Masonry Rehabilitation

by Stéphane P. Hoffman
Department of Civil Engineering
and Applied Mechanics
Faculty of Engineering
McGill University, Montreal
February, 1994

A Thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfilment of the
requirements of the degree of
Master of Engineering

Abstract

This thesis is divided into two parts: a brief summary of current knowledge in the area of masonry rehabilitation and a report of an ongoing case study on the effects of insulating a heritage masonry building.

Although information relevant to masonry rehabilitation is abundant, it is spread throughout numerous texts and technical publications. The first part of this thesis attempts to summarize current knowledge in the area of masonry rehabilitation. Subjects that are covered include: the agencies of masonry deterioration, the treatment of moisture problems, mortar repairs; the repair and replacement of damaged units and, finally, the cleaning of masonry.

The second part of this thesis presents the background information on the Customs Examining Warehouse, a description of the renovation and a summary of the analysis of the effects of insulating the building. The method for monitoring the effects of the insulation is explained with particular attention to the various sensors and the instruments used in data gathering and the computer programs created to process this data. This information should be a useful guide for processing the data gathered from sensors and other instrumentation installed in the Winnipeg Customs Examining Warehouse.

Abstrait

Cette thèse est divisée en deux parties: un bref sommaire des techniques de réhabilitation de la maçonnerie et un rapport sur les effets d'isoler un bâtiment historique en maçonnerie.

Il existe plusieurs sources d'information sur la réhabilitation de la maçonnerie; cependant, cette information est dispersée à travers divers textes et rapports techniques. La première partie de cette thèse consiste donc d' un bref sommaire des techniques de réhabilitation de la maçonnerie. Ce sommaire inclut les agences de détérioration de la maçonnerie, le traitement des problèmes d' humidité, la réparation du mortier, la réparation et le remplacement des éléments de maçonnerie et le nettoyage de la maçonnerie.

La seconde partie de cette thèse consiste d'un bref historique et d' une description du Winnipeg Customs Examining Warehouse, suivi par un sommaire des rénovations et de l'analyse des effets d'isoler ce bâtiment. Le procès utilisé pour la collection des données sur les effets de l' isolation est expliqué en détail avec emphase sur l' instrumentation et les programmes d' ordinateur pour l' analyse des données. Cette information sera utile pour le traitements des données en provenance du Winnipeg Customs Examining Warehouse.

Acknowledgement

The author would like to take this opportunity to thank Dr. Saeed Mirza, Professor at McGill University, for his encouragement and support. Special thanks to Dr. Paul Maurenbrecher, Senior Research Officer at the Institute for Research in Construction, for the insight and guidance provided on this project, as well as, Jeff Marans for his advice concerning the operation of the datalogger and Charles Kingsley for his input on the EXCEL macros.

Parts of this thesis has been adapted from various texts on the subject of masonry deterioration and rehabilitation. The relevant texts for each section are listed at the start of every chapter. Contribution of the various authors are gratefully acknowledged.

Table of Contents

Chapter 1

Introduction

Masonry construction consists of individual units laid side by side and bonded together with mortar. Man has been building significant masonry structures for about ten millennia. It is one of the oldest building techniques and has been proven to last for centuries if carefully constructed. Although the earliest masonry structures were simple walls of rubble carefully stacked several meters thick, the art of masonry evolved quickly. By about five thousand years ago man had mastered sun dried clay brick construction and attained a surprising degree of sophistication in megalithic construction. The classical Greek period and the roman empire are renowned for masonry structures of great beauty and utility such as temples, palaces, aqueducts and bridges. Two thousand years ago, the romans had a knowledge of concrete and mortars which surpassed in strength and durability anything that was produced subsequently until the eighteenth century. Although for several centuries there was a general decline in the quality of mortar, masonry continued to be used as the principal construction material and there are many superb examples of cathedrals, castles and bridges throughout the middle ages and the renaissance

Although examples of massive arched or vaulted masonry structures in the European tradition are rare in North America, masonry construction was still the building system of choice for commercial, institutional and industrial structures throughout most of the nineteenth century. Masonry was more commonly limited to the exterior walls of buildings, either as load bearing walls or as cladding. Before the advent of steel frames, many important commercial, institutional and industrial buildings were of solid masonry construction. These bearing-wall structures had solid masonry exterior walls with an internal frame of heavy timber beams and joists. The walls supported the framing of the floors and the roof. The thickness of the masonry walls varied according to the weight they carried and the height of the building. Walls 900 to 1200 mm (3 to 4 ft) thick at the base were not uncommon for multi-story buildings. The walls were gradually tapered towards the top with a series of set backs at each floor level on the interior face. The floor beams would then rest on the narrow ledges created by these setbacks. The wythes of solid brick walls were typically interconnected with rows of headers every sixth or seventh course.

The development of structural steel and reinforced concrete about one hundred years ago led to a general decline in the use of masonry. Steel and reinforced concrete being able to resist both tension and compression were seen as being more versatile and led to lighter and taller structures than was possible with masonry which could only resist compression and which required on its mass for stability. The use of masonry declined and for many years was relegated to the role of infill walls and veneers. By the late nineteenth century, steel frames were commonly used for multi-story buildings. Thick masonry bearing walls were gradually replaced with relatively thin, non-bearing curtain walls about 300 mm (1 ft) thick, supported at each floor level. The masonry walls were simple finishes over the frame rather than part of the structural system. This freed up additional floor space and allowed for more spacious windows. The brick walls often enclosed the steel frame for the purpose of fire protection. The late nineteenth century also saw the introduction of the more economical masonry cavity walls with light wood framing. The cavity walls consisted of two wythes of masonry separated by an air space. The interior layer was typically load bearing while the exterior one was simply cladding. The two layers of masonry were bonded together with headers or metal ties.

Because of their durability, many of these masonry structures have survived to present times and have become a part of our built heritage. The built environment is an essential part of the achievements of the society that constructed it. An individual building may be important for what it embodies of its builders or for what it represents of those builders. The way it looks, the irreplaceable craftsmanship of its construction, the skill evident in its component parts and their combination on a distinctive piece of ground are visual and tactile evidence of a specific era, now gone forever. The building is also associated to people and events in the past, to individual or shared memories. History is less tangible, yet more powerful: reverence for history has a longer and broader tradition than appreciation of architecture and is more easily communicated. Some remarkably ugly and graceless buildings are nevertheless cherished by their communities.

Unfortunately, buildings do not last unless maintained against the relentless forces of age, weather and decay. Since few buildings receive proper maintenance, many of our masonry buildings have suffered from the ravages of time and will eventually require some kind of repairs or rehabilitation. Although masonry has emerged once again as a viable structural material, universities have not kept pace with these developments and masonry has not received the attention it merits in structural design courses. Most modern engineers have not received much, if any, formal education regarding the properties, behavior and design principles for masonry. As a consequence there is a need for more information on masonry rehabilitation. Many fine old buildings have lost their special look and feel, and much of their heritage value, in being modernized for new extended use. The long-term success of masonry rehabilitation will depend on the quality of the work, on proper care of the old and proper fit of the new.

The advice in this thesis is intended to be helpful in suggesting a right treatment. If the reader learns from the following pages that the difficulties are greater and the alternative methods more in number than he had thought, he may come to realize what an infinity of care must be exercised in arranging for and carrying out masonry rehabilitation.

The information presented in the following sections has been adapted from the works of (Glainville and Hatzinikolas, 1989), (Fram, 1988), (London, 1988), (Ward, 1986), and (City of Ottawa, 1989).

1.1 Rehabilitation versus Restoration

Different approaches to masonry repairs are taken depending on the overall objectives of the project. It is therefore important to understand the difference between rehabilitation and restoration.

Rehabilitation is the process of returning a property to a state of utility, through repairs or alteration, which makes possible an efficient contemporary use while preserving those portions and features of the structure which are significant to its architectural, historical and cultural values. This assumes that at least some repairs or alteration of the building must take place to provide for an efficient contemporary use; however, these repairs and alteration should attempt to minimize damage or destruction of the materials and features that are important in defining the building character.

Restoration is defined as the accurate recovery of the form and details of a structure and its setting as it appeared at a particular period of time by means of the removal of later work or by the replacement of missing earlier work. This implies that the only changes to be made would be those that return the structure to its original appearance.

If a building is properly maintained in good condition, major repairs may never become necessary, although small repairs are a part of regular maintenance. Regular inspection and immediate correction of small defects will usually forestall costly major repairs and replacement. It is often possible to patch, splice, consolidate or otherwise reinforce or rebuild damaged elements. If this is not enough, replacement of portions of extensively deteriorated or missing parts or features by carefully matching surviving parts may be necessary. Although using the original materials is preferred, substitute materials may sometimes be acceptable if the original appearance is matched. Elements should not be removed in an attempt to create a modern appearance or to avoid maintenance costs.

1.2 Characteristics of Heritage Buildings

Although it is vital to preserve our built heritage, not all buildings can be saved. It is therefore important to understand which building characteristics have heritage value. There is a wide assortment of building characteristics associated with heritage value, but they can be divided into three categories related to historic, environmental, and architectural values. The following is a description of these three categories and the associated building characteristics. This description is adapted from (City of Ottawa, 1989) which is itself based upon the internationally recognized Parks Canada system for the evaluation of historic buildings (Kalman, 1979).

1.2.1 Historical Value

In the context of evaluating individual heritage buildings or buildings in a potential heritage conservation district, history refers to broad economic, social, political and cultural characteristic of a city's history that are reflected or associated with the building and/or its neighborhood. The historical heritage value of buildings is based on four characteristics: the age of the building, the fashion in which the building reflects historical trends and the building's association to historical events and/or figures.

1.2.1.1 Date of Construction

The date of construction of a building is usually very specific and, as such, is a good indicator of its potential historic significance. This characteristic ensures that a building's age is given some consideration in determining its historic significance. It is also ensures that older structures, which cannot be linked to a specific trend, or cannot be associated with an event or person, are not completely overlooked with respect to historical significance. The importance attached to a building's date of construction will vary from one neighborhood to another. In a city's older districts, late nineteenth century buildings would have more value than the buildings constructed in the mid to late twentieth century. However, in a post war suburban division, a 1940's building would be more indicative of the subdivision's history. Similarly, hundred year old buildings might be common in a province like Quebec, but in the western provinces they would be a rare occurrence and as such have more historical heritage value.

1.2.1.2 Trends

A building's association with historical trends is the most important of the four historical criteria. Over and above their association with people or events, buildings visually represent the historic trends on a local, regional or national level. Buildings can reflect a particular social, economic, political or cultural pattern characteristic of a city's history and/or the history of a potential heritage district. Historical trends are often a driving influence in the decision to erect a specific building and the choice of its location. Therefore, a building which can be linked to a specific and important trend associated with a city's or neighborhood's history, or one considered to be the only remaining building related to such a trend, would have historical heritage value.

1.2.1.3 Events

A building may also have historical heritage value if it can be directly linked to an event of local, regional or national importance. This characteristic is generally applicable only to a limited number of buildings. However, the historical importance of a building that is associated with a noteworthy historical event cannot be overlooked in evaluating its heritage value. In evaluating this characteristic, it is important to make a distinction between one time human interest events, and events which have long lasting consequence. Ideally, the building should be associated with a single event, possibly related to the building's function, which has had significant long term consequences socially, culturally, politically or economically for the city, region or nation.

1.2.1.4 Persons

A building's association with a notable person, group, institution, or corporation can increase its heritage value. The building should be directly linked to a person or entity of significant local, regional or national prominence. As with the previous criterion, this characteristic is generally applicable only to a limited number of buildings. Nonetheless, the historical significance of a building's past residents is an integral part of its heritage value. Therefore, historical heritage value would be attributed to a building with strong ties to a person or entity who was important in the history of the city, region or country. Typically, these buildings would have been the residence of a prominent person or the headquarters of an important institution.

1.2.2 Environmental Value

The environmental value of heritage buildings is based on three characteristics: how well a building fits in with its surroundings, how prominent the building is as a heritage landmark in its environment, and whether the building has an historical association with its surroundings by being a significant component of the community life. Since it is the visual relationship of buildings in an area that contributes to the identity of a potential heritage district, these considerations are particularly important in evaluating the heritage potential of buildings in identified heritage districts, besides evaluating how newer buildings fit into the heritage environment of these districts. The setting and surrounding landscape features should also be evaluated as a part of this process

For buildings not located in a heritage district, their environmental value is considerably less important. However, this is not to say that such buildings are without environmental value. These buildings may be landmarks or may have strong historical and symbolic associations with the community. Consequently, consideration of environmental value is still necessary, although it is not as important as the historical and architectural categories in determining their potential heritage value.

1.2.2.1 Design Compatibility

Design compatibility evaluates buildings relative to neighboring structures and their surroundings. The basis for evaluation is determined by the prevailing mass, scale, color, details, landscape and setting associated with a group of buildings. Thus, a building that, in conjunction with surrounding landscape features and adjacent buildings, forms a highly distinctive and compatible urban grouping would have environmental heritage value. In cases where there is a concentration of compatible new buildings that overwhelm a few remaining heritage buildings, evaluation is according to whether the newer buildings are compatible with the few remaining heritage buildings. This ensures that all buildings are evaluated from a heritage perspective.

1.2.2.2 Landmark

Recognizable landmarks also have environmental heritage value because of their prominence and ability to provide a point of reference. These buildings serve as a visual, historical, cultural or socio-economic reference point for the city or its community. Such buildings should be highly visible or a strong point of reference from several location in the city. On rare occasions, unique and highly visible structures become associated with their city as a distinguishing feature of the skyline.

1.2.2.3 Community Context

Community context deals explicitly with the functional and symbolic role of potential heritage buildings in the life and identity of the community. These building have a strong historical association with their neighborhood, either in public use or in private use with public associations. Historically and/or presently, they are an integral part of community life and for sentimental or symbolic reasons, have become a significant part of the community. As can be surmised, the community context criterion has limited applications, with only a limited number of buildings having such a high value. However, the importance of including this criterion cannot be overlooked since the unique attributes of communities are often related to the public buildings which were important to life in the community. Although these buildings may lack landmark status or design compatibility, they have a distinct environmental value established by their continued association with community life, or by their former association with community life, which makes them symbolically or sentimentally significant to the community identity.

1.2.3 Architectural Value

The evaluation of the potential architectural heritage value of buildings is concerned primarily with their visual aspects and design qualities. This is not limited to only buildings which can be given academic labels as to their particular architectural style, but also includes vernacular buildings, which represent the common building style of a city or a particular neighborhood. The architectural heritage value of buildings is based on the following characteristics: how well the building reflects a particular architectural style, how significant is the building design, the extent to which the building has been altered, and the prominence of the designer and/or the builder.

1.2.3.1 Style

Style refers to the shared characteristics of buildings from a given era that is associated with a distinct and recognizable appearance. The basic characteristics of a building include profile, massing, dimensioning of elements, detailing, and preference for certain materials and colors. The building evaluation is based on comparison with other buildings of similar style. To have architectural heritage value, the building should be a notable, unusual or early example of a particular architectural style, type or convention. If many buildings of the same style survive, the building should be an excellent or very early example. In most North American cities, absolute purity or conformity to a particular architectural style is rare. Rather, many notable heritage buildings contain elements of different styles, or they are considered to be characteristic of a local place or period. To account for the prominence of vernacular architecture, the evaluation is based on comparison with buildings of similar characteristics.

1.2.3.2 Design

Design considers the composition, craftsmanship and architectural details irrespective of style. Building may have significant architectural heritage value because of the excellence, artistic merit or uniqueness of their design, composition, craftsmanship or details. Unusual or notable proportions, decorations, color, texture, and workmanship are prime considerations for evaluating design. Unique, innovative or early example of structural systems or construction techniques also deserve attention. A building that is particularly significant to its neighborhood as a result of the excellence of its design, would have architectural value. Such a building should have historical associations with the neighborhood and be generally intact. Exterior alterations can have an impact on the original design qualities of buildings, however, integrity should be considered only if the alterations have compromised the original character of the building. Minor negative alterations such as aluminum storm doors, or other alterations which have enhanced the building, should not considered in evaluating its design.

1.2.3.3 Integrity

In evaluating the architectural heritage value of a building, it is important to consider its architectural integrity. This evaluation should be independent of its style or design value. A building of notable style or excellent design may have been altered over the years in such a manner as to compromise its architectural heritage value. A building of lesser architectural merits may have heritage value if it has been carefully preserved. Therefore, the important stylistic elements of the building should be intact, without alterations or additions of an insensitive or irreparable nature. However, relatively newer buildings should not be assessed as having architectural heritage value simply on the basis of their high architectural integrity. To have architectural heritage value on the basis of architectural integrity, a building should bet very close to its original form in terms of its major elements and be readily capable of being restored.

1.2.3.4 Designer / Builder

Finally, a building may have architectural heritage value if it was designed by an architect, engineer or other design professional, or was constructed by a builder whose work is of local, regional or national importance. This characteristic is generally applicable only to a limited number of buildings. However, the contributions of prominent or innovative design professionals to our architectural heritage must not be overlooked. Well known designs of established architects have importance beyond their style or design value that merits consideration in the evaluation of their architectural heritage value

1.3 Canadian Heritage Legislation

In Canada, the subject of heritage conservation and the relevant legislation falls within the jurisdiction of both the Federal and Provincial governments. However, as outlined in the Canadian Constitution, all matters pertaining primarily to property and civil rights are under exclusive provincial jurisdiction. Therefore, the primary responsibility for heritage protection belongs principally to the provinces. Provincial Governments in turn delegate some of their powers to the governments of municipalities and regional communities. The result is a sometimes confusing mixture of provincial and municipal laws that change from province to province and municipality to municipality.

This report, adapted principally from (Ward, 1986), will examine the existing legislation at each of the three levels of government: federal, provincial and municipal. The following sections will review the Federal Government's heritage legislation and the regulations concerning federally owned heritage structures. Typical provincial heritage legislation and different systems for heritage conservation currently found in Canada are also examined. The last section will describe the various legal means by which municipal governments can protect heritage structures within their boundaries.

1.3.1 Federal Level

In general, the Federal Government is under no legal obligation to protect its heritage structures, because federal property is exempt from provincial and municipal legislation. The Federal Government's heritage legislation is outlined in the Historic Sites and Monuments Act of 1953, which allows the Federal Government to designate National Historic Sites throughout Canada. However, the Federal Government does not have the legal authority to prevent the alteration or demolition of designated sites. Therefore, their designation has no legal effect. The Federal government can do very little to preserve national historic sites unless they purchase them. Over one hundred historic sites have been acquired by the government and are being scrupulously restored by Parks Canada.

Under the Historic Sites and Monuments Act, structures deemed worthy of heritage designation are referred to an advisory body called the Historic Sites and Monuments Board of Canada. The Board consists of seventeen members: the Dominion Archivist, an officer of the National Museums, an officer of Environment Canada and representatives of the provinces and territories. Ontario and Quebec each have two representatives and the other provinces and the two territories have one each. The Board advises the Minister of the Environment on matters of national historic and architectural significance. After a period of study the Board may recommend that a structure be designated as a national historic site. At such time a plaque is erected identifying the site as a National Historic Site. The Board can also recommend that the government purchase the structure or enter a cost sharing agreement for its restoration and conservation. In any event, the government is not bound by the Board recommendations.

In 1970, the Canadian Inventory of Historic Buildings was established as a tool for the Board. The Canadian Inventory of Historic Buildings is a list of federal, provincial and municipal heritage buildings, as designated by these authorities. This Inventory also contains additional information concerning the heritage status and ownership of federally owned buildings, however, it is simply a listing service and does not include any evaluation of the heritage value of the buildings nor does it provide any kind of protection from alteration or demolition.

The Federal Government has also established an interdepartmental body known as the Heritage Buildings Conservation Committee. Established in 1976, the Committee is responsible for preventing or minimizing damage to heritage property caused by public works project. The Committee oversees the interaction between the various federal departments and agencies which directly or indirectly affect cultural property. It reviews proposed federal projects to evaluate their impact on heritage structures and suggests alternatives designed to preserve them.

1.3.1.1 Federal Policy on Heritage Buildings

More recently, the Federal Government adopted the Policy on Federal Heritage Buildings, which states that federal property will be managed to provide for and encourage the conservation of heritage buildings. Furthermore, the Government of Canada will encourage continuity of use and function for federally owned heritage buildings. The degree of protection afforded to federal heritage buildings is commensurate with their architectural and design integrity, their landmark status and urban setting, and their historic importance. The policy also states that the Government of Canada will explore all reasonable alternatives when the heritage character of a building is jeopardized.

The implementation of the Policy on Federal Heritage Buildings is the responsibility of Parks Canada. In 1982, an advisory body, the Federal Heritage Building Review Office was created with the mandate to evaluate the heritage potential of federal buildings and to review any alterations to designated federal heritage buildings proposed by their owner. All federal departments must submit their potential heritage buildings for evaluation by the Review Office. The Review Office evaluates the buildings and defines their heritage character. It may designate the building as Classified or Recognized. A Classified Building is a federal building of the highest heritage significance which the department is directed to protect. A Recognized Building is a federal building with the second highest heritage significance which the department is encouraged to protect. The departments are required to maintain designated buildings so that their heritage character is not endangered. Departments planning repair, renovation, or demolition of a federal heritage building must first seek the advice of the Review Office, which will assess the nature and extent of the intervention and will give specific directions or offer expert advice to ensure the protection of the heritage character of the building. Departments proposing to acquire or dispose of a building with an age of 40 years or more must consult the Review Office.

1.3.2 The Provincial Level

Under the Canadian Constitution, the Provinces have exclusive jurisdiction over all the land that falls within their boundaries. The Provinces are therefore responsible for all legislation concerning the development and use of the land within their jurisdiction, and includes the power to enact heritage legislation.

The Provincial Governments each have their own legislation concerning heritage conservation. Therefore the laws and procedures for protecting heritage buildings vary from province to province. Table 1.1 lists the relevant heritage statutes for each province. The provincial heritage statutes authorize the provincial governments to designate heritage sites, and to prohibit any alterations or demolition on these sites without formal approval from the appropriate ministry. Most provinces have established historical boards for advice on matters relating to heritage conservation. Only Quebec and Alberta require the government to consult with these boards in all matter concerning heritage conservation. In any event, the government is not bound by the board recommendations.

The power to designate heritage structures is typically reserved for provincial authorities. In such a system, only the province can protect heritage structures. The municipal governments cannot designate structures under the provincial heritage statutes. However, they can refer structures considered worthy of designation to the provincial government for evaluation.

Under some provincial heritage statutes, protection can be granted by either the province or the municipality. The provincial government and the local municipal councils both have the power to designate a structure under the relevant heritage statute. Municipal designation may be subject to provincial approval and sometimes offer less protection than provincial designation.

Table 1.1 Provincial heritage statutes

Province	**Statutes**
Alberta	Historical Resources Act
British Columbia	Heritage Conservation Act
Manitoba	Heritage Sites and Objects Act
New Brunswick	Historic Sites Protection Act
Newfoundland	Historic Objects, Sites and Records Act
Nova Scotia	Heritage Property Act
Ontario	Heritage Act
Prince Edward Island	Recreation Development Act
Quebec	Cultural Properties Act
Saskatchewan	Heritage Property Act

All ten provinces and two territories have either a one or two tiered system. The only exception is Ontario, where the province protects only archeological sites, and only the municipal governments can protect historic sites. Ontario is therefore the only province without a provincial mechanism to protect historical sites.

In addition to these heritage statutes, the various Provincial Planning Acts and Environmental Assessment Acts may also contain legislation that can be applied for Heritage Conservation. Planning Acts deal with the development and use of land and may provide legislation concerning the designation of specific areas for special use. This legislation may be adapted to create heritage areas or districts. The Planning Act may also contain regulation pertaining to the demolition of structures which can be used to prevent or delay the demolition of heritage structures. Environmental assessment acts are designed to

Table 1.2 Summary of Provincial Heritage Legislation July 1985 (Ward, 1986)

Province	**NF**	**PEI**	**NS**	**NB**	**QC**	**ON**	**MN**	**SK**	**AL**	**BC**
Are clear criteria given for the definition of Heritage Property?	No	No	No	No	No	No	No	Yes	No	No
Must notice be given of impending demolition of unregistered Heritage Property?	No	No	No	No	No	No	No	No	No	No
Is Government under any obligation to protect Heritage Property?	No	No	No	No	No	1	No	1	1	1
Can demolition of an unclassified building be delayed pending study?	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Can definitive protection againstdemolition to a building?	Yes	Yes	Yes	Yes	Yes	1	Yes	Yes	Yes	Yes
Is area around building protected?	No	No	No	No	Yes	No	No	No	No	No
Can government decissions ondesignation be appealed to higherauthority under statute?	No	No	No	No	No	No	No	No	No	No
Is the definitive preservation of districts specially forseen?	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Can maintenace of Heritage Properties be enforced?	No	Yes	No	No	Yes	No	Yes	Yes	Yes	No
Can Heritage Properties be inspected?	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Does government have right of first refusal on the sale of Heritage Property?	No	No	No	No	Yes	No	No	Yes	Yes	No
Can Heritage Properties be exempted from building codes?	No	No	No	No	No	No	No	No	Yes	Yes
Can illigeally altered Heritage Properties be restored at owner's expense?	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes

Note 1 Archeological Sites Only

protect the environment by requiring the preparation of an environmental assessment of a proposed project. These environmental assessments typically require a study of the impact of a proposed project on the existing environment. Depending of the Act definition of environment, the assessment can be extended to include historical sites.

The following sections describe the heritage legislation of three provinces chosen to illustrate the three provincial heritage conservation systems found in Canada. Manitoba is an example of the one tiered system where only the provincial government can designate heritage structures. Quebec is an example of the two tiered system where both the provincial government and the local municipalities can designate heritage structures. Finally, Ontario has a unique system where only the municipalities can designate heritage structures.

1.3.2.1 Manitoba Provincial Legislation

Heritage legislation for the province of Manitoba is outlined in the Historic Sites and Objects Act of 1970. This Act, administered by the Department of Culture, Heritage and Recreation, empowers the government to designate any land or structure an historic site. Under the Act any site, parcel of land, building or structure can be declared a historic site, irrespective of its size. The Act further states that no person shall damage, destroy, remove, improve or alter an historic site without a valid permit and only to the extent authorized by such a permit. The government is thus authorized to accept or reject any proposed construction, alteration or demolition on designated historic sites.

Potential heritage buildings are brought to the attention of the Historic Resources Branch which examines the building and prepares a report for the Historic Site Advisory Board. This Board, in turn, advises the government regarding structures worthy of protection. If the structure has heritage potential the Board may recommend that it be designated as a provincial historic site and protected under the Historic Sites and Objects Act. Alternatively, it may recommend that the structure be identified with an historic site marker but not be protected under the Act.

In addition to this, the Planning Act of 1975 allows the government to declare special planning areas for the preservation of historic structures and sites. This prevents any form of development not sanctioned by the provincial government in consultation with the municipality.

1.3.2.2 Quebec Provincial Legislation

In Quebec, Heritage property is protected by the Cultural Property Act which is administered by the Department of Cultural Affairs. Under this Act the Minister can designate property for protection against alteration, demolition and unsympathetic construction. The Minister is legally required to consult with the twelve member cultural Property Commission prior to designating a building. If the structure has heritage value, the Commission will advise the Minister to designate the building as a recognized or classified structure. The building is protected as soon as the Minister advises the owner of its intention to classify the building. The Act also empowers the Minister of Cultural Affairs, in consultation with the Cultural Property Commission, to acquire by agreement or expropriation recognized or classified property. The Ministry is responsible for maintaining a register of all recognized and classified structures. Once a year a list of newly recognized or classified structures is printed in the Gazette Officielle Du Québec.

Any structure designated as recognized by the Minister of Cultural Affairs cannot be altered, restored, repaired or demolished without giving the Minister and the Municipal Clerk or Secretary Treasurer sixty days notice. If there are no objections at the end of this period, the owner may proceed with the proposed changes. The owner must also give the Minster sixty days notice prior to selling the building. If the building is fifty years or older, the Minister can purchase the structure for the asking price providing he makes his intentions known during the sixty day delay period.

Structures designated as classified by the Minister of Cultural Affairs cannot be altered, restored, repaired or demolished without the authorization of the Minister in consultation with the Cultural Property Commission. The Minister can withhold his authorization indefinitely. Furthermore the owner of a classified structure is responsible for appropriate maintenance of the classified structures, which cannot be sold without Ministerial approval which may be withheld indefinitely. If the structure is offered for sale, the Ministry has the right of purchase regardless of the age of the structure. The Cultural Property Act extends automatic protection to the land and buildings within a 152 meter (500 ft) radius of a classified structure. Within this area one cannot subdivide the land, change the use of the land, modify the landscape, or alter the exterior appearance of the buildings without the authorization of the Minister in consultation with the Cultural Property Commission. The Minister is empowered to grant a reduction of up to 50% of municipal taxes on any classified structures of a non-commercial nature.

The Cultural Properties Act also allows the Minister in consultation with the Cultural Property Commission to recommend the establishment of an historical district to a committee of ministers. In a historic district, the land cannot be divided subdivided, parceled out without the approval from the Ministry. Likewise, alteration to the arrangement, ground plan or utilization of a structure as well as any construction, alteration or demolition requires the authorization of the Minister in consultation with the Cultural Property Commission. In addition, signs or billboards shall not be posted, altered or demolished without prior authorization from the Ministry. Buildings within an historical district are not subject to the same restrictions a single classified structures. The Minister cannot comment on or stop the sale of such buildings. The 152 meter radius protection zone does not apply, and there is no reduction in the municipal taxes for heritage district, buildings. Within the district some buildings may not be recognized or classified. Nonetheless, the Minister can declare a group of buildings or the entire district as protected.

Historical structures can also be protected using Environmental Impact Assessment procedures which require inventory and investigation before government financed programs can proceed. Under the Environment Quality Act of 1972, a project initiator must submit an Environmental Impact Assessment statement to the Department of the Environment for technical review. This report may be required to include the impact on the cultural, archeological and historical heritage. The report is submitted to the Department of the Environment for evaluation. The Department of Cultural Affairs reviews the report and submits its comments to the Department of the Environment. The Bureau d' Audiences Publiques sur l' Environment then informs the public about the project and, after a public hearing, its findings are reported to the Minister. Finally, the Minister sends the impact statement and the request for the authorization certificate, along with any other documents considered appropriate, to the government or a Cabinet committee for the final decision.

In addition, under the Land Use Planning and Development Act of 1979, the Minister of Municipal Affairs may act on the behalf of a regional county, municipality, or a local municipality that fails to take action within the specified period or before the deadline established by the Act. The Minister can impose a development plan on these municipalities and henceforth, municipal by-laws would need to conform to that plan.

1.3.2.3 Ontario Provincial Legislation

The current statute for Heritage Conservation in Ontario is the Heritage Act of 1974, which is administered by the Minister of Citizenship and Culture in consultation with the Ontario Heritage Foundation. Under this Act, the responsibility for preserving heritage is the sole responsibility of the municipalities. It should be noted that historic sites outside the municipal boundaries are not protected by the Heritage Act. The only structures eligible for provincial protection are ruins, burial mounds, petroglyphs and earthworks. Ontario is therefore, the only province without a provincial mechanism to protect historical sites. Prior to the enactment of the Heritage Act, the province had the power to designate historical sites under the Archeological and Historic Sites Act of 1970. Such sites could not be altered or excavated without ministerial approval.

The Ontario Heritage Foundation was established under Part II of the Ontario Heritage Act. Its Board of Governors consist of not fewer than twenty one private citizens. Apart from advising the Minister of Citizenship and Culture on matters relating to provincial heritage, the Foundation supports, encourages and facilitates the conservation, protection and preservation of provincial heritage by conducting research, educational and communications programs. The Foundation is involved in the preservation, maintenance, reconstruction, restoration and management of property of historical, architectural, archeological, recreational, aesthetic and scenic interest. The Foundation is legally entitled to receive, acquire and hold property in trust for the people of Ontario. Legally, the Foundation can do very little to preserve heritage structures unless they purchase them.

Provincial heritage planning is generally conducted under the Environmental Assessment Act of 1975, which requires preparation and submission of reports containing an assessment of the environmental impact of proposed development. The Act specifies the factors to be included in the reports. This includes a description of the proposed undertaking, its positive and negative effects on the environment and the means which are available to mitigate the adverse effects. This requirement is important for heritage conservation because the Act definition of environment includes the built environment:

the social, economic and cultural condition that influence life of man or community, as well as any building, structure, machine or other device or thing made by man. The assessment must also include an evaluation of the advantages and disadvantages to the environment of an undertaking, the various methods of carrying out the undertaking and the alternatives to the undertaking. The assessment is scrutinized by the provincial ministries and agencies having a mandated concern with the undertaking or its alternatives. Their comments are incorporated into a government review. The preparation of the review is coordinated by the Environmental Assessment Branch of the Ministry of the Environment. Both the assessment and the review are available for public inspection. Any person may then comment in writing on the environmental assessment, the government review and the project and may also require a public hearing by giving notice in writing to the Minister. The hearing, if called, is held before the Environment Assessment Board. The Board may rule on the adequacy of the assessment and whether the undertaking should proceed. If the assessment is found to be inadequate, or if shortcomings are detected in the proposed undertaking, the Board may decide that the project should not proceed at that time. The Board may also approve the project with or without conditions. The decision of the Board is not immediately binding. There is a twenty eight day delay during which the Minister of the Environment, with the approval of the Cabinet, can vary the decision in whole, or in part or require that a new hearing be held. Thereafter the Board decision becomes legally binding on all parties.

However, Ontario Regulation 293 severely limits the Environmental Assessment Act as far as heritage conservation is concerned. Proclaimed in 1976, Ontario Regulation 293 states that when an undertaking was started prior to 1975, the date of the Act, its retirement is exempt from the relevant provision of the Act. The demolition of a building built prior to 1975 is considered as the retirement of the building and as such is not subject to the procedure set forth in the Act. However, the Cabinet may, upon request, designate a project as being subject to the Environment Assessment Act not withstanding the fact that the project may not, at present, be subject to the Act.

A final recourse for intervention by the provincial government is outlined in the Planning and Development Act of 1973. Under this Act, the Treasurer of Ontario can by a complicated procedure direct the drafting of plans and the enactment of zoning by-laws. Thus if the Treasurer believes strongly that an area should be the object of heritage conservation efforts, he could order a plan accordingly and henceforth, municipal by-laws would need to conform to that plan. The Treasurer can also make Ministerial zoning orders, the equivalent of zoning by-laws on his own initiative. If there is any conflict with a by-law already in effect, the order is to prevail

1.3.3 The Municipal Level

Municipalities derive their powers from provincial legislation that delegates them certain legal authority under the various Planning or Municipal Acts. Thus they can legally protect heritage buildings through local land use legislation and procedures. Some provinces also authorize municipalities to designate historical sites under the relevant provincial statute. More importantly, almost all municipalities can legislate local building use and control bulk, height and set backs of buildings. They can also control most other aspects of building design, alteration and construction with local bylaws. In this manner municipalities can control the design of new structures or alteration of existing buildings in a heritage area. However, the federal and provincial government properties are exempt from municipal legislation.

The following sections describe the municipal heritage legislation of two provinces chosen to illustrate the sometimes dramatic difference in municipal authority with respects to heritage conservation. Ontario has a unique system where only the municipalities can designate heritage structures yet the municipalities have limited powers to protect such

Table 1.3 Summary of Municipal Heritage Legislation (July, 1985) (Ward, 1986)

Province	**NF**	**PEI**	**NS**	**NB**	**QC**	**ON**	**MN**	**SK**	**AL**	**BC**
Is heritage conservation an obligatory part of municipal planning?	No	No	No	No	No	No	Yes	No	No	No
Is municipality obliged to file environmental impact assessment on demolition of heritage?	No	No	No	No	No		No	Yes	Yes	No
Can municipality give permanent protection to buildings?	Yes	No	No	Yes	No	No	Yes	Yes	Yes	Yes
Can municipality regulate:										
bulk and heigth	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Design	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No
Use	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Set-back	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Signs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Can municipality accept or reject applications for construction on heritage sites on a dicretionary basis?	Yes	No	No	Yes	No	Yes	Yes	Yes	No	Yes
Can municipality enforce maintenance										
of dwelling interiors	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
of dwelling exteriors	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
of non-residential interiors	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No
of non-residential exteriors	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No
Can illegally altered buildings be restored at owner's expense?	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes

structures. Quebec is an example of the two tiered system where both the provincial government and the local municipalities can designate heritage structures.

1.3.3.1 Ontario Municipal Legislation

Three statutes empower Ontario municipalities to exercise limited powers over heritage buildings: the Heritage Act, the Planning Act and the Municipal Act. A municipality may pass a by-law designating the property under the Heritage Act. This does not require a change in the official plan. However, it does require consultation with the Local Architectural Conservation Advisory Committee, if one exists. A notice of intent is passed by the local council and served upon the owner. As soon as the notice is given, controls on alteration and demolition come into effect. The owner may appeal to the Conservation Review Board, but the municipal council is not bound by the Board decision. The Board will make recommendations to the municipal council, which then has the discretion to decide whether or not to proceed with the designation.

All alteration to a designated site must be approved by the council which may refuse such permission indefinitely. However, Ontario municipalities cannot refuse demolition permits indefinitely. The municipal council is given ninety days to decide whether it favors demolition. If it decides against demolition, it can refuse to issue a demolition permit for an additional 180 days. At the end of that delay, the building may be demolished.

Municipalities may also designate Heritage Conservation Districts under the Heritage Act. The munipacility's official plan must include general heritage policy statements that indicate the municipal council acceptance of heritage conservation in principle and its commitment to act in order to protect the heritage of the municipality. The municipal council should also pass a by-law establishing a Local Architectural Conservation Advisory Committee if one does not already exist. A heritage district plan must then be prepared and the approval of the Ontario Municipal Board obtained. Once the area has been designated, the owners of all buildings in the heritage preservation district must apply for municipal permission for external alteration, construction or demolition. As is the case for individually designated buildings, permission for alteration can be refused indefinitely, but refusal to permit demolition can not extend beyond 180 days. Owners who are denied an alteration or demolition permit may appeal to the Ontario Municipal

Board whose decision, unlike the Conservation Review Board, will be binding on the municipality.

The Planning Act empowers Ontario municipalities to regulate the use of private and public lands within their boundaries, including preparation of general and area plans and their implementation in municipal legislation, especially zoning by-laws. The Act enables municipalities to negotiate agreements with landowners about the conditions for developing properties in addition to zoning requirements and further enables them to undertake special studies and plans for redevelopment areas. Most of the Act powers are subject to approval by senior levels of government, including regional authorization of site plan and subdivision plan approvals, ministerial approval of official plan documents, and administrative reviews, approvals and appeals before the Ontario Municipal Board.

1.3.3.2 Quebec Municipal Legislation

In Quebec, four statutes define municipal powers: the Cities and Towns Act of 1964, the Municipal Code, the Cultural Properties Act and the Land Use Planning and Development Act of 1979. Cities and towns are governed by the Cities and Towns Act while villages, parishes and townships are covered by the Municipal Code. The Quebec government has also created three regional communities: the Quebec City and Montreal Urban Communities and the Outaouais Regional Community. The municipalities within these communities are governed by the Acts creating these communities.

The Cultural Properties Act allows Quebec municipalities to enact a by-law designating a building a Historic Monument. The municipal council is required to consult with the local Advisory Committee. If such a committee has not been established, the council shall consult with the Planning Advisory Committee established under the Land Use Planning and Development Act.

Under the by-law the owner is responsible for the good maintenance of the structure. He cannot alter, restore, repair or demolish the structure without the authorization of the council in consultation with the Advisory Committee. The owner must comply with all conditions set by the council in consultation with the Advisory Committee. Upon being given notice by the owner, the council has forty days to study the demand and render its decision. If there are no objections at the end of this period, the owner may proceed. Where a municipal permit is required, the application for the permit stands in place of the notice.

Under the Cities and Towns Act and the Municipal Code, any municipality may adopt a by-law prohibiting the demolition, for up to twelve months of any structure that might be a cultural property or that is on land that might be a historic or natural site under the Cultural Properties Act. However, the municipality must send a request to the Minister of Cultural Affairs within fifteen days of adopting such a by-law, in order for the structure to be recognized or classified as a cultural property. Municipalities may not refuse to grant a building permit, unless a notion of motion to amend a land use by-law has been issued. For a period not exceeding two months after such a notice is served, no permit may be granted for work or utilization that will be prohibited in the zone if the by-law is adopted. The Cities and Towns Act and the Municipal Code permit municipalities to implement any program to acquire structures involved in a planning program in their central sector or center. They may also acquire, control and administer immovables, do required enhancement, restoration, demolition or excavation work, and alienate or lease them for the desired purpose.

Municipalities established under the Land Use Planning and Development Act are required to prepare and adopt a development plan for their territory. Identification of areas of cultural, aesthetic or ecological interest is a mandatory part of the development plan. After the plan is adopted, the municipalities must adopt or modify their planning programs and by-laws to comply with the development plan. In the planning program the municipalities may designate zones to be renovated, restored or protected, The Land Use Planning and Development Act also empowers municipalities to create by-laws on such aspects as land use, density, size and height of structures, architecture, outside appearance and exterior finish.

1.4 Scope of Thesis

The first part of this section of this report consist of a summary of state-of-the-art knowledge in the area of deterioration, repair, and rehabilitation of masonry structures. As a brief introduction to the restoration and renovation of heritage buildings, Chapter One reviews the various aspects of heritage buildings and the relevant Canadian heritage legislation. The principal agents of masonry deterioration are then considered in Chapter Two. This is followed by individual chapters on the treatment of moisture problems, mortar repairs, the repair and replacement of damaged units and, finally, the cleaning of masonry. The remaining chapters of this thesis is meant as a case study of the effect of the effect of insulating masonry buildings. As such, it includes background information on the Customs Examining Warehouse, a description of the renovation and a summary of the analysis of the effects of insulating the building. The method for monitoring the effects of the insulation is then explained with particular attention to the various sensors and instruments used in data gathering and the computer programs created to process this data.

chapter 2

Agencies of Masonry Deterioration

Masonry is one of the oldest and most widely used construction material. Although the rapid development of structural steel and reinforced concrete in the last hundred years has led to a decrease in the use of masonry as a structural material, masonry is still widely used as a cladding material. Masonry has continued to be popular because it is also one of the more durable building materials known to man. Masonry structures erected by civilizations long since dead have survived to the present times and are a testament to the durability of masonry.

However, this does not mean that masonry is immune to the ravages of time. Although highly resistant, masonry is nonetheless subjected to numerous forms of deterioration. All forms of masonry deterioration can be classified as either chemical reactions or physical processes. Chemical reactions usually involve substances that weaken the structural matrix of masonry materials and produce harmful by products whereas physical processes typically involve either excessive stresses caused by dimensional changes or erosion by mechanical means.

A number of agencies can affect the durability and performance of masonry structures and lead to premature failures. Moisture is the principal agent involved in the deterioration of masonry. No other substance is as widely associated with the deterioration of masonry. Water is not only a deteriorating agent by itself, it is also a vital component in virtually all other forms of masonry deterioration. An often overlooked aspect of masonry deterioration is biological decay. A number of biological organisms play a significant role in the deterioration of masonry. They weaken the masonry and make it more susceptible to other forms of deterioration. Whether it involves bacteria accelerating chemical reactions or marine organisms boring into the masonry, these biological agencies all contribute to the gradual deterioration of the masonry. The chemical agencies of masonry deterioration include a wide range of substances, most of them man made, which can react with the components of masonry. The most harmful chemicals are unfortunately common pollutants such as carbon dioxide and sulfur oxides. Masonry structures that have endured centuries of weathering are now deteriorating at an alarming rate because of the increasingly polluted nature of the atmosphere. Physical agencies usually involve erosion by mechanical means or damage from excessive stresses resulting from differential movements, structural overloading, and the extreme heat experienced during fires.

It is important to remember that the deterioration of masonry is likely to involve a combination of agencies whose interaction over a long period leads to the gradual destruction of the masonry. It is also important to look at the masonry as a whole and not concentrate on a single component. Masonry structures comprise units connected by mortar joints; if either the units or the joints deteriorate, the structure tends to lose its integrity. The deterioration of jointing material leaves units loose and able to drop out; it thus destroys the proper transmission of forces throughout the structure and may reduce the transfer of loads between units to a series of point loads, inducing high local stresses and possibly cracking individual units.

This section deals with the principal agencies involved in the deterioration of masonry: moisture, biological agencies, chemical agencies and physical agencies. The information in the following sections was adapted from the works of (Amorosso and Fassina, 1983), (Weber and Zinmeister, 1991), (Ashurst and Ashurst, 1988), (Winkler, 1973), (London, 1988), (Sowden, 1990), (Drysdale and Suter, 1991), (Ransom, 1981) and (CIRIA, 1986)

2.1 Moisture

Moisture in solid, liquid or vapor form can be regarded as the principal agent causing deterioration in masonry structures. Water is a powerful agency of deterioration in itself but also plays at vital role as a facilitator in virtually all forms of deterioration. In the absence of water, numerous chemical reactions could not occur, soluble salts would not be dissolved and would not migrate or recrystallize, airborne atmospheric pollutants would not dissolve and could not remain in contact with the masonry, and therefore the deterioration of masonry would be greatly reduced. Similarly, without water, virtually all forms of biological life involved in the decay of masonry would perish. Although some processes of physical deterioration could be expected to continue in the absence of water, many rely to some extent on water in the generation of internal stresses. This section examines the various processes in which water is the principal agent of deterioration: leaching and salt crystallization, freeze thaw action, moisture movement and the corrosion of metals.

2.1.1 Leaching and Salt Crystallization

One of the most common and extensive source of masonry deterioration caused by moisture is the leaching and transportation of soluble salts by water and, as the water evaporates, their eventual recrystallization on the surface or in the pores and voids of the masonry. The soluble salts distributed over a large surface can concentrate into small areas on a wall. This section does not address the chemical transformations involved in the deterioration of masonry but rather the transportation of soluble salts by water and the physical processes that occur when it evaporates.

Salts entrapped in masonry materials may stem from various sources that include ground water salts, products of unfavorable reactions between polluted rainwater and masonry materials, road salts, residual deposits from improper chemical cleaners and soluble salts naturally present in masonry materials. The most common salts include sulfates, chlorides, nitrates and carbonates of alkali metals and magnesium. In solution, these salts are very mobile, moving along the surfaces and in and out of pores of the masonry. The soluble salts distributed over a large surface can concentrate into small areas on a wall. These movements occur periodically according to the season and the amount of precipitation. The most intense deterioration due to salts occurs when wet to dry cycling is most frequent. Large differences usually occur between day and night in spring and early summer.

Leaching is the process by which these salts are dissolved and carried away by water. What effect the leaching of these salts will have on the masonry materials will depend on the importance of these salts in the make up of the material. If the salts consist only of impurities, such as the sulfate and iron salts found in certain kinds of clay bricks, their removal will not alter the strength or durability of the material. However, where these soluble salts are the result of some form of chemical interaction between an aggressive chemical and the minerals that form the material's structural matrix, as is the case when acids attack the calcite in limestone, the leaching will result in the eventual weakening of the masonry.

In some extreme cases where mortar has been allowed to deteriorate, water runoff can also carry away sand and other fine aggregates resulting in the complete loss of the jointing material. This has been known to occur especially in masonry foundations. In the case of solid masonry walls with rumble filed cores, percolating water can wash out the deteriorating mortar leaving only a shell with no tensile strength. Localized wash out of aggregates from the core of the wall result in bulges on the masonry surfaces

A more serious aspect of leaching is the crystallization of the dissolved salts on the surface or, even worse, within the pores and voids of the masonry. The site of deposition and the effects thereof is determined by a delicate balance between evaporation of water and the re-supply of solution to that site. Salt crystallization on the surface of the masonry is termed efflorescence and crystallization beneath the surface is termed subflorescence, or crypto-efflorescence.

2.1.1.1 Efflorescence

Efflorescence typically manifests itself as a whitish haze in the form of blotches, patches and bands on the masonry surface. It is a frequently observed phenomenon, occurring wherever walls are percolated with moisture. Efflorescence tends to concentrate on specific parts of a building, typically at the border between wet and dry zones, and as such offers a good indicator of the extent of moisture penetration. Different sources of moisture penetration result in different patterns of efflorescence. Long horizontal bands along the base of a structure are the upper limit of rising dampness and are indicative of ground moisture problems. Termed tidemarks, these bands can be quite wide as the ground water level changes with the weather and the seasons. A similar effect can also occur due to splash back from nearby sidewalks and roadways. Efflorescence below roof lines and cornices is indicative of rain penetration due to poor flashing along the junction between the roof and wall. Bands of efflorescence coinciding with the level of the floors can be a sign of water accumulation in the cavity. Blotches and patches are more commonly associated with localized problems such as defective gutters and drains or leaky plumbing. Efflorescence occurring over large areas is more indicative of air leakage and internal condensation from improperly vented bathrooms and kitchens. Efflorescence can also occur indoors when moisture condenses on a surface and runs down.

When efflorescence takes place, salts are brought to the surface in solution during the wetting phase, and during the drying phase evaporation form salt crystals on the surface. The crystallization of soluble salts on the surface of the masonry is due to the low rate of ventilation, which cause an evaporation rate lower than the rate of replenishment of water by capillary migration from the inside of the wall. The salt crystals are formed mostly outside the pores and consequently the disruptive effect is smaller. The efflorescence is usually more developed in the convex parts of the wall due to the fact that, at the same temperature, the water vapor pressure over a convex surface is higher than over a flat one.

Apart from aesthetic aspects, efflorescence as such is not considered to be very harmful with respect to the destructive forces exerted on the masonry. These kinds of surface stains do not cause any particular deterioration. Sudden efflorescence may result from recent work such as repointing mortar joint but should disappear through normal weathering. However, persistent or recurring efflorescence is indicative of extensive moisture transport within the masonry and in many cases a more advanced state of salt deterioration.

Some salts are more prone to crystallize on the surface areas of masonry, forming a surface crust of different properties from the underlying material. Efflorescence arising from limestone and marble tends to form a calcitic surface crust. Although some believe this to be a self protecting mechanism of natural stone, it often results in dramatic spalling and exfoliation.

2.1.1.2 Subflorescence

In the early stages of the deterioration process, subflorescence does not cause visible alterations. The visible symptoms of salt crystallization are efflorescence, salt fretting, honeycombing, exfoliation and spalling. The serious nature of these problems is evident from the fact that besides aesthetic considerations, the service life of the masonry may be extremely limited.

Capillary action and diffusion processes are responsible for salt migration within the pore system. By this process, more or less concentrated solutions of salts are transported from inner areas to the surface. Salts are deposited internally when the rate of surface evaporation is higher than the rate of replenishment of water by capillary migration from the inside of the wall. The high rate of evaporation prevents the formation of a liquid film on the exterior surface and most of the evaporation occurs within the masonry. Larger pores are emptied and moisture retreats inward and below the surface of the wall. The migration of solution toward the exposed surface is very slow and dissolved salts accumulate in the pores, channels and crevices below the exterior surface. A necessary condition for salt crystallization inside a material is the presence of a supersaturated solution. The state of supersaturation in a capillary is achieved by partial evaporation of water, by a temperature drop or a combination of the two. Once a certain concentration level is reached crystals form and over time accumulate within the capillaries and pores of the masonry.

As these crystals grow, they exert pressure on the pore walls. The crystallization pressure of certain salts can generate extreme internal forces capable of cracking brick and stone, sometimes even into powdery fragments. Table 2.1 lists the crystallization for some common salts. In addition, some types of salts common to deteriorating masonry undergo a reaction with water in which water molecules are incorporated into the lattice of the salt crystals. This process is accompanied by an extraordinary increase in volume. At low temperatures and high relative humidities, the hydration pressure developed against the pore wall of masonry are extremely high and are of the same magnitude as the typical crystallization pressures. Table 2.2 lists the hydration pressure of some common salts. When the pressures of crystallization and hydration exceed the tensile strength of the masonry, the evaporation surface is rapidly disintegrated. The final crumbling of the thin surface layer can result in localized spalling, blistering or exfoliation.

Table 2.1 Crystallization Pressure of Salts (Weber & Zinsmeister, 1991)

Salt	**Pressure at 0°C in MPa**	**Pressure at 50°C in MPa**
$CaSO_4 \cdot 1/2\, H_2O$	33.5	39.8
$CaSO_4 \cdot 2\, H_2O$	28.2	33.4
$MgSO_4 \cdot 7\, H_2O$	10.5	12.5
$MgSO_4 \cdot 6H_2O$	11.8	14.1
$MgSO_4 \cdot H_2O$	27.2	32.4
$Na_2SO_4 \cdot 10\, H_2O$	7.2	8.3
Na_2SO_4	29.2	34.5
NaCl	55.4	65.4
$Na_2CO_3 \cdot 10\, H_2O$	7.8	9.2
$Na_2CO_3 \cdot 7\, H_2O$	10.0	11.9
$Na_2CO_3 \cdot H_2O$	28.0	33.3

Table 2 2 Hydration Pressure of Salts (Weber & Zinsmeister, 1991)

Reaction: $CaSO_4 \cdot 1/2\ H_2O \rightarrow CaSO_4 \cdot 2\ H_2O$

Relative Humidity in %	Pressure at 0°C in MPa	Pressure at 20°C in MPa	Pressure at 60°C in MPa
100	219.0	175.5	92.6
70	160.0	114.5	25.4
50	107.2	57.5	0.0

Reaction: $MgSo_4 \cdot 6\ H_2O \rightarrow MgSO_4 \cdot 7\ H_2O$

Relative Humidity in %	Pressure at 10°C in MPa	Pressure at 20°C in MPa	Pressure at 30°C in MPa
100	14.6	11.7	9.2
70	9.7	6.8	4.0
50	5.0	1.9	0.0

Reaction: $Na_2CO_3 \cdot H_2O \rightarrow Na_2CO_3 \cdot 7\ H_2O$

Relative Humidity in %	Pressure at 0°C in MPa	Pressure at 20°C in MPa	Pressure at 30°C in MPa
100	93.8	61.1	43.0
70	63.7	28.4	9.4
50	24.3	0.0	0.0

A similar process can occur when the exterior surface of the masonry has been treated with an impervious coating. Moisture accumulates under the sealant and salt crystallization may occur if the solution becomes supersaturated. Pervious coatings are less likely to cause problems since they do not interfere with the normal movement of moisture to the exterior of the masonry. Such coatings allow the water vapor to enter and leave through the pore of the masonry. Nevertheless, it is always possible that some salt crystallization could develop under the surface of the coating. In either case if salt crystallization takes place, the coating may peel, bringing with it part of the masonry surface.

Soluble salts washing down one kind of stone can enter the pores of another type of masonry and cause considerable damage. Since magnesium salts are more soluble and their expansion on crystallization is greater, washings from magnesium limestone onto calcium limestone frequently cause salt crystallization damage. Similarly, washings from limestone carried onto sandstone can result in severe deterioration, even if the sandstone is of good quality. Bricks are also liable to deterioration where there is direct washing from limestone strings, band courses and cornices. This leads to disruption of the surface due to an accumulation of calcium carbonate and calcium sulfate filling the pores of the brick.

Another particular type of stone decay associated to subflorescence is alveolar erosion or honeycombing, which is characterized by the fact that disintegration proceeds preferentially in some areas forming deep cavities, termed alveoles, while nearby surfaces may remain unaffected. This process is frequently associated with surfaces exposed to high winds, where evaporation occurs in the pores immediately below the surface. The process undergoes progressive acceleration when a cavity is formed because wind speed inside it increases due to air eddies. Alveolar erosion is more common in non-homogeneous materials because the separate components have different physical properties that lead to faster evaporation in one part. Alveolar erosion can also occur in homogeneous materials if the external conditions associated with the internal structure cause one area to evaporate more quickly than another. Water will be drawn towards areas of rapid evaporation.

Resistance to leaching and salt crystallization depends on pore size distribution. A macroporous material is more resistance to the stress induced by crystal growth than a microporous material, because the latter hold water for a protracted period. Pore size distribution indicates only the probable durability of materials of average porosity because resistance to leaching and crystallization also depends on both the total porosity and the cohesiveness of the material. The resistance of masonry material is essentially a function of the ease with which it allows moisture movement. A relatively impervious material such as marble would have a higher resistance than carbonaceous sandstone, a more pervious material of a similar mineral make up. Thus a material of low porosity is likely to be much more durable than one with a very high porosity

2.1.2 Freeze Thaw Action

Frost damage is the result of water freezing within the pores of the masonry materials. The position and exposure of the masonry materials are major determinants in establishing locations susceptible to frost action. Frost action will damage sound masonry only when it has a very high moisture content. Therefore areas subject to frost action typically correspond to areas of moisture infiltration. Common areas of frost damage are free standing elements such as parapets and chimneys, along roof lines and other areas subject to poor drainage, as well as masonry in contact with very damp ground such as foundations and retaining walls. Impervious exterior masonry coatings that allow moisture accumulation at the surface of the masonry are also susceptible to frost action. The forms of damage can vary widely and include deep cracking, spalling, surface scaling and exfoliation. In many cases, frost action may simply have accelerated damage resulting from some other cause of masonry deterioration.

Temperature variations around the freezing point will produce more serious damage in masonry materials than continuous freezing. Quick temperature changes around the freezing point are especially harmful to masonry, since it undergoes numerous freeze-thaw cycles in short periods of time. Estimates of the number of freeze thaw cycles to which a given material is exposed to annually will help determine the likelihood of frost damage. Records that merely list the number of days in which the air temperature changes from a positive to a negative value are insufficient. Even if the air temperature remains below 0°C, a displacement of the 0°C isotherm may occur in the masonry surface as a result of solar infrared irradiation. Therefore the masonry can be affected by several freeze thaw cycles per day even when the temperature remains constant. Thus frost decay in masonry materials is not governed solely by air temperatures, but also by other environmental factors such as sunlight, cloud cover and haze.

The disruptive forces of freezing water are generated by the volumetric expansion, as water is transformed to ice crystals. The total increase amounts to roughly 9% of the original volume. The total pressure that may be exerted upon the walls of pore can be as high as 212 MPa at -22°C (-8°F). The disruptive forces of ice crystals within the pores do not become effective as long as the crystal growth is essentially free and not oriented towards the pore walls. The situation becomes critical when 91% or more of the inner volume is filled with water and the volumetric expansion exceeds the remaining open inner space. The crystallization pressure is related to the pore distribution in the material, the degree of saturation, the frost penetration speed and the permeability of the material.

The saturation coefficient, which is a ratio of empty to filled pores, is used to define the frost resistance of materials. Materials with a saturation coefficient of more than 0.9 are liable to frost damage, whereas those with a coefficient below 0.8 are not. Geometry and size of pores also play an important part in determining frost resistance. Resistance depends not only on the total porosity but also on the pore structure and the proportion of fine pore present; the resistance to attack increases as this proportion decreases. Masonry materials containing tiny pores with radii smaller than 5x10-9 m are considered prone to frost damage. It is also known that when a water saturated porous material freezes, ice crystals first form in the coarser pore spaces and water is withdrawn from the finer pore. In narrow capillaries, rapid cooling prevents this pressure release into adjacent pores and the disruptive forces focus completely upon the pore walls. Capillaries with a wide bottle neck allow expansion of freezing water, even under rapidly cooling conditions. Stratified stones are more susceptible to frost damage since the pressure of crystallization tends to separate bedding planes. This can result in serious damage depending on the vertical or horizontal position of the bedding planes in the wall. Improperly laid stones will tend to develop exfoliation that eventually spall off.

2.1.3 Moisture Expansion

Reversible and irreversible moisture movements are known to occur in masonry. All porous building materials exposed to the weather take up water. Therefore these materials can be expected to shrink or swell according to changes in their moisture content. Reversible moisture expansion is common to most masonry materials. This kind of moisture movement is usually small and is not problematic. In dense stones, like granite, moisture movement is negligible. More porous stones such as limestone and sandstone can experience a reversible wetting and drying movement of 0.06 to 0.08%. A similar moisture movement occurs in bricks: 0.02 % in clay bricks and 0.04 to 0.06% in calcium silicate bricks and concrete blocks. Reversible moisture movement rarely result in cracking. Soft mortar joints used in older buildings and expansion joints used in modern ones can easily accommodate such small movements. Approximate movements of some commonly used masonry materials are presented in Table 2.3.

Table 2.3 Reversible Moisture Movement of Masonry Materials (Ransom, 1981)

Material	Approximate Movement (%)
Granite	Negligible
Limestone	0.06-0.08
Sandstone	0.06-0.08
Clay Bricks	0.02
Calcium Silicate Bricks	0.02-0.04
Concrete Blocks	0.04-0.06

It is the irreversible movement, which is usually many times greater, that can lead to cracking. Clay products have a tendency show expansion on wetting that is not wholly reversible on drying. This is a result of the firing of the material during the manufacturing process. Irreversible moisture movement occurs when newly fired bricks absorb moisture. Typical expansion in individual bricks can be around 0.1% and even as much as 0.2% in some cases. Around half of that movement, however, will occur within the first week after manufacture. The net effect is a very gradual continuing expansion over a very long period. This irreversible expansion in clay brick can lead to cracking of walls at setbacks and corners. In a similar manner, cement products show an initial shrinkage upon setting, followed by a similar continuing contraction as the excess water introduced during the manufacturing process gradually evaporate. Typical shrinkage is approximately 0.025 to 0.035% in calcium silicate bricks, 0.04 to 0.06% in concrete blocks and 0.04 to 0.1% in normal density concrete. This irreversible shrinkage may also cause several visible defects in masonry.

Irreversible expansion and shrinkage can cause problems, particularly when associated with opposing movements in structures. Severe cracking and spalling of the brick have occurred in multistory buildings with steel or reinforced concrete frames. As steel exhibits no moisture movement, steel frames restrain the surrounding brick masonry as it expands. Reinforced concrete frames with their irreversible shrinkage can put additional stresses on the expanding brick masonry. In early reinforced concrete frame building, and indeed in some later ones, no movement joints were fitted between the top of the brick cladding and the concrete floor level above. This results in an unintentional load being applied to the outer wythe of the masonry. This can result in bulging and even bending of the masonry walls from one story to the next. In some cases the resulting stress can be sufficient to cause spalling of the bricks at floor level

2.1.4 Corrosion of Metals

Metallic elements are often found in masonry structures. Common metallic elements found in masonry structures include: beams, columns and other elements of structural steel frames embedded in exterior masonry walls for fire protection, supporting elements such as shelf angles and lintels, reinforcement such as steel bars used in modern reinforced masonry and connectors like tie rods, anchors and ties used in conjunction with cavity walls. Metal is also used for water shedding elements such as roofing and flashing as well as water carrying elements like drains, down spouts and plumbing, and architectural elements like canopies, flagpoles and signs mounted on the masonry. Where the performance of masonry structures depends on the strength of metal supports, degradation due to corrosion can be both serious and costly.

Although bronze, copper and lead are used to some degree in masonry structures, the most widely used metal is iron in the form of either cast iron or steel. Unfortunately, iron is the most susceptible to corrosion by water and water born agents. Metallic components can corrode either in the exposed atmosphere of masonry cavities or while embedded in mortar. The corrosion of metallic elements sometimes results in localized staining on the face of the masonry. Although these stains are relatively harmless, they can provide a warning that extensive corrosion is occurring within the masonry. The formation of ferrous oxide, commonly known as rust, is accompanied by a significant increase in volume. Therefore, when ferrous metals embedded in the masonry rust they exert expansive pressures. This can result in horizontal cracking of the mortar joints coinciding with the location of the corroding element. In severe cases, the expansive pressure of rust formation can also lead to localized spalling of the masonry. The combined effects of corrosion and stress can cause stress cracking resulting in the eventual failure of the element. Corrosion can also lead to a considerable reduction in the cross sectional area of an element which in turn results in a reduced load carrying capacity and excessive deflections. Corrosion failures of connectors and supporting elements result in a loss of structural support, unevenly distributing the load and creating cracks, bulges and, in extreme cases, surface separations.

Steel embedded in mortar is inhibited from rusting by the high alkalinity of the surrounding mortar. Carbon dioxide present in water reduces this alkalinity by the carbonating the alkalis and thus increasing the vulnerability of steel to corrosion. In a good quality cement mortar, penetration of carbon dioxide is extremely slow and rusting may be almost indefinitely postponed. When the mortar is permeable, carbonation can reach the depth of the steel far more rapidly with consequent loss of rust inhibition. Moisture acts as an electrolyte in the formation of a galvanic cell that results in the subsequent corrosion of metal elements in the masonry.

Steel protected by zinc, known as galvanized steel, has a resistance to corrosion largely dependent upon that of the zinc. Rapid corrosion of galvanized wall ties has occurred in the presence of sulfur compounds in the mortar. A greater resistance to corrosion is imparted to the steel when it is alloyed with at least 10% chromium and other alloying agents. Steels so alloyed are known as stainless steels.

2.2 Biological Agencies

Biotic decay of masonry structures is a very complex process and is often overlooked. Plants and animals can attack masonry to a large extent both by mechanical and chemical action. While bacteria, the lowest forms of organisms, attack by chemical means only, higher forms of life such as plants use both mechanical and chemical action. This section deals with the various organisms known to have a damaging affect on masonry: microorganisms, algae, fungi, lichens and mosses, vegetation, boring organisms and birds

2.2.1 Microorganisms

Microbiological attack is mostly of a chemical nature. Chemical secretion and photosynthetic activity produce and accelerate chemical reactions responsible for stone decay. Secretion of organic acids by the bacteria will readily attack both silicate and carbonate minerals. Several types of bacteria are known to effect quick and irreversible alteration of natural stone. Autotrophic bacteria obtain their energy by chemical oxidation and reduction and as such play an important role in stone decay. Strains of autotrophic bacteria are identified by their activity and include: calcite bacteria, iron bacteria, nitrogen-fixing bacteria and sulfur bacteria.

Calcite bacteria are found mostly on limestone surfaces where they participate in the dissociation of carbonate minerals. Iron bacteria are important oxidizers of iron minerals. Nitrogen fixing bacteria act on nitrogen compounds to form nitrous oxide. It has been suggested that this process could be responsible for the biological degradation of carbonate rocks by converting calcium carbonate into soluble nitrate salts. Sulfur bacteria act on sulfur, transforming it into an acid solution effective in stone attack. Sulfur compounds are transformed by sulfate reducing bacteria (Desulfovibrio) into hydrogen sulfide that is in turn oxidized by an aerobic sulfur bacteria (Thiobacillus). The resultant is sulfuric acid that can damage carbonaceous materials.

Bacterial growth requires a nutrient rich medium, which is constituted of moist masonry material in shady areas of belt courses, cornices and areas with rising dampness.

2.2.2 Algae, Fungi, Lichens and Moss

Algae are typically multicellular nonvascular plants usually possessing chlorophyll. They are autotrophic which means that they do not depend on other plants for their nutritive processes but can use inorganic sources common in masonry materials. Wherever suitable conditions of dampness, warmth and light occur, algae will develop rapidly, becoming apparent as a bright green, but occasionally dark green, brown or pink, coloration. The drying of the masonry surface will result in the death of the algae that will then form surface deposits. In time wind born dirt, bird droppings and other organic matter will be added to this deposit of dead algae. These deposits of dead algae and other organic matter permit the development of fungi and lichens. These accumulating deposits eventually form humus, an organic soil, permitting higher forms of vegetation to develop particularly mosses, a class of primitive green land plants.

Fungi are parasitic plants devoid of chlorophyll while lichens are composed of fungi and algae living in a symbiotic relationship The symbiotic nature of algae and fungus in lichen is characterized by slow growth and the ability to attach themselves to bare rock surfaces without the need of supporting soil. As such they are the main agents in the formation of humus from which higher plant life can emerge. The lichens live either within the rocks or on their surfaces. Lichens growing within aggregates of translucent minerals bring forth discolored patches of brown and pink. Lichens attack the masonry surface by means of water retention and secretion of acids. The rough and spongy character of the lichen can retain water for a long time and keep the stone surface moist underneath. This can contribute to damage as the masonry is unable to rid itself of the moisture. The deterioration of the masonry is also strongly accelerated by the action of carbonic, humic and various other complex organic acids that are produced from the organic remains.

Lichens are classified into three main types depending on the form of their surface growth. Foliose lichens have a surface growth in the forms of leaves or scales that are attached to the surfaces by threads. Fructicose lichens have branching surface growths that are attached to the surface at their base. Crustose, type of lichen most often associated with the deterioration of stone, has a surface growth that forms a crust in close contact with the masonry surface. When the crust is removed by scrubbing or scraping, the surface growth will eventually regenerate and return to its original dimensions.

The fungi in lichen penetrate into the masonry by exploring cracks and fissures as well as by generating organic acids such as oxalic acid. In carbonaceous materials, these acids enable the lichen to dissolve stone material that is usually re-deposited as calcium oxalate in or close to the surface of the stone. If the calcium oxalate is deposited immediately beneath the growth as is the case with some crustose lichens, the result will be dense patches of calcium oxalate deposits that will persist even if the growth is entirely removed by brushing, scraping or through the use of biocides. In some cases, calcium oxalate will accumulate within the lichen itself, eventually killing it, leaving a calcium oxalate lichen fossil. In many cases, however, the surface growth simply becomes relatively inactive and eventually falls away to reveal a clean masonry surface that will then be recolonized by the remaining growth. Although crustose lichen activity is typically associated with the identification of the immediate masonry surface, owing to the deposits of calcium oxalate, severe weakening of the surface may occur at greater depth and, when accompanied by crystallization of soluble salts or freeze thaw action, the densified surface may spall away.

The organic acids generated by lichens and mosses not only damage carbonaceous stones such as limestones and sandstones with a carbonating matrix, but will also attack lime mortars and can cause etching damage on granite, glazed bricks and terra cotta

Urban and industrial areas are less susceptible to lichens and mosses since these plants are rejected by the presence of soot or sulfates. Although a polluted atmosphere will limit the growth of lichens and mosses, some resistant species may be able to develop. Certain forms of pollution from such sources as fertilizer factories may even result in accelerated lichen growth that may in turn lead to spalling and contour scaling resulting in the progressive loss of the masonry surface.

2.2.3 Vegetation

Vegetation growth on and around structures is often considered to enhance their appearance, softening their lines and setting them in an attractive environment. However plants like creepers, shrubs and trees can have more disruptive effect on masonry structures than bacterial attack and the biological effects of algae, fungi, lichens and mosses. The physical effect of the growths of roots and suckers as they penetrate joints and cracks in search of moisture can be major contributors to the disintegration of masonry structures.

Plants begin to cause concern when they develop significant root systems that can initiate mechanical damage. Roots have extraordinary penetrative powers and destructive capabilities. They infiltrate any available crevices and their growth forces them open and allow the access of water and air, and hence promote weathering. Plant roots are not expected to penetrate sound masonry surfaces or well-cemented mortar joints. Roots tend to grow along rough masonry surfaces where they interact with the minerals chemically and extract sparse nutrients through surface attack while they continuously seek a weaker joint or crack which will permit entry of the root tip. The chemical weathering of stone by vegetation is accomplished by small hydrogen cations produced by the root system that are easily exchanged with negatively charged nutrient metal cations in the stone. Once the break up process has started it is strongly accelerated by the action of various organic acids.

Well established, decorative climbing plants and creepers have a beauty and value of their own and although they may enhance the appearance of masonry buildings, the effects of some growths can be very destructive. Creepers and ivy may have the advantage of insulating masonry surfaces from weather extremes but they equally inhibit evaporation and tend to maintain these surfaces in a permanently moist condition. Possibly even more serious is the extent to which they prevent proper examination and conceal deterioration. In the case of ivy, a more serious problem is its rapid growth with aerial roots intruding into joints and displacing stones or bricks. Suckers and tendrils will also contribute to surface decay, especially of mortar, by the secretion of organic acids. In the case of rumble filled solid stone walls, ivy may penetrate deeply into the lime core work and seriously threaten the stability of the entire wall.

Certain species of trees, particularly elms, poplars and willows, make high moisture demand on the subsoil and can thereby affect foundations. Clay soils undergo considerable change in volume with varying moisture content, shrinking as the water is absorbed and expanding as water is absorbed. The root system that extends into such soils and removes water from the ground can cause settlement damage, which will be exacerbated by seasonal variations. The effect is most marked when foundations are shallow, as they frequently are for older structures. However deep foundations are not necessarily immune, as root penetration to considerable depths is possible and for mature trees drying influence can extend to a depth of 5 m (15 ft) or more. As a rough guide, roots extend horizontally for a distance equal to the height of the tree. Single trees should therefore be located no nearer to an existing structure than their mature height. For groups or rows of trees competing for water over a limited area, the distance should be increased to 1.5 times the mature height.

2.2.4 Boring Organisms

Certain forms of marine life have been known to damage masonry by attaching themselves to the surface and boring into it. The intertidal marine zones, which are the shore line between high and low tide, are most endangered by rock borers. This is the zone that may involve such man made structures as docks, bridges and sea walls. Under optimal conditions, bio-erosion can progress often at catastrophic rates, which can occasionally be 25 times faster than ordinary marine erosion constituting of solution and mechanical abrasion by wave action.

Boring is achieved either by mechanical abrasion or by chemical etching. In the case of mechanical abrasion, the strong foot of the organism anchors its end against the wall near the hole while the sharp edged shell abrades the masonry surface by turning back and forth around its long axis. Various mollusks are mechanical rock borers in carbonate rocks, concrete and soft shale. The species angel wings (Pholas) have been known to bore at the rate of 12 mm (1/2 in.) per year to a total depth of 150 mm (6 in.). Some species of sea urchins (Echinus and Eucidaris) are also able to dig by means of abrasion, sinking their sharp teeth, located in the center at the bottom of their body, into the rock underneath at the rate of approximately 10 mm per year.

Chemical borers are restricted to carbonate rocks. Boring clams are often only the initial borers and are typically followed by other boring organisms that dig an intricate network of channels of various sizes leading to the eventual disintegration of the rock surface. Some species of clams (Lithophaga) dig straight, smooth channels at a rate as high as 12 mm per year and to a depth of 100 mm (4 in) by acid secretion. Boring mussels (Mytilus) are the most common of the boring organisms in limestone. After the clams, some species of worms (Polychaete) continue a network of generally densely spaced small round or oval channels. Sponges (Cliona) complete the work of fragmentation to a depth of 25 mm

(1 in), whereupon the friable debris crumbles as sand to the bottom. These primitive sponges bore at a rate as high as 14 mm per year by advancing plasma into the rock substance

In addition to these marine organisms, some wild species of wasp and bee will burrow into soft mortar and even some weak stones instead of their normal habitat of easily eroded rock and earth banks. The holes burrowed by these insects can be up to 75 mm (3 in) deep. The insects will then lay several eggs at the end of the hole, each egg being supplied with enough nutrition to enable the development and emergence of an adult to occur. Each new bee or wasp will in turn burrow its own hole. This process weakens the masonry by providing numerous cavities that facilitate the penetration of water and dissolved chemicals. The treatment of masonry bee problem needs to deal with the unhatched pupae as well as the existing bee population.

2.2.5 Birds on Buildings

Urban buildings with their ledges, ornamental details and roof overhangs are often inhabited by a variety of birds seeking a place for rest, refuge and breeding. Pigeons and sparrows are the two most common species of birds nesting on buildings owing to the ease with which they have adapted to the urban environment. Structures near large bodies of water may also provide likely perches for seagulls. The areas on the building where these birds congregate will quickly accumulate large quantities of excrement. In addition to being visually obnoxious bird droppings may contain significant amounts of phosphoric and nitric acids. These acids will etch masonry surfaces and chemically react with carbonaceous materials to form calcium phosphates and some nitrates.

In addition to their chemical action on the masonry surface, these excrements, together with the clay, straw and other materials used in nesting, provide additional organic matter that encourages the development of lichens and mosses. These accumulations of organic matter also retain water, keeping the masonry surface wet. This can contribute to damage if the masonry is unable to rid itself of the excess moisture.

2.3 Chemical Agencies

Chemicals are the most powerful agents of destruction of masonry. Chemical corrosion is a process during which minerals common to certain masonry materials are converted into more soluble compounds by reaction with chemical pollutants. This chemical deterioration is then amplified by the high pressures of crystallization and hydration of the new minerals. The physical resistance of the masonry is degraded, and voids and hairline cracks develop and create surfaces that are more susceptible to absorb water and harmful chemicals dissolved in it. The typical sources of harmful chemicals are the atmosphere, rainwater, ground water, sea water, bacteria and other biological growth on or within the masonry. There are three possible pathways whereby these chemicals are introduced into masonry: by solution in rainwater, sea water and ground water, by aerosols in fog or urban smog and by diffusion of gaseous particles.

Industrialization has brought significant changes in the environment that has in turn resulted in an increased rate of chemical deterioration of masonry structures. The common substances associated with this chemical deterioration of masonry are carbon dioxide, sulfur oxides, nitrogen oxides and chlorides. In this section all four of these chemicals and their effects on masonry will be discussed. Each subsection will address the common sources of the particular chemical substance, the corrosive effects it has on the masonry and the nature of the potential dangers of the soluble salts formed in these reactions.

2.3.1 Carbon Dioxide

Carbon dioxide (CO_2) is a natural constituent of the atmosphere but, with its recent sharp increase in concentration in the urban and industrial environments, it may be regarded as a pollutant. High carbon dioxide concentrations in urban atmospheres can double and even triple the weathering rate of limestone and marble.

Carbon dioxide in air dissolves in rainwater to form carbonic acid (H_2CO_3). The weak acid solutions formed by the dissolution of carbon dioxide in rainwater dissolve the calcium and magnesium carbonates ($CaCO_3$ and $MgCO_3$) in limestone, dolomite, marble, lime mortars and plasters because they form the much more soluble calcium and magnesium bicarbonates ($Ca(HCO_3)_2$ and $Mg(HCO_3)_2$). Slightly acidic rainwater can also affect calcareous sandstones in that carbonate of lime that cements grains of sand are attacked rapidly, destroying the structure of the stone surface. Calcium bicarbonate is a hundred times more soluble than calcium carbonate. The amount of calcium and magnesium carbonate dissolved by rainwater depends mainly on the water temperature and the concentration of carbon dioxide in the atmosphere. An increase in temperature causes a decrease in the carbon dioxide dissolved. Water temperatures near freezing dissolve close to twice the quantity of carbon dioxide of water than at 25 °C.

The leaching action of slightly acidic rainwater on marble surfaces is frequently associated with the re crystallization of water soluble calcium bicarbonate. The dissolved carbon dioxide tends to evaporate when the solution temperature increases and the result is the formation of calcium carbonate deposits. The calcium carbonate formed is characterized by larger crystals and by a more porous structure compared to the original that is microcrystalline and non-porous. The increase in porosity caused by the recrystallization of water soluble calcium bicarbonate is harmful to the stone since it allows acidic solutions and soluble salts to penetrate more deeply into the masonry and to accelerate decay. In addition some carbonate salts such as sodium carbonate (Na_2CO_3) can generate significant crystallization pressures that can greatly accelerate the deterioration of the masonry. Sodium carbonate can also generate significant hydration pressure as it incorporates water molecules in its crystalline structure.

2.3.2 Sulfur Oxides

Sulfur compounds present in the atmosphere are the result of combustion of coal, oil and natural gas. Burning of coal contributes the most to the formation of sulfur oxides with the combustion of oil and the smelting of sulfide ores playing a somewhat lesser role. Sulfur compounds are also commonly found in the soil and therefore in ground water. They can attack foundations and penetrate by rising dampness in walls. Bricks made from earth clays may also contain sulfates, although the amount is usually quite small. Nevertheless, these sulfates can migrate in aqueous solution if the masonry is saturated.

Sulfur is present in the atmosphere as gaseous compounds mainly as sulfur dioxide (SO_2) and sulfur trioxide (SO_3). Evidence indicates the predominance of sulfur dioxide over sulfur trioxide in the atmosphere. Gaseous sulfur dioxide is absorbed by calcareous materials and oxidized on its surface. This process involves the absorption of sulfur dioxide by solid particles followed by the formation of sulfurous acid (H_2SO_3) in the presence of water, where partial neutralization to sulfites (salts of SO_3) may occur, and subsequent oxidation to sulfuric (H_2SO_4) acid and sulfates (salts of SO_4) take place

The removal of sulfur dioxide from the atmosphere by rainwater acts as a cleaning process for the air but at the same time it is responsible for the formation of potentially acidic solutions. In the atmosphere, the oxidation of sulfur dioxide involves dissolution in water droplets that may be present in clouds or fog followed by the formation of sulfur trioxide that is further oxidized by air and other oxidants. Gaseous sulfur trioxide in the atmosphere exists only if the water vapor concentration is very low. Normally water vapor is present in sufficient quantities to combine with sulfur trioxide to form droplets of sulfuric acid.

Sulfuric acid is an extremely corrosive acid that etches polished and glazed surfaces and is dangerous to all types of masonry. Extremely vulnerable stones are limestone and marble as well of various types of calcareous sandstones. In both cases, gypsum is formed and is responsible for surface erosion and crust formation. The presence of large amounts of calcium sulfate is often considered to be an indicator of acid rain attack.

Sulfates are generally less soluble and mobile with respect to other salts and can therefore move inside the porous material only in the initial state of formation, when they are still in solution. When water evaporates, sulfates precipitate on the pore walls as hydrated salts, and can then become dehydrated salts. If the humidity is not very high, dehydrated salts are not dissolved but they hydrate and increases in volume, thereby exerting a pressure on the walls of the pores. The damaged produced by sulfate salts is not due to their water solubility but to their property of existing in different hydration states. These salts are deposited in the pores from their supersaturated solutions as hydrates and as the evaporation of water proceeds, the deposit of these hydrates dries out. Each time that a transformation from one state to another takes place, a change in volume occurs. The amount of damage resulting from the rhythmic contraction and expansion on the walls of the pores is dependent on the pressure of hydration. When it surpasses the resistance of the wall in the pores, the latter are broken up and as a consequence more space becomes available for the precipitation of salts.

Dissolved sulfates can also react with the tricalcium aluminate, common in portland cement, to form calcium sulphoaluminate or ettringite. The crystallization of this salt is accompanied by a large increase in volume that can exert tremendous pressure on the pore walls. However, this reaction with tricalcium aluminate will only occur under wet or saturated masonry with an available source of sulfates. The more common sulfates involved in this reaction are the sodium and magnesium sulfates which are more soluble than calcium sulfate.

2.3.3 Nitrogen Oxides

Nitrates (salts of NO_3) are found in an environment of decomposing organic materials. They are present in masonry located near agricultural lands and graveyards. Atmospheric pollution is an other source. Nitric oxide (NO) is produced by combustion engines. In exhaust gases, some of the nitric oxide is oxidized to nitrogen dioxide (NO_2). In the atmosphere, nitric oxide is also oxidized to nitrogen dioxide in the presence of ozone. In general the atmospheric process tends to oxidize the nitrogen oxides into nitric acid (HNO_3). Where free nitric acid occurs its prolonged action will affect masonry materials by converting different substances into nitrates. Carbonaceous material will be particularly affected as the calcium carbonate will be converted into the more soluble calcium nitrate. Another effect of nitrogen oxides is their role in the oxidation of sulfur dioxide

The role of nitrates in the deterioration of masonry is not very clear; it can be correlated to their action as soluble salts inside the walls of buildings. If the amount of water supplied is constant and the evaporation takes place over a long time, crystals of nitrates grow outward from the surface. If the supply of water is low, the disruptive effect on the wall pore is negligible even if there is surface efflorescence. Evidence of nitrate formation on masonry is rare since nitrate salts are highly soluble and therefore easily washed away from the masonry surface. Sometimes nitrates can be detected in high concentration in masonry material. In this case, however, the salts are more likely to be created by biological growth on the masonry material.

2.3.4 Chlorides

Chlorides (salt of Cl)are quite common in coastal regions since they are mainly of maritime origins. Two main ways of transportation are from soil by rising dampness in walls and marine aerosols transported by wind. Chlorides are also found in the de-icing salts used on sidewalks and roads. Elemental chlorine is widely used in the chemical and plastic industries as well as in water and sewage treatment plants. Hydrogen chloride (HCl) is an air pollutant emitted from industrial sources such as hydrochloric acid manufacturing plants and the combustion of coal, paper and chloride containing plastic. Sometimes hydrochloric acid can enter into the atmosphere from theses industrial processes.

Hydrochloric acid (HCl) is a strong acid which in contact with masonry surface transform calcium carbonate into calcium chloride. The role of hydrochloric acid in the deterioration of masonry has never been clarified because chlorides are rarely formed as a deterioration product. Like nitrate compounds, chlorides are very soluble and are difficult to identify in deterioration layers.

Chlorides are extremely dangerous, because they are very soluble and hygroscopic and during condensation of water from surrounding air are the first salt to be re dissolved. Once in solution they are very mobile and thus they penetrate and break up many crystalline structures. Their hygroscopic nature allows them to absorb moisture from the air and to retain it in the masonry. When they crystallize they form very porous deposits which because of their capillarity absorb water. Their presence lowers the temperature of hydrate salts, thereby facilitating the transformation from one state of hydration to another, especially for sulfite salts. The leaching out of the cementing media observed in stones containing chlorides tends to pulverize masonry materials. During the drying phase chloride crystals form to a certain point in the pores; their hygroscopicity absorbs other water and chloride solution from the surrounding pores. When the drying phase is completed the crystals exert a high pressure on the walls of the pores in which they have grown. A small change of relative humidity of the air or the water content of the porous material causes rhythmic hydration and dehydration of salts or a renewal of crystal growth and consequently a further pressure against the wall pore. If the water supply continues, chloride crystals are again dissolved and due to their high mobility they are transported to other zones more favorable for crystallization. As a consequence, chloride crystals can exert their disruptive action more quickly and at different points in porous materials

2.3.5 Natural Rust

The crust of the earth has a 5% iron content, therefore it is not surprising to find naturally occurring iron minerals in masonry materials such as stone and brick. Common iron minerals include green or black ferromagnesian silicates, yellowish ferrous sulfides, and gray to dark brown ferrous carbonate. Bricks made from clay often contain ferrous oxide. Generally these iron minerals do not cause serious deterioration unless they are subject to weathering. Previously hidden iron minerals in the masonry can become exposed due to gradual deterioration. When exposed to weathering, these minerals may start to corrode and form rust stains on the masonry. In some cases their corrosion may seriously damage the masonry surface. Masonry cleaning involving steel brushes has been known to deposit specks of iron which can cause a similar form of staining

Of the two forms iron sulfide (FeS_2), pyrite can occur in almost all types of rocks, whereas marcasite is restricted to sedimentary rocks. Both minerals when exposed to air dissociate and oxidize equally fast to rust. The solid ferrous sulfide takes up oxygen as soon as the sulfide is in contact with rainwater and the atmosphere leading to ionized iron and sulfate. These are then oxidized to form ferric hydroxide and sulfurous or sulfuric acid. Surface etching by the released sulfuric acid can be frequently observed in marbles and other carbonate rocks. The presence of iron and sulfur bacteria is believed to greatly accelerate the oxidation process.

Ferrous carbonate ($FeCO_3$), also known as siderite, occurs occasionally as gray or light brown grains in some marbles and other carbonate rocks. Siderite is much less soluble than calcite or dolomite. Their solubility depends on the presence of carbon dioxide in the atmospheric or in the attacking water. Upon contact with rainwater, siderite oxides at the surface form rust like spots that resemble those produced after the weathering of pyrite. The yellowing of many crystalline white marbles by so called aging may originate from siderite.

Biotite, the black mica in granite, loses its iron from the silicate lattice at the beginning of the weathering process because the iron is only loosely built into this lattice. Iron almost immediately precipitates as a natural rust halo near the biotite flakes. The presence of larger quantities of biotite flakes evenly distributed throughout the stone may spread to an almost even ochre cast over the stone.

2.4 Physical Agencies

Physical agencies of masonry deterioration typically involve either excessive stresses or erosion by mechanical means. Erosion is typically a surface problem involving either mechanical abrasion due to repeated contact with hard objects or constant bombardment by small particles that gradually weaken the masonry surface. Physical deterioration caused by excessive stresses is an internal process whereby increasing loads are applied to the masonry until its capacity is exceeded. Excessive stresses in masonry typically arise from differential movements and volume changes between different components of the structure. Tension and shear forces develop when the masonry cannot accommodate these movements. Since masonry is inherently weak in tension, these forces can often exceed the capacity of the masonry and cause cracking. Common sources of differential movements include those which involve a change in volume, such as moisture and thermal movements, and those which involve displacements or deformations like ground movements, the deflection of structural elements and the creep of materials under load. Excessive stresses can also result from overloading of the masonry. Although not common, overloading can occur if the masonry is not designed properly to resist the existing forces or if dead or live loads are increase due to renovations or a change in the function of the building. Another agent of physical deterioration that deserves mention is fire. Although, masonry is not a combustible material, fire can damage masonry by subjecting it to intense temperature that can cause disruptive dimensional changes.

2.4.1 Differential Movement

All building materials expand and contract with changes in temperature and moisture content. In addition, the structure as a whole is subject to movements due to dead and live loads, to settlement or subsidence of the foundations and creep of the materials. These deflections and change in dimensions may not be harmful. It is the combination of different movements that may give rise to damage. As long as the building was designed to accommodate these movements, no damage will result. In the past, masonry structures relied on the soft lime mortar to accommodate these movements. In more recent construction where hard cement mortars are used, expansion joints filled with compressible materials are introduced at regular intervals to accommodate these movements. However, when these movements are restrained, the resulting forces can exceed the capacity of the masonry and the result is usually cracking. By cracking, the masonry is forming its own movement joints. The decision on whether or not to repair cracks depends on whether there is any risk to the stability of the structure and if the cracks are likely to encourage rain penetration. Special attention is required for horizontal displacements where a course of masonry projects so as to form a ledge where water may collect. Once the cause of cracking has been resolved and the situation is stable, the cracks can be repaired.

2.4.1.1 Thermal Movement

Temperature changes cause dimensional changes in materials, which expand with an increase in temperature and contract with a decrease in temperature. These changes cause stresses which if not accommodated can exceed the strength of some materials and cause distortion and cracking. Thermal movements in masonry depend on material properties, the exposure and the extent to which it is insulated.

The two natural properties of masonry that affect thermal movements are the coefficient of expansion and the absorptivity. The coefficient of expansion is the increase in dimension per degree Celsius. The coefficients for some common masonry materials are given in Table 2.4. Absorptivity is a measure of the ability of a substance to absorb radiation. Dark surfaces have a higher absorptivity and as such heat and cool faster than light colored surfaces. Significant thermal movement can occur and cause distortion when masonry materials of similar coefficients of thermal expansion but of different color are used. Problems have been reported when dark marbles and light granite have been used in alternate bands.

Thermal movements depend not only upon the nature of the material but also upon its exposure and the extent to which it is insulated. Seasonal variations in the temperature of masonry surfaces can be as high as 90°C in northern climates, but diurnal variations are also very important. Masonry exposed to direct sunlight will experience a greater diurnal variation in temperature than shaded or masonry facing north. Damages from thermal movements result in part from the extent of the temperature change but also from the time over which the temperature changes occur and the frequency of these changes.

Table 2.4 Thermal Expansion of Common Masonry Materials (Ransom, 1981)

Material	Coefficient of Linear Expansion per °C×10-6	Unrestrained Movement for 50°C change (mm/m)
Clay Brick	5-6	0.25-0.3
Calcite Brick	13-15	0.65-0.75
Granite	8-10	0.4-0.5
Limestone	6-9	0.3-0.45
Marble	8	0.4
Concrete and Mortars	9-13	0.45-0.65

Temperature changes can be quite sudden; sunlight breaking through a frost laden fog can heat up a surface very rapidly. Similarly, rain falling on a sun heated surface applies a severe quenching shock. Therefore, the masonry surface, being more exposed to the weather, is likely to be subjected to greater movement than the structural backing and especially when the surface is thin and the structure is massive. The degree to which the masonry is insulated against temperature variations also affects thermal movements. In the case of a wall with an insulated cavity, the masonry on the warm side of the insulation is kept at a more or less constant temperature while the masonry on the cold side is subjected to frequent changes over a wide range of temperatures. Therefore, the exterior masonry can experience a wide range of thermal movements while the internal temperature within the masonry remains unchanged. Likewise, interior masonry walls, such as partition walls, framing into exterior walls do not experience the same thermal movement.

The extent and nature of the damage caused by thermal movement depends upon the physical and mechanical properties of the materials and the extent and frequency of the temperature changes. Thermal expansion is theoretically reversible, however, the masonry structure often expands horizontally by sliding and returns to its original position only if it remains uncracked. Thermal movements, like moisture movements, lead to cracking when the masonry is not free to expand and contract. However, unrestrained movements rarely, if ever, occur in practice and that restraint can lead to a build up of stresses that can crack the masonry.

Masonry walls are typically restrained along their bottom edge by the friction with the foundation, which is buried in the soil and does not experience the same amount of thermal movement. During expansion there is generally some slip towards the end of the wall and the masonry may overhang the masonry by a small amount. In the process of slipping over the edge of the foundation the masonry may tear away a small piece from the corner of the foundation. When the masonry contracts, the friction between the masonry and the foundation again restrains the movement and can cause large tensile forces. Since masonry is weak in tension, one or more vertical cracks may occur in the wall. Vertical cracks extending the height of the structure are common at corners where two expanding or contracting wall sections meet. These are especially common at reentrant corners where the sections of masonry on either side of the return expand or contract and tend to rotate the return.

Since cracks occur where long sections of masonry have their movement restrained, they often occur at the corners of openings such as doors and windows which introduce weaknesses in the wall. The long uninterrupted sections of masonry above and below windows experience greater movements than the shorter masonry sections between these openings. Upon expanding, these long uninterrupted sections can cause diagonal shear cracks in the shorter sections. Similarly, upon contraction, vertical tension cracks can occur in the masonry sections below these openings.

Another common defect associated with thermal movement is the expansion of flat concrete roofs. These can change appreciably with diurnal changes in temperature, particularly if the surface finish is dark in color. The roof then tends to move outwards at the top of the top of the walls and may push the top courses of masonry out slightly. Cracking then occurs within the internal plaster finish, usually near to the corners of the building and close to the junction of the roof with the walls. Some cracking in the mortar joints of the external wall just beneath the roof may also be seen. At the roof level, parapets are another potential source of problems. Parapets are exposed on three sides and are therefore subjected to a higher range of temperatures. Since parapets are also uninterrupted along the length of the building, they can expand more than the masonry below the roof line and cause diagonal cracks at corners.

Finally, thermal and moisture movements also occur in the vertical direction. In high-rise buildings these can take the form of differential movements between the masonry surface and the internal structure. This results in an unintentional load placed on the outer wythe of the masonry. This can result in bulging and even bending of the masonry walls from one story to the next. In some cases, the resulting stress can be sufficient to cause spalling of the bricks at the floor level.

2.4.1.2 Ground Movement

Ground movement is a time-dependent process, and if the building is sufficiently ductile to accommodate differential movements, no damage results from ground movements. All movement in gravel, sandy soils, and a considerable proportion of that of clay soils occurs within two to three years after construction. The period of consolidation of clay

Chapter 3

Treating Moisture Problems

Moisture is probably the greatest source of damage to old buildings and is perhaps the most difficult to identify and correct. Excessive moisture attributable to rain, ground water and condensation can inflict damage ranging from dampened interior finishes to deterioration of structural components such as the freeze-thaw spalling of masonry. Building defects and poor maintenance often exacerbate moisture problems. Very often deterioration or poor workmanship in building elements such as roofs, flashing, windows and foundations, rather than the masonry walls themselves, cause the problems. Lack of maintenance can also exacerbate moisture problems. More common than building defects, maintenance-related problems are normally easy to remedy and may include clogged or broken down spouts, drains, leaky roofs, deteriorated flashing or loosely fitting window frames.

Possible solutions for moisture problems include better drainage, preventing moisture migration within the masonry with flashing and damp proof courses, and where necessary surface treatment to water proof the masonry. These should be followed if necessary with treatments to remove salt encrustations on or within the masonry that build up as a result of the moisture problem.

Because excess moisture does not always leave evidence such as staining, salts or corrosion, a moisture meter should be used to measure high but invisible moisture levels. With complex moisture problems, it may be necessary to undertake selected physical examinations, tests or long term monitoring to differentiate between condensation, ground water and rain penetration as sources.

Condensation can be dismissed as a likely source if it can be ascertained, using a psychrometric chart that temperature and humidity conditions do not reach the dew point. If it is unclear whether condensation is occurring, the temperature and relative humidity should be monitored with a hygro-thermograph over an extended period of time, preferably through a winter and summer cycle.

Rising dampness from ground water can be eliminated if the ground water levels are well below the foundations. If no ground water is encountered, the source of the moisture problem is probably limited to rainfall and attendant conditions such as poor site drainage, puddling at foundation walls or back splash.

Rain penetration can usually be traced to junctions in the building such as flashings and windows. Penetration through the masonry walls can be dismissed as a cause of moisture problems if there is a cavity in the wall, or if the walls are more than 300 mm (12 in) thick and in generally sound condition.

Additional physical probing can help verify the exact wall configuration, the presence of proper flashing, damp proof course, foundation wall connections, and basement slab details. Detailed examination of surface coating can help determine whether they act as vapor retardents or breathable layers. Laboratory identification of efflorescent salts may also help identify the source of moisture.

If multiple treatments are to be used, treatments for rain penetration and condensation problems should be addressed first. Correcting these problems may allow the masonry become sufficiently dry to handle other moisture problems naturally. It should be kept in mind that successful treatment may not be possible for all moisture problems. Drastic measures such as rebuilding walls or foundations are not recommended for buildings of historical significance. Neither should old and historic buildings be the testing ground for untried materials or techniques.

The information in the following sections has been adapted from the works of. (Amorosso and Fassina, 1983), (Weber and Zinmeister, 1991), (Ashurst and Ashurst, 1988), (Winkler, 1973), (London, 1988), (Sowden, 1990), (Drysdale and Suter, 1991), (Lstiburek and Carmody, 1992), (Ransom, 1991), (Smith, Honkala and Andres, 1979), (Highfield, 1987) and (Gauri, Holdren and Vaughan, 1983)

3.1 Movement of Moisture

In order to properly treat moisture problems, it is important to assess how water reaches the masonry and to consider its movement in the masonry. There are three principal processes by which water can penetrate masonry. The first involves wind driven rain that is forced into the wall by wind pressure and capillary suction. The second involves capillary absorption in which water is drawn into the pores of the masonry. Capillary absorption can occur whenever the masonry is in direct contact with water. Capillarity is also responsible for moisture movement within the masonry. Lastly, water can penetrate masonry by condensation. When water vapor reaches the maximum concentration possible at a given temperature below the dew point temperature of the nearby air, it forms a film of liquid water. The proper identification of the source of moisture penetration is the first step in the treatment of moisture problems. However, it is also important to understand how water evaporates from the masonry, since most of the damage in masonry occurs during the drying processes.

3.1.1 Rain Penetration

The majority of water that penetrates into porous masonry comes from the outside environment during rain. However, only a fraction of this occurs as a result of direct penetration of walls by rain. Most of the rainfall on buildings is disposed by gravity flow. Rain penetration of walls occurs when a film of water is formed over the surface and it is forced into the wall by wind pressure and capillary suction. Rain penetration depends on the construction and condition of the exposed surface. The walls of a building exposed to wind and rainwater, are subjected to greater penetration of rainwater. Driving rain is carried along by wind at an angle to the vertical so that it strikes vertical surfaces of buildings. Rain deposit and its migration over buildings facades is affected by exposure to driving rain and its directional variation with time. Air currents and air pressures due to wind are among the factors contributing to rain penetration. Wind causes rain to strike the wall, and this may lead to air pressure differences across the wall. The main pathways of rain penetration in walls are cracks, crevices and joints. The state of the surface is poorer in those parts which are exposed directly to rain water and wind. Therefore, orientation and exposure conditions may influence deterioration, especially in the presence of cracks and other openings. Rain and snow may also penetrate directly through any gaps in the structure, particularly at the junction of windows and doors with walls and at joints between roof and wall.

3.1.2 Capillary Action

Another way in which water penetrates porous masonry is due to rising dampness resulting from capillary absorption. Transport of water through porous materials depends on the capillary structure. The size of the suction force depends upon the nature of the surface and the diameter of the pores. The suction pressure increases as the diameter of the pores decreases, and is very large for pores with a diameter below one micrometer. This phenomenon is called capillary suction. The cause of capillary suction is the attraction of water molecules towards the walls of the pores. The capillary suction is frequently large enough to offset the force of gravity and make water rise inside pores that are sufficiently small.

It should be noted that transportation of liquid water can take place either horizontally or vertically. Horizontal movement occurs when a water film forms on the masonry surface and water is drawn into the wall. Vertical transportation of water occurs when water enters the wall from above through leaking gutters and deteriorated flashing, or it rises in walls from the ground by contact with water bearing stratum. For thin and homogeneous walls, the movement of water is prevailingly horizontal across the joints and the pores. For thick walls, the movements of water inside the wall are prevailingly vertical because the influence of gravitational forces is not negligible. In this case, it is difficult to separate the influence of rising dampness from that of rain penetration, which occurs first in the lower part of the wall. Vertical water movement is also present in cavity bearing walls which are less susceptible to moisture penetration from hard driving rain compared to walls of solid masonry.

The most common moisture problem associated with capillary action is rising dampness. The level of the water table is seldom far below the surface of the ground. Materials in contact with the ground draws up this moisture by capillary action into their pores. The height to which ground water can rise, if not obstructed, can be considerable. The maximum height of capillarity rise is often marked by a white efflorescent rim or a dark, wet margin that remains wet. Cases of attacks are not infrequent where the damp proof course, although present, has been bridged and therefore rendered ineffective.

3.1.3 Condensation

Absorption of water vapor in a porous body can take place by condensation processes. A maximum water vapor concentration exists for each temperature. When the water vapor reaches the maximum concentration possible for a given temperature and it arrives on surface where the temperature is equal to lower than the dew point of water vapor of the surrounding air, condensation occurs. Surface condensation takes place in the presence of two simultaneous conditions: low surface temperatures and high relative humidities of the nearby air. The first is caused by inadequate thermal insulation of walls and roofs. The latter condition results from the introduction or production of moisture and inadequate ventilation inside the building. The liquid water may then move into the pores by means of capillary suction.

Water may also condense within the masonry if the temperature reaches the dew point somewhere in the interior of the wall. This phenomenon, called interstitial condensation, takes place when the temperature of the surface facing the interior environment is above the dew point temperature of the surrounding air and the temperature inside the wall is lower than this temperature. In capillaries, water can be forced to condense before the dew point of the surrounding air is reached. Old masonry, constructed from materials of high density and high thermal conductivity, may not appear to be subjected to interstitial condensation. In reality, an old masonry structure, which is frequently very thick, exhibits different temperatures inside and outside, and thus there is a temperature gradient across the wall.

Air leakage and vapor diffusion are the two processes responsible for condensation. Air leakage occurs through cracks and crevices in the masonry, especially at the junction of the roof and wall and at door and window openings. The pressure difference between the conditioned space and the exterior can cause air to leak into the lower part of the building and leak out through the roof and upper stories. The resulting inward leakage of air is called infiltration and the outward leakage exfiltration. Infiltration increases with wind pressure. When the wind blows, high surface pressures are created on the windward side of the building and low pressures on the leeward side. Because of the pressure difference between the two sides of the building, air is easily sucked out through pores in materials, holes, cracks, and other openings. As this warm moist air escapes, it may cool to below the dew point temperature and condensation occurs. Air flow speeds must be low enough for the air to cool to the dew point temperature before it exits the air leakage path. Fast flowing air can warm the surfaces of the flow path above the dew point temperature of the out flowing air and condensation may not occur.

Water vapor diffusion processes also play an important part in moisture movement in masonry. Diffusion is defined as the migration of gases through solids. Water vapor, which is almost always present in the atmosphere, penetrates into the pores and a specific quantity is held in the porous material depending upon the relative humidity of the air. The amount of water vapor that is absorbed by a porous masonry depends on the relative humidity of the surrounding air. Depending on the extent of temperature gradients, water vapor diffusion is responsible for a more or less substantial moisture transport. Water vapor diffusion is especially high during winter seasons when the indoor temperatures are by far higher than the outdoor temperatures, which leads to extreme differences in water vapor pressure on the inside and outside of a building. In a heated building the inner surface temperature is higher than the dew point of water vapor moving into pores close to the surface. Thus warmer air from the inside diffuses into the wall and when the water vapor reaches the pores where the temperature is lower than the dew point, it may condense there. This condition takes place especially on very cold days.

Besides the above mechanisms, high water content in a building material can be effected by the presence of soluble salts, attracting moisture from the surrounding air. Such types of salts are termed hydroscopic and include calcium chloride, sodium sulfate and sodium nitrate. Walls contaminated with these salts absorb much higher quantities of water from the air than that by ordinary condensation.

3.1.4 Evaporation

It is important to remember that deterioration processes do not take place mostly during the absorption of water, but when water evaporates. In fact, most of the damage in masonry occurs during the drying processes. Evaporation from the surface of a porous body is governed by external factors such as the environmental conditions and by internal factors such as the movement of water to the surface. The environmental conditions comprise the temperature and relative humidity of the air and its velocity near the surface. The rate of evaporation increases with temperature, with decreasing relative humidity of nearby air and with increasing velocity of air flow past the drying surface. As for the internal factors, water molecules on the surface passing into the vapor phase cause a migration of water to the surface which depends on the structure of the material.

Evaporation takes place initially from the surface at a rate which depends on the environmental conditions. In the absence of ventilation and in the presence of high relative humidity, the evaporation rate is very low and the surface remains wet. If ventilation occurs, the evaporation rate increases and the surface remains wet. Evaporation continues at a constant rate as long as water can move to the surface quickly enough to compensate for the loss by evaporation. Inside the pores, the lack of air circulation causes rapid saturation. This equilibrium cannot remain for a long time because a porous body is composed of pores of different sizes. Water molecules in larger pores passes into the vapor phase more rapidly than those in smaller ones. When the amount of water brought to the surface becomes too small to keep the surface wet, the rate of evaporation falls off. Therefore, when water can move easily in a material, most of the drying takes place at the surface, whereas in a dense material the initially constant rate of evaporation persists for only a small proportion of the drying period. The surface may dry long before all of the pores have emptied, and at some point below the surface, the material may still be saturated. The water front retreats into the wall and the rate of evaporation decreases rapidly and is inversely proportional to the distance from the surface. When the water content of the porous body decreases below the critical water content, movement of water to the surface is no longer possible and only the less efficient vapor diffusion process remains available.

3.2 Improving Drainage

One of the first step in treating moisture problems is to reduce the amount of water in direct contact with the masonry. It is especially important to prevent standing water that can saturate masonry. The two most important sources of water are precipitation, such as rain and snow, and ground water. Rainwater accumulated over the entire roof area is concentrated at the building perimeter where it can find its way into parapets and masonry walls. Even when a drainage system directs the rainwater off the roof, if it is deposited at the base of the wall, it will seep into the ground and saturate the soil along with the foundation. Excessive moisture in the soil is absorbed by the foundation walls and it rises upward by capillary action in a phenomenon known as rising dampness. Water entry at the roof and foundation levels can be significantly reduced by proper drainage. The purpose of drainage is to remove excess water as quickly as possible. Establishing proper drainage should be the first step in any attempt to treat moisture problems since even a slight change in the equilibrium can reduce moisture problems substantially.

3.2.1 Roof Level

Roof assemblies typically concentrate rainwater collected from an entire building footprint at the building perimeter. All good roof design should incorporate the provision of adequate drains or gutters and down spouts to carry all roof water away to a storm drainage system. Gutter and down spout systems should direct water away from the building. It is important that rainwater be taken away from the perimeter of the building to prevent dampness penetration through the walls. Modern plastic PVC rainwater systems have been found durable and maintenance free if correctly installed with adequate brackets and seals. Older rainwater systems are less durable, or they suffer other drawbacks. Cast iron can be long lasting if properly maintained but maintenance is often expensive and consequently poor. The hidden surfaces such as gutter interiors are often left unpainted. Asbestos cement rainwater systems appear to have a useful life span of about thirty years and then become porous. Precast concrete rain gutters need periodic internal bituminising to avoid downward penetration of water into the walls beneath, especially at the joints. Where an existing rainwater system needs repair and repainting it is often advisable to consider complete renewal in PVC plastic since the cost is often comparable and the final results would require less maintenance.

To protect the top of the wall against infiltration of water, the parapet should be capped with stone, terra cotta or concrete slabs or metal copings, which should be sloped to drain. Copings should overhang the wall to keep water away and should have a drip. Buildings with flat roofs, which generally have cavity walls, usually have a metal coping. With low parapets, this coping interlocks with the roof counter flashing and is nailed to a wood strip incorporated into the masonry facing. Even if the coping is well sloped toward the roof to drain off water, rust holes are always a possibility, therefore, the roof membrane should be extended under the coping. Traditionally, copings extend at least 25 mm (1 in) out from the walls; this is quite effective in reducing weathering on the top meter of the wall. A coping of at least 100 mm (4 in) should be provided and it must have a lip that extends out by a fraction of an inch.

Masonry chimneys are often located on a gable wall or within the end wall. In row housing, they were typically incorporated into the party wall. Because stacks are exposed to the weather and rarely have caps, water infiltrates and leads to faster deterioration than in the rest of the chimney. Caps made of beveled mortar or a stone slab should be installed to project at least 50 mm (2 in) beyond the face of the stack. A drip should be included to shed the water away from the stack.

Cornices are projecting horizontal elements that crown or subdivide facades or decorate the lintels over openings. In solid walls, they are made from header stones, well anchored into the masonry wall. For cavity walls or large overhangs, they are anchored to the structure with metal ties. Because a cornice projects from the facade, it must be designed to shed water. The top face should have a slope of at least 10 degrees and should be covered with metal flashing. The flashing should be similar in color to the material being covered, and it should cover the whole top of the cornice. To protect the joint between the cornice and the masonry facing, the flashing should extend up to the facing and it should be interlocked with the parapet coping or inserted into a racked joint in the wall.

A sill covers the bottom of the window or door opening and prevents water from penetrating into the wall. It is generally made of a single piece of stone, sometimes wood or more recently, concrete. A sill must have a slope of at least 10 degrees to drain the rainwater and it should also have a drip, a small groove found on the underside edge of the sill. This groove prevents water from running back under the sill and onto the wall, where it can lead to deterioration of the mortar, the masonry and eventually, the wall itself. For the same reason, it is also important for the sill to project sufficiently from the wall. If the sill has no drip, one can be cut using a radial saw. Although a skilled craftsman might be able to do this in place, it is generally necessary to remove and reinstall the sill. An insufficient slope or the presence of cracks in the sill also causes water infiltration. The sill must then be repaired and reinstalled or replaced. When repairing the sill, flashing can be placed under the sill to reduce the chance of water infiltration. The ends of such window sills should be turned up to prevent water running along the wall, forming mustache shaped patterns below the windows.

3.2.2 Foundation Level

The simplest and most important method to improve drainage at the foundation level is to slope the ground away from the building and extend the roof down spouts farther out. Rain puddling and back splash should be avoided by ensuring that roof runoff is controlled with proper gutters and down spouts and that the ground drains away from the building. Gutters and down spouts should direct water away from the building above grade and not tie into a below grade drainage system. The ground should slope away from foundation walls and swales used to redirect surface runoff as necessary. Paving material at the base of the wall should be at least 50 mm (2 in) from the building. A gravel strip 600 mm (2 ft) wide or more reduces backsplash and helps drain water away.

Rainwater absorption by backfill material can cause ground water to concentrate at the building perimeter. Locating heavily irrigated flower beds and gardens immediately adjacent to the building perimeter has similar effects. A drain screen controls below grade water by placing free draining material immediately adjacent to the foundation walls. This free draining material, typically sand or gravel, allows for the free flow of water downwards toward the subgrade drainage system. Assuming that there is no hydrostatic pressure, the water running down the foundation wall surface travels through the smaller pores of the soil rather than into any larger cracks in the foundation wall. The upper portion of the backfill around foundations should consist of an impermeable material such as clay to drain as much runoff away from the building as possible.

A common treatment for reducing, but not necessarily eliminating, rising dampness and related moisture problems arising from ground water and poor site drainage is to install footing drains. These drains reduce the quantity of water affecting the wall by collecting rainwater falling near the building and by lowering high ground water levels. As ground water rises, it enters the drainage pipe and is carried away. Drainage pipes should be sloped to facilitate drainage and should be connected an open space, to a sump or to a storm sewer. It should be noted that storm sewer systems tend to back up during heavy rainfalls and can pipe water to the foundation rather than away from them. Therefore check valves should be installed at storm sewer connections that allow water to flow only away from the foundation.

Footing drains were traditionally installed beside the base of the foundations by laying short sections of perforated terra cotta or concrete pipes end to end, spaced slightly apart. Modern perforated plastic PVC weeping pipes can also be installed. The drainage pipe should be encased in crushed stone free of fines. The holes in any of these materials collect water but can also collect sand or earth, eventually clogging up the system. Roots seeking moisture can also make their way into the drain. As a preventative measure, the drain, or at least the gaps between the sections of the drain, are covered with building paper or another filtering material.

Footing drains are most practical where the entire periphery of the building is accessible and water can be drained away from the building without pumping. Urban sites pose several complications: inaccessibility of the building periphery to trenching, inability to estimate the quantity of ground water, difficulties in establishing property boundaries and limiting liability for damage to adjacent properties, and inability to establish positive drainage of collected water, therefore pumps are required. Building foundations may be disturbed by the digging of large deep trenches and buildings on wooden piles or footings can be severely jeopardized when ground water conditions are altered.

Because the cost of footing drains systems can be low, they may be a first choice, especially if the site does not drain well. Drains cannot guarantee the arrest of rising dampness, but even a slight change in the soil moisture equilibrium could reduce the problem substantially. After installation, the effect should be monitored by taking moisture readings of the masonry at regular intervals. The excavations for the installation of drainage pipes provide the opportunity to repoint deteriorated mortar joints in masonry foundation and the application of some form of surface coating to prevent water penetration.

3.3 Flashing and Damp Proof Courses

Proper drainage may reduce the amount of water that can penetrate the masonry but it cannot prevent moisture movement within the masonry. This is where proper flashing and damp proof courses become important. Two similar yet different elements, flashing and damp proof courses, play an important role in preventing the migration of moisture within the masonry. Flashing promotes drainage from the masonry, whereas the damp proof courses close off the surface to moisture movement.

Flashings serve several important functions: they direct water out of construction joints; they direct water out of masonry assemblies; and they prevent water from flowing along the wall surface by providing a drip edge. An often overlooked function of the flashing is to direct water away from the masonry. Flashings should extend sufficiently outward from the masonry surface to provide a drip edge that properly sheds water.

Flashings are commonly used as coping for walls and along the junction between roof and wall such as at gable ends, parapets and chimneys. The flashing is usually made of metal, such as aluminum, copper, galvanized iron or lead, or bituminous materials. Although this type of flashing is subject to more intense weathering, deterioration is easier to identify and repair. It is also easier to install such flashing, if none existed.

Flashing is also installed within the wall to drain the water that makes its way into the masonry. Internal flashing is commonly made of plastic such as polyethylene and is typically found beneath the wall coping, at openings such as doors and windows and at the base of the cavity wall. Old buildings often do not have such flashings, and it can be hard to introduce them in existing construction. Although many old buildings have cavity walls, they are not necessarily a proper rain screen. Early cavity walls had only a narrow air space that is often filled with mortar droppings, no flashing at base of wall or at openings, no weep holes, poor ties and an often leaky back up wall. The retrofit of such walls, when they show signs of dampness, is much harder to accomplish. It requires the cutting out of the lower courses, the cleaning out mortar droppings, the installation of flashing along the base of the wall and then replacing the bricks with proper weepholes. Window replacements are an opportunity to install flashing at the lintel and sill levels. Flashing should be placed under the sill to reduce the chance of water infiltration. The ends of such window sills should be turned up to prevent water from running along the wall, forming mustache shaped patterns below the windows. Flashing should also be added when replacing a lintel in a cavity wall. In cavity walls, the air space is usually interrupted by the lintel. If this is the case, flashing should be inserted above the lintel and weep holes should be provided to drain the water that may collect.

There will be times, however, when it is necessary to establish a barrier within the masonry to prevent water migration. This is where damp proof courses can be useful. They prevent capillary migration of moisture from one section of the masonry to another by creating a water tight barrier. The installation of a damp proof course can be considerably easier than the installation of an internal flashing. The most common location for damp proof courses is at the junction between the masonry walls and the foundation to prevent rising dampness. Most methods described here refer to installation at the base of a wall. However, there are many other locations where a damp proof course can be used to prevent moisture migration. Such locations include the junction between top of the exterior walls and the parapet as well as the base of chimneys that form an integral part of the wall. The physical insertion of a suitable impervious barrier remains the preferred method, however, the recent advances in chemical injection techniques make it a viable option.

Before thinking of introducing a new damp proof course, it is important to ensure that one does not already exist. Damp proof courses are not always visible on the exterior surface, and in some cases, adequate damp proof courses are present but have somehow been bridged, allowing moisture migration. A common cause of bridging of the existing damp proof course in an external wall is the building up of soil, or the addition of new paving, to a level above that of the damp proof course. However, this short circuiting of the existing damp proof course, can easily be alleviated simply by lowering the adjacent soil or paving level back 150 mm (6 in) below that of the damp proof course. Other common causes of bridging include an external rendering applied over the damp proof course, or new mortar pointing carried out over the outer edge of the damp proof course. These also have the effect of short circuiting the damp proof course by providing a path for rising moisture to pass around it. These problems can be easily overcome by cutting back the rendering to above the damp proof course level, or by raking out the offending mortar pointing. Another cause of short circuiting of the damp proof course is the accumulation of snow against the masonry walls. As the snow melts, moisture can enter the masonry above the damp proof course. Therefore snow should not be allowed to accumulate against masonry walls, nor should it be piled against such a wall during the snow removal process. A similar effect occurs on roofs where the snow is allowed to accumulate against the parapets. Provided that the damp proof course is in good condition, the problem should not recur once the residual moisture has dried out from the wall.

The installation of damp proof course can be both time consuming and expensive, but it is imperative in any building suffering from capillary dampness caused by a lack of, or failure of, a damp proof course. No treatment of rising dampness should be undertaken without first considering the likely effects of changing the moisture content within a wall. Consideration must be given to the removal of salts after the installation of a damp proof system. A damp proof course installation coupled with the introduction of central heating frequently brings massive efflorescence as the damp proof zone dries out.

3.3.1 Physical

The horizontal cutting through a wall and the insertion of a positive damp proof course is an effective system of preventing dampness due to capillarity. The traditional method of inserting a damp proof course is to remove short lengths of brick course at a time and replace them with dense brick or slates. Alternatively, the same bricks can be replaced with a new damp proof course incorporated during the process. Less costly is the physical insertion of a new damp proof course by cutting or grinding through a bed joint with a hand saw or power tool in lengths of about 0.4 to 0.5 m (15 to 20 in) and inserting an impervious membrane such as a metal sheet, bitumen felt, dense polyethylene or other suitable material.

Slate and dense bricks make good and long lasting damp proof courses, but it is neither very suitable for restoration work because two courses of slate make a wide and conspicuous joint, nor is it desirable to show a course of bricks in stone masonry. Insertion of a metal, bitumen felt or dense polyethylene sheet is preferred because it does not produce a very thick joint. Metal sheets with protective coatings have been used to form a positive damp proof course. However, experience has shown that coatings are often damaged in transit and during installation, leaving the metal, commonly aluminum, exposed to salt attacks. High density, heavy duty polyethylene sheets, sometimes filled with carbon black, are likely to be more reliable than standard gauge metal barriers.

Although the use of power tools on masonry is generally discouraged, the cutting of a slot through the wall for the insertion of the damp proof course necessitates the use of special cutting tools. Some of the most efficient cutting is now carried out with chain saws cutting a 7 mm (1/4 in) wide slot. Chain saws are available to cut through up to 1.5 m (59 in) thicknesses. Another useful cutting tool is a flexible glass fiber disc impregnated with carborundum up to 0.6 m (24 in) in diameter, driven by a portable motor with a flexible drive and fitted with a vacuum extract which eliminates almost entirely the enormous dust problem associated with this operation. Where cutting may cause unacceptable amounts of vibration in the walls of a sensitive nature, the cut can be made using a diamond coring drill

One of the major problems associated with cutting through a wall, however carefully it is packed and supported as work proceeds, is the risk of settlement after installation. Cutting through a wall also causes major disturbances to internal surfaces. A system that minimizes the risk of settlement involves a series of heavy duty polyethylene sheet envelopes. The envelopes are slid into a wall as the saw is removed and are then filled with grout under pressure following the insertion and overlapping of the subsequent envelope.

A new, versatile physical insertion system involves the insertion of polyester resin in a cut through the full thickness of the wall to form a damp proof course that structurally integrates the wall above and below the cut. Walls up to 1200 mm thickness of solid brick or stone construction are cut by a chain saw. A slot 420 mm long is formed by a series of 25 mm diameter drill holes; it is then thoroughly dried and a specially designed trough is fixed to each side. Polyester resin is then poured into these to a level above the top of the cut. After initial curing has taken place, the resin is trimmed off along the line of the wall. The completed barrier is formed in alternate sections so that no section longer than 420 mm is ever left unsupported. Whilst knowledge of the service life of resins is still limited, a system of this kind is certainly more positive and is longer lasting than a single chemical injection with resin. It is, however, proportionally expensive.

A last form of physically inserted damp proof courses are high capillary tubes. In the last century, a perforated fire clay brick course was sometimes installed to encourage drying out, and in subsequent attempts to increase drying in the wall the high capillary tube system has been used extensively. This system introduced small earthenware tubes into previously drilled holes in the wet wall up to a shallow angle of ten to fifteen degrees. The holes penetrate two thirds of the wall thickness. The tubes are bedded into the holes in a mortar that should be as weak and laid as dry as possible. The objective is to attract moisture to the drying tubes where it would be encouraged to evaporate as quickly as possible. There is, however, an inherent problem here, since the tubes that are capable of attracting water by capillarity may be unable to lose that water by evaporation. They can also become hygroscopic by deposition of soluble salts. Of course the holes must be spaced fairly closely together and preferably installed in two or three staggered courses to have any significant drying effect, and in such circumstances they also function as a partial damp proof course, since water cannot cross them. Installations of this type cannot be expected to solve serious dampness problems, although they may have a useful role to play when there is penetrating dampness or where they are used in conjunction with another installation to check the amount of drying out that takes place on the internal wall surfaces. However, practical experience has shown the high capillary tube to be of very limited effectiveness in the control of rising dampness and in some circumstances the tubes could increase the humidity locally.

3.3.2 Chemical

Until fairly recently, the physical insertion of a damp proof material into a slot cut into an existing masonry joint was the most widely used method of installing new damp proof courses. However, the chemical injection method has now overtaken the physical insertion techniques and is used extensively as a means of overcoming rising dampness in walls. Chemical damp proof courses are currently the most promising method for installing damp proof courses across thick masonry walls. The principle is to establish a water repellent zone across the wall by injecting chemicals in the area above the ground level where a damp proof course would normally be installed. Water repellents work on the principle of lining, rather than blocking the pores within the material being treated. This allows the passage of some water vapor, but prevents the rise of liquid moisture. Materials include aluminum stearates, silicone solution in organic solvent and water soluble silicone compositions that become water repellent upon curing. These materials line the walls of the pores of the masonry and change the contact angle, thus inhibiting the capillary attraction up the wall. Some systems add a rubber latex emulsion intended to block the pores with a flexible material.

Aqueous siliconate solutions are usually allowed to drip feed into the wall from rows of reservoir bottles whereas the silicone solutions in solvent and the siliconate/latex mixture are normally pumped in under pressure. Both require a line of closely space drillings and both require experienced contractors to carry out the installation. Success of this type of system depends on uniform diffusion through the thickness of the wall.

The walls are first exposed externally to at least 150 mm (6 in) below the proposed damp proof course level. This may involve some landscaping to modify the exterior ground surface. On the interior, skirtings and floor boards adjacent to the walls suffering from capillary rise should be removed and checked for timber decay. If timber decay is evident, this should be treated and additional under floor ventilation provided, if necessary. Plaster and other surface rendering should be cut away to 450 mm (18 in) above the last visible signs of dampness. If dampness is not evident, expose 230 mm (9 in) of wall along the proposed damp proof course line. Once the wall to be treated has been exposed, the final selection of the course of masonry to be treated can be made. With a timber floor this should ideally be below the timber level to prevent decay. With a solid floor, such as a concrete slab on grade, the course immediately above the floor level should be selected to eliminate the possibility of short circuiting through the floor. If access to this course externally is not possible due to ground conditions, the injection should take place 150 mm (6 in) above ground level. Injecting into engineered bricks or other dense masonry should be avoided where possible. The next step is to drill the holes for injection of the damp proof solution. The 10 mm (2/5 in)or 12 mm (1/2 in) diameter injection holes should be drilled horizontally into the walls, 120 mm to 150 mm on centers, to a depth of two thirds of the wall thickness. The drillings are best made in the thickness of mortar joints wherever possible, since filled drillings in masonry always show and tend to become more obtrusive with age. When the holes have been cleaned of dust, the pump, feed lines and injector lances are connected to the pre drilled holes and the mouth of each hole is sealed. The wall is now ready for injection; the control valve is opened and the pressure injection process commences. When the section of wall being treated is saturated, injection can commence at the next set of drillings. In addition to other precautions, stone paving against a wall should be protected against excessive spillage of silicone, which may have the effect of forming a shallow surface skin vulnerable to spalling in the presence of moisture and salts.

For solid walls, between 230 mm (9 in) and 460 mm (18 in) thick, and for cavity walls, the injection is carried out in two stages. After the outer zone or skin of the wall has been treated, further drilling and the injector lances are passed through the original holes to treat the inner zone or skin. In walls consisting of two skins of face work with a rubble infill, it may well be necessary to carry out a grouting operation of the damp proof zone before introducing expensive chemicals into fill a wall with a high percentage of voids. In order to achieve an effective damp proof course in this type of walls, the infill must be treated separately. After injecting the outer facing and the inner skin, separate drillings are made directly through into the rubble, which must be flooded with injection fluid to extend the moisture resistant band across the full thickness of the wall.

An alternate system involves the placement of frozen pellets of siliconate solution into the holes drilled into a wall. The pellets melt, diffuse into the wall and the solution cures to form a barrier. Yet another system involves the injection of a special mortar into a similar series of holes. In the presence of water, deposition and spread of insoluble pore blocking salts from the mortar takes place. The main disadvantage of both these systems is that it is difficult to place enough material in the wall for them to be effective.

3.3.3 Electro Osmotic Systems

Various electrical systems are believed to inhibit the passage of water up a wall. Capillary rise produces an electrical potential, and the application of a DC voltage to linked electrodes buried in a wet wall and in the ground is considered to control the passage of water. Passive systems seek to ground the wall by linking electrodes in the wall with electrodes of similar metal in the ground, or to produce an electrical potential by galvanic action using dissimilar metals for the two sets of electrodes. Active systems apply an electrical potential from an external source between the sets of electrodes. Only the active system can be described as electro osmotic but no difference in terminology is made commercially.

Water is strongly held along the masonry-water interface by electrostatic attraction. The water is immobilized and its mechanical properties resemble more or less that of a rigid solid. The great resistance of such ordered water can well function as a screen or membrane because this water is much denser, can be as much as twenty times more viscous than ordinary water and does not freeze above -40°C.

The electrodes are set in holes equal to approximately half the depth of the wall. On a wall one meter (39 in) thick the electrodes would need to be set in 500 mm (19.5 in) and spaced approximately 650 mm (25.5 in) apart. In a positive system, these electrodes would be linked to the ground with a 15 mm (3/5 in) copper tube. An alternative arrangement places the electrodes in the wall at a depth of 150 mm (6 in) in a regular triangular pattern at one meter (39 in) spacings.

One of the major problems with the electro-osmotic systems has been the rapid depletion of electrodes acting as positive anodes in negatively charged walls. However, platinized titanium and other resistant materials have largely overcome this particular problem

3.4 Surface Treatments

There are numerous kinds of surface treatments but they can all be classified as either permeable or impermeable. An impermeable coating is one that completely seals the surface allowing neither liquid flow nor vapor diffusion. A permeable coating is one that will prevent liquid flow but will still allow vapor diffusion.

Since applying an inappropriate coating inevitably leads to serious deterioration of the surface, it is crucial that the moisture exchange that occurs across the wall be well understood. Above grade, moisture from within masonry structures tends to migrate to the drier outside area. Below grade, it migrates in the opposite direction; it moves from the damp soil outside to the drier area inside the building. Therefore, it is important that the exterior surface coatings on walls above grade, designed to prevent rain penetration, should not interfere with the normal movement of moisture to the exterior of the wall. An impermeable barrier applied to the exterior of a masonry wall above grade traps the moisture migrating outward. The freezing and thawing of the entrapped moisture may well result in the blistering and deterioration of the coating and crazing of the masonry. Therefore, on walls above grade, any impermeable coatings should be on the inside of the wall, while the outside should have a permeable barrier. Below grade the reverse is true, the impermeable barrier should be on the exterior and the permeable one on the interior.

There are three common applications for surface coatings on masonry walls. An impermeable coating is often applied to the foundation walls to seal their surface and thus prevent rising dampness. An impermeable coating can also be applied to the interior masonry walls to act as a vapor barrier and prevent excessive moisture migration from the building interior to the drier outside area. Surface coatings are also applied to exterior masonry wall to prevent excessive penetration of rainwater. This last application has proven to be the most problematic.

General assumptions about the permeability of masonry walls can lead to expensive and unnecessary treatments with water repellent liquids. The cause of dampness is often inaccurately diagnosed. If the walls are unusually thin, or unusually permeable, water penetration through masonry may take place, especially in conditions of extreme exposure. If penetration persists after all other sensible remedial work has been carried out, such as correct pointing of joints and cracks and repair of defective copings, gutters, down pipes and flashings, then there may well be a case for the use of water repellent treatment. Water repellents are intended to improve the resistance of masonry to rain penetration. Modern water repellents line the pores of the bricks, stones and mortar with a water repellent material, which inhibits capillary absorption. Treated surfaces still absorb water during prolonged rainfalls but allow the evaporation of trapped water as the treated zone remains permeable to water vapor.

Water treatments are not a substitute for other maintenance work. Experience has shown that there are relatively few situations where a water repellent treatment alone has solved a major moisture penetration problem. The application of water repellents may, in some situations, exacerbate decay. This can happen as a result of water containing salts in solution evaporating from behind the treated surface, leaving salt crystals in the pores. Repeated crystallization cycles can then lead to disruption and spalling of the treated surface. In addition to this hazard, the thermal and moisture movements of the thin treated surface layer may be sufficiently different from those of the underlying masonry to generate shear stresses, leading eventually to failure.

Sometimes, colorless water repellents are applied after cleaning masonry surfaces as dirt inhibitors. Such treatments are successful in this role for the duration of the repellent on the masonry surface, but this tends to deteriorate relatively quickly, even though the repellent may persist in the pores of the treated layer. Re-treatment is possible, but is rarely carried out in practice because of the expenses involved in providing access to most building facades. Unfortunately, the deterioration of the repellent on exposed surfaces is rarely uniform and patchy appearance can result. Even the short term benefits of water repellents as dirt inhibitors are therefore debatable and rarely justify the cost of the materials and labor. Any proposal to use them needs very careful consideration.

In applying coatings to masonry, masonry material properties such as porosity, surface roughness, alkalinity and the presence of soluble salts are of key importance. While some masonry is porous to small water molecules, coatings generally contain much larger molecules. Therefore, some denser masonry materials are relatively non-porous to coating materials. Since the chemical constitution of the masonry substrate and coatings differ markedly, little chemical bonding takes place and adhesion depends mainly on mechanical keying. Most clay bricks exhibit considerable roughness for good adhesion; glazed bricks and terra cotta are an exception.

One of the chemical properties of masonry that affects its ability to hold a coating is its degree of alkalinity, which is the amount of basic salts it contains. Most masonry materials are normally neutral but the mortar in which they are set can be quite basic. Most concrete masonry units are highly alkaline, unless they were steam cured. Alkalis react with the oils or oil containing vehicles in some type of coatings in a process called saponification. As result, the dry film becomes soft and tacky, and if the process is carried far enough, it reverts to a liquid form. It is therefore necessary to guard against such a reaction. There are three possible steps that might be taken in this regard. One is to ensure that if an appreciable amount of alkalis are present, coatings are used at least for the prime coat, that do not contain oils. Another is to try to ensure that the affected surface remains so dry that the reaction cannot occur. With most exterior surfaces, this is practically impossible. The third alternative is to try and neutralize the alkali chemically. This is done with an acid solution. This treatment only neutralizes a thin surface layer, and subsequent passage of water through the material can bring fresh alkalis to the surface.

Another chemical characteristic of some masonry products is the presence of soluble salts. As water from the interior of the masonry migrates to the surface and evaporates, it can leave crystalline deposits at the interface between the masonry surface and the coating. Crystallization of these salts exerts a force sufficient to overcome the strength of the coating. It is not sufficient that the masonry surface be free of efflorescence. Any danger of these salts being drawn to the surface in the future must be determined.

Moisture content of the masonry also has a great effect on the performance of coatings. Oil-based and solvent-based coatings cannot be successfully applied to a damp surface as proper adhesion cannot develop. Even though the surface may appear to be dry, moisture may remain in the interior of the masonry and the application of a coating may trap this moisture which if it migrates to the coated surface may cause a number of problems already mentioned. A moisture content of 12% or less is considered satisfactory for coating purposes.

3.4.1 Parging and Stucco

Parging usually refers to the application of a thin coat of mortar directly applied to the exterior of masonry walls, particularly below grade as a damp proof measure for rough masonry, foundation and basement walls. Where the subsoil does not cause a build up of hydrostatic pressure, this may be all that is required to provide adequate waterproofing. Stucco generally refers to the thicker coat built up in several layers over masonry walls, most often on a mesh or furring strips. It is sometimes whitewashed or scored to resemble cut stone, making rough stone or even bricks look like more expensive materials.

Traditional parging and stucco are lime based and can tolerate movement in the wall. Lime based parging forms a permeable coating, allowing, moisture to move through and evaporate. As such it can be a suitable coating for the exterior, above ground masonry walls. Parging of portland cement are commonly used below grade and although it is less permeable than lime parging, it is still considered permeable. However, it is brittle and easily develops fine cracks, especially when applied on masonry foundations. These cracks then draw moisture into the wall through capillary action and trap it inside, leading to failure of the parging. Nonetheless, cement pargings are often applied on foundation walls, sometimes as a base coat to even a rough foundation before another form of surface coating, commonly a bituminous one, is applied.

For application below grade, type M mortar is recommended and is applied in two coats, each at least 6 mm (1/4 in) in thickness. The first coat should be roughened when partially set, hardened for 24 hours and then moistened before the second coat is applied. The second coat should be moist cured for at least 48 hours before backfilling. Parging should be troweled to a smooth, dense surface, extending from the footing to at least 150 mm (6 in) above the finished grade. It should be beveled at the top to form a wash and thickened at the bottom to form a cove between the base of the wall and the footing.

3.4.2 Bituminous Coatings

Bituminous coatings are materials that are produced from coal tar or asphalt. They are furnished in solid form to be melted for hot application and in liquid form, either diluted with solvents or emulsified with water, for application at normal room temperature. Bituminous coatings are impermeable and provide an excellent resistance to the penetration of water. Their cost is low and they are widely used where appearance is not important.

The coating is applied with broom, brush or spray, preferably over a bituminous primer coat. Application of bituminous coatings may be made in combination with some reinforcing material, such as bitumen saturated tar paper to form a built up membrane. It is recommended that the membrane be made up entirely of coal tar products or of asphaltic products but not a combination of both. Cotton, felt, asbestos felt, woven glass fabric and glass fiber mat are all available as bitumen saturated ply material. The masonry surface should first be coated with a bituminous primer. The surface is then mopped with hot bitumen or cold bituminous emulsion, and a layer of fabric is rolled or broomed into the coating, overlapping about 300 mm (12 in) at the sides and ends. The process is repeated until from two to six plies of fabric have been applied, depending on the hydrostatic pressure to be resisted. Membranes of this type have the advantage of maintaining the continuity of waterproofing over possible defects in the wall.

3.4.3 Natural and Synthetic Waxes

Although less common today, beeswax and other natural waxes, fats, linseed oil based varnishes and paraffins were among the first products to be used to protect masonry because of their water repellent properties and chemical inertness. Applied to smooth surfaces and then polished, waxes form an impermeable protective coat. A fairly clear distinction can be made between natural and synthetic waxes.

Natural waxes can be of animal fat, vegetable or mineral origin. They are mainly made of esters, fatty acids and high molecular weight alcohols and of a smaller quantity of acids, free alcohols and hydrocarbons. Beeswax dissolved in turpentine applied to smooth surfaces and then polished forms a protective coat for some length of time. However, one drawback is poor adhesion of the wax to the support and its tendency to become sticky and collect dirt. Petroleum derived waxes include the paraffin wax group, the petrolatum group and the petroleum ceresin group. This last category includes microcrystalline waxes that show special characteristics in relation to other waxes. Microcrystalline wax is a mixture of solid hydrocarbons with a high melting point and good plasticity in contrast to brittle paraffin waxes. The smaller crystals of microcrystalline wax allows them to have flexibility at low temperatures, good adhesion and waterproof properties.

Synthetic waxes, such as polyethylene waxes, consist of polymerized hydrocarbons, ester and oxidized hydrocarbons. In relation to natural waxes, synthetic waxes have increased heat stability and a resistance to hydrolysis and chemical reactions. They are also soluble in many organic solvents. Polymers in synthetic waxes dissolve in water to form clear solutions and are also soluble in organic solvents. They do not hydrolyze or deteriorate under typical conditions. As their molecular weight increases, their water solubility, vapor pressure, hygroscopicity and solubility in organic solvents decreases. At the same time, the freezing or the melting range, specific gravity, flash point and viscosity increase.

The use of waxes for treating masonry is fairly restricted as they often cause yellowing and dulling of the treated surfaces. In the presence of humidity and calcium carbonate, they give rise to the formation of soaps that bleach the original color of the treated surface. Furthermore, the repellent nature of waxes disappears with time and blisters form occasionally under the layer of wax. The depth of impregnation of the layer is always very shallow. Therefore a wax based protection is only valid on non-porous masonry and on good quality limestone

3.4.4 Paints

Paints are one of the most commonly used form of masonry surface coatings. Paint is often used to waterproof or consolidate low quality or deteriorating masonry. There are three kinds of paints commonly used on masonry: latex paints, oil-based paints and portland cement paints and each has its own special characteristics. Only latex paints are permeable to moisture vapors.

Latex paints are water emulsions of such resinous materials as butadienne-styrene, polyvinyl acetate, epoxy resins and acrylic resins. To these basic ingredients are added extenders, pigments, preservatives, defoaming agents dispersing agents and flow agents to produce paints that dry throughout in about one and one half hours as the water of emulsion has evaporated. They may be applied either to dry or damp surfaces, require no curing and provide a permeable barrier. Polyvinyl acetate emulsions produce a much tougher film than the butadiene-styrene types and can be used for exterior as well as interior coatings. One of its most important uses is for an exterior finish for masonry and stucco. Neither of the above latex paints can be successfully applied to a glossy surface and both must be protected from freezing before and during the application.

Oil-based paints are manufactured from the resins of natural oils such as linseed oil, dehydrated castor oil, fish oil, soybean oil or from alkyd resins. The latter are a synthetic formulation obtained by combining a drying oil such as linseed oil with glycerin and an acid component. The oil based paints designed for masonry application are usually reinforced with styrenated oils to improve their resistance to alkalis, but to achieve success with them, surface alkalinity must be reduced by pretreating the surface. They may then be applied to a dry surface. Since they form an impermeable coating, care must be taken to ensure that moisture within the wall does not build up behind the film where it may cause the paint to fail by blistering and peeling.

Portland cement paints are produced in standard and heavy duty types and are sold in powdered form in a variety of colors, to be mixed with water just before use. The standard type paint contains 65% portland cement by weight and is suitable for general use. The heavy duty type contains 80% portland cement and is used where there is a continuous and excessive contact with moisture. An additive, composed of siliceous sand is available for use as a filler on porous or rough textured surfaces. Such paints are applied to a moist surface with a stiff brush and dampened by a fine water spray for 48 to 72 hours until the cement cures. They set by hydration of the cement which bonds with the masonry surface. Portland cement paints contain very little organic matter and are not subject to attack from alkalis, which may be present on some masonry surfaces. When properly applied and cured, they provide good protection against moisture.

Silicate paints contain a binder of potassium silicate. Typical components are potassium silicate, alkali resistant pigments, extenders and thixotropic additives. Silicate paints are highly alkaline; after application they undergo a neutralization reaction with carbon dioxide in the atmosphere. The fact that amorphous silicon dioxide is formed as binding material makes these paints extremely durable. The alkali carbonate by-product is formed only in small quantities that are leached out in the course of several years. Silicate paints should be considered something quite different from film forming paints. Their excellent adhesion to porous masonry is due to a moderate penetration capability. Silicate paints are unburnable and the amorphous quartz type binder provides excellent breathability. Despite these favorable properties, silicate paints are not suitable for all types of masonry. Due to the high alkalinity of silicate paints, they may make iron materials more soluble, resulting in unsightly rust stain.

3.4.5 Acrylic Resins

The remarkable transparency, clarity and weathering characteristics of acrylics have allowed rapid development of their use in the restoration of works of art. Furthermore, they resist sunlight, heat and adverse weather conditions well; they are largely insensitive to water and are barely oxidized when temperatures are not too high, thus proving most satisfactory for outdoor use.

A very wide range of acrylic polymers exists. Although acrylics, in particular polymethyl methacrylate, are extremely transparent, a small amount of UV absorber is usually added to retard yellowing with time. Polymethyl methacrylate also has a good resistance to oxidative photodegradation and only suffers thermal degradation when temperatures excess 200°C. Acrylics do not withstand organic solvents well, however, they can resist weak acids well and they are not subject to microbiological erosion. Ketones, esters and aromatic hydrocarbons are in general very good solvents for acrylic resins. However, alcohols however, are poor solvents for methacrylate polymers.

Acrylics are also made in the form of aqueous dispersions, which have a lower viscosity than the corresponding solution, because the viscosity of dispersions is largely independent of the concentration of solid matter. Formation of a film results from the evaporation of water that brings the particles closer together until they come in contact with one another. The film thus formed is impermeable to water but permeable to water vapors. Polymethyl methacrylate is highly resistant to water and is only slightly susceptible to alkaline solutions at ambient temperatures. However, when temperatures exceed 100°C, polymethyl methacrylate films are saponified and become soluble in sodium hydroxide.

Acrylics can also be converted to thermosetting resins by addition of a cross linking agent such as diamines or peroxides. A number of copolymers can be obtained from mixtures of acrylic and methacrylic esters that can be easily linked under the influence of a catalyst. When applied to a building such products will prevent penetration of water into the walls. Furthermore, condensation or ground moisture originating inside the building cannot be drawn through the wall by capillary action, but it can dissipate only by diffusion as a vapor. Thermosetting acrylic resins offer good waterproofing characteristics and are more resistant to abrasion and to freeze thaw action. However, they cause a slight change in color, and are less reversible and more vulnerable to efflorescence.

3.4.6 Epoxy Resins

Epoxy resins have been used for the consolidation and protection of masonry. Epoxy resins are condensation polymers that can form a wide variety of products now used in civil engineering and masonry conservation. Their versatility is due to their distinctive physical-chemical structure. Various combinations of hardeners, fillers and additives produce varnishes, adhesives, molding resins, synthetically bound mortar and concrete and stone impregnation and protection products. Epoxy resins are rarely used alone, but are transformed into a thermosetting material by the addition of a polyfunctional curing agent, or hardener, which modifies the chemical structure and physical properties of the resin. Because of the exothermic reaction of the epoxy resin with polyfunctional amines can sometimes cause bubbles inside the hardened mass, it is not recommended to prepare too great a quantity of the resin at any one time. It must also be pointed out that the ratio of resin to hardener is rather critical in such a system. To obtain a well-hardened resin, attention must be paid to the type and quantity of curing agent used Too low or too high a degree of cross linkage can result in a final product of inferior quality. The hardening of the resin is always accompanied by the production of heat of polymerization. The room temperature and the temperature reached during the reaction have a great influence on the cross linkage and properties of the final product. A certain increase in temperature is desirable to decrease the viscosity of the mixture. Epoxy resins are highly resistant to acids, bases and organic solvents. However, completely colorless epoxy resins or ones that do not yellow with time are hard to find. Outdoor exposure of epoxy resins may result in chalking and this residue must be removed with soap and water to restore the original appearance. Epoxy resins often form an impermeable coating, therefore, care must be taken that moisture within the wall does not build up behind the surface layer.

The viscosity of resins is of prime importance when they are to be used to impregnate masonry with the lowest possible viscosity ensuring deep penetration by the resin. Part of the difficulty involved in penetrating masonry with an epoxy is due to the hydrophobic properties of the resin, even in its uncured state. Greatly improved results have been achieved with pentaerynthritol tetraglycidyl ether monomer that is soluble in water. Solutions of 33% of this resin in acetone and water with a cycloaliphatic hardener have been used for surface protection. Impregnation of masonry using this method both consolidates it and allows it to breathe, mainly because its porosity is reduced but not totally obstructed. The speed of capillary movement of the solution increases if the masonry is first impregnated with a solvent.

The masonry is first immersed in a mixture of water and organic solvent in which the resin is completely soluble. The use of water ensures the elimination of any gases and soluble salts contained within the masonry. It also facilitates deep penetration of the solvent into the stone. Impregnation with resin is carried out once the water in the masonry has been fully substituted by the organic solvent. For deep impregnation, a low density resin is used; its density can be increased as the surface is reached. This effectively reduces structural differences between the treated and untreated masonry. Acceleration of the weathering process has been observed in such epoxy treated masonry exposed to an atmosphere rich in sulfur dioxide. This has been attributed to perforations in the surface film of the resin that let sulfur trioxide through which then creates pockets of sulfurous acid. Elimination of the surface layer of epoxy on masonry is desirable for many reasons. This can be achieved by use of a solvent before the curing process is completed or by light sanding when the resin has hardened completely. This then prevents the formation of a continuous surface that hinders the normal humidity exchange between the inside and outside of the masonry. It also reduces the risk of the characteristic yellowing of expoxides.

3.4.7 Vinyl Polymers

Vinyl polymers form an important family of thermoplastic product used in the field of protective coatings. Polyvinyl acetate has good resistance to sunlight, particularly to UV radiation. Polyvinyl acetate can be applied either as a solution in toluene, acetone or alcohol solvent or in an aqueous emulsion if surface active agents are added. Low viscosity has been obtained with 1.5% solutions of vinyl acetate in toluene and ethyl alcohol (3:1). However, the low concentration means that several coats must be applied to obtain a sufficiently thick protective layer. The addition of a few percent of dibutylphthalate in the form of a plasticizer to the polyvinyl acetate solution prevents the rapid evaporation of the solvent and hence formation of films of mediocre quality.

The polyvinyl acetate particles dispersed throughout the emulsion have a diameter of 0.1 μm that allows them to penetrate even materials of fairly low porosity. The adhesive strength of polyvinyl acetate is not always very high, especially on siliceous surfaces. Therefore it is sometimes necessary to use primers to ensure good bonding between the surface and the vinyl polymer. Polyvinyl acetate films are colorless, highly transparent and highly resistant to cracking and yellowing. They do not suffer erosion by bacteria or lichen; they are very permeable to water vapor and are resistant to abrasion. However, polyvinyl acetate cannot withstand the effect of prolonged load, especially at high temperatures.

3.4.8 Unsaturated Polyesters

Unsaturated polyesters are condensation products of glycols with an unsaturated dibasic acid such as maleic or fumic acids. Polyesters are difficult to dissolve using inactive solvents, which reduces their use for impregnating masonry. However, they can be diluted using a solvent reactive monomer system such as styrene or acrylic, vinyl or allyl esters. Every precaution must be taken when styrene is employed because it is a potent carcinogen. Different types of fillers are often added in the production of polyesters in order to make reinforced products, to lower prices, modify viscosity, control exothermicity during curing and to reduce shrinkage. Polyesters have a certain sensitivity to water and can undergo saponification in basic media. However, they have good resistance to acids and hydrocarbons. Polyesters are often used in the production of mortars and concrete with a polymeric matrix. These concretes have a higher tensile strength than concretes with hydraulic binders. In spite of the fact that curing of unsaturated polyesters takes place without release of by-products, shrinkage after hardening is quite significant and far greater than that in epoxides. When in contact with a basic medium, unsaturated polyesters can saponify and this leads to poor adhesion and a weakening of the chemical bonds. The use of unsaturated polyester for impregnation of masonry is fairly limited because there are few solvents suitable for reducing their viscosity. There is also a danger of reducing the porosity of the masonry too much as hardening of resin takes place without releasing solvents or by-products. Impregnation under pressure is recommended.

3.4.9 Silicone Coatings

Silicones were among the first synthetic polymers to be used for waterproofing masonry. Silicone is a colorless resinous material produced synthetically from silicon dioxide. When applied to masonry surfaces, silicone causes no change in color or texture. The advantage of silicone-based treatment is due to the fact that these polymers render the impregnated material water repellent but not water proof. The material does not actually seal openings but it does retard water absorption by changing the contact angle between water and the walls of the capillaries in the masonry. Therefore, a silicone coating on a porous masonry allows for a colorless, almost invisible finish, which does not completely fill the pores, but prevents capillary action whilst allowing the movement of vapors.

Silicones are distinguished from other polymers by their good thermal characteristics and oxidative stability. The behavior of silicones is largely dependent on such inorganic properties as their good thermal stability and their chemical inertness. They can be used at temperatures ranging from -50°C to 300°C with only a small variation in viscosity. Their chemical inertia towards atmospheric agents such as the sun, poor weather and ozone make them ideal for exterior application. The water repellent character of silicones is also partly due to their low surface tension and the orientation of molecules at the masonry surface. Silicones also have a low surface tension that allows them to penetrate porous materials and form a film that allows the masonry to breathe whilst at the same time they do not obstruct the pores. However, the repellent nature of treated surfaces practically disappears after six years.

Silicones are available in pure form or as concentrated organic solutions. Silicones in solutions of toluene or xylene can be found in the form of an already completely condensed product, in which case, hardening is by evaporation of the solvent. Sodium methyl siliconate ($CH_3Si(OH)_2ONa$) in aqueous solution can be used as an alternative to silicones dissolved in organic solvents for masonry treatment. Silicic acid alkoxy ester has been used for waterproofing masonry because it can form SiO_2 by saponification. Alkyl-alkoxy-silanes constitute effective water repellents but are not useful as consolidation materials.

Water repellents based on silicone resins are applied in concentration of 5%. Silicone does not bridge large openings, and when masonry with a coarse, open texture is involved, a fill coat should be applied under the silicone. Application of silicone is commonly accomplished by flooding the surface with a low pressure spray. The facade is simply flooded with a controlled amount of material at a maximum pressure of 0.1 MPa (15 psi). Suitable equipment includes electric pumps, hand sprayers and airless sprayers. During the application, the formation of fog must be avoided. The solutions are applied to the surface in such a way that a part runs down the facade in a smooth stream cascade. In general, this type of flooding is carried out two or three times, depending on the absorptive capacity of the masonry. The surface of the masonry should not be allowed to dry completely between the sprayings. The top layer of the masonry may require special treatment since it has the least contact time with the solution.

To prevent evaporative losses, measures against direct irradiation by the sun must be taken such as the installation of temporary awnings. The treated area should also be protected from rain for a certain period of time. However, due to their special formulation, products based on silanes develop their water repellent qualities within four to six hours after application. This self protection mechanism guarantees an unequaled reliability in job site application.

3.5 Desalinization

The capillary movement of moisture through masonry is often associated with salt deposition that tends to be concentrated mainly at or close to the wall surfaces. The disruptive forces associated with the crystallization of these salts cause decay, usually seen as pitting, flaking or powdering of the masonry and surface efflorescence. Drying out of walls associated with a damp proofing treatment or the elimination of the source of moisture entry may also lead to an increase in the amount of salt at or near the wall surface and deterioration may increase rather than diminish unless measures are taken to reduce the salt content of the masonry. Certain salts, particularly chlorides, are hygroscopic and can take up moisture directly from the atmosphere, and dampness and deterioration may persist even after the moisture problem has been resolved. In these circumstances, salts must be removed, or at least substantially reduced, from the surface if deterioration is to be controlled. To remove all soluble salts in the context of a building is of course impossible but a significant reduction in the outer 100 mm may have the effect of stabilizing a previously friable surface or may prepare the way for a consolidant or a surface coating whose curing process would be seriously inhibited by a high concentration of salts such as sodium chloride.

Three methods of removing some of the soluble salts from decaying masonry include the use of clay poultices, the used of a sacrificial sand-lime parging and a new suction method. These techniques are mainly suitable for large plain areas of masonry or simple architectural details. They should not be used on delicate, damaged surfaces of carving or sculptures, nor should the process be used where the pre-wetting would create problems for plaster, painting or embedded wood or metal. Where these methods are considered to be appropriate, they may have to be incorporated into a long term maintenance program, perhaps at every five to ten year intervals, particularly if there is a persistent replenishment of soluble salts. In other situations, where the source of contamination has been removed, a single treatment may be sufficient to effect a long term improvement.

3.5.1 Lime Sand Parging

The application of a sacrificial parging is a technique that reduces the concentration of soluble salts and protects the masonry. A porous parging is applied to the wall and evaporation of moisture from the wall results in soluble salts being transferred from the masonry to the parging. The parging will deteriorate with time and may require renewal, but the masonry is protected against continued decay. A sacrificial parging can be used either to reduce the salt content of a wall where rising dampness treatment is carried out or it can be used to protect a wall against attack where rising dampness cannot be prevented.

The wall is first wetted and a parging of one part slaked and screened lime putty to four parts fine sand is applied at least 12 mm (1/2 in) thick to a height of 50 mm (2 in) above the salt crystallization and evaporation zone. The parging should not be overworked with a trowel as optimum moisture evaporation and salt transfer can be obtained when the render has an open texture and a rough finish to increase the surface area. A practical and visually pleasing way of achieving this is to scrape the surface down after rendering with a fine toothed edge of a hack saw blade. This is carried out after the surface has begun to stiffen.

As salts transfer to the parging and crystallize there, the parging will break down. Salt contaminated parging deposits at the base of the wall should be collected frequently. Where contamination is severe, the application of a single coat of parging is insufficient to reduce the salt content to an acceptable level and further treatment is required. The remains of the first coat should be carefully removed, the wall re-wetted and a second coat applied.

Sacrificial sand lime pargings are a relatively slow method of masonry desalinization. A period of several months may be required depending on the amount of salt and the extent of evaporation. However, the process is however inexpensive and easy to undertake. Most success has been achieved before the installation of any damp proofing was carried out.

3.5.2 Clay Poultices

This form of deep washing of masonry involves saturation and the subsequent application of an absorbent clay poultice to try and reduce the level of potentially damaging soluble salts concentrated within the surface of the decaying masonry. A further use of the absorbent clay poultices is as a temporary plaster after the installation of a damp proof course. The cycle of wetting and poultice application may need to be repeated several times to reduce the salts to an acceptable level. Clay poultice desalinization is a lengthy process but it does not require a lot of supervision, expensive equipment or highly skilled workmen.

In principle, the desalinization technique is very simple. A wall is saturated for several days by spraying with mists of clean water, until wetting has occurred to a considerable depth. Fine sprays mounted on a boom delivering 200 liters per hour are sufficient to feed six spray heads covering an area of seven meters square. The spray set-up must be designed to produce a consistent pattern of wetting. The wetting period is determined by the construction of the wall and the porosity of the masonry, but it is likely to extend over three days and nights. Small areas may be persistently wetted manually but this is labor-intensive and tends to be less effective. In some situations, it is sensible to carry out dry brushing before wetting, making sure that the loose material is removed from the site. During the wetting process temporary gutters are required to collect runoff from the wall surfaces and to conduct it to a runoff point well away from the base of the masonry wall. More information on water cleaning is provided in the section on masonry cleaning.

When the wetting process is complete, the absorbent clay, usually attapulgite or sepiolite clays (50 mesh), is added to just enough clean water to make a soft, sticky paste. Water must not be added to the clay, otherwise a lumpy unworkable mix is formed. The clay poultice can then be mixed by hand or by using a small mechanical mixer, depending on the quantity required. When free of lumps, the poultice is plastered onto the wet masonry wall in a single layer 20 to 25 mm (up to 1 in) thick using a broad trowel. A 50 kg bag of clay covers approximately three square meters. In its freshly mixed state, the clay has very good adhesion and it can be leveled reasonably accurately, even by a relatively inexperienced workman. An important part of the technique is ensuring good contact at all points. To help the clay keep its bond for as long as possible, a light gauge plastic or galvanized wire mesh is pressed into the poultice and tacked carefully into the joints with galvanized staples. Any springiness in the mesh can be reduced by localized cutting with wire snips and pressing the cut ends into the clay. In some cases where the wall surface is heavily contoured the overall adhesion of the clay can be assisted by cutting strips of burlap soaked in a runny slurry of attapulgite clay and pressing these into the poultice. These strips, approximately 75 mm (3 in) wide, may be used alone or with a wire mesh. Wire mesh is essential on a large area or flat surface where the weight of the clay tends to induce pulling away from the surface.

When the treated wall is fully plastered, it must be protected from direct sun or rain or from any heat source that produces rapid drying. A ventilated space can most easily be set up with a tarpaulin or reinforced plastic sheet as a tent. As the poultice dries out, it draws salt laden water from the masonry. Water evaporating from the clay face leaves behind salt crystals that can usually be seen in the form of efflorescence on the clay. Drying conditions and the thickness of the wall dictate the contact time that varies considerably from a few days to a few weeks. One month is not unusual for drying out, during which the clay lightens in color, cracks, shrinks and detaches from the wall. At this stage the staples are withdrawn with pliers, and the bulk of the clay may be rolled up on its wire reinforcement. The spent clay should be put at once into plastic sacks or otherwise removed from the site. Small amounts of clay still adhering may be brushed off the wall with a stiff bristle brush. Special care must be taken to remove all traces of dry clay from the joints. These sweepings must also be removed from the site.

3.5.3 Suction Technique

An alternative method of removing excess salt from masonry makes use of suction while fresh water is run over the stone surface. Although still in an experimental phase, further development could provide a method that could permit almost complete extraction of salts in a short time.

In laboratory experiments, a stream of running water is applied on all sides of a stone previously impregnated with a solution of sodium chloride. The vacuum pump is started after nearly a half hour of water application which resulted in water penetration to a depth of at least 19 mm (3/4 in) into the stone. A vacuum pump with the capacity to displace nearly 150 l of air per minute is connected to a funnel 75 mm (3 in) in diameter and suction is applied by attaching the funnel to the surface of the stone using a silicone sealant. A suction force of 87 to 96 kPa is applied to bring water through stone and remove the soluble salts. Analysis of the water drawn through the funnel would indicate that the extracted water is nearly saturated and confirms that the suction procedure is effective in removing soluble salts. The salt content is reduced to an almost indeterminable quantity at and near the site of suction application. Upon drying, efflorescence does not appear on the suction treated specimen.

The above suction technique appears to promise maximum removal of the salt in the shortest time possible and with the least expense. The application of industrial air compressors, which can displace large volumes of air, and a proper design of exit ports could permit cleaning of several square meters of surface per day. Needless to say it is essential to develop appropriate systems for specific needs.

Chapter 4

Mortar Repairs

Mortar is the material that binds together the individual masonry elements into a structural entity ensuring a watertight seal. Mortar also compensates for irregularities in the stones or bricks, which would otherwise lead to non-uniform stresses and cracking of the masonry units. A wall made up of several small units absorbs inevitable slight movement, including variations in the temperature and moisture gradient, settlement and vibration. To absorb these movements, the mortar must be somewhat weaker than the masonry units; otherwise the masonry units become the weakest part of the wall, and even slight movements would cause the brick or stone to crack or spall. If the mortar is too strong, it also tends to be more impermeable to the moisture than the masonry units and thus prevent drying through the joints; consequently moisture movement is concentrated in the bricks or stones leading to damage of the masonry.

The information in the following sections is adapted from the works of (Ashurst and Ashurst, 1988), (London, 1988) and (Sowden, 1990)

4.1 Repointing Cracked and Deteriorated Joints

Unlike most other parts of a building, mortar joints are not designed to be permanent, although a good pointing job should last from 50 to 100 years. Repointing is the process of removing deteriorated mortar from the joints of a masonry wall and replacing it with new mortar. Properly done, repointing restores the visual and physical integrity of the masonry. Improperly done, repointing not only detracts from the appearance of the building, but it may in fact cause physical damage to the masonry units themselves

The decision to repoint is most often related to some obvious sign of deterioration such as disintegrating mortar, cracks in mortar joints, loose units, damp walls or damaged plaster work. Because repointing alone does solve all these problems, their true cause should be determined and dealt with before repointing, or the mortar deterioration will continue and the repointing would have been a waste of time and money.

Repointing is a lot harder than it looks. Preparing the joints properly, getting a good color and texture match, and filling the joints so that the mortar adheres properly is the job of an expert. Repointing is both expensive and time-consuming because of the extent of hand work and special materials required; however, repointing only those areas that require work rather than an entire wall may avoid unnecessary expense.

As a rule, if the pointing is firm, intact and not eroded more than 9 mm (1/3 in), it should be left as it is. The following circumstances warrant repointing: when the mortar is deeply eroded or has fallen out; when joint cracks have formed in the mortar; when the masonry units and the mortar do not adhere, resulting in a crack or gap between the two, or when the mortar is sitting loosely in the joint. It is unlikely that all the joints of a building would need repointing. Just because a screwdriver can be poked into the mortar joint does not necessarily mean it needs replacing; the lime mortar found in most older buildings should not be very hard. Good practice calls for repointing only those parts of the wall that really need it, not necessarily the entire wall. However, to maintain a uniform appearance, some sound mortar may be sacrificed if a majority of mortar joints in the same location have deteriorated and need to be replaced. It is important to carefully assess whether fine joints in stone or brick need repointing as removing old mortar presents an especially difficult task. Also, removing portland cement mortar is quite difficult, and the removal process could prove more harmful to the masonry than leaving the mortar in place, unless signs of spalling are obvious.

It is generally better to remove paint or clean the masonry before repointing. However, if the mortar is badly eroded, allowing moisture to penetrate deeply into the wall, the joints should be temporarily plugged with foam backer rods or strippable caulking or repointing should be done before cleaning. Repointing should be carried out as one operation after all masonry repairs are completed.

In choosing contractors or masons, it is useful to have them prepare a test panel on which joint preparation and repointing skills can be demonstrated. First, an area of masonry in good shape is selected to serve as the control section for comparison purposes. Then, a meter square (three foot square) section of masonry is selected, preferably in an inconspicuous location that includes the types of masonry, joint styles and variety of problems expected on the actual job, and it is repointed. The joints of the panel should be checked before being filled to ensure that they are properly cleaned out and are checked again on completion against the original control panel. Once accepted, the test panel can serve as a standard reference for the entire job.

4.1.1 Mortar

After deciding to repoint, the next question is what kind of mortar to use. All mortars are made from the same basic ingredients: water, an aggregate, usually sand, and a binder such as lime, cement or a mixture of the two. Lime was used almost exclusively as a binder until the introduction of portland cement in the 1870s. Additives are sometimes added to modify the color, increase the resistance to frost or speed up the setting time of the mortar, although their use is not generally recommended for old and historic buildings.

Aggregates make up the largest part of mortar. While sand is now used almost exclusively, other products also serve as aggregates in older buildings. Sand gives mortar most of its characteristic color and texture. Sand color may range from white to gray to yellow within a single sample. Also, because sand was not often screened and graded as it is today, the size of grains may vary from fine to coarse. Therefore in order to match the range of colors and grain size in the original sample, it may be necessary to obtain sand from several sources and then combine it. Even in a simple, small job, some coarse grade sand may have to be added to the standard packaged sand, unless the joints are so fine that the look of the mortar does not play an important visual role.

Natural beach or river sand has rounded edges and provides a better visual match with old mortar. Natural sand can produce good plasticity with less water, allowing the mortar to be forced into the joints more easily and forming a better contact with the old mortar and the masonry. Manufactured sand, made by crushing stone, has sharp, angular edges. It generally produces higher strength mortar but may be more difficult to work and to match visually with old mortar. The sand in repointing mixes should be clean and should match the original as closely as possible to provide the proper color without other additives.

Other aggregates in mortar usually make up a very small portion of the total. However, these aggregates may be important in achieving a good color and texture match. For heritage buildings, it is especially important to identify them in the original mortar and specify them in the new one, suggesting if possible where they may be obtained. Other materials that may be found in old mortars include animal hair, clay particles and partially burned lime.

Binders in mortar are a cementing material generally consisting of lime and portland cement in various proportions. Lime is the binder of choice for repointing old masonry. It can be used alone, or, in certain cases, cement may be added to improve setting and durability. The proportion of cement may be increased according to the strength of the masonry and the exposure of the wall. High lime mortar is soft and porous and changes little with temperature fluctuations. Because it is slightly water soluble, it can reseal hairline cracks by combining with moisture from the air. Until World War II, quicklime (calcium oxide) was used, made by burning limestone (calcium carbonate). It was then slaked by adding water to create hydrated lime (calcium hydrate); lumps of fresh quicklime were added to water, the mixture was stirred until the chemical reaction was complete, it was strained through a mesh and, finally stored for at least two weeks under water in sealed containers. Handling lime in this form was quite dangerous, even for experienced workers. Since World War II, pre-hydrated lime, a powder form, which can be mixed immediately before use and with more safety, has generally replaced quicklime, despite the fact that traditional slaked lime is considered to produce a better quality mortar.

Cement was used widely by the end of the nineteenth century; the most common cement powder in use today is portland cement, an extremely hard cement that is virtually impermeable to water. It is much too hard to be used as the only binder in mortar, particularly for older masonry of soft brick and stone. Ordinary gray portland cement may also have a high content of harmful soluble salts. However, white non-staining portland cements have a low alkali content, which can help avoid efflorescence and are usually mixed with lime to quicken the setting. Speeding the initial set can improve durability and increase frost resistance.

Portland cement combined with gypsum, hydrated lime or limestone dust as well as clays and other substances is sold as premixed masonry cement in a variety of colors. In northern areas, this mix includes agents to increase frost resistance. There are two problems with masonry cement. It is generally too hard, particularly with the soft bricks and weak stone of older buildings. Adding more than the normal amount of sand might weaken it enough to make it acceptable for use with harder brick and stone. The second problem is that the composition of the mix, rarely indicated on the package can vary considerably from one manufacturer to another. If an acceptable mix is found, masonry cement can save time and is less subject to inconsistency than mortars mixed on site, however, it must be specified that the contractor is not to substitute another brand.

In new construction, additives are sometimes used to modify the chemical reactions in mortar in order to increase durability or improve working qualities. Modern chemical additives are, as a rule, unnecessary and may have a detrimental effect on old masonry walls.

Anti-freeze compounds, such as calcium chloride, were once commonly used to retard the freezing of the water in the mortar when pointing was carried out at near freezing temperatures. These additives tend to be detrimental to high lime mortars because they introduce salts, which may later cause efflorescence, stimulate corrosion of metals in walls and even break down mortar.

Air entraining agents are often used in northern climates to increase the amount of air in cement mortars, thereby, improving their plasticity and resistance to freeze thaw cycle. However, these agents may also reduce bonding ability and compressive strength.

Although chemical, or bonding, agents can improve the bond with old mortar and adjacent surfaces, they is no substitute for proper joint preparation. They increase the strength of the mortar unnecessarily while making it less porous and more brittle. They can affect color, giving a bluish or greenish tint, reduce breathability and by dramatically reducing the ability of the mortar to weather, prevent the aggregates from naturally producing a proper color match to the old mortar. In addition, it is difficult to clean off mortar mixed with these agents and smeared on the masonry surface.

4.1.1.1 Mortar Analysis

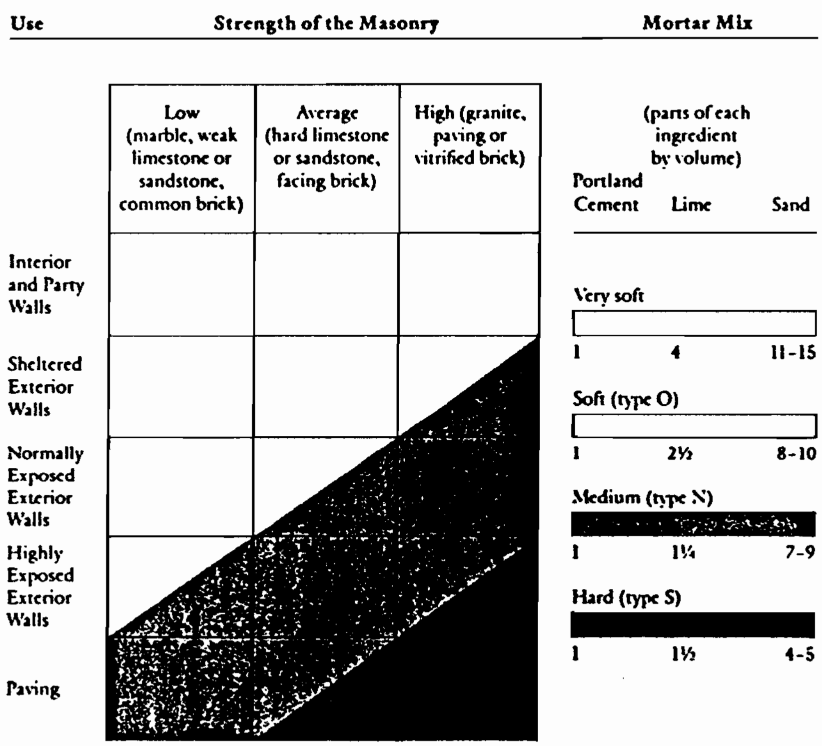
Unweathered samples of the mortar to be matched should be removed with a chisel. If the masonry has been repointed several times, it is important to remove several samples of the different mortar to obtain a mean mortar sample, clearly avoiding the more recent samples. The largest section should be set aside to be used later for comparison with the repointing mortar. The remaining samples should be reduced to a fine powder with a wooden mallet. To establish the nature of the binder, part of the powdered mortar is stirred into diluted hydrochloric acid. If there is a vigorous chemical reaction and most of the binder disappears, leaving clean aggregates, then the binder was lime. Cement leaves a murky liquid that dissolves very slowly over several days. To establish the nature of the aggregates, some must be isolated. The aggregates left after the dissolution of the binder in acid can be rinsed and dried. The aggregates can then be examined with a microscope or magnifying glass. The range of colors and the varying sizes of the individual grains should be noted as well as the presence of other materials.

4.1.1.2 Mix Formula

No single mix can be used for all repointing projects. The mix depends on the circumstances, particularly the type of masonry and its exposure. Historical research on a building may turn up the formulation of the original mortar mix, which is usually a good guide in selecting a repointing mix. Although a century old mortar eventually deteriorated, this does not mean that anything was wrong with it; mortars have a limited life span. Even if the formulation of the original mortar mix is known, it may produce a different looking mortar using the ingredients available today. Knowing the formulation of the existing mortar, however, is a useful aid in developing an appropriate mortar mix for many rehabilitation and most restoration projects, and is especially useful with buildings of special historical significance.

A pure lime-based mortar is quite slow to cure; while it initially sets in three days, it takes months to develop its full strength. with soft historic brick and limited exposure, a little white portland cement can be added to accelerate the setting and improve its durability. With hard bricks and average strength stones, the proportion of cement in the binder may be increased from 20 to 40%. With highly exposed granite, the cement might make up as much as 50% or more of the mortar. Figure 4.1 shows appropriate mortar mixes for various kinds of traditional masonry under different exposure conditions.

Figure 4.1 Guide to Mortar Mixes (London, 1988)



4.1.1.3 Matching Original Mortar

It is not sufficient to simply match mortar properties; the new mortar should also visually match the color and texture of the existing mortar. The aesthetic tradition of stonework is generally different from that of brick masonry, as the joints are usually close in color and texture to the stone. Every attempt should be made to follow this tradition working on the basis of the surviving evidence. With brickwork, the final color and texture of the mortar is particularly important as it forms up to 30% of the surface area of the wall, so in time, the colored texture of the sand will dominate.

It is best to achieve a color match through careful selection of aggregates and binding materials; this will produce the most consistent and permanent results. The color of the aggregates, especially sand, is important because it controls the overall color. The grading of the sand particles is also significant because of its effects on the properties of both plastic and hardened mortar and its contribution to the texture of the repointed mortar surface. However, if it is not possible to obtain a proper color match, it may be necessary to use a mortar pigment. In fact, in the late nineteenth century, some mortars were colored with pigments to match or contrast with the masonry units; red, brown and black pigments were commonly used. If colors are required, chemically pure synthetic oxide pigments, which are alkali proof and resistant to UV radiation, should be specified to prevent bleaching and fading. They should not exceed 10% of the volume of the binder. Carbon black should be restricted to no more than 3% by weight. Organic dyes should not be used because they inevitably fade.

To match old and new mortars, a broken off sample can be snapped in half to expose its unweathered interior and compared directly with a cured sample of the new mix. Samples from several mixes can be prepared to select the closest match. Setting can be speeded up in an oven. Alternatively, the old mortar sample can be wetted and compared to the wet mix of the new mortar. If the new sample matches the unweathered surface of the old mortar sample, it should eventually weather to match the original mortar on the building exterior.

Even with the best efforts at matching the old mortar color, texture and materials, a difference is usually visible, partly because the new mortar has been matched to the unweathered portion of the original mortar. If the mortars have been properly matched, it is best to let the new one age naturally. No artificial aging technique should be used without careful evaluation and testing. Various substances, ranging from solution of potassium permanganate and carbon black to beer and manure, are commonly used to stain the new mortar. Staining is generally an unreliable and unstable technique; it may provide an initial match but the old and new mortars may then weather differently, leading to visual differences after a few seasons. Also, some mixtures used to stain the mortar may be harmful to the masonry.

Tooling may also affect the appearance of the joint. The tooled joints may not match the mortar in adjacent weathered joints whose lime or cement has eroded, leaving the sand exposed on the surface. Also, a smoothly tooled joint may not be visually appropriate for rough rubble walls. If a weathered appearance is desired to match the existing surviving work, a rough texture can be produced after the initial set of the mortar has taken place by light spraying, by stiff bristle stippling or by dabbing with coarse sacking. Experience and understanding of what is required on the part of the mason is essential. Of the above techniques, stippling with the end of a stiff bristle brush is probably the most successful. The bristles should not be dragged across the face but tapped against it. Timing is critical and no specification can substitute for experience. If the technique is applied too soon, mortar is removed too easily and the bond forming between mortar and masonry unit is disrupted. However, if the technique is applied too late, it is difficult to make an impression and vigorous effects may be implemented with wire brushes or masons' drags to achieve the desired effect. Apart from leaving a pleasant, weathered appearance, the rough textured joint tends to assist the wall to dry out and to concentrate on the wetting and drying activity in the joints. Techniques that seriously abrade the surface should be avoided.

4.1.1.4 Mortar Preparation

Mortar should be mixed carefully to avoid lumps and uneven color and ensure uniform strength and texture. Dry ingredients should be mixed first before adding any water. Water used in mortar mixes should be pure enough to be drinkable. It should be clean and free of salts, acids, alkalis or large amounts of organic material. Half the water should be added, followed by mixing for approximately five minutes. The remaining water should then be added in small proportions until the desired consistency is reached. The proper consistency uses the minimum amount of water to allow mortar to stick to a trowel held upside down. More water makes the mortar easier to work but it shrinks more, smears more easily and is not as strong. The total volume of water necessary may vary from batch to batch, depending on the weather conditions. It is best not to work at freezing temperatures, or if this is unavoidable, to warm the sand and water and protect it from freezing.

Mortar should be used before it begins to harden, generally between one and two hours of final mixing. The mortar should not be mixed in too large a quantity. Retempering or adding water after the initial mix is prepared should not be done. A mix of lime and sand with no cement can be made up in advance and stored in airtight containers; the cement, if necessary, is added only when the mortar is used.

4.1.2 Preparing the Joints

The difference between a good and poor repointing job is not always obvious. Merely brushing away the loose mortar and refilling the mortar joint produces a repointing job that may look good for several months, but within a few years the mortar will pop out of the joints. Good preparation of the joint requires careful work but it is essential to achieve a repointing job to last the 50 to 100 years. It is during preparation for repointing that the masonry runs the greatest risk of permanent damage; cleaning out the joint should be undertaken only by experienced workers using hand tools under close supervision of an experienced mason. Time for cutting out, which may be considerable, must be properly scheduled. Inadequate cutting out and the inevitable shallow depth of repointing which follows is a complete waste of time and money.

Raking out may be a simple operation without any risk to the masonry units where the mortar is substantially decayed, but it is over-simplifying the situation to say that the joint does not need repointing if it requires cutting out. Not infrequently, the face of a lime joint is lost in its early life, before sufficient drying out and carbonation takes place to enable it to resist the winter, but more protected mortar survives to become extremely hard. The empty joint at the face may be considerably risky to leave alone, and additional cutting out may be required to achieve enough depth for repointing. More often, cutting out is necessary to remove dense repointing of an earlier period, especially where this mortar is causing problems because of its high strength, impermeability and tendency to trap water behind it and accelerate the deterioration of the masonry.

All loose, crumbling, powdery, excessively soft, badly deteriorated or cracked mortar should be raked out to a uniform minimum depth and the full width of the joint, preferably using hand rather than power tools. As a rule, joints should be cleaned out to a minimum depth of 25 mm (1 in) and never to a depth less than their width. To ensure an adequate bond, the joint should be raked to a depth between two and two and a half times the width of the vertical joint, usually 13 to 19 mm (1/2 to 3/4 in) deep with brick and 25 to 50 mm (1 to 2 in) with wider stone joints. Wide joints, especially liable to exposure to extreme weathering, should be cut out to a minimum of 38 mm (1 1/2 in) or even 50 mm (2 in). Proper depth ensures that there is adequate surface contact between the mortar and masonry so that surface adhesion and friction creates a good bond without the use of special bonding agents. Mortar should be removed cleanly from the masonry, leaving square corners and a flat surface at the back of the cut. Any loose and deteriorated mortar beyond this minimum depth should also be removed. Sometime the mortar disintegrates to such an extent that the joints are largely empty, in which case they must first be deep tamped and, if necessary, grouted to fill the joint to the required depth for repointing. If tamped or grouted mortar comes closer to the surface than 25 to 38 mm (1 to 1 1/2 in), it must be cut back to the proper depth and to a square before repointing can proceed. A fine joint requires careful cutting with a fine toothed saw blade or hooked knife blade. The inserted blade indicates when an adequate depth has been cut out. It is advisable to cut out to a depth of 25 mm (1 in).

The best way to remove old mortar is by hand using a small headed chisel, no wider than half the width of the joint. Although handwork is more time-consuming than using power tools, it presents far less risk of permanently damaging the brick or stone. Cutting out should be achieved with quirks, plugging chisels, long necked jointing chisels and toothed masonry chisels together with a 1.1 kg (2 1/2 lb.) club hammer. Impact should be at an oblique angle to the joint face, not directly onto it. Hack saw blades and masonry saws may also be useful. Drilling with masonry drills is a useful way of creating an initial breach into a strong mortar. All cutting out should leave a clean, square face at the back of the joint to provide optimum contact with the new mortar.

For most part, power tools such as circular saws with carbide blades or pneumatic impact hammers almost always damage the edge of masonry units and over cut the end of joints, especially the vertical joints in a brick wall. Damage to the brick or stone not only affects its visual character but can also lead to accelerated weathering. Power tools may appear to do an acceptable job during demonstration by a contractor, but when construction is under way and the day wears on workers using power tools tire and the masonry inevitably suffers.

Power tools, if they are used to remove masonry joints, should be used only under the most controlled circumstances. Where joints are uniform and wide, it may be possible to begin the removal process using power tools, if the work is done by experienced workers under close supervision. Exceptionally small carborundum or diamond discs may be used in cutting out the middle third of continuous horizontal mortar joints, but only on regular coursed work with level beds where running rules can be fixed to the wall as guides for the power tools. The risks of over running are obvious, and extreme caution must be used not to cut into the masonry units, or increase the width of the joint. The remaining top and bottom thirds of the horizontal joint, along with the vertical joints, should be finished by hand with a chisel.

In certain circumstances, such as removing portland cement from very narrow joints, very low power, high speed power tools in the hands of a skilled worker might not be as risky as using a hammer and chisel, but only if the mortar must really be removed. Specifying that the mason or contractor replace all bricks or stones damaged during mortar removal with an exact match is one way to encourage the adequate care is taken to avoid damage, but it could have the unintended effect of encouraging carelessness. Power tools should not be risked on buildings of great significance.

Before filling the joints, any bricks or stone that are loose should be reset. Any piece of brick that has been chipped off while chiseling out the old mortar can be glued back with ceramic glue; stone can be reattached with epoxy. The prepared face should be cleaned out with a soft or stiff bristle brush and thoroughly flushed out with water, avoiding unnecessary saturation. Fine joints must be flushed out using a large hypothermic syringe and clear water until water runs out clean. All dust and loose material must be removed, working from the top to the bottom of the wall. If old, weathered out joints have been colonized with algae or lichens a biocide treatment should be used on the dry surface as part of the cleaning. At the time of filling, the joints should be damp to prevent excessive water absorption from the new mortar, but no standing water should be present.

4.1.3 Filling the Joints

To prevent freezing or excessive evaporation of water in the mortar, repointing is best carried out when the wall temperatures are between 5° and 35°C (40° and 95°F). During hot weather, repointing should be done on the shady side of the building to slow the setting; the wall should be covered with burlap or a tarpaulin while the mortar sets.

If the joints have dried out after cleaning, they must be wetted before placing the new mortar. The area to be repointed should be damp, but not wet, to slow down the absorption of water from the new mortar before it is properly set; otherwise, the mortar will not cure and adhere properly and thus it will be weaker. Freestanding water or excessive dampness will delay the curing or cause excessive shrinkage.

The mortar is pushed into the joint from a board and ironed in with the maximum possible pressure. Pointing trowels are in common use but pointing keys can also be extremely useful. These may be cranked bronze or steel flat ,or beaten out rod or even wood, improvised to suit the particular work at hand. Even if the mortar is placed in the joints with a gun, which is increasingly popular where large areas are involved, the mortar must be subsequently packed with a pointing key. The function of these keys is to push the mortar evenly into the full joint width; this they can do because they fit into the joint and do not try to achieve compaction from the surface alone. In irregular work, this is particularly important.

Ideally, the joint should be filled in successive layers, allowing each layer to harden before adding the next layer. Layering minimizes overall shrinkage, which can reduce the water tightness of the joint. Joint areas deeper than 25 mm (1 in) should be filled first, compacting the new mortar in several layers until the back of the joint is flat. Then a 9 mm (1/3 in) layer of mortar is applied to the back of the joint, packing it well into the back corners. Several 9 mm (1/3 in) layers are needed to fill the joint flush with the surface of the masonry. Each layer of mortar should be allowed to reach thumbprint hardness before the next layer is applied. If deep pointing is to be carried out in one operation without layering, the mortar should be stiff and well compacted.

Some joints are so fine that they make traditional pointing impractical. Stone masonry with fine joints may be worked to true, flat beds but more commonly are hollow bedded to allow for a generous mortar fill and a fine joint at the face. This is an economic way of producing a fine quality appearance. To fill these very narrow joints without smearing mortar on the masonry surface, masking tape can be used to protect the brick or stone. A strip of adhesive tape is laid over the joint and slit into the open joint with a sharp knife blade. The edges of the tape are pressed into the cut and the mortar pressed home with a pointing key. After compacting as much mortar as possible into the slit, the tape is carefully peeled away.

Alternatively, the mortar can be inserted between two strips of plastic that are placed in the joint. Two thin sheets of stiff plastic, approximately 150 mm by 225 mm (6 in by 9 in) for the bed joints and two sheets approximately 150 mm by 75 mm (6 in by 3 in) for the vertical joints. A finely screened mortar is prepared and then spread with a trowel on the plastic sheet with the second sheet laid on top to form a sandwich. The mortar should form a 50 mm (2 in) wide band between the sheets. This sandwich is then maneuvered into the back of the clean, damp, joint. The two leaves of plastic are opened where they project from the joint and the blade of a flat ironing tool inserted in between them against the face of the wall. Keeping a firm pressure on the blade, the two sheets of plastic are removed, one at a time, and the mortar remains in the joint. Any surplus or spread of mortar can be trimmed off with a clean pointing trowel.

A third technique for repointing fine joints involves grouting. A small pointing trowel or spatula is used to seal the outer surface of the joint with a thin coat of mortar, 3 to 5 mm deep. A hypothermic syringe can then be used to slowly inject grout into the joint. This grout typically consists of four parts hydraulic lime, one part finely powdered brick dust and twelve parts gauging liquid. The gauging liquid consists of water to which one half part of acrylic emulsion is added. Holes should be opened at approximately 150 mm (6 in) center to check the grout flow and allow air to escape. These holes can then be cleaned off the surface with a hand spray and a small bristle brush. This method is suitable for fine joints in stone ashlar, but it is not recommended for brick masonry.

The mortar face should be filled flush, or slightly recessed to avoid spreading the mortar over the face of the masonry. If the stones or bricks have retained their sharp arrises then the joint should be filled flush again. Long years of weathering, however, would normally have blunted these arrises and sometimes the original face of some stones would have spalled off. Flush filling in these cases greatly increases the apparent width of the joint and, therefore, great care must be taken to keep the face of the new mortar within the original joint width, however far back that may be. This type of finishing, however, is not adequate and can actually make the surface more porous by creating a rough texture. To give mortar a smooth, denser outer layer, the joint must be tooled. Even if an untooled joint is being matched, it is generally best to tool and then let the joint weather or treat the surface to match.

Tooling is the process of smoothing the joint with a finishing tool narrow enough to be placed inside the joint. This tool, commonly known as a sliker, is pulled over the surface of the mortar to compress it. By bringing the binder to the surface, compression creates a slick film, often a color different from the rest of the joint. This film, which may initially inhibit water absorption and evaporation to weather with time or it can be carefully removed after pointing. Proper timing is essential. If the mortar is tooled when it is too soft, the color will be lighter than expected and hairline cracks may develop; tooling when the mortar is too hard may cause dark streaks and prevent good closure of the mortar against the unit.

The shape of the joint plays an important part in its efficiency and durability. Pointing styles used on masonry and methods of producing them should be examined and reproduced to match the original joint profile. A mortar joint should shed water to avoid accumulation and penetration of rainwater between the mortar and the masonry units. From this point of view, the best profile is the concave joint; the worst is a joint that projects from the masonry, exposing a wide surface of the mortar to weathering. Thick strap pointing overhanging the joint shortens the life of the masonry, especially when the surface is already weakened. If the original pointing had joint shapes that did not shed water properly or that had excessively thin edges that have broken off, it would be wise to select a joint shape that resembles the original but is more technically sound. The appropriate joint depends on the type of masonry. Because fieldstone and old brick have irregular edges, completely flush joints should be avoided, as they would leave thin, delicate edges that could easily break off and allow water to infiltrate; here, joints should be slightly recessed and concave. Flush joint may be appropriate only for thin joints with regularly cut stone or regular brick, but these, too should be properly tooled, not merely scraped with a trowel. Occasionally, horizontal and vertical joints in a wall may have been tooled differently. Some buildings have recessed horizontal joint while the vertical joints were finished flush and pigmented to match the masonry, thus creating the illusion of horizontal bands. Pointing styles also differed from one facade to the other, with the front walls receiving greater attention than side and rear walls.

When stopping for the day, repointing should end at joints in the building, for instance, vertical elements such has pilasters or the edges of an arch or horizontal elements such as window sills or a string course. Finished work should be protected from direct sun and rain until the face has dried and hardened. In hot weather, a light misting will help slow down the setting and prevent suction from adjacent masonry. Burlap or tarpaulin can be used to keep off the sun or heavy rain for the first few days.

Carefully executed repointing should need little cleaning. Bits of mortar that fall off the trowel or are forced from the joint edges by tooling are best removed with a stiff dry or lightly dampened brush after the mortar has undergone initial set, but before it has hardened. Hardened mortar can usually be removed with a wooden paddle or, if necessary with a chisel. Smears on the wall should be cleaned up after a day or two, after the mortar has developed some resistance. This should be done with a stiff natural bristle brush and plain water. On glazed or polished surfaces, only soft cloth is appropriate. Because the binder of lime rich mortars is acid soluble, acetic acid may also be applied with a small brush and then flushed with water. Improper cleaning of a large area can lead to mortar deterioration and discoloration as well as efflorescence.

If a full wash down of the building is required to remove mortar bits, test panels should be used to evaluate the effects of the cleaning methods. New mortar joints are especially susceptible to damage, because they do not become fully cured for several months. The mortar should be completely hardened before a masonry cleaning project is undertaken; thirty days is usually sufficient, depending on the weather and exposure.

Following repointing work, efflorescence occasionally appears within a few weeks of repointing, although this is rare with lime mortars. It should disappear through normal weathering.

4.1.4 Scrub Coating

The terms slurry coating and scrub coating refer to new techniques that involve brushing a thinned, low aggregate coat of mortar over the entire surface of the masonry. When dry, this coat is scrubbed off the brick or stone with a stiff brush, presumably leaving sufficient mortar in the joints. Other methods, termed mask and grout or tape and grout, call for taping the edges of the joints to protect the masonry and brushing the slurry in the joints. These techniques may seem appealing because they are quick and inexpensive compared to traditional repointing and do not require skilled craftsmanship. However, they should not be confused with or substituted for true repointing and are especially inappropriate for heritage buildings.

Scrub coating may be of limited use in sealing hairline cracks in the mortar, particularly with very fine joints where repointing would be difficult. For the most part, these superficial cosmetic techniques do more harm than good. They tend to mask joint detailing or tooling, have a service life of only a few years and may be extremely difficult to clean from the surface of the masonry without leaving a residue called veiling.

4.2 Grout Injection

The consolidation masonry often involves the need to stabilize walls by filling cracks and voids within their thickness. The injection of liquid grout avoids dismantling and rebuilding defective masonry in many cases. This operation is most commonly used when cracks extend deep within solid masonry walls or when thick walls of double skin construction with rubble core filling have been subjected to the percolation of water for many years. The tendency of this washing action is to cause the mortar to disintegrate and either wash out of open joints or accumulate as loose fill at the base of the wall, sometimes causing bulging, cracking and displacement of stones. The absence of such evidence from the surface, however should not be taken to indicate a solid and stable condition within. Disintegrated joints must always be raked out and probed for voids and sounding with a hammer carried out to test for hollows. The removal of selected units and the drilling of deep cores, 100 mm (4 in) in diameter are other ways of investigating the core. Shallow stones placed in the wall as put log fillers can often be conveniently removed to allow for exploratory coring. In special circumstances where large areas are involved, it may be advisable to carry out a detailed investigation of areas where voids or internal fractures are suspected. Examination may be by gamma radiography, ultrasonic measurement or ground penetrating radar.

4.2.1 Grout Mixture

Grout consist of a binder usually blended with other fine powders as fillers and with admixtures to improve or modify the liquid and hardened properties of the grout. The variety of grout mixtures is as great as the variety of mortars, although until recent times grouts consisted only of ordinary portland cement and water.

Cement used in grouting can be of almost any type, but ordinary portland cement (Type 10) is used more often, with rapid hardening and sulfate resisting cements specified for appropriate conditions. A more finely ground cement will permeate fine fissures better and set more quickly. Although neat cement grouts are sometimes used where high strength is required these are not recommended for grouting masonry walls. Large quantities of this kind of neat cement grout can create considerable problems because of the formation of partially soluble materials such as calcium and sodium hydroxide during the setting reaction. These soluble salts may cause stains, efflorescence and local surface failures due to crystallization pressures. Simple cement grouting of large voids is not even very efficient; there are often difficulties associated with poor mobility, high shrinkage and final brittleness. Although such grouts have the attraction of low costs and simplicity, the safest and simplest course is to eliminate them, especially from work on heritage buildings. Lime is the preferred binder for grout used on older buildings. Lime combined with fly ash can produce a mobile, low to medium strength grout that is suitable to fill voids in double skin rubble cored walls. Non-hydraulic lime cannot be used without a setting agent.

Sand is often cheap and readily available. If used as a filler in grouts, it should be fine, with a maximum particle size not exceeding 0.5 mm, and mixed in proportions of up to three parts of sand to one part of binder. A greater proportion of sand is difficult to pump. Grouts containing sand are of high strength but will not penetrate fissures less than about three times the maximum particle size in width because of bridging across the gap.

Pozzolans react with free lime in the presence of water to form a cementitious compound, and therefore when they are used in a cement grout, they increase the strength of the mix besides acting as fillers, improving pumpability and flow characteristics and reducing bleeding. One of the most useful material is low sulfate pulverized fuel ash, also known as fly ash, which over the past decade has been used increasingly with cement, lime, or a mixture of both, to provide bulk or aid mobility and suspension. Fly ash is an excellent inexpensive artificial pozzolan when available with the appropriate quality and fineness. Ground granulated blast furnace slag is another inexpensive artificial pozzolan, and this slag and fly ash are frequently used as fillers for low strength large volume cavity filling grouts. Natural pozzolans, such as finely ground shale, pumicite and diatomite, are more expensive and are used for improving the grout properties in special circumstances.

Clays, especially bentonite, absorb water and form gel structures, thus stabilizing a grout and preventing bleeding, the formation of a layer of water on the upper surface of a grout that can cause cavities when the latter sets. Where strength is required in the set grout, bentonite up to 5% by weight of water may be used. At higher proportions, there will be little strength; the bentonite is used as a filler for reducing the cost.

A wide variety of admixtures is also available, including accelerators or retarders to regulate the rate of set and hardening. Plasticizers and air entrainment agents are used to improve the handling properties, along with expanders and anti-dispersant agents. Admixtures should be regarded as aids to good grouting practice but not as a substitute for it. Their suitability should be verified with trial mixes when necessary. Admixtures are usually used in relatively small quantities, requiring care in mixing; the effect of over-dosage and under-dosage should be ascertained.

Unless the grouting operation is very small or very specialized, it is recommended that pre-bagged grout mixtures be used as much as possible. For standard void filling in historic masonry, a pre-bagged grout mix of one part lime to one part of fly ash and one half part of bentonite is often suitable. A higher strength grout may be supplied such as a mix of one part of low sulfate cement, two parts of lime and one part of fly ash. The solids to water ratios are typically between 50 and 75%. Water used in grouts should preferably be from a public water supply and be of a quality fit for drinking. It should not contain any detrimental substances.

4.2.2 Grouting Techniques

There is a choice of four basic methods which are dictated by the nature and condition of the masonry. In its simplest form, grouting may be carried out by hand pouring into clay cups formed on the face of a wall. Gravity grouting is particularly suitable where the masonry is very susceptible to movement under pressure, and is the system most commonly used on heritage structures. Pumped systems of various kinds may be used to deal with most grouting problems. Vacuum systems may be useful where fine fractures and small scale voids are suspected.

4.2.2.1 Hand Grouting

Local grouting can be carried out very efficiently by hand. This technique is suited to small, isolated voids or fine cracks and is frequently carried out in association with repointing. The traditional hand grouting technique makes use of small clay cups formed with modeling clay against the masonry surface. Grout is poured in and allowed to disperse through the void around which the cup is formed. The grout is topped up, normally until the level is held. Grouts used in this manner are commonly the same type used in gravity systems, including hydraulic lime - sand mixtures. Flushing out of the cavities with water must precede the grouting in the usual manner. When the grout has set, the cup and residue may be broken off the wall and the surface brushed down. Cutting and repointing follow where necessary.

Smaller fractures and cavities may be filled using hypothermic syringes. Finely ground hydraulic lime and fly ash or brick dust may be used through large syringes. Patterns of small voids, such as cracks along the top of bed joints may be filled by drilling and inserting self-sealing grouting dowels, fitted with nipples. A hand grouting gun may be filled with a grout such as hydraulic lime and brick dust gauged with an acrylic emulsion as the vehicle. Grouts of this kind are highly mobile and may be forced considerable distances by hand.

Cracks may also be grouted through syringes, or through guns and grout dowels with polyester and epoxy resins, especially where sealing and re-adhesion are required. The viscosity and strength of such materials can be modified for particular requirements. The cost is high and may be prohibitive on large areas.

4.2.2.2 Gravity Grouting

The simplest method of grouting large areas is gravity grouting. Small holes are drilled into the wall where voids have been located, or are anticipated. They should be about one meter (36 in) apart horizontally and 450 mm (18 in) vertically on a staggered pattern. After the holes are drilled, they should be washed out thoroughly with clean water, pouring the water in at the top holes and continuing to pour until the water runs out clean at the bottom. During this process a note should be taken of the joints through which the water runs out; before grouting these joints must be tightly filled with tow or clay pressed well to a depth of 40 to 50 mm (1 1/2 to 2 in) into the joint.

The grouting apparatus required for filling large voids consists of one or two open galvanized iron pans with outlets in the bottoms. A union with a 38 mm (1 1/2 in) diameter galvanized pipe is fitted to the outlet, which in turn is connected by means of couplings to several lengths of 38 mm (1 1/2 in) diameter hose terminating in a galvanized iron nozzle 18 mm (5/7 in) in diameter fitted with a stopcock. Each grout pan is provided with a wooden plug about 450 mm long to fit into the hole in the pan bottom, and with a plunger in the form of a rubber cup on a wooden handle. This plunger is used when the grout is flowing to give an added impetus to flow in the event of an airlock or other stoppage in the tube. The nozzle of the delivery hose is inserted into the lowest hole and plugged round with tow.

To operate the simple equipment, two men are stationed at the upper level with the grout pans regulating the flow into the delivery hose from one pan and mixing the grout in a second pan ready for use, so that a continuous operation can be carried out. A third man is stationed at the lower level to open and close the stopcock on the nozzle as required. Ample supplies of water and grout components must be kept on the scaffold.

When the grout has been mixed to the right flow consistency in the pan the wooden plug is withdrawn and the grout flows down the delivery hose. The stopcock on the nozzle is then opened allowing the grout to flow into the wall until the grout level in the wall has risen sufficiently to start to flow out of the series of holes immediately above it. The grouting of these holes may then be stopped, and another section of the wall prepared or grouted while the first begins to set. After the initial set, the tow or clay can be stripped from the joints in readiness for pointing at a later stage. The next lift can then be pointed in the same fashion. One meter lift (36 in) should be taken as the maximum lift at the time to avoid the build up of pressure from liquid grout behind loose face stones. A pressure of about 70 to 80 kPa (10 to 15 psi) is obtained in the hose with the pan placed about 3.5 to 4.5 m (11 1/2 to 15 ft) above the point of inlet.

4.2.2.3 Pressure Grouting

The most common method of injecting grout is to supply it under pressure to the point of injection from where it can penetrate and permeate voids and fractures by displacing the gases and liquids therein or by compressing them. Since permeation of grout can only take place as air and water are displaced, provision for their escape must be considered. If gases within the pores are compressed rather than displaced, some grout may be expelled when the injection pressure is released. By choosing grout of suitable viscosity and setting or gelling characteristics and by skillful injection procedure, highly successful results can be obtained.

Hand and power operated pumps usually consist of a mixer diaphragm pump, suction and delivery hoses and metal nozzles fitted with stopcocks. Hand operated pumps are recommended for ancient masonry in unstable conditions. The maximum pressure obtained depends on the model being used, but a range of 70 to 280 kPa (10 to 40 psi) is normal. Lower pressures are obtained with hand operated pumps, which have a capacity of 18 to 45 liters / minute (4 to 10 gallons / minute). Power operated pumps have a capacity of 1300 to 1800 liters / hour (290 to 400 gallons / hour). The compact nature of these assemblies usually permits the plant to be located adjacent to the work in progress and cuts down on the hose lengths required. The preparation of the masonry surface is similar to the one described for gravity systems. The nozzles are fitted into the holes and plugged around with tow. The lowest nozzle is then coupled to the delivery hose. One man is required to operate the mixer, one to operate the pump and one to open and close the stopcock as required. When all is ready, the stopcock is opened on the nozzle and the pump started. The level of the grout rising up the wall is indicated by the seepage of grout from weep holes that can then be plugged with clay. When the grout reaches the next line of nozzles, the lower stopcock can be closed, the delivery hose removed and coupled to the nozzle above. The lower nozzle can be left in place until the grout has set.

The rate and amount of injection at each injection point depends on the nature and viscosity of the grout, the fissure size and the permeability of the structure, and the pressure applied. Considerable experience is required in choosing the most suitable combination of hole spacing, grout material and pressure employed in a particular situation in light of the available information as to the nature of the structure. Great care must always be taken to avoid excess pressure build up, which could cause disruption of the structure.

Injection normally commences at the lowest level and progresses upwards and sideways in a systematic manner. It continues at each injection point until refusal is reached at a predetermined limiting pressure, when a predetermined maximum amount of grout has been injected at that point or until grout emerges freely at adjacent injection points. In this last case, injection at the original point can be stopped and the hole plugged, and the operations can be continued at the adjacent holes from which grout has flowed.

When grout is injected to refusal at any point, without evidence of spread to the adjacent holes, consideration should be given to the provision of an intermediate pattern of secondary injection holes to ensure satisfactory and complete grouting. When an injection point accepts grout without refusal or build up of back pressure, grout must be leaking away and steps are required to deal with this situation. These may include the use of quick setters, flocculating agents and fillers or very thick grout in successive small injections to set in and block the leakage paths progressively.

Leakage of grout at adjacent injection points and through the structure, as well as expelled air bubbles and water, can give a useful indication of the grout the spreading of grout. Leakage should be stemmed with quick setting mortar, or by caulking if necessary. Repointing the surface joints of a masonry structure prior to grouting can be helpful in retaining the grout, but such repointing is seldom grout-tight. In order to avoid unsightly staining of the masonry surface, all grout leakage should be promptly cleaned off before the grout can set.

Water flow through a structure being grouted should be controlled to avoid the washing away of the unset grout. It should initially be channeled into a few defined points in which pipes have been set and water emerging from elsewhere should then be controlled by quick setting mortars. Grout injection should commence away from the piped leakage points and work towards them, progressively reducing the flow and sealing the other parts of the structure until the piped leakage points themselves can finally be injected.

Water takes the line of least resistance, and it is common to find that, after apparently successful grouting to control percolation, leaks appear elsewhere after a period of days to weeks owing to the pressure build up. Further treatment may then be required in the new leakage areas. Percolation can often be reduced to insignificant amounts, or at least controlled, but can seldom be stopped completely, as grouting is not water proofing. Some residual dampness is common.

On completion of grouting, all injection pipes should be removed and the points made good in an appropriate matter; the final cleaning up of the surface includes the removal of temporary caulking and spillage.

4.2.2.4 Vacuum Grouting

Vacuum systems entail enclosing the area to be grouted in an air tight transparent, flexible shroud such as a polyethylene sheet. Air is evacuated from the shrouded area by means of an air line to a powerful vacuum pump and a tap opened to allow suction of the material from the grout pan. When impregnation is complete, as observed through the polyethylene sheet, the tap is closed until the grouting material is set. In spite of the obvious attractions of grouting under vacuum, the practical difficulties on site must be acknowledged and not underestimated. Presently, application to masonry structures is limited.

4.3 Patching Parging and Stucco

Parging usually refers to the application of a thin coat of mortar directly applied to the exterior of masonry walls, particularly below grade as a damp proof measure for rough masonry, foundation and basement walls. Stucco generally refers to the thicker coat built up in several layers over masonry walls, most often on a mesh or furring strips. Stucco is generally applied in three coats, thus reducing cracking and making a smoother final coat possible. It is sometimes whitewashed or scored to resemble cut stone, making rough stone or even bricks look like more expensive materials.

Common failures in parging and stucco include crazing of the surface, cracking, separation from the backing, or between the coats, and crumbling or powdering of the surface due to salt crystallization. Most failures are attributable to water penetration. Cracks draw moisture into the wall through capillary action and trap it inside, leading to failure of the parging. Although it may be tempting to completely remove badly deteriorated stucco and expose the brick or stone, it is important to remember that the stucco was probably applied for a good reason. An unpleasant surprise may await underneath. It is also particularly difficult to remove stucco from a brick wall without damaging the bricks. Most stucco repairs require only patching, which should always be done if stucco was the original treatment for heritage buildings.

Despite the care exercised in this type of patch repair, the possibility of differences in appearance must be anticipated. Nevertheless, if these patch repairs are neatly keyed into the original and matched as closely as possible, they will not disfigure the final weathered appearance of the wall in which they are set. However, if they are ragged or carelessly matched, they will always look bad and the variations are likely to become more obvious with weathering.

4.3.1 Mortar Mix

Traditional parging and stucco are lime based and can tolerate movement in the wall. Parging of portland cement is less permeable, however, it is brittle and easily develops fine cracks. Mixes for stucco or parging repairs are very similar to the mortar mixes. A typical mix for lime stucco is two parts of lime to one part of white portland cement and nine parts of sand with a little animal hair. For portland cement parging, the mix should consist of one part of portland cement to one part of lime and six parts of sand for the undercoats and the top coat of areas with severe exposure. Where the exposure is not severe, a mortar mix similar to the one for lime pargings is satisfactory for the top coat. For application below grade a mix of one part portland cement to 1/4 part lime and 3 1/2 parts sand, is recommended and sulfate resisting cement specified as required. The patching material should look the same and have chemical and physical properties compatible with the original. A soft lime and sand stucco should not be patched with portland cement.

4.3.2 Removing Delaminated Parging

Deteriorated areas will be evident or may be detected by tapping the wall with a wooden mallet. The loose stucco will sound hollow. Areas of rendering which are extensively cracked, or are sounding hollow, should be cut out with sharp chisels down to a sound surface, the scratch coat or the masonry itself.

When stucco is lined out in imitation of masonry joints, cutting out should always follow the joint lines, even to the extent of removing some of the soundly adhering material around the cracked areas. Stucco which is not lined out should still be cut out in rectangular profiles around the failures, to avoid ragged repairs. Because it is hard to disguise a patch, it is best to replace sections of a wall between logical break points. On the other hand, as much of the original material as possible should be retained, so that the smallest possible area requires to be patched, especially on heritage buildings.

The decayed area should be cut back with square edges, or with slightly undercut edges on all but the bottom. Cracks should be cleaned out and all edges along cracks should also be undercut to allow the patch to grip. Adequate key must be ensured by raking out the joints to 16 mm minimum depth, or by hacking the background or scoring the preceding undercoat.

After cutting out, all dust, loosely adherent material, efflorescence and any organic growth must be removed thoroughly by bristle brushing and treatment with a biocide. The area to be patched must be clean, firm and sterile. Before any rendering is applied to a surface, the background must be damped to reduce and control suction, especially in hot weather. If the surface is not sufficiently damp, it will soak water from the render as it is applied, and reduce the effectiveness of the bond and the strength of the render.

4.3.3 Applying New Coat of Mortar

Patches are laid in several layers directly on the masonry, or on galvanized metal lath attached to the masonry. Two base coats, 9 to 13 mm (3/8 to 1/2 in) thick, are first applied: the scratch coat followed by the second or brown coat. Each coat is scratched to improve the bond with the next coat, and the wall should be wetted down before applying each coat. A week later, the finish coat is applied, made up of a higher lime mix to prevent shrinkage and cracking. This final 3 to 6 mm (1/8 to 1/4 in) coat is given a smooth or textured finish to match the rest of the wall. Rapid drying can be avoided by working on an overcast day, or late in the afternoon or by misting with a hose. To allow the surface to breathe, it is best not to paint or seal the stucco. Tints should be used to match the original color.

Chapter 5

Repair and Replacement of Damaged Masonry Units

Once the cause of masonry deterioration has been identified and the source of the problem eliminated, it may be desirable to repair or replace the damaged masonry units. Not all deterioration or damage can be, or even needs to be repaired. Thus, if the damage caused by the wearing away of the surface from weathering or blistering is only slight, it may be best to leave the masonry as it is. On the other hand, damage that threatens the structure, such as cracks that allow water to penetrate into the wall, must be repaired. If a few stones in a wall are partially missing, broken, cracked, chipped, badly weathered or otherwise deteriorated, they should be repaired or replaced.

The heritage value of a building rests in its original materials, and it is best to conserve materials by stabilizing deterioration rather than undertaking the irreversible act of cutting out and replacing them. With buildings of notable significance, it may be better to conserve the somewhat weathered or damaged original materials. Although most repairs are carried out for mostly cosmetic reasons, they also make the masonry less susceptible to further damage. Techniques for the repair of damaged masonry can be divided into two categories: mechanical repairs and plastic repairs. When a new piece of the same or a compatible material is mechanically attached with mortar, glue, epoxy or pins, it is called a mechanical repair. When the patch is a malleable material that hardens in place, it is called a plastic repair or composite patch. When the internal structure of the masonry units has been weakened by leaching of their natural binding agents, the masonry deteriorates rapidly as the surface skin spalls, blisters or scales off under the effects of salt encrustation and freeze-thaw action. In some cases, these units may be preserved by applying a consolidant to strengthen their weakened structure. However, in most cases, the units will have deteriorated to a degree where it is preferable to replace them with new materials.

The information in these sections was adapted from the works of (Amorosso and Fassina, 1983), (Weber and Zinmeister, 1991), (Ashurst and Ashurst, 1988) and (London, 1988)

5.1 Mechanical Repair

Fractured masonry can often be refastened or replacement pieces can be attached with mechanical repairs. These techniques may be appropriate for use on stone that has cracked, delaminated or exfoliated, as well as on pieces of masonry that have become detached from the wall. All mechanical repair techniques are similar. They involve attaching a piece of masonry to a surface to replace damaged or missing material. The piece can be either the original material, a new piece of matching stone or a stone like substitute such as artificial stone, a small piece of precast concrete made to resemble stone.

5.1.1 Reattachment

With this procedure, also called concealed repair, detached pieces of stone are held in place by adhesive and pins. If possible, the parts to be glued should be removed from the wall to facilitate working on the broken surface. All surfaces should be clean of dirt, stone dust and oil. The remaining original masonry is first cleaned out and cut back, and holes are drilled or grooves chiseled to provide a key for the bonding material. The prepared surface is cleaned free of dust and stone chips using a stiff nonmetallic masonry brush. All stone and other surface adjacent to the area being repaired should be protected with rubber cement, which is removed after the repair has been completed. The mortar joints affected by the repair work should be raked out and repointed after the work is done.

Common bonding materials are cement grouts and epoxy. Epoxy resins are particularly good for reattaching small, carved details or other decorative elements and for making small dutchman repairs. Epoxy resins used in masonry repair should have the consistency of thin paint, be rigid when cured and be insensitive to moisture and resistant to solvents, acids and alkalis, especially if the building is to be cleaned later with these products. The manufacturer should be consulted on the best epoxy resin for the job. A hardening agent is added to the resin so that it may harden; it must then be used before it sets (between 1/2 and 1 1/2 hours, depending on the type of resin) and must be kept at a relatively constant temperature and protected against the weather while it cures (between 1 1/2 and 6 hours). Most epoxy resins are translucent, with a slight yellow tint. Adding dry, sifted stone dust to the resin and hardener mix helps match the resin to the rest of the masonry. Epoxy should not be used for large pieces, as the impermeable layer would trap moisture. In these cases, anchors, such as metal clips, should be used to attach the new piece mechanically, or the piece may be set in a fine lime mortar grout, which would allow moisture to escape.

For lintels and other projecting and bearing members, reinforcing pins of stainless steel, bronze or thermoplastic can be used. Traditionally four to six times its diameter in length, each pin should be scored or threaded to provide a gripping edge for the adhesive. Holes are drilled in both the base piece of masonry and the replacement piece. The depth of a hole is two to three times the pin diameter and the width is 1/8 inch larger than the diameter. Epoxy is placed in the holes, the pins are set in the base piece, more epoxy is applied uniformly on one of the broken surfaces, and the two pieces are joined together.

All surplus glue is cleaned immediately, and the joint is left to dry, protected from the weather.

5.1.2 Dutchman Repair

A dutchman repair is the piecing-in of a small patch of natural stone or precast concrete imitation stone as a treatment for chipped or damaged stone. The piece is held in place with an adhesive such as epoxy and attached using a procedure similar to reattachment. The joint between new and old should be kept as narrow as possible to maintain the appearance of a continuous surface.

A typical example of this is the halving of decayed mullions in tracery windows, where the decayed stone is cut back to the glass line and half mullions glued to the face of the surviving internal half. Although the modern resin adhesives are excellent, it is always unwise to rely on the interface bond alone. Therefore, the halving technique relies on dowel pins of stainless steel or phosphor bronze or even of glass fiber. The use of pins and epoxy mortars has enabled valuable masonry features, shattered as the result of bombing or fire, to be saved, which otherwise would have been lost.

5.1.3 Crack Repair

There are various sophisticated techniques for repairing cracks with epoxies. These are difficult to execute and should be attempted only by expert masons. Small cracks are covered with non-oily modeling clay to prevent leaks, and then epoxy is injected with a syringe. For large cracks, a series of holes is made in the clay, epoxy is injected into the lowest hole until it comes out the next higher one, then the first hole is plugged and the epoxy is injected into the second, working up to the top. After drying, the clay is removed and the surface of the crack filled with the same kind of mix used for plastic repair. Another technique is to first fill the surface of the crack with a plastic repair mix such as lime and stone dust, embedded with small plastic tubes. Epoxy is then injected through the tubes deep into the crack; finally, the ends of the tubes are cut off. The techniques are similar to the grout injection treatment used to repair cracks in walls.

5.1.4 Exfoliation Repair

For stones that are in the process of delaminating, such as face-bedded sandstone or limestone, a complex and somewhat tricky process can be used. This innovative procedure involves drilling staggered rows of countersunk holes through the face of the stone. An adhesive grout of epoxy resin (simpler and stronger) or an acrylic modified cement (sometimes used in larger cavities, as it is less expensive) is then injected and allowed to spread into the gaps behind the delaminating layers. A 60 milliliter, single-use syringe designed for use by veterinarians may be useful in delivering the adhesive grout into the drill holes. Stabilizing pins are inserted into the holes to act as reinforcement and the surface of the holes is finished to match the rest of the stone.

The drilling and injection of holes to receive resin and reinforcement requires great care and thoughtful preparation of the site. The viscosity of the resin should permit the drilling to be filled adequately under the pressure from a gun or a hypodermic syringe, whichever is appropriate. After holes have been drilled it is essential to remove all the dust; they must be flushed out with a solvent, or, if drying time is available, with water. Flushing out is best achieved with the same apparatus that is used to inject the resin. Small holes may sometimes be cleared of dust by blowing out with a small tube.

One of the problems associated especially with smaller holes is the entrapment of air when the resin is injected. The amount of resin injected into the hole must take account of the displacement that occurs when the reinforcement is inserted. Unless the hole is very small in diameter, the resin should not come too close to the surface. For a drilling 6 mm

(1/4 in) in diameter, prepared to take a 3 mm (1/8 in) rod, the drilling should be injected for approximately 2/3 of its depth. Pins should be cut to size before injecting the resin. The heads of the pins should not be closer to the surface than 6 mm (1/4 in) for the small diameters, to 12 mm (1/2 in) for large diameters, allowing the outer 6 to 12 mm (1/4 in to 1/2 in) to be filled with a fine matching mortar. Where possible, wire pins should be turned at the end to provide a better key. Rods should be threaded for the same reason and if glass fiber is used, it should be well roughened.

5.1.5 Veneering

A new veneer of stone or a substitute material can be used to replace a deteriorated surface or to hide repair work. If the stone must be completely removed and a like material is unavailable, the gap can be filled with mortar and a stone veneer applied to match the rest of the wall. The back of the cavity is filled with a series of thin layers of mortar until a space exactly the size of the veneer piece is left. Several days later, the sides and back of the cavity are covered with a fast setting mortar and the veneer piece is laid in. Alternatively, the veneer piece can be mechanically attached with metal anchors without filling in behind them. The veneer can be obtained by removing stones from another unobtrusive place in the building and slicing them into layers a few inches thick.

Brick slips may also be inserted instead of a full-size unit. Brick slips are facings of about 25 mm (1 in) thickness although it may be possible to cut thinner slips from whole bricks. Repair using brick slips should be limited to individual bricks or to relatively small areas of the brickwork. The slips must be solidly bedded in the prepared indent on a bed of mortar with or without the assistance of purpose-made or patent clips. The cavities formed should be clean and regular and the mortar used compatible with that in the original brickwork. In particular, the refacing of larger areas with slips bedded in an epoxy or other resin mortar is to be discouraged because of the membrane effect that will trap moisture and may result in spalling of the patched area or adjacent bricks. Where the area requiring repair is more extensive, it may become necessary to tie in a new leaf of matching brickwork, using header bricks, suitable ties or anchors, as appropriate.

5.2 Plastic Repairs

Plastic repair, or composite patching, is a useful technique that may sometimes be used as an alternative to cutting out and piecing in with new stone or brick. Plastic repairs are of particular interest and importance because the technique frequently permits the retention of more original material with much less disturbance than would be possible for the execution of conventional masonry repairs. The technique, used to repair problems such as delamination, exfoliation and spalling, can be quite successful if limited to small cavities or areas of missing stone 25 to 75 mm (1 to 3 in.) deep. The method involves careful removal of decayed material, cleaning and sterilization of the cavity and placing, compacting and finishing a series of coats of mortar to reconstruct the missing surface. A good patch should match the color, texture and surface treatment of the rest of the stone. It should adhere well and have physical characteristics similar to the original stone (hardness, moisture transmission, expansion and contraction), or else the existing stone will be damaged by the patch.

Plastic repair is exacting work, and only experienced craftsmen can be relied on to make a good patch. If properly carried out, plastic repair may be less obtrusive and less expensive than a replacement in natural stone. On the other hand, if poorly done, a patch will not only be visually apparent, but will also shrink and separate; water will get into cracks and the whole patch can pop out, leaving the stone even more damaged. Failure of plastic repairs may be both cosmetic and mechanical. Over-strong mortars, mortars relying on bonding agents instead of mechanical keying and large surface areas in exposed positions can cause mechanical failures. Even if it is well done, a patch will never look and weather exactly the same way as the natural stone, therefore patches should not be used over very large areas.

5.2.1 Mortar Mixes

The material used for plastic repair is similar in composition to mortar or stucco mixes: typically one part of binder to about three parts of aggregate made up with water. However, plastic repair mixes vary according to the type of masonry being repaired. They should always be a bit weaker that the masonry so that if deterioration takes place, it will be in the patch, and not in the stone. Plastic repairs carried out using too hard a mix may not adhere or may accelerate weathering and deterioration of the adjacent natural stone, partly because of the different rates of expansion. Epoxy should be used only for small repairs, because it is too strong and is impermeable to water.

A typical binding agent is made up of equal parts of lime and white portland cement, with a small amount of non-reemulsifiable acrylic latex to increase cohesion and durability. Most of the plastic repair mortars are based on a lime binder, but repairs to sandstones and bricks may be carried out better using a cement binder and a plasticizer, or a masonry cement. This is because sandstone that is already decaying may further deteriorate in the presence of lime washing into the edges of the prepared cavities and because the strong color of some sandstones and bricks are not easily matched when lime is included.

The strength of the repair mortar is not as important as its resistance to wetting-drying cycles. Similar properties of porosity and water absorption are therefore important. In this matter, test cubes may be informative as an ad hoc test, observing the amounts of water taken up into cubes of mortar and stone set in a test tray. A compromise must be made between the mortar strength closest to that of the surviving stones or bricks and the strength considered necessary for a particular exposure. If the exposure is demanding, a higher-strength mortar will require using hydraulic additives. Hydraulic additives for repair mixes include, in order of increasing strength: finely powdered brick dust, hydraulic lime, pulverized fuel ash, white cement, masonry cement and ordinary portland cement. In no circumstances should a repair mix be selected on exposure grounds alone where its strength may adversely affect the condition of the adjacent original fabric. The repair should be designed to fail in advance of the material being repaired.

Epoxy resin repairs based on 12 to 18 per cent epoxy resin, by weight, have performed well. This proportion of resin is able to recreate the natural stone structure by gluing the aggregate together at the points of contact and leaving the pores unfilled. These repairs seem to have similar properties of porosity and thermal expansion to the surrounding natural stone.

Sand and/or crushed stone is the usual aggregate used in repair mixes. Ideally, the final coat should be made up with the same kind of stone as is being repaired, either crushed stone from the building itself or matching stone from a salvage or stone yard, ground to pass through a screen and washed thoroughly. If an accurate color match cannot be made with the proper choice of aggregates, small amounts of alkali-stable dry pigments can be used to make the patch blend in with the original masonry, although these may reduce the strength of the repair and the color may eventually alter.

A high proportion of aggregate to binder in the cement: aggregate mix is a further advantage when matching a strong-colored sandstone. The mortar preparation must always ensure that the grains of sand and stone dust are adequately coated with the binder paste. Natural sandstone often has mica in it, which sparkles, and a repair made with only sand will look flat. If it is not possible to get crushed sandstone for the patch, some crushed mica, glass or marble dust may be added.

Some of the best mortar repairs for brickwork has been carried out with sharp sand with strong natural color and with a masonry cement binder, sometimes using a styrene butadiene rubber additive. Pigments should be avoided and it should be noted that lime frequently imparts an undesirable pastel appearance. A typical mix would be one of part masonry cement to five or six parts of sharp sand and brick dust. Bonding additives should be the exception, rather than the rule.

In comparison with natural stone, plastic repairs may look rather dull and lifeless. The only way to achieve a proper color match is by preparing test samples. First, the sands, crushed stone and, if necessary, dry pigments are blended to approximate the color of the stone, noting carefully the quantity of each component. Possible variations can be mixed. The dry mix gives a good indication of the final color. The mixture is completed with binder and water. After curing for 48 hours, part of each sample is treated with the proposed finishing treatment, and then samples are compared with the original stone. The process is repeated until a good match has been achieved. Patches should be made to match a clean, unweathered area of the original stone, perhaps from the back of the area to be patched, so that the patch will weather to the same color. However, the color and texture of the patching material may not change over time in the same way as the natural stone. Several colors may be needed to match the natural variation between several stones or even within one stone. As a last resort, plastic repairs may be painted to match adjacent areas of masonry. Composite patches should also match the stone in texture and surface tooling. Details of some of the mixes for plastic repairs are presented in Table 5.1.

Table 5.1 Plastic Repair Mixes (Ashurst and Ashurst, 1989)

Type of Masonry	Mix Formula
	1 part masonry cement
Brick	3 1/2 parts sharp sand
	1 1/2 parts soft staining sand
	1 part hydraulic lime
Sandstone	2 parts sharp sand
	1 part soft staining sand
	1 part white cement
Limestone	2 parts lime putty
	10 parts aggregate

5.2.2 Surface Preparation

The stone must be properly prepared to ensure that a good bonding surface exists between the old and the new materials. The surface of the deteriorated stone is scraped and chiseled down to a sound layer; deep grooves are cut into the cleaned-out surface to provide a solid anchorage. The cavity to house the repair should be carefully cut out to a minimum depth 25 mm (1 in). A mechanical key is provided by undercutting the edges of the remaining stone to a slight dovetail and by drilling small holes, 12 mm (1/2 in) in diameter and 12 mm (1/2 in) in depth, into the sound masonry when more than a 25 mm (1 in.) depth is to be filled or when work is done on a vertical surface. To make the patch fit in with the visual character of the wall, a regular shape is usually the best with smooth-faced regularly cut stone and an irregular shape with rough-faced and randomly laid stone. Each individual stone should be patched separately, otherwise a patch that crosses two or more stones will crack as the stones shift. Wood strips are placed in adjacent mortar joints to contain the repair; the joints should be repointed afterward. A thorough washing of the area with water and bristle brushes completes the preparation.

To give better support to plastic repairs of greater depth or if the elements to be repaired have a considerable overhang, such as cornices and moldings, various forms of reinforcement are often used. All cavities exceeding 50 mm in depth and extending over 50 mm^2 in surface area should include reinforcement. These may range from simple pins to complex armatures and may include rods, pins, wires, screws, anchors or a mesh. The most common materials are copper, phosphor bronze, stainless steel or polyester. After drilling to receive the reinforcement, the holes are filled with portland cement, epoxy resin or, more rarely, lead. Drilling should attempt to enlarge the cavity slightly to form a dovetail key. Holes must be flushed out with white spirit and allowed to dry before fixing. At least 20 mm of cover should be allowed for any reinforcement.

5.2.3 Application

Individual stones must be repaired separately and if necessary pointing between repairs must be carried out separately. Areas should never be repaired as a render and joint-scored. Pointing of adjacent joints should be carried out as a separate operation. The cavities should be well wetted before the mortar is placed to avoid dewatering. The mortar is laid in many thin layers, between 9 and 12 mm (3/8 and 1/2 in.), to reduce shrinkage and cracking when drying. Each layer should set usually about two to four hours before the following coat is applied. The first, or slurry coat should be the thinnest to get into the nooks and crannies of the stone. Then, while it is still moist, the first of a series of scratch coats is laid. Each coat is wet down before the next coat is applied. The mortar must be very firmly compacted and is best built up in excess of the required finish line and then scraped back with a fine saw blade. The final finish coat should match the color, texture and surface finishing of the original stone.

The repair may be finished directly to the required profile using a wood or felt-covered float, or with a damp sponge or coarse cloth. To achieve the proper texture, the surface must be treated to expose the grains of stone or sand; otherwise, only the smooth surface and color of the binding material will be visible. There are several ways to do this.

When the patch has partially cured to a leather like surface, it can be stippled with a damp sponge or a dry trowel with a wooden float. The patch can also be lightly etched with acetic acid after it has cured at least 48 hours. Other parts of the building must be well protected; great caution must be exercised near limestone and marble. Alternatively, the surface of the patch can be rubbed after it has cured well. Surface tooling can be done either when the patch is partially cured or after it is well cured using stone tools. Ingenuity provides other finishing tools appropriate to the texture of the finish required. Unsuitable tools to be avoided are steel towels or dry, absorbent pads; the first will leave an undesirable and unnatural latency on the surface and the second will risk the removal of water from the repair too soon. An alternative repair finishing method is to build up the repair in excess of the required profile and then to work it back after an initial set has commenced on the surface with special tools.

Mortar repairs must be protected from direct sun or other rapid drying conditions. This may be achieved with damp cotton wool pads on small-scale repairs or with damp sacks on larger areas. Care taken during preparation and after placing of the repair will avoid one of the most common problems associated with this kind of work, the appearance of fine, shrinkage cracks during drying.

5.3 Consolidation

All masonry materials undergo aging and deterioration processes. Some alter slowly, in ways that rarely cause alarm and are visually pleasing; others, after a time of slow change, begin to degrade more dramatically, as cementing matrices fail or surface skins spall, blister or scale off as accumulations of soluble salts create internal stresses in the course of cyclic wetting and drying.

The main function of consolidants is to bind particles together within the stone. The most important of a consolidant is to reestablish the cohesion of particles in deteriorated stone. The restoration of the internal integrity of a natural stone matrix is achieved by the deposition of a new durable binding material within the pore system, a process that should significantly improve measurable physical properties such as compressive strength, modulus of rupture, elasticity and abrasive resistance. The ideal agent would consolidate friable stone or brick by forming a new weather resistant binder after it has been injected into a masonry unit. By modifying the pore structure, which reduces the absorption of water and other harmful substances, and by increasing the tensile strength, the damage caused by salt crystallization would be significantly smaller.

Several other factors are important to the overall success of this approach. A good consolidant must have substantial penetration, accompanied by deposition of the consolidant to the full thickness of the weathered zone. The application of the consolidant should result in a continuous hardness profile; formation of an artificial crust by a chemical hardener must be avoided by all means. The deposition of the consolidant within the pores of the masonry should lead to only a minimal reduction of its water vapor permeability. There should be no deleterious chemical or physical interaction between the consolidant and the building stone. Once cured the consolidant should cause little or no aesthetic alterations or change in the gloss, color or texture of the original masonry. The consolidant should not be a hazard to health or safety during handling and application,

Attempts at consolidating masonry are by no means new. For centuries people have sought ways to bring disintegrating (crumbling, spalling, sugaring) masonry back together and to increase masonry strength and its resistance to deterioration. However, the scientific examination of decay mechanisms and consolidants is less than one hundred years old.

The idea of a surface treatment that will consolidate friable, delicate stone or ceramic material is obviously very appealing to anyone faced with the problems of conserving either small surface areas of high intrinsic value, or large areas where complete replacement seems to be the only other option. Nevertheless, consolidants should be used only on masonry or sculpted surfaces that are deteriorating it an obviously unacceptable and readily quantifiable manner. The causes of deterioration should have been properly identified and adequately understood. All possible ways of improving the situation by modifying the environment of the deteriorating masonry, such as physical moisture barriers, flashings, humidity controls, stitching, surface and joint repairs should have been explored before applying any kind of consolidation treatment.

Consolidants, even when carefully and correctly selected, can not perform miracles. They must not be considered as grouts, void fillers or bridges, or adhesives. However, all consolidants should be applied only by experienced applicators who, as a minimum qualification, should be able to discuss the work authoritatively and knowledgeably.

For now, the only situation that might warrant consolidation would be stone with important detail which is deteriorating so rapidly that the material would be lost in the next few years. Even for this rare exception, consolidants should never be used without comprehensive laboratory testing and field evaluation and the advice of an experienced, independent stone conservator knowledgeable about these experimental techniques. The remainder of this section outlines the current use of surface consolidants with particular reference to historic masonry and especially architectural detail.

5.3.1 Glue and Gelatin

Materials based on gelatin and glue are important from a historic point of view. Since the turn of the century, these materials have been used as a consolidant. Diluted solutions of 2 to 5% solid content have been applied to several buildings. Such solutions have only a limited penetration and tend to form surface crusts. A long term performance and sufficient consolidation cannot be expected since these organic materials are easily degraded by weathering and they undergo rapid decomposition under acidic environmental influences.

5.3.2 Alkali Silicate

Alkali silicate formulations are known as fixatives. When compared to organic products consolidation techniques with alkali silicate, commonly known as water glass, have a been valuable step towards the development of modern consolidants. Alkali silicate is a non stochiometric dispersion of silica in sodium or potassium hydroxide. These water soluble formulations of low molecular weight penetrate slowly into the stone. Rapid precipitation of silica is often responsible for the insufficient penetration, besides the high viscosity. No reports are available that claim to have achieved a penetration deeper than 3 mm (2/16 in.). The neutralization of the alkali silicates with the carbon dioxide provided from the atmosphere results in the formation of amorphous silica, which is extremely insoluble, accompanied by an unfavorable carbonate salt deposit such as Na_2CO_3 and K_2CO_3. Unless the basic constituents can be removed by rinsing procedures, the alkali carbonates formed influence negatively the water vapor transmission features of the masonry, causing unsightly whitish deposits on the surface or typical subflorescence damage. Glass type encrustations, uptake of dirt and soiling of surfaces are also frequently observed. Another negative side effect is the reduced frost resistance. By condensation and other water absorption mechanisms, larger quantities of moisture are trapped behind the surface crust. The high alkalinity of these solutions has also led in some cases to etching of the masonry surface.

5.3.3 Fluorosilicons

Anther inorganic consolidant used extensively throughout the nineteenth century was based on the salts of fluorosilicic acid. Fluorosilicic acid reacts readily with carbonates, oxides or hydroxides to form neutral salts of sodium, potassium, aluminum, magnesium, zinc and lead. Alkali salts are rarely used to consolidate weathered stone due to their poor solubility. However, magnesium, aluminum and zinc fluorosilicates can react with carbonates and form, in the case of aluminum, an aluminum gel and a silica gel that both have consolidating and water proofing properties, and calcium fluoride, which, although it is not a binding agent, is a very stable salt. The reaction takes place at the expense of the calcium carbonate, that is, to the detriment of the main constituent of the stone itself. Such a treatment can only have a beneficial effect if the carbonate is in a powdery form, either because the stone has disintegrated or is disintegrating, or because the carbonate cement in the stone no longer acts as a binder. Fluorosilicate treatments also deposit a sort of enamel on the treated stone that completely blocks the pores and makes the material impervious, even to the passage of gas.

5.3.4 Barium Hydroxide Solutions

Barium salts have also been used on several occasions, from the nineteenth century onwards, to harden and protect weathering stone. They were particularly important in cases that involved transformation of calcium sulfate to insoluble sulfates that are more resistant to both atmospheric erosion and leaching by water. The product used for this treatment consisted of barium hydroxide, urea $CO(NH_2)_2$ and glycerin, and it produced good results on certain marbles and calcite limestones. Glycerin has a secondary role and prevents formation of barium hydroxide crystals in the solution. Urea facilitates deep penetration of the hydroxide and constitutes a source of carbon dioxide. The carbon dioxide produced by the hydrolysis of urea serves to consolidate the interior of the stone. Carbonation of the surface of the stone takes place by reaction of the barium hydroxide with the atmospheric carbon dioxide. Upon reaction with carbon dioxide insoluble carbonates are formed but these have no or minimal capacity of binding particles together. Precipitation of new crystalline material is sometimes achieved only in the surface layer, promoting delamination under weathering influences. In addition, calcareous materials together with urea can also form salts that accelerate decay.

5.3.5 Lime Water

Lime water has been used as a consolidant on soft limestone, where much of the calcium matrix had been leached over the course of time, leaving the stone in a loose and friable condition. Lime water contains small quantities of calcium hydroxide, approximately 0.14g per 100 ml of water at 15°C. Traditionally, it is siphoned from the slaking tank after lime has been slaked in excess of water and after all slaking has ceased and the water is clear. Usual practice now is to stir lime putty into a container of water and leave it to stand until the water is clear. It is important that the lime water be protected from the air, otherwise it will carbonate and become ineffective. A number of different methods have been used to achieve this in a practical way; the most recent development is the covering of the surface of the lime water in its container with a float of polystyrene sheet stock, pierced only by a siphon tube fitted with a filter.

When required, the lime water is drawn off by a hand pump into spray bottles or directly to a lance with a control valve and adjustable nozzle, checking from time to time that the water has not accidentally become clouded through disturbance of the lime at the bottom of the bin. Any cloudy water is rejected and the water allowed to stand until it is clear again. Approximately forty applications of lime water are flooded onto the surface of the limestone over a period of several days. Application can continue as long as the surface will absorb, but excess lime water should not be allowed to stand on the surface of the stone and is removed by sponges that are then squeezed out in clean water.

5.3.6 Acrylic and Epoxy Resins

In contemporary restoration, acrylic and epoxy resins are most frequently utilized. The extraordinarily high bonding capacity of resins has led to their use as consolidants. Organic monomer molecules are directly applied to the stone and forced to polymerize in the capillary system by UV or an internal catalyst. Other techniques utilize oligomeric or polymeric substances, diluted in volatile solvents, to achieve deep penetration. After evaporation, these long chain materials are deposited into the pore space. Rapid evaporation may draw the polymers back to the surface, thus forming undesirable surface crusts. However, resins have a tendency to turn yellow as they age. Some organic polymers are also susceptible to degradation by UV radiation and acid rain. More information on acrylic and epoxy resins can be found in section 3.4 - Surface Treatments.

5.3.7 Tetraethyl silicates

Tetraethyl silicates are, from a chemical point of view, esters of silicic acid, extremely unstable compounds, that undergo rapid and complete decomposition under the influence of water to form an insoluble cementing material. Tetraethyl silicates are easily hydrolyzed. Partial reaction with water initiates polymerization. The connection of several monomer units leads to a three-dimensional network. The complete curing requires two to three weeks, depending on the temperature conditions and moisture concentration.

One of the most favorable properties of tetraethyl silicate consolidants is the viscosity, which is lower than that of water, permitting excellent penetration into porous and dense substrata. The amorphous silica deposited into the pore space of natural stone is extremely durable and weather resistant. In chemical composition, it is nearly identical to naturally occurring siliceous binding material. No other type of consolidants has been studied so extensively and no other system has ever had a longer track record of successful treatment than tetraethyl silicate based products.

For very soft and porous sandstone approximately 100% improvement in physical strength as a rule of thumb can be achieved with introduction of as little as approximately 2% of the new binding material. The changes in pore size distribution by treatment were found to be small. Total porosity may not be affected by more than 10%. Therefore, the water vapor transmission characteristics of the treated stone are largely unchanged. This desirable behavior can be explained by the fact that the commercially available products contain volatile additives, by condensation of tetraethyl silicate molecules, low molecular weight units are split off and evaporate. Concurrent to the evaporation of the condensation by-product ethanol, the jelly type intermediate slowly undergoes a shrinkage process, recreating an almost completely open space. Out of 100g of product applied to the masonry, 35 g of solid amorphous silica is precipitated in the capillary system.

Contemporary products contain partially polymerized ethyl silicates, which are synthesized from silicone tetrachloride by including substochiometric amounts of water during manufacturing. The use of oligomeric units is advantageous for several reasons. Higher amounts of amorphous silica are formed upon hydrolysis, ensuring a better consolidation effect than the monomeric species. Oligomeric tetraethyl silicates are also somewhat cheaper to produce.

A reasonable reaction time for the complete curing of the product in the pore space of a stone ranges from 14 to 28 days. The reaction speed is influenced slightly by temperature and water that is a reaction partner for the condensation of the tetraethyl silicate. The application temperature should range between 10°C and 25°C. Relative humidities in between 40 and 70% constitute optimum curing conditions. The very small amount of moisture necessary for the initiation of the chemical curing process is provided by the hygroscopic moisture content of the building material itself. Moisture that migrates from the surrounding air into the stone material is responsible for completion of the curing process.

Product formulations that solidify quicker tend to form a glass like deposition on the stone surface; too slow a formulation, however, may lead to intolerable material losses by evaporation.

Preconsolidation treatment should be carried out before cleaning the masonry. The purpose is to ensure sufficient stability of very soft or seriously deteriorated material. Between cleaning and consolidation, a sufficient period of time should elapse, ensuring restitution of the masonry in a dry state. As a rule, consolidants are applied by flooding the surface. Suitable equipment includes electric pumps, airless sprayers or low pressure spraying devices. Pressure application does not improve penetration. Brush application cannot be recommended since the exact amount of material applied cannot be predetermined.

In order to allow penetration of a sufficient amount of product into a natural stone of high absorption capacity, the technique of subsequent saturation is utilized. The product is applied to the surface in a pressureless jet to achieve preliminary saturation. After an interval of approximately ten to twenty minutes, during which the product is transported by capillary forces into the stone matrix, a new quantity of the material is applied again. For the purpose of achieving deeper penetration, tetraethyl silicates should not be lower than 70% concentration, otherwise the amount of cementing material formed in the pore space would be insufficient. Three saturating applications with twenty minute intervals constitute the first cycle. The masonry must not be allowed to dry completely between these sprayings. This is followed by a forty minute dwell time. The second cycle, again consisting of three applications with twenty minute intervals is then carried out. Again, a dwell time of forty minutes follows. The third and final cycle is analogous to the first or second cycle.

On critical stones with slow absorption characteristics, it is necessary after the last cycle to rinse the surface slightly with pure, water-free solvent to avoid changes in color or gloss by deposition of surplus material on the surface. Suitable solvents include acetone, alcohol or ketons. Additional rinsing improves penetration and prevents product accumulation on the surfaces.

The application of the total specified amount of material on two following days is not feasible. It imparts the risk of crust formation on the surface of the masonry. Also, overnight, the intermediate formation of silica gel may already have proceeded to such an extent that the penetration of new material is impeded. Therefore, the consolidation program should be scheduled in such a way that an area representing a structural or architectural unit can be completed in one day.

Freshly treated surface must be protected from rain for a period of three days. Elevated temperatures above 25°C should be avoided. The loss of tetraethyl silicate by evaporation might be considerable. Treated areas should be protected from direct radiation by setting an awning above or veiling the scaffolding. It is not recommended to work at temperatures below 5°C because the curing process would be slowed down dramatically. It is not recommended to accelerate the curing process by adding water or a more active catalyst. This procedure has not proven to be beneficial, since it encounters the risk of an uncontrolled reaction mechanism, the proliferating gel formation.

5.4 Unit Replacement

If a brick or stone is so badly damaged that it cannot be repaired, it must be replaced. In selecting which units are in need of replacement, it is important to consider both their value and their function. The intrinsic value of any worked stone in a building varies considerably with the age of the building and the quality and condition of the detail. All viable forms of repairs should be considered before deciding on the replacement of valuable carvings and details. The replacement of ashlars is certainly less controversial than the replacement of carved details, but no replacement should be undertaken lightly. The function of any stone that is under consideration for replacement must also be clearly understood. Decaying units, that have a structural role to play, have a clear priority for replacement, irrespective of their intrinsic value. Typical stones in this category are copings, weatherings, quoin stones and voussoirs. It is generally better to replace such stones than attempt to repair them. The expense of a scaffolding is, in itself, an encouragement to repair or replace borderline stones that might, or might not survive until the next scaffolding program.

5.4.1 Selection of Replacement Unit

It is always best to replace a brick or stone with an exact match of the original in terms of composition, color, texture, strength, finishing and porosity. Even with stones or bricks within a wall that may not be seen, a match is preferable at last in terms of size, strength and moisture resistance.

The best match for a stone is most likely to be one from the same quarry. A stone distributor should be able to identify a local stone and determine where it was quarried. If the original quarry is no longer in operation, the equivalent may be obtained from another quarry. Ensure that the new stone is of good quality with no clay veins or other obvious weaknesses. In the case of sedimentary rocks, it must be ensured that the block is cut so that the bedding planes are in the proper direction. Stones must be carefully matched to original sizes and profiles. Sometimes the original profile may not be readily determined, especially when there has been extensive weathering or where there has been a succession of repairs and replacements perhaps over several hundred years. The exterior face of a replacement stone should be finished with the same surface treatment as the original, and all ornamental details should be reproduced. Sometimes matching stones may be salvaged from a demolition yard. Failing that, an existing stone from the building can be sliced and used as surface veneer to replace several missing stones.

Artificial stone may be used to replace stone, matching the surface finish to a certain extent in the casting process. Pigments may also be used to match the original stone. However, artificial stones tend to age differently from the surrounding masonry. These concrete units are often reinforced with steel, as would be the case with modern precast panels, particularly if they play a structural role as in lintels. The reinforcing bars should be made of stainless steel or at least be well set in from the surface 25 mm (1 inch). Otherwise, they are prone to water penetration, which would lead to rust and cause the concrete to crack or the surface to spall.

Because brick is a manufactured product, it may be difficult in today's market to find a brick replacement that matches the original dimensions, color, finish and shape. In some cases, it may be necessary to order custom-made brick from a manufacturer or craftsman who specializes in reproducing historic bricks.

Old bricks may be found in a demolition yard or site or bought from a dealer who specializes in recycled building materials. Cracked or damaged bricks should be avoided, and lower quality, more porous common or fill bricks should never be used as exterior facing. Because it is often difficult to identify a face brick by sight, testing may be required. Before using second hand bricks, all of the old mortar must be removed, not an easy task as the brick is easily damaged, particularly, if the mortar to be removed is cement-based.

Occasionally a damaged or extensively weathered brick may be reversed by carefully cutting it out, cleaning off the mortar and placing it in reverse position back in the wall. There is little point in reversing decayed bricks of poor quality since the same decay process will take place in the other half of the brick once exposed to the weather. The cutting out and reversal of bricks is labor-intensive and in practice it is rarely carried out. Acid may assist the breakdown of hard mortar adhering to the brick beds during the cleaning process; bricks must be soaked before acid treatment in clean water and thoroughly washed afterwards.

Even with a relatively good match, the area of replaced brick and stone will probably look slightly different from the rest of the wall, at least until the replacement units have weathered. To prevent the wall from looking too mottled, it is best to make the area as simple a geometric shape as possible.

5.4.2 Removal of Damaged Unit

If only a few isolated stones or bricks must be replaced, each should be removed without touching the surrounding masonry. The physical process of cutting out the old stone varies according to the situation, but due care is required to ensure that the surviving adjacent stones are not damaged. If the stone is to be wasted it may be broken down with vertical saw cuts after the initial cutting, or broken up with a hammer and chisel. When the deteriorated stone or brick is chiseled out, care should be taken to avoid damaging the edges of the adjoining elements, particularly when removing the old mortar. Piecing may be very small in good-quality work and the cut out should be made with small, sharp chisels and small saw blades to a neat, square profile.

5.4.3 Installation of New Unit

The fit of the new element should first be tested by fitting it into its space without mortar. The replacement stone or brick should slide into the space left by the old unit and still leave sufficient joint space. The stones are raised into position by hand, hoist, or hand winch depending on their weight and location in the building. The cavity or open bed to receive them are carefully cleaned out and a mortar bed is spread onto the wetted, old stone. The mortar used should be similar in composition to the mortar of the surrounding joints. The new stone must also be dampened to avoid the risk of dewatering the mortar. The four sides of the space and the back face, if it is a solid masonry wall, are covered with sufficient mortar so that there are no air spaces left when the replacement element is pushed into place. The stone is handled into position and eased into the correct alignment with the aid of the lubrication provided by the wet mortar. The new stone is lined up and properly set up by tapping it with a wood or rubber mallet. If it enters too far, it must be removed and more mortar must be added in the space.

Very heavy stones may require temporary additional support. A stone may be placed on wedges of wet wood, or if it is a heavy block, of non-corrosive metal. Lead or slate packs may also be used. The wedges are positioned so that they are covered with at least 38 mm (1 1/2 in.) of mortar when pointing is completed.

With a large stone it may not be possible to rely on mortar to keep the new stone in place, and it may be necessary to fit it in place with metal anchors. If a large area is to be faced up with new stone it is essential that the new skin should be cramped back with a staggered grid of stainless steel fishtail cramps or other suitable restraint fixing.

After all of the new elements have been installed and adjusted, the joints should be repointed to match the rest of the wall. The repaired area should then be scrubbed clean with a brush and water to remove all excess mortar. Finally, in some instances, it may be desirable to weather the surface of the stone artificially.

Chapter 6

Masonry Cleaning

The cleaning of exterior masonry is perhaps the most visible aspect of contemporary rehabilitation work. However, the cleaning of masonry is a complex and delicate process that requires a good knowledge of the nature of the stains, the characteristics of the masonry and the properties of the various cleaning techniques. More damage can be done to a masonry surface in one day of cleaning with an inappropriate technique than in a century of normal weathering.

The information in these sections was adapted from the works of (London, 1988), (Higgins, 1985) and (Stahl, 1984).

6.1 Initial Considerations

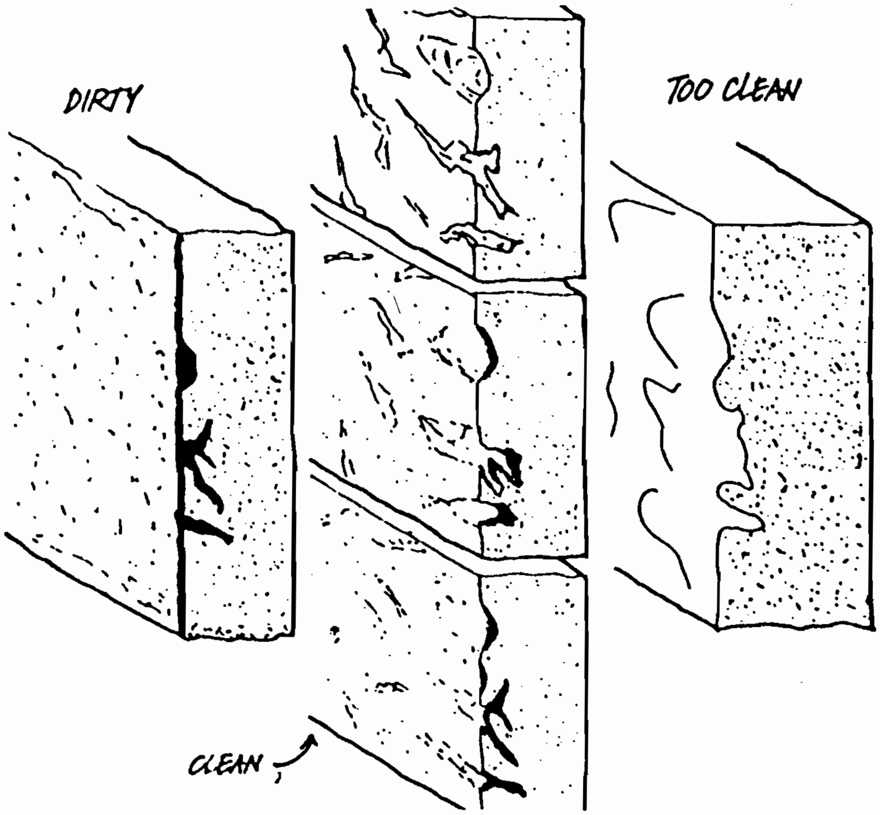
The cleaning of any building should be undertaken only after a careful evaluation of the goals of the operation and the consequences for the structure. Buildings are usually cleaned for purely aesthetic reasons. For many, the cleaning is a facelift, a cosmetic rejuvenation symbolizing perhaps a dramatic transformation of internal use. Owners or developers may want the building to look new and have dramatic before and after pictures to show clients. However, it is wrong to try to make a historic building look new. Removing all signs of aging sacrifices the character of the building and reduce its heritage value. Over time. masonry color may soften and give the building a rich patina that is often destroyed by radical cleaning techniques. Removing this natural surface eliminates a portion of the masonry and leads to accelerated deterioration.

Unless it can be shown that the dirt, paint or stain on the masonry surface is actually harming the masonry, it should be left alone. However, evidence may exist that the dirt and pollutants are harming the masonry. An encrustation of soot can absorb moisture and make the surface more susceptible to atmospheric pollutants and temperature changes. A dirty masonry surface has a much greater surface area that attracts more dirt and stays wet longer. This accumulation can aggravate freeze-thaw and biological attack of the surface. Certain types of stains or surface deposits can also attack the surface of the masonry. A reasonable aim is then to remove harmful stains, heavy dirt encrustations, dark streaks and sooty grime as much as possible, while leaving the natural characteristics that come with the age of the building.

6.1.1 Level of Cleaning

The objective of masonry cleaning is to remove the dirt encrustation without damaging the masonry surface. Cleaning should not go too deep into the masonry surface. The desired level of cleaning should be established prior to the start of the cleaning operations and not be allowed to progress any deeper than absolutely necessary. Cleaning should not erode the surface of the masonry nor should it progress so deep into the masonry that the surface itself is removed. Figure 6.1 illustrates the desirable level of cleaning. The cleaner the desired result, the more difficult it becomes to remove the dirt without removing some of the masonry surface. Cleaning a porous surface too deeply erodes the surface and exposes the material to more dirt accumulation and additional damage.

Figure 6.1 Microscopic Views of Surface Cleaning (Fram, 1988)



6.1.2 Nature of Masonry Stains

Common masonry stains include dirt, smokes, soot, rusts, copper, vanadium, magnesium, graffiti, paint, oil, tars, bird droppings and organic matter such as moss, algae, lichen and fungi. To remove stains in the most effective, yet least damaging manner, it is important to analyze the nature and origin of the stains. The nature of the stain often dictates what technique must be used to adequately clean the masonry.

The most typical form of staining in urban and industrial areas is simply grime or dirt. Dirt is a surface deposit of airborne particulate solids, mostly carbon soot and dust, held together with an organic glue consisting of unburnt tars present in a polluted atmosphere and bound to the masonry as much by electrostatic attraction as by molecular absorption. The pattern of dirt dispersion on a surface reflects the degree of local attraction as well as the surface pattern of the rain runoff. The dirt accumulates and combines with the byproducts generated by the deteriorating masonry to form a gray or black film or crust on the masonry surface.

It is important to distinguish this accumulation of dirt from the natural patina acquired by masonry materials over time. This patina is a beneficial chemical transformation of stone induced both during the working of the stone by the mason and by subsequent weathering. The cleaning process must remove the dirt accumulations without damaging the natural patina of the stones, or the original worked and tooled masonry surface.

6.1.3 Nature of the Masonry Materials

The ease of cleaning also depends largely on the nature of the material to be cleaned. The following material characteristics can affect the cleaning process: hardness, porosity, permeability and surface finish. The chemical composition of the masonry determines if adverse reaction with cleaning products can occur. Generally, it is the easiest to remove dirt from hard, inert material with a smooth surface and low permeability and porosity. A thorough understanding of the physical and chemical properties of the masonry would help avoid the inadvertent selection of damaging cleaning materials. Table 6.1 lists common masonry materials and rates their compatibility with of various cleaning technique

The interaction between the material and the foreign matter that contaminates it may determine how the masonry surface will weather once cleaned. Therefore, analysis of the masonry materials should include the potential adverse effects of cleaning techniques to determine the most effective method of breaking the bond between the dirt and the masonry surface. Prior cleaning attempts or water proofing may also affect how the masonry and the cleaning solution will interact.

Table 6.1 Compatibility of Masonry Materials and Cleaning Techniques

(Higgins, 1985)

Cleaning methods

Recommended	○
Acceptable	A
Use caution	C
Danger	x

	Water-spray	Water, Medium-pressure	Water, High-pressure	Surfactant	Steam	Acid-wash	Alkaline-wash	Organic gel or poultice	Special poultice	Abrasive blast, dry	Abrasive blast, micro	Mechancial grinding
Brick, soft	A	C	x	A	A	Ⓒ	C	A	A	x	x	x
Brick, medium	A	A	C	A	A	Ⓐ	A	A	A	x	C	x
Brick, hard	A	A	A	Ⓐ	A	A	A	A	A	C	A	x
Brick, glazed	A	C	x	Ⓐ	C	x	C	A	C	x	x	x
Terra cotta, plain	A	C	x	Ⓐ	C	C	C	A	C	x	C	x
Terra cotta, glazed	A	x	x	Ⓐ	C	x	C	A	C	x	x	x
Marble, plain	Ⓐ	A	x	A	A	x	C	A	C	x	x	x
Marble, polished	Ⓐ	C	x	A	A	x	C	A	C	x	x	x
Limestone, soft	Ⓐ	C	x	A	C	x	C	A	C	x	C	x
Limestone, hard	Ⓐ	A	C	A	A	x	C	A	A	C	A	x
Calcareous Sandstone, soft	Ⓐ	C	x	A	C	x	C	A	C	x	C	x
Calcareous Sandstone, hard	Ⓐ	A	C	A	A	x	C	A	A	x	x	x
Silicious Sandstone, soft	C	C	x	A	C	Ⓒ	C	A	C	x	C	x
Silicious Sandstone, hard	C	A	C	A	A	Ⓐ	C	A	A	C	A	x
Granite, friable	C	x	x	A	C	C	C	A	C	C	C	x
Granite, hard plain	A	A	A	Ⓐ	A	A	A	A	A	A	A	x
Granite, polished	A	A	A	Ⓐ	A	x	C	A	C	x	x	x
Concrete, friable	Ⓐ	C	x	A	C	C	A	A	A	C	A	x
Concrete, sound	A	A	A	A	A	A	A	A	A	Ⓐ	A	C
Cast-stone, friable	Ⓐ	C	x	A	C	C	C	A	A	C	A	x
Cast-stone, sound	A	Ⓐ	C	A	A	A	A	A	A	C	A	x
Slate	Ⓐ	C	x	A	A	C	C	A	A	C	C	x
Glass-block	A	A	C	Ⓐ	C	x	x	A	C	x	x	x

When analyzing the possible effects of a cleaning technique on the masonry, it is important to consider the characteristics of the mortar as well as well as those of the masonry units. The mortar is what binds the masonry units together and its deterioration can lead to serious masonry problems. Modern portland cement mortars are very resistant to most forms of cleaning but softer lime mortars, widely used until the 1920s, are more vulnerable. Cleaning techniques that may be harmless for the masonry units could prove disastrous for the mortar. Pressure washing masonry with water may not damage hard masonry units but it can easily wash out the lime mortar. Acid cleaning is another technique that can cause severe deterioration of lime mortars.

6.1.4 Test Patches

The best way to prevent masonry damage from an inappropriate cleaning is to do several small test patches to observe the effects of the cleaning technique on the masonry. Test applications of proposed cleaning techniques should always be made prior to proceeding with the cleaning operation. The selection of a cleaning technique is commonly accomplished by testing several methods to determine an acceptable level of cleaning.

These test patches should be located in unobtrusive areas. Buildings with several types of masonry materials or different surface finishes may require several tests in different areas. There may also be combinations of several types of stains that no single cleaning technique can remove. Test patches may, therefore, indicate that different cleaning techniques will be required in different areas of the building.

Test applications should cover an area of sufficient size to give true indication of its effectiveness. Test patches should encompass at least 0.25 square meters (2 sq. ft) and include masonry joints. For large stones, a test area should include several stones and mortar joints. Wherever possible, the test area should include each different element to be cleaned.

The tests should begin with water washing, the gentlest technique, and move up to harsher methods only when the gentler ones do not produce acceptable results. The tests should include several intensities for each method; for water cleaning, test different pressures and durations should be tested; with chemicals, various concentrations should be examined.

The masonry should be allowed to dry completely before attempting to judge the effectiveness of the cleaning technique. The cleaned surface should be closely examined for any signs of deterioration or discoloration. The test patches should be allowed to weather for at least a few weeks, especially when chemicals are used, to make sure that stains or efflorescence do not appear. With heritage buildings, the test patches should be allowed to weather for as much as a year. The delays involved are inconsequential when compared to the damage and disfigurement that may arise from the use of an inappropriate cleaning method.

6.1.5 Health and Environmental Concerns

The potential health and environment effects of a cleaning method must be carefully evaluated to ensure the safety of the workers and the general public as well as prevent damage to the surrounding structures, fauna and flora.

Workmen should be made aware of the possible dangers associated with the cleaning products All workmen should wear appropriate protective clothing to protect from the effects of dust and chemicals. Standard protective clothing consists of rubber gloves, safety boots, waterproof suits, hard hat, safety glasses and adequate face protection. When a chemical cleaning method is used workers should be provided with gas masks.

Prolonged exposure to chemical cleaners in either liquid or vapor forms can cause serious heath problems if the appropriate equipment is not worn.

When using a dry grit blasting method, the workers must also wear helmets equipped with a system to provide filtered air. Abrasive methods of removing dirt create airborne dust that can pose a serious health hazard, particularly if lead based paints are being removed, or if the abrasive material or masonry contains crystalline silica. Common sand contains this mineral, which can cause silicosis, a serious lung disease. For this reason, non-siliceous abrasives are preferred. Abrasive cleaning of masonry such as sandstone that contains silica should employ a wet grit method to help keep down the dust.

Care should also be taken to ensure that the public is not harmed by the cleaning operations. Adequate protection against the spread of dust, dirt, chemicals, water and residues should be provided with proper enclosure of scaffolding and sheeting. Water misting sprays may be required to prevent chemical wind drift. The site should be closed off to prevent pedestrians or children from coming in contact with any harmful products used in the cleaning process. All hazardous materials should be stored under lock and key. Inspectors or owners wishing to observe the cleaning process should be supplied with appropriate protective clothing. All opening in the walls should be properly sealed to prevent dust and chemical vapors from entering the building. The openings should be covered with a plastic sheet and caulked around the perimeter until a satisfactory seal is established. Closely fitted boarding must then be installed over the sheeting as further protection.

Safety measures must also be taken to prevent damage to adjacent building materials and surrounding property. All adjacent areas and adjoining materials must be protected against damage by the cleaning technique. This includes but is not limited to glass breakage, corrosion of metal trims and fixtures, damage to wooden trims, etching of glazed surface by chemicals, roof damage from chemical action or puncture and staining of interior walls. Proper sealing with plastic sheeting and caulking covered by rigid boarding usually provides adequate protection but strippable latex rubber coatings may be required to protect valuable materials like stain glass windows. Rainwater leaders, eaves, troughs and gutters should be protected from blockage by residues before work commences. Suitable protection must be installed at drains, but the normal flow must not be restricted.

Adjacent buildings should be covered with plastic sheeting to prevent staining and damage from wind blown dust and chemicals. Care should be taken to prevent excess water from the cleaning operations from ponding in nearby yards or seeping into basements. Likewise nearby automobiles must be protected from wind blown chemicals that could cause etching of the glass or spotting of the paint finish.

Plants must be protected from the effects of chemicals, dusts and residues. When chemicals are used, adjacent plants, shrubs and lawn should be pre-soaked and kept moist by providing constant water misting from soaker hoses. When acid cleaners are used, lime filled trenches should be installed to absorb and neutralize acidic residues and runoff. Animal life, ranging from domestic pets to songbirds can also be affected by chemical runoff.

6.2 Water Cleaning

Cleaning masonry with water is generally the simplest operation, the safest for the building and the environment and the least expensive method. Water cleaning methods are best suited for the removal of common dirt and soot accumulations. Soiling strongly bound with siliceous materials resists removal by water cleaning alone and requires some form of chemical treatment in combination with water washing. The four commonly used water cleaning methods are hand scrubbing, spraying, pressure washing and steaming. Each of these methods can be used on its own, or in combination with other techniques such as finishing rinses with chemical products.

Water cleaning can present a few problems. Water can seep through deficient seals around windows and doors. Also, porous masonry can absorb excess amounts of water during the cleaning process, particularly, if large quantities are used. Clay bricks and sandstones are particular vulnerable because of their high permeability. The excess water can penetrate to the interior of a building, causing water stains and molds. Within the wall, it can damage insulation, lead to rot in wooden elements and corrode hidden metal elements. Corrosion of iron ties in the masonry leads to rust stains and localized spalling of the masonry, and also to a weakening of the structural supports. It is, therefore, important to minimize water penetration during the cleaning process. It must be ensured that the wall is watertight, all damaged areas have been repaired, and the masonry and joints, including mortar and caulking, are sound. All door and window openings must be sealed with a polyethylene sheet taped all around; a sheet of plywood can be placed in front of the polyethylene for additional protection. With a well sealed wall and a technique that uses only a limited amount of water, the degree of water penetration is tolerable even with moderately absorbent masonry walls

If a wall is washed repeatedly, excess water can also bring soluble salts from within the masonry to the surface, forming efflorescence. In dry climates, the water may evaporate inside the masonry, leaving the salts slightly back of the surface. Efflorescence, while not itself harmful to the masonry, does provide a warning sign that moisture is present. Water used for cleaning can also mobilize other impurities in masonry, such as metallic ions that can cause permanent rust like discoloration.

A similar effect is caused by impurities such as iron and copper in the water supply itself. The chlorides in chlorinated water can bring iron to the surface. Even soft water may contain harmful amounts of these chemicals. Acidic water can damage carbonate based masonry like limestone and marble. The dissolving action of acid on carbonate material can result in pitting of the masonry beneath the more resistant soiling, especially during prolonged periods of soaking. Lime mortars are similarly affected. Regular or hard water is better suited to for this type of masonry because of the retarded cleaning action. Therefore, any water used in the cleaning process should be clean, potable, have a neutral pH (pH=7) and be free of contaminants. In addition, to limit iron in the water, all piping and fittings should be of plastic or non-ferrous materials.

Water methods must not be used during periods of cold weather because water within the masonry can freeze, causing the stone or brick to spall or split and crack. Because a wall may take weeks of good weather to dry after cleaning, buildings should not be water cleaned within a few weeks of the first average frost date, or whenever local forecasts predict cold weather.

6.2.1 Hand Scrubbing

Hand scrubbing is an effective yet often overlooked cleaning method in many situations. All that is required is a bucket, a bristle brush and a garden hose. A soft natural bristle, nylon or fiber brush is preferred; steel brushes are too abrasive and leave specks that rust. An area is wetted by sprinkling with a hose, then the surface is brushed using extra effort in the dirtiest areas and, finally, the area is rinsed with the hose. A small amount of non-ionic detergent can be added to the water. Scraping with wood and plastic tools can assist in loosening the deposits and improve the action of water cleaning. Hand scrubbing is somewhat time-consuming and is most effective with weakly adhering dirt. It is most often used on glazed and polished surfaces, on buildings of particular significance, or by homeowners doing their own work.

6.2.2 Spraying

Spraying relies only on a hose using regular water pressure. A fine mist of water over several hours loosens the bond of the dirt, which is then washed off. In general, the finer the mist the better are the results. The spraying process should be interrupted regularly to reduce the quantity of water used and to allow the soiling encrustation to swell and contract, which helps to loosen it from the masonry. A timer can be installed on the hose for this purpose and set to provide a few seconds of spraying every few minutes, making certain not to let the masonry dry completely between the sprayings. The time required for this operation varies considerably with the type and degree of soiling, but generally anywhere from a day to several weeks of misting is required. Once the layer of soiling is sufficiently loosened, a rinse with a garden hose, and with additional manual scrubbing, if necessary, should be enough to remove the dirt from the wall.

On a small building the hose and heads can be mounted at the top of the wall on a scaffolding. For a large building they are moved periodically down the wall in order to cover the entire surface area. Extra heads can be placed at heavily soiled areas (under cornices and ledges) and hard to reach places (behind carved areas). The three commonly used misting techniques include: dripping water down the wall through a perforated hose placed along the top, spraying the wall with a low-volume, wide angle sprinkler 1.5 L/min. (1/3 gallon/min.), and projecting a fine mist on the wall by covering a hose head with cloth.

When using a technique requiring large quantities of water, check the pH balance of the water as well as the presence of trace metals, especially iron. Acidic water, which may damage certain limestones and marble, should be treated before use; water containing iron compounds can stain masonry.

6.2.3 Pressure Washing

Pressure washing depends on mechanized pressure. Low pressure water jets 0.34 MPa (50 psi) can be used to clean stone and hard brick. Water jets with a pressure of 0.7 MPa (100 psi) or more can cause considerable damage to soft stones and brick. Pressure washing can be effective alone on loosely adhered dirt but is most often used in association with chemicals. It is important to keep the hose nozzle moving and special care must be taken on soft lime mortars, which are easily removed. High pressure jets, 1.4 MPa (200 psi), have the same effect as abrasive cleaning and their use should be avoided on old masonry.

6.2.4 Steam Cleaning

Although once a common method, steam cleaning is now rarely used because it is slow, generally no more effective than plain water and poses safety problems for the operator. It may still be useful, however, in removing oily stains, such as those from chewing gum, and soiling on highly carved or ornamental surfaces with a low risk of surface abrasion. Steam cleaning has also proved effective in removing deep seated soiling after acid cleaning. Gypsum bound soiling, however, responds better to cold water cleaning. Steam cleaning is considered a water cleaning method and must observe the same provisions for dry out time and precautions against frost damage.

Steam is generated on site in a flash boiler at grade and compressed to run to the work face by a system of pipes. Consideration must be given to the drop of pressure in the line between the compressor and the work face. The steam is transmitted to a lance with a 12 mm (1/2 in) nozzle aperture and directed against the masonry surface at a low pressure 0.14 to 0.34 MPa (20 to 50 psi). Greasy soilings on calcareous stones require a working time of one minute per square foot. Heavily soiled areas require considerably more time.

Heavy soiling can be scrubbed by hand using a natural bristle or nylon brush to assist in the steam cleaning. Detergents and chemicals may be added to supplement the cleaning power of the steam, however, caution must be exercised because some combination may be hazardous to the operator or the masonry. Steam cleaning is an extremely dangerous operation and considerable care must be taken in providing adequate protective equipment and proper scaffolding.

6.3 Chemical Cleaning

The use of chemical products in masonry cleaning has increased significantly in the past few years. Chemical cleaning is generally an acceptable technique for cleaning old masonry and is certainly the most effective and the least damaging method of removing paint. However, if not properly carried out, it can also cause staining, efflorescence or other damage; it is also potentially very dangerous to the operator, and extreme caution must be exercised. Chemicals can also be very dangerous to the environment.

The main types of chemicals used are acids, alkalis, surfactants and inorganic salts. These chemicals are used mostly for removing common soot. Once the dirt is removed, bits of tar, spots of oil, rust and all kinds of other stains on the masonry may be revealed. These stains can then be treated with an appropriate poultice. Because most chemicals are water-based, they have many of the potential problems of plain water. However, compared to water washing, the use of chemicals somewhat reduces the quantity of water needed, limiting the risk of water penetration.

If chemicals are not used properly, they can cause water damage, dissolve certain types of masonry and produce discoloration. Incorrectly chosen cleaning products can cause damaging chemical reactions with the masonry itself. Marble and limestone, for example, are dissolved easily by acidic cleaners, even in dilute forms. Chemicals also may change the color of the masonry rather than remove soiling and may leave a hazy residue in spite of heavy rinsing. In addition, chemicals can react with components of mortar, stone and brick to create soluble salts that can form efflorescence. Advance testing should help avoid these problems.

Chemical cleaning should be undertaken only by professionals. Unfortunately, too many contractors have little expertise or understanding of masonry, different types of staining or even the chemicals with which they are working. When approaching cleaning companies, references must be requested and previous work reviewed. If chemical cleaning is determined to be the best course of action, the chemicals to be used must be determined; these should preferably be proprietary cleaning products that have been properly tested and are backed by the reputation of a known manufacturer. Secret formulas, that cleaning contractors mix up in their garage, should be avoided; if these are truly old formulas, they probably are based on hydrochloric acid. These formulas also may be pure hydrofluoric acid without other useful components.

Chemical cleaning is generally carried out with some variation of the following method. The wall is first sprayed with water. Wetting the masonry avoids excessive penetration of chemicals and dirt and helps soften the soiled crust. Paint stripper, however, is applied to dry masonry. The chemical products are then spread over the surface of the masonry with a brush or a sprayer. These products include surfactants, organic compounds with powerful properties of detergency and wetting to clean and penetrate the masonry. Finally, the cleaners and the dissolved soils are removed by thoroughly rinsing with a low-pressure, less than 0.34 MPa (50 psi) jet of warm water. With some alkaline cleaners, the use of a neutralizer before the final water rinse is advised.

Another method, used for special problems in localized areas, involves applying a chemical paste called poultice, after the crusty soil has been removed. Sticky products such as chewing gums, adhesives or tar can be hardened with dry ice and then broken off.

6.3.1 Acid Cleaners

Acid cleaners are used for cleaning most granites, sandstones, non-calcareous stone and unglazed bricks. The acid loosens the dirt, which can then be rinsed off easily. To determine if the stone is acid soluble, put a few drops of diluted hydrochloric acid (muriatic, HCl) on the surface; if it bubbles or foams, the stone should not be cleaned with an acid. Acid should never be used to clean limestone, marble or sandstone that contains calcium carbonates because it has a rapid dissolving action on these stones. Lime based mortar and pointing are similarly affected. Acid can also damage the finish of glazed and polished surfaces such as glass, glazed terra cotta and polished granite.

All adjacent surfaces should be adequately protected from acid and rinse water. Special attention must be paid to the possible wind drifts and seepage. All glazed and polished surfaces must be protected from any contact with the acid cleaner. These areas should be masked with both a strippable latex rubber spray and plastic sheeting covered with close fitting boarding. The perimeter should be caulked to prevent seepage. Care should also be taken to prevent corrosion of scaffolding and swing-stage equipment.

Hydrofluoric acid (HF) is the most commonly used acid cleaner, as it is the only one that does not form soluble salts that harm brick and stone. However, it is very toxic and corrosive and it can damage glass and aluminum, which must, therefore, be protected. It should be used in a maximum concentration of 5 percent although it is preferable to use a weaker solution of 1 to 3 percent plus a second application on heavily soiled areas. Chemical cleaning with acid should not be attempted at temperature below 10°C.

Hydrofluoric acid based cleaners do not work well below this temperature. Excessive amounts of chemicals are required and proportionally greater rinsing is necessary. The result is a greater chance of damage to the masonry face and pointing.

Because acids can lead to rust stains on certain stones by dissolving otherwise insoluble iron compounds, some include rust inhibitors. Complex agents such as orthophosphoric acid or phosphoric acid (H_3PO_4) are sometimes added to acid in a limited concentration (0.25%) to reduce metallic salt deposition on the surface of the masonry. These chemicals act as a chelating agent that sequesters metallic ions and transforms them into insoluble complexes. Thorough washing and maintaining a constantly wet masonry face during the cleaning process prevents the deposition of these products on the masonry.

Hydrochloric acid (HCl) is strong but less efficient as a cleaner and should not be used on old masonry; it causes efflorescence and color changes if the stone has a high iron concentration. The formation of hygroscopic iron chloride compounds can result in severe staining of the surface of the masonry. Crystallization of these compounds in the pores of the masonry exerts considerable pressure and can be quite destructive of weak or fissured material. Old brick is particularly susceptible to damage from this form of acid.

Prior to starting the acid cleaning the masonry wall should be hosed down with water until the surface is thoroughly wet and water begins to flow down the wall. The cleaning solution should be applied from the bottom of the wall and working up to the top. Starting at the bottom minimizes the redeposition of cleaning residues, a common cause of staining. The cleaning solution should be allowed to remain on the masonry more than a maximum of ten minutes. During this time the wall surface must remain wet. The wall should then be rinsed, starting at the bottom and working up and then back down again. The masonry should be allowed to dry before evaluating the effectiveness of the cleaning.

At the midday break and at the end of the work day, all areas being cleaned must be washed down to remove all traces of acids, checking the pH of the surface to ensure neutrality.

6.3.2 Alkaline Cleaners

Alkalis (caustics) can be used on acid sensitive masonry materials such as limestone or marble, glazed brick and glazed terra cotta, although they are rarely needed because most of these materials respond well to cleaning with water and detergents.

The most commonly used products have a potassium hydroxide (KOH), ammonium hydroxide (NH_4OH or ammonia), or sodium hydroxide (NaOH or caustic soda) base. Many commercial cleaners are based on sodium hydroxide. Sodium hydroxide requires greater effort to rinse thoroughly and should not be used on weak, friable or very old and historic masonry, because it tends to cause salt deposits. Ammonium hydroxide is safer for use on calcareous stone. Complexing agents and organic bleaches are typically added to prevent salt deposits and to give a more even final appearance to the masonry. Foaming surfactants are necessary to hold the ammonia in solution during the cleaning process.

The alkali cleaner is typically sprayed onto the masonry in the same fashion as acid cleaners and allowed to react with the soiling for five to thirty minutes before being rinsed down. In an alternate cleaning method, the alkaline cleaning solution is sprayed onto the masonry in the same fashion as for the cleaning method of water spraying. The solution is allowed to run down the face of the masonry to a plastic lined gutter at the base of the wall and pumped back to the top of the spray system. This is allowed to continue until a satisfactory degree of cleaning is obtained. Similar cautions as with a water spray system must be observed. At the end of the process the surface should be rinsed down with water to remove all traces of chemicals.

Alkaline cleaners can produce efflorescence and may result in brownish stains if iron compounds exist in the stone. As a safeguard, the surface to be cleaned should be wetted beforehand and neutralized afterward by rinsing with a mild acid solution such as acetic acid to avoid stains. Alkalis, like acids, must not be used on stones with very high iron content. Alkalis can also damage paint, wood and some metals.

6.3.3 Inorganic Salts

Sodium hexametaphosphate (NaHMP or Calgon) is an effective, neutral agent able to dissolve gypsum bound soiling on masonry. This cleaner requires a long contact time with soiling to effectively break down the gypsum, and is usually combined with either basic or acidic compounds and surfactants to improve the cleaning action. A solution of 5% NaHMP, 0.25% ammonium formiate, 0.05% surfactant and ethanol amine to pH 9 is an effective gypsum solubilizer for use on limestone. It is applied in combination with a thixotropic gel or used with a recirculating system to give a long contact time with the masonry.

6.3.4 Surfactants

Surface-active agents, or surfactants, are used to dislodge minute insoluble particles that are tightly held to the masonry surface by molecular attraction and allow the particles to be flushed away. Surfactants can be used alone with water in concentration of 1 to 2 % by weight or volume, or in lesser concentrations as part of formulations with acidic, neutral or alkaline bases. Most commercial cleaning formulations include some form of surfactants.

There are three types of surfactants commonly available: anionic detergents, non-ionic detergents and cationic cleaners. Most of the commonly available detergents are anionic and are generally not suitable for masonry cleaning. These products require high temperatures and soft water to work effectively. They react with magnesium, calcium and iron ions to form soap curds that are difficult to remove. Non-ionic detergents are more suitable for masonry cleaning. They can be used with hard water at low temperatures and are often combined with thickeners to improve the cleaning action. Alkyl-ethylene-oxide type detergents are satisfactory for general masonry cleaning. Cationic cleaners such as long-chain or fatty amines are not good general cleaners. They should not be combined with anionic cleaners as they form insoluble precipitates. However, they are useful in acidic formulations to remove bacteriological slimes and in disinfection work. Quaternary ammonium salts can be used for this cleaning operation.

6.3.5 Organic Solvents

Organic solvents are employed to break down soiling that is soluble only in non-aqueous liquids: paints, grease, oil, waxes, tars, resins, adhesives, rubbers, lacquers, varnishes and plastics. Once broken down these stains can be emulsified with a surfactant and rinsed away with water. Organic solvents are normally used with pastes, gels or poultices to minimize soaking and thus minimize transfer of soiling deeper into the masonry.

Two different kinds of organic solvents are available for cleaning purposes: petroleum-based solvents and synthetic solvents. Petroleum-based solvents such as xylene ($C_6H_4(CH_3)_2$), toluene ($C_6H_5CH_3$) and benzene (C_6H_6) are useful in breaking down oils and paints. Xylene is the safest; toluene is more volatile and benzene is highly toxic and carcinogenic. All are flammable. Special solvents are available with high flash points such as Stoddard Solvent (38°C) and 60°C Flash Point Solvent. These do not volatize appreciably below their flash point and are, therefore, useful in poultices and gels

Synthetic solvents are mainly chlorinated hydrocarbons similar to those for dry cleaning solutions. These are quite poisonous and must be used with care. They are, however, non-flammable. Perchlorethylene and methylene chloride are examples of common synthetic solvents. There are many solvents available, each with its own particular properties.

6.3.6 Poultices

Poultices, or leaching packs, involve spreading a chemical paste on the masonry to loosen the dirt or stain. The packs then draw out the dirt as they dry, thus avoiding the reabsorption of dissolved material into the masonry. This technique is used to remove stains from porous masonry and for more general cleaning problems inside buildings where it is impossible to use water. Poultices may be applied successfully to remove stains such as oil, tar, plant materials (lichen and algae), graffiti (including spray paint), metallic stains such as iron or copper and occasionally some types of salt deposits (efflorescence)

The paste is made up of an inert, absorbent material such as talc, chalk powder, clay, or whiting and mixed with a binder such as clean acid free cotton waste, sawdust or even shredded paper. These inert materials should be obtained in pure form, ensuring that they are not in fact acidic. The paste is then saturated with a liquid medium to dissolve the specific kind of stain. Water is used for most chemical poultices but organic solvents are required for stains soluble only in solvents. Glycerin is often added as a thickener and to slow down evaporation.

Generally, a layer about 9 to 12 mm (1/3 to 1/2 in.) thick is applied on pre-wetted masonry. Poultices should be applied to whole stones up to the joints to avoid patchy looking, unevenly cleaned stones. A support mechanism is often required for heavy poultices to stop them from falling off before the pack is completely dried. A non-ferrous or plastic expanded mesh is used. The mesh can be attached to the wall with non-staining fasteners. The entire area is then covered with a plastic sheet to slow down the drying process. Once the poultice has dried out, it can be removed carefully by hand with the aid of wooden spatulas and bristle brushes. Finally, the area is rinsed off with water. Several applications will probably be required to completely remove the stain

6.3.6.1 Copper and Bronze Stains

Stains are most often found in areas affected by runoff from copper flashing, gutters and fasteners. They can also be found adjacent to bronze statuary or architectural details. These stains are often very localized and can be treated with a poultice. Stains on siliceous material can be treated with a water-based solution of 10% sulfamic acid (H_2SO_3) in a poultice pack. Stains on carbonate material can be treated with a water-based solution of 2 to 5% ammonium carbonate ($(NH_4)_2CO_3$) in a poultice pack.

6.3.6.2 Vanadium Stains

Vanadium stains are typically green and are suspected to result from impurities in the masonry or possibly an interaction with vanadium alloys in the fasteners and anchors. Although vanadium stains are easily cleaned by a solution of 227 g (1/2 lb.) of potassium or sodium hydroxide (KOH or NaOH) to 1.14 l (one quart) of water, this process may result in sodium salts unless it is applied in the form of a poultice.

6.3.6.3 Iron Stains

These stains commonly result from the rusting of steel or cast iron members, flashing or fasteners in contact with the masonry. It may also result from the rusting of iron ties embedded within the masonry. Localized staining should be treated with a poultice. Stains on siliceous material can be treated with a solution of orthophosphoric (H_3PO_4) or oxalic acid ($H_2C_2O_4$), 10% by weight, and sodium salt of ethylene diaminetetra acetic acid, 2% by weight in water mixed into a poultice paste. Stains on carbonate material can be treated with a 15% solution of sodium citrate ($NaC_6H_7O_7$) in water, mixed with equal parts of glycerin and worked into a poultice paste. More wide spread staining requires acid cleaning with a solution of oxalic acid (one pound per gallon). Ammonium bifluoride 50 g/l (1/2 pound per gallon) hastens the reaction by generating fluoric acid. This technique is not suitable for carbonate materials. The same method is also effective in removing welding splatter. Brown stains that do not respond to these treatments are probably manganese stains.

6.3.6.4 Manganese Stains

Oily brown in appearance, manganese stains are caused by impurities in brick. They usually appear on mortar joints and seem to run down the interface of the masonry unit and the mortar. Manganese stains can be removed by chemical cleaning with a solution of one part by volume of acetic acid (CH_3CO_2H or vinegar), a weak acid, at 80% concentration or stronger, one part hydrogen peroxide (H_2O_2), a strong oxidizing agent, at 30 to 40% concentration and six parts of water. Even when completely removed, the stains may return within a few days.

6.3.6.5 Grease, Oil and Tar Stains

Often found on areas beneath or adjacent to tar and gravel roofs, these stains can also occur at grade from asphalt roadway splatter. These stains are best treated with a solution 20% by volume of petroleum solvent, 10% chlorinated hydrocarbon solvent, 2% non-ionic surfactant and water to 100%, mixed into a poultice.

6.4 Abrasive Cleaning

Abrasive or mechanical cleaning techniques such as sand blasting and the use of power sanders are unacceptable cleaning methods for old and historic masonry. These techniques destroy the appearance, original materials and physical well being of a building. Abrasive cleaning of masonry results in the removal of the hard fired exterior surface of brick or terra cotta or the hard skin of stone, thus exposing the softer interior to weathering and rapid deterioration. It can damage pointing and joint details, leading to water penetration. It damages or destroys carving and other decorative detailing. It results in a roughening and pitting of the surface, increasing the possibility of water and dust accumulation and causing rapid and uneven soiling as the masonry ages. Other parts of the building are likely to be damaged because abrasive techniques are hard to control. Mechanical cleaning using tools such as wire brushes, rotary wheels, power sanders similarly damage the masonry. In addition, it can deposit small metallic particles that can cause rust, thus staining the masonry.

6.4.1 Blasting

Blasting is the most common abrasive technique and involves spraying under pressure a material that impacts or abrades the surface: sand, ground slag, crushed walnuts or almond shells, crushed eggshells, synthetic particles, glass beads and micro-balloons. Only non-siliceous grits should be used since silica dust causes silicosis. Sandstone and concrete also contain considerable amounts of silica that can be released as dust during the blasting process. Scaffolding must be enclosed with tarpaulins around the work area to limit dust drift from the blasting operations. Whenever possible blast cleaning should be done during calm weather or at night to reduce the dust nuisance. The operator and all workman assisting in the cleaning operation as well as observers must be equipped with respirators that should be worn at all times. A hand trigger control should be used on the blast head to better control the operation and to allow the operator to stop at will and observe the results. After the cleaning operation is completed, the wall should be given an air blast to remove dust and grit from the masonry. The site is to be cleaned of all spent grit and dust at the end of each working day. The waste is to be wetted down and disposed of in closed containers.

Wet grit or hydrosilica cleaning combines a grit material such as those listed above with water. However, the detrimental effect on the masonry is the same. In addition, water will be driven deep into the wall where it may cause severe masonry damage. While not normally considered, an abrasive cleaning technique using water at high pressures can also cause the masonry surface to abrade.

A delicate method of abrasive cleaning uses micro-abrasive grit on small hard to clean areas of carved, cut or molded ornaments on building facades. Originally developed by museum conservators for cleaning sculptures, this technique employs a fine powder such as glass beads, micro-balloons, aluminum oxide, silica flour or crushed dolomite powder at approximately 0.07 to 0.34 MPa (10 to 50 psi) by a very small, almost pencil like pressure instrument. This technique has limited practical applicability on large scale building cleaning projects because of the cost and the relatively few persons competent to handle the task.

6.4.2 Mitigating the Effects of Abrasive Cleaning

Not much can be done to mitigate the damages caused by abrasive cleaning. It is impossible to recover lost crisp edges, tool marks or other indications of craft technique. Harder, denser stone of uniform composition should continue to weather with little additional deterioration. Unfortunately, some types of sandstone, marble and limestone weather at an accelerated rate one their protective surface has been removed. Softer types of masonry and particularly bricks are most likely to require some remedial treatment if they have been abrasively cleaned. Because the potential treatments are both technically and aesthetically problematic, it may be best not to intervene unless there are definite signs of deterioration, such as spalling.

compound to cling to a vertical surface. The remover must remain on the surface for a period of up to several hours; the work area should be kept moist by adding chemicals as required.

Alkaline strippers with a base of sodium or potassium hydroxide are generally more economical and work particularly well on linseed oil based paints. However, they can cause efflorescence and, like all other cleaners, they must be thoroughly rinsed off. A weak hydrofluoric acid based cleaner is sometimes applied as a neutralizer before rinsing. Some other coatings applied to masonry surfaces, such as lime washes, including whitewash and color wash, are soluble in acid.

Organic solvents, such as methylene chloride, tend to be more expensive but they are more effective in dissolving most types of paints as well as more recent products such as urethane varnishes or epoxy. However, they can spread stains deeper into the masonry, unless used in a poultice form which is not always a practical way to remove paint from a large area. They are generally quite toxic and used only when other methods are not adequate.

Graffiti removal presents another problem. If the wall was previously dirty, the cleaned area might be lighter than the rest of the wall and the ghost of the offensive message still evident. The whole wall must be cleaned, or an attempt can be made to dirty the cleaned area artificially so that it matches the rest of the wall.

Chapter 7

Monitoring the Effects of Insulating a Heritage Masonry Building

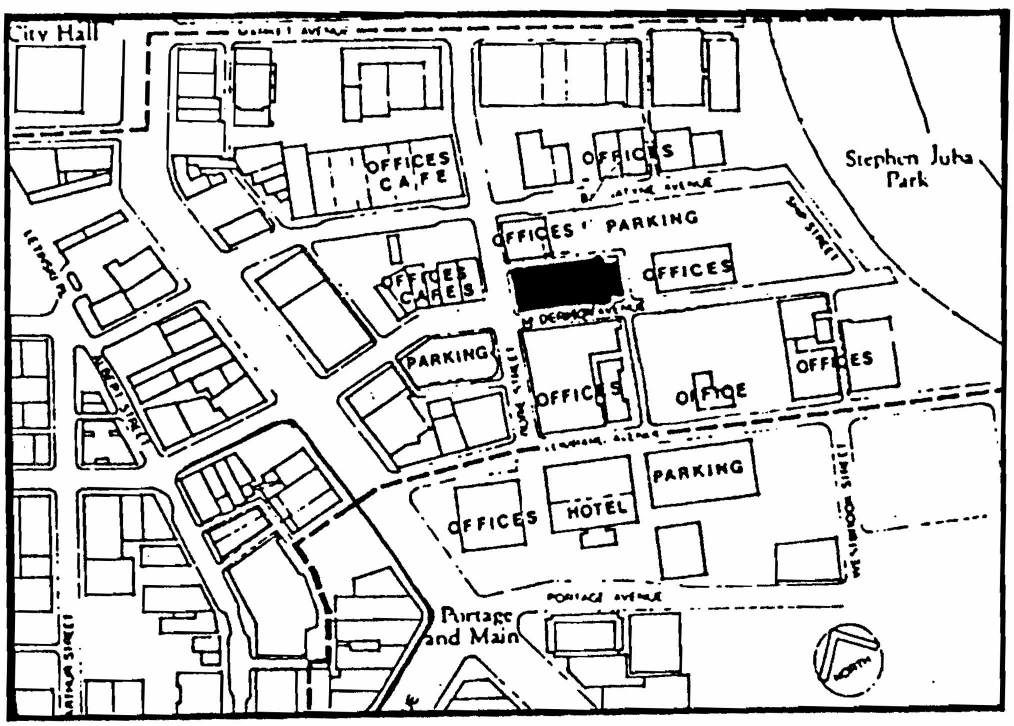
The Winnipeg Customs Examining Warehouse, a historic masonry building owned by the Federal Government, was recently renovated to house the Artifact Restoration Workshops and Laboratories of the Canadian Parks Service. To accommodate this new tenant, the indoor temperature and relative humidity in the building must be maintained at a constant level. Therefore this heritage building has undergone a complete retrofit of its exterior walls, windows and roof. This renovation consisted of the insulation of the exterior masonry walls and the application of air and vapor barriers, a new insulated roof membrane, the replacement of all windows and doors and the installation of a forced air HVAC system. The consultants for this project were responsible for the initial building inspection, providing the design for the retrofit of the exterior walls, windows and roof, and installing and servicing the sensors. The Institute for Research in Construction was responsible for analyzing and monitoring the effects of the proposed retrofit.

The second part of this report addresses the process used in monitoring the effects of the insulation on the masonry walls. It is meant primarily as a guide for processing of the data during the next eighteen months. As a brief introduction, in Chapter 7, the building being monitored is described in terms of its historic background, environmental context and building description. The initial condition of the building and the renovations undertaken are then explained. This is followed in Chapter 8 by a summary of the analysis of the effects of insulating of the exterior masonry walls. Chapter 8 also describes the components of the data gathering system and the process for data gathering. Finally, Chapter 9 is an explanation of the programs used in the data processing. The SPLIT parameter files and the EXCEL macros are described in terms of the various areas of analysis.

7.1 The Customs Examining Warehouse

In 1988, the Canadian Parks Service was in need of more spacious facilities for its Artifact Restoration Workshop and Laboratories. Their former location at 578 Saint Mary's Road, Winnipeg, was considered undersized and unsafe. It was therefore recommended that they relocate to the Winnipeg Customs Examining Warehouse, a federally owned building at 145 McDermont Avenue (Figure 7.1). Sufficient space was available on the fourth floor of this historic masonry building to meet the current needs of the Canadian Parks Service. The following background information and building description is adapted from (MacFarlane, 1988).

Figure 7.1 Location of the Winnipeg Customs Examining Warehouse



7.1.1 Historic Background

The Winnipeg Customs Examining Warehouse was a direct result of the projectionist stand of the late nineteenth century Federal Government trade policies. During this period, tariffs imposed on American goods favored British and European imports entering Western Canada from the East. The late nineteenth century also saw the realization of several railway links to Winnipeg. The year 1878 marks the completion of the railway between Saint Paul, Minnesota and Winnipeg. Then, in 1882, the main line of the Canadian Pacific Railway was extended from Port Arthur (Thunder Bay), linking Winnipeg to the East. Three years later, in 1885, the completion of the railway linked Winnipeg with the Pacific coast. With the completion of these railways, customs business at Winnipeg expanded greatly. By the end of the century, Winnipeg was the third largest city in Canada (National Revenue Review, 1937). The city became, and remained for several years, the pivotal point for trade in the booming West. The increased activity necessitated expanded facilities and in 1905 the Commissioner of Customs called for a new Customs Examining Warehouse.

The original Customs House, built in 1873-74, was a brick building set on a stone foundation with a frontage of 54 feet and a depth of 56 feet. The ground and first floors were occupied by Customs Officers and the attic served as the residence of the Collector of Customs. A small warehouse was added at an unknown later date and these buildings served until the construction of the new Custom Examining Warehouse. The first Customs House, at what is now known as 198 Main Street, was well located for its function, being near Fort Gary with its trade associations. By 1905, when the site was chosen for the new Customs House, Winnipeg had grown enormously. This growth was reflected in the changing aspect of its downtown core. The commercial center of the city had shifted away from Fort Gary and toward the Grain Exchange on Rorie Street and the banks along Main Street (Saunders, et al, 1974). Consequently, the new Customs House was located nearby, on the corner of Rorie and McDermont Avenue, in the surrounding Warehouse and Exchange Districts. Thus the construction of the Customs Examining Warehouse at 145 McDermont Avenue reflects this shift in commercial activity and the resulting physical development.

7.1.2 Environmental Context

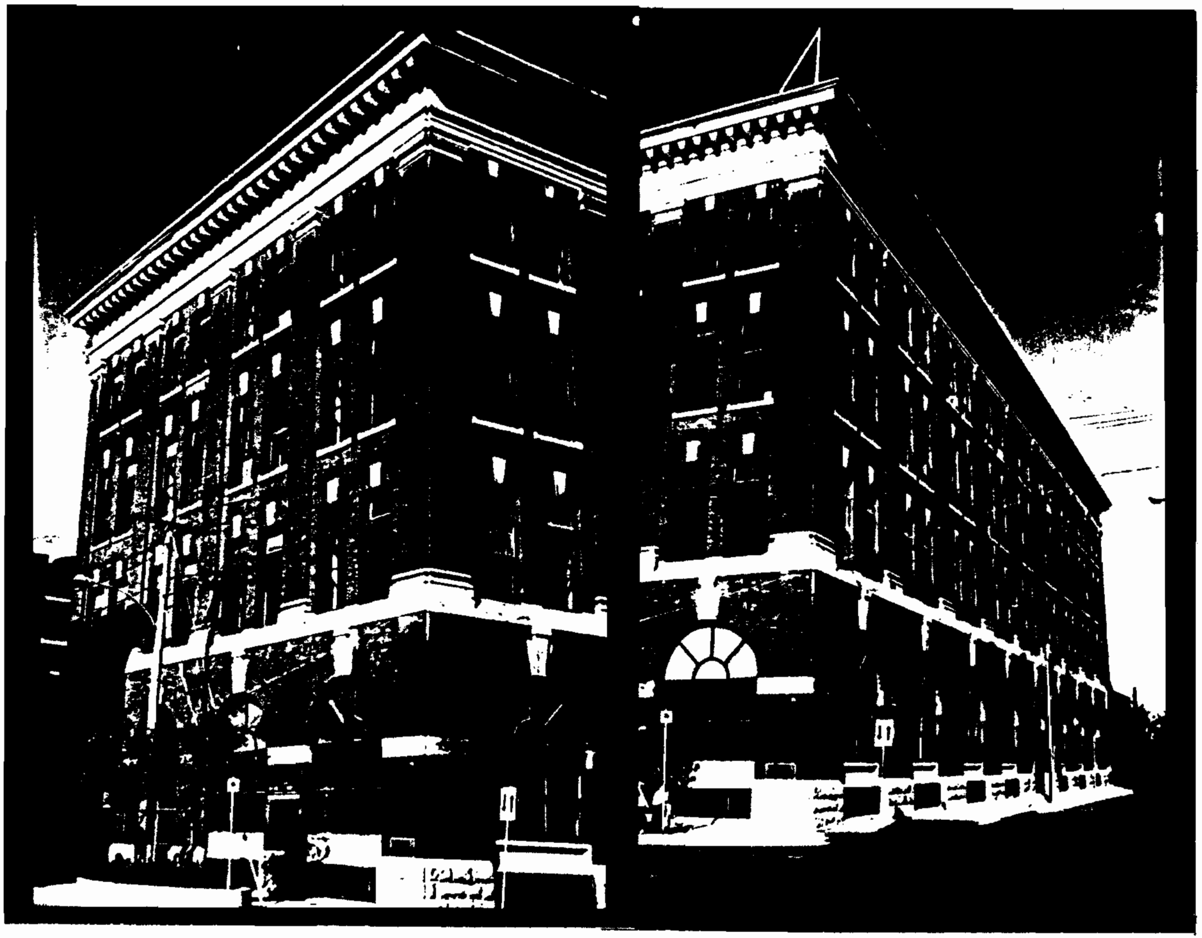
The Customs Examining Warehouse is located within the Exchange District as identified by the Winnipeg Core Initiative program. The Exchange District is defined as a twenty block area north of Portage and Main, composed primarily of commercial and warehouse buildings constructed between 1882 and 1916. The strong heritage character of the area is respected and maintained. The Customs Examining Warehouse is sympathetic to the surrounding structures not only in terms of scale and materials but also in function and age. Contemporary buildings situated nearby include the former Galpern Candy Company (1906) at 165 McDermont, the Criterion Hotel (1903) at 214 McDermont and the Marshall Wells warehouse (1900) at 123 Bannatyne. These buildings contribute to the general cohesiveness of function and age which defines the area (Saunders, et al, 1974). The intrusion of modern structures such as the tiered parking garage to the southwest of the Customs Examining Warehouse has been minimal and does little to lessen the heritage character of the area. The Warehouse District as a whole has undergone a tremendous revitalization in recent years, with the conversion of many old warehouse buildings to office and residential use and the introduction of many restaurants and small retail outlets. Furthermore, the city's main theater and concert facilities are located in this neighborhood and the result is a busy, popular, high profile district, of which the Customs Examining Warehouse is an integral part.

7.1.3 Building Description

The Winnipeg Customs Examining Warehouse is a massive, masonry clad building, dominating the corner of Rorie and McDermont. It is a four story, flat roof structure with a simple rectangular massing. The building occupies an area roughly 1440 m² (15500 sq. ft.) in size with a frontage of 58.2 m (191 ft) along McDermont Avenue and 24.7 m (81 ft) on Rorie Street (Figure 7.2). Located on the east side of the building, a single story, covered drive measuring 10.4 by 24.7 m (34 by 81 ft), brings the frontage on McDermont Avenue to 68.6 m (225 ft). The building is clad in red clay bricks with stone trim on all four sides. The detailing of the building is in a classical neo-Palladian style. Winnipeg's Warehouse and Exchange Districts yield many similar examples of straightforward functional structures. These buildings are typically three to six stories in height with straight fronts, flat roofs and facades dominated by the regular pattern of their fenestration (Whiffen, 1981). Their detailing is typically classical in nature with rounded arches, emphasized keystones, shallow pilasters, entablatures and overhanging cornices. The Winnipeg Customs Examining Warehouse is a solid, attractive, somewhat conservative building which reflects these common contemporary stylistic trends in its design and detailing.

The building design is very symmetrical with all four sides receiving similar treatment. The ground level is given emphasis and visual weight through the use of rusticated stone banding and high round headed arched openings with massive keystones. These arched openings typically contain a set of three windows. Above the ground level, shallow pilasters divide the facades into a series of symmetrical bays in which are inserted a pair of rectangular windows. The building is topped with an entablature and overhanging cornice. The grid pattern set up by the contrasted horizontal and vertical elements set up a rhythm which is carried the length of each elevation, broken only on the ground level by the covered drive.

Figure 7.2 Winnipeg Customs Examining Warehouse
viewed from south-west corner



The Customs Examining Warehouse was of modern construction, designed to be fire proof throughout. The four story building included one passenger and four freight elevators as well as iron stairways. The building structural system consists of a steel frame with reinforced concrete floors and roof. The steel frame forms a grid, 4 bays wide by 9 bays long. However, there are no steel columns in the exterior pilasters on the west side of the building. This is in accordance with the original construction drawings, yet no information is available that would explain why steel columns were omitted. The perimeter columns are built up I-shapes consisting of 4 angles connected to steel plates. The interior columns are box shapes consisting of steel plates and two C channels with an occasional I-shape inserted in between. The steel columns are completely encased in brickwork of two types; a red clay brick on the exterior and a light colored brick on the interior. The 610 mm (24 in) deep girders and 380 mm (15 in) deep joists are I-shapes and both have spans of approximately 6.1 m (20 ft) These I-beams are connected to the columns with rivets. The girders and joists are encased in concrete and a concrete floor is cast on top of them. The roof has an added layer of light weight concrete to provide a slope and may also have been intended to provide some insulation. The building rests upon a concrete foundation. The basement walls are concrete with a limestone facing. The basement floor slab is 719 mm (28 in) thick. The column footings have been reinforced with steel I-beams. Beams are placed side by side and interconnected. A second series of perpendicular beams is then placed on top of these and the entire system is encased in concrete. The building was designed in a manner calculated to allow for two additional story. This was a common practice and reflected the anticipated growth of Winnipeg after 1908.

The exterior walls are non-load bearing brickwork with the exception of the west wall. Two types of bricks make up the exterior masonry wall. The bulk of the wall is made up of sand-lime bricks but solid clay bricks were used for the exterior face. The facing bricks were laid in stretcher bond (no headers) using a mortar of the same color as the bricks. The mortar is probably a mixture of ground brick dust, lime and sand. The face bricks are bonded to backup bricks by a combination of metal strip ties and by cutting the inside corner of the face bricks. Interior bricks are laid diagonally into these corners. This type of bonding is not very strong and is likely to have allowed some differential movement. The interior sand-lime bricks are laid in common bond (a row of headers every sixth course) probably using a lime mortar. Both the clay brick and the sand-lime brick are about the same size; approximately 210 x 102 x 60 mm (8 1/4 x 4 x 2 3/8 in). However, the thickness of the mortar joints is different and therefore, the mortar beds between the facing brick and the sand-lime backup are usually out of alignment. The thickness of the wall varies from 1220 mm (48 in) at the ground level to 760 mm (5 3/4 in) at the upper floors. Parts of the east wall are thinner , measuring 300 mm (13 in). The interior surfaces of the wall are typically painted bricks. The only exception is the south side inward from the second column from both the east and the west walls. This portion encompasses the front entry stairwell and office space. Here the interior finish consists of lathe and plaster with a paint finish. The plaster was applied over a steel mesh mounted on 25 mm (1 in) steel channels spaced 300 mm (12 in) on center.

Although designed to accommodate major additions, the building has received few alterations. Early annual reports from the Department of Public Works suggest that there was an isolated problem with work on the parapet wall and cornice. In 1928 the former was repaired and latter renewed (Dominion of Canada, 1928). Seven years later, extensive repairs were made to the exterior brick and stonework which included the dismantling and rebuilding of a portion of the north west corner where the brickwork had cracked owing to settlement (Dominion of Canada, 1935). In the 1930's, the original maple flooring in the examining area was replaced with asphalt. The four freight elevators were replaced in 1959 by two more spacious modern elevators. This entailed the casting of a new reinforced concrete floor over a substantial part of the original elevator shaft and the filling in of certain windows with a brick veneer on a concrete block backup. During the 1960's, new fire doors and partitions were added but the interior layout remained much the same. Other than these minor repairs and alterations, the building has remained much as it was in 1908 (Public Works Canada, 1984).

The building design is possibly the work of David Ewart, Chief Architect with the Department of Public Work from 1897 to 1914. All plans coming from the office bore Ewart's signature making it difficult to determine exactly which of the staff architects was responsible for a specific design. The building contractor was the J. J. McDiarmid Co. Ltd., general builders and contractors. As a successful contractor James McDiarmid was responsible for the construction of several important buildings including the Manitoba Legislative Building. McDiarmid was not simply a contractor, but also designed several buildings as well as some local parks and golf courses. Prominent in local affairs, McDiarmid was one of the founders of the Winnipeg Art Gallery and the Winnipeg School of Art (Berry, 1982).

7.2 Building Renovation

The Artifact Restoration Workshops and Laboratories of the Canadian Parks Service require near constant indoor temperature and relative humidity. To accommodate this, the Winnipeg Customs Examining Warehouse required a complete retrofit of its exterior walls, windows and roof. These renovations consisted of the insulation of the exterior masonry walls, a new insulated roof membrane, the replacement of all windows and doors and the installation of a forced air HVAC system. All of these renovations had to be carried out without altering the appearance of this historic building.

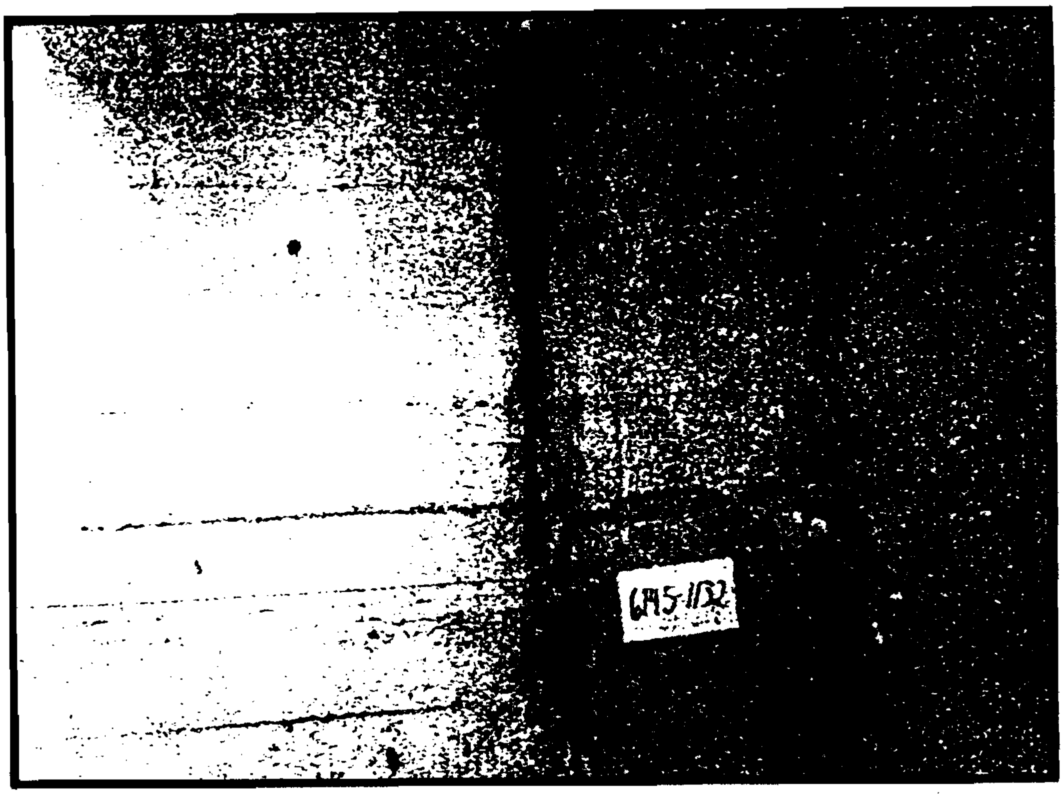
7.2.1 Initial Building Condition

Prior to any renovations, the building was carefully inspected by the consultants. Both the interior and exterior were surveyed for cracks, damaged masonry and other signs of distress. However, an in depth structural analysis was not carried out as this was beyond the scope of the project. The following summary of the building's initial condition is based upon the "Preliminary Report" prepared for Public Works Canada (NTL, 1991).

7.2.1.1 Inspection of the Building Interior

It is not unusual to expect some settlement in a heavy structure over an eighty year period. However, the foundation appeared in good condition with the exception of some minor cracks at the Rorie Street loading dock. There were vertical cracks around the abandoned coal chute openings on the east wall (Figures 7.3). The east wall also exhibits waviness when sighted along the plane of the wall. A continuous crack had formed along the loading dock walls exhibit at approximately the elevation of the window sills (Figure 7.4).

Figure 7.3 Vertical crack at coal chute opening



Some water penetration had occurred through the north wall, resulting in a number of puddles on the floor (Figure 7.5). The wall exhibited no obvious structural deficiencies, however some remedial repairs to prevent further water penetration was required. Although the basement floor slab was cracked in numerous places, lack of major cracking in the walls indicated a sound foundation. Plastered interior walls, which are present only on the south side of the building, were free of cracks. Such brittle finishes tend to crack easily with foundation settlement. The absence of cracks supports the conclusion of a sound building foundation.

Figure 7.4 Cracking of foundation wall near the loading dock

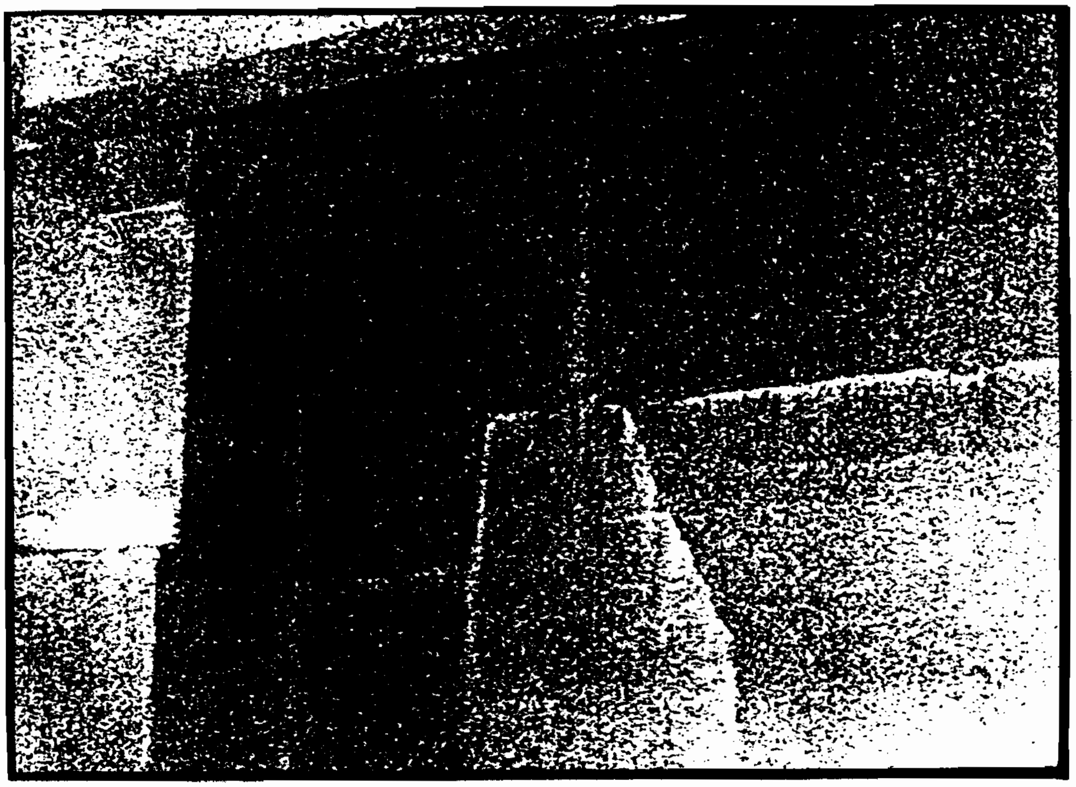
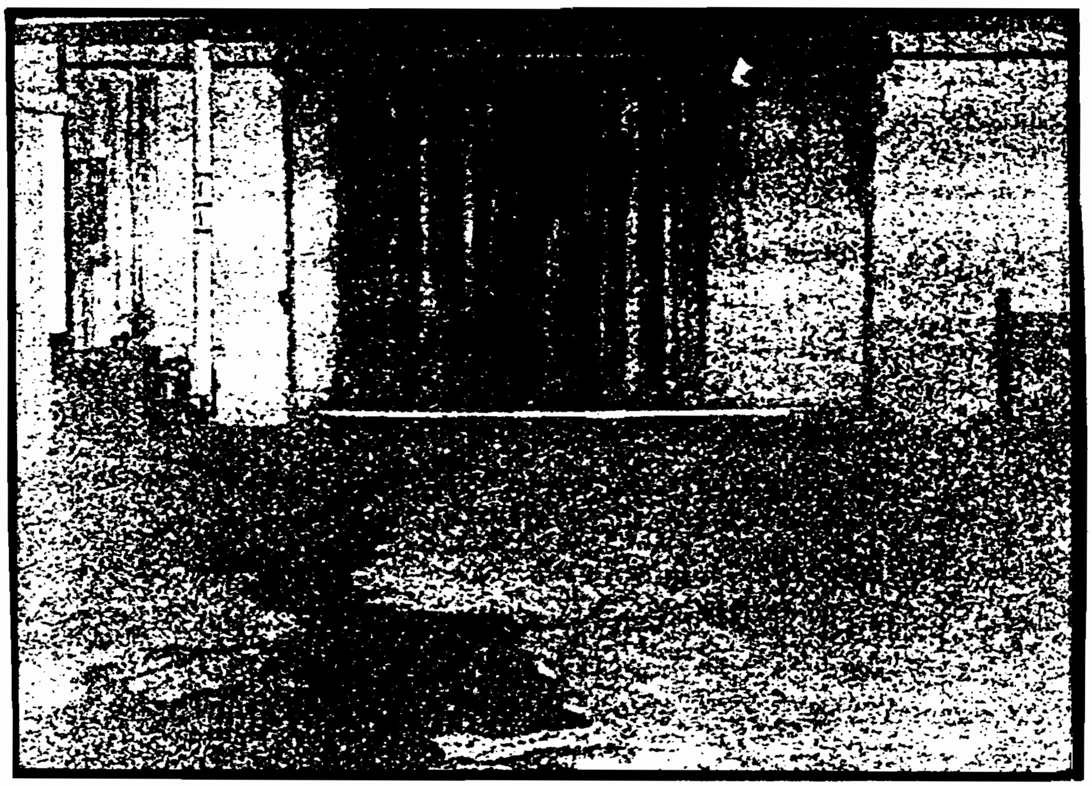
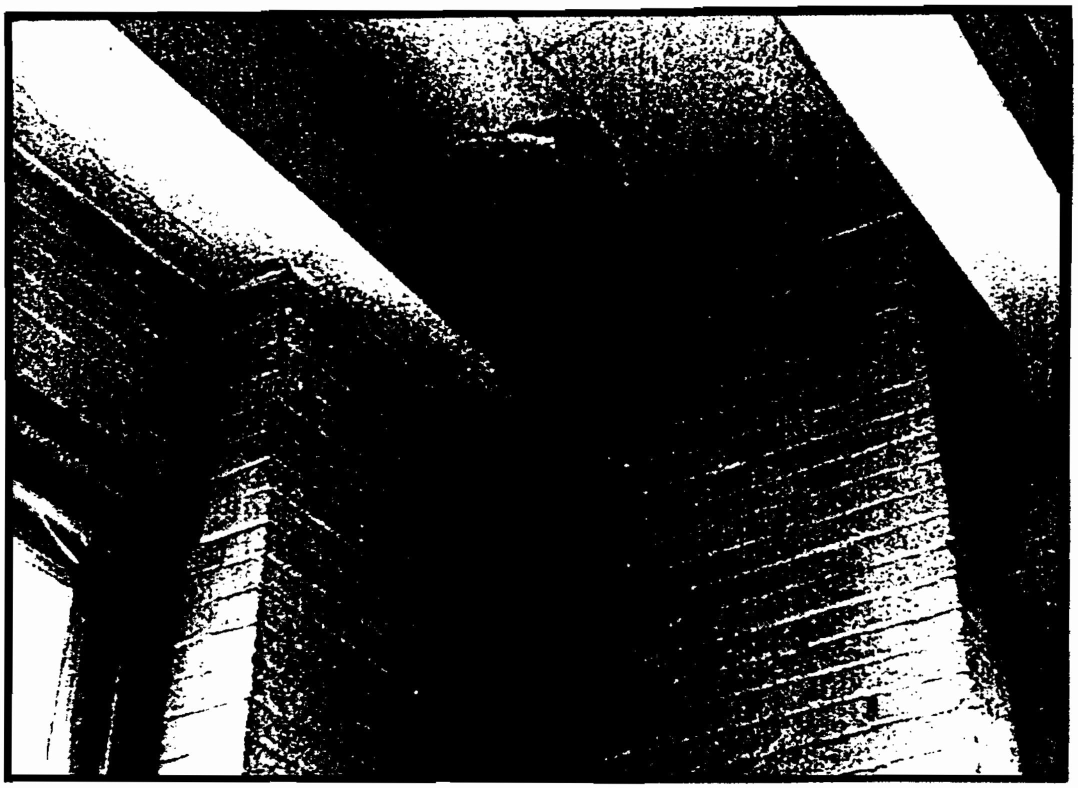


Figure 7.5 Water entry through north foundation wall



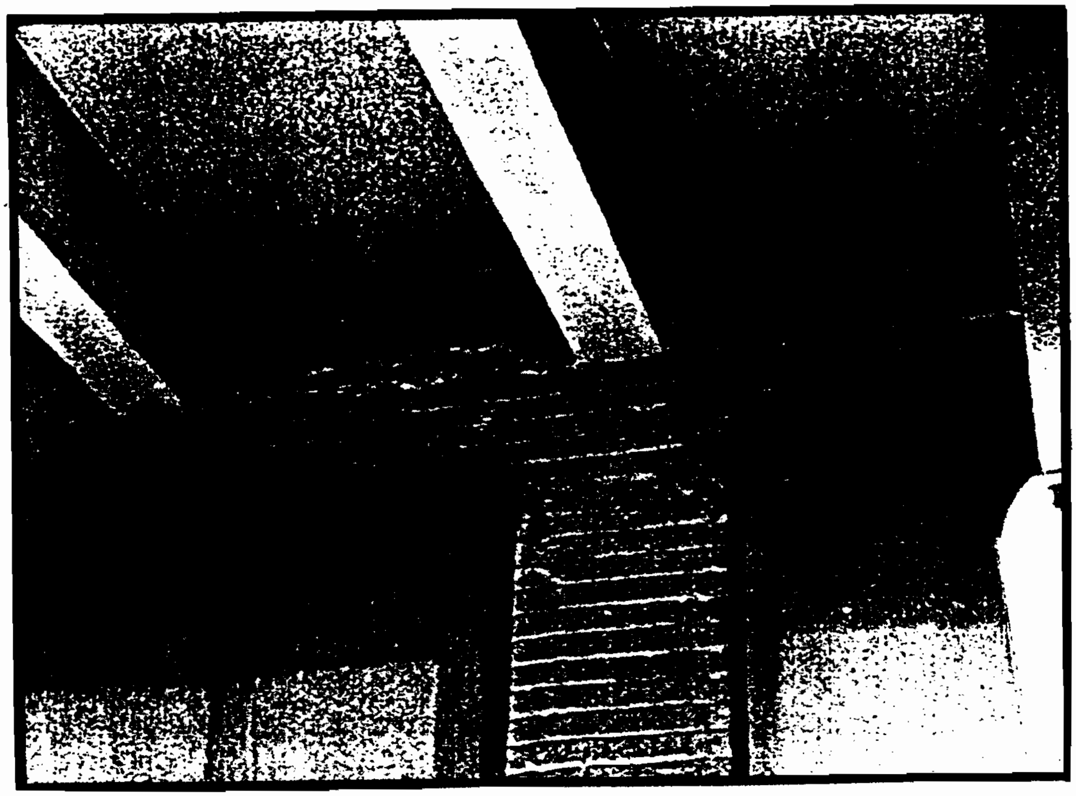
The exposed masonry of the interior walls was inspected for any signs of distress. The worst interior cracks occurred at the top of the solid masonry columns in the north-west and south-west corners of the building (Figure 7.6). The omission of steel structural members at these locations was likely the cause of the cracks. These cracks resulted probably from differential movement between the solid masonry load bearing west wall and the building steel frame.

Figure 7.6 Crack on south-west corner, 4th floor



Major horizontal cracks, about 10 mm (2/5 in) in width, were also observed running under the floor beams tying into the east wall (Figure 7.7). These cracks occurred on the second, third, and fourth floors. However, the cracks did not appear to be structurally significant. They did not pass through the pilasters and were not evident on the exterior. The somewhat different appearance of the brickwork above these cracks suggested that the work was performed at different times. These cracks may in fact reflect the transition between different phases of work.

Figure 7.7 Horizontal crack on east wall, 2nd floor



Minor cracking was also observed around the windows at random locations. The cracks usually occurred at the heads of the windows. The worst cases occurred around the third and fourth floor windows in the east and north walls (Figure 7.8). There was some water damage on the ceiling of the fourth floor beneath the cornice. An inappropriate flagpole connection allowed water to penetrate into the cornice below. Finally, a steel column on the south wall was exposed approximately 0.6 m (2 ft) above the floor (Figure 7.9). There was no sign of rusting.

Figure 7.8 Crack above window in north wall, 4th floor

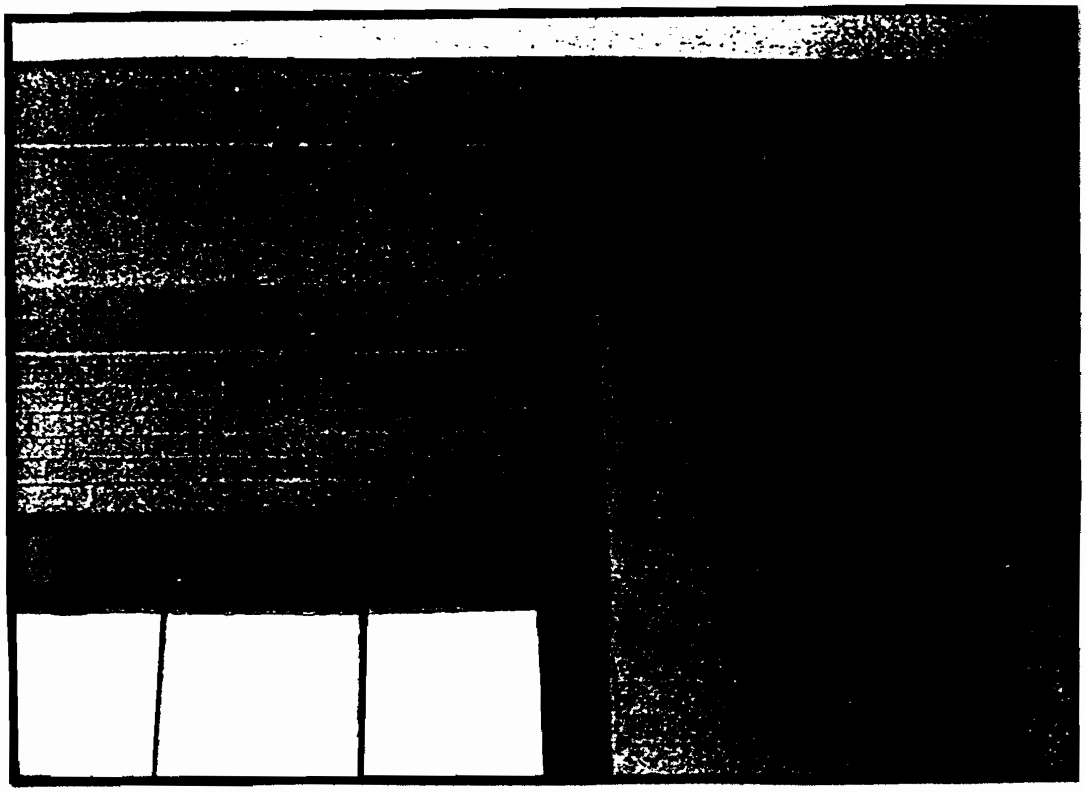
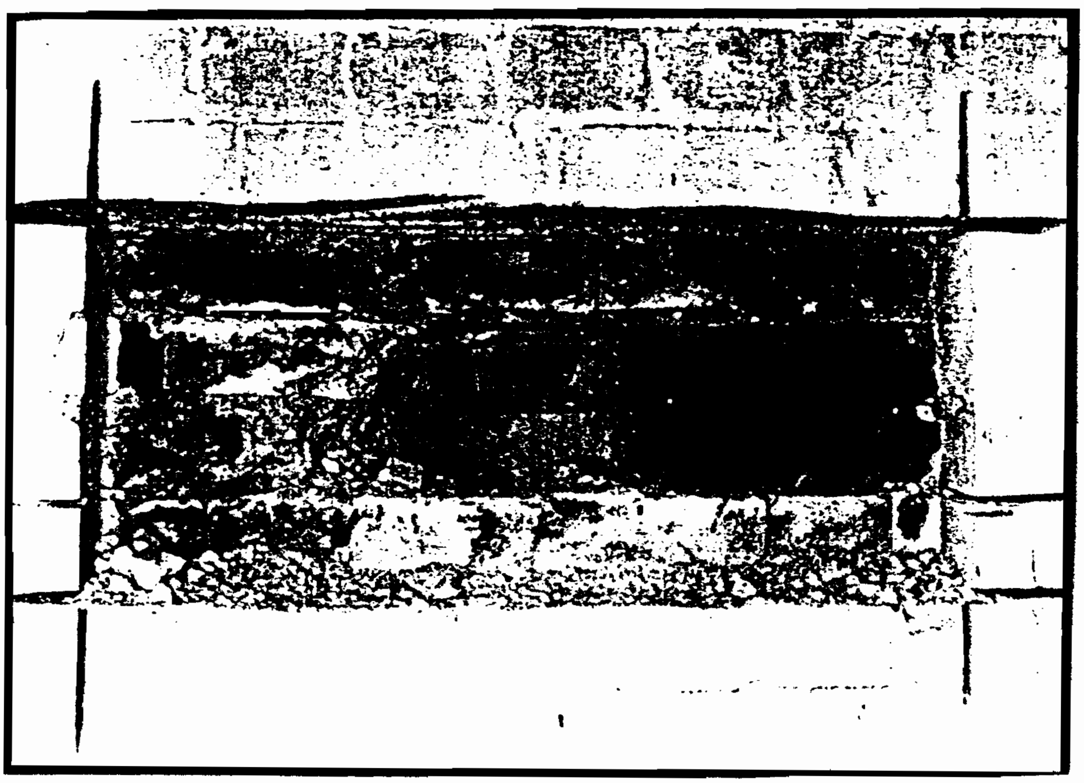


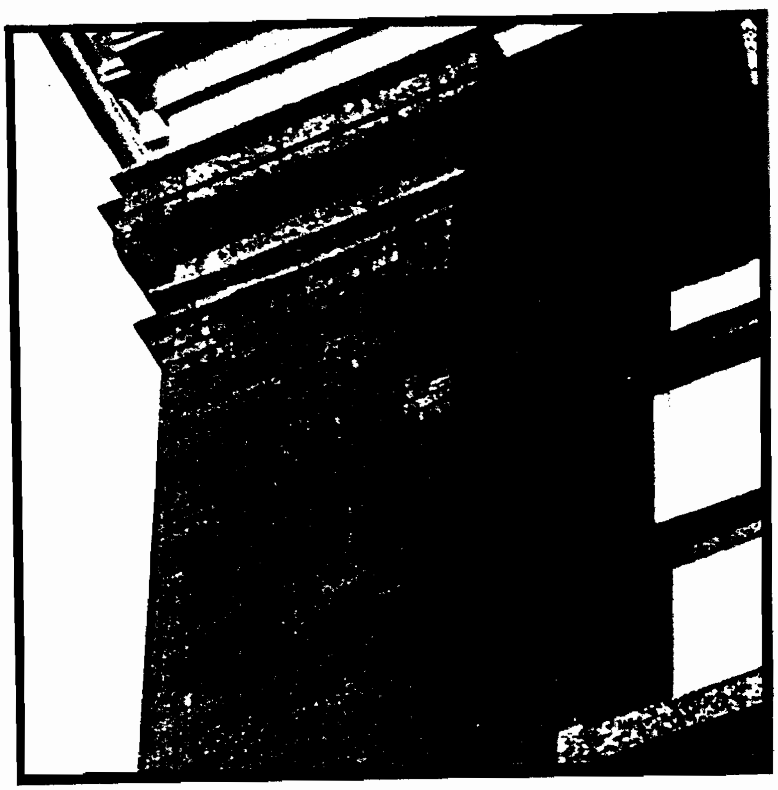
Figure 7.9 Cut in interior wall showing bricks and steel column



7.2.1.2 Inspection of the Building Exterior

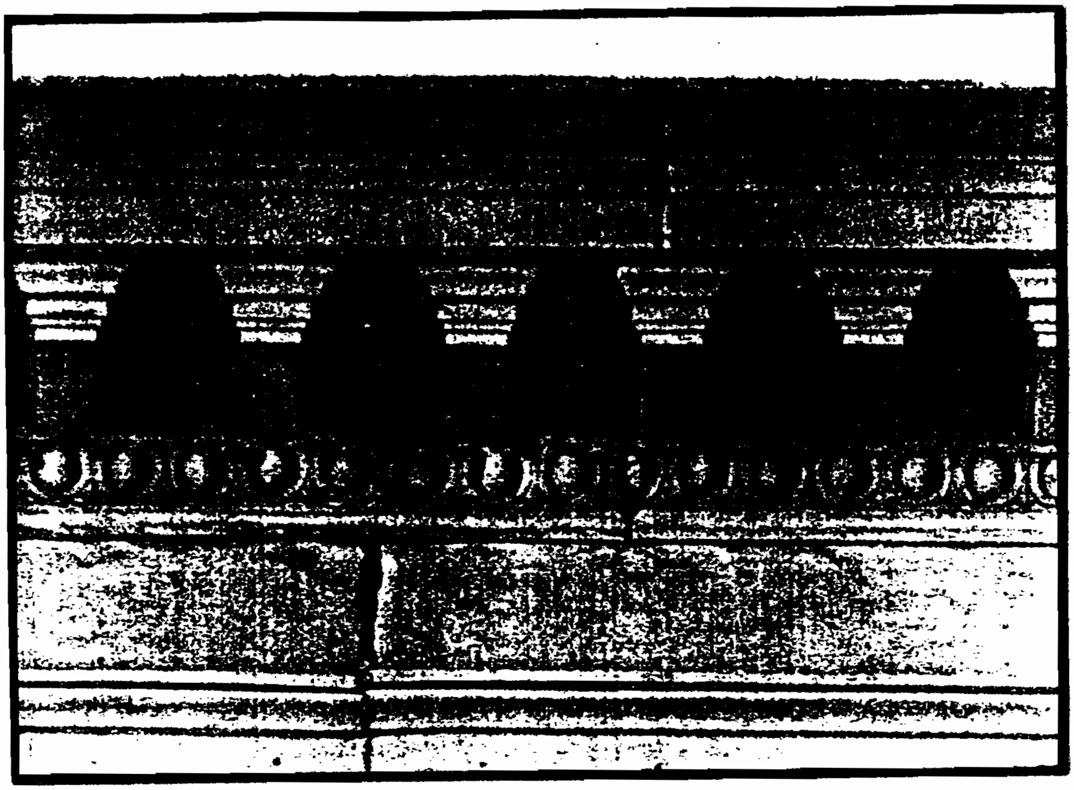
The masonry of the exterior walls was inspected for any signs of distress. Control and expansion joints were not normally incorporated into the thick masonry walls of older buildings and none were observed in the Customs Examining Warehouse. Cracking of the exterior masonry was very random and for the most part inconsequential. The cracking may have been the result of the building providing its own expansion joints. There were however some notable exceptions. Major cracks had occurred in the north-west and south-west corner columns (Figure 7.10). Their location coincided with the interior cracks at the top of the solid masonry columns in the north-west corner of the building. However, the exterior cracks tended to be larger, up to 6 mm (1/4 in) in width. Like the interior cracks, they were probably caused by differential movement between the load bearing masonry wall and the steel frame. Subsequent moisture penetration and freeze thaw action probably account for their lager width. Nevertheless, the cracks had not yet penetrated to the building interior.

Figure 7.10 Crack on south-west corner



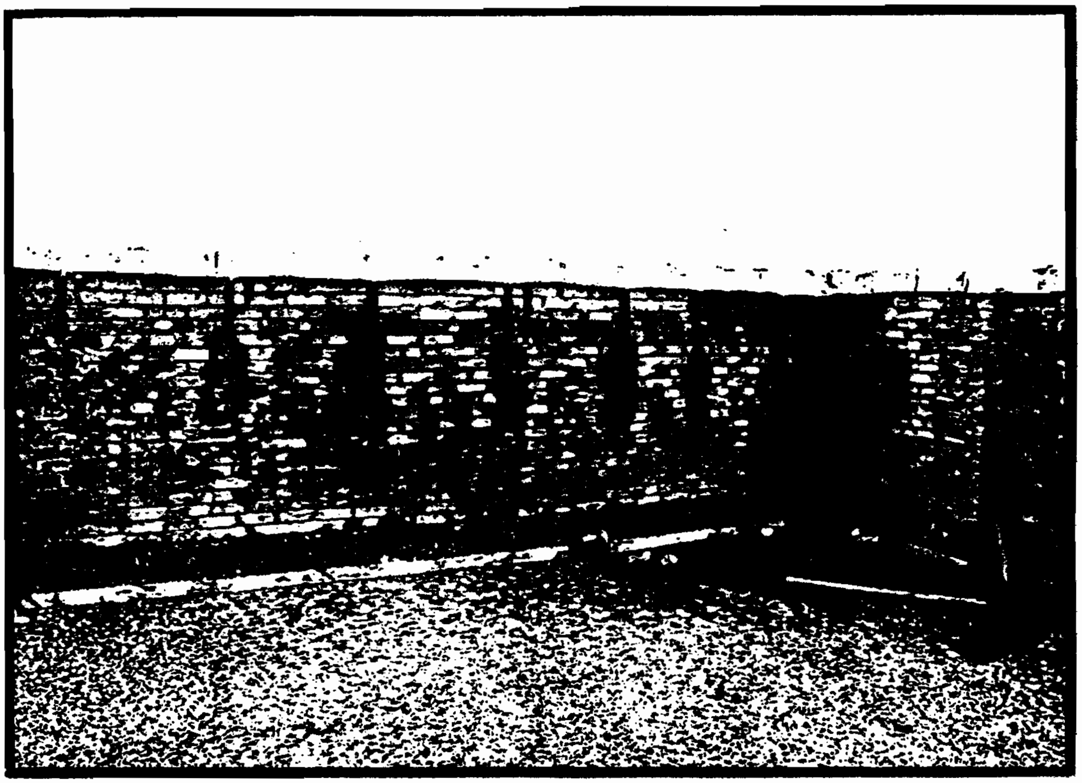
Some of the worst masonry damage occurred on the parapet wall. The cornice showed signs of displacement from panel to panel, probably caused by thermal movement (Figure 7.11).

Figure 7.11 Crack in cornice on west side



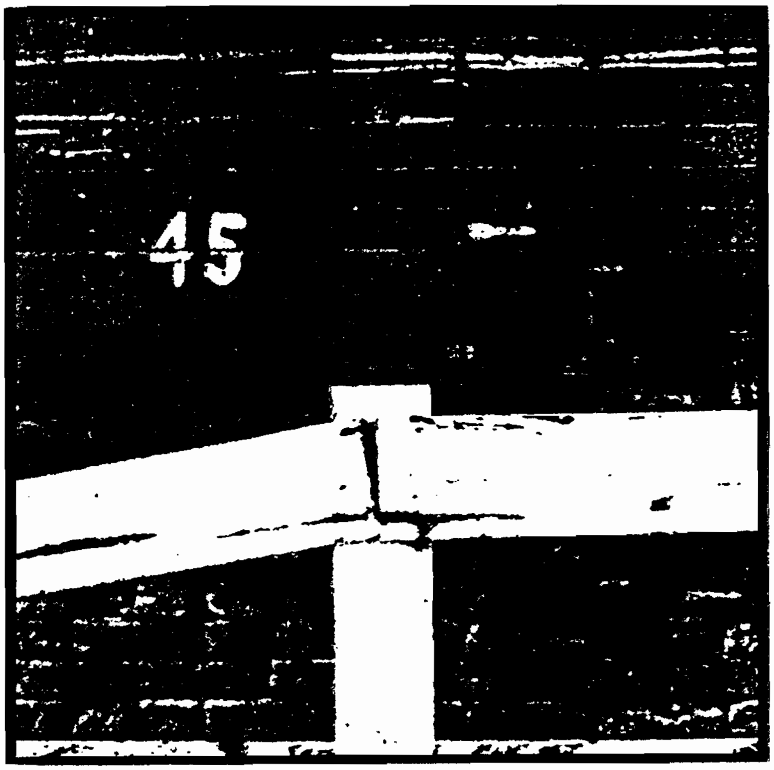
The masonry of the parapet backup wall was in poor condition. There were numerous cracks and dislodged or deteriorated mortar (Figure 7.12). The damage probably resulted from poor flashing details that lead to water penetration.

Figure 7.12 Deteriorating masonry on parapet wall



The covered driveway is another distressed area of the building. The east wall of the main building exhibits major cracking on the pilasters supporting the roof beams. The covered driveway exterior wall exhibits numerous cracks both on the garage and exterior sides. There appears to be no correlation between these two crack patterns. There was also considerable erosion of the first eight courses of brick on the exterior of the covered drive way (Figure 7.13). It is possible that snow mixed with salt was piled against this wall during snow clearing operations and, upon melting, soaked into the bricks resulting in salt crystallization and deterioration.

Figure 7.13 Erosion of brick on east wall of the covered drive



On the north wall regular cracking had occurred in the first floor arches. In addition, numerous bolts are evident on the north wall. No information was provided explaining the purpose of these bolts.

Inspection of the roof assembly revealed the deteriorated condition of the roofing membrane. A prominent crack in the membrane had occurred on the west end of the roof (Figure 7.14). Numerous areas of exposed roofing felt and collapsed striping were visible. A small section of the roof membrane was cut out at a point along the crack. The concrete deck beneath the membrane showed signs of deterioration (Figure 7.15). The damage was most likely due to water penetration and subsequent freeze thaw action. In spite of all this, no evidence of roof leaks was found.

Figure 7.14 Fracture of roof membrane

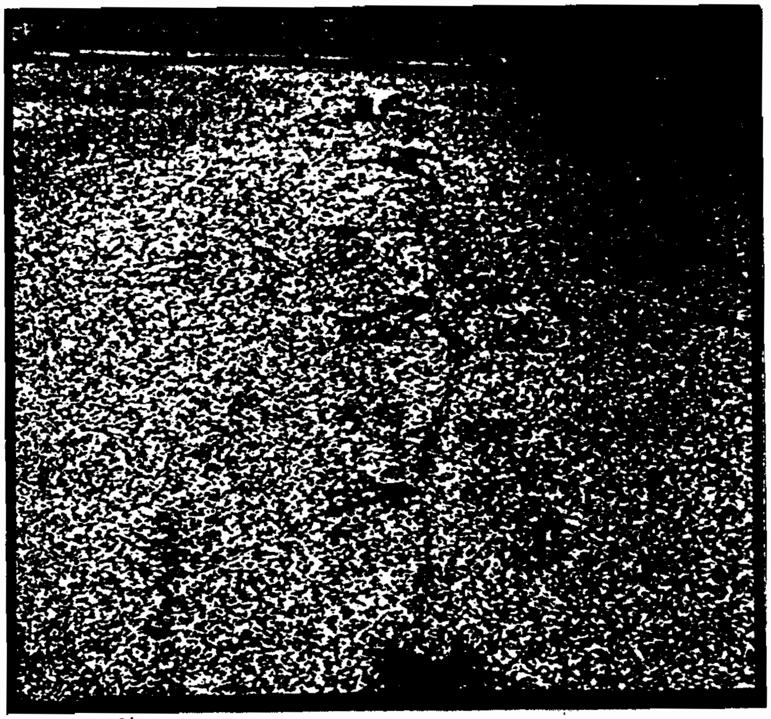
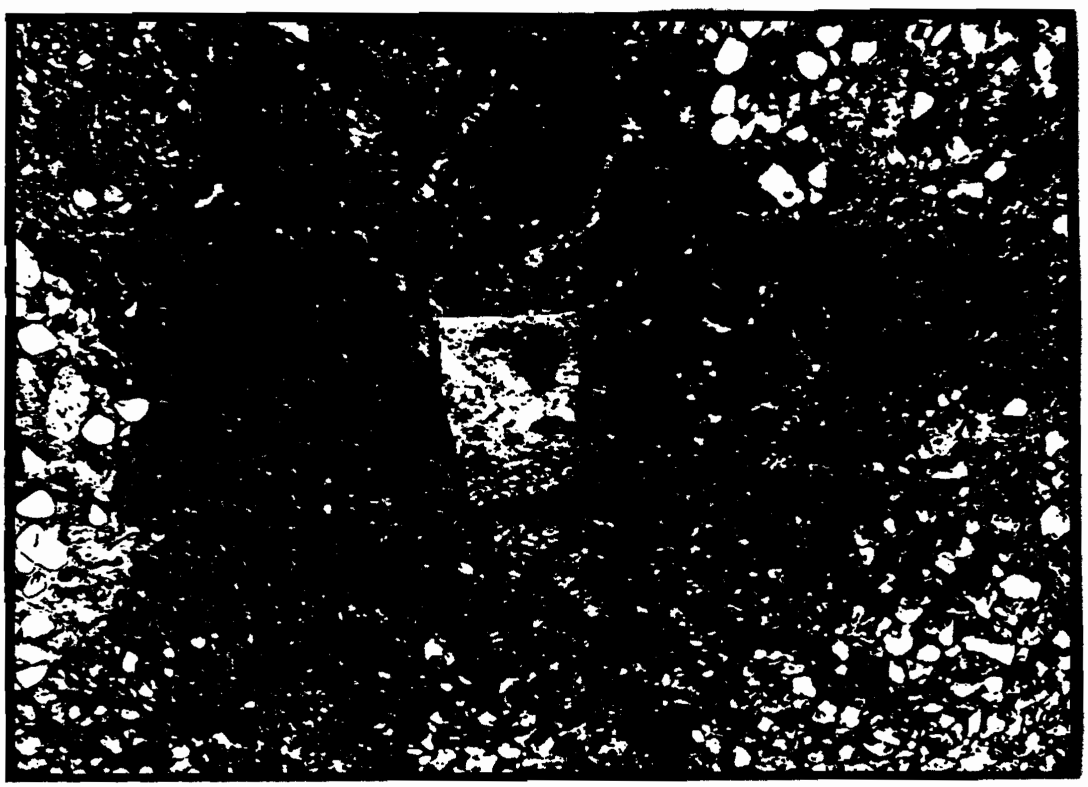


Figure 7.15 Cut in roof membrane showing deteriorated concrete slab



7.2.2 Building Renovation

The primary objective of this renovation was the application of insulation to the walls of the Customs Examining Warehouse. The building had to be insulated to meet the requirements of the new tenant without altering its historic exterior. Therefore the insulation would have to be applied to the inside of the exterior walls. Space restriction limited the total retrofit wall thickness to 150 mm (6 in). A suitable wall insulation system was chosen and a computer analysis was performed to ensure that the renovation would not be detrimental to the exterior masonry. In addition, the necessary minor masonry repairs were completed, a new forced air HVAC system was installed and all of the existing windows were replaced. The following summary of the building renovation is based upon the "Detailed Insulated Wall Design" prepared for Public Works Canada (NTL, 1991).

7.2.2.1 Masonry Repairs

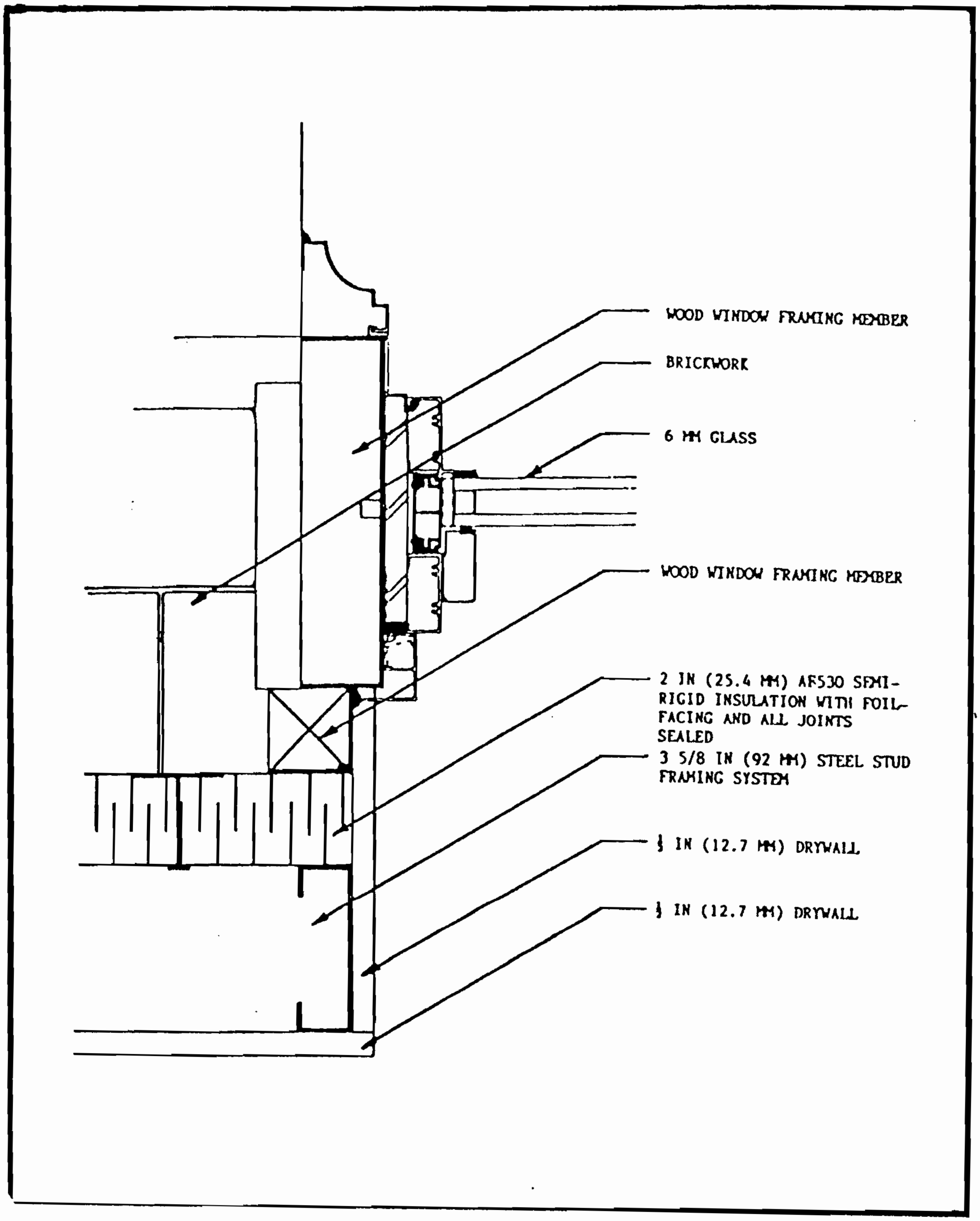
Remedial action was undertaken on the north foundation wall to prevent water penetration. Cracks in the foundation walls were filled by injection of a cement base grout. Minor cracks in the interior masonry walls were cleaned and repointed. The major cracks in the masonry of the north-west and south-west corners and along the floor beams of the second, third and fourth floors were cleaned, were injected with a grout compatible with the existing materials and repointed. Similarly, the minor cracks in the exterior masonry walls were cleaned and repointed. The larger cracks in the western corners, like their interior counterparts, were cleaned, grouted and repointed. A new parapet wall was built using concrete blocks. The cornice was repaired and a new flashing cap installed to prevent water infiltration into the parapet. The cracks in the masonry of the east wall and the covered driveway were cleaned and repointed with grout injected where necessary. The spalling bricks along the bottom of the covered driveway wall were replaced. The cracks in the brick arches were also repaired with grout injections and repointing. Once the repairs were completed, the masonry was carefully cleaned.

7.2.2.2 Window Replacement

Windows are thermally weak spots in the building enclosure. A large portion of the heat loss occurs through the fenestration. Insulating the exterior walls would be pointless if no action was taken to limit heat loss through the windows. Air leakage along their perimeter and heat loss through their surface must be minimized. In the case of the Customs Examining Warehouse, fenestration accounts for a large portion of the surface of the exterior walls. Therefore, all of the windows in the building were replaced with sealed, double glazed windows.

Steel frame windows were installed on the north side and aluminum frame windows on other three sides. Due to the metal on the outside frames of the window, it was important to ensure that no direct contact with the masonry occurred. Otherwise, the thermal bridge created would lead to condensation and moisture infiltration into the masonry. Wood framing members were installed around the windows to act as a thermal break between the metal frame and the surrounding masonry (Figure 7.16).

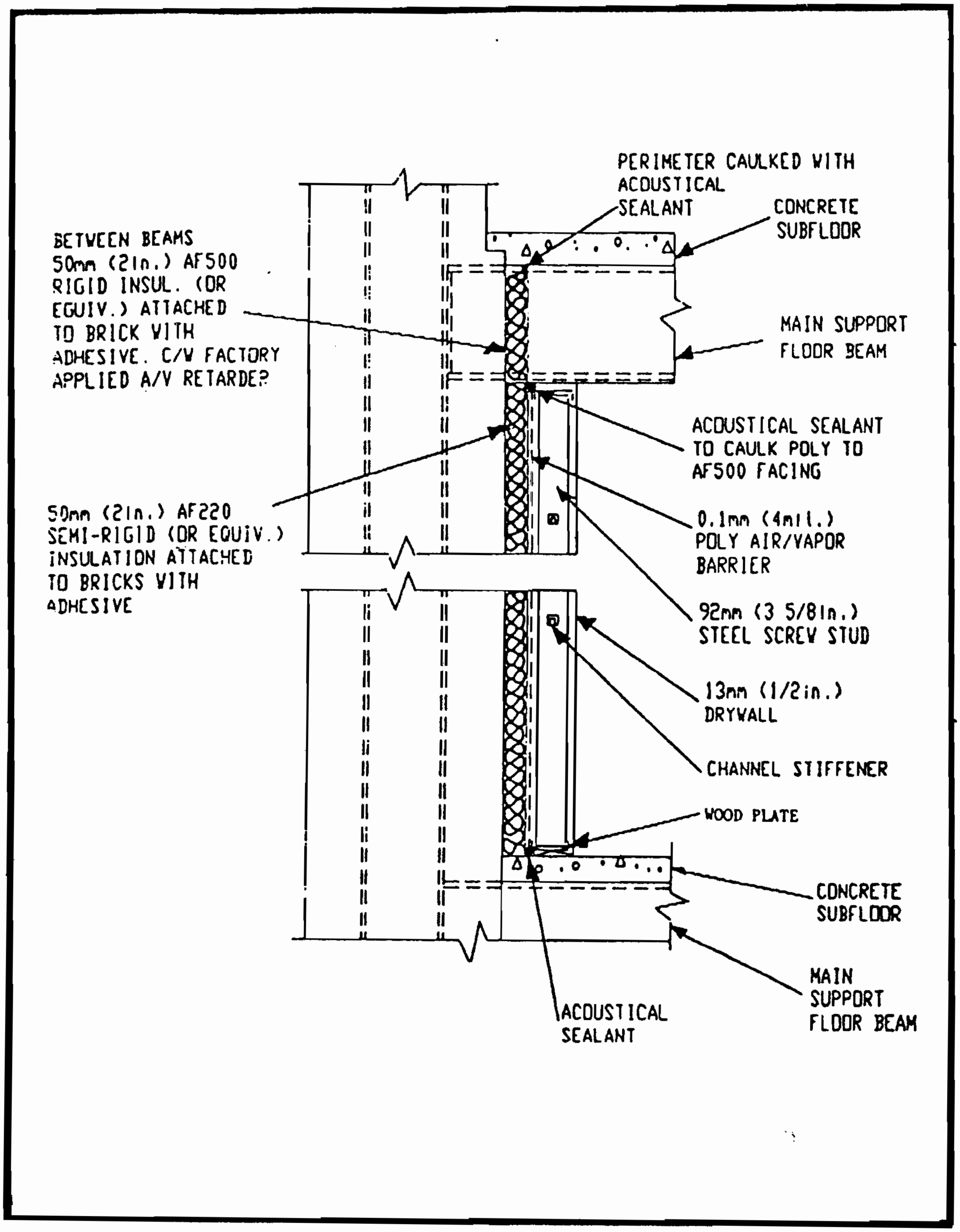
Figure 7.16 Typical horizontal section (plan view) through window frame



7.2.2.3 Insulation of the Exterior Walls

For the renovation of historic buildings, the common method for insulating the inside of the exterior walls is to construct a frame wall, fill the spaces between the studs with fiber glass insulation, and after the electrical wiring has been completed, to apply polyethylene over the studs and insulation. This method was rejected for two reasons: it would create thermal bridges through the studs and into the brickwork and ensuring continuous air and vapor barriers would be difficult, especially around electrical outlets. In this case, the application of a continuous layer of insulation directly against the brickwork was more appropriate. Fiber glass insulation was rejected because of the problems associated with attachment to the brick work. Insulation boards were examined and the selection narrowed to these three types: extruded polystyrene board (Styrofoam), glass reinforced polyisocyanurate, and compressed glass fiberboard. Styrofoam was rejected for two reasons: its combustibility and its rigidity. A very rigid board would not conform well to the irregularities of the masonry walls. The two remaining boards were quite similar. The glass reinforced polyisocyanurate had a higher thermal resistance and lower retail cost but it was also more combustible and more rigid. The compressed glass fiberboard was not only more flexible, it was also non-combustible. Therefore, compressed glass fiberboard was selected as the most appropriate wall insulation for the Customs Examining Warehouse. The insulation board has a factory applied aluminum foil facing on one side rated as a Type I Vapor Diffusion Retarder. A complete computer analysis by IRC determined that 50 mm (2 in) thick wall insulation, RSI 1.47 (R 8.4), would be unlikely to cause any masonry damage provided that the insulation and the air and vapor barriers were properly installed. Figure 7.17 shows a vertical section through the wall insulation system.

Figure 7.17 Exterior wall section through column and beam



A number of different attachment methods were examined but metal clips were selected as the most appropriate method of attaching the board insulation to the masonry. The clips consist of a 50 mm (2 in) square galvanized steel base with a series of small holes over its surface and a metal spike protruding from the center. The clips were attached to the interior masonry walls with an adhesive and allowed to dry for a day. Scaling paint and other loose materials were removed prior to attachment to that ensure the clips adhered to the brickwork. Board insulation covering the entire wall surface was carefully applied over the clips (Figure 7.18). Pieces of board insulation were cut to fit between the floor beams and installed over clips. A 300 mm (12 in) wide strip of insulation board was also installed against the underside of the floor slab and tightly fitted against the wall insulation. Once the board insulation was snug and tightly pressed to the wall, washers were installed over the clips and the protruding spike was cut. The joints between the insulation panels were then sealed with a 50 mm (2 in) wide foil tape. Small pieces of tape were also placed over each washer. The joints where the insulation board met the beams and the underside of the floor slab were caulked with an acoustic sealant. When all the seams and joints were sealed, an air leakage test was performed in each area to ensure the insulation system was air tight. This process involved the temporary installation of a portable blower door assembly into a door frame and either pressurizing or depressurizing the space. Using a smoke generator, air leaks can then be identified. Any leaks found were sealed with foil tape or acoustic sealant as appropriate.

A framing system was installed in front of the wall insulation to provide a support for the drywall and a space for the utilities. Using screw studs, a steel stud frame wall was constructed. To prevent direct metal to concrete contact and to provide a base for the application of the drywall, wooden backing members were installed beneath the screw track of the steel stud walls and at the end of the insulation extending out from the wall along the underside of the floor slab. The studs were placed 400 mm (16 in) on center with channel stiffeners. Steel stud framework was constructed to fit between floor beams and attached to the framewall. Finally, 12 mm (1/2 in) drywall was installed over the entire frame wall. The joints were sealed with tape and drywall compound and the surface was sanded and painted.

Figure 7.18 Insulation fixed on inside face of exterior masonry wall

The front entry vestibule and stairwell with its original plaster finish could not be insulated in the same fashion. Space constraints prevented the installation of insulation or wall framing. Instead the space between the lath and plaster and the masonry was insulated by drilling holes through the plaster and injecting foamed in place polyurethane, RSI 0.71 (R 4). Holes 12 mm (1/2 in) in diameter were drilled every 0.6 m (2 ft). Polyurethane was injected at one quarter of its usual density to prevent the possibility of plaster cracking. Once the curing was complete, the holes were filled and the surface appearance restored.

The existing roofing membrane was replaced with a new protected membrane roof system. The old membrane was removed and a new membrane applied to the concrete deck. Insulation boards, RSI 3.52 (R 20), were then installed over the new membrane and covered with crushed stone. Flashing was installed along the junction of the parapet wall and the insulated roof to prevent the infiltration of water. The flagpole connection was also renewed to prevent water infiltration.

Chapter 8

Analysis of the Effects of Insulating the Exterior Walls and Data Gathering

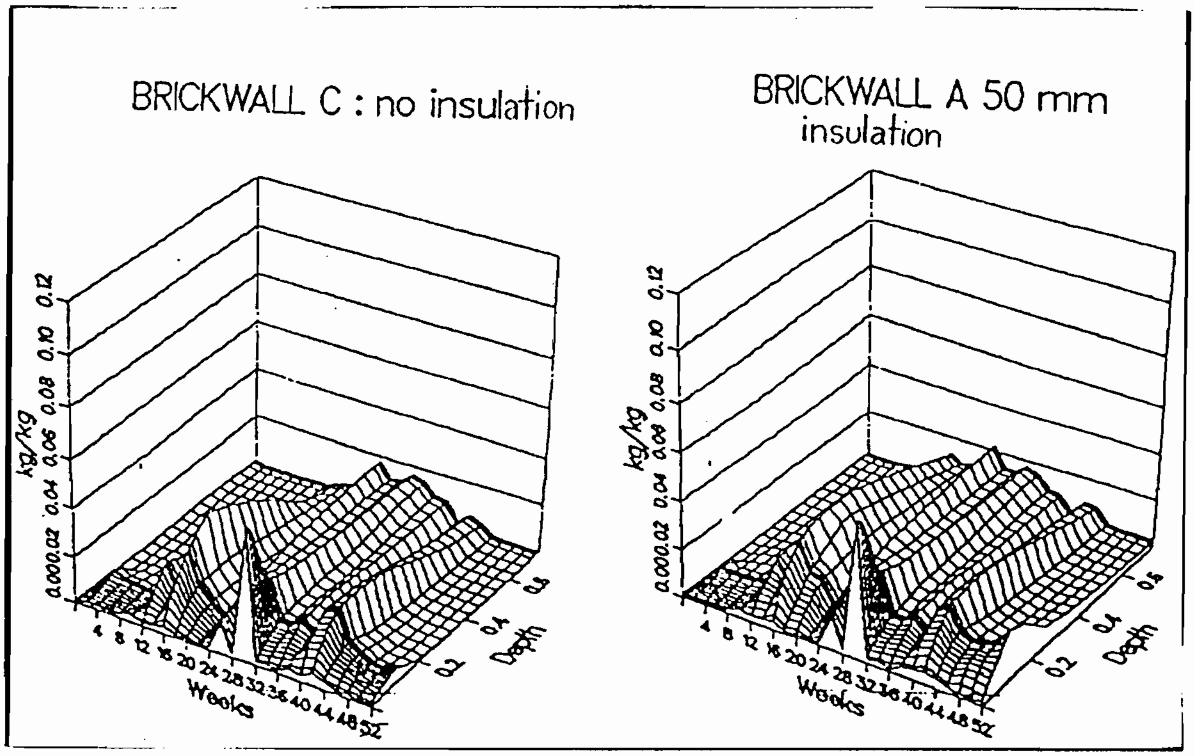
A thorough analysis of the possible effects of any restoration should always be undertaken to prevent unforeseen damage to the existing building. In the case of the Winnipeg Customs Examining Warehouse, the main concern was to ensure that the exterior walls would not be over-stressed as a result of the renovation process. This was mostly related to how insulating the building would affect the masonry. The brick moisture may rise as a result of reduced heat flow through the insulated wall and higher indoor humidity. This could lead to increased freeze-thaw action and spalling of the brick surface. The insulation of the building may also result in increased heat flow through existing thermal bridges. This additional heat flow could result in localized deterioration of the masonry. There were also concerns that the insulation of the exterior walls would result in higher thermal stresses in the masonry. This could lead to cracking of the masonry in areas of increased stress. Therefore. it was important to determine the level of insulation that could be installed without damaging the masonry. Detailed theoretical analyses were undertaken to determine the possible effects of insulating this building. The following summary of the various analyses undertaken are adapted from the IRC Interim Report, (Chidiac et al, 1991).

8.1 Moisture and Thermal Analysis

The moisture and thermal analysis was performed by IRC in conjunction with the VTT, the Technical Research Center of Finland. VTT provided a computer program called TRATMO2. The brick properties relevant to the computer analysis were determined by laboratory experiments on samples from the Customs Examining Warehouse. The computer analysis took into account humidity, temperature, solar radiation, rain and wind direction and velocity. The exterior weather data used in the analysis was obtained from the records of the Atmospheric Environment Service for the Winnipeg International Airport. The interior conditions were held constant at 21°C and 30% relative humidity. The brick moisture content after one year exposure was first computed assuming zero initial moisture. This moisture content was then used as the initial moisture for all subsequent analysis. Simulations were performed for 25 mm (1 in) and 50 mm (2 in) thick compressed glass fiberboard wall insulation and compared with the results for the existing uninsulated wall. Each simulation consisted of a full year exposure, calculated on an hourly base.

The installation of 50 mm (2 in) compressed glass fiberboard wall insulation resulted in a 40% reduction in surface heat flow. The effects of insulation on the moisture levels were negligible. The computer analysis predicted an increase in moisture levels in the insulated wall but it was within acceptable limits and presented no danger to the durability of the wall. During the winter months, the highest moisture content was observed in December. It occurred near the brick face, within the section of the wall affected by subzero temperatures (Figure 8.1). At that time, the moisture content was approximately 2% by weight, well below the saturation level of 12%. No cumulative increase in moisture from one year to the next was observed for the weather data used in this analysis. The initial results indicate that the insulation should not cause any moisture problem. This conclusion is valid only if an effective air and vapor barrier is installed to prevent indoor moisture from penetrating the wall. If a vapor barrier is not installed on the warm side of the insulation, simulations show accumulation of moisture at the interface between the insulation and the masonry wall.

Figure 8.1 Charts of brick moisture level variation with time and depth



8.2 Analysis of Thermal Bridges

The analysis of the building renovations included a study of the thermal weak points in the building envelope. These areas are the most vulnerable to deterioration of the exterior masonry. Thermal bridges are paths for heat flow between the interior and exterior surfaces. They create a potential for surface condensation and increased thermal stresses in the building components. A simple visual inspection prior to the renovations revealed no signs of deterioration as a result of thermal bridges. However, insulation of the exterior walls may result in new thermal bridges that could conduct more heat than sections of the construction did originally.

The analysis of potential thermal bridges was performed using two different computer programs: KOBRU86 and TRISCO (Physibel Building Physics, 1990). KOBRU86 was used for the two-dimensional steady state analysis and TRISCO for the three-dimensional analysis. Both programs calculate heat transfer using the energy balance technique. The weather data used in the computer analysis was a static set of exterior conditions that modeled a two week cold spell. An exterior temperature of -30°C was selected. The typical interior conditions were assumed to be 21°C and 30% relative humidity. The dew point temperature was used as a simple criteria for evaluating the results. When the surface temperature is kept above the dew point, no condensation will occur. For the typical interior conditions of 21°C and 30%, the dew point temperature is 3°C. If the interior temperature is increased to 24°C at 30% relative humidity, the dew point temperature would increase to 5°C. If the humidity increased to 60% at 21°C, the dew point would then rise to 9.7°C. Five potential thermal bridges were studied. Simulations were performed for 25 mm (1 in) and 50 mm (2 in) thick compressed glass fiberboard wall insulation compared to the existing uninsulated condition. The initial results indicate that the insulation should not cause any problems with thermal bridges.

The first thermal bridge analyzed was the north-east corner detail between the third and fourth floor. The corner detail has a thermal bridge due to the steel column in the brick pilaster as well as the two thermal bridges from the adjacent windows. Since it was evident that these three thermal bridges could not be modeled independently, the full section was modeled. The detailing of the window, the window frame, any blocking between the frame and the brick and the treatment of the recessed section of wall from the window were extremely important. This is the most critical thermal bridge in the building. Heat flow occurred around the window frame, from the bricks exposed to the outside air to the ones exposed to the inside air. The most effective way of stopping this heat flow was to extend the insulation of the inside wall to the thermal break in the frame. Insulation providing a thermal resistance of RSI 0.53 (R 3) would be sufficient to prevent condensation. The window framing detail should be carefully designed to minimize condensation. It is especially important that the metal frame should be in direct contact with the masonry. The reduction in heat flow due to the insulation of the exterior walls could be negated by poorly designed window details and insufficient insulation of the recess. The steel column encased in the masonry of the corner did not radically change the inside temperatures. No special precautions should be required to deal with this area.

The second thermal bridge analyzed was the intersection of the outside wall with the interior wall of the elevator shaft. The partition walls of the elevator shafts and the entrance stairwell are directly connected to the exterior masonry wall. This is a potentially serious thermal bridge that could result in the cooling of the outer edge of the partition walls. Therefore, the intersection of the partition and the exterior walls was analyzed for the south wall at mid-height. The analysis showed that although the intersection was a major thermal bridge, the edge of the partition wall did not fall below 15°C. The uninsulated wall performance was adequate and there is no need to install insulation on the partition walls. Adding 50 mm (2 in) fiberboard insulation to the inside surface of the exterior walls reduced heat flow by 20%.

The next thermal bridge analyzed was the roof parapet wall. The wall was analyzed at a point between columns where the low density concrete was near its maximum thickness. This is an area that is expected to provide a path for heat flow. Prior to the insulation of the roof and the exterior walls, the 15°C isotherm was located along the inner surface of the embedded beam, below the roof slab. The freezing plane (-5°C) was about 75% of the distance from the outside surface. This appeared to be adequate. With the installation of RSI 3.52 (R 20) insulation to the roof and RSI 1.47 (R 8) insulation to the inside surface of the exterior walls, the wall surface temperature was above 15°C and the ceiling temperature was 15°C at the edge next to the embedded beams. Over 60% of the wall was below freezing and only a small corner of the roof slab froze. The modifications appear to be quite safe and thermal bridges should not cause any problems. The inside of the parapet where it joins the roof insulation will experience many freeze thaw cycles. Therefore, this area should be kept as dry as possible. Insulation of the walls and roof reduced heat flow for the edge section by 40%.

Another thermal bridge analyzed was the basement wall below a window. This area was selected because it was furthest from the columns and beams that carry heat into the basement walls and because the extended column footing will carry heat from below into the wall. The added heat flow would more than balance the heat loss from the basement wall into the masonry wall sitting at the top of the foundation wall. It was assumed that the backfill on the wall was clay and not the higher conductivity sand. After a long cold spell, the freezing plane would run from the center of the window to a point half way down the uninsulated exterior wall. Most of the inside of the basement wall was above 15 °C. With the full height of the basement wall insulated, the freezing plane would run, after a similar cold spell, from a point one meter above the floor on the inside of the wall to the outside bottom corner of the wall. Almost all of the wall would be below freezing and half of it below -5°C. However, the likelihood of such an extended period of -30°C weather is small and the freezing plane should not reach the bottom of the wall. If the wall was originally backfilled with sand, the freezing point could reach the bottom of the wall but the probability of frost heave would be small because of the good drainage characteristic of sand. After insulation, the heat flow from the basement walls and outer 3 m of floor would be reduced by 27%.

The last thermal bridge analyzed was the intersection of the floor I-beam and column at the third floor level. The connection of the I beam under the floor with the column in the exterior wall was an ideal thermal bridge for heat flow into the wall.

The position of the column half way through the wall moderated the effect on the inside surface temperature. The covering of concrete on the I-beam also moderated the depression of the inside surface temperature. Therefore, prior to the installation of insulation, the inside surface temperature only dropped to 15°C next to the beam below the slab and over the center of the beam on the floor surface. The application of insulation to the interior surface of the wall lowered the temperature near the I-beam because the column temperature dropped as did the mean temperature of the wall. The temperature reached 12.2°C on the upper surface of the floor slab and 14.8°C on the lower surface. The beamed reached a temperature of 14.6°C. Adding insulation to the walls reduced heat flow by 19%. Adding insulation to the bottom of the floor slab would further reduce heat flow.

8.3 Thermal Stress Analysis

This analysis was divided into two parts. The first part was a thermal analysis to determine the temperature changes brought on by the insulation. The second part consisted of a stress analysis to evaluate the induced stress from the change in temperature. The analysis was performed using the AFEMS (FEM Eng. Corp., 1991) computer program. This finite element program can perform both thermal and stress analyses. The finite element analysis was used to determine the additional thermal stresses in the masonry walls of the third story, south-west corner. Since the calculated changes in moisture level were very small, the effects of moisture were not included in this analysis. Modeling the exterior walls of the building with the restraints at the floor level required a three dimensional-model. Because of the limitations on the size of the finite element model, some assumptions as to the geometry of the structure were necessary. It was assumed that the building had double symmetry in the plan view and exhibited symmetrical behavior between floors. These were not accurate assumptions but the resulting errors did not significantly alter the behavior of the building. For the purpose of the thermal analysis, the intersection between the masonry wall and the slab was assumed to act as an adiabatic surface. This meant that there would be no heat exchange between these two elements. The error introduced by this simplification was not significant since the temperature changes at that interface were not severe. The connection between the various components of the wall section was another problem encountered in this analysis. No differential movement was allowed between the exterior facing bricks and the interior bricks. It was assumed that the two parts of the masonry wall were completely bonded, both thermally and structurally. There was also insufficient information to properly determine how the steel frame and concrete floor interact with the masonry wall. A simple observation at one location revealed no direct structural connection. Therefore, to simplify the analysis, the steel columns were not incorporated in the model. However, there are connections with the floor beams. In order to assess the possible interaction, three cases were studied. In the first case, the masonry wall was assumed to be completely independent of both the concrete slab and the steel columns. The only connections were located at the end of the steel beams resting on the western portion of the masonry wall. For the second case, the wall was assumed to be connected to every steel beam, and the beams rigidly connected to the concrete slab. This resulted in a similar fixity for both the north and west side of the wall at the end of the steel beams. In the last case, the wall was assumed to be structurally bonded to the steel beams on the north side and connected to the end of the steel beams on the west part of the masonry wall. These three cases were expected to reflect the upper and lower bounds for the behavior of the masonry wall.

Adding insulation to the inside surface of the masonry wall altered the temperatures within the wall and resulted in higher thermal stresses. The deformation pattern for all three cases were similar. The different conditions imposed did not alter the overall deformation and the thermal load was therefore the predominant factor. The results of the analysis indicated significant local tensile stresses approaching the expected tensile stress of the masonry. The maximum tensile stress was 0.65 MPa, which occurred at the corner for all three cases. This additional stress in combination with any existing tensile stresses may lead to cracking. However, this is expected to be confined to small areas. In any case, the added thermal stresses are likely to be less than indicated since the analysis was based on conservative assumptions. The fact that the steel members were not included in the model lead to an overestimation in the response of the masonry wall. The stiffer steel members would attract more load, thereby resulting in a stress redistribution that would reduce the load on the masonry. Some relative movement between the two types of bricks is expected and would also reduce the stresses acting on the masonry. Furthermore, unfilled collar joints behind the facing brick will act as extra insulation, reducing the thermal gradient across the wall. The initial assumption of triple symmetry appeared to be the most critical with respect to stress distribution and magnitude. It is likely that the wall behavior has been over-constrained by these assumptions. For these reasons, the results can be interpreted as a high upper bound.

8.4 Data Gathering

A program to monitor the performance of the renovated buildings was initiated in order to determine the reliability of the analytical models used in evaluating the effects of installing wall insulation on the inside surface of the masonry exterior walls. Two adjacent exterior wall sections were instrumented to monitor the temperature and moisture changes over a period of 18 months. One was typical of the new insulated wall section and the other was left in its original uninsulated condition. This will allow a comparison of temperature gradients and moisture levels between the insulated and uninsulated walls. With respect to temperature, the following aspects are of particular interest: the temperature variation with time across the insulated and uninsulated wall sections, the effect of thermal bridges on temperature and the heat flow or thermal resistance of the insulated and uninsulated wall sections. For moisture, the relevant aspects include: the moisture levels with time across the insulated and uninsulated wall section, rain wetting of the exterior walls, the occurrence of condensation on wall or floor surfaces caused by thermal bridges and possible condensation of steel members in exterior wall. Another important aspect is the measurement of movement across a vertical crack in corner column.

8.5 Sensor Location

The instrumented wall sections are located between the third and fourth floors, on the north side of the north-west corner, facing Bannatyne Avenue. This location was chosen because it is in an area of the building where there are no offices or laboratories. Therefore there will be less disturbance to the occupants, and the wall sections will all be exposed to the same interior temperature and humidity. The north-west corner is also believed to be one of the surfaces most exposed to wind driven rain. This corner is the intersection between the load bearing masonry wall and the steel frame. As such it is the area most susceptible to cracking due to moisture movement and increased thermal stresses. The west side was originally chosen for instrumentation but it proved difficult to access. The north side was easier to access and the presence of the steel columns embedded in the pilasters made for a more interesting choice. Although the effects of steel columns will complicate calculations, it could prove interesting to see what effects they have on the temperature gradient and if they are in danger of corroding. The sensors were installed on the external and internal surfaces of the wall as well as within the wall section. For detailed information on the location of the sensors consult Appendix B.

8.6 Sensor Description

The following is a simple description of the various sensors used in monitoring the Winnipeg Customs Examining Warehouse. They are grouped according to the main aspect which they monitor.

8.6.1 Temperature Sensors

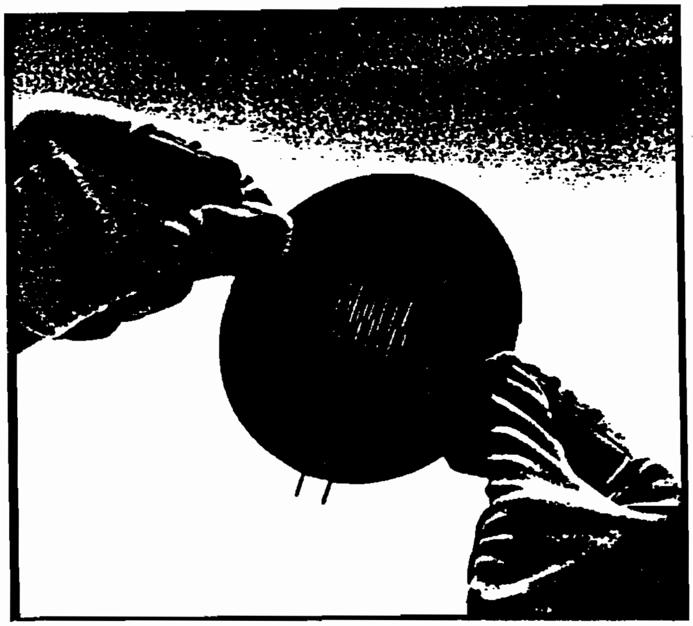
8.6.1.1 Thermocouples

Thirty three T type thermocouples are used to measure the temperature variation across the wall at various locations. They are Thermo Electric P-24-T thermocouples with polyvinyl chloride rip-cord insulation, 24 AWG, equivalent to a wire diameter of 0.5 mm. The thermocouples were installed at least 10 mm along the isotherm.

8.6.1.2 Heat Flux Transducers

Heat flux transducers measure heat flow and give a direct indication of the thermal resistance of the walls. Heat passing through the sensor generates a difference in temperatures between the two sides of the sensor. The difference in temperature is detected with a thermopile formed by a large number of thermocouples in series. This temperature difference is then used to calculate the heat flow. Two heat flux transducers were required, one on the insulated section and one on the corresponding uninsulated section of the wall. The transducers used are 100 mm diameter disks, model PU 4.3, obtained from TNO, the Institute of Applied Physics, in Holland (Figure 8.2).

Figure 8.2 Heat flux transducer



8.6.2 Moisture Sensors

8.6.2.1 Brick Resistance Moisture Sensors

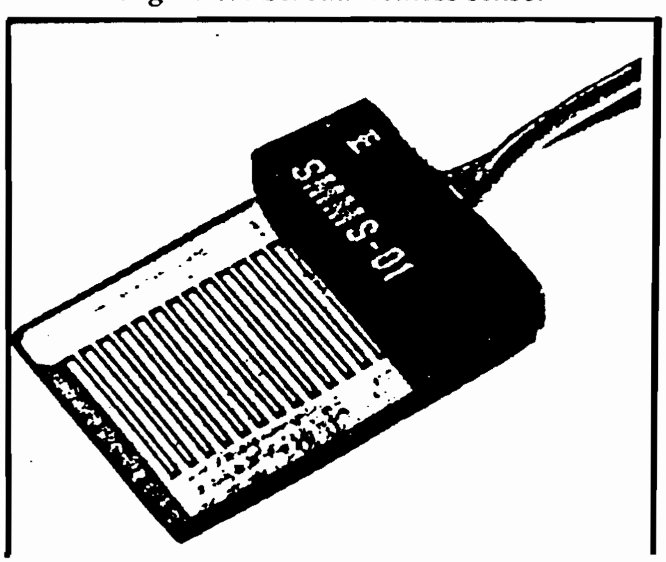
Thirteen brick resistance moisture sensors measure the variation in moisture levels with time at various locations in the wall. Two types of resistance sensors are used. The first type, used on the masonry surface, measures resistance across brass pins set into the brick or mortar joint. Two brass rivets, manufactured by IRC, were press fitted into holes drilled 10 mm apart into the brick. The brass rivets are 3.2 mm in diameter and 13 mm in length, excluding the head. For locations within the wall, different type of sensors were used. They measure resistance across two wires fixed onto a small ceramic plug fitted into the wall (Figure 8.3). IRC prepared small brick blocks with two wires glued to them. Holes were drilled into the wall in which the cubes were then inserted and set in mortar. A 1 MOhms resistor was installed in parallel with the sensors. The resistance obtained from the sensors varies in range from 40 kOhms when saturated to 20 to 30 MOhms when almost dry. AC excitation is used to reduce the effects of polarity.

Figure 8.3 Brick resistance moisture sensor

8.6.2.2 Wetness Sensors

Wetness sensors are used to indicate condensation or other forms of wetting occurring on a surface. Six wetness sensors were installed at locations subject to rain, air leakage and condensation. Sereda wetness sensors, model SMS-01, were obtained from Epitek. The sensors consist of a small electrochemical cell of alternating gold and copper electrodes on an insulating substrate (Figure 8.4). A small DC voltage is generated from the cell in the presence of water in the liquid or solid form. Specifications state that the output is 20 to 40 mV DC into a 10MW load. However, ASTM-G84 states that the output could be up to 100 mV.

Figure 8.4 Sereda wetness sensor



8.6.2.3 Relative Humidity and Temperature Sensors

These sensors are used to measure the humidity and temperature of the inside and outside air as well as the air within the cavity of the insulated wall section. Given the relative humidity and temperature, the dew point temperature can then be calculated. The relative humidity and temperature sensors are from General Eastern and have a 2% relative humidity accuracy over a range of 20-95% They have a current output but a resistor was added to the circuit converting the output into volts. Each sensor has one output for relative humidity and one for temperature. The sensor installed on the building exterior was adjusted to function at lower temperatures.

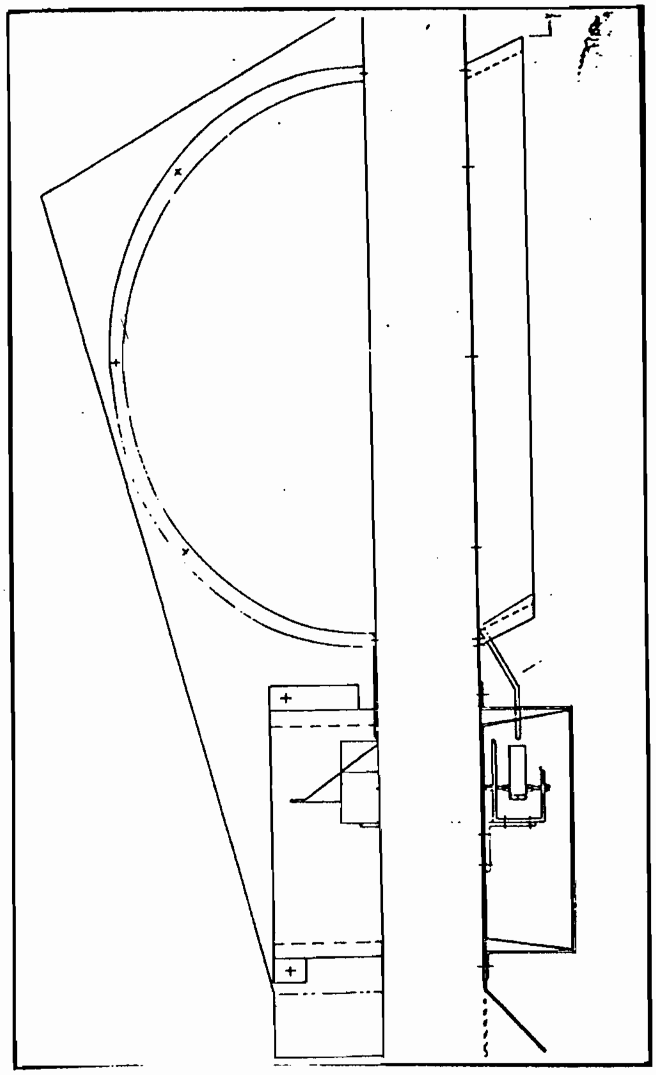
8.6.2.4 Rain Gauges

Rain collectors were attached to exterior face of the masonry to measure the amount of rain driven onto the wall. The rain collectors consist of two tipping rain gauges attached to a pulse counter. A wall mounted funnel conveys the rain to the tipping bucket. These rain gauges were manufactured by IRC, based on a Swedish design (Figure 8.5). The smaller rain gauge counts a pulse every two bucket tips. It takes 4.6 ml of water to tip the bucket. Thus one pulse is equivalent to 9.2 ml. The larger gauge counts a pulse every bucket tip. It takes 3.6 ml to tip the bucket. The general wind speed and direction will be obtained from the weather station at the Winnipeg International Airport.

8.6.2.5 Pressure Transducer

A pressure gauge was installed to measure difference between outside and inside air pressure. This will give an indication of the potential for air leakage, and the wind pressures on exterior face of the wall during periods of rain. A Statham pressure transducer, model PM5TC was used.

Figure 8.5 Rain gauge

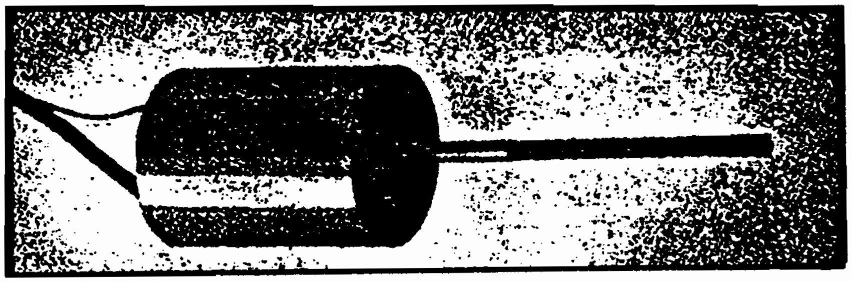


8.6.3 Movement Sensors

8.6.3.1 Linear Variable Differential Transformer

An LVDT gauge was installed to see if there is any movement occurring across one of the cracks in the masonry of the corner pier. The linear variable differential transformer will monitor any movement of the crack in the corner pier. The Pickering DC-DC LVDT. Model 7303-Y3-A0 utilizes a free floating core assembly with input and output leads (Figure 8.6). It has a range of ± 12.5 mm (± 0.5 inch) and linearity of± 0.1%. It requires a 6 V DC input and has a nominal maximum output 2.2 V DC.

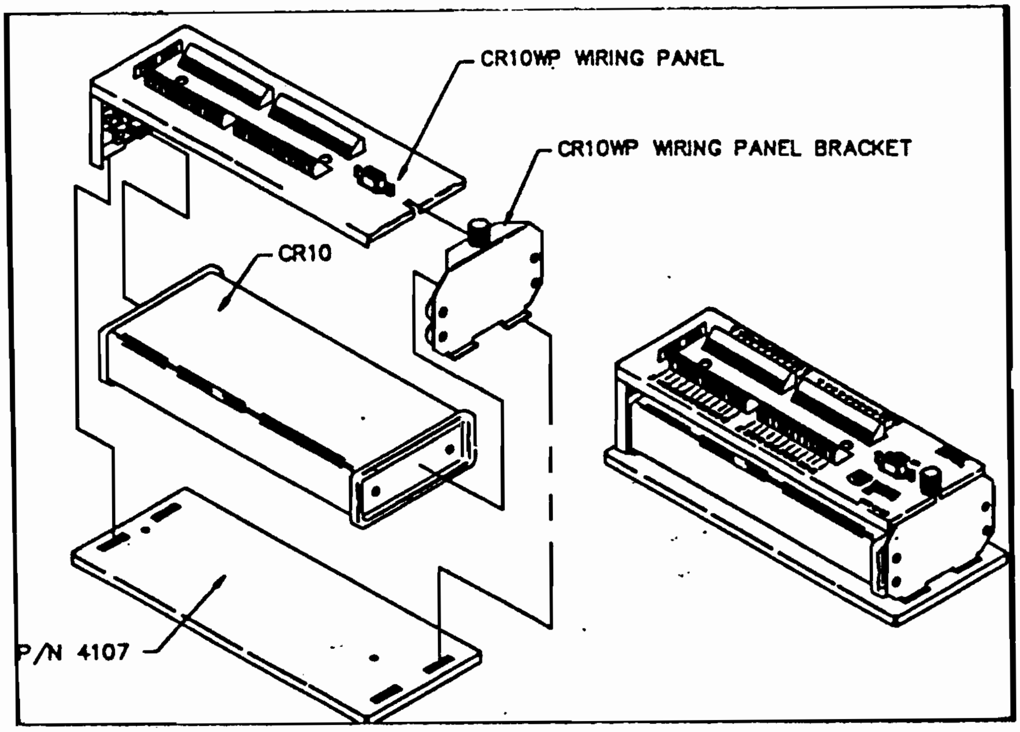
Figure 8.6 Linear Variable Differential Transformer



8.7 Datalogger

The sensors are monitored with a CR-10, Campbell Scientific datalogger (Figure 8.7), developed for stand alone use. The datalogger is accessed by telephone through a modem. Originally developed to gather weather data, this versatile unit can measure DC voltages from 1 micro volt to 2.5 volts, resistance and conductivity including DC and AC resistance measurements with set-ups for making bridge measurements, relative humidity and temperature sensors, type T thermocouples with a resolution down to 0.05°C, and pulse counters for rain gauges. Included with the datalogger is a software package for its programming. There are four main programs: EDLOG, SPLIT, TERM and TELCOM (Campbell Scientific Inc., 1991). EDLOG is used to program the datalogger operations. SPLIT is used to manipulate the data. TELCOM is used to download data from the datalogger and TERM is used to download programs to the datalogger. These programs are stored in the C:\EDLOG directory of the computer. The CR10 has only 12 single ended analog channels but this can be augmented by the use of a multiplexer. If multiplexers are added, four of the channels on the CR10 have to be reserved for them. To accommodate the numerous sensors used in monitoring the two wall sections, two multiplexers were necessary. The Cambell Scientific AM416 multiplexer has 64 single ended channels (32 differential).

Figure 8.7 Campbell Scientific CR10 datalogger



Dielectric absorption can have a serious effect on low level measurements (i.e. 50 mV or less). The primary rule to follow in minimizing dielectric absorption is to avoid PVC insulation around the conductors. PVC cable jackets are permissible if the jacket is outside the shield. Therefore in wiring the sensors the following recommended wires were used: Belden 8641 one shielded pair polyethylene 24 AWG, Belden 8771 one shielded three conductors polyethylene 22 AWG and Belden 8723 2 shielded pair polypropylene 22 AWG.

8.7.1 Datalogger Programming

The code for the operation of the datalogger was written using EDLOG, a computer program provided with the datalogger's software package. The files relevant to the datalogger operation are stored in the C:\EDLOG\PEG6 directory. The datalogger program consists of a series of instructions for reading the various sensors at the specified time interval, performing some simple statistical calculations and storing the data (Table 8.1). The program specifies the channel in which the various sensors are connected to the datalogger or the relay box. Figure 8.8 illustrate the wiring system used at the Winnipeg Customs Examining Warehouse. The following outline of the program currently in use. To facilitate viewing, its appearance has been slightly modified with the use of a word processor.

Figure 8.8 CR10 datalogger wiring diagram

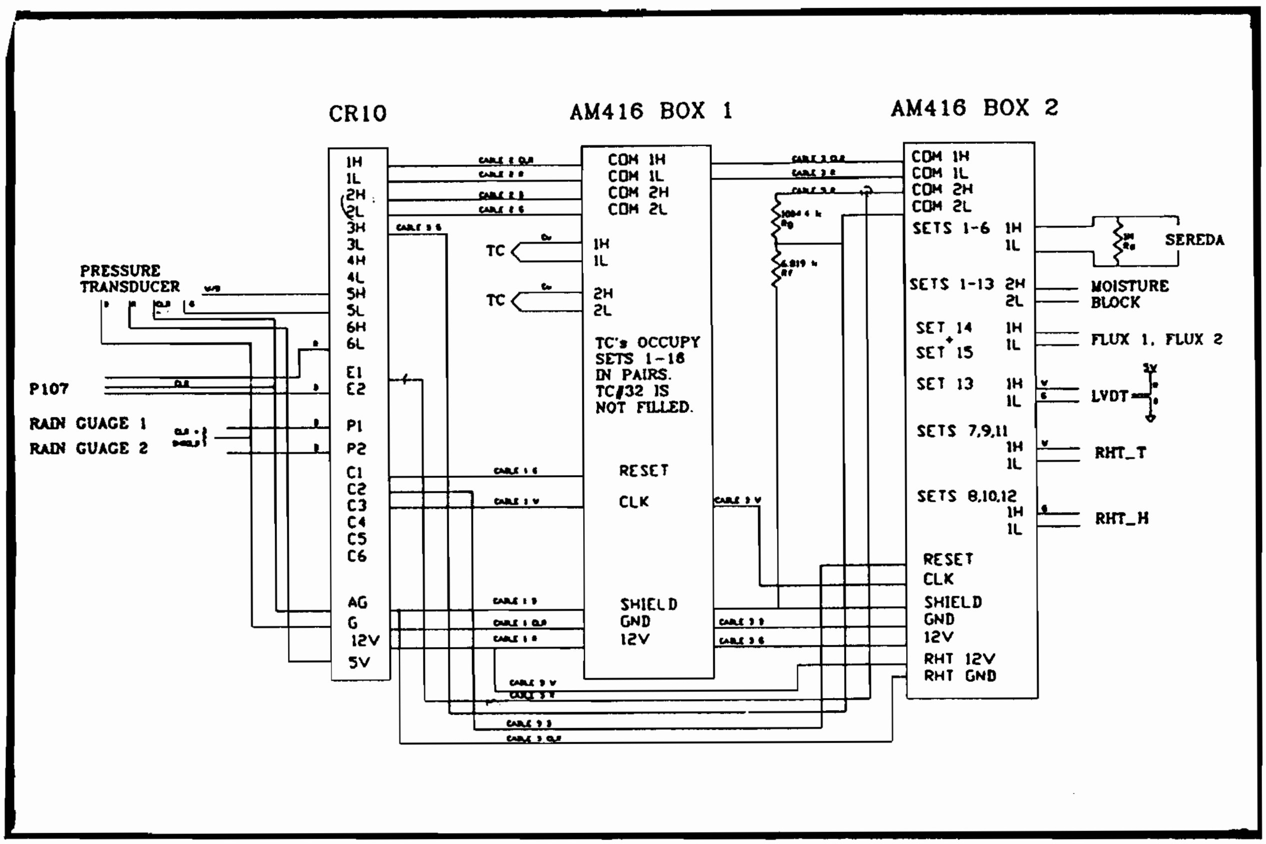


Table 8.1 Datalogger Program

Datalogger Program

***1 Table 1 Programs**
01: 60 Sec. Execution Interval

CR10 Statements:

Check Battery Voltage
01: P10 Battery Voltage
01: 66 Loc [:Battery]

Check CR10 Internal Temperature
02: P17 Module Temperature
01: 67 Loc [:Int Temp]

Read the two Rain Gauges
03: P3 Pulse
01: 2 Reps
02: 1 Pulse Input Chan
03: 12 Switch closure
04: 1 Loc [:Rain Gg#1]
05: 1 Mult
06: 0.000 Offset

Read the Pressure Transducer
04: P2 Volt (DIFF)
01: 1 Rep
02: 13 25 mV fast Range
03: 5 IN Chan
04: 63 Loc [:Pascals]
05: 56.851 Mult
06: 95.299 Offset

Read the temperature probes in the expansion boxes
05: P11 Temp 107 Probe
01: 1 Rep
02: 11 IN Chan
03: 02 Excite all reps w/EXchan 2
04: 3 Loc [:TempBox 1]
05: 1 Mult
06: 0.000 Offset

AM416 Expansion Box 1
Enable Box 1

06: P86 Do
01: 41 Set high Port 1
The loop count of 16, with a step size of two and two repetitions in the P14 statement, reads the thermocouples in groups of two sixteen times. The two repetitions increment the channel after each reading and the input location index 5-- increments the input location after each reading. The P14 statement alternates between input channels, while the location index steps from memory location TC#1 to TC#32. since there are only thirty one thermocouples, the last one should be ignored.

07: P87 Beginning of Loop
01: 0 Delay
02: 16 Loop Count

08: P90 Step Loop Index
01: 2 Step

09: P86 Do
01: 73 Pulse Port 3

Reading the Thermocouples
10: P14 Thermocouple Temp (DIFF)
01: 2 Reps
02: 13 25 mV fast Range
03: 1 IN Chan
04: 1 Type T (Copper-Constantan)
05: 3 Ref Temp Loc TempBox 1
06: 5-- Loc [:Box1 TC#1]
07: 1 Mult
08: 0.000 Offset

11: P95 End

12: P86 Do
01: 51 Set low Port 1

AM416 Expansion Box 2
Enable Box 2

13: P86 Do
01: 42 Set high Port 2

The first loop reads six wetness sensors and 6 moisture sensors. the wetness sensors are all live on channel 1 and the moisture sensors are all live on channel 2 so the input channel is not incremented but the memory location is. There are thirteen moisture sensors in all and they are all live on channel 2 in the AM416, but they are fed back to channel 5 on the CR10. A multiplier of 1000 was included for the moisture readings to compensate for the CR10's insufficient output processing precision. These readings should therefore be divided by 1000 before they are used in any analysis.

14: P87 Beginning of Loop
01: 0 Delay
02: 6 Loop Count

15: P86 Do
01: 73 Pulse Port 3

Reading the Wetness Sensors
16: P2 Volt (DIFF)
01: 1 Rep
02: 14 250 mV fast Range
03: 1 IN Chan
04: 37-- Loc [:Sereda #1]
05: 1 Mult
06: 0.000 Offset

Reading the first six Moisture Sensors
17: P5 AC Half Bridge
01: 1 Rep
02: 15 2500 mV fast Range
03: 5 IN Chan
04: 1 Excite all reps w/EXchan 1
05: 2500mV Excitation
06: 50-- Loc [:Moist #1]
07: 1000Mult
08: 0.00 Offset

18: P95 End

The second loop reads the three RHTs and the remaining Moisture Sensors. this time seven readings are taken, even tough there are only three RHTs. The relative humidity measurements are fed to channel 1 in three blocks with the three temperature measurements in the following three blocks. The LVDT also uses channel 1 and that completes the group of seven sensors on channel 1. There are another seven moisture sensors on channel 2.

19: P87 Beginning of Loop
01: 000 Delay
02: 7 Loop Count
20: P86 Do
01: 73 Pulse Port 3

Read the three RHTs and the LVDT
21: P2 Volt (DIFF)
01: 1 Rep
02: 15 2500 mV fast Range
03: 1 IN Chan
04: 43-- Loc [:RHT_13_T]
05: 1 Mult
06: 0.00 Offset

Read the last seven Moisture Sensors
22: P5 AC Half Bridge
01: 1 Rep
02: 15 2500 mV fast Range
03: 5 IN Chan
04: 1 Excite all reps w/EXchan 1
05: 2500mV Excitation
06: 56-- Loc [:Moist #7]
07: 1000Mult
08: 0.000 Offset

23P95 End

24: P87 Beginning of Loop
01: 000 Delay
02: 2 Loop Count

25: P86 Do
01: 73 Pulse Port 3

Read the two Heat Flux Transducers
26: P2 Volt (DIFF)
01: 1 Rep
02: 13 25 mV fast Range
03: 1 IN Chan
04: 64-- Loc [:Flux 1]
05: 1 Mult
06: 0.00 Offset

27: P95 End

Format Output
28: P86 Do
01: 52 Set low Port 2

29: P53 Scaling Array (A*loc +B)
01: 43 Start Loc [:RHT_13_T]
02: .04296 A1
03: -47.266 B1
04: .05705 A2
05: -29.228 B2
06: .04235 A3
07: -46.565 B3
08: .05637 A4
09: -25.569 B4

30: P53 Scaling Array (A*loc +B)
01: 47 Start Loc [:RHT_15_T]
02: .05228 A1

03: -67.093 B1
04: .05236 A2
05: -24.543 B2
06: .00763 A3
07: 32.241 B3
08: 1 A4
09: 0 B4

Perform statistics on almost everything every cycle, but only save data every hour
31: P92 If time is
01: 000 minutes into a
02: 10 minute interval
03: 30 Then Do

32: P86 Do
01: 10 Set high Flag 0 (output)

33: P77 Real Time
01: 1110Year,Day,Hour-Minute

34: P72 Totalize
01: 2 Reps
02: 1 Loc Rain Gg#1

35: P70 Sample
01: 65 Reps
02: 3 Loc TempBox 1

36 P95 End

37: P71 Average
01: 16 Reps
02: 50 Loc Moist #1

38: P96 Serial Output
01: 71 SM192/SM716

39: P End Table 1

* 2 Table 2 Programs
01: 1 Sec. Execution Interval

01: P87 Beginning of Loop
01: 000 Delay
02: 10 Loop Count

Read Pressure Transducer
02: P2 Volt (DIFF)
01: 1 Rep
02: 13 25 mV fast Range
03: 5 IN Chan
04: 63 Loc [:Pascals]
05: 56.851 Mult
06: 95.299 Offset

03: P95 End

04: P92 If time is
01: 000 minutes into a
02: 10 minute interval
03: 10 Set high Flag 0 (output)

Perform statistics
05: P77 Real Time
01: 1110Year,Day,Hour-Minute

06: P71 Average
01: 1 Rep
02: 63 Loc Pascals

07: P82 Standard Deviation
01: 1 Rep
02: 63 Sample Loc Pascals

08: P73 Maximize
01: 1 Rep
02: 00 Time Option
03: 63 Loc Pascals

09: P74 Minimize
01: 1 Rep
02: 00 Time Option
03: 63 Loc Pascals

10: P96 Serial Output
01: 71 SM192/SM716

11: P End Table 2

8.7.2 Frequency of Measurements

Spot measurements are taken for most sensors every 10 minutes. The exceptions are the pressure transducer, resistance moisture sensors and heat flux transducers. The pressure transducer is monitored every second; the readings are accumulated over 10 minutes and then output as average, maximum, minimum and standard deviation. The resistance sensors and heat flux meter are monitored every 60 seconds; the readings are accumulated over 10 minutes and output as an average.

8.7.3 Data Output Format

The datalogger stores the data in vector arrays after every 10 minutes. There are two arrays for every 10 minute period for a total of 288 data arrays per day. There have been occasions when the datalogger omitted or duplicated an array but these are rare and will not cause any serious problems The arrays are in a comma delineated ASCII format. The first four elements in the arrays are: the array identification number, the year, the Julian day and the time. The first type of array is the longest. It has the identification number 132 and contains all of the measurements with the exception of the statistics on the pressure differential readings. These are stored on a separate array with the identification number 204. The following is a list of sensor readings according to their corresponding element number in the array and their memory location in the datalogger.

Table 8.2 Format of output arrays

First Array

Element #	Memory Location	Program Label	Description
1		132	Data Array ID
2			Year
3			Julian Day
4			Hour and minute
5	1	Rain Gg#1	Rain Gauge 1
6	2	Rain Gg#2	Rain Gauge 2
7	3	TempBox 1	Internal Temperature
8	4		
9	5	Box1 TC#1	Thermocouple 12
10	6	Box1 TC#2	Thermocouple 10
11	7	Box1 TC#3	Thermocouple 11
12	8	Box1 TC#4	Thermocouple 9
13	9	Box1 TC#5	Thermocouple 34
14	10	Box1 TC#6	Thermocouple 20
15	11	Box1 TC#7	Thermocouple 21
16	12	Box1 TC#8	Thermocouple 35
17	13	Box1 TC#9	Thermocouple 36
18	14	Box1 TC#10	Thermocouple 22
19	15	Box1 TC#11	Thermocouple 43
20	16	Box1 TC#12	Thermocouple 8
21	17	Box1 TC#13	Thermocouple 1
22	18	Box1 TC#14	Thermocouple 7
23	19	Box1 TC#15	Thermocouple 41
24	20	Box1 TC#16	Thermocouple 42
25	21	Box1 TC#17	Thermocouple 3
26	22	Box1 TC#18	Thermocouple 5
27	23	Box1 TC#29	Thermocouple 44
28	24	Box1 TC#20	Thermocouple 4
29	25	Box1 TC#21	Thermocouple 33
30	26	Box1 TC#22	Thermocouple 45
31	27	Box1 TC#23	Thermocouple 25
32	28	Box1 TC#24	Thermocouple 6
33	29	Box1 TC#25	Thermocouple 48
34	30	Box1 TC#26	Thermocouple 24
35	31	Box1 TC#27	Thermocouple 46
36	32	Box1 TC#28	Thermocouple 47
37	33	Box1 TC#29	Thermocouple 26
38	34	Box1 TC#30	Thermocouple 23
39	35	Box1 TC#31	Thermocouple 2
40	36	Box1 TC#32	
41	37	Sereda#2	Sereda Sensor S2
42	38	Sereda#11	Sereda Sensor S11
43	39	Sereda#13	Sereda Sensor S13
44	40	Sereda#12	Sereda Sensor S12
45	41	Sereda#3	Sereda Sensor S3
46	42	Sereda#1	Sereda Sensor S1
47	43	RHT-13-T	RHT#13 Temperature
48	44	RHT-13-H	RHT#13 Humidity

8-23 missing

Element #	Memory Location	Program Label	Description
49	45	RHT-14-T	RHT#14 Temperature
50	46	RHT-14-H	RHT#14 Humidity
51	47	RHT-15-T	RHT#15 Temperature
52	48	RHT-15-H	RHT#15 Humidity
53	49	LVDT	LVDT
54	50	Moist#1	Resistance Sensor R21
55	51	Moist#2	Resistance Sensor R31
56	52	Moist#3	Resistance Sensor R30
57	53	Moist#4	Resistance Sensor R20
58	54	Moist#5	Resistance Sensor R32
59	55	Moist#6	Resistance Sensor R2
60	56	Moist#7	Resistance Sensor R34
61	57	Moist#8	Resistance Sensor R1
62	58	Moist#9	Resistance Sensor R3
63	59	Moist#10	Resistance Sensor R23
64	60	Moist#11	Resistance Sensor R33
65	61	Moist#12	Resistance Sensor R4
66	62	Moist#13	Resistance Sensor R22
67	63	Pascals	Air pressure sensor
68	64	Flux 1	Heat Flux Transducer 1
69	65	Flux 2	Heat Flux Transducer 2
70	66	Battery	CR10 Battery voltage
71	67	Int Temp	Internal Temp. CR10
72-84			Moist. Sensor Avg.
85			Avg. Pressure Diff.
86-87			Heat Flux Avg.

N.B. Please note that thermocouples 23 and 24 have been interchanged. Analysis of their temperature readings suggested that they were crosswired or had been labeled incorrectly.

Second Array

Element #	Memory Location	Program Label	Description
1		132	Data Array ID
2			Year
3			Julian Day
4			Hour and minute
5			Pressure Diff. Avg.
6			Standard Deviation.
7			Maximum
8			Minimum

8.7.4 Program Modifications

Since the start of the monitoring at 10:30 on Monday April 19th (Julian Day 109), 1993, the datalogger program has been modified on two occasions. The original program was replaced at 12:45 on Thursday, June 17th (Julian Day 168), 1993. The new program had two important modifications. A multiplier of 1000 was included in the statement for the brick resistance moisture sensor readings to compensate for the CR10's insufficient output processing precision. The statements concerning the statistic were modified and the output of statistics performed on the pressure differential readings were stored in a separate array. The current program was downloaded to the datalogger at 14:30 on Wednesday, July 27th (Julian Day 208), 1993, to replace the previous version which used an incorrect multiplier in the reading of the rain gauges. It should be noted that the installation of the new programs caused a temporary interruption of the monitoring process and may result in some anomalies in the daily data file for those specific dates.

8.8 Data Gathering Process

Although the datalogger has large amounts of storage space, the data should be downloaded on a regular basis. In the case of the Winnipeg Customs Examining Warehouse, the data is downloaded every morning except on weekends and holidays. However, the datalogger should be able to store up to one week's worth of data in the present format without any difficulties. The data is downloaded with the use of an Inmac Clear Signal 2400 modem and the TELCOM program provided with the datalogger's software package. To call Winnipeg with the modem and download the data the command line is:

C:\EDLOG\TELCOM PEG5\PEG5/c.

TELCOM will then access the datalogger and download the data to the PEG5.DAT file in the C:\EDLOG\PEG5 directory. The incoming data is simply appended to the end of the existing data file. Once this is completed, a back-up copy is made in the form of a compressed file. Since the data will take up large amounts of computer space, the back-up copy of PEG5.DAT is a compressed file, PEG.ZIP, created with the PKZIP program (PKWare Inc., 1993). Each time data is downloaded to the PEG5.DAT file the PEG.ZIP file must be updated. To update the PEG.ZIP file the command line is:

C:\EDLOG\PEG5\ZIP /f PEG.

The process outlined above can also be accomplished in Microsoft Windows by choosing the program item labeled Winnipeg in the program group Windows Applications. The icon for this program item is a yellow telephone. Double clicking this icon with the mouse activates the file WINNIPEG.BAT. This file is programmed to call the datalogger, download the data, and update the PEG.ZIP file.

The PEG5.DAT file should not be allowed to become too large. To prevent this from happening the following process is used once a week on Monday. First, the PEG5.DAT file is renamed PEG5-??.DAT. The last two digits of this new file name is the week's ID number Using a word processor, the new file is accessed and the data arrays associated with the current day are transferred to a new file. This new file is named PEG5.DAT. In completing this process, the end of file marker must not be deleted. The EOF marker, typically illustrated as a square should be located immediately after the carriage return of the last data array in the PEG5-??.DAT file. If the EOF marker is omitted, it will cause problems during the data processing. The PEG5-??.DAT file should now contain only days for which the complete data record is available and is then ready for data processing. The PEG.ZIP file associated with the PEG5-??.DAT file should be renamed PEG-??.ZIP and be transferred to disk. Finally, it is necessary to create a new PEG.ZIP file using the new PEG5.DAT file. This is accomplished with the following command line:

C:\EDLOG\PEG5\ZIP PEG.ZIP PEG5.DAT.

Chapter 9

Data Processing

The data from the datalogger must first be processed, before it can be analyzed. The raw data must be converted and organized in a fashion suitable for analysis. The data processing is achieved using the SPLIT program (Campbell Scientific Inc., 1993) supplied with the datalogger software and a spreadsheet program, in this case Microsoft EXCEL, version 4.0 (Microsoft Corp., 1992). Using these programs a series of files were written to process the information on a weekly basis

9.1 Process Description

The first step in the data processing is to break down the weekly raw data files, PEG5-??.DAT, into daily data files. This is accomplished using the DAY.PAR parameter file for the SPLIT program. This process does not modify the raw data but simply divides it into daily sections. The individual daily data files are named DAY93???.DAT with the last three digit representing the Julian date.

Once the data has been divided into daily sections, it is processed with SPLIT using a series of parameter files. These parameter files are programmed to scan the daily data file and extract the sensor readings relevant to a particular area of analysis. There are five areas of analysis. The first area of analysis studies heat flow and the thermal gradient across the wall. The second deals with the moisture levels in the masonry. The third monitors rain wetting of the exterior wall. The fourth is concerned with thermal bridges and condensation. Finally, the fifth area of analysis is the monitoring of crack movement. Each of theses areas of analysis has at least one parameter file. At the same time, as they extract the relevant sensor readings, the parameter files make all the necessary conversions and calculations. In some cases, the data is averaged over 30 or 60 minute periods. They also reorganize the data in a format suitable for spreadsheets. Each parameter file produces two data files. The first is a coma delineated ASCII file with the extension DAT or PRN. These files can be further manipulated with SPLIT. Presently, they are of no further use and can be deleted. The second type of file contains the same data but in a format which is suitable for printing or use with spreadsheets. These files are identified by the RPT extension. A series of five numbers, the year (93) followed by the Julian date (001 to 365), are included into the name of all output files.

These files are then imported into an EXCEL worksheet where the data is used in creating a series of charts to simplify analysis. There is an EXCEL macro file corresponding to each individual parameter file. The macro files handle any data modifications that could not be accomplished with SPLIT. They contain all of the necessary instructions for data processing and drafting of charts. The macros are programmed to scan the data and to print the charts only if an event of importance to the analysis has occurred The worksheet is initially saved in the C:\WINNIPEG\ANALYSIS directory and, if there are no errors, it is then transferred to the C:\WINNIPEG\XLS directory. When the Excel worksheet has been saved, the associated RPT file is no longer of any use and can be deleted.

9.2 General Format

All the SPLIT parameter files have a very similar format. The same can be said for the EXCEL macros. Therefore, before explaining the particular functions of each file, their general format is described. All of the SPLIT parameter files, EXCEL macros and other control files relevant to the data processing are stored in the C:\WINNIPEG\BATS directory.

9.2 1 SPLIT Parameter Files

The SPLIT parameter files have a simple straight forward format consisting of a series of statements. First, the input data file must be specified. More than one file can be specified in which case SPLIT scans all files for relevant data. The same file can be listed twice to allow extra operations to be performed. Once the input file has been entered the name of the output file must be specified. The output files are typically sent to the C:\WINNIPEG\ANALYSIS directory to await further processing. The exception is the daily data files which do not require any further modification and are sent to the C:\WINNIPEG\DATA directory. After the input and output files have been specified, there are three condition statements to be entered. The first instructs SPLIT when to start reading the data file. If it is left blank SPLIT starts at the beginning of the file. If the data is to be averaged, 4[10] is usually specified. This instructs SPLIT to skip the first array and start processing only when the fourth element of the array is equal to 10. Since the fourth element is time, this ensures that time will be read on the hour or half hour. The next statement instructs SPLIT when to stop processing. It is typically left blank which means that SPLIT will stop when it reaches the EOF marker. If SPLIT cannot find the EOF marker, an error message appears. The last of the three condition statements instructs SPLIT to copy data only from the specified arrays. If left bank, all arrays are read. Typically 1[132], or 1[204] is specified to tell SPLIT to read only the arrays with that matching ID. Following the three condition statements, the various functions to be performed are listed with specified array elements.

9.2.2 EXCEL Macros

All of the EXCEL macro files have a simple format. The input is the *.RPT file produced by the SPLIT parameter files. The output is an EXCEL worksheet with the same name as the input file but with the XLS extension. The macro starts by opening the specified input file and parsing the data. It then performs any data modifications required prior to creating the charts. Once that is completed the macro selects the relevant data, locates the charts on the spreadsheet and draws them. After the charts are completed, the macro scans the data to determine if an event of importance to the analysis has occurred. It then formats the charts and if required print them. Finally, it saves the file as an EXCEL worksheet.

9.3 Detailed Description of Data Processing

The following is a detailed description of the files used to process the data. They are organized according to the various areas of analysis. The code for each file is shown and explained in detail. Some of the files reproduced here have been altered slightly with a word processor to make them easier to view.

9.3.1 Daily Data File

Although not an area of analysis, the processing of the weekly data file is an important step. The SPLIT parameter named DAY.PAR (Table 9.1) simply divides the weekly data file, PEG5-??.DAT, into daily data files. The data is not modified in any way during this process. The daily data files are named DAY93???.DAT, with the last three digits being the Julian date. The condition statement to start and stop processing must be specified. The condition statement to start processing is the Julian date of the daily data file being created. The condition statement to stop processing is the Julian date of the following day.

Table 9.1 DAY.PAR

Names of input DATA FILE:	c:\edlog\peg5\PEG5_??.DAT
Name of OUTPUT FILE to generate:	c:\winnipeg\DAY93???.DAT/0
START reading in:	3[???]
STOP reading in:	3[???]
COPY from:	
SELECT elements #:	

9.3.2 Heat Flow and Thermal Gradient

The first area of analysis studies heat flow and the thermal gradient across the wall. The relevant sensors are: the heat flux transducers F1 & 2; the temperature reading from the relative humidity and temperature sensors RHT 13T, 14T and 15T; and the thermocouples T 3-6, 20, 21, 23, 24, 26, 33, 34, 36, 41, 43-45, and 48. The readings are averaged over thirty minute intervals. The data processing for this area of analysis is divided into two parts.

9.3.2.1 HF1.PAR

The first part is a comparison of the heat flow and thermal gradient across the insulated and uninsulated wall sections. The SPLIT parameter file is named HF1.PAR (Table 9.2) and produces an output file named HF93???a.RPT. The heat flow is calculated using the heat flux transducer calibration equation:

$$\text{Heat Flow in W/m}^2 = C*\{([T-20.0]*0.0004) +1.0\}*V$$

where C is the transducer's calibration value, T is the temperature in degrees Celsius and V the voltage reading from the transducer.

Table 9.2 HF1.PAR

Names of input DATA FILE:		c:\winnipeg\data\DAY93???.DAT
Name of OUTPUT FILE to generate:		C:\winnipeg\analysis\HF93???a.PRN/R/0
START reading in:		4[10]
STOP reading in:		
COPY from:		1[132]
SELECT elements:	L1	smpl(4;3),
	L2	avg(86;3)*(((avg(23;3)-20.0)*0.0004) +1.0)*6.5,
	L3	avg(87;3)*(((avg(32;3)-20.0)*0.0004) +1.0)*6.2,
	L4	avg(27,47,19,30,23,17,15,14,51;3),
	L5	avg(47,32,26,38,38,51;3),
	L6	smpl(4;3)

The first and last lines in the selection of data read the time. The second and third lines calculate the averaged heat flux transducer readings. The calculation is based on the average temperature from thermocouples T 41 and T 6, respectively, and the calibration value specific to each heat flux transducer. Line four is the average of the various temperature readings across the insulated wall section. Line five is the average of the various temperature readings across the uninsulated wall section.

9.3.2.2 HF1.XLM

The EXCEL macro associated with the HF93???a.RPT files is named HF1.XLM (Table 9.3). On the worksheet, the data is arranged in columns in the following order: Time, F1, F2, RHT13T, T43, T44, T45, T41, T36, T21, T20, RHT15T, RHT13T, T6, T5, T24, T23, RHT15T, and Time. The macro does not modify the data in anyway. There are three charts (Figure 9.1) on the worksheet, all located on the second page. The first illustrates heat flow variation versus time for the insulated and uninsulated wall sections. The second chart is the temperature gradient across the insulated wall at 5:00 and 17:00. This closely coincides with the maximum and minimum daily exterior temperatures. The third chart is the temperature gradient across the uninsulated wall at 5:00 and 17:00. There is no specific event for which these charts should be printed. Rather a sample print out at regular intervals is sufficient. The print command of the macro has therefore been disabled by deleting the = signs that preceded it. If automatic printing of the charts is desired simply add a = sign in front of the command.

Figure 9.1 Charts produced by macro HF1.XLM

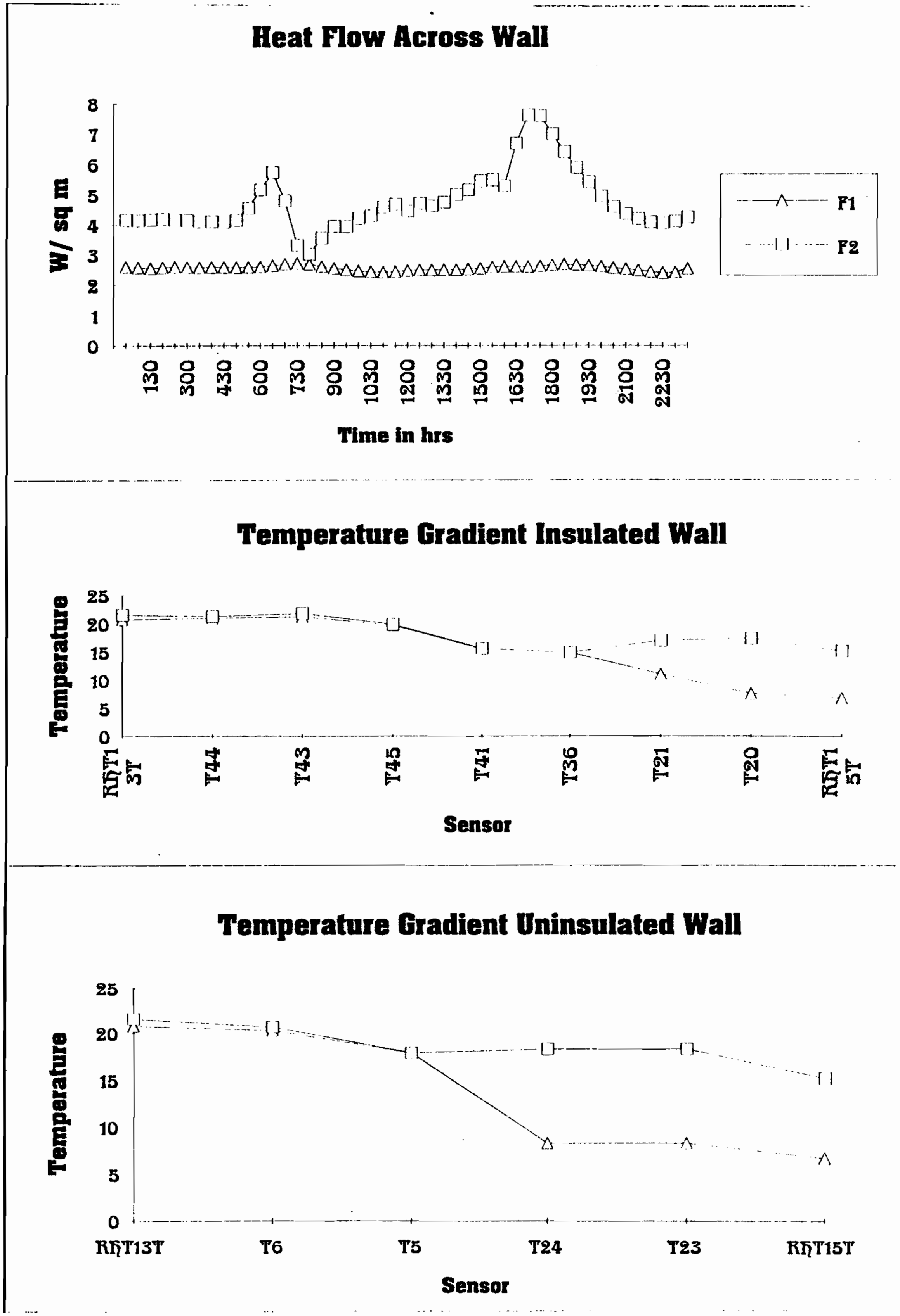


Table 9.3 Macro HF1.XLM

```
        C! sets directory and asks which file to open
"=DIRECTORY(""C:\WINNIPEG\ANALYSIS"")"
"=OPEN?(""C:\WINNIPEG\ANALYSIS\HF93???a.RPT"",,,2)"
        C! parses data
"=SELECT(""R7C1:R55C1"")"
"=PARSE(""[30][4.95][8.82][20.8][21.2][21.4][19.4][11.6][10.0][5.0][1.2][0.3][20.8][19.5][14.1][2.1]
[6.0][0.3][30]"")"
"=SELECT(""R5C1"")"
"=PARSE(""[TIME][F1][F2][RHT13T][T44][T43][T45][T41][T36][T21][T20][RHT15T][RHT13T][T6]
[T5][T24][T23][RHT15T][TIME]"")"
        C! deletes an unwanted dividing line
"=SELECT(""R6C1"")"
"=CLEAR(3)"
        C! selects data for heat flow chart
"=SELECT(""R5C1:R53C3"")"
=COPY()
        C! locates chart on spreadsheet
"=CREATE.OBJECT(5,""R56C1"",1.5,1.5,""R70C10"",0,0.75,1,TRUE)"
        C! draws heat flow chart
"=CHART.WIZARD(TRUE,""R5C1:R53C3"",4,2,2,1,1,1,""Heat Flow Across Wall"",""Time in
hrs"",""W/ sq m"","""")"
        C! selects data for chart of temperature gradient across insulated wall
"=SELECT(""R5C4:R5C12,R15C4:R15C12,R40C4:R40C12"",""R40C4"")"
=COPY()
        C! locates chart on spreadsheet
"=CREATE.OBJECT(5,""R70C1"",1.5,1.5,""R84C10"",0.75,0,1,TRUE)"
        C! draws chart
"=CHART.WIZARD(TRUE,""R5C4:R5C12,R15C4:R15C12,R40C4:R40C12"",4,2,1,1,2,2,""Temperature
Gradient Insulated Wall"",""Sensor"",""Temperature"","""")"
        C! selects data for chart of temperature gradient across uninsulated wall
"=SELECT(""R5C13:R5C18,R16C13:R16C18,R40C13:R40C18"",""R40C13"")"
=COPY()
        C! locates chart on spreadsheet
"=CREATE.OBJECT(5,""R84C1"",1.5,0,""R98C9"",47.25,12,1,TRUE)"
        C! draws chart
"=CHART.WIZARD(TRUE,""R5C13:R5C18,R16C13:R16C18,R40C13:R40C18"",4,2,1,1,2,2,""Temperat
ure Gradient Uninsulated Wall"",""Sensor"",""Temperature"","""")"
        C! sets up charts for printing
"=SELECT(""Chart 1"")"
"=FORMAT.MOVE(1.5,0,""R50C1"")"
"=FORMAT.SIZE(0,0.75,""R70C10"")"
"=PAGE.SETUP("""",""&R&F"",0.75,0.75,1,1,FALSE,FALSE,FALSE,FALSE,1,1,100,1,1,FALSE)"
        C! plots the page displaying the charts
"PRINT(2,2,2,1,FALSE,FALSE,1,FALSE,1)"
        C! asks for the name of file to be saved
"=SAVE.AS?(""C:\WINNIPEG\ANALYSIS\HF93???a.XLS"",1,"""",FALSE,"""",FALSE)"
=RETURN()
        C! end
```

9.3.2.3 HF2.PAR

The second part deals with the comparison of the thermal gradient in the uninsulated wall for two sections of different thickness and the variation of the interior masonry surface temperature over the height of the insulated wall section. The SPLIT parameter file is named HF2.PAR (Table 9.4) and produces an output file named HF93???b.RPT.

Table 9.4 HF2.PAR

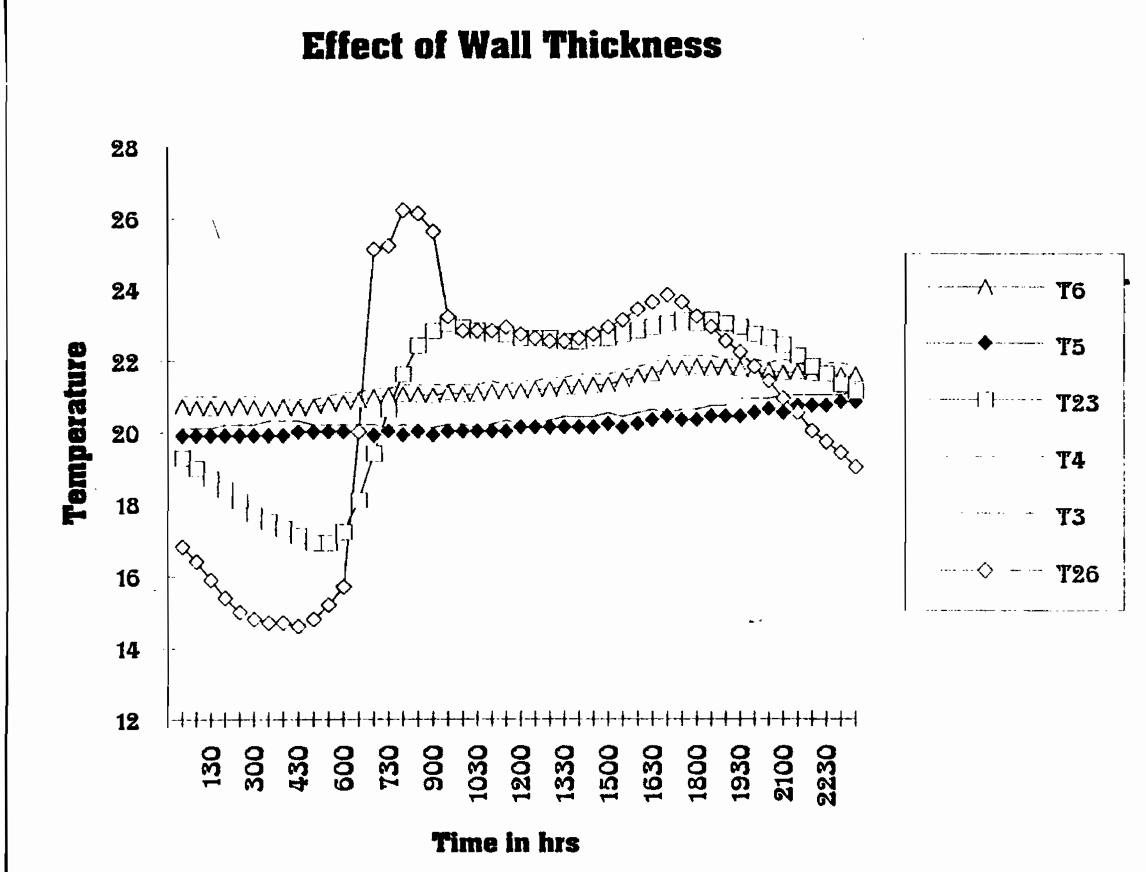
Names of input DATA FILE:	c:\winnipeg\data\DAY93195.DAT
Name of OUTPUT FILE to generate:	C:\winnipeg\analysis\HF93195b.PRN/R/0
START reading in:	4[10]
STOP reading in:	
COPY from:	1[132]
SELECT elements #: L1	smpl(4;3),
L2	avg(32,26,34,28,25,37;3),
L3	avg(33,23,13,29;3),
L4	smpl(4;3)

The first and last lines in the data selection statement read the time. Line 2 is the average of the various thermocouple readings relevant to the analysis of the thermal gradient in the uninsulated wall for two sections of different thickness. Line 3 is the average of the various thermocouple readings relevant to the analysis of the variation of the interior masonry surface temperature over the height of the insulated wall section.

9.3.2.4 HF2.XLM

The EXCEL macro associated with the HF93???b.RPT files is named HF2.XLM (Table 9.5). On the worksheet, the data is arranged in columns in the following order: Time, T6, T5, T23, T4, T3, T26, T48, T41, T34, T33, and Time. The macro does not modify the data in anyway. There are two charts on the worksheet (Figure 9.2) , both located on the second page. The first is the temperature variation versus time across the uninsulated wall for two sections of different thickness. The second chart is the temperature variation versus time over the height of the insulated wall. There is no specific event for which these charts should be printed. Rather a sample print out at regular intervals is sufficient. The print command of the macro has therefore been disabled by deleting the = signs that preceded it. If automatic printing of the charts is desired simply add an = sign in front of the command.

Figure 9.2 Charts produced by macro HF2.XLM



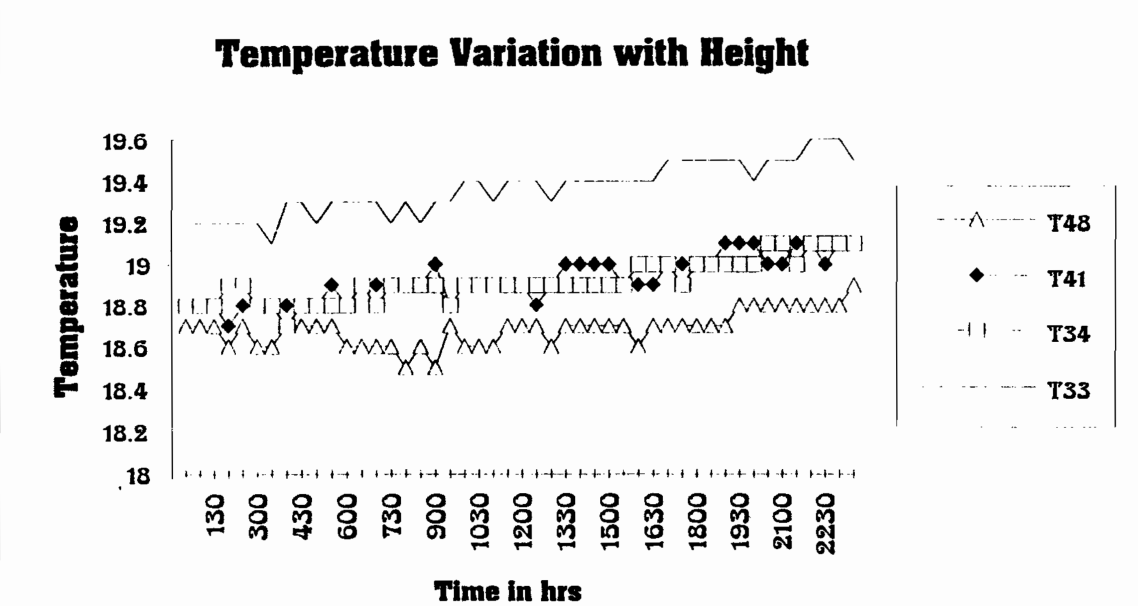


Table 9.5 Macro HF2.XLM

```
        C! sets directory
"=DIRECTORY(""C:\WINNIPEG\ANALYSIS"")"
        C! asks which file to open
"=OPEN?(""C:\WINNIPEG\ANALYSIS\HF93???b.RPT"",,,2)"
        C! parses data
"=SELECT(""R7C1:R55C1"")"
"=PARSE(""[30][19.47][14.1][6.0][19.6][14.1][2.0][14.9][11.6][11.5][11.8][30]"")"
"=SELECT(""R5C1"")"
"=PARSE(""[TIME][T6][T5][T23][T4][T3][T26][T48][T41][T34][T33][TIME]"")"
        C! deletes unwanted dividing line
"=SELECT(""R6C1"")"
"=CLEAR(3)"
        C! selects data for chart of the effect of wall thickness
"=SELECT(""R5C1:R53C7"")"
=COPY()
        C! locates chart on spreadsheet
"=CREATE.OBJECT(5,""R56C1"",1.5,0.75,""R70C9"",46.5,0,1,TRUE)"
        C! draws chart
"=CHART.WIZARD(TRUE,""R5C1:R53C7"",4,2,2,1,1,1,""Effect of Wall Thickness"",""Time in hrs"",""Temperature"","""")"
"=FORMAT.SIZE(46.5,12,""r77c9"")"
        C! selects data for chart of temperature variation with height of wall
"=SELECT(""R5C1:R53C1,R5C8:R53C11"",""R5C8"")"
=COPY()
        C! locates chart on spreadsheet
"=CREATE.OBJECT(5,""R78C1"",1.5,0,""R99C10"",0,0,1,TRUE)"
        C! draws chart
"=CHART.WIZARD(TRUE,""R5C1:R53C1,R5C8:R53C11"",4,2,2,1,1,1,""Temperature Variation with Height"",""Time in hrs"",""Temperature"","""")"
        C! sets up charts for printing
"=SELECT(""Chart 1"")"
"=FORMAT.MOVE(1.5,1.5,""R50C1"")"
"=FORMAT.SIZE(46.5,12,""R75C9"")"
"=SELECT(""Chart 2"")"
"=FORMAT.MOVE(1.5,1.5,""R76C1"")"
"=FORMAT.SIZE(0,0,""R99C10"")"
"=PAGE.SETUP("""",""&R&F"",0.75,0.75,1,1,FALSE,FALSE,FALSE,FALSE,1,1,100,1,1,FALSE)"
        C! plots the page displaying the charts
"PRINT(2,2,2,1,FALSE,FALSE,1,FALSE,1)"
        C! asks for name of file to be saved
"=SAVE.AS?(""C:\WINNIPEG\ANALYSIS\HF93???b.XLS"",1,"""",FALSE,"""",FALSE)"
=RETURN()
        C! end
```

9.3.3 Moisture Levels

The second area of analysis deals with the moisture levels in the masonry. The relevant sensors are: the wetness sensors S11-13 and the brick resistance moisture sensors R 1-4, 30-34, and 20-23. The readings are averaged over sixty minute intervals. Two different methods of processing the data for this area of analysis have been developed because the brick sensor reading may not be valid when the temperature drops below -1°C. The first method assumes that the brick sensor reading is not affected by low temperatures. The second method checks the temperature reading from the nearest thermocouple to check if the brick moisture reading is valid. The relevant thermocouples are T 1, 4-6, 20-21, 23-24, 35-36, 42, and 48. A SPLIT parameter file and EXCEL macro have been developed for each of these two methods. By comparing the results from these two methods of data processing, it should be possible to determine the effects of low temperatures on the brick resistance moisture sensors.

9.3.3.1 MOIST1.PAR

The SPLIT parameter file for the first method is named MOIST1.PAR (Table9.6) and produces an output file named MO_93???.RPT. The data processing of the brick resistance moisture sensors requires some calculations. The datalogger reads the voltage ratio of the brick moisture sensor, $\chi = Vx/V1$, for the circuit. This voltage ratio is then converted to the masonry resistance which is used to estimate the moisture level in the brick. The masonry resistance is calculated using the equation:

$$Rm = Rs * Rg / (Rg - Rs) \text{ where } Rs = Rf \{(1 - \chi) / \chi)\}.$$

Given that Rg = 1004.4 kohms and Rf = 6.819 kohms, the above equation can be expressed as:

$$Rm = \{(1/\chi -1)*1004.4\}/\{147.294 - (1/\chi -1)\}$$

Table 9.6 MOIST1.PAR

Names of input DATA FILE:	c:\winnipeg\data\DAY93???.DAT,
Name of OUTPUT FILE to generate:	c:\winnipeg\analysis\mo_93???.PRN/r/0
START reading in:	4[10]
STOP reading in:	
COPY from:	1[132]
SELECT elements #: L1	R20=1000.0/avg(75;6)-1.0,
L2	R21=1000.0/avg(72;6)-1.0,
L3	R30=1000.0/avg(74;6)-1.0,
L4	R31=1000.0/avg(73;6)-1.0,
L5	R33=1000.0/avg(82;6)-1.0,
L6	R34=1000.0/avg(78;6)-1.0,
L7	R32=1000.0/avg(76;6)-1.0,
L8	R22=1000.0/avg(84;6)-1.0,
L9	R23=1000.0/avg(81;6)-1.0,
L10	R3=1000.0/avg(80;6)-1.0,
L11	R1=1000.0/avg(79;6)-1.0,
L12	R4=1000.0/avg(83;6)-1.0,
L13	R2=1000.0/avg(77;6)-1.0,
L14	smpl(4;6),
L15	smpl(R20*1004.4/(147.294-R20);6),
L16	smpl(R21*1004.4/(147.294-R21);6),
L17	smpl(R31*1004.4/(147.294-R31);6),
L18	smpl(R30*1004.4/(147.294-R30);6)
L19	smpl(R33*1004.4/(147.294-R33);6),
L20	smpl(R34*1004.4/(147.294-R34);6),
L21	smpl(R32*1004.4/(147.294-R32);6)
L22	smpl(R22*1004.4/(147.294-R22);6),
L23	smpl(R23*1004.4/(147.294-R23);6),
L24	smpl(R3*1004.4/(147.294-R3);6),
L25	smpl(R1*1004.4/(147.294-R1);6)
L26	smpl(R4*1004.4/(147.294-R4);6),
L27	smpl(R2*1004.4/(147.294-R2);6),
L28	avg(42,44,43;6),
L29	smpl(4;6)

It is important to mention that the appearance of the MOIST1.PAR file shown above was slightly modified. The file processing commands are actually divided into four reading of the initial data file due to the limited capacity of the SPLIT program. The first twelve lines in the data selection statement calculate the $(1 - \chi) / \chi$ ratio for the various brick resistance sensors. The ratio, labeled R?, is expressed as $(1/\chi - 1)$ and multiplied by 1000 because of the multiplier used to compensate for the insufficient data output processing of the datalogger. Lines 15 through 27 calculate the averaged masonry resistance using

R?*1004.4/(147.294 - R?). Line 28 is the averaged wetness sensor readings. Lines 14 and 29 read the time.

9.3.3.2 MOIST1.XLM

The EXCEL macro associated with the MO_93???.RPT files is named MOIST1.XLM (Table 9.7). On the worksheet, the data is arranged in columns in the following order: Time, R20, R21, R31, R30, R33, R34, R32, R22, R23, R3, R1, R4, R2, S11, S12, S13, and Time. The macro modifies the resistance readings prior to creating the charts. The first modification eliminates any invalid readings. The brick is considered dry when its resistance is greater than 40 000 kOhms and any reading greater than this is considered irrelevant. Negative resistance readings are also possible as a result of a discontinuity in the equation used to calculate the masonry resistance. This only occurs when the sensors are very dry. Therefore macro is programmed to scan the brick resistance readings and replace any values smaller than 0 or greater than 40 000 kOhms with the value of 40 000. The values are then modified so that the curve becomes more linear, remaining close to zero when the masonry is dry and rising as the moisture levels increase. The macro is programmed to calculate a new set of values using the equation:

$$Rm' = \{A - \log(Rm)\}/B$$

where

$A = 4.61 \approx \log(40\ 000)$, 40 000 kOhms being the highest possible value

$B = 0.16$ a value chosen to create an upper limit of 20 provided that no value is smaller than 16.2 kOhms

There are three charts on the worksheet (Figure 9.3), all located on the second page. The first chart illustrates the variation of the brick moisture levels versus time across the insulated wall section. The second chart illustrates the variation of the brick moisture levels versus time across the uninsulated wall section The third chart, the wetness sensor readings versus time, indicates periods of wetness. The macro is programmed to scan the values in the first two charts for any moisture level readings greater than 2.0. A reading of 2.0 coincides with a masonry resistance value equal to 20 000 kOhms. If the macro finds such a reading, it automatically prints all three charts. Otherwise it simply saves the file without printing any of the charts.

Figure 9.3 Charts produced by macro MOIST1.XLM

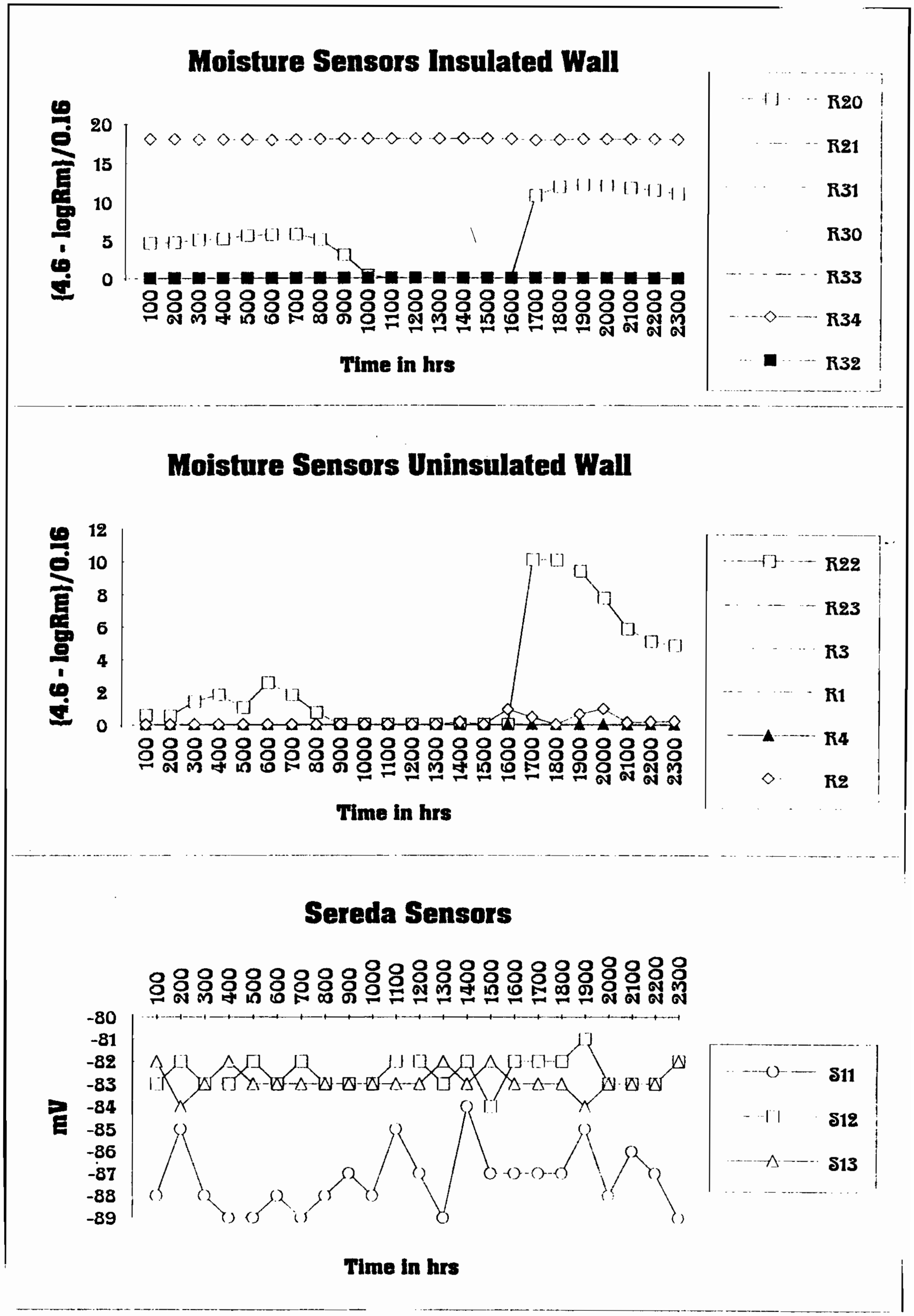


Table 9.7 Macro MOIST1.PAR

```
        C! sets directory
"=DIRECTORY(""C:\WINNIPEG\ANALYSIS"")"
        C! asks which file to open
"=OPEN?(""C:\WINNIPEG\ANALYSIS\MO_93???.RPT"",,,2)"
        C! parses data
"=SELECT(""R7C1:R31C1"")"
"=PARSE(""[100][26207][1638][26207][26207][26207][3823][26207][26207][26207][26207][26207]
[26207][26207][-80][-81][-84][100]"")"
"=SELECT(""R5C1"")"
"=PARSE(""[TIME][R20][R21][R31][R30][R33][R34][R32][R22][R23][R3][R1][R4][R2][S11][S12]
[S13][TIME]"")"
        C! deletes an unwanted line
"=SELECT(""R6C1"")"
=CLEAR(3)
        C! replace all moisture reading greater than 40000 or smaller than 0
"=FOR.CELL(""pointer"",""R7C2:R30C14"",TRUE)"
=IF(VALUE(pointer)<0)
"=FORMULA(40000,pointer)"
=ELSE.IF(VALUE(pointer)>40000)
"=FORMULA(40000,pointer)"
=END.IF()
=NEXT()
        C! Makes a copy of Rm values prior to modifying
"=SELECT(""R5C2:R29C14"")"
=COPY()
"=SELECT(""R5C19"")"
=PASTE()
        C! Calculates the chart values
"=SELECT(""R7C2"")"
"=FORMULA(""=(4.61-LOG(RC[17]))/0.16"")"
=COPY()
"=SELECT(""R7C2:R29C14"")"
=PASTE()
        C! selects data for chart of moisture in the insulated wall
"=SELECT(""R5C1:R29C8"")"
=COPY()
        C! locates chart on the spreadsheet
"=CREATE.OBJECT(5,""R50C1"",1.5,0.75,""R67C10"",0,0,1,TRUE)"
        C! draws the chart
"=CHART.WIZARD(TRUE,""R5C1:R29C8"",4,2,2,1,1,1,""Moisture Sensors Insulated Wall"",""Time in
hrs"",""{4.6 - logRm}/0.16"","""")"
        C! selects data for chart of moisture in the uninsulated wall
"=SELECT(""R5C1:R29C1,R5C9:R29C14"",""R5C9"")"
=COPY()
        C! locates chart on the spreadsheet
"=CREATE.OBJECT(5,""R67C1"",0.75,1.5,""R83C10"",0,0,1,TRUE)"
        C! draws chart
"=CHART.WIZARD(TRUE,""R5C1:R29C1,R5C9:R29C14"",4,2,2,1,1,1,""Moisture Sensors Uninsulated
Wall"",""Time in hrs"",""{4.6 - logRm}/0.16"","""")"
        C! selects data for chart of the Sereda sensors
```

```
"=SELECT(""R5C1:R29C1,R5C15:R29C17"",""R29C15"")"
=COPY()
        C! locates chart on spreadsheet
"=CREATE.OBJECT(5,""R83C1"",1.5,0,""R99C9"",47.25,0,1,TRUE)"
        C! draws chart
"=CHART.WIZARD(TRUE,""R5C1:R29C1,R5C15:R29C17"",4,2,2,1,1,1,""Sereda Sensors"",""Time in hrs"",""mV"","""")"
        C! sets up charts for printing
"=PAGE.SETUP("""",""&R&F"",0.75,0.75,1,1,FALSE,FALSE,FALSE,FALSE,1,1,100,1,1,FALSE)"
        C! checks for moisture
"=SET.NAME(""flag"",0)"
"=FOR.CELL(""currentcell"",""R7C2:R29C14"",TRUE)"
=IF(VALUE(currentcell)>2)
"=SET.NAME(""flag"",1)"
=BREAK()
=END.IF()
=NEXT()
        C! print page displaying the charts
=IF(flag=1)
"=PRINT(2,2,2,1,FALSE,FALSE,1,FALSE,1)"
=END.IF()
        C! asks for the name of file to be saved
"=SAVE.AS?(""C:\WINNIPEG\ANALYSIS\MO_93???.XLS"",1,"""",FALSE,"""",FALSE)"
=CLOSE()
=RETURN()
        C! ends
```

9.3.3.3 MOIST2.PAR

The SPLIT parameter file for the second method is named MOIST2.PAR (Table 9.8) and produces an output file named R&T93???.RPT. It has the same format as MOIST1.PAR and the masonry resistance is calculated in the same manner. The only difference is the additional readings from the thermocouples. Although nearby temperature readings are available for all the brick moisture sensors only the ones with sensors susceptible to low temperature are used.

Table 9.8 MOIST2.PAR

Names of input DATA FILE:	c:\edlog\DAY93???.DAT
Name of OUTPUT FILE to generate:	c:\EDLOG\R&T93???.PRN/r/0
START reading in:	4[10]
STOP reading in:	
COPY from:	1[132]]
SELECT elements #: L1	R20=1000.0/75-1.0,
L2	R21=1000.0/72-1.0,
L3	R30=1000.0/74-1.0,
L4	R31=1000.0/73-1.0,
L5	R33=1000.0/82-1.0,
L6	R34=1000.0/78-1.0,
L7	R32=1000.0/76-1.0,
L8	R22=1000.0/84-1.0,
L9	R23=1000.0/81-1.0,
L10	R3=1000.0/80-1.0,
L11	R1=1000.0/79-1.0,
L12	R4=1000.0/83-1.0,
L13	R2=1000.0/77-1.0,
L14	smpl(4;6),
L15	smpl(R20*1004.4/(147.294-R20);6),
L16	avg(14;6),
L17	smpl(R21*1004.4/(147.294-R21);6),
L18	avg(15;6),
L19	smpl(R31*1004.4/(147.294-R31);6),
L20	avg(17;6),
L21	smpl(R30*1004.4/(147.294-R30);6),
L22	avg(16;6)
L23	smpl(R33*1004.4/(147.294-R33);6),
L24	smpl(R34*1004.4/(147.294-R34);6),
L25	smpl(R32*1004.4/(147.294-R32);6)
L26	smpl(R22*1004.4/(147.294-R22);6),
L27	avg(38;6),
L28	smpl(R23*1004.4/(147.294-R23);6),
L29	avg(34;6),
L30	smpl(R3*1004.4/(147.294-R3);6),
L31	avg(26;6),
L32	smpl(R1*1004.4/(147.294-R1);6),
L33	avg(21;6)
L34	smpl(R4*1004.4/(147.294-R4);6),
L35	smpl(R2*1004.4/(147.294-R2);6),
L36	smpl(42,44,43;6)

Even numbered lines 16 through 22 and odd numbered lines 27 through 33 calculate the averaged thermocouple readings.

9.3.3.4 MOIST2.XLM

The EXCEL macro associated with the second method is named MOIST2.XLM (Table 9.9). On the worksheet, the data is arranged in columns in the following order: Time, R20, T20, R21, T21, R31, T36, R30, T35, R33, R33, R32, R22, T23, R23, T24, R3, T5, R1, T1, R4, R2, S11, S12, and S13. The macro modifies the resistance readings prior to creating the charts in the same manner as MOIST1.XLM. However, after it has replaced the invalid resistance readings and calculated the new values, the macro is programmed to delete any resistance reading from sensors exposed to temperatures below -1°C. It accomplishes this by first scanning the temperature and replacing value greater than -1°C with a value of 1.0 and those smaller than or equal to -1°C with 0.0. It multiplies the modified temperature readings to the new resistance values and then scans the product, deleting all 0.0 values it finds. This results in discontinuities in the chart curves indicating the periods when the temperature is below -1°C for a specific sensor. By comparing the charts produced by the two different methods it should be possible to determine if the resistance readings are valid when temperature is below -1°C. The printing of the charts is handled in the same fashion as in MOIST1.XLM.

Table 9.9 Macro MOIST2.PAR

<u>*C! sets directory and asks which file to open*</u>
"=DIRECTORY(""C:\WINNIPEG\ANALYSIS"")"
"=OPEN?(""C:\WINNIPEG\ANALYSIS\R&T93???.RPT"",,,2)"
<u>*C! parses data*</u>
"=SELECT(""R7C1:R31C1"")"
"=PARSE(""[100][26207][-2.1][2059][3.4][26207][12.5][26207][11.8][26207][2974][26207][26207] [-1.0][26207][4.3][26207][17.1][26207][16.1][26207][26207][-77][-81][-85]"")"
"=SELECT(""R5C1"")"
"=PARSE(""[TIME][R20][T20][R21][T21][R31][T36][R30][T35][R33][R33][R32][R22][T23][R23][T24][R3][T5][R1][T1][R4][R2][S11][S12][S13]"")"
<u>*C! deletes an unwanted line*</u>
"=SELECT(""R6C1"")"
=CLEAR(3)
<u>*C! Makes a copy of values prior to modifying*</u>
"=SELECT(""R5C1:R29C25"")"
=COPY()
"=SELECT(""R5C53"")"
=PASTE()
<u>*C! Replaces all moisture readings greater than 40000 or smaller than 0*</u>
"=FOR.CELL(""current"",""R7C54:R30C54,R7C56:R30C56,R7C58:R30C58,R7C60:R30C60,R7C62:R30C65,R7C67:R29C67,R7C69:R29C69,R7C71:R29C71,R7C73:R29C74"",TRUE)"
=IF(VALUE(current)<0)
"=FORMULA(40000,current)"
=ELSE.IF(current>40000)
"=FORMULA(40000,current)"
=END.IF()
=NEXT()
<u>*C! Makes a reference copy*</u>
"=SELECT(""R5C53:R29C77"")"
=COPY()
"=SELECT(""R5C27"")"
=PASTE()
<u>*C! Calculates the chart values*</u>
"=FOR.CELL(""pointer1"",""R7C28:R29C28,R7C30:R29C30,R7C32:R29C32,R7C34:R29C34,R7C36:R29C39,R7C41:R29C41,R7C43:R29C43,R7C45:R29C45,R7C47:R29C48"",TRUE)"
"=FORMULA(""=(4.61-LOG(RC[26]))/0.16"",pointer1)"
=NEXT()
<u>*C! replaces temperature readings with a zero if it is < -1.0 or with a one if it is greater*</u>
"=FOR.CELL(""currentcell"",""R7C29:R29C29,R7C31:R29C31,R7C33:R29C33,R7C35:R29C35,R7C40:R29C40,R7C42:R29C42,R7C44:R29C44,R7C46:R29C46"",TRUE)"
=IF(currentcell<-1)
"=FORMULA(0,currentcell)"
=ELSE()
"=FORMULA(1,currentcell)"
=END.IF()
=NEXT()
<u>*C! multiplies moisture reading by one or zero now all faulty moisture readings are zero*</u>
"=FOR.CELL(""pointer2"",""R7C2:R29C2,R7C4:R29C4,R7C6:R29C6,R7C8:R29C8,R7C13:R29C13,R7C15:R29C15,R7C17:R29C17,R7C19:R29C19"",TRUE)"
"=FORMULA(""=RC[26]*RC[27]"",pointer2)
=NEXT()

```
        C! deletes faulty moisture reading
"=FOR.CELL(""currentcell2"",""R7C2:R29C2,R7C4:R29C4,R7C6:R29C6,R7C8:R29C8,R7C10:R29C13,
R7C15:R29C15,R7C17:R29C17,R7C19:R29C19,R7C21:R29C22"",TRUE)"
=IF(currentcell2=0)
"=FORMULA("""",currentcell2)"
=END.IF()
=NEXT()
        C! Calculates the chart values
"=FOR.CELL(""pointer3"",""R7C10:R29C13,R7C21:R29C22"",TRUE)"
"=FORMULA(""=(4.61-LOG(RC[52]))/0.16"",pointer3)"
=NEXT()
        C! selects data for chart of moisture in the insulated wall
"=SELECT(""R5C1:R29C2,R5C4:R29C4,R5C6:R29C6,R5C8:R29C8,R5C10:R29C12"",""R5C10"")"
=COPY()
        C! locates chart on the spreadsheet and draws the chart
"=CREATE.OBJECT(5,""R49C1"",0.75,0,""R66C10"",0,12,1,TRUE)"
"=CHART.WIZARD(TRUE,""R5C1:R29C2,R5C4:R29C4,R5C6:R29C6,R5C8:R29C8,R5C10:R29C12"",4
,2,2,1,1,1,""Moisture Sensors Insulated Wall"",""Time"",""{4.61 - logRm}/0.16"","""")"
        C! selects data for chart of moisture in the uninsulated wall
"=SELECT(""R5C1:R29C1,R5C13:R29C13,R5C15:R29C15,R5C17:R29C17,R5C19:R29C19,R5C21:R29
C22"",""R5C21"")"
=COPY()
        C! locates chart on the spreadsheet and draws chart
"=CREATE.OBJECT(5,""R67C1"",0.75,0.75,""R83C10"",0,0,1,TRUE)"
"=CHART.WIZARD(TRUE,""R5C1:R29C1,R5C13:R29C13,R5C15:R29C15,R5C17:R29C17,R5C19:R29
C19,R5C21:R29C22"",4,2,2,1,1,1,""Moisture Sensors Uninsulated Wall"",""Time"",""{4.61 -
logRm}/0.16"","""")"
        C! selects data for chart of the Sereda sensors
"=SELECT(""R5C1:R29C1,R5C23:R29C25"",""R5C23"")"
=COPY()
        C! locates chart on spreadsheet and draws chart
"=CREATE.OBJECT(5,""R83C1"",0.75,0.75,""R99C10"",0,0,1,TRUE)"
"=CHART.WIZARD(TRUE,""R5C1:R29C1,R5C23:R29C25"",4,2,2,1,1,1,""Sereda
Sensors"",""Time"",""mV"","""")"
        C! sets page set up for printing
"=PAGE.SETUP("""",""&R&F"",0.75,0.75,1,1,FALSE,FALSE,FALSE,FALSE,1,1,100,1,1,FALSE)"
        C! checks for moisture
"=SET.NAME(""flag"",0)"
"=FOR.CELL(""currentcell3"",""R7C2:R29C2,R7C4:R29C4,R7C6:R29C6,R7C8:R29C8,R7C10:R29C13,
R7C15:R29C15,R7C17:R29C17,R7C19:R29C19,R7C21:R29C22"",TRUE)"
=IF(VALUE(currentcell3)>2)
"=SET.NAME(""flag"",1)"
=BREAK()
=END.IF()
=NEXT()
        C! print page displaying the charts
=IF(flag=1)
"=PRINT(2,2,2,1,FALSE,FALSE,1,FALSE,1)"
=END.IF()
        C! asks for the name of file to be saved
"=SAVE.AS?(""C:\WINNIPEG\ANALYSIS\R&T93???.XLS"",1,"""",FALSE,"""",FALSE)"
=RETURN()
```

9.3.4 Rain Wetting of Exterior Wall

This area of analysis monitors rain wetting of the exterior wall. The relevant sensors are: the rain gauges RG1and 2, the wetness sensor S1, the brick resistance sensors R 20 and 22, and the pressure transducer. The data is not averaged. In addition to the principal data processing file for this area of analysis, there is a file with the summary of the pressure differential for the entire week.

9.3.4.1 RAIN.PAR

The SPLIT parameter file for the principal data processing is named RAIN.PAR (Table 9.10) and produces an output file named RN_93???.RPT. The masonry resistance is calculated in the same manner as in the MOIST1.PAR parameter file

Table 9.10 RAIN.PAR

Names of input DATA FILE:	c:\winnipeg\data\DAY93???.DAT
Name of OUTPUT FILE to generate:	c:\winnipeg\analysis\rn_93???.PRN/R/0
START reading in:	4[10]
STOP reading in:	
COPY from:	1[132]
SELECT elements #: L1	R20=1000.0/75-1.0,
L2	R22=1000.0/84-1.0,
L3	4,
L4	5*3.6,
L5	6*9.2,
L6	46,
L7	1004.4*R20/(147.294-R20),
L8	1004.4*R22/(147.294-R22),
L9	85

The first two lines in the data selection statement calculate the ($1/\chi$ -1) ratio for the two brick resistance sensors. Line 3 reads the time. Lines 4 and 5 read the pulse count from the two rain gauges and multiplies them by the water volume per count. Line 6 reads the wetness sensor. Lines 7 and 8 calculate the masonry resistance using R?*1004.4/(147.294 - R?). Finally, line nine 9 the pressure differential.

9.3.4.2 RAIN.XLM

The EXCEL macro associated with the RN_93???.RPT files is named RAIN.XLM (Table 9.11). On the worksheet, the data is arranged in columns in the following order: Time, RG1, RG2, S1, R20, R22, and Pressure. The macro modifies the resistance readings prior to creating the charts in the same manner as MOIST1.XLM. There are four charts on the worksheet (Figure 9.4), all located on the fifth page. The first is a simple bar chart showing the amount of rainfall on the wall versus time. The second chart, showing the wetness sensor readings versus time, indicates periods of wetness. The third illustrates the variation of the exterior surface brick moisture levels. The fourth chart is the pressure differential reading versus time. The macro is programmed to scan the rain gauge readings for any values greater than zero and scan the moisture reading for values greater than 2.0. If it finds one, it will automatically print all four charts. Otherwise it will simply save the file without printing any of the charts.

Figure 9.4 Charts produced by macro RAIN.XLM

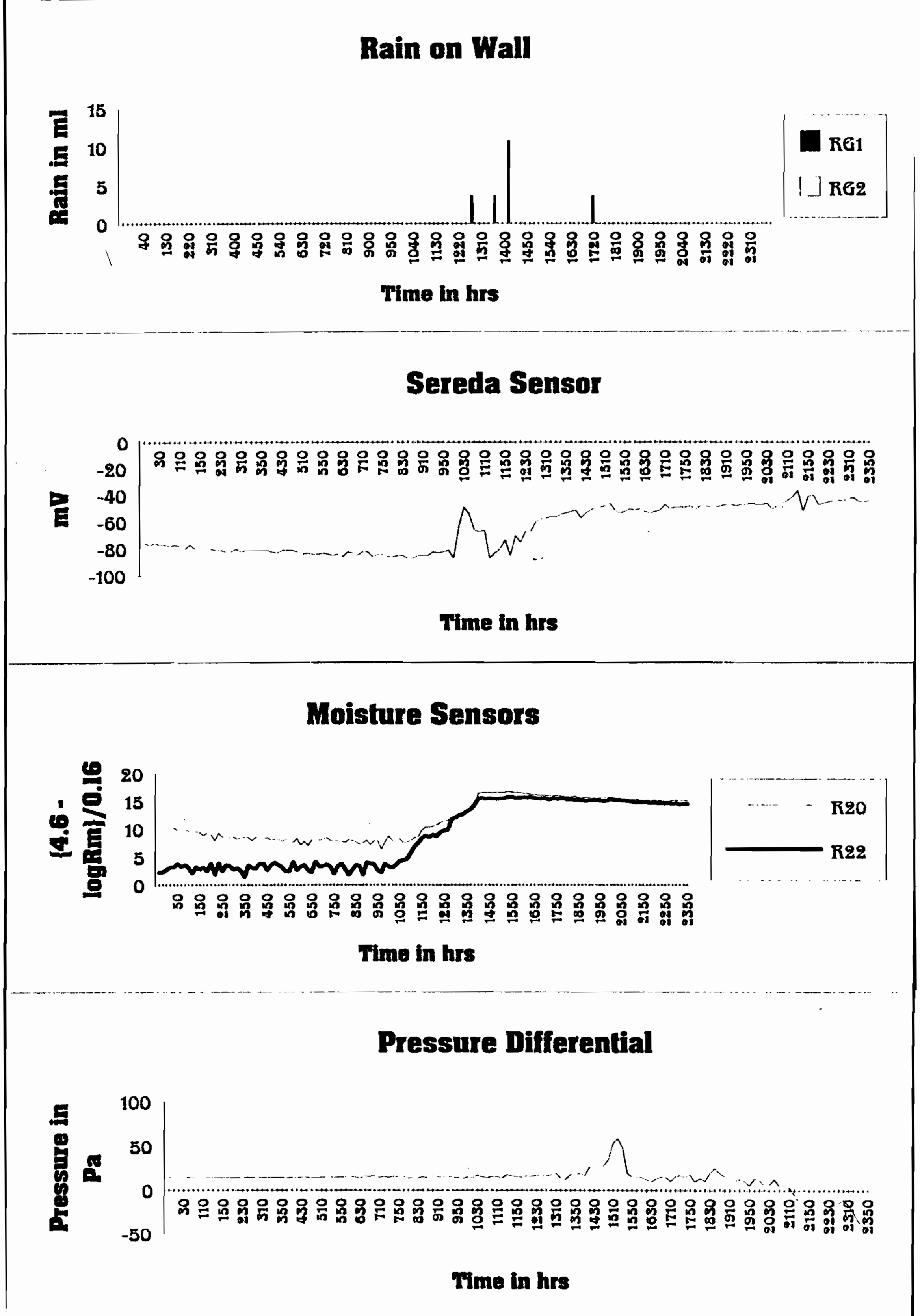


Table 9.11 Macro RAIN.XLM

```
        C! sets directory and asks which file to open
"=DIRECTORY(""C:\WINNIPEG\ANALYSIS"")"
"=OPEN?(""C:\WINNIPEG\ANALYSIS\RN_93???.RPT"",,,2)"
        C! clears page break created by SPLIT
"=SELECT(""R58C1:R66C1"")"
=CLEAR(1)
"=SELECT(""R118C1:R126C1"")"
=CLEAR(1)
"=SELECT(""R169C1:R180C1"")"
=CLEAR(1)
        C! cuts & pastes to join data divided by page breaks
"=SELECT(""R127C1:R168C1"",""R168C1"")"
=CUT()
"=SELECT(""R118C1"")"
=PASTE()
"=SELECT(""R67C1:R159C1"",""R159C1"")"
=CUT()
"=SELECT(""R58C1"")"
=PASTE()
        C! parses data
"=SELECT(""R7C1:R150C1"")"
"=PARSE(""[0][0.0][0.0][-82][26207][26207][13.9]"")"
"=SELECT(""R5C1"")"
"=PARSE(""[TIME][RG1][RG2][S1][R20][R22][PRES]"")"
        C! deletes unwanted dividing line
"=SELECT(""R6C1"")"
=CLEAR(3)
        C! replaces all moisture readings greater than 40000 or smaller than 0
"=FOR.CELL(""pointer"",""R7C5:R154C6"",TRUE)"
=IF(VALUE(pointer)<0)
"=FORMULA(40000,pointer)"
=ELSE.IF(VALUE(pointer)>40000)
"=FORMULA(40000,pointer)"
=END.IF()
=NEXT()
        C! Makes a copy of Rm values prior to modifying
"=SELECT(""R5C5:R150C6"",""R150C6"")"
=COPY()
"=SELECT(""R5C8"")"
=PASTE()
        C! Calculates the chart values
"=SELECT(""R7C5"")"
"=FORMULA(""=(4.61-LOG(RC[3]))/0.16"")"
=COPY()
"=SELECT(""R7C5:R150C6"")"
=PASTE()
        C! selects data for chart of rain fall
"=SELECT(""R5C1:R150C3"")"
=COPY()
        C! locates chart on the spreadsheet
```

```
"=CREATE.OBJECT(5,""R1C10"",0.75,1.5,""R12C19"",0,12,1,TRUE)"
        C! draws the chart
"=CHART.WIZARD(TRUE,""R5C1:R150C3"",3,1,2,1,1,1,""Rain on Wall"",""Time in hrs"",""Rain in ml"","""")"
        C! selects data for chart of Sereda sensor
"=SELECT(""R5C1:R150C1,R5C4:R150C4"",""R150C4"")"
=COPY()
        C! locates chart on the spreadsheet
"=CREATE.OBJECT(5,""R13C10"",0.75,0.75,""R25C19"",0,0,1,TRUE)"
        C! draws the chart
"=CHART.WIZARD(TRUE,""R5C1:R150C1,R5C4:R150C4"",4,2,2,1,1,2,""Sereda Sensor"",""Time in hrs"",""{4.61 - logRm}/0.16"","""")"
        C! selects data for chart of moisture sensors
"=SELECT(""R5C1:R150C1,R5C5:R150C6"",""R150C5"")"
=COPY()
        C! locates chart on the spreadsheet
"=CREATE.OBJECT(5,""R25C10"",0.75,0.75,""R36C19"",0,0,1,TRUE)"
        C! draws the chart
"=CHART.WIZARD(TRUE,""R5C1:R150C1,R5C5:R150C6"",4,2,2,1,1,1,""Moisture Sensors"",""Time in hrs"",""{4.6 - logRm}/0.16"","""")"
        C! selects data for chart of pressure differential
"=SELECT(""R5C1:R150C1,R5C7:R150C7"",""R150C7"")"
=COPY()
        C! locates chart on the spreadsheet
"=CREATE.OBJECT(5,""R36C10"",0.75,0.75,""R49C18"",47.25,12,1,TRUE)"
        C! draws the chart
"=CHART.WIZARD(TRUE,""R5C1:R150C1,R5C7:R150C7"",4,2,2,1,1,2,""Pressure Differential"",""Time in hrs"",""Pressure in Pa"","""")"
        C! sets up charts for printing
"=PAGE.SETUP("""",""&R&F"",0.75,0.75,1,1,FALSE,FALSE,FALSE,FALSE,1,1,100,1,1,FALSE)"
        C! checks for rainfall
"=SET.NAME(""flag"",0)"
"=FOR.CELL(""currentcell"",""R7C2:R150C3"",TRUE)"
=IF(VALUE(currentcell)>0)
"=SET.NAME(""flag"",1)"
=BREAK()
=END.IF()
=NEXT()
        C! checks for moisture
"=FOR.CELL(""currentcell"",""R7C5:R150C6"",TRUE)"
=IF(VALUE(currentcell)>2)
"=SET.NAME(""flag"",1)"
=BREAK()
=END.IF()
=NEXT()
        C! prints page dispalying the charts
=IF(flag=1)
"=PRINT(2,5,5,1,FALSE,FALSE,1,FALSE,1)"
=END.IF()
        C! asks name of file to be saved
"=SAVE.AS?(""C:\WINNIPEG\ANALYSIS\RN_93???.XLS"",1,"""",FALSE,"""",FALSE)"
=RETURN()
```

9.3.4.3 WIND.PAR

The SPLIT parameter file for the weekly summary of the pressure differential is named WIND.PAR (Table 9.12) and produces an output file named PD_93???.RPT. It accesses the seven daily data files and copies the date, time and pressure differential readings to the output file. The data is not modified or averaged.

Table 9.12 WIND.PAR

Names of input DATA FILE:	c:\winnipeg\data\DAY93???.DAT, c:\winnipeg\data\DAY93???.DAT, c:\winnipeg\data\DAY93???.DAT, c:\winnipeg\data\DAY93???.DAT, c:\winnipeg\data\DAY93???.DAT, c:\winnipeg\data\DAY93???.DAT, c:\winnipeg\data\DAY93???.DAT
Name of OUTPUT FILE to generate:	c:\winnipeg\analysis\PD_93???.PRN/0/r
START reading in:	
STOP reading in:	
COPY from:	1[204]
SELECT elements #: L1	4,
L2	Edate(3;2),
L3	5

The first line in the data selection statement reads the time. The second reads the Julian date and converts it to day and month. The last line is the pressure differential reading.

9.3.4.4 WIND.XLM

The EXCEL macro associated with the PD_93???.RPT files is named WIND.XLM (Table 9.13). On the worksheet, the data is arranged in columns in the following order: Time followed by the pressure differential readings for Monday through Sunday. The macro does not modify the pressure differential readings in any way. The data is rearranged so that the date is located at the top of the column of pressure differential readings for the day. There are seven charts on the worksheet, located on page five through seven. They are the pressure differential readings versus time for each day of the week. There is no specific event for which the charts should be printed. Rather a sample print out at regular intervals is sufficient. The print command of the macro has therefore been disabled by deleting the = signs that preceded it. If automatic printing of the charts is desired simply add an = sign in front of the command.

Table 9.13 WIND.XLM

```
        C! sets directory
"=DIRECTORY(""C:\WINNIPEG\ANALYSIS"")"
        C! asks which file to open
"=OPEN?(""C:\WINNIPEG\ANALYSIS\PD_93???.RPT"",,,2)"
        C! deletes page break created by SPLIT
"=SELECT(""R58C1:R66C1"")"
=CLEAR(3)
"=SELECT(""R118C1:R126C1"")"
=CLEAR(3)
        C! cuts & pastes to join data divided by page breaks
"=SELECT(""R127C1:R168C1"",""R168C1"")"
=CUT()
"=SELECT(""R118C1"")"
=PASTE()
"=SELECT(""R67C1:R159C1"",""R159C1"")"
=CUT()
"=SELECT(""R58C1"")"
=PASTE()
        C! parses data
"=SELECT(""R7C1:R150C1"")"
"=PARSE(""[0][26 4][16.01][27 4][15.43][28 4][14.77][29 4][14.59][30 4][15.79][1 5][13.79][2 5]
[13.43][0]"")"
"=SELECT(""R5C1"")"
"=PARSE(""[TIME][DATE][PRES][DATE][PRES][DATE][PRES][DATE][PRES][DATE][PRES]
[DATE][PRES][DATE][PRES][TIME]"")"
        C! deletes an unwanted line
"=SELECT(""R6C1"")"
=CLEAR(3)
        C! copies the date to the column heading for the pressure differential
"=SELECT(""R7C2"")"
=COPY()
"=SELECT(""R5C3"")"
=PASTE()
"=SELECT(""R7C4"")"
=COPY()
"=SELECT(""R5C5"")"
=PASTE()
"=SELECT(""R7C6"")"
=COPY()
"=SELECT(""R5C7"")"
```

```
=PASTE()
"=SELECT(""R7C8"")"
=COPY()
"=SELECT(""R5C9"")"
=PASTE()
"=SELECT(""R7C10"")"
=COPY()
"=SELECT(""R5C11"")"
=PASTE()
"=SELECT(""R7C12"")"
=COPY()
"=SELECT(""R5C13"")"
=PASTE()
"=SELECT(""R7C14"")"
=COPY()
"=SELECT(""R5C15"")"
=PASTE()
        C! Cuts & pastes data series together
"=SELECT(""R5C15:R150C16"",""R5C16"")"
=CUT()
"=SELECT(""R5C14"")"
=PASTE()
"=SELECT(""R5C13:R150C15"")"
=CUT()
"=SELECT(""R5C12"")"
=PASTE()
"=SELECT(""R5C11:R150C14"")"
=CUT()
"=SELECT(""R5C10"")"
=PASTE()
"=SELECT(""R5C9:R150C13"")"
=CUT()
"=SELECT(""R5C8"")"
=PASTE()
"=SELECT(""R5C7:R150C12"")"
=CUT()
"=SELECT(""R5C6"")"
=PASTE()
"=SELECT(""R5C5:R150C11"",""R5C11"")"
=CUT()
"=SELECT(""R5C4"")"
=PASTE()
"=SELECT(""R5C3:R150C10"",""R5C10"")"
=CUT()
"=SELECT(""R5C2"")"
=PASTE()
        C! selects data for chart
        C! locates chart on spreadsheet
        C! draws chart
"=SELECT(""R5C1:R150C2"")"
=COPY()
"=CREATE.OBJECT(5,""R1C10"",0.75,1.5,""R16C18"",47.25,12,1,TRUE)"
"=CHART.WIZARD(TRUE,""R5C1:R150C2"",4,2,2,1,1,1,""Pressure Differential"",""Time"",""Pressure in Pa"","""")"
```

```
"=SELECT(""R5C1:R150C1,R5C3:R150C3"",""R150C3"")"
=COPY()
"=CREATE.OBJECT(5,""R17C10"",1.5,0.75,""R33C18"",0,0,1,TRUE)"
"=CHART.WIZARD(TRUE,""R5C1:R150C1,R5C3:R150C3"",4,2,2,1,1,1,""Pressure
Differential"",""Time"",""Pressure in Pa"","""")"
"=SELECT(""R5C1:R150C1,R5C4:R150C4"",""R150C4"")"
=COPY()
"=CREATE.OBJECT(5,""R33C10"",2.25,1.5,""R50C18"",0,0,1,TRUE)"
"=CHART.WIZARD(TRUE,""R5C1:R150C1,R5C4:R150C4"",4,2,2,1,1,1,""Pressure
Differential"",""Time"",""Pressure in Pa"","""")"
"=SELECT(""R5C1:R150C1,R5C5:R150C5"",""R150C5"")"
=COPY()
"=CREATE.OBJECT(5,""R50C10"",2.25,1.5,""R67C18"",0,0,1,TRUE)"
"=CHART.WIZARD(TRUE,""R5C1:R150C1,R5C5:R150C5"",4,2,2,1,1,1,""Pressure
Differential"",""Time"",""Pressure in Pa"","""")"
"=SELECT(""R5C1:R150C1,R5C6:R150C6"",""R150C6"")"
=COPY()
"=CREATE.OBJECT(5,""R67C10"",1.5,0.75,""R82C18"",0,12,1,TRUE)"
"=CHART.WIZARD(TRUE,""R5C1:R150C1,R5C6:R150C6"",4,2,2,1,1,1,""Pressure
Differential"",""Time"",""Pressure in Pa"","""")"
"=SELECT(""R5C1:R150C1,R5C7:R150C7"",""R150C7"")"
=COPY()
"=CREATE.OBJECT(5,""R83C10"",1.5,0.75,""R99C18"",0,0,1,TRUE)"
"=CHART.WIZARD(TRUE,""R5C1:R150C1,R5C7:R150C7"",4,2,2,1,1,1,""Pressure
Differential"",""Time"",""Pressure in Pa"","""")"
"=SELECT(""R5C1:R150C1,R5C8:R150C8"",""R150C8"")"
=COPY()
"=CREATE.OBJECT(5,""R99C10"",0.75,0.75,""R115C18"",0,12,1,TRUE)"
"=CHART.WIZARD(TRUE,""R5C1:R150C1,R5C8:R150C8"",4,2,2,1,1,1,""Pressure
Differential"",""Time"",""Pressure in Pa"","""")"
        C! sets up charts for printing
"=SELECT(""Chart 2"")"
"=FORMAT.SIZE(0,0,""R33C19"")"
"=SELECT(""Chart 3"")"
"=FORMAT.SIZE(0,0,""R50C19"")"
"=SELECT(""Chart 4"")"
"=FORMAT.SIZE(0,0,""R67C19"")"
"=SELECT(""Chart 5"")"
"=FORMAT.SIZE(0,12,""R82C19"")"
"=SELECT(""Chart 6"")"
"=FORMAT.SIZE(0.75,0,""R99C19"")"
"=SELECT(""Chart 7"")"
"=FORMAT.SIZE(0,12,""R115C19"")"
"=PAGE.SETUP("""",""&R&F"",0.75,0.75,1,1,FALSE,FALSE,FALSE,FALSE,1,1,100,1,1,FALSE)"
        C! prints pages displaying charts
"PRINT(2,5,7,1,FALSE,FALSE,1,FALSE,1)"
        C! asks for name of file to be saved
"=SAVE.AS?(""C:\WINNIPEG\ANALYSIS\PD_93???.XLS"",1,"""",FALSE,"""",FALSE)"
=RETURN()
        C! end
```

9.3.5 Thermal Bridges and Condensation

This area of analysis is concerned with thermal bridges and condensation. The relevant sensors are: the wetness sensors S2 and S3; the temperature readings from the relative humidity and temperature sensors RHT13 and RHT14; and the thermocouples T 1, 2, 5-10, 11-12, 22, 25, 35-36, 41-42, and 45-48. The data is averaged over sixty minute periods. The data processing is divided into two parts.

9.3.5.1 TBC1.PAR

The first part calculates the dew point temperature and compares it to the thermal gradient of the insulated and uninsulated wall section to check for possible condensation. It also checks the window surface and steel lintels for condensation. The SPLIT parameter file is named TBC1.PAR (Table 9.14) and produces an output file named TB93???a.RPT. The dew point temperature is calculated from the relative humidity and temperature of the RHT sensors. First, the water vapor pressure at saturation is calculated using the equation:

Pws = exp.{-5800.22206/T+1.3914993-0.048640239*T
+0.000041764768*T^2.0-0.000000014452093*T^3.0
+6.5459673*ln(T)}

where T is the temperature in degrees Kelvin.

Then the partial water vapor pressure is calculated using the equation:

Pw = ln(Pws*RH/100.0)   where RH is the relative humidity in percent.

Finally, the dew point temperature is obtained using the equation:

DewPt = -35.957-1.8726*Pw+1.16893*Pw^2.0.

These equations are valid only if the temperature is above 0°C.

Table 9.14 TBC1.PAR

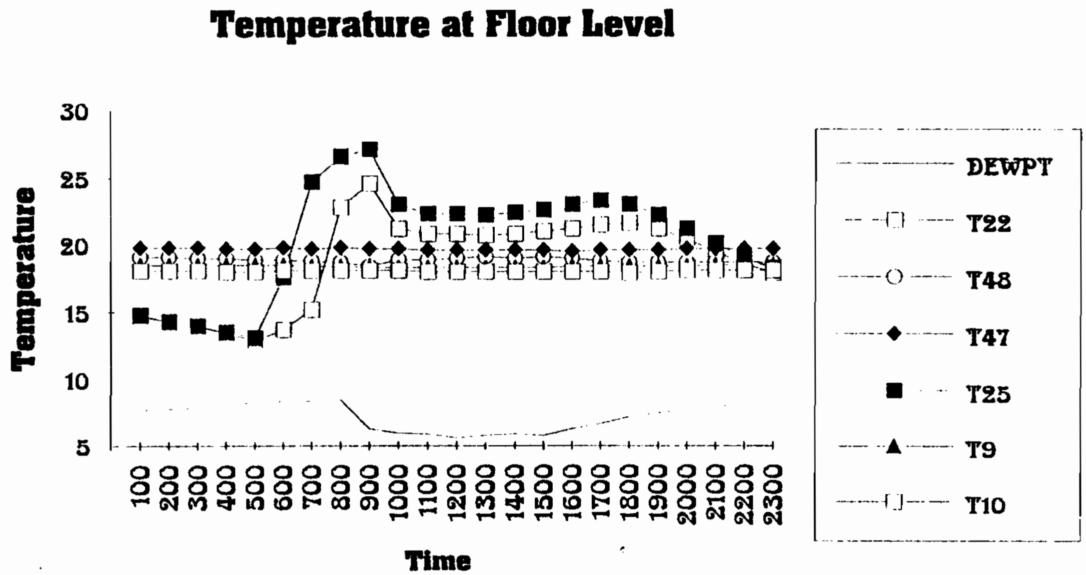
Names of input DATA FILE:		c:\winnipeg\data\DAY93???.DAT
Name of OUTPUT FILE to generate:		C:\winnipeg\analysis\TB93???a.PRN/0/R
START reading in:		4[10]
STOP reading in:		
COPY from:		1[132]
SELECT elements #:	L1	T=avg(47;6)+273.1596,
	L2	P = exp(-5800.22206/T+1.3914993-0.048640239*T + 0.000041764768*T^2.0 -0.000000014452093 *T^3.0 + 6.5459673*ln(T)),
	L3	A=ln(P*avg(48;6)/100.0),
	L4	D=-35.957-1.8726*A+1.16893*A^2.0,
	L5	smpl(4;6),
	L6	avg(47,48;6),
	L7	smpl(D;6)
	L8	avg(18,33,36,31,12,10,35,22,20,41,11,45,9;6)

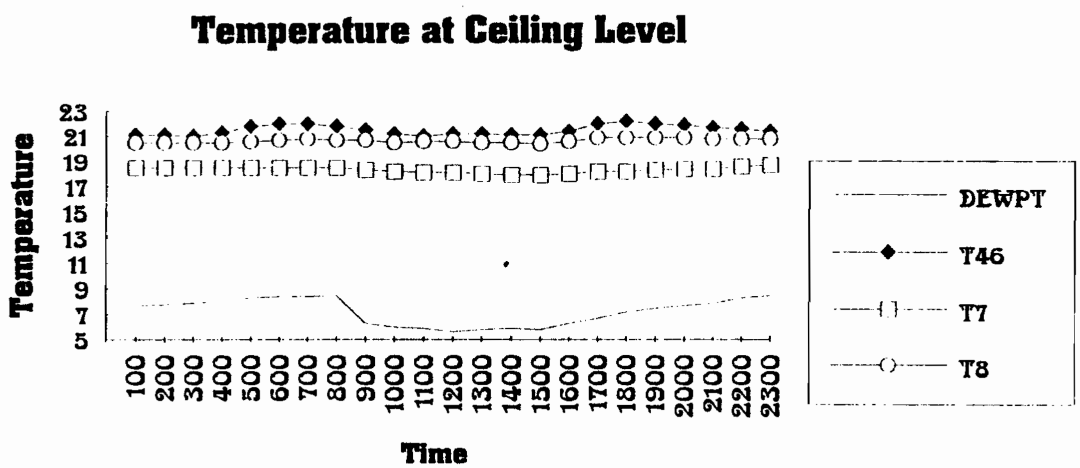
The first line of the data selection statement converts the averaged temperature reading from the RHT sensor into degrees Kelvin. The second line calculates Pws. The third line calculates Pw using the averaged relative humidity reading from the RHT sensor. Line 4 then calculates the dew point temperature. Line 5 reads the time. Line 6 reads the average temperature and relative humidity. Line 7 reads the averaged dew point temperature. The last line reads the averaged wetness sensor readings and the averaged temperatures from the thermocouples.

9.3.5.2 TBC1.XLM

The EXCEL macro associated with the TB93???a.RPT files is named TBC1.XLM (Table 9.15). On the worksheet, the data is arranged in columns in the following order: Time, RHT13T, RHT13H, DEWPT, T22, T48, T47, T25, T9, T10, T46, T7, T8, S2, T11, S3, T12. The macro does not modify the readings in any way. There are four charts on the worksheet (Figure 9.6), located on page two and three. The first chart compares the variation of the dew point temperature and surface temperatures versus time at the floor level of both the insulated and uninsulated wall sections. The second chart compares the variation of the dew point temperature and surface temperatures versus time at the ceiling level of both the insulated and uninsulated wall sections. The third chart shows the variation of the dew point temperature and surface temperatures of the window and steel lintel. The fourth chart, showing the wetness sensor readings versus time, indicates condensation on the window surface and steel lintel. The macro is programmed to scan for temperature readings that exceed the dew point temperature. It does this first for the two wall sections and then for the window surface and the steel lintel. If it finds one, it automatically prints the relevant charts. Otherwise it simply saves the file without printing any of the charts.

Figure 9.5 Charts produced by macro TBC1.XLM





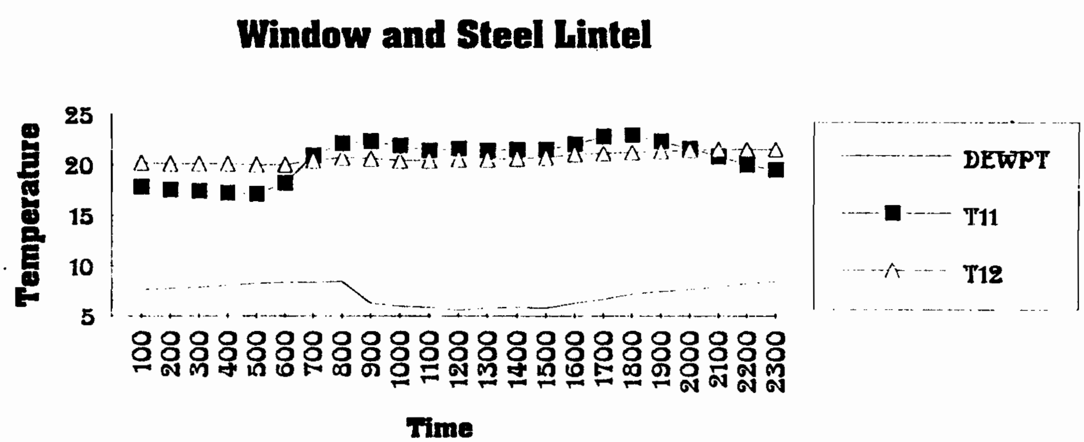


Table 9.15 Macro TBC1.XLM

```
        C! asks which file to open
"=OPEN?(""C:\WINNIPEG\ANALYSIS\TB93???a.RPT"")"
        C! parses data
"=SELECT(""R6C1:R30C1"")"
"=PARSE(""[100][20.8][16][-5.0][1.3][14.9][17.6][1.6][16.7][16.1][22.4][19.0][19.6][-88][12.0][-84]
[17.6]"")"
"=SELECT(""R4C1"")"
"=PARSE(""[TIME][RHT13T][RHT13H][DEWPT][T22][T48][T47][T25][T9][T10][T46][T7][T8][S2]
[T11][S3][T12]"")"
        C! deletes an unwanted line
"=SELECT(""R5C1"")"
=CLEAR(3)
        C! selects data for chart 1
"=SELECT(""R4C1:R28C1,R4C4:R28C10"",""R4C4"")"
=COPY()
        C! locates chart on spreadsheet
"=CREATE.OBJECT(5,""R50C1"",0.75,0.75,""R76C10"",0,0,1,TRUE)"
        C! draws graph
"=CHART.WIZARD(TRUE,""R4C1:R28C1,R4C4:R28C10"",4,2,2,1,1,1,""Temperature at Floor
Level"",""Time"",""Temperature"","""")"
        C! selects data for chart 2
"=SELECT(""R4C1:R28C1,R4C4:R28C4,R4C11:R28C13"",""R4C11"")"
=COPY()
        C! locates chart on spreadsheet
"=CREATE.OBJECT(5,""R76C1"",0.75,0.75,""R99C10"",0,0,1,TRUE)"
        C! draws graph
"=CHART.WIZARD(TRUE,""R4C1:R28C1,R4C4:R28C4,R4C11:R28C13"",4,2,2,1,1,1,""Temperature at
Ceiling Level"",""Time"",""Temperature"","""")"
        C! selects data for chart 3
"=SELECT(""R4C1:R28C1,R4C4:R28C4,R4C15:R28C15,R4C17:R28C17"",""R28C17"")"
=COPY()
        C! locates chart on spreadsheet
"=CREATE.OBJECT(5,""R99C1"",0.75,0.75,""R125C10"",0,0,1,TRUE)"
        C! draws graph
"=CHART.WIZARD(TRUE,""R4C1:R28C1,R4C4:R28C4,R4C15:R28C15,R4C17:R28C17"",4,2,2,1,1,1,""
Window and Steel Lintel"",""Time"",""Temperature"","""")"
        C! selects data for chart 4
"=SELECT(""R4C14:R28C14,R4C16:R28C16,R4C1:R28C1"",""R4C1"")"
=COPY()
        C! locates chart on spreadsheet
"=CREATE.OBJECT(5,""R125C1"",1.5,0.75,""R148C10"",0,0,1,TRUE)"
        C! draws graph
"=CHART.WIZARD(TRUE,""R4C1:R28C1,R4C14:R28C14,R4C16:R28C16"",4,2,2,1,1,1,""Sereda
Sensors"",""Time"",""mV"","""")"
        C! sets up charts for printing
"=PAGE.SETUP("""",""&R&F"",0.75,0.75,1,1,FALSE,FALSE,FALSE,FALSE,1,1,100,1,1,FALSE)"
"=SET.NAME(""flag1"",0)"
"=FOR.CELL(""dewpt"",""R6C4:R28C4"",TRUE)"
"=FOR.CELL(""currentcell"",""R6C6:R28C9,R6C11:R28C13"",TRUE)"
=IF(currentcell<dewpt)
```

```
"=SET.NAME(""flag1"",1)"
=BREAK()
=END.IF()
=NEXT()
=IF(flag1=1)
=BREAK()
=END.IF()
=NEXT()
        C! prints pages displaying charts
=IF(flag1=1)
"=PRINT(2,2,2,1,FALSE,FALSE,1,FALSE,1)"
=END.IF()
        C! checks for condensation
"=SET.NAME(""flag2"",0)"
"=FOR.CELL(""dewpt2"",""R6C4:R28C4"",TRUE)"
"=FOR.CELL(""currentcell2"",""R6C15:R28C15,R6C17:R28C17"",TRUE)"
=IF(currentcell2<dewpt2)
"=SET.NAME(""flag2"",1)"
=BREAK()
=END.IF()
=NEXT()
=IF(flag2=1)
=BREAK()
=END.IF()
=NEXT()
        C! prints pages displaying charts
=IF(flag2=1)
"=PRINT(2,3,3,1,FALSE,FALSE,1,FALSE,1)"
=END.IF()
        C! asks for name of chart to be saved
"=SAVE.AS?(""C:\WINNIPEG\ANALYSIS\TB93???a.XLS"",1,"""""",FALSE,"""""",FALSE)"
=CLOSE()
=RETURN()
        C! end
```

9.3.5.3 TBC2.PAR

The second part of the data processing calculates the dew point temperature for the insulated wall cavity and checks for possible condensation. It also monitors the effects of the steel columns on the thermal gradient of both the insulated and uninsulated wall sections. The SPLIT parameter file is named TBC2.PAR (Table 9.16) and produces an output file named TB93???b.RPT. The dew point temperature is calculated in the same fashion as in TBC1.PAR.

Table 9.16 TBC2.PAR

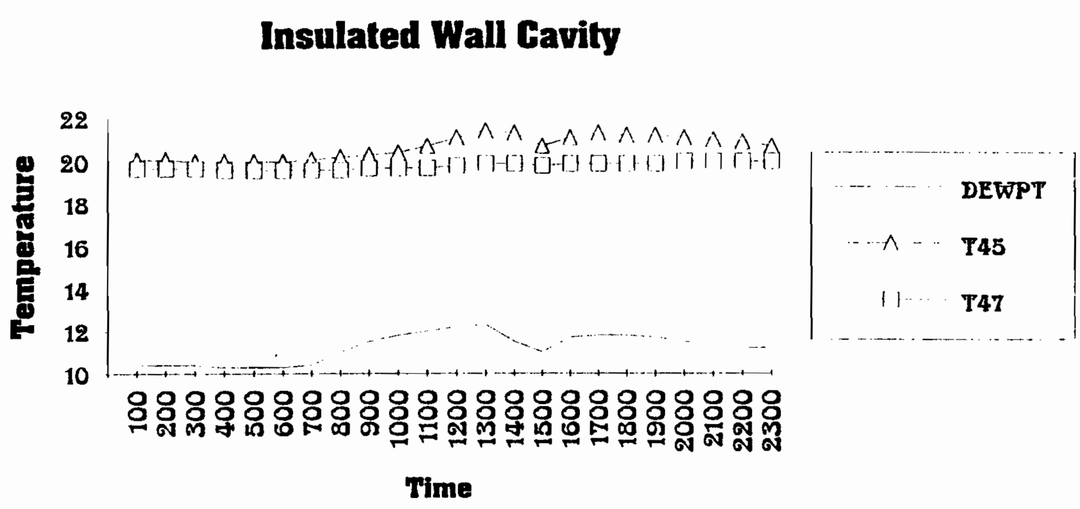
Names of input DATA FILE:		c:\winnipeg\data\DAY93???.DAT
Name of OUTPUT FILE to generate:		C:\winnipeg\analysis\TB93???b.PRN/0/R
START reading in:		4[10]
STOP reading in:		
COPY from:		1[132]
SELECT elements #:	L1	T=avg(49;6)+273.1596,
	L2	P=exp(-5800.22206/T+1.39149930.048640239*T +0.000041764768*T^2.0-0.000000014452093 *T^3.0+6.5459673*ln(T)),
	L3	A=ln(P*avg(50;6)/100.0),
	L4	D=-35.957-1.8726*A+1.16893*A^2.0,
	L5	smpl(4;6),
	L6	avg(49,50;6),
	L7	smpl(D;6)
	L8	avg(30,36,24,23,16,17,39,32,21,26;6)

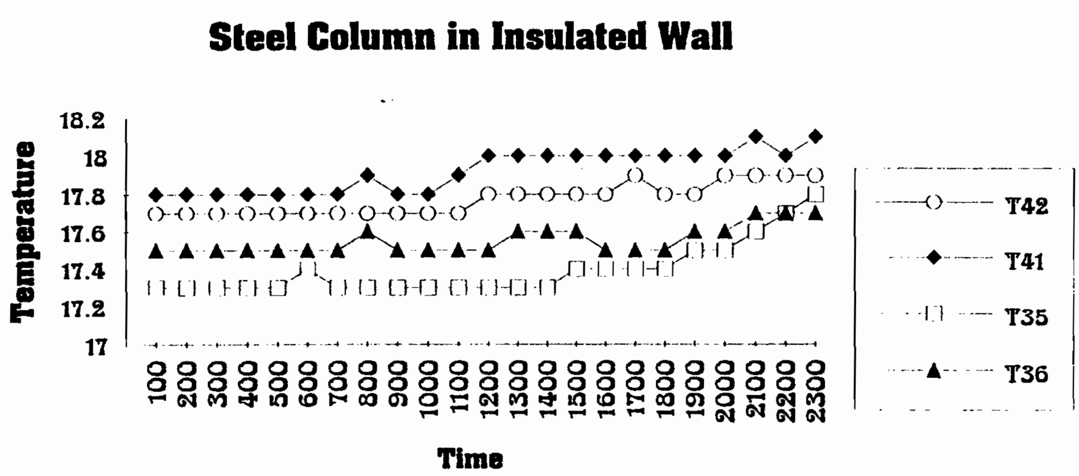
The first line of the data selection statement converts the averaged temperature reading from the relative humidity and temperature sensor into degrees Kelvin. The second line calculates the water vapor pressure at saturation. The third line calculates the partial water vapor pressure using the averaged relative humidity reading from the relative humidity and temperature sensor. Line 4 then calculates the dew point temperature. Line 5 reads the time. Line 6 reads the averaged temperature and relative humidity. Line 7 reads the averaged dew point temperature. The last line reads the averaged temperatures from the thermocouples.

9.3.5.4 TBC2.XLM

The EXCEL macro associated with the TB93???b.RPT files is named TBC2.XLM (Table 9.17). On the worksheet, the data is arranged in columns in the following order: Time, RHT14T, RHT14H, DEWPT, T45, T47, T42, T41, T35, T36, T2, and T6. The macro does not modify the readings in any way. There are three charts on the worksheet (Figure 9.6), all located on page two. The first chart compares the variation of the dew point temperature and surface temperatures versus time for the insulated wall cavity. The next two charts illustrate the effect of the steel column on the wall temperature for the insulated and uninsulated sections. The macro is programmed to scan for temperature readings that exceed the dew point temperature. If it finds one, it automatically prints the charts. Otherwise, it simply saves the file without printing any of the charts.

Figure 9.6 Charts produced by macro TBC2.XLM





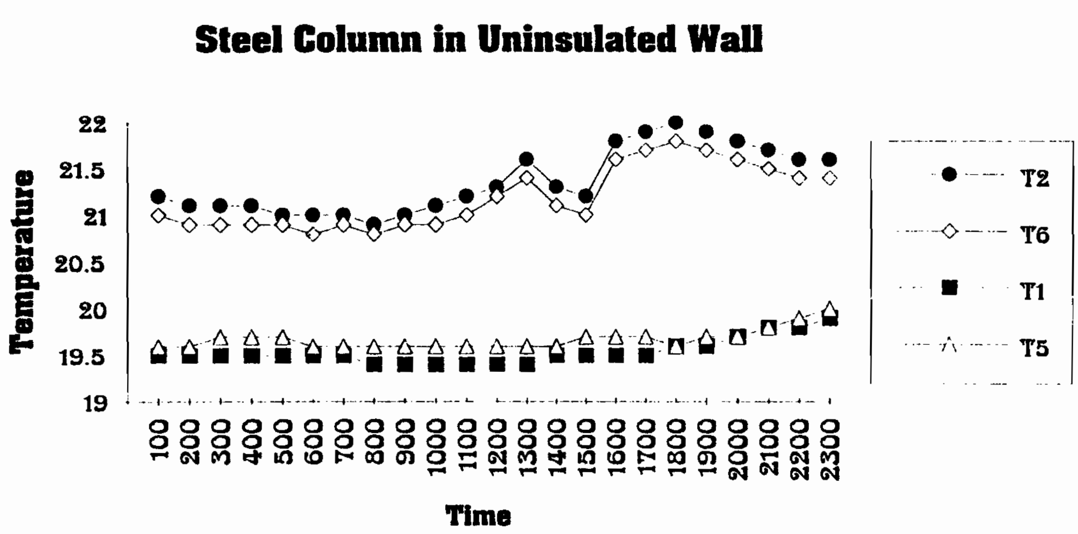


Table 9.17 Macro TBC2.XLM

```
        C! sets directory
"=DIRECTORY(""C:\WINNIPEG\ANALYSIS"")"
        C! asks which file to open
"=OPEN?(""C:\WINNIPEG\ANALYSIS\TB93???b.RPT"",,,2)"
        C! parses data
"=SELECT(""R6C1:R30C1"")"
"=PARSE(""[100][20.4][18][-4.2][19.4][17.6][11.0][11.6][9.1][10.0][19.4][19.5][13.2][14.1]"")"
"=SELECT(""R4C1"")"
"=PARSE(""[TIME][RHT14T][RHT14H][DEWPT][T45][T47][T42][T41][T35][T36][T2][T6][T1][T5]"")"
        C! deletes an unwanted line
"=SELECT(""R5C1"")"
=CLEAR(3)
        C! selects data for chart1
"=SELECT(""R4C1:R28C1,R4C4:R28C6"",""R4C4"")"
=COPY()
        C! locates chart on the spreadsheet
"=CREATE.OBJECT(5,""R49C1"",0.75,12,""R67C10"",0,0,1,TRUE)"
        C! draws chart
"=CHART.WIZARD(TRUE,""R4C1:R28C1,R4C4:R28C6"",4,2,2,1,1,1,""Insulated Wall
Cavity"",""Time"",""Temperature"","""")"
        C! selects data for chart2
"=SELECT(""R4C1:R28C1,R4C7:R28C10"",""R4C7"")"
=COPY()
        C! locates chart on the spreadsheet
"=CREATE.OBJECT(5,""R67C1"",0.75,0.75,""R83C10"",0,0,1,TRUE)"
        C! draws chart
"=CHART.WIZARD(TRUE,""R4C1:R28C1,R4C7:R28C10"",4,2,2,1,1,1,""Steel Column in Insulated
Wall"",""Time"",""Temperature"","""")"
        C! selects data for chart3
"=SELECT(""R4C1:R28C1,R4C11:R28C14"",""R4C11"")"
=COPY()
        C! locates chart on the spreadsheet
"=CREATE.OBJECT(5,""R83C1"",0.75,0.75,""R99C10"",0,0,1,TRUE)"
        C! draws chart
"=CHART.WIZARD(TRUE,""R4C1:R28C1,R4C11:R28C14"",4,2,2,1,1,1,""Steel Column in Uninsulated
Wall"",""Time"",""Temperature"","""")"
        C! sets page layout for printing
"=PAGE.SETUP("""",""&R&F"",0.75,0.75,1,1,FALSE,FALSE,FALSE,FALSE,1,1,100,1,1,FALSE)"
        C! checks if the dew point exceeds temperatures
"=SET.NAME(""flag"",0)"
"=FOR.CELL(""dewpt"",""R6C4:R28C4"",TRUE)"
"=FOR.CELL(""currentcell"",""R6C5:R28C6"",TRUE)"
=IF(currentcell<dewpt)
"=SET.NAME(""flag"",1)"
=BREAK()
=END.IF()
=NEXT()
=IF(flag=1)
=BREAK()
```

```
=END.IF()
=NEXT()
        C! prints page displaying the charts
=IF(flag=1)
"=PRINT(2,2,2,1,FALSE,FALSE,1,FALSE,1)"
=END.IF()
        C! asks for name of file to be saved
"=SAVE.AS?(""C:\WINNIPEG\ANALYSIS\TB93???b.XLS"",1,"""",FALSE,"""",FALSE)"
=CLOSE()
=RETURN()
        C! end
```

9.3.6 Movement of Cracks

The last area of analysis is the monitoring of crack movement The relevant sensors are : the Linear Variable Differential Transducer and thermocouple T8.

9.3.6.1 LVDT.PAR

The SPLIT parameter file is named LVDT.PAR (Table 9.18) and produces an output file named MV-???.RPT. It accesses the seven daily data files and copies the date, time LVDT reading and the thermocouple. The data is averaged over six hour periods.

Table 9.18 LVDT.PAR

Names of input DATA FILE:	c:\winnipeg\data\DAY93???.dat,
	c:\winnipeg\data\DAY93???.dat,
	c:\winnipeg\data\DAY93???.dat,
	c:\winnipeg\data\DAY93???.dat,
	c:\winnipeg\data\DAY93???.dat,
	c:\winnipeg\data\DAY93???.dat,
	c:\winnipeg\data\DAY93???.dat
Name of OUTPUT FILE to generate:	c:\winnipeg\analysis\MV_93???.PRN/r/0
START reading in:	
STOP reading in:	
COPY from:	1[132]
SELECT elements #: L1	smpl(4;36),
L2	avg(53;36)-16.06,
L3	avg(16;36)

The first line in the data selection statement reads the time. The second line calculates the crack movement using the specified offset for the LVDT. The third line reads the averaged temperature from the thermocouple.

9.3.6.2 LVDT.XLM

The EXCEL macro associated with the MV_93???.RPT files is named LVDT.XLM (Table 9.19). On the worksheet, the data is arranged in columns in the following order: Time, LVDT, and T8. The macro does not modify the readings in any way. There is only one chart on the worksheet (Figure 9.7). It is located on page two. The chart illustrates the crack movement versus time. The macro is programmed to scan for movement greater than 0.1 mm. If this occurs it automatically prints the chart. Otherwise, it simply saves the file without printing the chart. Because of the nature of this chart, the macro requires special instruction that can only be given by opening the chart itself. Therefore prior to running this macro the user must specify the file name for the line:

```
"=UNHIDE(""MV_93???.RPT Chart 1"")"
```

The last three digit of the file name is the Julian date. This will allow EXCEL to open the chart and carry out the necessary modifications.

Figure 9.7 Chart produced by macro LVDT.XLM

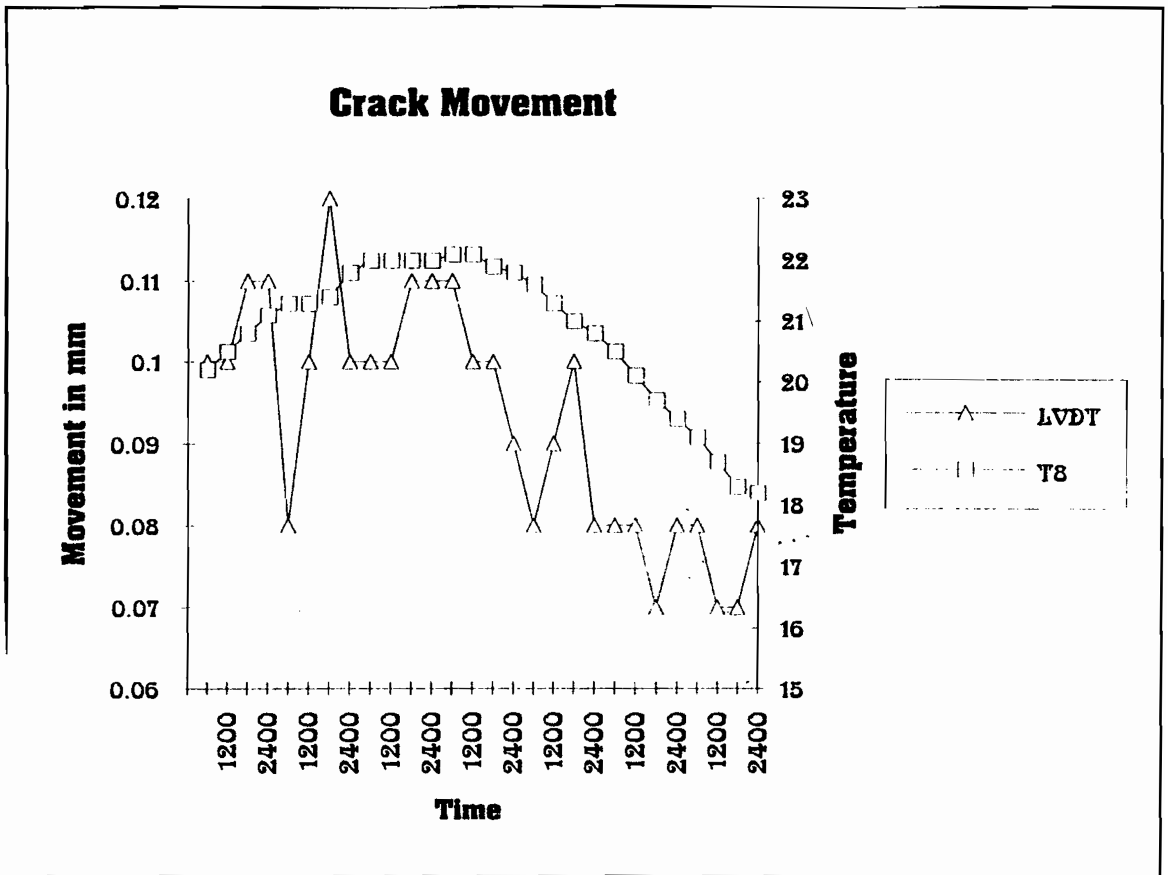


Table 9.19 Macro LVDT.XLM

```
        C! opens the file
"=OPEN?(""C:\WINNIPEG\ANALYSIS\MV_93???.RPT"")"
        C! parses the data
"=SELECT(""R6C1:R9C1"")"
"=PARSE(""[550][-0.01][9.7][550][0.05][9.7][550][0.02][10.7][550][0.02][10.8][550][0.01][10.5][550]
[0.01][10.4][550] [0.01][10.5]"")"
"=SELECT(""R4C1"")"
"=PARSE(""[TIME][LVDT][T8][TIME][LVDT][T8][TIME][LVDT][T8][TIME][LVDT][T8][TIME]
[LVDT][T8][TIME][LVDT][T8][TIME][LVDT][T8]"")"
        C! deletes an unwanted line
"=SELECT(""R5C1"")"
="CLEAR(3)"
        C! modifies time values
"=SELECT(""R6C1"")"
"=FORMULA(""600"")"
"=SELECT(""R7C1"")"
"=FORMULA(""1200"")"
"=SELECT(""R8C1"")"
"=FORMULA(""1800"")"
"=SELECT(""R9C1"")"
"=FORMULA(""2400"")"
        C! cuts and pastes data together for chart
"=SELECT(""R6C1:R9C1"",""R9C1"")"
=COPY()
"=SELECT(""R6C4"")"
=PASTE()
"=SELECT(""R6C7"")"
=PASTE()
"=SELECT(""R6C10"")"
=PASTE()
"=SELECT(""R6C13"")"
=PASTE()
"=SELECT(""R6C16"")"
=PASTE()
"=SELECT(""R6C19"")"
=PASTE()
"=SELECT(""R6C22"")"
"=SELECT(""R6C4:R9C6"")"
=CUT()
"=SELECT(""R10C1"")"
=PASTE()
"=SELECT(""R6C7:R9C9"",""R9C7"")"
=CUT()
"=SELECT(""R14C1"")"
=PASTE()
"=SELECT(""R6C10:R9C12"",""R9C12"")"
=CUT()
"=SELECT(""R18C1"")"
=PASTE()
"=SELECT(""R6C13:R9C15"")"
```

```
=CUT()
"=SELECT(""R22C1"")"
=PASTE()
"=SELECT(""R6C16:R9C18"")"
=CUT()
"=SELECT(""R26C1"")"
=PASTE()
"=SELECT(""R6C19:R9C21"")"
=CUT()
"=SELECT(""R30C1"")"
=PASTE()
"=SELECT(""R4C4:R4C21"")"
=CLEAR(3)                \
        C! selects data for chart
"=SELECT(""R4C1:R33C3"",""R33C1"")"
=COPY()
        C! locates chart on the spreadsheet and draws chart
"=CREATE.OBJECT(5,""R50C1"",3,2.25,""R77C9"",46.5,0,1,TRUE)"
"=CHART.WIZARD(TRUE,""R4C1:R33C3"",4,2,2,1,1,1,""Crack Movement"",""Time"",""Movement in
mm"","""")"
        C! opens chart for modifications
"=UNHIDE(""MV_93172.RPT Chart 1"")"
"=MOVE(46.75,24.25)"
"=SIZE(431.25,258.75)"
        C! adds an overlay
=ADD.OVERLAY()
        C! adds a y - axis for the overlay
"=AXES(TRUE,TRUE,FALSE,TRUE)"
        C! adds title to the new axis
=ATTACH.TEXT(5)
"=FORMAT.FONT(0,1,FALSE,""MS Sans Serif"",10,TRUE,FALSE,FALSE,FALSE)"
"=FORMULA(""=""""Temperature"""""")"
        C! closes the chart
=HIDE()
        C! sets up the document for printing
"=PAGE.SETUP("""",""&R&F"",0.75,0.75,1,1,FALSE,FALSE,FALSE,FALSE,1,1,100,1,1,FALSE)"
        C! checks for excessive movement
"=SET.NAME(""flag"",0)"
"=FOR.CELL(""currentcell"",""R6C2:R33C2"",TRUE)"
=IF(VALUE(currentcell)>0.1)
"=SET.NAME(""flag"",1)"
=BREAK()
=END.IF()
=NEXT()
        C! prints the page displaying the chart
=IF(flag=1)
"=PRINT(2,2,2,1,FALSE,FALSE,1,FALSE,1)"
=END.IF()
        C! saves file
"=SAVE.AS?(""C:\WINNIPEG\ANALYSIS\MV_93???.XLS"",1,"""",FALSE,"""",FALSE)"
=CLOSE()
        C! end
```

9.4 Batch Files

In order to reduce the amount of time required to process the weekly data file, a series of batch files were created. These files are located in the C:\WINNIPEG\BATS directory with the other control files. There are two types of batch files. The first is for the execution of the SPLIT parameter files and the second for the EXCEL macros.

9.4.1 SPLIT Batch Parameter Files

The first type of files have the same filename as the associated SPLIT parameter file but with the BAT extension. They contain the input information required to process one week of data. These batch files must be executed from the C:\EDLOG directory, where the SPLIT program resides. Table 9.20 shows the typical command line for each of these batch files.

Table 9.20 Batch Files

BATCH FILE NAME	TYPICAL COMMAND LINE
DAY.BAT	c:\edlog\split day/r peg5_??.dat day93???.dat/0 3[???] 3[???]
HF1.BAT	c:\edlog\split hf1/r day93???.dat hf93???a.dat/0/r
HF2.BAT	c:\edlog\split hf2/r day93???.dat hf93???b.dat/0/r
MOIST1.BAT	c:\edlog\split moist1/r day93???.dat, ... day93???.dat mo_93???/0/r
RAIN.BAT	c:\edlog\split rain/r day93???.dat rn_93???.dat/0/r
TBC1.BAT	c:\edlog\split tbc1/r day93???.dat,day93???.dat tb93???a/0/r
TBC2.BAT	c:\edlog\split tbc2/r day93???.dat,day93???.dat tb93???b/0/r

The command line typically specifies the name of input and output files. Before the file can be used the proper file names must be specified by replacing the ? symbols with the appropriate numbers. DAY.PAR is slightly different. The user must also specify the starting and finishing point. This is accomplished by replacing the ? symbols in the first set of square brackets with the Julian date for the current file and with the Julian date for the following day in the second set of square brackets.

9.4.2 EXCEL Batch Macros

The second type of batch files are not true batch files. They are actually longer EXCEL macros. Copies of the original macro were pasted one after the other to process one week of data in a single run. These batch macros have the same file as the original macro with the addition of BAT at the end. The statements for opening the input file and saving the output file were modified so that they can be executed automatically. The user must first enter the batch macro and specify the input and output file names for each copy of the macro. The statement that must be modified are:

```
"=OPEN(""C:\WINNIPEG\ANALYSIS\*.RPT"")"

"=SAVE.AS(""C:\WINNIPEG\ANALYSIS\*.XLS"",1,"""",FALSE,"""",FALSE)
```

Once these statements have been modified to use the proper input and output file names, the macro is ready to run.

9.5 Recommendations for Future Data Gathering and Processing

During the first four months of data processing the computer programs were gradually refined. The data was closely monitored and the programs were modified for any abnormalities. The output files were gradually modified to obtain a simpler display format. All of the programs for data processing have been thoroughly tested and are now performing adequately. With the exception of the those noted below, the various sensors are also performing adequately. However, with the arrival of colder weather the sensors will experience a wider range of values. The results should be carefully monitored to ensure that the sensors are all performing as expected. When periods of below freezing temperature are observed, both versions of the data processing files for the moisture levels should be used. The results should indicate if the low temperature affect the brick resistance moisture sensors. If this is the case, the second version of the data processing files for the moisture levels should be used. The files for processing the rain wetting data will also have to modified to properly read the two exterior moisture sensors.

The format of the charts could be further improved but this would require additional modifications to the macros each time they are used. To modify a chart format on the EXCEL worksheet, the chart must first be opened with the EXCEL macro command UNHIDE. This command requires the input of the file name for the worksheet on which the chart is located. For each chart to be modified, the user will have to specify the correct file name each time the macro is used. This would increase the time required to set up the batch macros to process the weekly data. Currently, the file name must be entered for only two commands per copy of the original macro in the batch macro. These are the OPEN and SAVE AS commands. If the chart format is modified, the number of command entries would be increased to seven or eight per copy of the original macro in the batch macro. It will be up to the researchers who will be using these charts in their analysis to determine if the modification of the chart format justifies the additional time required to process the data.

Some researchers have also expressed interest in an alternate labeling system for the legend. Presently the legend is used to relate each curve to a specific sensor. Some would prefer to see labeling according to the depth of the sensor within the wall cross section. If required, this can be easily accomplished in three fashions. The first method consist of changing the column headings on the EXCEL worksheet. The legend uses these column headings to label the curves on the chart. Therefore, changing the column headings also changes the legend labeling system. Although simple, this method is time-consuming if many files are to be altered. The second method would consist of including commands in the EXCEL macro so that it automatically changes the column headings each time a file is processed. This can be accomplished with the use of the FORMULA command. The last method accomplishes the same thing but in a simpler fashion. The column headings on the worksheet are created by the SPLIT parameter file. Each parameter file contains a list of the column headings. The column headings can be changed easily but they are limited to seven digits/characters.

There are some small details that warrant investigation in the near future. Thermocouples T23 and T24 have been interchanged. Analysis of their temperature readings suggested that they were crosswired or had been labeled incorrectly. The wiring and labeling of these two thermocouples should be carefully inspected to see if this is a correct assumption.

Brick resistance moisture sensor R34 has been indicating high levels of moisture. The sensor is located on the interior masonry surface at the bottom of the insulated wall section. Large puddles of water were present in this area during the renovations and this may explain the high moisture readings. Sensor R32, also located at floor level, exhibited similar behavior but appears to have dried out. However, the condition of the sensor should be inspected to ensure that it is functioning properly.

The rain gauges have received very little rain although the weather data for the Winnipeg International Airport indicate that the region has experienced substantial amounts of rainfall. It is possible that the rain gauges are simply sheltered by the cornice. If this is the case, their relocation should be considered. However, it is also possible that small particles are blocking the funnel and preventing rain from entering. Therefore the rain gauges should be thoroughly inspected. It should also be noted that rain gauge No. 2 counts a pulse for every two tips of the bucket. The rain gauge also requires a slightly higher volume of water per tip (4.6 ml versus 3.6 ml). Since the readings observed for the other rain gauge were sometimes for only one tip of the bucket, rain gauge No. 2 may be missing readings because it requires two tips to register one pulse. Modifying this rain gauge to read one pulse per tip of the bucket should therefore be considered.

Finally, the wetness sensors are still not performing as expected. Further testing might be required. The sensors should be inspected to check if they have suffered any damage during installation and to ensure that they are properly connected.

Chapter 10

Conclusion

10.1 Rehabilitation of Masonry Structures

In summary the first consideration in masonry repair is to determine the overall objectives of the project. It is therefore important to understand the difference between rehabilitation and restoration. Rehabilitation is the process of returning a property to a state of utility, through repairs or alteration. Restoration is defined as the accurate recovery of the form and details of a structure and its setting as it appeared at a particular period in time. Although it is vital to preserve our built heritage, not all buildings can be saved. It is therefore important to understand which building characteristics have heritage value. The building characteristics associated with heritage value can be divided into categories related to historic, environmental, and architectural values. Heritage legislation will determine to what extent heritage buildings can be altered. In Canada, the primary responsibility for heritage protection belongs principally to the provinces. Provincial Governments in turn delegate some of their powers to the governments of municipalities and regional communities. The result is a sometimes confusing mixture of provincial and municipal laws that change from province to province and municipality to municipality.

Before any repairs are undertaken the cause of the deterioration must be properly identified and remedied. Masonry deterioration can be classified as either chemical reactions or physical processes. Chemical reactions usually involve substances, most of them man made, which can react with the components of masonry and weaken their structural matrix, producing harmful by products. Physical processes typically involve either excessive stresses caused by dimensional changes or erosion by mechanical means.

A number of biological organisms also play a significant role in the deterioration of masonry both by physical and chemical action. However, moisture is the principal agent involved in the deterioration of masonry. Water is not only a deteriorating agent by itself, it is also a vital component in virtually all other forms of masonry deterioration. Nevertheless, it is important to remember that the deterioration of masonry is likely to involve a combination of agencies whose interaction over a long period leads to the gradual destruction of the masonry.

Since moisture is probably the greatest source of damage to old buildings, the treatment of moisture problems should be addressed before undertaking any other masonry repairs. Possible solutions for moisture problems include better drainage, preventing moisture migration within the masonry with flashing and damp proof courses, and where necessary surface treatment to water proof the masonry. These should be followed if necessary with treatments to remove salt encrustations on or within the masonry that build up as a result of the moisture problem.

Once the cause of masonry deterioration has been identified and the source of the problem eliminated, it may be desirable to repair or replace the damaged masonry units. Although most repairs are carried out for mostly cosmetic reasons, they also make the masonry less susceptible to further damage. Techniques for the repair of damaged masonry can be divided into two categories: mechanical repairs and plastic repairs. If the internal structure of the masonry units has been weakened by leaching of their natural binding agents, the units may be preserved by applying a consolidant to strengthen their weakened structure. However, in most cases, the units will have deteriorated to a degree where it is preferable to replace them with new materials.

Unlike most masonry materials, mortar is not designed to be permanent, although a good mortar should last from 50 to 100 years. Repointing is the process of removing deteriorated mortar from the joints of a masonry wall and replacing it with new mortar. Properly done, repointing restores the visual and physical integrity of the masonry. Mortar repairs also involve grout injection to stabilize walls by filling cracks and voids within their thickness. The injection of a liquid grout avoids dismantling and rebuilding defective masonry in many cases.

The cleaning of exterior masonry is perhaps the most visible aspect of contemporary rehabilitation work. However, the cleaning of masonry is a complex and delicate process that requires a good knowledge of the nature of the stains, the characteristics of the masonry and the properties of the various cleaning techniques. Cleaning masonry with water is generally the simplest operation, the safest for the building and the environment and the least expensive method. Chemical cleaning is generally an acceptable technique for cleaning old masonry however, if not properly carried out, it can also cause staining, efflorescence or other damage. The main types of chemicals used are acids, alkalis, surfactants and inorganic salts. Abrasive or mechanical cleaning techniques such as sand blasting and the use of power sanders are unacceptable cleaning methods for old and historic masonry. These techniques destroy the appearance, original materials and physical well being of a building.

10.2 Monitoring the Effects of Insulating Masonry

The Winnipeg Customs Examining Warehouse had to undergo an extensive retrofit to meet the stringent requirements set forth by the Canadian Parks Service for temperature and relative humidity in the Artifact Restoration Workshops and Laboratories. Most historic masonry buildings would not usually require such an extensive retrofit. However, in this case, the goal was not only to reduce the amount of heat loss but to ensure that the building could maintain constant environmental conditions in even the worst type of weather. The exterior masonry walls were closely inspected and any cracks or deteriorated joints were repointed to prevent infiltration. All of the exterior doors and windows were replaced with modern units to reduce the amount of heat loss by conduction. These new windows and doors were carefully detailed to prevent infiltration around their perimeter and conduction through the surrounding masonry. The badly deteriorated roof membrane was replaced with a new protected membrane roof with adequate insulation to reduce heat loss through the roof slab. New flashing was installed along the junction of the insulated roof and the parapet wall to prevent water infiltration. The exterior walls were insulated on their inside face with rigid insulation to increase their thermal resistance and reduce heat flow. This rigid insulation included an air and vapor barrier to prevent moisture from accumulating in the masonry. The basement walls were insulated in a similar fashion. Finally, a forced air HVAC system was installed to maintain the required interior environmental conditions.

The Institute for Research in Construction did several analysis to ensure that the masonry of this historic building would not be damaged as a result of the added insulation. The analysis determined that no moisture build up would occur in the masonry and that the added thermal stresses would not be excessive. To ascertain the reliability of the various analysis methods used to predict the possible effect of the added insulation, a monitoring program was established. Two sections of the exterior, one insulated and the other left uninsulated will be monitored over an eighteen month period to study the effects of the added insulation on the masonry. The data obtained from this study will be evaluated and compared with the results predicted by the various methods of analysis. The data will also be used to further calibrate the analysis methods to obtain better results in predicting the effects of insulating masonry buildings. Finally, if these analysis methods prove to be accurate they can then be used to evaluate the retrofit of other masonry structures and eventually establish scientific guidelines for insulating masonry structures. In any event, this study will lead to a better understanding of the possible side effects of insulating masonry buildings.

References

1. Amorosso, G.G. and V. Fassina,
Stone Decay and Conservation.
Elsevier, New York, 1983.

2. Ashurst J. and N. Ashurst,
Stone Masonry.
Halsted Press, Toronto, 1988.

3. Ashurst J. and N. Ashurst,
Brick, Terracotta and Earth.
Halsted Press, Toronto, 1988.

4. Ashurst J. and N. Ashurst,
Mortars, Plasters and Renders.
Halsted Press, Toronto, 1988.

5. Berry, V.,
James McDiarmid.
Winnipeg Art Gallery, Winnipeg, 1982

6. Chidiac, S.E., Kumaran, K., Maurenbrecher, A.H.P. and Shirtliffe, C.,
The Effects of Upgrading the Thermal Resistance of the Walls and Roof of the Custom Examining Warehouse. Report No CR-6516.1,
Institute for Research in Construction, Ottawa, 1991.

7. Denhez, M.,
Heritage Fights Back.
Heritage Canada, Ottawa, 1978

8. Drysdale, R. G. and G. T. Suter,
Exterior Wall Construction in High-Rise Buildings.
Canada Mortgage and Housing Corporation, Ottawa, 1991

9. Fram, M.,
Well Preserved: the Ontario Heritage Foundation's Manual of Principles and Practice for Architectural Conservation.
Ontario Heritage Foundation, Toronto, 1988.

10. Gauri, K., G. Holdren and W. Vaughan,
Cleaning Efflorescences from Masonry.
ASTM STP 935 Cleaning Stone and Masonry, J. Clifton Editor
American Society for Testing Materials, Philadelphia, 1983.

11. Glainville, J. I., and Hatzinikolas,
Engineered Masonry Design
Winston House Enterprises, Winnipeg, 1989.

12. Highfield, D.,
Rehabilitation and Re-use of Old Buildings.
E. & F. Spon, London, 1987.

13. Kalman, H.,
The Evaluation of Historic Buildings.
Parks Canada, Ottawa, 1979.

14. London, M.,
Masonry. How to Care for Old and Historic Brick and Stone.
Preservation Press, Washington, 1988.

15. Lstiburek, J. and J. Carmody,
Moisture Control Handbook.
Van Nostrand Reinhold

16. MacFarlane, K.,
Customs Examining Warehouse. Building Report 88-52,
Federal Heritage Building Review Office,Ottawa, 1988.

17. Ransom, W.,
Building Failures. Diagnosis and Avoidance.
E. & F. Spon, New York, 1981.

18. Saunders, I., Rostenski, R., and Carrington, S.,
Early Buildings in Winnipeg. Manuscript Report No. 389, Vol. V,
Parks Canada, Ottawa, 1974.

19. Smith, R., T. Honkala and C. Andres,
Masonry: Materials Design Construction.
Reston Publishing, Reston, 1979

20. Sowden, A.M.,
The Maintenance of Brick and Stone Masonry Structures.
E. & F. Spon, New York, 1990.

21. Ward, E.N.,
Heritage Conservation - The Built Environment. Working Paper No. 44,
Land Use Policy and Research Branch, Land Directorate,
Environment Canada, Ottawa, 1986.

22. Weber, H. and K. Zinmeister,
Conservation of Natural Stone.
Expert Verlag. Ehningen, 1991.

23. Whiffen, M.,
American Architecture Since 1780.
M.I.T. Press, Cambridge, Massachusetts, 1981

24. Winkler, E. M.,
Stone: Properties, Durability in Man's Environment.
Springer-Verlag, New York, 1973

25. *AFEMS*.
FEM Engineering Corporation, Inglewood, California, 1991

26. *Detailed Insulated Wall Design*.
National Testing Laboratories Limited, Winnipeg, 1991

27. *EDLOG, SPLIT, TELCOM & TERM*.
Campbell Scientific Inc., Logan, Utah, 1991.

28. *Growth at the Port of Winnipeg*. Vol. X. No. 12,
National Revenue Review, Ottawa, 1937

28. *Handbook for Evaluating Heritage Buildings and Areas*.
Heritage Section, Community Planning Branch,
Planning and Development Department, City of Ottawa, Ottawa, 1989.

29. *KOBRU86*,
Physibel Building Physics, Maldegem, Belgium, 1990

30. *Microsoft EXCEL*. Version 4.0,
Microsoft Corp., Redmond, Washington, 1992.

31. *PKZIP*.
PKWare Inc., Brown Deer, Wisconsin, 1993

32. *Preliminary Report*.
National Testing Laboratories Limited, Winnipeg, 1991

33. *Report of the Minister of Public Works on the Works Under His Control for the Fiscal Year Ended March 31,1928*.
Dominion of Canada, Ottawa, 1928

34. *Report of the Minister of Public Works on the Works Under His Control for the Fiscal Year Ended March 31,1935*.
Dominion of Canada, Ottawa, 1935

35. *TRISCO*.
Physibel Building Physics, Maldegem, Belgium, 1990

36. *Structural Renovation of Traditional Buildings*. CIRIA report 111, Construction Industry Research & Information Association, London, 1986.

Appendix A
Section Details

This appendix contains section details produced by the National Testing Laboratories to illustrate the extent of the renovations.

Figure A-1 Basement floor plan

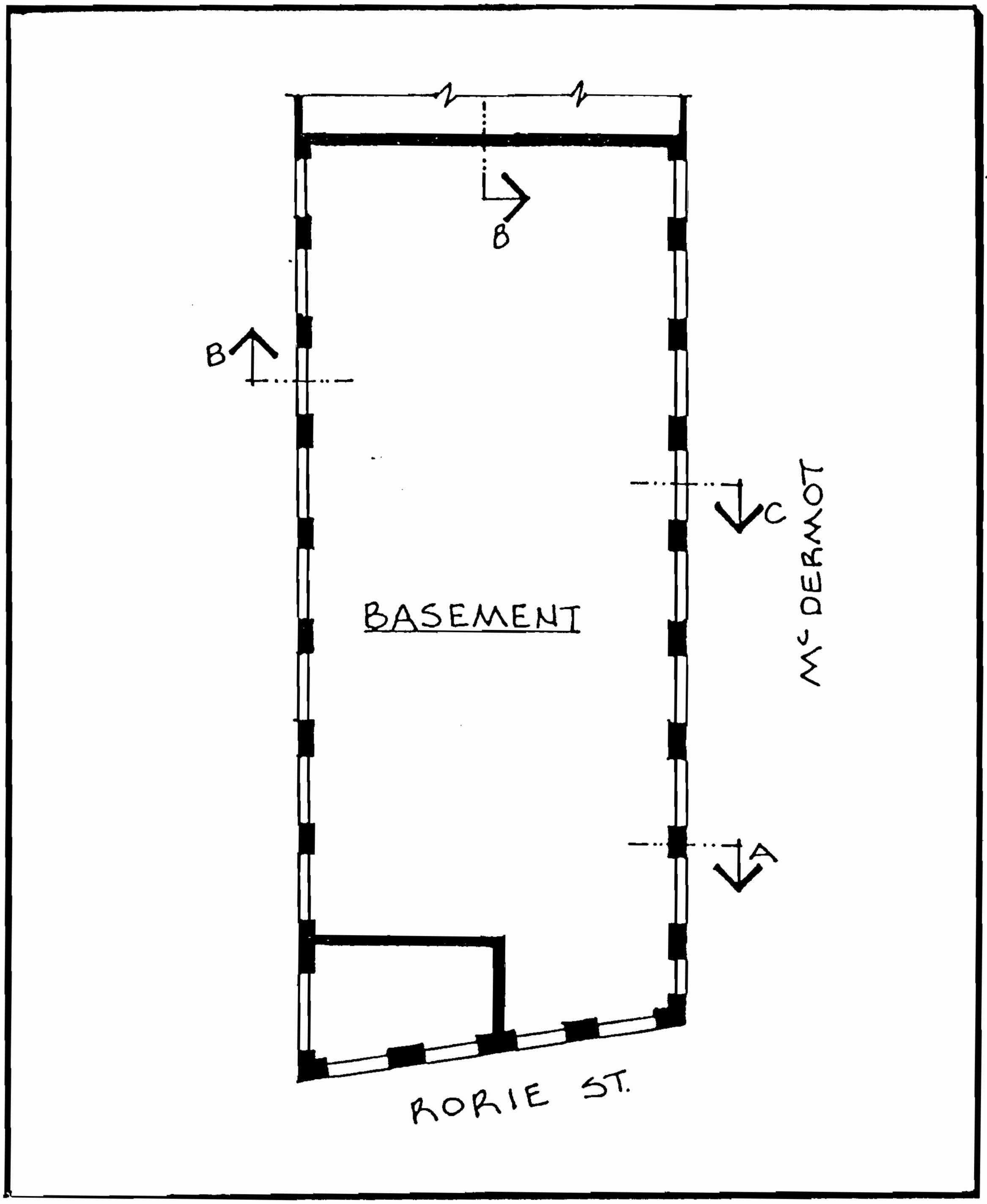


Figure A-2 Ground floor plan

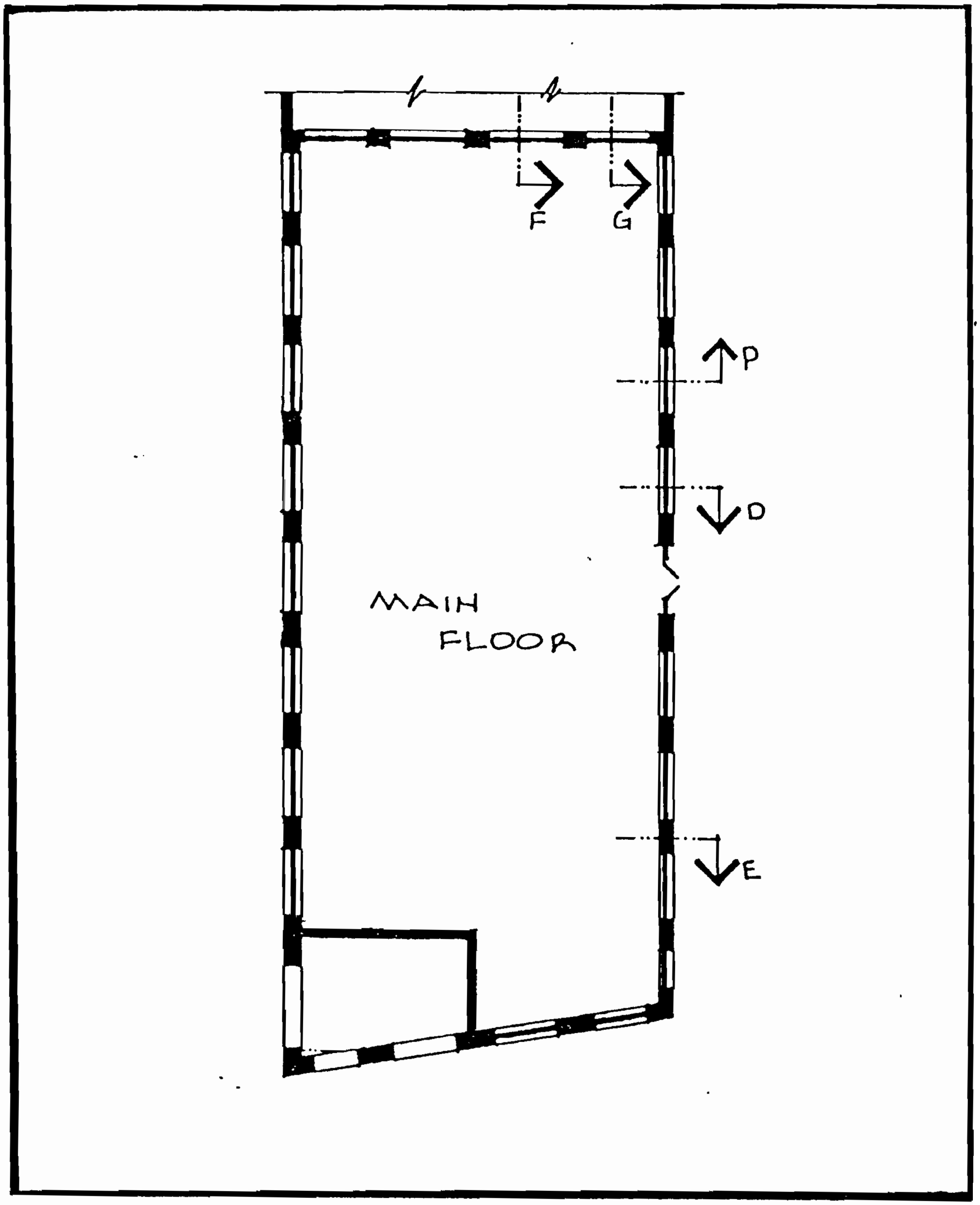


Figure A-3 2nd, 3rd, and 4th floor plan

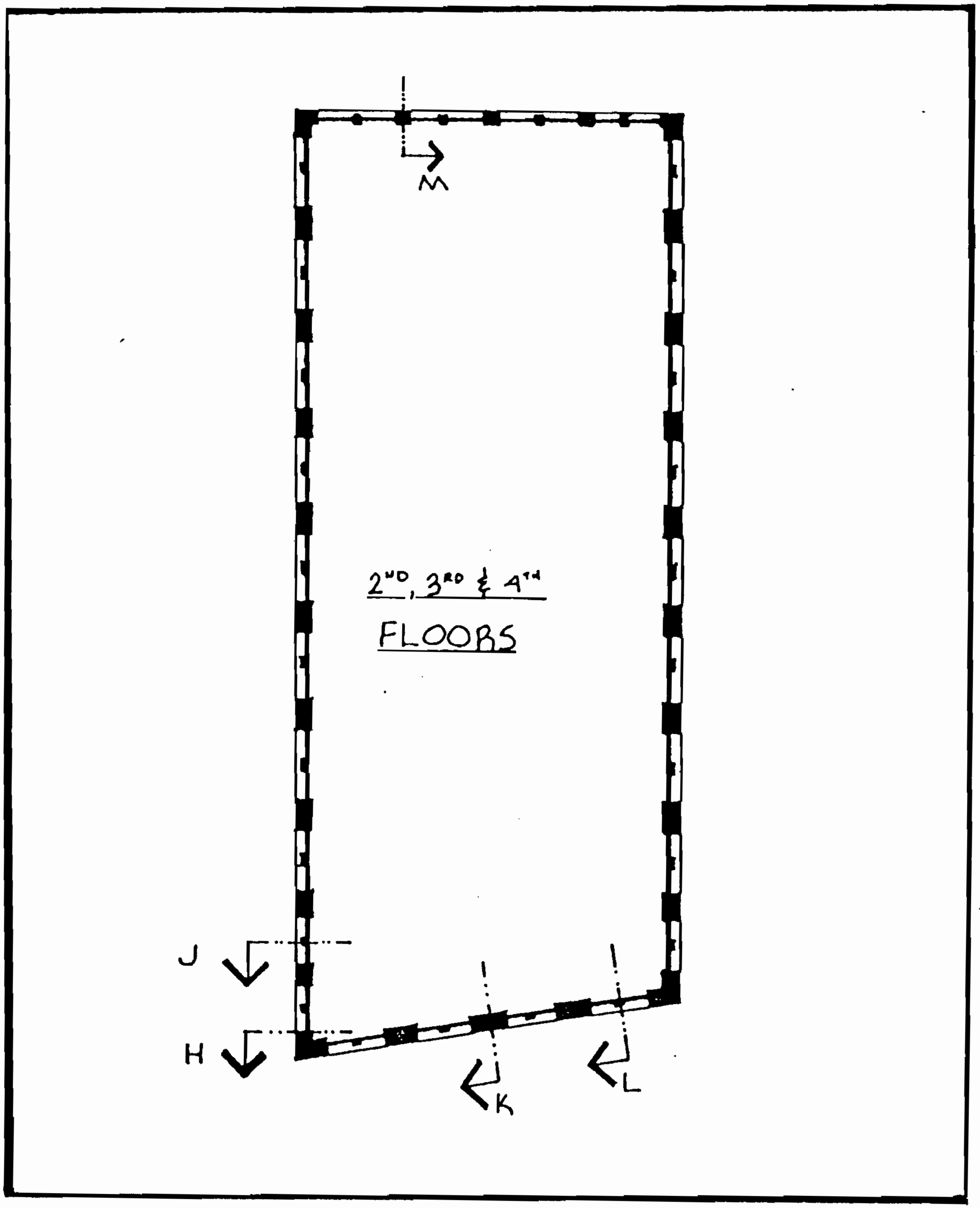


Figure A-4 Section A through foundation wall

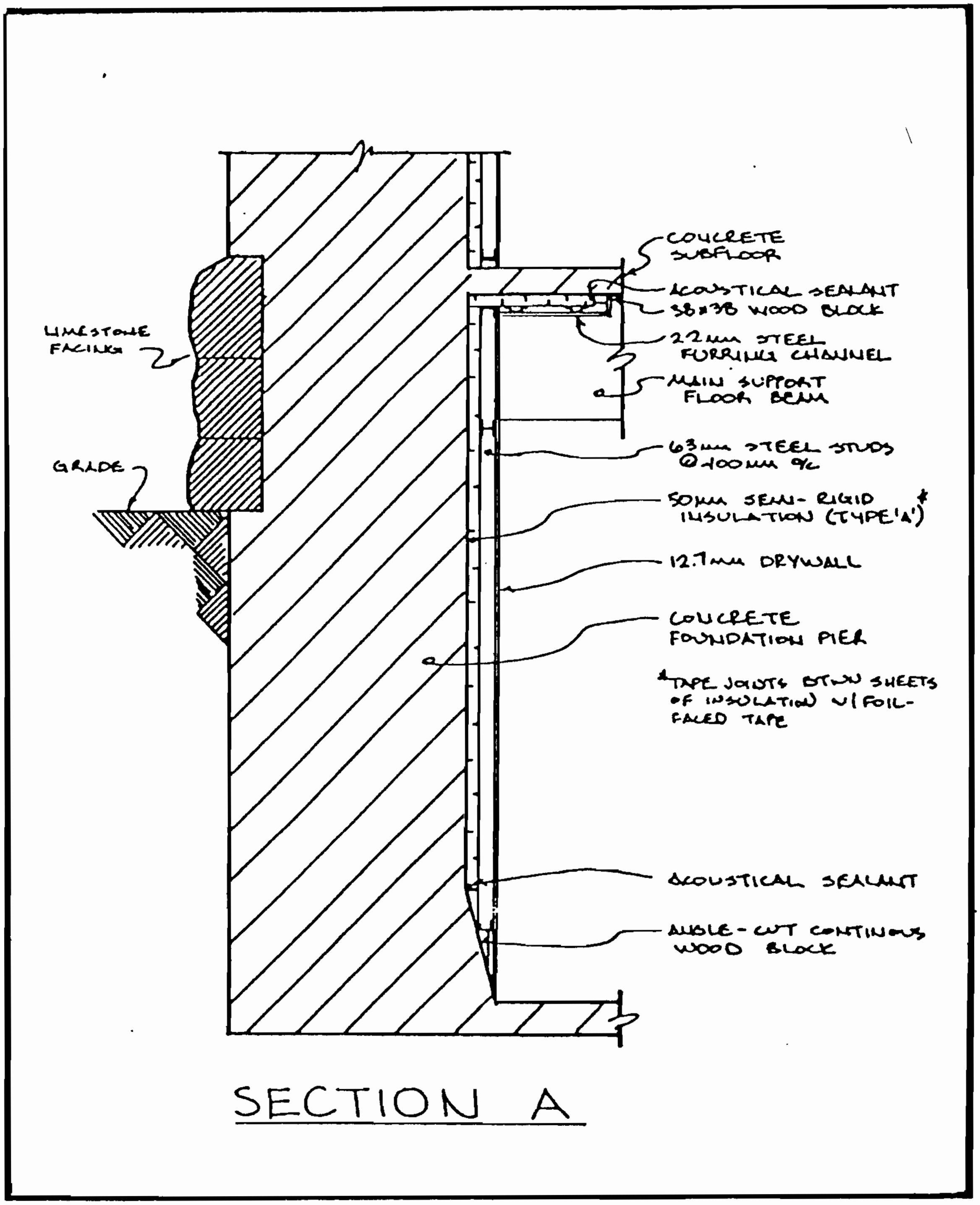


Figure A-5 Section B, through basement window on north side

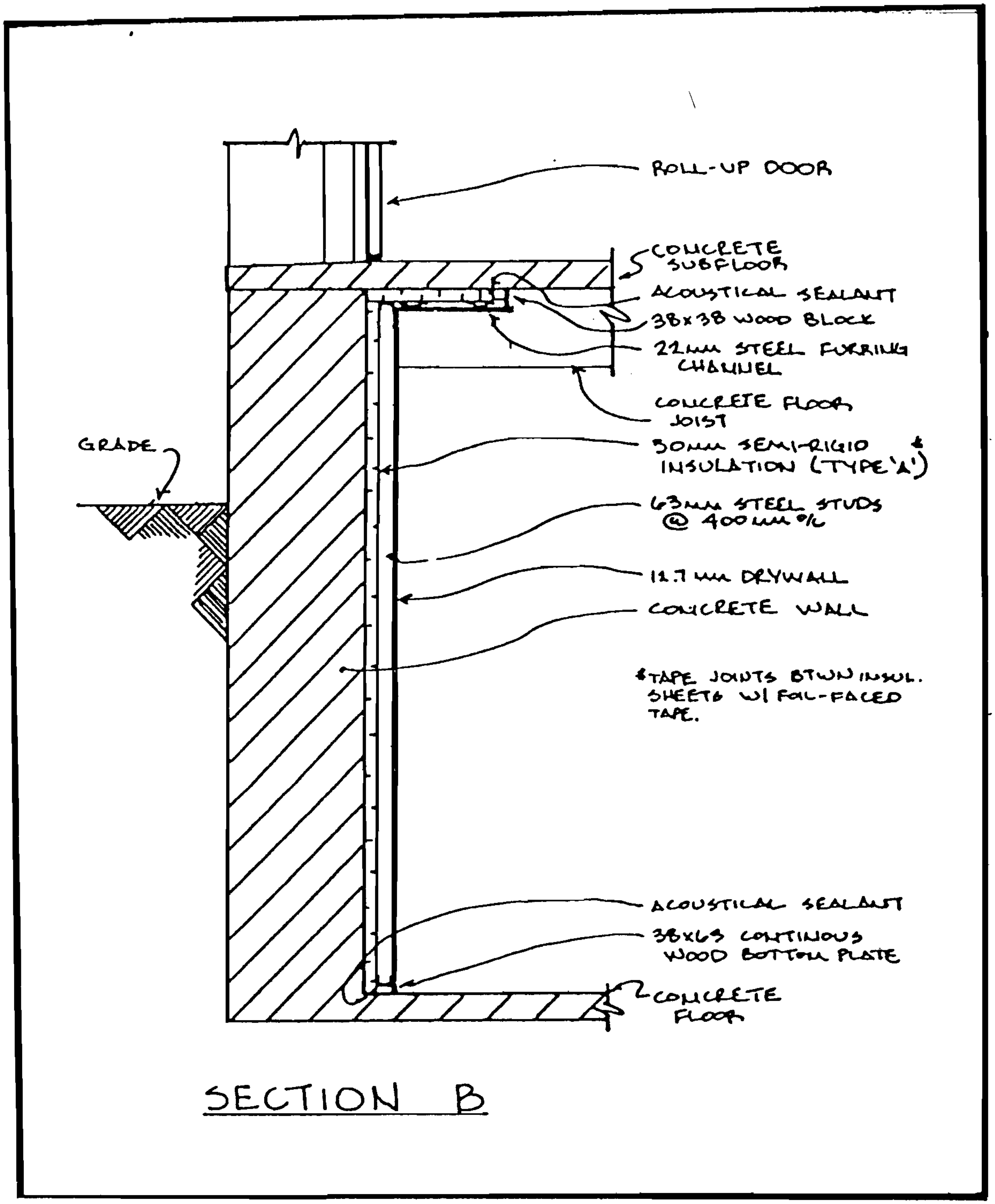


Figure A-6 Section C through basement window on south side

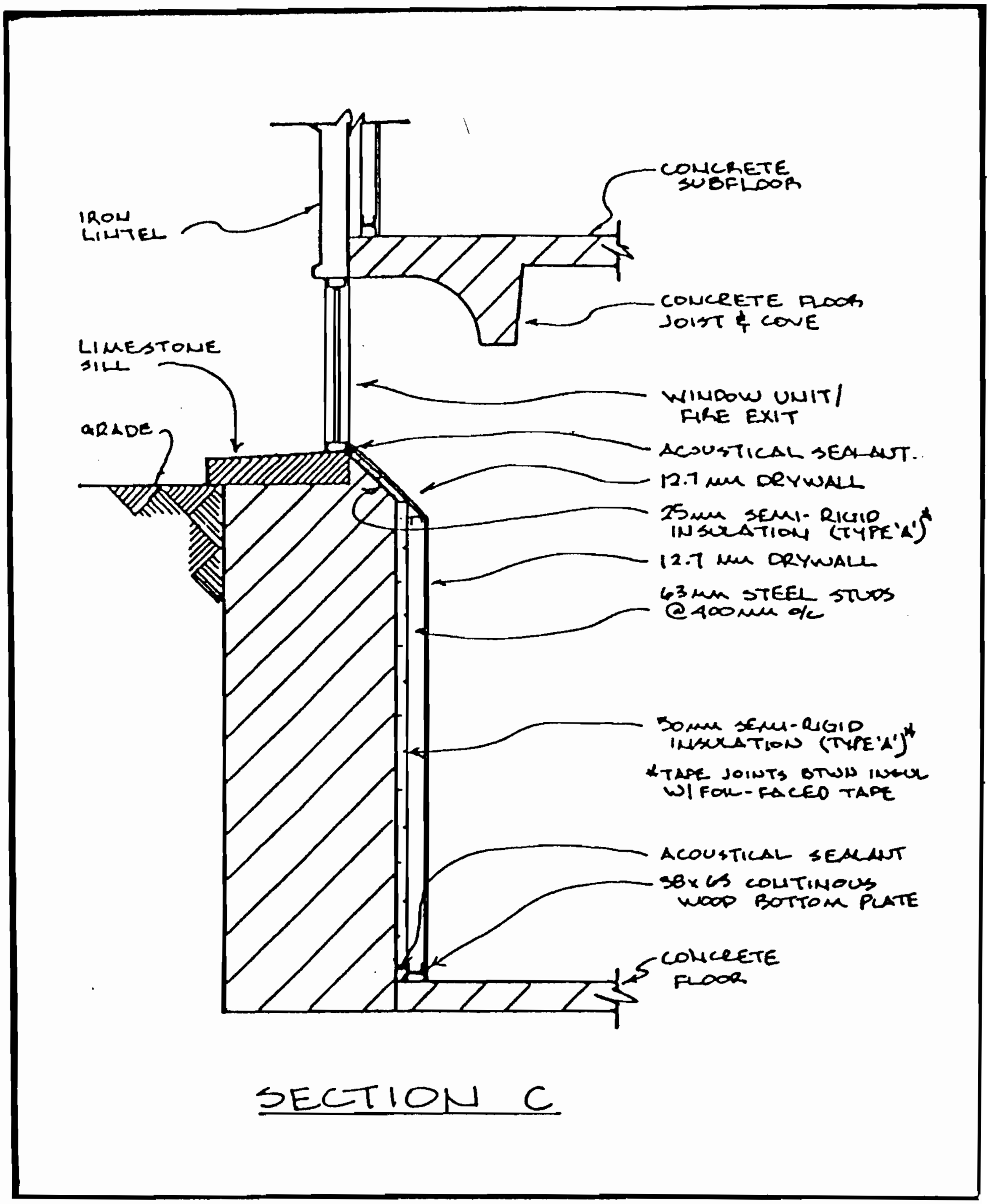


Figure A-7 Section D through ground floor window

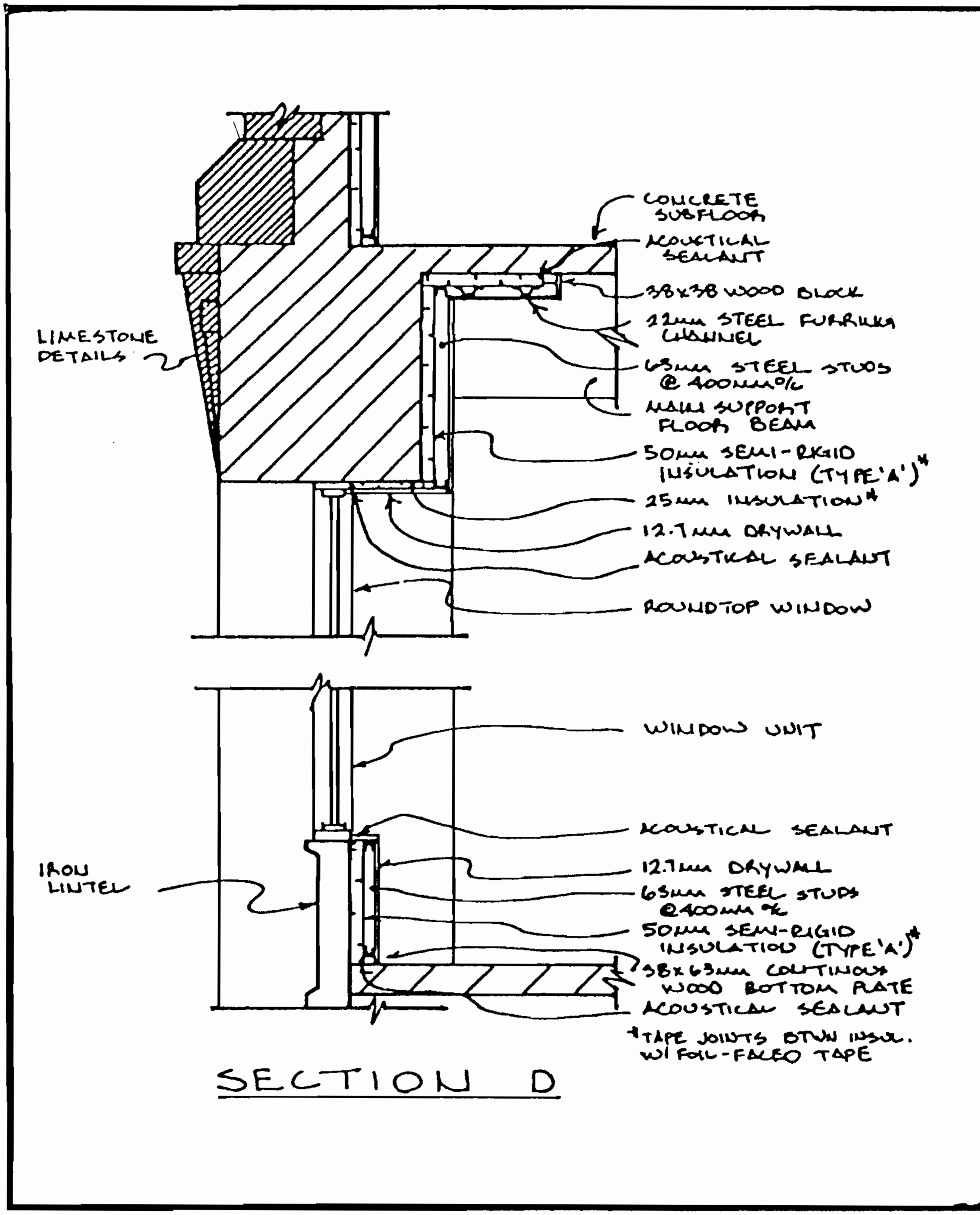


Figure A-8 Section E through ground floor wall

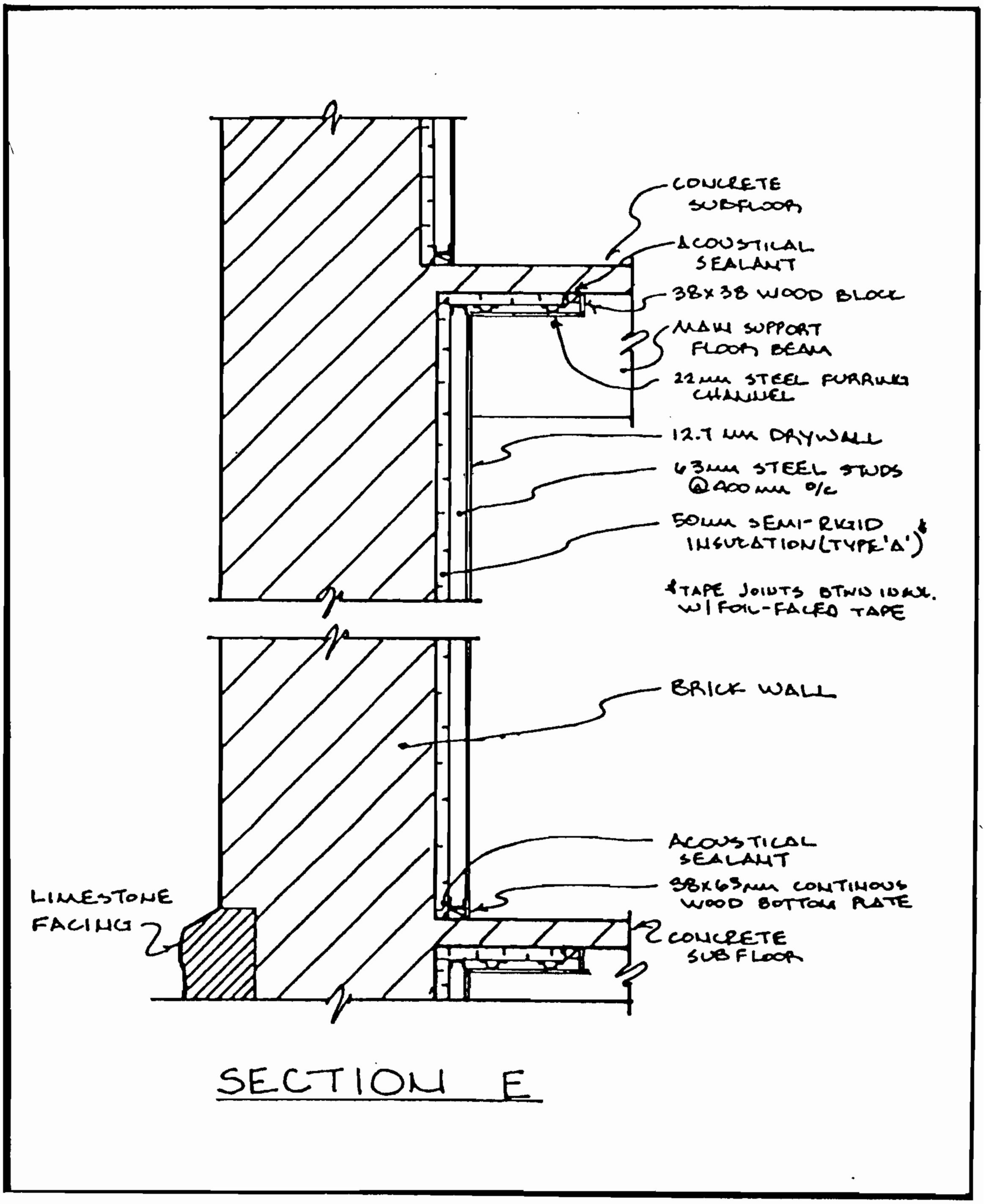


Figure A-9 Section F through ground floor wall of loading dock

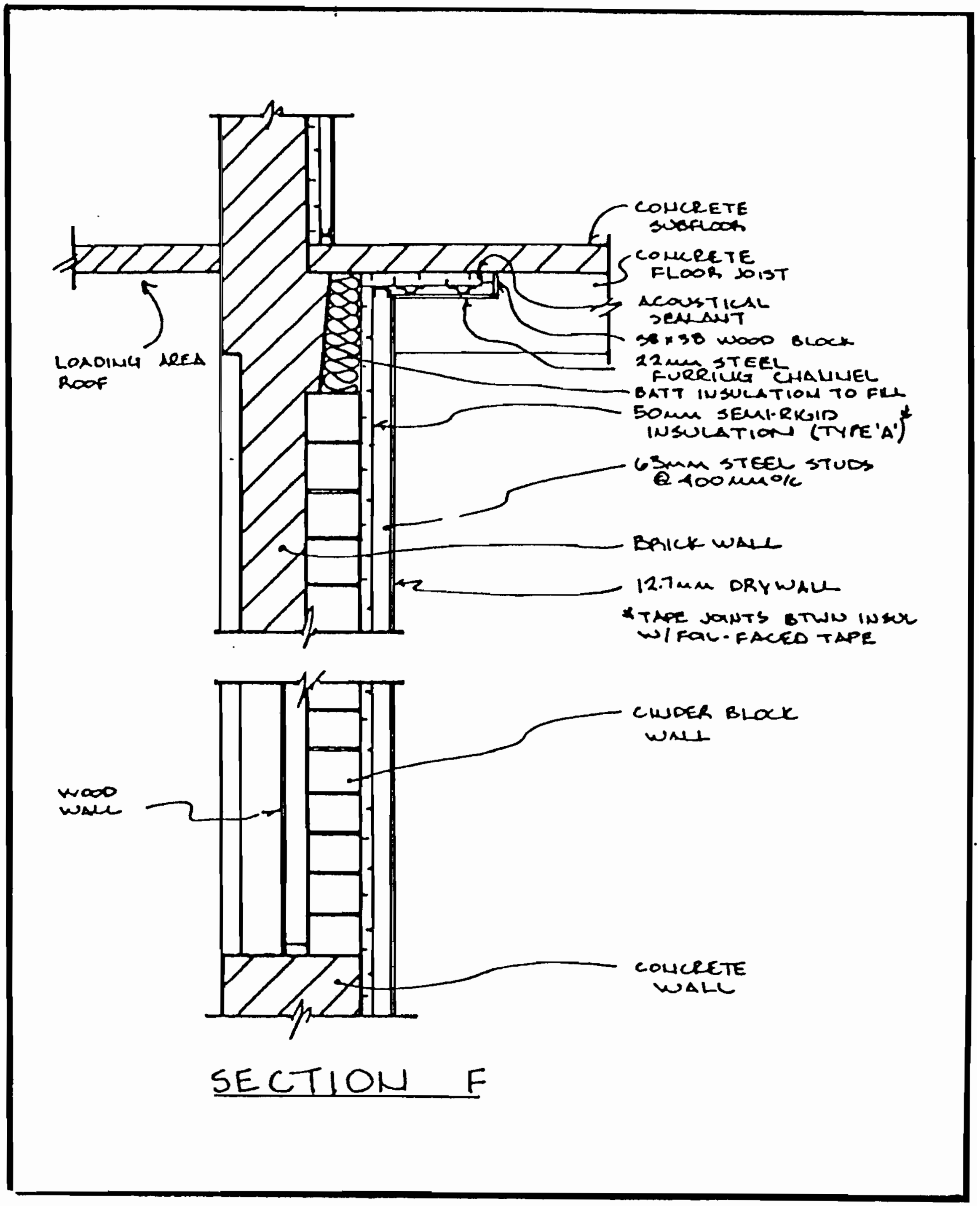


Figure A-10 Section G through ground floor wall of loading dock

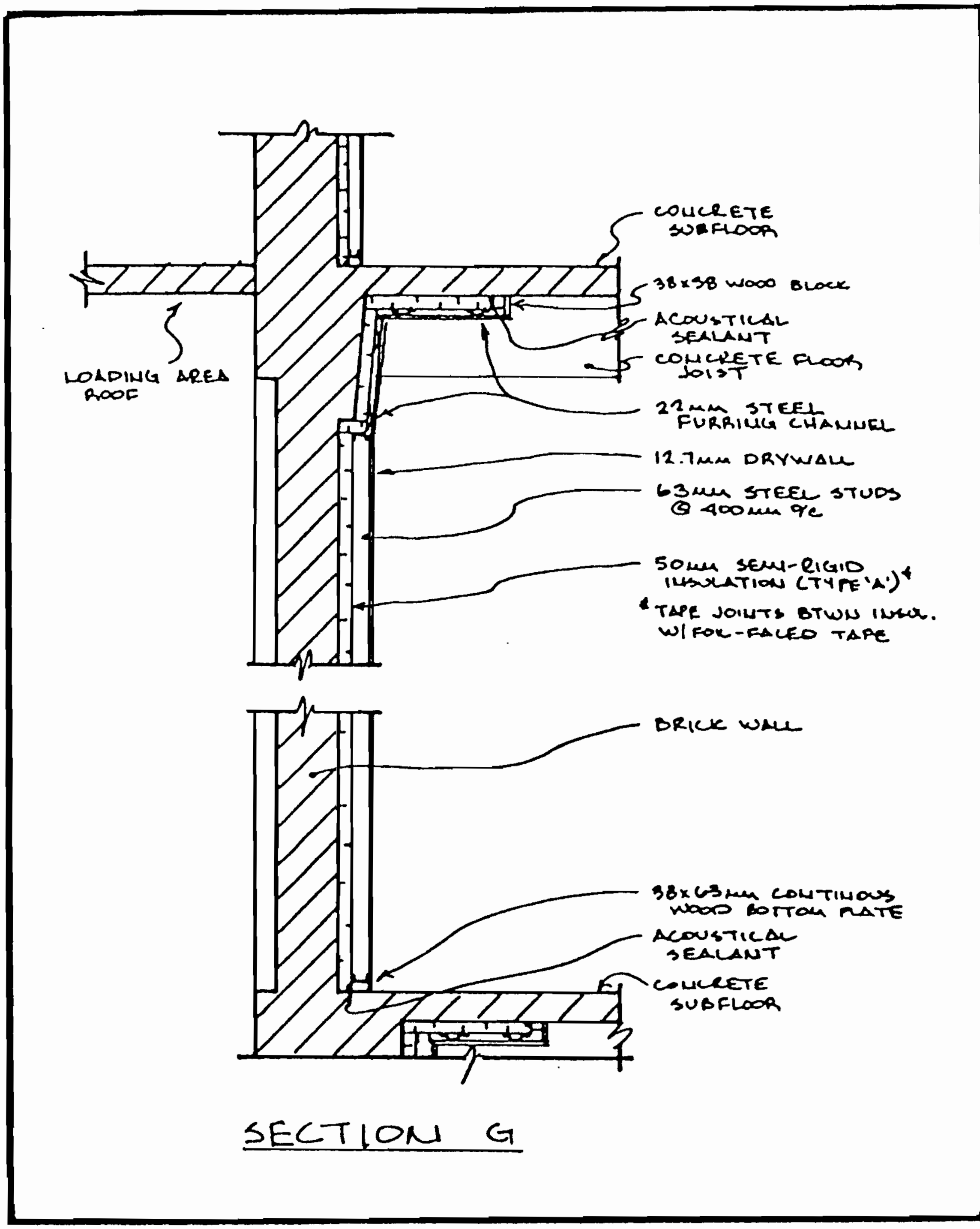


Figure A-11 Section H through upper floor wall

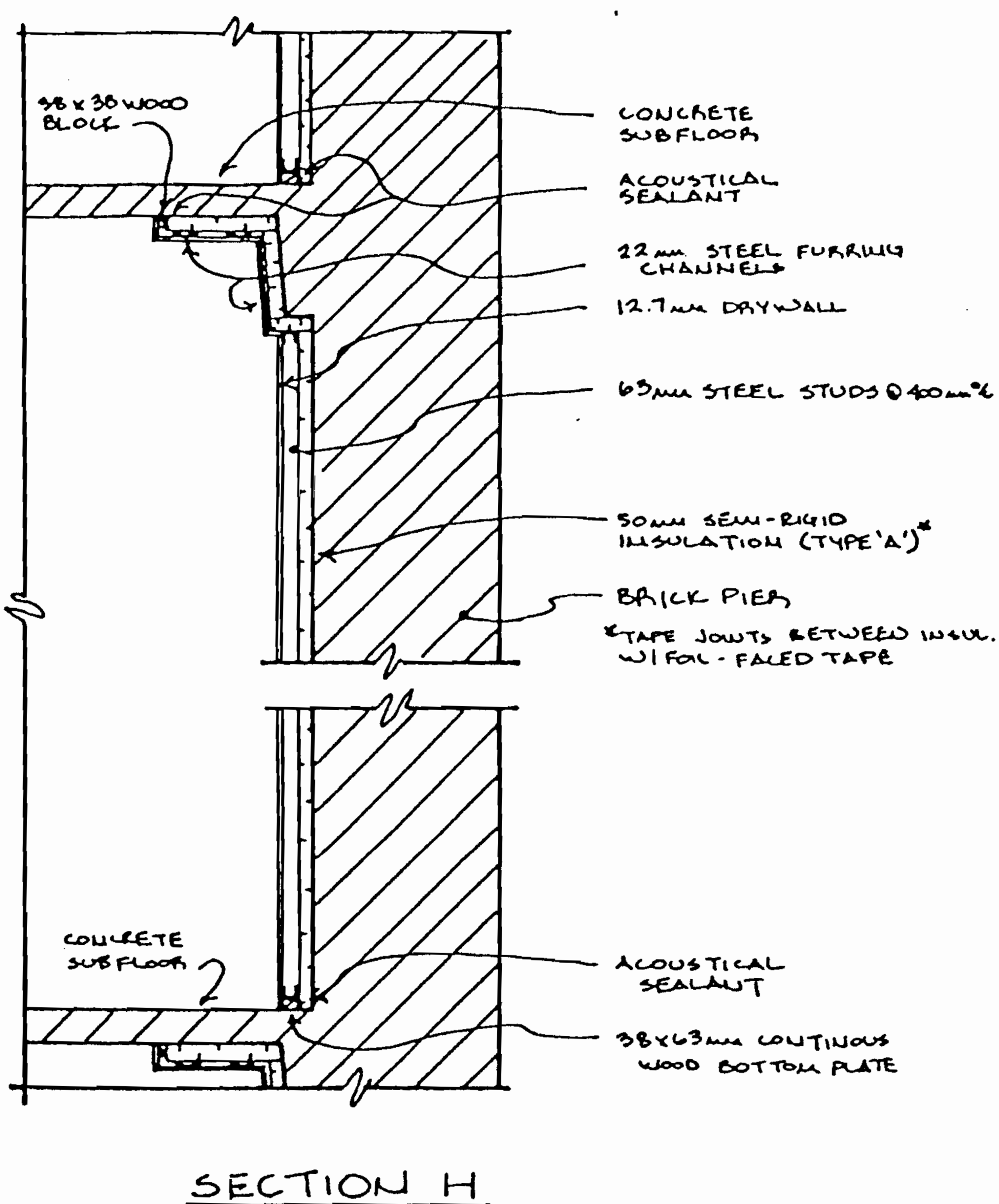


Figure A-12 Section J through upper floor window

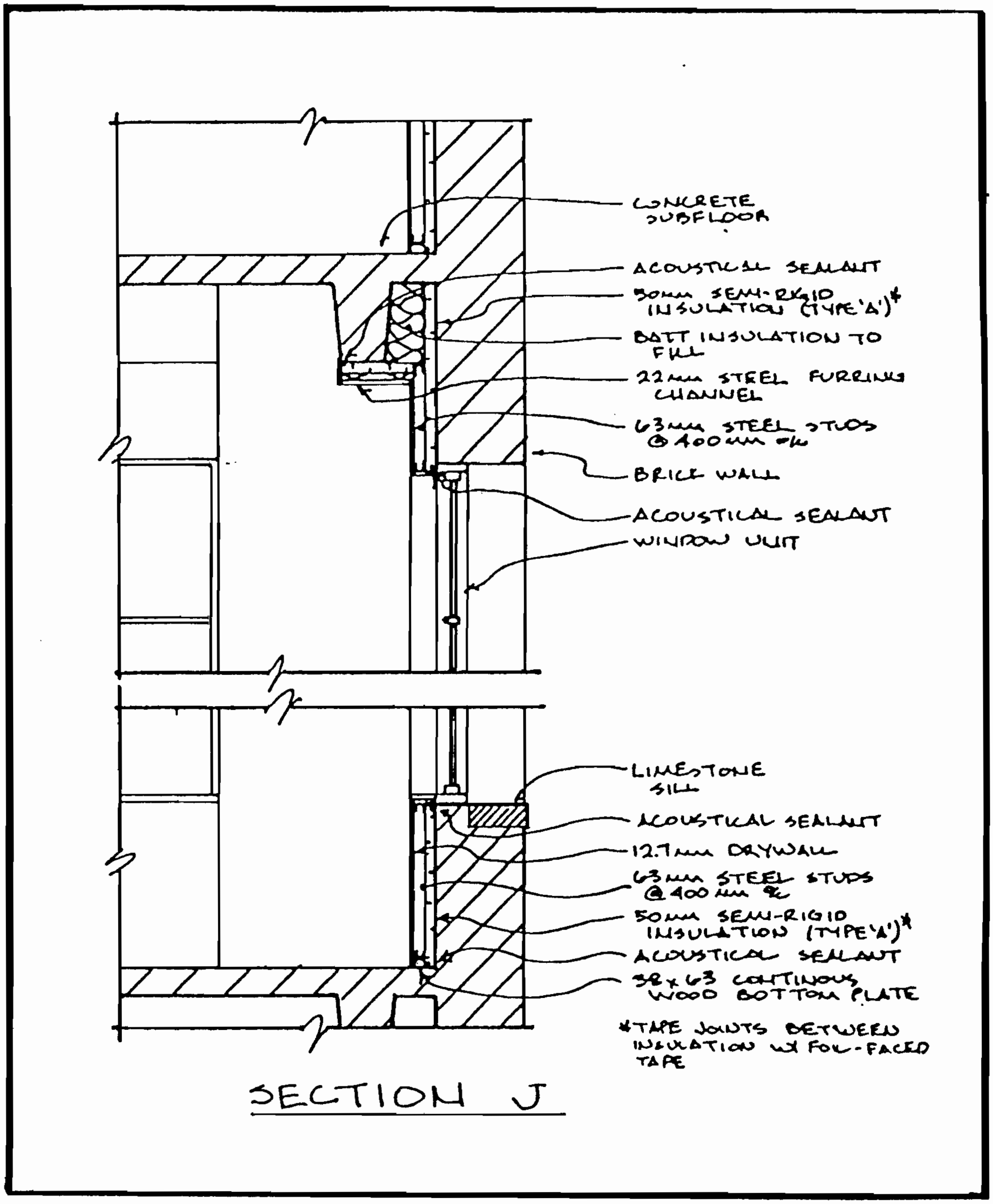


Figure A-13 Section K through load bearing masonry wall

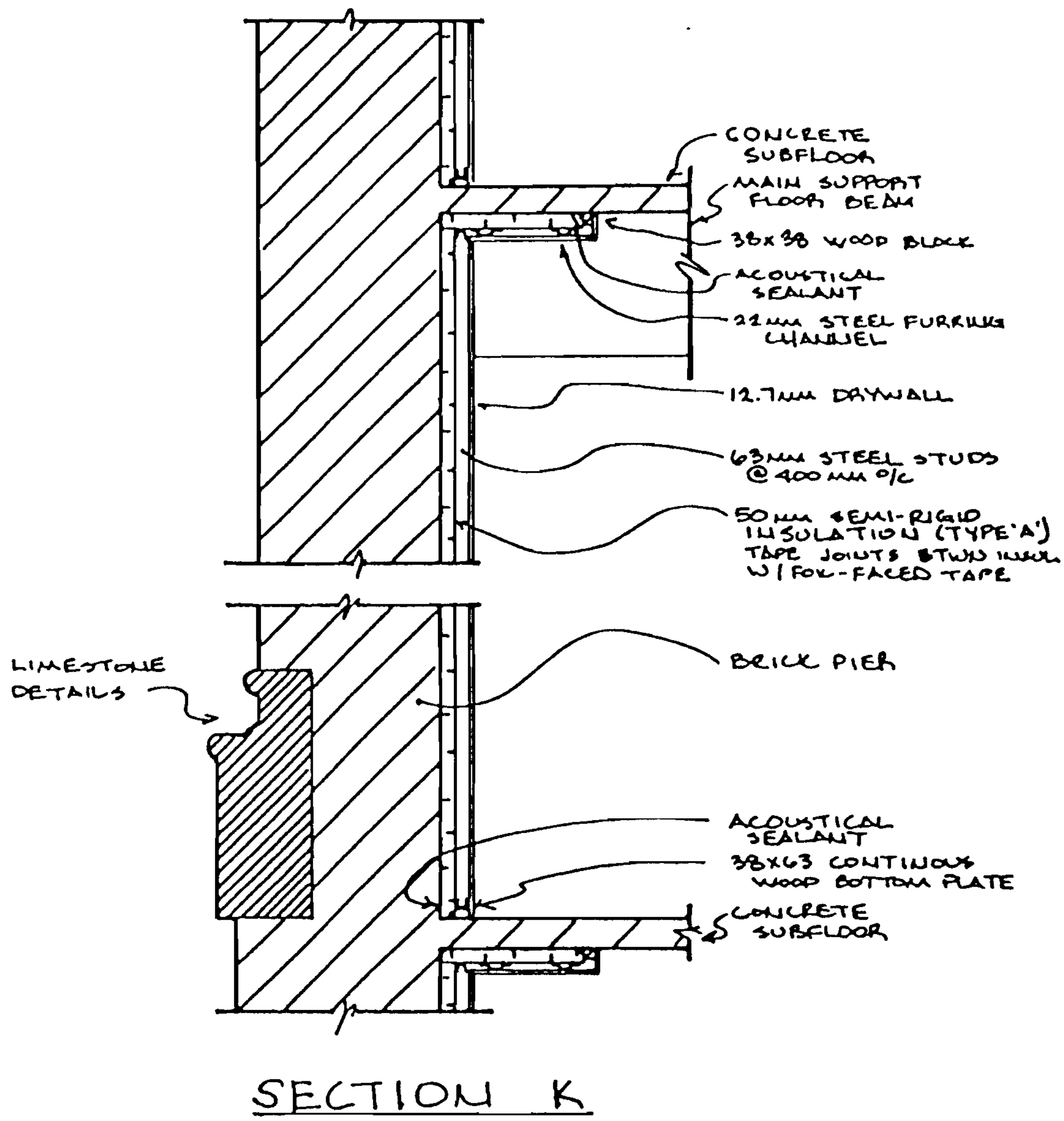


Figure A-14 Section L through window in load bearing masonry wall

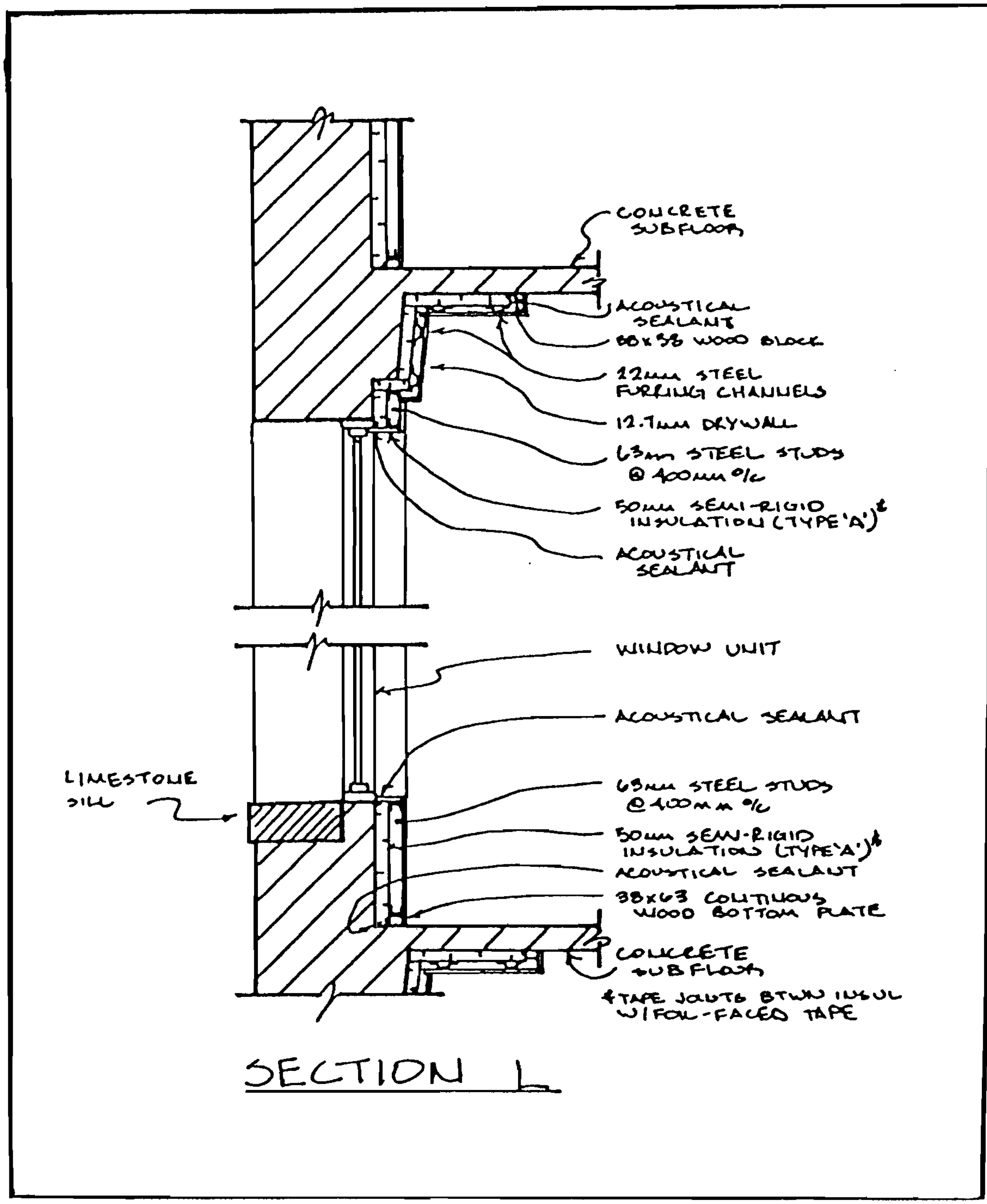


Figure A-15 Section M through east wall

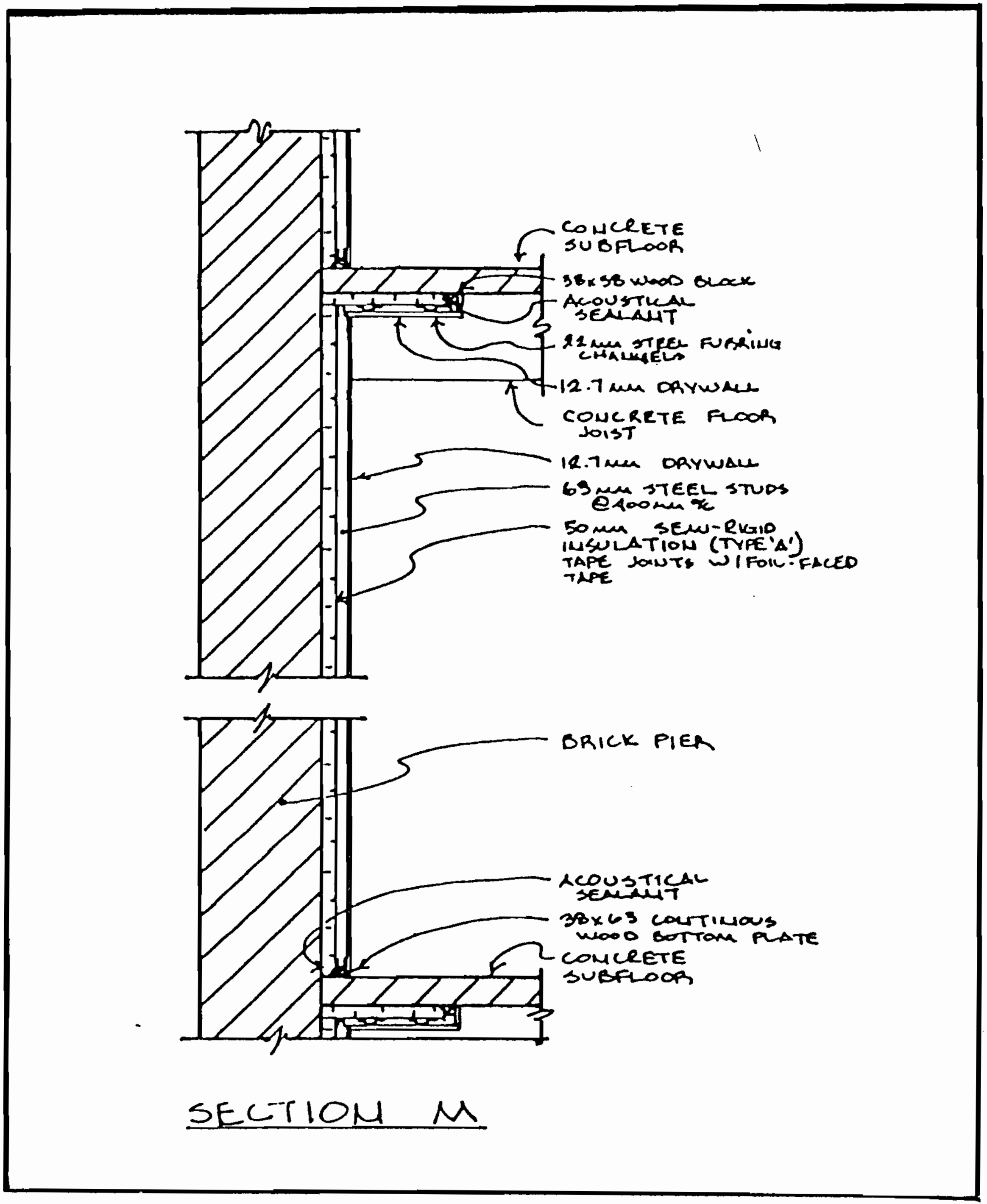
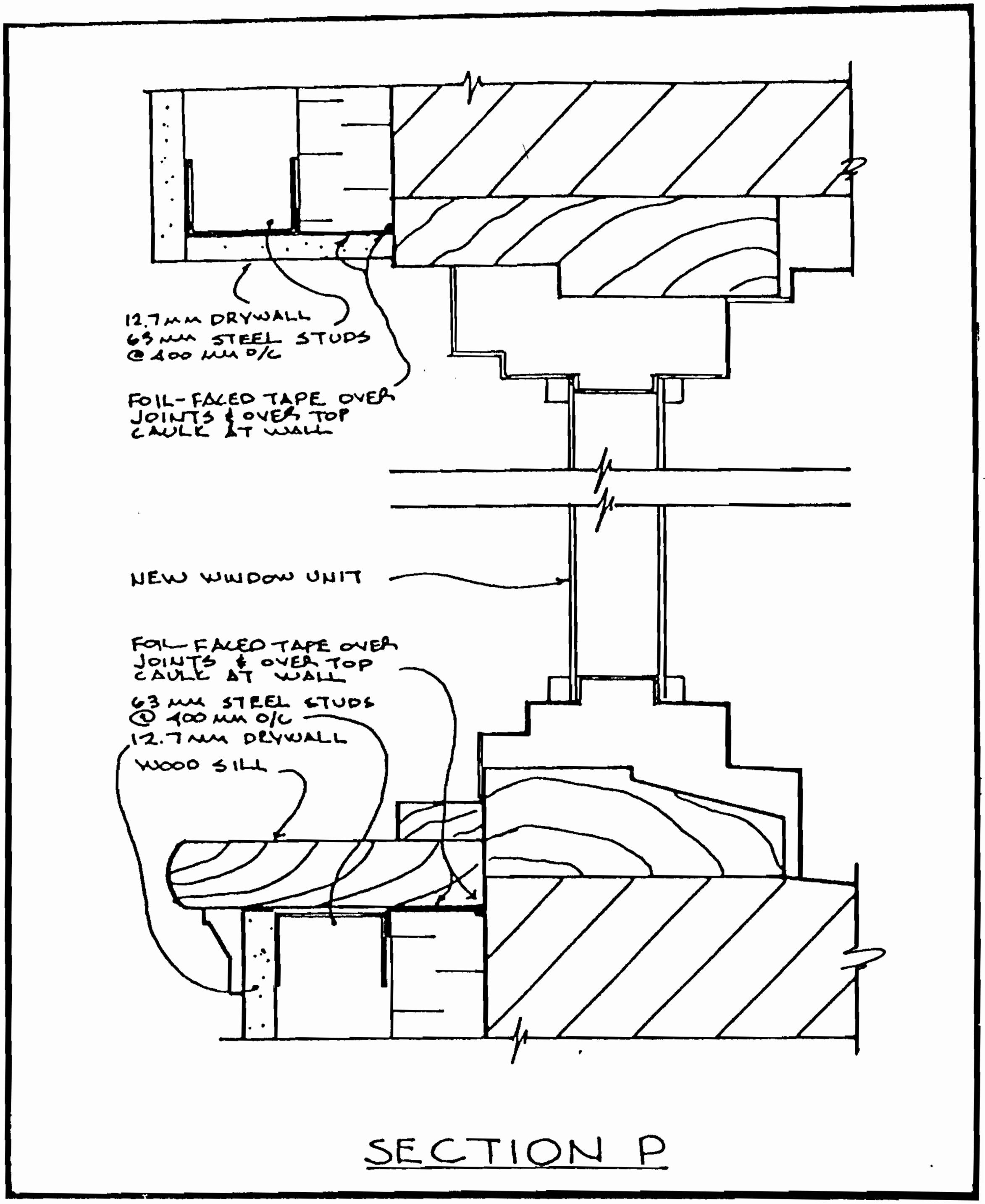


Figure A-16 Section P vertical window detail



Appendix B
Sensor Location

This appendix contains a list with the location of the sensors accompagnied by a series of diagrams.

List of Sensor According to Location

Sensors on exterior face of insulated wall section
Holes in wall filled with a 1:1:6 mortar

Thermocouples

T21	95 mm into wall about midway up the wall
T20	On wall surface about midway up the wall
T22	On wall surface at floor level

Resistance sensors

R20	Brass pins on the surface of the wall
R21	Clay moisture block 93 mm into wall

Rain gauge

RG1	Large rain gauge

Sensors on interior face of insulated wall section

Holes in wall filled with a 1:3:12 mortar

Thermocouples

T33	Top opening
T34	2nd opening from top
T35	In hole drilled to steel column (heat shrink cover)
T36	In hole drilled offset from steel column (heat shrink cover)
T41	On brick surface left side of main opening
T42	On brick surface right side of main opening
T43	Exterior of drywall
T44	Interior of drywall
T45	Foil surface at main opening (tape backing used to electrically insulate soldered end from foil).
T46	At beam-drywall intersection (room side)
T47	At floor level underneath drywall (just placed under dry wall section when it was placed back in).
T48	Wall-floor junction in bottom opening

Resistance sensors

R30	Sand-lime moisture block in hole drilled to steel column
R31	Sand-lime moisture block in hole offset from steel column
R32	Brick resistance sensor placed on floor touching wall and under insulation
R33	Pin sensor in brickwork in main opening
R34	Pin sensor in brickwork in bottom opening

Sereda sensors

The Sereda sensors where placed on the inner face of the insulation foil with the sensor grid facing the insulation.

S11	2nd opening from the top
S12	Main opening
S13	Bottom opening

RHT sensors

RHT14 In stud space of main opening

RHT13 On face of drywall

Heat flux transducer

F1	Against brickwork at main opening (serial # PU 4.3.0223). Fixed on using draft stop sealant.

Sensors on interior face of uninsulated wall section

Thermocouples

T1 In hole into wall at column
T2 At surface of wall at column
T3 In left hole into wall
T4 At surface by left hole into wall
T5 In right hole into wall
T6 At surface by right hole into wall
T7 Top of wall beneath beam perpendicular to wall
T8 Top of wall beneath beam parallel to wall
T9 At bottom of wall at column
T10 At bottom of wall in line with right hole
T11 Window. Attached with a clear, waterproof plastic tape
T12 Steel lintel above window

Resistance sensors

R1 In left hole in wall
R2 At surface by left hole
R3 In right hole in wall
R4 At surface by right hole

Sereda sensors

S2 Window. Attached using Bostik RTV silicone sealant.
S3 Steel lintel above window. Glued on with epoxy.

Heat flux meter

F1 On inner surface of brick wall (serial # PU 4.3.0224). Attached with Bostik RTV Silicone sealant. Thickness of sealant between sensor and wall estimated to vary from 2-5 mm. Surface covered with a 100 mm circular cork disk, 4 mm thick using removable double sided tape (3M double coated, window film mounting tape; tape in 12 mm strips).

Sensors on exterior face of uninsulated wall section

Thermocouples

T24 On wall surface about midway up the wall

T23 94 mm into wall about midway up the wall

N.B. Please note that T23 and T24 have been interchanged. Analysis of their temperature readings suggested that they were crosswired or had been labeled incorrectly

T25 On wall surface at floor level

T26 On thinner wall section about midway up the wall

Resistance sensors

R22 Brass pins on the surface of the wall

R23 Clay moisture block 94 mm into wall

Rain gauge

RG2 Small rain gauge

Sereda sensor

S1 Close to rain gauge

RHT sensor

RHT15

Pressure sensor

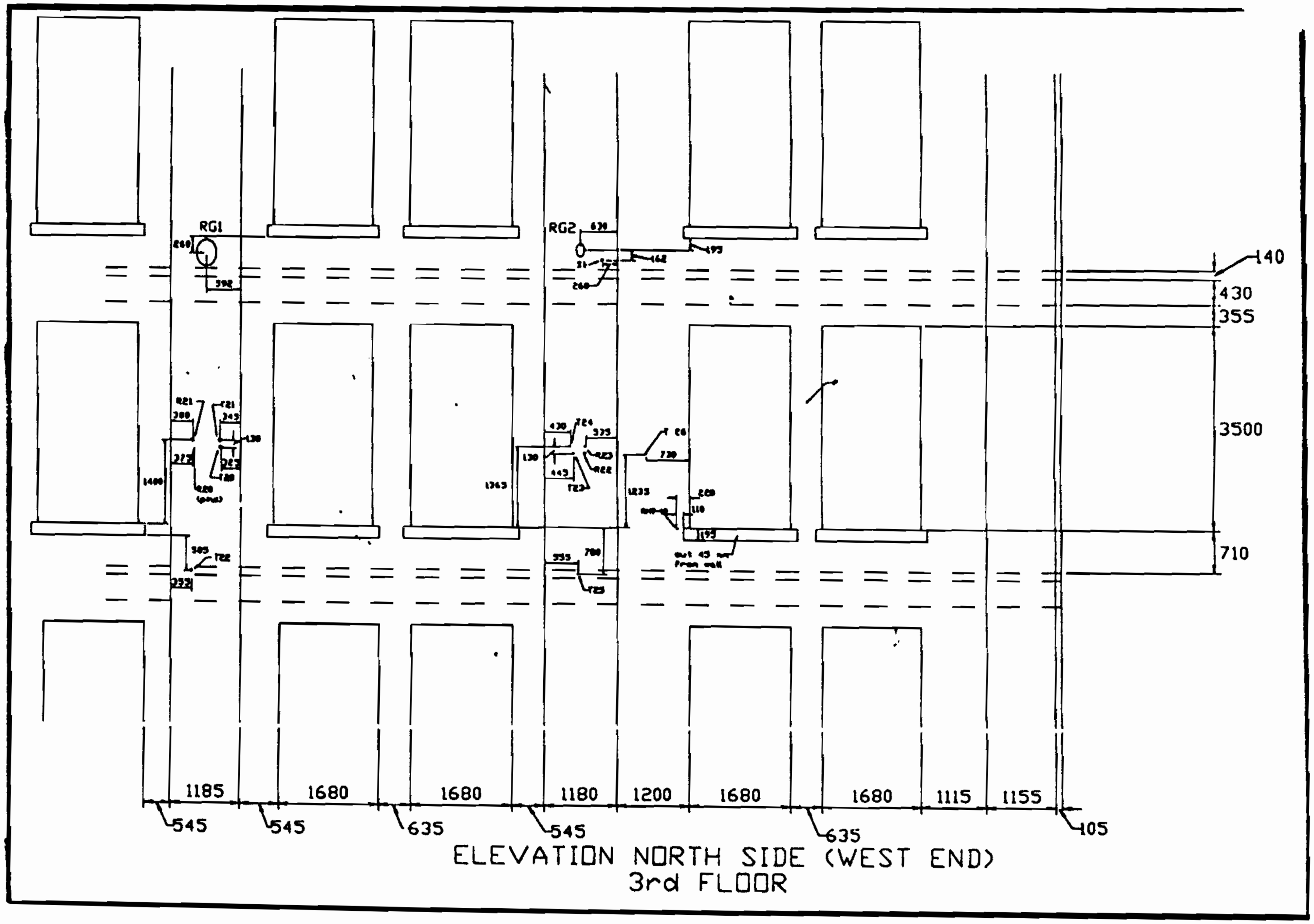


Figure B-1 Sensor location on exterior elevation

Figure B-2 Sensor location on exterior of the uninsulated wall section

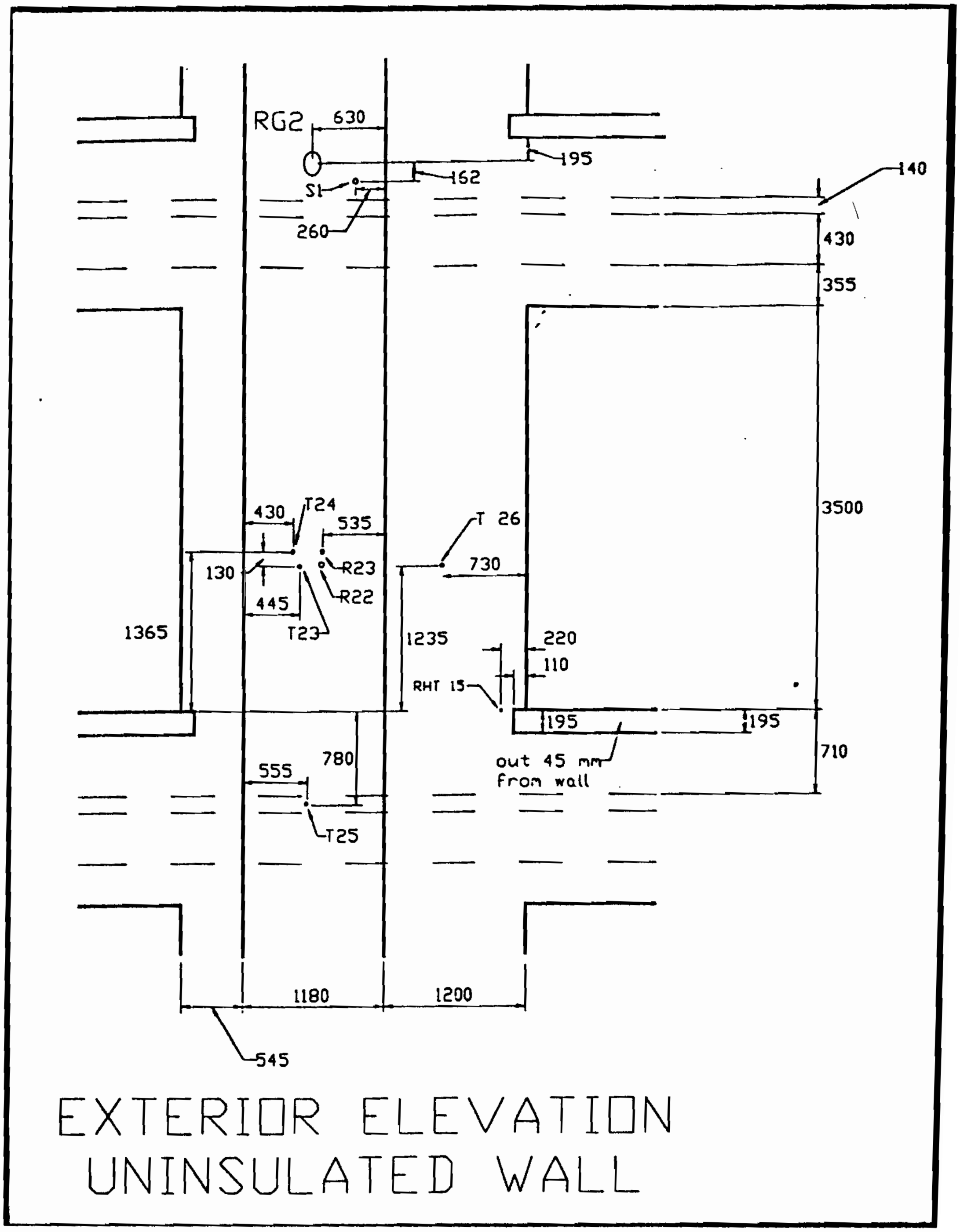
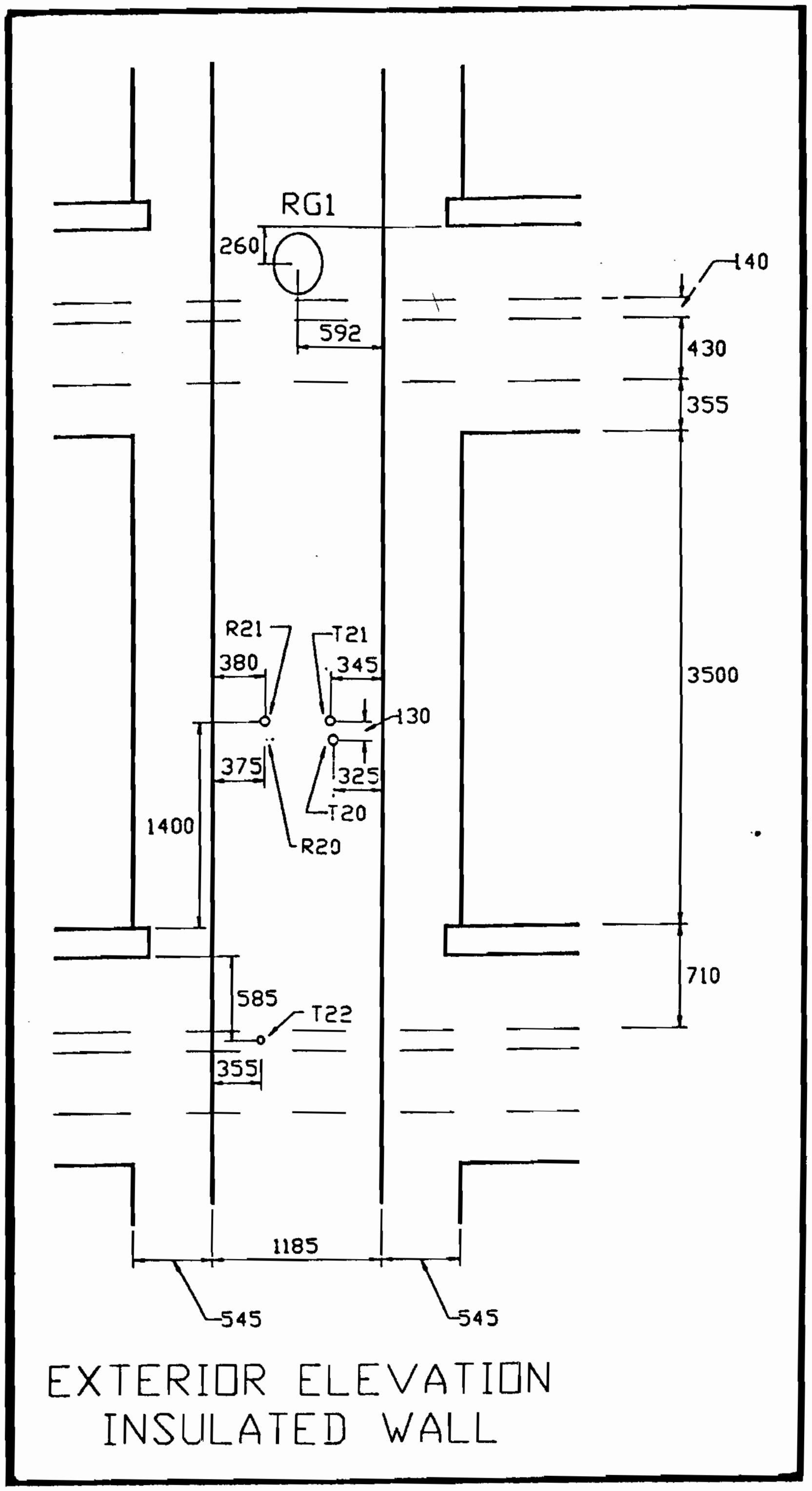
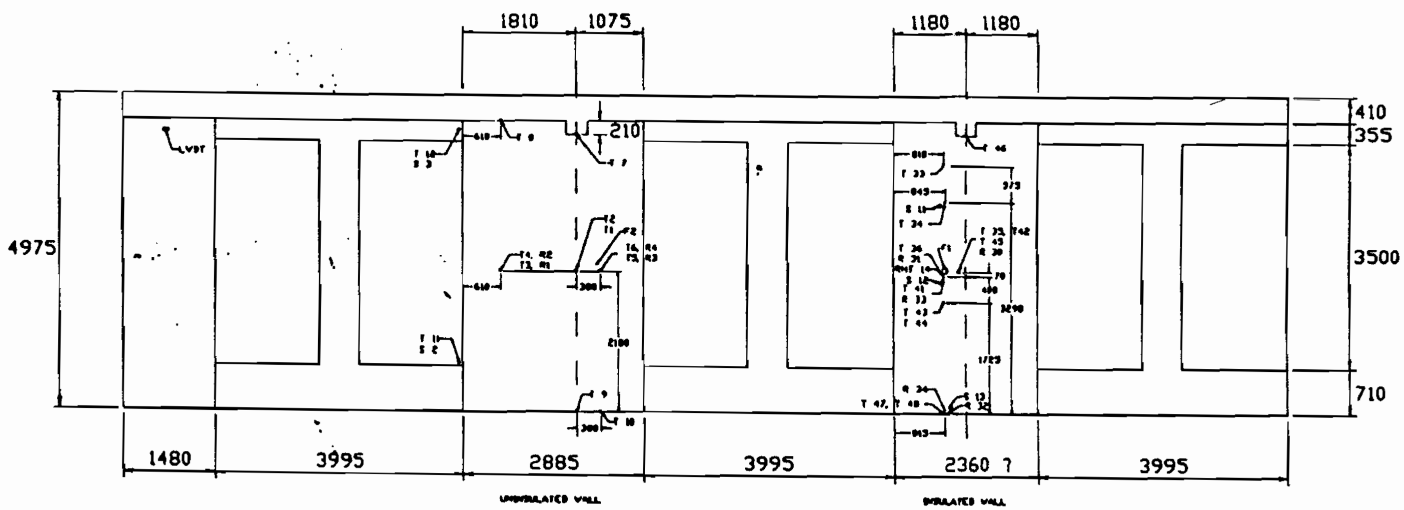


Figure B-3 Sensor location on exterior of the insulated wall section





INTERIOR ELEVATION NORTH SIDE (WEST END)
3rd FLOOR

Figure B-4 Sensor location on interior elevation

Figure B-5 Sensor location on interior of the uninsulated wall section

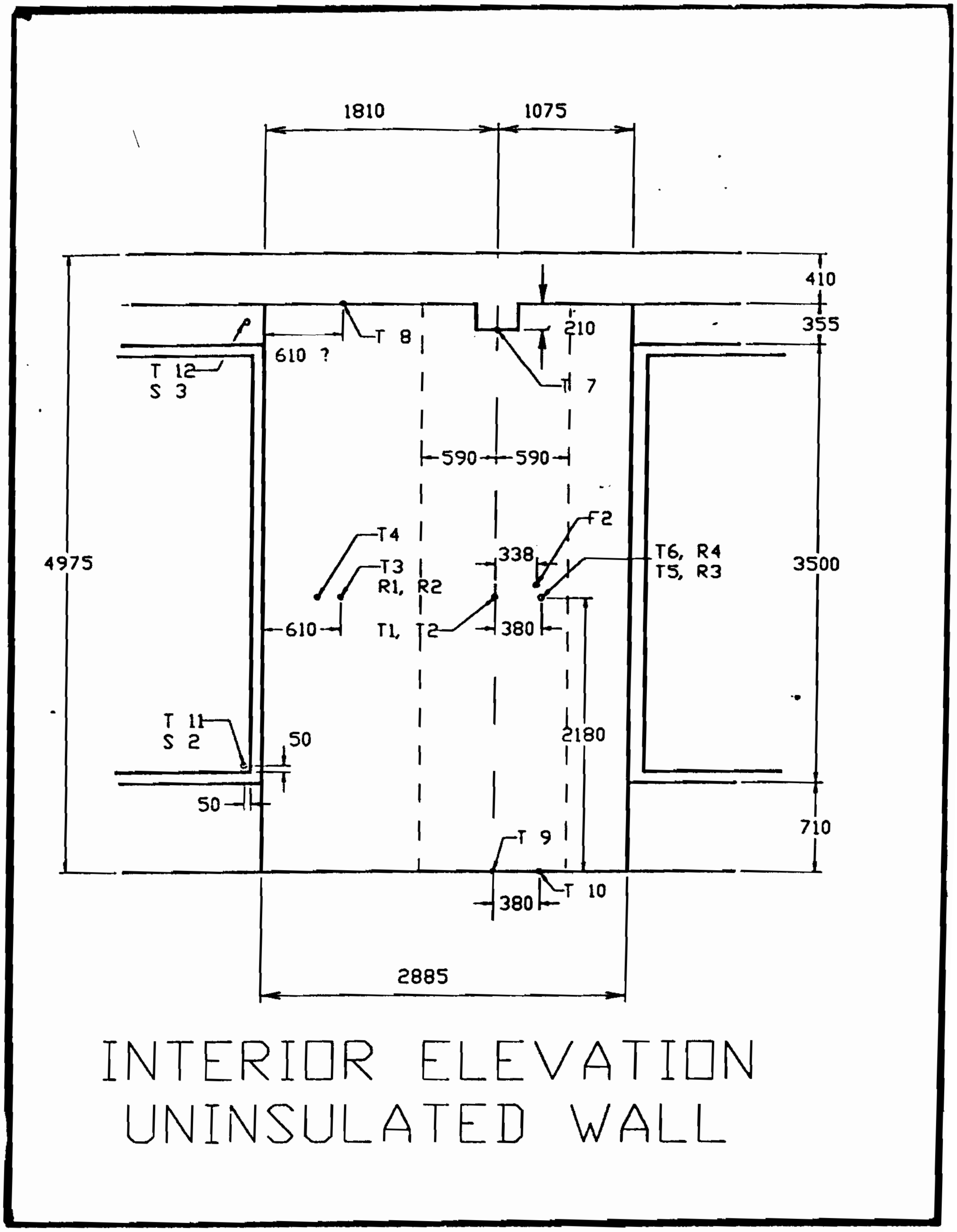
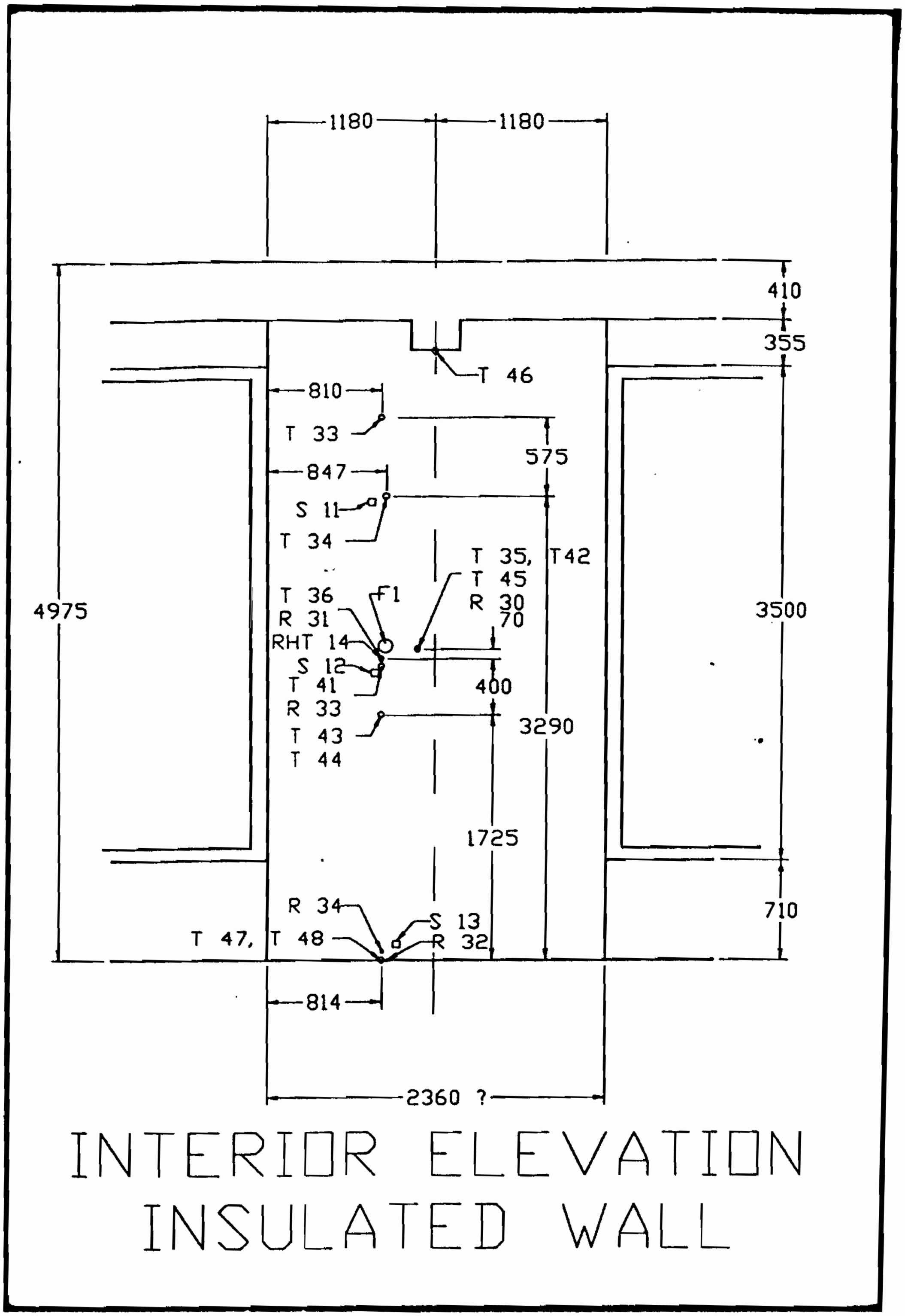


Figure B-6 Sensor location on interior of the insulated wall section



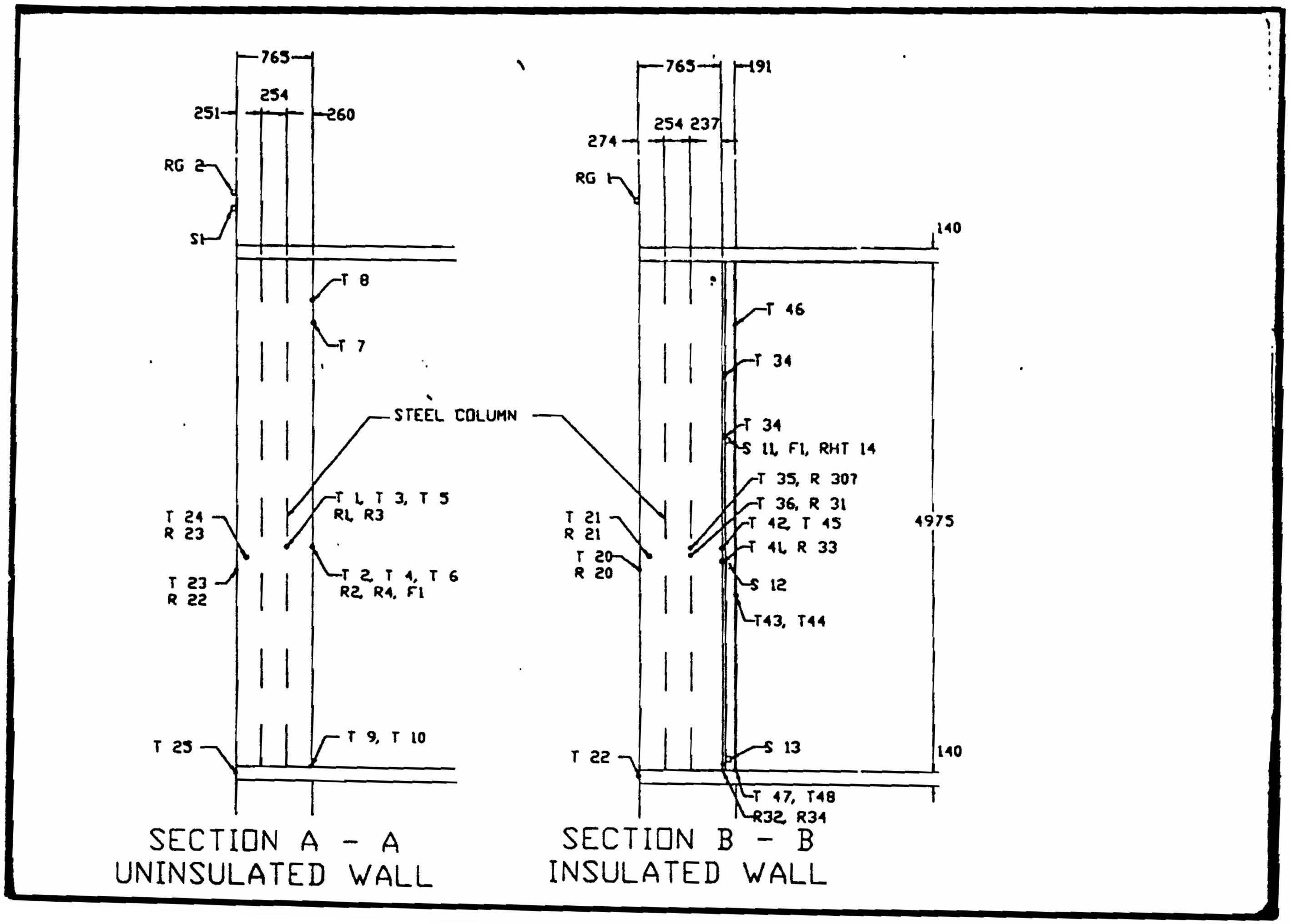
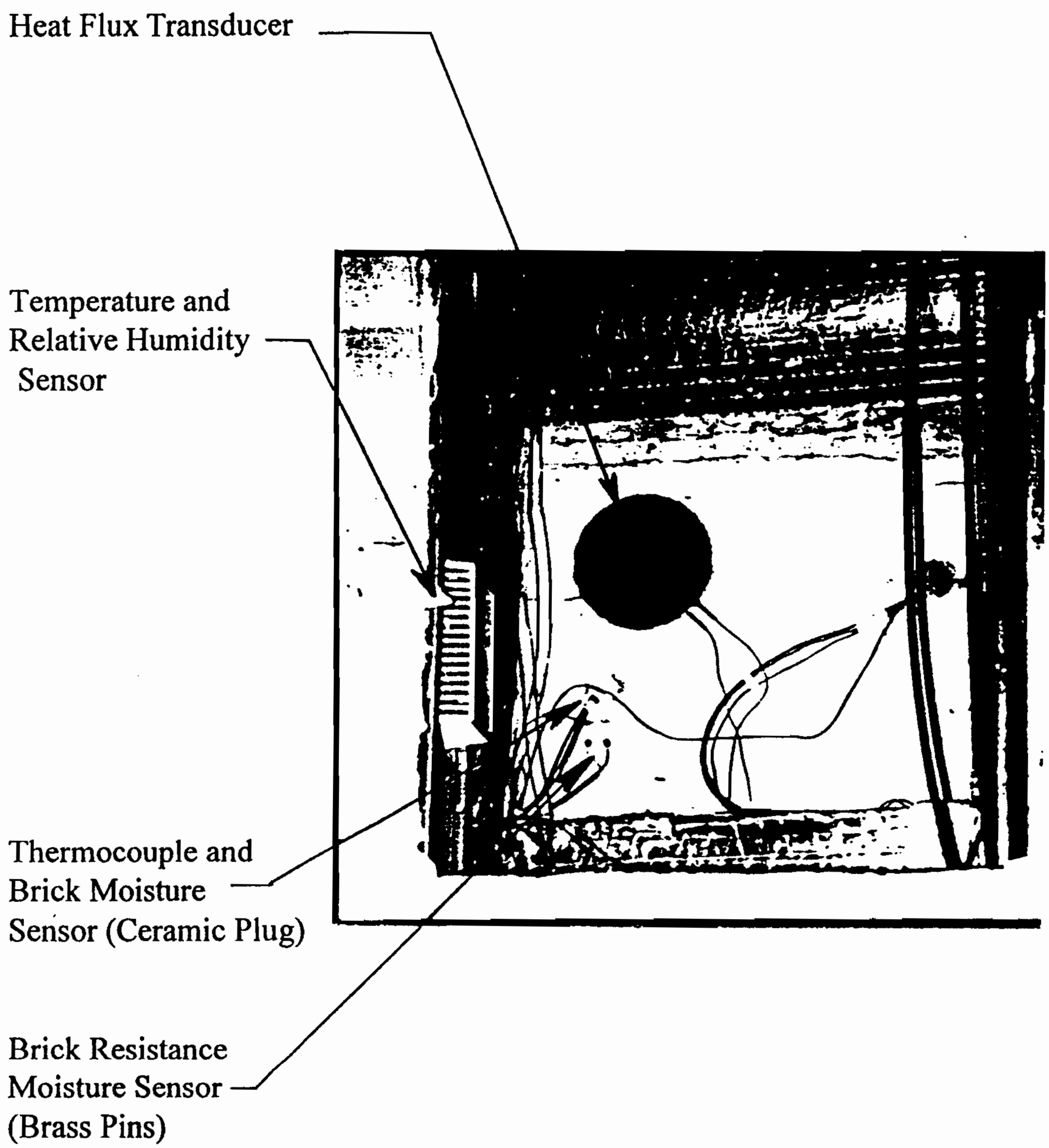


Figure B-7 Sensor location through wall cross section

Figure B-8 Main Opening at mid-height in insulated wall



Bibliography

1. Amorosso, G.G. and V. Fassina,
   Stone Decay and Conservation.
   Elsevier, New York, 1983.

2. Ashurst J. and N. Ashurst,
   Stone Masonry.
   Halsted Press, Toronto, 1988.

3. Ashurst J. and N. Ashurst,
   Brick, Terracotta and Earth.
   Halsted Press, Toronto, 1988.

4. Ashurst J. and N. Ashurst,
   Mortars, Plasters and Renders.
   Halsted Press, Toronto, 1988.

5. Berry, V.,
   James McDiarmid.
   Winnipeg Art Gallery, Winnipeg, 1982

6. Chidiac, S.E., Kumaran, K., Maurenbrecher, A.H.P. and Shirtliffe, C.,
   The Effects of Upgrading the Thermal Resistance of the Walls and Roof of the Custom Examining Warehouse. Report No CR-6516.1,
   Institute for Research in Construction, Ottawa, 1991.

7. Denhez, M.,
   Heritage Fights Back.
   Heritage Canada, Ottawa, 1978

8. Drysdale, R. G. and G. T. Suter,
   Exterior Wall Construction in High-Rise Buildings.
   Canada Mortgage and Housing Corporation, Ottawa, 1991

9. Falkner, A.,
   Without Our Past.
   University of Toronto Press, Toronto, 1977.

10. Fram, M.,
Well Preserved: the Ontario Heritage Foundation's Manual of Principles and Practice for Architectural Conservation.
Ontario Heritage Foundation, Toronto, 1988.

11. Gauri, K., G. Holdren and W. Vaughan,
Cleaning Efflorescences from Masonry.
ASTM STP 935 Cleaning Stone and Masonry, J. Clifton Editor
American Society for Testing Materials, Philadelphia, 1983.

12. Glainville, J. I., and Hatzinikolas,
Engineered Masonry Design
Winston House Enterprises, Winnipeg, 1989.

13. Hechler, J.J., Boulanger, J., Noël, D., Dufresne, R., and Pinon, C.,
A Study of Large Sets of ASTM G 84 Time-of-Wetness Sensors.
ASTM SP 1000 Silver Anniversary Volume, Philadelphia, 1990.

14. Highfield, D.,
Rehabilitation and Re-use of Old Buildings.
E. & F. Spon, London, 1987.

15. Hutcheon, N.B. and Handegord. G.O.P.,
Building Science for a Cold Climate.
National Research Council of Canada, Ottawa, 1983

16. Jokien, E. P.,
Canadian Heritage Conservation.
Lone Pine Publishing, Edmonton, 1987.

17. Kalman, H.,
The Evaluation of Historic Buildings.
Parks Canada, Ottawa, 1979.

18. Lion, E.,
Building Renovation and Recycling.
John Wiley & Sons, Toronto, 1982.

19. London, M. and Bumbaru, D.,
Traditional Masonry. Technical Guide No.3
Héritage Montreal, Montreal, 1986.

20. London, M.,
Masonry. How to Care for Old and Historic Brick and Stone.
Preservation Press, Washington, 1988.

21. Lstiburek, J. and J. Carmody,
Moisture Control Handbook.
Van Nostrand Reinhold

22. MacFarlane, K.,
Customs Examining Warehouse. Building Report 88-52,
Federal Heritage Building Review Office,Ottawa, 1988.

23. Ransom, W.,
Building Failures. Diagnosis and Avoidance.
E. & F. Spon, New York, 1981.

24. Reiner, L.E.,
How to Recycle Buildings.
McGraw-Hill, Toronto, 1979.

25. Saunders, I., Rostenski, R., and Carrington, S.,
Early Buildings in Winnipeg. Manuscript Report No. 389, Vol. V,
Parks Canada, Ottawa, 1974.

26. Smith, R., T. Honkala and C. Andres,
Masonry: Materials Design Construction.
Reston Publishing, Reston, 1979

27. Sowden, A.M.,
The Maintenance of Brick and Stone Masonry Structures.
E. & F. Spon, New York, 1990.

28. Thompson, W.P., Lehrman, J., Denhez, M., Rostecki, R., and Filler, G.,
Winnipeg's Historic Warehouse Area.
Heritage Canada, Ottawa, 1976

29. Ward, E.N.,
Heritage Conservation - The Built Environment. Working Paper No. 44,
Land Use Policy and Research Branch, Land Directorate,
Environment Canada, Ottawa, 1986.

30. Weber, H. and K. Zinmeister,
Conservation of Natural Stone.
Expert Verlag. Ehningen, 1991.

31. Whiffen, M.,
American Architecture Since 1780.
M.I.T. Press, Cambridge, Massachusetts, 1981

32. Winkler, E. M.,
Stone: Properties. Durability in Man's Environment.
Springer-Verlag, New York, 1973

33. *AFEMS.*
FEM Engineering Corporation, Inglewood, California, 1991

34. *Detailed Insulated Wall Design.*
National Testing Laboratories Limited, Winnipeg, 1991

35. *EDLOG. SPLIT, TELCOM & TERM.*
Campbell Scientific Inc., Logan, Utah, 1991.

36. *Growth at the Port of Winnipeg.* Vol. X. No. 12,
National Revenue Review, Ottawa, 1937

37. *Handbook for Evaluating Heritage Buildings and Areas.*
Heritage Section, Community Planning Branch,
Planning and Development Department, City of Ottawa, Ottawa, 1989.

38. *Heritage Structures Manitoba.*
Public Works Canada, Ottawa, 1984

39. *KOBRU86,*
Physibel Building Physics, Maldegem, Belgium, 1990

40. *Microsoft EXCEL.* Version 4.0,
Microsoft Corp., Redmond, Washington, 1992.

41. *PKZIP.*
PKWare Inc., Brown Deer, Wisconsin, 1993

42. *Preliminary Report.*
National Testing Laboratories Limited, Winnipeg, 1991

43. *Report of the Minister of Public Works on the Works Under His Control for the Fiscal Year Ended March 31.1928.*
Dominion of Canada, Ottawa, 1928

44. *Report of the Minister of Public Works on the Works Under His Control for the Fiscal Year Ended March 31.1935.*
Dominion of Canada, Ottawa, 1935

45. *TRISCO.*
Physibel Building Physics, Maldegem, Belgium, 1990

46. *Structural Renovation of Traditional Buildings*. CIRIA report 111, Construction Industry Research & Information Association, London, 1986.