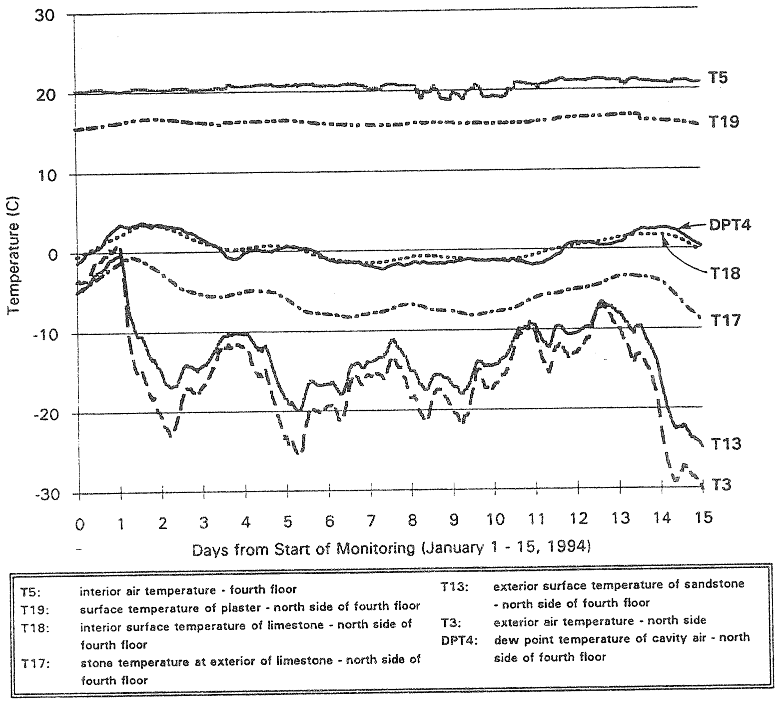

Fig. 10 Temperature Profile Through Stone Masonry Wall in January, North Side

To determine the wetness in the stone masonry walls across the thickness of the wall, electrical resistance moisture sensors were installed. The sensors consisted of two pins, about 50 mm (2 in.) apart, on the end of lead wires with a 50 kΩ resistor in parallel between the pins. The sensors read 49 kΩ if the masonry was dry with lower readings indicating the presence of moisture. Laboratory tests on small stone samples indicate the following relationship between resistance and wetness.

49 kΩ indicates "dry"
45 kΩ indicates "damp"
35 kΩ indicates "wet"
20 kΩ indicates "very wet"

Fig. 11 illustrates the moisture in the masonry wall on the south side during December 1993. It is interesting to see that the interior face of the limestone remains dry during this measuring period whereas the exterior sandstone face is often "wet" and the band course is generally "damp". On two days, when rain hit the wall, the band course gets "very wet". After the second rainfall (on Day 10), a drop in temperature then caused the moisture to freeze in the sandstone which resulted in a false reading of "damp" or "dry".

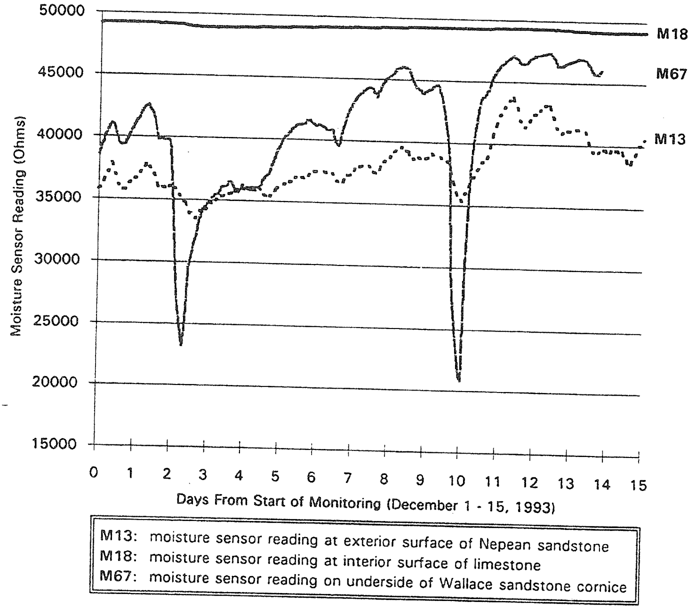

Fig. 11 **Moisture Conditions in Stone Masonry Wall during Winter Weather, South Side**

The key findings of the moisture measurements in the stone masonry are:

- Throughout the year, the north side masonry wall was wetter than the south wall. This indicates that the north wall does not dry out as readily as the south wall due to the absence of direct sun light.

- Precipitation is the main source of moisture in the stone masonry walls. Fluctuations in the moisture readings can be directly attributed to weather conditions. Increased wetting occurs only during precipitation against the walls.
- Exfiltration of moist interior air is a minor contributing factor to the moisture in the stone masonry walls.
- The band courses experience much more severe wetting than the main walls.

CONCLUSIONS

The information gathered during this monitoring program led to the following conclusions:

- The primary source of moisture in the stone masonry walls is precipitation.
- Protruding sandstone elements, such as band courses and buttresses, are experiencing much more severe wetting during rainy weather than the vertical wall elements.
- The air barrier is not air tight and exfiltration of moist interior air contributes in a minor degree to the wetting of the stone masonry walls.
- During the winter months, the face of the sandstone masonry is typically exposed to approximately 80 freeze/thaw cycles.
- During much of the coldest period (December to March), the entire stone masonry wall section is frozen.
- The mechanical systems are inadequate to properly compensate for rapid changes in weather conditions.

The monitoring program confirmed the previous assessment, based on visual documentation, that the primary cause of sandstone deterioration is due to weathering and not due to air exfiltration.

RECOMMENDATIONS

The stone masonry restoration program will include the replacement and repair of cracked and spalled stones and the complete tuck pointing of the mortar joints.

To reduce the potential for future deterioration of the exterior sandstone masonry, all band courses and buttresses will be covered with lead-coated copper flashings.

Additional recommendations, to be implemented in conjunction with interior renovations at some later date, include the replacement of the mechanical systems to ensure more stable and lower humidity levels inside the museum. It was also recommended that the walls not be insulated as this would subject the entire wall section to more freeze/thaw cycles each winter.