

FILLING IN THE BLANKS: DOCUMENTING CONCEALED FABRIC AND DETERIORATION IN  
EXISTING STRUCTURES

John M. Evans

A THESIS

in

Historic Preservation

Presented to the Faculties of the University of Pennsylvania  
in Partial Fulfillment of the Requirements of the Degree of

MASTER OF SCIENCE IN HISTORIC PRESERVATION

2015

---

Advisor

John Hinchman

Lecturer, Graduate Program in Historic Preservation

---

Program Chair

Randall F. Mason

Associate Professor

## **Acknowledgements**

Thank you to John Hinchman, George C. Skarmeas, and Dominique M. Hawkins, who provided their expertise, advice and support throughout this process.

## Table of Contents

Acknowledgements .....	ii
Table of Contents .....	iii
List of Figures .....	v
List of Illustrations .....	vi
1. Introduction .....	1
2. Concealed Conditions in the Practice of Architecture .....	4
2.1 Preamble .....	4
2.2 Importance.....	5
2.3 Current Industry Standards and Guidelines.....	8
2.4 Cost-Efficient Investigation .....	12
3. Subsurface Investigation Methods.....	19
3.1 Preamble .....	19
3.2 Archival Research.....	21
3.3 Recording & Visual Condition Assessment.....	24
3.4 Non-Destructive Testing .....	25
3.5 Probes & Destructive Examination .....	38
3.6 Comparing Available Technologies and Techniques.....	39
4. Developing a Comprehensive Subsurface Investigation Program .....	44
4.1 Preamble .....	44
4.2 Key Concepts .....	45
4.3 Conclusion: Structuring an Investigation Program.....	52

5. Bibliography .....	60
6. Index.....	65

## List of Figures

<b>Figure 2-1:</b> Virginia State Capitol – Ground Floor Plan excerpt (HABS, 1988) .....	10
<b>Figure 3-1:</b> Virginia State Capitol – excerpt of Ground Floor Plan (John K. Peebles, et.al., 1904)	23
<b>Figure 3-2:</b> Nondestructive Evaluation of Wood: Factors that can be determined using NDT. ....	40
<b>Figure 3-3:</b> Appropriate Test Methods to Evaluate or Investigate Various Masonry Conditions. ...	41
<b>Figure 3-4:</b> Comparative summary of subsurface investigation methods (by author) .....	43

## List of Illustrations

<b>Illustration 2-1:</b> Potential combinations of investigative cost and information obtained.....	12
<b>Illustration 2-2:</b> Proposed relationship between understanding and cost for a typical investigative technique .....	13
<b>Illustration 2-3:</b> Potential wasted expense in a project where investigation continues beyond the level of information required .....	15
<b>Illustration 2-4:</b> Potential for wasted expense from improper selection of investigative technique	16
<b>Illustration 2-5:</b> Chart illustrating potential risk due to insufficient investigation.....	17
<b>Illustration 4-1:</b> Chart showing an idealized progression of investigation.....	50
<b>Illustration 4-2:</b> Flowchart showing basic approach to subsurface investigation in historic buildings .....	59

## 1. Introduction

The need to develop a highly accurate set of “as-found” condition documents presents a significant challenge in the practice of architecture for any project involving an existing building. For the majority of new buildings, an adequate construction documentation package can be developed simply by applying industry standards along with carefully engineered and well-detailed methods and materials. In contrast, projects involving intervention in existing buildings require an in-depth understanding of the existing building, its methods of construction, and its condition (ie, extent of deterioration). This requirement is particularly critical in the practice of preservation architecture, when renovation, adaptive re-use, and/or restoration projects affect structures with physical fabric of intrinsic historic value.

Since the advent of heritage documentation and recording programs such as HABS/HAER, professionals have attempted to define the challenges and requirements for documenting the physical fabric of existing structures in a systematic manner. Tools such as the HABS Guidelines attempt to ensure that recording is performed in a responsible manner that meets certain minimum standards; however, these standards and guidelines address only visible conditions, those that can be measured and photographed and those where physical reality is fully observable.

The desire to understand and interpret concealed conditions is by no means a new problem, since man has been adding to existing buildings for as long as they have existed. Yet, advancements in technology have allowed a marked increase in the ability to understand both the layout of concealed elements, such as wood framing configurations, and the existence of

deterioration mechanisms invisible to the naked eye. Unfortunately, these advancements have not necessarily corresponded with the development of standards and guidelines for systematically approaching this type of recording.

This thesis, an effort to tackle this difficult problem, is organized in three basic parts.

Chapter 2 describes the “what”, “why”, “when”, and “where”. What are concealed conditions? Why are they important to the practice of architecture? When is it important to document them, and when can they be left for future generations to uncover? Where are the locations that are most important to document?

Chapter 3 is the first portion of the “how”. It describes the techniques, technologies and methods that form the basis of any investigation into concealed conditions in a historic building, and attempts to organize them in a way that allows for comparative analysis based on their respective strengths and weaknesses.

An important note: while a significant portion of this Chapter is, by necessity, focused on the basic explanation of a variety of non-destructive testing (NDT) technologies, this thesis is not a study of NDT. It is an analysis of the full range of methodologies and techniques that can be applied to the specific problem of concealed fabric and deterioration in historic buildings. While NDT methods are often viewed as the tools of choice for investigating these concealed conditions, this thesis discusses a more overarching grouping referred to here as “subsurface investigation”<sup>1</sup>. SI techniques are not limited to just NDT but include a broader range of methods, from simple visual survey to selective probes, that should not be overlooked or overshadowed by NDT. The full

---

<sup>1</sup> This term is commonly used in geotechnical investigation of below-grade conditions, but it is equally applicable here, and provides the advantage of a clear distinction between NDT and the broader range of methods included in SI.



range of SI techniques all work to record fabric and conditions that are impossible to see without specialized tools and methods.

Building upon this theme, Chapter 4 is the second portion of the “how”. Using the toolbox presented in the previous sections, it describes the fundamental concepts that must be understood to organize a successful program for investigating concealed conditions in a systematic way.

This approach is based partially on the author’s experience and involvement in assessments and investigations of significant historic structures, over the course of the past thirteen years. It is written from the perspective of an architect who has been involved in extremely large and complex interventions in National Historic Landmark buildings, with construction budgets ranging from \$10 million to over \$100 million. On the surface, it may seem that the issues relating to these types of “high-road” buildings are very different from those involved in small projects dealing with vernacular architecture or buildings of moderate significance. Yet, it is the author’s opinion – and hope – that this experience has resulted in an illustration of concepts and ideas that are applicable to a wide range of projects and situations.

## 2. Concealed Conditions in the Practice of Architecture

### 2.1 Preamble

In the context of preservation architecture, the term “concealed conditions” is commonly used to describe a wide range of building fabric and deterioration that are not visible to the naked eye. In some cases, there may be some visual evidence at the surface level that indicates what lies beneath, but determining the true configuration, extent and cause of the subsurface condition typically requires additional specialized methods.

Generally speaking, concealed conditions fall into two major categories.<sup>2</sup> The first category includes the materials and assemblies that are part of the basic construction of a building, but are concealed by additional layers or materials. Typical examples include the configuration of wood framing members, thickness of structural masonry backup, and location of steel lintels embedded within a brick wall. To use a medical analogy, these “healthy” concealed conditions are the bones of the building, concealed beneath its skin.<sup>3</sup>

The second category includes deterioration mechanisms that have negatively affected a building or structure, but are also not visible at the surface. Typical examples of this type of concealed condition include rot and deterioration of wood framing, mortar loss within a masonry

---

<sup>2</sup> A review of available case studies also included several special cases that fall outside the normal practice of preservation architecture, but could certainly be considered concealed conditions, such as the use of infrared thermography to detect termite activity. These special cases are outside the scope of this thesis, although many of the principles discussed still apply. (Gilberg, Mark, Claudia Riegel, Bob Melia, and Jack Leonard. “Detecting Subterranean Termite Activity with Infrared Thermography: A Case Study.” APT Bulletin 34:2/3 (2003): 47-53.)

<sup>3</sup> In some cases, such as undersized structural elements or poorly selected materials, the assemblies themselves may actually lead directly to deterioration. Still, the existence and general configuration of the elements can still be considered part of this first category.

wall, or oxidation of a concealed steel lintel. Extending the analogy above, these “unhealthy” types of concealed conditions are the cancer that attacks the building from within.

This thesis does not focus on either type exclusively. Instead, it attempts to identify the issues, applicable techniques, and strategies that apply to the recording of concealed conditions in preservation architecture in an overarching manner. Throughout this text, in accordance with the accepted terminology in the architectural profession, the term “concealed conditions” is used to apply to both building fabric and deterioration mechanisms collectively.

## **2.2 Importance**

Clearly, subsurface investigation to develop an understanding of both types of concealed conditions in building design and construction is not a novel pursuit. This type of knowledge would have been important even for ancient interventions in existing structures;<sup>4</sup> however, over the past fifty years, efforts to assess and understand these conditions in existing buildings have become increasingly formalized. This trend has been driven largely by increased formalization of architectural drawings and specifications, and made possible by the development and increasing accessibility of specialized non-destructive techniques.<sup>5</sup>

The necessity for understanding concealed fabric and deterioration in the practice of preservation architecture stems from four broad areas of concern: historic fabric identification and

---

<sup>4</sup> Even technologies considered “modern” may have a longer history than generally assumed. In researching this thesis, the author found mention of what could be considered “non-destructive testing” occurring as early as 1878: Ihseng, M.C. “The Modulus of Elasticity in Some American Woods, as Determined by Vibration.” *Van Nostrand's Eclectic Engineering Magazine* 19 (1878): 8-9.

<sup>5</sup> Miller, Hugh C. “Preservation Technology Comes of Age in North America: Part 1.” *APT Bulletin* 37:1 (2006): 55-59. Web. 11 Nov. 2014 and Miller, Hugh C. “Preservation Technology Comes of Age in North America: Part 2.” *APT Bulletin* 37:2/3 (2006): 61-65.

protection; proper repair of existing fabric and deterioration; design of new interventions; and, cost/risk management.

The most basic issue relating specifically to concealed fabric in any historic building is the proper consideration for important historic materials that are not directly observable. Important fabric may be unknowingly concealed behind later layers or additions; while this does not absolve the architect of responsibility for its protection or recording, it is often the reason why valuable fabric suffers irreparable damage. Historic preservation standards necessitate a careful approach. Before any repair or intervention is undertaken, ideally all historic materials must be located, identified, assessed, documented and evaluated. Any project involving a historic structure must take into account the potential significance of concealed fabric and the risk of damage if the existing conditions are not understood.<sup>6</sup>

The key design process relating to concealed conditions in any existing building is the ability of the architect and the design team to develop comprehensive construction documentation for a proposed intervention. When repairing or conserving existing materials and assemblies, concealed deterioration mechanisms – such as mortar loss within a masonry wall – may require very different types of repairs than those that occur at the surface. Targeted work such as roofing or flashing repairs cannot be properly applied without a complete understanding of the cause of the failure, including specific locations where moisture infiltration is occurring.

For projects that include both repair to existing fabric and new design interventions, the issue of concealed conditions is even more complex. Beyond the required repairs to deteriorated

---

<sup>6</sup> Clark, Kate. "Informed Conservation: The Place of Research and Documentation in Preservation." APT Bulletin 41.4 (2010): 5-10.

building fabric, new design interventions require an understanding of additional layers and types of conditions. Proper installation and planning of any new systems in an existing building, including mechanical ductwork, electrical conduit and plumbing piping, depends on knowledge of existing systems and the identification of potential pathways for routing new systems within the building. Structural repairs or upgrades depend greatly on a knowledge of existing structural systems, which are concealed beneath finishes or other materials.<sup>7</sup>

Concealed fabric and deterioration also have a significant impact on risk management and project planning. Accurate budgeting for any project involving significant intervention in an existing building depends greatly on the ability of the design team and the estimator to properly assign costs to each element of a project. When concealed conditions are not properly understood, it may prevent the team from properly anticipating the work required to address them, which can make accurate documentation and estimating extremely difficult. If the extent of the unknown conditions is anticipated and catalogued, they can be accounted for in cost models, which helps reduce these hidden cost impacts to the extent possible.<sup>8</sup> Doing so often requires additional investigation and recording of the true subsurface fabric and deterioration in key areas.

Due to the combined factors of fabric identification, proper repairs, design of new interventions, and cost management, it is clear that the recording of concealed conditions should be a significant part of the process in designing an intervention in any historic structure. Unfortunately, this is by no means a straightforward exercise. While it may be relatively simple to

---

<sup>7</sup> An excellent example of the understanding of concealed conditions in structural design is described in: Mason, James A. "Nondestructive Analysis of and Strengthening Design for a Historic Church Tower in Kentucky." APT Bulletin 36:1 (2005): 35-43.

<sup>8</sup> Staley, Ronald D. "Successful Preservation Implementation: A Planned Approach to Risk Management." APTI Practice Points 01. APTI, 2010, 3.

photograph every visible surface on a historic building, it is practically impossible to “reverse-engineer” all aspects of the structure that lie beneath, and fully understand any concealed deterioration. Even if it were technically achievable, at present, the cost and time required for such a comprehensive effort would be prohibitive for any building of even moderate complexity. The crux of the problem for the preservation architect is therefore to determine exactly which subsurface conditions are important for the proposed project, and to what extent of detail and accuracy they must be recorded to produce a successful result.

### **2.3 Current Industry Standards and Guidelines**

Due to the fact that every building and project is unique, it is impossible to apply a pre-determined set of guidelines to identify what concealed conditions are required to be recorded when executing the design and construction documentation. Industry standards do exist that provide guidance on addressing concealed conditions for defined projects such as building façade inspections<sup>9</sup> and hazardous materials surveys<sup>10</sup>; however, these and similar standards are geared towards situations where the problem is clearly understood in advance. A building façade inspection or a hazardous materials survey must answer one simple question: “Do any conditions exist that present a hazard to the public?” On the other hand, a comprehensive assessment of a historic building for a proposed intervention must consider a nearly infinite number of questions, each of which may have an impact on the parameters of the proposed intervention.

---

<sup>9</sup> An example: “ASTM E2270-14, Standard Practice for Periodic Inspection of Building Facades for Unsafe Conditions”, ASTM International, West Conshohocken, PA, 2014, [www.astm.org](http://www.astm.org).

<sup>10</sup> An example: “ASTM E2356-14, Standard Practice for Comprehensive Building Asbestos Surveys”, ASTM International, West Conshohocken, PA, 2014, [www.astm.org](http://www.astm.org).

Basic rules and approaches to recording – for example, utilizing non-destructive methods of investigation before proceeding with destructive ones - are well-understood and well explained in available literature (see **Chapter 3** for more on this topic). Yet, in deciding exactly what concealed conditions are of critical importance to a specific building or project, the preservation architect is left largely to his own education, training and ethical judgment. The common sources of guidance for preservation professionals provide precious little guidance in this area. The HABS/HAER program – the most common and well-known recording program for historic buildings – was never intended to serve the function of identifying non-observable fabric, and is therefore conspicuous in its avoidance of the issue of concealed conditions. Neither their guidelines for measured drawings<sup>11</sup>, nor the *Secretary of the Interior's Standards for Architectural and Engineering Documentation*,<sup>12</sup> discuss the recording of conditions beyond those that are visible, accessible, and measurable. With some rare exceptions, HABS drawings do not attempt to delineate concealed items such as chases or chimney flues. For example, contrast the HABS drawing of the Virginia State Capitol shown in **Figure 2-1** with the 1904 construction drawing of the same area of the building (**Figure 3-1**).

---

<sup>11</sup> National Park Service, "HABS Guidelines: Recording Historic Structures and Sites with HABS Measured Drawings," NPS Heritage Documentation Programs - HABS, 2008.

<sup>12</sup> National Park Service, "Secretary of the Interior's Standards for Architectural and Engineering Documentation," NPS, 1983.

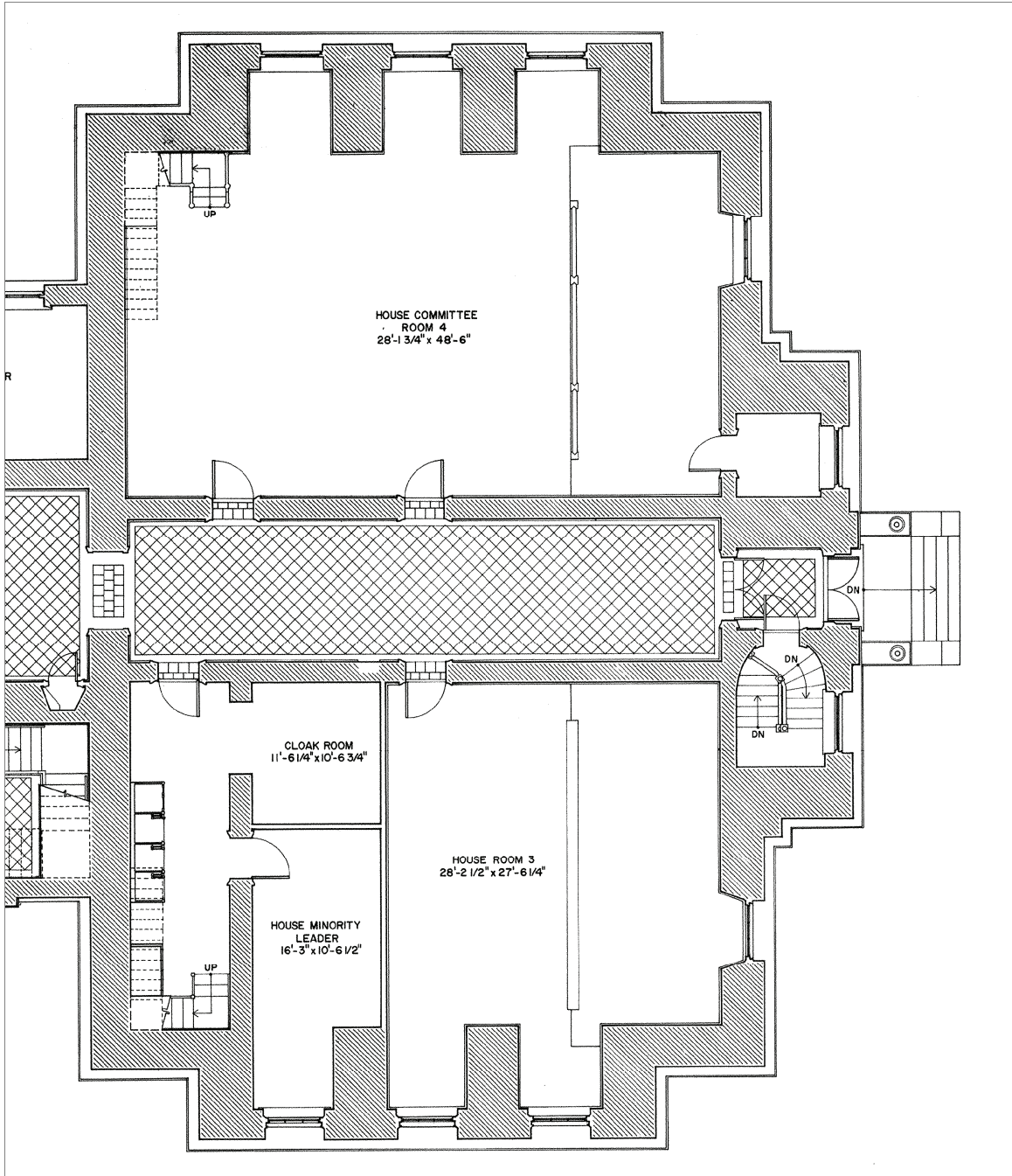


Figure 2-1: Virginia State Capitol – Ground Floor Plan excerpt (HABS, 1988)



Within the context of the modern practice of architecture, contractual and liability issues make the recording of concealed conditions an important and common consideration, but there is still little real guidance beyond the judgment and experience of the architect. The standard AIA Contracts between Owner and Architect do not discuss the extent of the responsibility of the architect to document concealed conditions. Still, construction contracts contain provisions for the contractor to charge an additional fee, in the form of a change order, for at least some types of conditions discovered during construction that are materially different from those shown on the construction documents.<sup>13</sup> A strong incentive therefore exists for the architect and the owner to produce documents that take into account to the greatest extent possible the conditions that may be uncovered during construction.

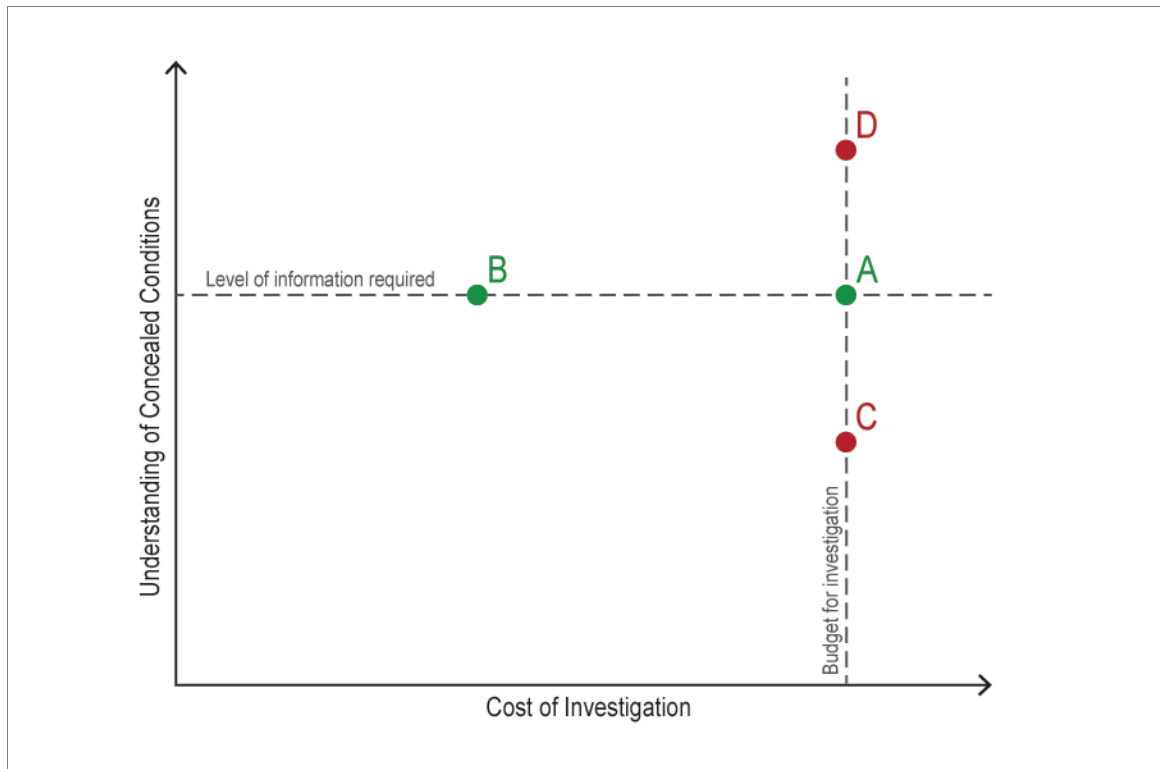
The guiding principle for an architect tasked with determining which concealed conditions should be documented – and to what extent – is what is known as the “standard of care” or “due diligence”. In professional practice such as architecture, this refers to an ethical decision that would be exercised by a “reasonably prudent” professional in the same situation. Obviously far from a definitive guideline for recording concealed conditions, this standard does at least make it clear that there is some minimum required level of responsibility of the architect. It is important to note here that the standard of care is considered in the context of the type of project and professional selection. A preservation architect hired specifically to examine and assess a structure clearly may be held to a higher standard than a generalist in the same situation.

---

<sup>13</sup> The American Institute of Architects A201 is the “standard”, but this is typical for most construction contracts.

## 2.4 Cost-Efficient Investigation

The recording of concealed conditions in existing buildings – as part of a proposed intervention – is essentially an exercise in balancing the cost of the subsurface investigation against the *useful* information required. Consider the chart shown in **Illustration 2-1**, plotting the understanding of concealed conditions against the costs of investigation.



*Illustration 2-1: Potential combinations of investigative cost and information obtained*

While it may not be simple to determine, every project requires a minimum level of information about concealed fabric and deterioration to produce accurate construction documentation. Similarly, in the real world, every project has a limit on the budget available for investigation. If the result of an investigation program falls at the location labeled “A” in **Illustration 2-1**, the investigation has yielded a successful result, obtaining the necessary information without

exceeding the budget. Of course, the location labeled “B” is even better, having obtained the same information for less. Location “C” indicates an unsuccessful investigation program; the required information was not obtained within the required budget. Location “D”, also undesirable, represents a case where the full budget was expended to obtain information that was not necessary for the project.

Of course, the main focus of this thesis is how subsurface investigative programs arrive at those termination points. The chart in *Illustration 2-2* shows the basic shape of most single investigative techniques, based on the experience of the author.



*Illustration 2-2: Proposed relationship between understanding and cost for a typical investigative technique*

The exact form of the curve may vary greatly for specific buildings, conditions and types of testing; however, the basic shape reflects that initial information is usually relatively easy to

ascertain, while highly specific and accurate data on concealed conditions becomes increasingly expensive to investigate and confirm. At some point, the curve becomes flat, as additional investigation with the same technique will fail to yield any new results.

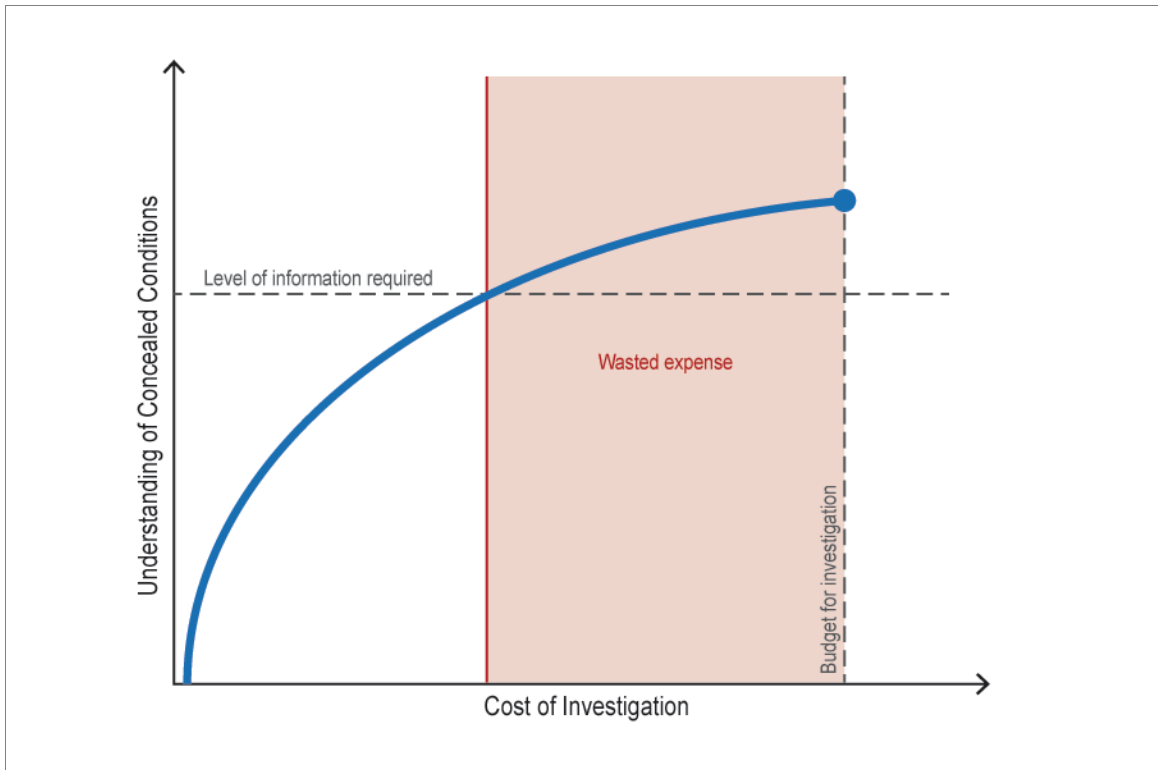
The goal of the preservation architect is to choose the “termination point” along this curve, based on an understanding of the correct balance between cost and the risk created by any unknowns. Given the lack of existing standards and the unique nature of the concealed conditions encountered in individual projects, an inexperienced architect may fall into one of two dangerous traps: attempting to mitigate the risk of concealed conditions entirely by investigating and recording them in an indiscriminate manner; or, by ignoring them under the assumption that any discrepancies will be discovered during construction and will be the responsibility of the contractor.<sup>14</sup> For the vast majority of projects, neither of these approaches will yield a satisfactory result.<sup>15</sup>

The urge to “document everything” can be problematic when applied to visible elements such as details and molding profiles; when extended to concealed conditions it can be even more dangerous. The most basic manifestation of this type of erroneous thinking is the expending of effort, time and money on answering questions about concealed conditions that have no material effect on the proposed work (refer to *Illustration 2-3*).

---

<sup>14</sup> To many architects’ dismay, the standard note to the contractor to “verify in field” does not absolve them from any responsibility for accurate documentation.

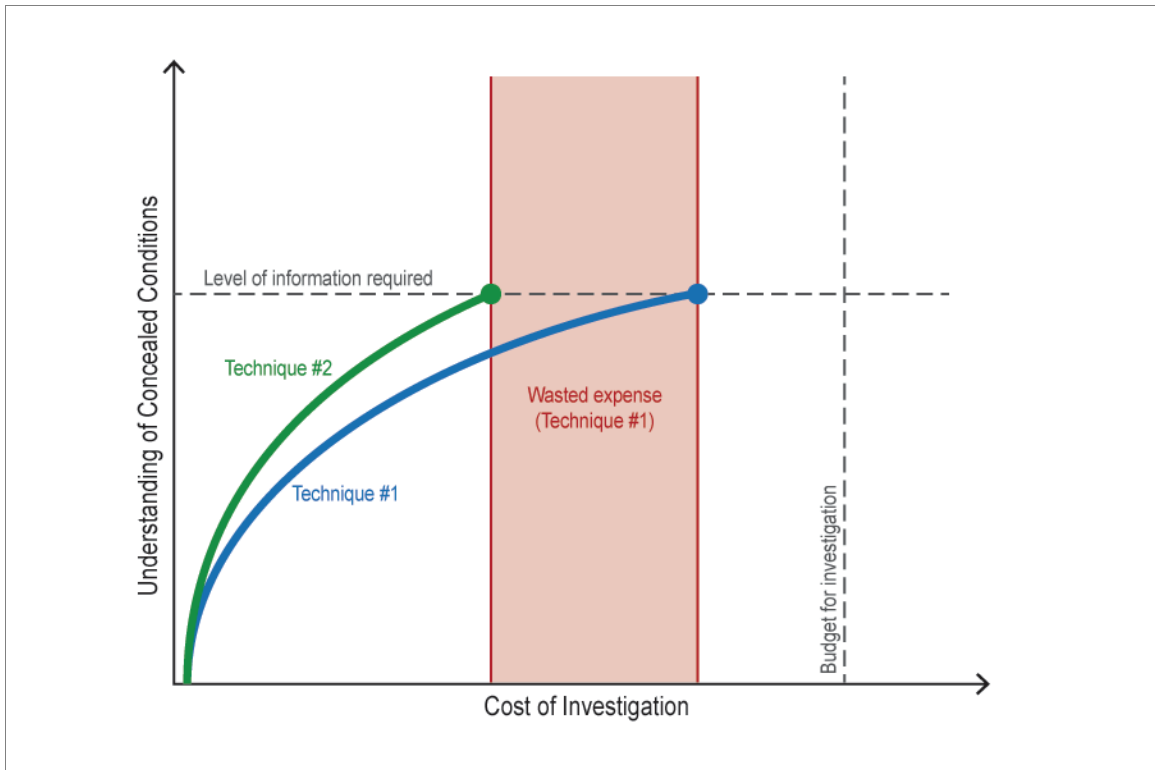
<sup>15</sup> For this reason, it is in the best interests of the client to hire architects who are properly trained to identify these potential issues.



**Illustration 2-3:** Potential wasted expense in a project where investigation continues beyond the level of information required

While there may be certain conditions or areas of concealed historic fabric of interest within a building or structure, the architect must resist the urge to transform a recording and design project into an academic research project.

In addition, the continued development of new recording and evaluation technologies and techniques has increased the potential for a misguided approach that focuses more on the tools than on the results (refer to **Illustration 2-4**).



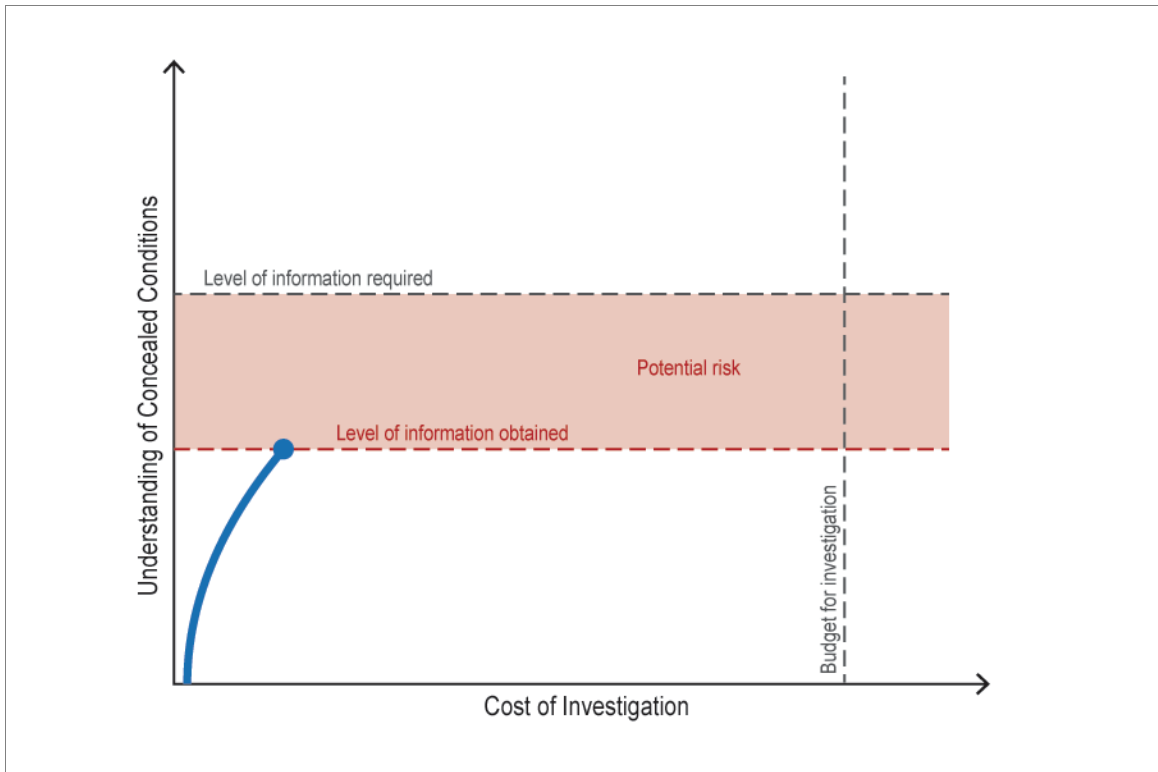
*Illustration 2-4: Potential for wasted expense from improper selection of investigative technique*

This approach can lead to the expenditure of significant sums of money on testing programs that may provide flashy or visually impressive results, without significantly adding to the impactful knowledge of the important conditions. It can also lead to the application of more expensive techniques when less expensive methods may be just as effective.<sup>16</sup>

Of course, the opposite extreme can be just as problematic (refer to **Illustration 2-5**).

---

<sup>16</sup> Linton, Linnea M. "Delaminations in Concrete: A Comparison of Two Common Nondestructive Testing Methods." APT Bulletin 36:2/3 (2005): 21-27 – this article provides an excellent example of how in many cases a cheaper method can be just as effective.



**Illustration 2-5:** Chart illustrating potential risk due to insufficient investigation.

When there is evidence, based on preliminary investigations or on prior experience, that concealed conditions may have a significant impact on proposed work, it would be negligent to simply ignore them during the recording and design of a project. When judiciously applied, non-destructive examination techniques can provide value to a project that exceeds their cost.<sup>17</sup> Additionally, selective areas of destructive probes and examination may be prudent during the early phases of a project, when they can be properly accounted for, to answer key questions regarding concealed conditions.

<sup>17</sup> Trujillo, Nicole, Thomas E. Boothby, and Erik Valentino. "Nondestructive Evaluation of Brick Masonry Using Air-Coupled Impact-Echo Analysis." *APT Bulletin* 44.2/3 (2013): 35-42 – article describes how a targeted NDT program helped hit a budget

Essentially, it is the job of the preservation architect to determine the level of information required, and to achieve this result in the most cost-effective manner. This may require a wide variety of tools, ranging from archival research to advanced non-destructive technologies. This balance is not easy to achieve, since it requires astute decision-making, a broad base of knowledge and experience, and ethical judgement, but it is absolutely critical to a project's success.



### **3. Subsurface Investigation Methods**

#### **3.1 Preamble**

Given the importance that concealed fabric and deterioration can play in the practice of preservation architecture, it is no surprise that significant effort has been focused on developing and understanding a recording approach. Essentially all texts and case studies researched for this thesis on the examination of existing historic buildings advocate, either implicitly or explicitly, a similar basic methodology for subsurface investigation (SI), involving four basic steps: archival research, visual assessment, non-destructive testing, and selective probes. Initial evaluation of the resource begins with a review of available existing drawings and recording, to develop a basic understanding of potential issues. This is followed by a general survey and visual examination. To further examine conditions that are undetermined by these basic methods, a variety of specialized techniques and technologies, such as thermal imaging, can be applied. Finally, probing or selective destructive investigation is undertaken where it is critical or required to determine the concealed conditions or confirm the findings of the non-destructive examination.

For the purpose of this study, these approaches are categorized in the context of the traditional roles of the preservation architects and engineers, non-destructive testing specialists, and contractors. The process of visual assessment describes the survey of conditions visible to the naked eye, conducted in the initial evaluation of a building or site. It includes basic visual techniques, through simple observation, in conjunction with enhanced techniques such as laser scanning and photogrammetry, as well as the use of binoculars and zoom lenses. It may also include simple investigations that require some physical contact with the building, such as the use

of hands to identify changes in texture, temperature or moisture content. Non-destructive testing, going beyond the visual assessment discussed above, generally includes a range of techniques, from simple borescopes to more specialized methods, which are targeted to reveal additional information about specific areas or conditions of concern. Finally, probing and selective destructive testing includes targeted techniques with an impact on building fabric, including work such as the exposure of previously concealed fabric.

It is important to understand that these four basic steps lie along a continuum, and in some cases the lines between visual assessment, non-destructive testing and probes are not clear-cut. Borescopes, for example, are generally considered non-destructive but may require a small hole to be drilled for inserting the scope. Similarly, load testing is commonly considered a non-destructive test for masonry construction, but in cases of sensitive historic fabric (or, for materials such as wood framing) the potential for damage may be unacceptable.<sup>18</sup> Resistance drilling, which uses a small-diameter needle to measure relative density in wood members, is described as a “quasi-nondestructive assessment method”<sup>19</sup>, acknowledging the potential for damage beyond what may be acceptable in certain cases. Further complicating matters, visual assessment, while fundamentally discussed as unique, is a subset of non-destructive testing – a 1976 APT journal article described visual observation as “the simplest of [nondestructive examination] techniques”.<sup>20</sup>

---

<sup>18</sup> Harvey, Jr., Donald W. and Michael P. Schuller. “Nondestructive Evaluation: Structural Performance of Masonry.” APT Practice Points 09. APTI, 2010. Web. 14 Oct. 2014, 2 – this article takes a more nuanced approach, categorizing tests as “destructive”, “non-destructive with minor repairs”, and “nondestructive”. Yet the issue persists: impact-echo testing is listed as non-destructive for masonry; it would hardly be such for glass tile or other fragile materials.

<sup>19</sup> Anthony, Ronald W. “Nondestructive Evaluation: Wood.” APT Practice Points 10. APTI, 2010. Web. 14 Oct. 2014, 3.

<sup>20</sup> Brown, Paul Wencil and James R. Clifton. “Nondestructive Techniques for Evaluating Metallic Artifacts of Historical Interest.” *Bulletin of the Association for Preservation Technology* 8.4 (1976): 4.

Based on a review of currently available literature, this section summarizes the basic techniques, uses and limitations of each of the four basic steps in the recording process: archival research; visual assessment and recording; non-destructive testing; and probes and selective destructive investigation. The matrix included at the end of this chapter (refer to *Figure 3-4*) provides a comparative summary of these techniques.

### **3.2 Archival Research**

Archival research – the study of existing drawings, specifications, reports and studies – can reveal valuable information about subsurface conditions in existing buildings. In particular, original construction drawings often provide a wealth of detailed data on construction techniques, structural configuration, materials and assemblies used, and areas of potential deterioration. For many 20<sup>th</sup>-century buildings, original drawings are quite detailed and accurate and can provide an excellent baseline understanding of concealed construction. For example, refer to *Figure 3-1*. This construction drawing from the 1904 addition to the Virginia State Capitol includes a wealth of valuable information regarding the chases and flues concealed behind the finish walls. This is evident when compared with the 1988 HABS drawings of the same area (refer to *Figure 2-1*).

Archival photographs can also be particularly useful, especially those taken during construction. Finally, previous reports and studies prepared since a buildings' completion, such as hazardous materials testing, structural inspection reports, or building manager's reports, can provide additional clues.

There are significant limitations though to what can be confirmed using archival documents. For older structures, constructed prior to the second half of the 19<sup>th</sup> century, construction documentation can be extremely limited and archival research may not provide much

insight into subsurface conditions. In addition, even when highly detailed construction documents are available, it is extremely rare that they are truly “as-builts”. Even when change-order documents are available, there is often not a reliable way to verify that there were no undocumented changes made during the construction process. There is no guarantee that later alterations have not been undertaken without proper documentation and recording, resulting in differing conditions from those shown on the original documents. Finally, even if this information existed at one point, it is very uncommon for any building or site to maintain a complete and comprehensive archive from which to conduct this type of research.

When it does exist, there are two major limitations in the use of archival information for understanding concealed conditions. The first is the level of confidence in the veracity of the information. While some interventions may be simple enough that historic drawings can be used as the basis for construction documents, in many cases, it is necessary to independently verify specific aspects of the original design to confirm they were in fact constructed in the manner depicted. The second is the information available, which is generally limited to concealed construction methods or techniques. Archival drawings simply cannot provide dependable information about the current state of concealed deterioration mechanisms.<sup>21</sup>

---

<sup>21</sup> Swanke Hayden Connell Architects. *Historic Preservation: Project Planning & Estimating*. Kingston, MA: R.S. Means Company, Inc., 2000, 31.



### 3.3 Recording & Visual Condition Assessment

#### 3.3.1 Basic Recording and Assessment

A comprehensive recording of the configuration and visible condition of a building is a fundamental element in any building evaluation. The first task in any investigation is to produce an accurate set of drawings (e.g., plans, sections, elevations) that depict the building in its current state. Traditionally accomplished using hand-measurement, new technologies such as laser-scanning and digital photogrammetry allow for the recording of existing conditions at a level of detail and three-dimensional accuracy that can often exceed manual techniques, particularly for complex or extremely large structures and buildings.<sup>22</sup> Detailed measured drawings can be a valuable “check” against archival information, can provide first clues as to distortions and defects that may lie beneath the surface, and can form a baseline for a more detailed investigation.

Building on this recording effort, a visual field inspection is conducted in order to understand any areas of deterioration or distress, or other anomalies. This is typically a two-stage process, beginning with a walk-through survey of the site and structure and later proceeding to a close inspection of areas of particular interest or concern. The results are typically recorded in the form of photographs, both overall and detailed, as well as field notes such as drawings, sketches, and data forms.<sup>23</sup>

The fundamental drawback of this type of assessment, as it relates to the recording of concealed conditions, should be self-evident, since even the most detailed recording and visual

---

<sup>22</sup> Skarmeas, George C. “From HABS to BIM: Personal Experiences, Thoughts and Reflections.” APT Bulletin 41.4 (2010): 51-52.

<sup>23</sup> Swanke Hayden Connell Architects, 30-32.

investigation program is limited to the observation of surface conditions. To the trained observer, however, visible evidence such as surface cracking patterns and other visible material deterioration can provide insight into what is happening beneath the surface. In some cases, this level of information may be perfectly adequate for making assumptions about required repairs and interventions at a gross level; however, when more complex, intrusive or costly work is planned, it is not prudent to rely solely on recording and visual assessment, since they provide only the roadmap for further investigation. In fact, in many cases, such as moisture infiltration that occurs in one area but is manifested in an entirely different portion of the structure, the visual assessment may actually provide misleading or incorrect information.

### **3.4 Non-Destructive Testing**

#### **3.4.1 Overview**

While archival research and visual assessment may provide valuable clues to the true nature of concealed conditions, this complementary information may not be sufficient to provide the level of confidence and detail required for a planned intervention. In such cases, the implementation of some sort of non-destructive testing/evaluation (NDT/NDE) program may be the next logical next step.<sup>24</sup>

There are a wide variety of devices, techniques and technologies that fall under the broad category of non-destructive testing. The American Society for Nondestructive Testing (ASNT),

---

<sup>24</sup> The terms non-destructive testing (NDT) and non-destructive evaluation (NDE) are used interchangeably in the practice of preservation architecture.

which focuses primarily on the use of NDT in manufacturing and engineering construction, defines fourteen distinct methods, ranging from visual testing to neutron radiographic testing. Within each of these methods are a variety of specific tools and techniques.<sup>25</sup>

Unfortunately, many of these NDT technologies are only feasible at the “micro” scale, when used to detect small, even microscopic, defects in manufactured parts. Others have been adapted over the past 50 years by the fields of architecture and engineering, specifically for the recording of concealed conditions in existing structures. Some of these are particularly applicable to preservation architecture.<sup>26</sup> While a complete survey of NDT technology is outside the scope of this paper, the most common techniques used specifically for historic buildings are described below, including:

- enhanced visual techniques;
- moisture meters;
- thermal / infrared testing;
- radiographic testing;
- electromagnetic testing;
- acoustic and ultrasonic testing.

---

<sup>25</sup> "Introduction to Nondestructive Testing." The American Society for Nondestructive Testing. ASNT, 2012. Web. 14 December 2014. <https://www.asnt.org/MinorSiteSections/AboutASNT/Intro-to-NDT>

<sup>26</sup> Various sources group and classify NDT methods in different ways; the classifications used in this section are focused on NDT in preservation architecture, rather than materials science/engineering.



### 3.4.2 Enhanced Visual Techniques

Included here as NDT due to their focused nature, this category includes a variety of specialized visual assessment techniques that blur the line between visual assessment and NDT. Digital photographs can be manipulated in ways that exceed the ability of the naked eye to detect certain defects or material variations. Photography using infra-red or ultraviolet wavelengths can highlight similar features that are not evident in visible light.<sup>27</sup> While intrinsically limited to the enhancement of surface conditions, these techniques can be particularly useful when combined with the use of zoom lenses or macro lenses, and are easily incorporated into a comprehensive visual survey with relatively limited expense.

Another common visual NDT method is the use of devices that allow visual inspection of areas that would otherwise be inaccessible, such as borescopes or closed-circuit television (CCTV) devices that use small cameras to feed a signal back to a monitoring unit. Common in the practice of civil engineering for the inspection of sewer lines, this technique is typically used in historic buildings to inspect chimney flues, ductwork, drains and other concealed chases.<sup>28</sup> In some cases, with careful recording and a camera unit that includes a measurement device, borescope and remote-camera inspection can provide accurate locational information for any anomalies discovered.

---

<sup>27</sup> Livingston, Richard A. "Nondestructive Testing of Historic Structures." *Science and Technology in Historic Preservation*. Ed. Ray A. Williamson and Paul R. Nickens. New York, NY: Kluwer Academic/Plenum Publishers, 2000, 106.

<sup>28</sup> Watt, David. *Surveying Historic Buildings*. Michigan, USA: Donhead, 2011, 86.

### 3.4.3 Moisture Meters

Perhaps the most basic form of non-destructive testing commonly used in historic buildings is the moisture meter. Moisture meters fall into two categories: electrical-resistance moisture meters use probes to translate resistance into moisture content, while capacitance moisture meters require only surface contact to determine moisture content.

Moisture meters can provide a simple way of comparing results between different areas of a wall or building, and they are relatively easy to use with some basic training. Unfortunately, the results (for materials other than wood) are relative and do not provide precise moisture content readings unless specific chemical and physical properties of the material in that specific application are known.<sup>29</sup> In addition, moisture meters are extremely limited in scope – they essentially provide a “point” measurement, requiring a significant number of individual tests to make any accurate determination of moisture conditions within a larger area.

### 3.4.4 Thermal / Infrared Testing

The measurement of infrared energy, or infrared thermography, is used to examine the condition of an object or surface by measuring its heat signature, in the form of infrared radiation emissions. Below the level of approximately 1000 degrees Fahrenheit, when objects become “red-hot”, infrared radiation is invisible to the naked eye. Using thermal imaging cameras, small variations in temperature within the normal range encountered in buildings can be captured, producing colorized images that demonstrate the temperature variation of the objects in the

---

<sup>29</sup> Watt, 67-68.

image.<sup>30</sup> Thermography can be passive, recording the normal heat signature of a structure or assembly, or active, using an artificial heat source to enhance differences in surface temperature.<sup>31</sup>

Passive thermography is one of the most common NDT techniques used in building diagnostics, for a variety of reasons. Thermal cameras have become relatively inexpensive, and they allow large areas to be investigated in a short period of time. Surface temperatures are measured in real time, allowing easy comparison of conditions over time or under different conditions.<sup>32</sup> Using a variety of lenses, images can be captured from significant distances, allowing inspection of tall or distant structures without the use of lifts or special access.

The use of infrared thermography as a broad-brush NDT technique is enhanced by its ability to detect, at least at a basic level, a wide variety of conditions invisible to the naked eye. It is often used in studies of building energy use, as a method of detecting defects such as air infiltration or poor insulation. It can detect layers of construction within an assembly, such as wood lath beneath plaster, and can be used to determine the layout of underlying structural members within a wall surface. Finally, it is one of the most effective tools available for quickly detecting moisture infiltration and saturation in buildings and assemblies. It can be used to “map” moisture distribution much more directly (and sometimes accurately, since it does not depend on soluble-salts content) than moisture-meter readings.<sup>33</sup>

There are three main limitations of infrared thermography as applied to building forensics. First, while the simplicity of the equipment – a modern thermal camera is no more difficult to

---

<sup>30</sup> Kubba, Sam A. A. *Architectural Forensics*. United States: McGraw Hill, 2008, 63.

<sup>31</sup> Rosina, Elisabetta and Elwin C. Robison. “Applying Infrared Thermography to Historic Wood-Framed Buildings in North America.” *APT Bulletin* 33:4 (2002): 38.

<sup>32</sup> The ability of thermal imaging to be easily replicated over time may be one of its most powerful advantages, and it does not appear to have been thoroughly utilized in any of the case studies examined.

<sup>33</sup> Rosina and Robison, 37-3

operate than a point-and-shoot digital camera – may be misleading; it requires careful calibration of the equipment and careful interpretation of the results. Inadequate knowledge of the principals of heat flow and infrared radiation can lead to misinterpretation and reporting of irrelevant results. Second, it must be executed under proper atmospheric conditions, when heat-flow patterns are ideal for the desired type of observation and type of information required. Passive thermography can be limited by the available heat-flow of naturally occurring temperature cycles, while active thermography presents challenges of scale for large investigations like those undertaken on buildings. Finally, while the results of thermographic investigation often reveal information about the existence of subsurface conditions, it must be understood that the raw data is qualitative and records only surface temperature.<sup>34</sup>

#### 3.4.5 Radiographic Testing

Radiographic testing methods employ x-ray or gamma radiation to penetrate a surface or object and show its internal characteristics, in a manner very similar to a medical x-ray. The extremely short wavelength of x-ray or gamma rays allow them to easily penetrate through most building materials. By directing the radiation through a material or object onto a film or electronic device, concealed conditions are recorded as contrasting dark and light areas.<sup>35</sup> While radiography can generally be applied to virtually any material or assembly where both sides are accessible, its effectiveness – and efficiency – are greatly affected by the density of the material to

---

<sup>34</sup> Swanke Hayden Connell Architects, 636.

<sup>35</sup> Kubba, 72.

be studied. Materials such as wood and plaster are relatively easy to examine with medical-type x-ray devices, while deeper penetration or examination of dense materials requires higher-energy gamma rays.<sup>36</sup>

Available case studies reveal that radiographic x-ray testing has provided excellent results in the context of examining concealed conditions, albeit under very specific circumstances. The level of detail provided is exceptional; for example, study of the images allows identification of specific types of nails, distinction between hand-split and sawn wood lath, and even detailed ornament that is concealed by thick coats of paint.<sup>37</sup> Finally, although depth-perception can be an issue, the images produced by radiography are similar to standard photographs and therefore easily interpreted.<sup>38</sup>

There are several disadvantages of radiography as an investigative technique for existing buildings. Compared with other available technologies, it can be expensive to implement, and requires careful adjustment and calibration to achieve consistent, useable results. In addition, the nature of the radiographic process requires that both sides of the material be accessible, limiting its use in certain areas of buildings such as foundation walls. Finally, the safety concerns inherent in the use of radiation as an investigative tool can make it impractical, particularly in buildings that must remain accessible to the public during the investigation.<sup>39</sup>

Recent advances in radiographic technology that offer the potential for improved information have yet to be utilized in building forensics, most likely due to their prohibitive cost

---

<sup>36</sup> Livingston, 103.

<sup>37</sup> Hart, David M. "X-Ray Investigation of Buildings." *Bulletin of the Association for Preservation Technology* 5.1 (1973): 9-21

<sup>38</sup> Anthony, Ronald W. "Condition Assessment of Timber Using Resistance Drilling and Digital Radioscopy." *APT Bulletin* 35:4 (2004): 21-26.

<sup>39</sup> Kubba, 72-73.

relative to their usefulness in this specific application. Computed tomography is a radiographic technique similar to a medical CAT scan, using a computer to reconstruct an image that represents a cross-section of the object or assembly from multiple views. This technique, common in manufacturing for reverse-engineering, can provide a level of detailed three-dimensional information impossible with traditional radiography.<sup>40</sup>

### 3.4.6 Electromagnetic Testing

#### *Magnetic Induction / Metal Detection*

Electromagnetic testing includes a number of NDT techniques, which utilize electromagnetic phenomena to investigate subsurface conditions. The simplest form of electromagnetic testing is magnetic induction, which applies an alternating current to an electromagnetic probe, creating a magnetic field. This field allows identification of concealed metallic materials using a pickup coil. This method has been utilized both to confirm the presence of metals (simple metal detection) as well as to verify their depth (use of covermeters to verify thickness of concrete over reinforcing).<sup>41</sup>

Magnetic induction can be used to detect a variety of concealed metallic objects, such as anchors, cramps, and dowels used to fasten masonry panels. The maximum depth to which metallic objects can be detected varies greatly depending on the assembly and the equipment used; it is generally around 12 inches for handheld devices used in typical building survey. Metal

---

<sup>40</sup> Livingston, 103.

<sup>41</sup> Livingston, 104-5.

detection is primarily able to provide locational information rather than dimensional information for the concealed objects, and it is particularly effective when “targeted” by other NDT techniques or visual inspection to identify likely locations of concealed metal.<sup>42</sup>

#### *Impulse Radar / Ground-Penetrating Radar*

Another common method of electromagnetic testing is impulse radar (also referred to as ground-penetrating radar). Impulse radar operates by sending radiowave pulses into a material; these pulses are absorbed or reflected by subsurface materials, in particular at the interface between differing materials. Since the velocity of the pulse created by the unit is known, the depth to the anomaly can be determined (an operating principle similar to the use of sonar or radar).<sup>43</sup>

Impulse radar is a broadly useful technique in building diagnostics. It can be used to map concealed structural conditions for large areas, such as steel floor framing below marble floors. It can identify steel columns within masonry walls at a sufficient level of detail to determine orientation, and can detect the presence of voids, pipes, and flues concealed behind finish walls, penetrating to a depth of several feet.<sup>44</sup> Impulse radar can also be used for detection of connections such as metal pins and cramps between masonry units, particularly when combined with metal detection methods.<sup>45</sup>

---

<sup>42</sup> Bransby-Zachary, Charles, George Ballard and Avigail Charnov. “Nondestructive Evaluation (NDE) of Embedded Iron and Steel.” APT Bulletin 45.1 (2014): 5-11.

<sup>43</sup> Livingston, 105.

<sup>44</sup> Kaplan, et al., 1-3.

<sup>45</sup> Bransby-Zachary, et al., 5-11.

Impulse radar has also been used to conduct comprehensive surveys of internal deterioration conditions in masonry construction. Deterioration of mortar in multi-wythe walls leaves behind voids that can be detected at a high level of detail by impulse radar testing. This type of deterioration can be detected by NDT well in advance of the appearance of any visual evidence.<sup>46</sup>

Impulse radar is not without its limitations, however. It requires direct access to a surface using a flat data collector, The raw output from the radar unit is abstract, can be difficult to interpret, and may provide ambiguous results. It does not penetrate through metal at all, and wet or water-saturated materials reduce its penetration depth (although this can be used as a test in itself, if used to locate high moisture content in otherwise-dry heterogeneous assemblies).<sup>47</sup> Voids or other changes in material may produce anomalous results that can be easily misinterpreted. Finally, because of the high velocity of the electromagnetic waves utilized by impulse radar, it cannot resolve distances – i.e., depths – of less than one or two inches.<sup>48</sup>

#### *Other Electromagnetic Methods*

While magnetic induction testing and impulse radar are by far the most common applications of electromagnetic NDT methods in building diagnostics, other more complex methods exist for specialized applications. Magnetic flux testing, commonly used in the testing of pipelines and structural steel cables, creates a magnetic field within a metal object itself, allowing discovery of imperfections that are concealed by paint, insulation or other forms of protection.<sup>49</sup> Free

---

<sup>46</sup> Mellett, James S. and Shelley E. Smith. "Using Ground-Penetrating Radar to Investigate Historic Masonry Buildings." APT Bulletin 41:2/3 (2010): 47-56.

<sup>47</sup> Swanke Hayden Connell Architects, 638.

<sup>48</sup> Livingston, 105.

<sup>49</sup> Kubba, 71.



electromagnetic radiation (FEMR) techniques use magnetic “tracers” and a receiving unit to follow known features, such as chimney flues or chases. Microwave investigation techniques utilize microwave energy to determine defects, primarily in massive construction such as solid concrete or masonry.<sup>50</sup>

### 3.4.7 Acoustic and Ultrasonic Testing

#### *Acoustic Testing / Sounding*

Analogous to visual testing described above, the most basic acoustic method of NDT uses the human ear as the measurement device. It may seem strange to consider tapping on walls with a hammer (to distinguish masonry construction from frame construction) in the same category as impact-echo testing, and this type of general examination probably falls more within the category of visual assessment described in **Section 3.3**. On the other hand, a comprehensive program of rubber-mallet testing to investigate the condition of individual masonry units, while relatively unsophisticated, certainly falls within the definition of NDT.<sup>51</sup> More standardized hammer testing, with specialized equipment, is a common method of investigating delaminations and defects in concrete structures.<sup>52</sup> One of the main disadvantages of acoustic testing is its subjective nature, making it difficult to get matching or comparable results with different personnel.

---

<sup>50</sup> Watt, 84.

<sup>51</sup> Ortega, Richard I. “Seeing with Different Eyes: NDE of Embedded Steel at Yale University.” *APT Bulletin* 45.1 (2014): 24. While this article only briefly alludes to the stone-sounding program, the author was personally involved in this project and its comprehensive nature.

<sup>52</sup> Linton, 21.

### *Pulse-Echo Testing / Pulse-Velocity Testing*

Other more sophisticated methods utilize ultrasonic stress waves to measure a variety of subsurface conditions in materials and assemblies. Pulse-echo testing measures the time required for a single pulse of sound to echo back from a feature such as an internal void, using the known speed of sound in the specific material to determine the depth of the feature. Because this method is most effective in homogeneous, flat materials, it has been successfully applied to simple problems such as the measurement of the thickness of metal cladding, but is somewhat limited in its application to the field of building diagnostics.<sup>53</sup>

A related approach, known as ultrasonic pulse-velocity testing, utilizes a transmitter and a receiver placed on opposite sides of a material at a known distance. This allows calculation of the sound velocity through the assembly. It can be used as a comparative technique, recording changes in effective velocity at different areas to determine degradation, defects, or heterogeneous construction.<sup>54</sup> The information provided by ultrasonic pulse velocity testing can also be used to compute other material properties that may be utilized for structural analysis.<sup>55</sup>

### *Impact-Echo Testing*

Impact-echo testing uses a device – such as a steel ball-bearing – to impact an object or assembly, generating a pulse of sound within it. This pulse can then be analyzed in a similar

---

<sup>53</sup> Livingston, 99.

<sup>54</sup> Livingston, 100.

<sup>55</sup> Kaplan, Marilyn E., Marie Ennis, and Edmund P. Meade. "Non-destructive Evaluation Techniques for Masonry Construction." *Preservation Tech Notes - Masonry Number 4*. National Park Service, 1997, 2.

manner to the pulse-echo method, using the elapsed time to measure the distance to a defect or discontinuity. Alternatively, the range of frequencies generated can be used to compute mechanical properties, similar to pulse-velocity testing.<sup>56</sup>

Impact-echo testing has been used extensively in the detection of voids and defects in monolithic concrete assemblies such as slabs and bridge decks.<sup>57</sup> It can also assist in more detailed analysis, to detect cracks and poor bonding in multi-wythe brick masonry walls, arches and vaults.<sup>58</sup> The equipment used in impact-echo testing is durable, lightweight and gravity-powered, making it a relatively inexpensive technique when compared to other methods such as impulse radar.<sup>59</sup>

Like all NDT methods, there are limitations to this technique. Traditional impact-echo testing methods require mechanical impact on the material, raising conservation issues for some materials (although more complex techniques such as air-coupled impact echo testing have mitigated this issue, in exchange for increased cost and complexity).<sup>60</sup> It requires careful calibration, which can increase the time and cost required if a large number of different assemblies are to be tested.<sup>61</sup> Finally, impact-echo testing is best suited to homogenous materials – such as concrete – rather than multi-layered assemblies.<sup>62</sup>

---

<sup>56</sup> Livingston, 100.

<sup>57</sup> Kaplan, et al., 2.

<sup>58</sup> Trujillo, et al., 35-42.

<sup>59</sup> Swanke Hayden Connell Architects, 639.

<sup>60</sup> Trujillo, et al., 35.

<sup>61</sup> Swanke Hayden Connell Architects, 640.

<sup>62</sup> Kaplan, et al., 4.

### 3.4.8 Hybrid Methods

While the NDT methods described above are discretely categorized, the underlying physical phenomena can be combined to create hybrid testing approaches if they are properly understood and applied. For example, microwaves can be used to create temperature differentials in objects that are then detected using infrared thermography. Magnetic coils can be used to generate stress waves in materials that are then measured using ultrasonic receivers.<sup>63</sup> While these advanced approaches are currently more common in materials science than building forensics, they may offer opportunities for architects and preservationists to solve particularly complex problems not easily addressed by any single method.

### 3.5 **Probes & Destructive Examination**

As described above, the wide variety of NDT techniques, particularly when combined with properly-conducted archival research and visual assessment, can provide valuable understanding of concealed building fabric and its condition. On the other hand, there is often no substitute for the information that can be gained by probes and selective destructive examination, which expose the concealed conditions to varying degrees. These methods involve the removal of layers of building fabric to reveal the underlying fabric or conditions for examination and recording. In many cases, the visual inspection of concealed structure or materials is an absolute requirement to confirm or refine the knowledge gained by non-destructive methods of investigation.

The range of investigations that fall under the category of probes and destructive examination vary greatly. Small areas of building fabric can often be removed very inexpensively,

---

<sup>63</sup> Livingston, 107.

and can expose underlying conditions for physical examination that provides accuracy and detail unrivaled by any NDT method. For layers of construction confirmed to have no historic value, the associated risk of damage in these investigations is also minimal.

In other cases, the removal of the amount of physical building fabric required for proper recording can be very expensive, when compared with NDT methods, and can create the potential for damage to valuable historic fabric. The number and location of these types of probes is generally limited, by both budget and logistical concerns. For this reason, probes and destructive disassembly of building fabric must be guided by professional judgment and informed by less intrusive methods such as NDT.<sup>64</sup> They should be carefully planned to discover the most information possible about concealed conditions within the acceptable limits of building-fabric removal for a specific project.<sup>65</sup>

### **3.6 Comparing Available Technologies and Techniques**

The technologies and techniques described in this Chapter comprise the basic “toolbox” for the recording of concealed conditions. It is exceedingly rare, if not impossible, for any subsurface investigation program to employ all of these available methods. It is therefore important to develop a framework for comparing the variety of available methods and selecting the ones most appropriate to the specific project. The goal is to develop an evaluation and testing

---

<sup>64</sup> Friedman, Donald. “Ambiguity in Building Investigation: A Study of Sampling and Decision-Making with Field Data”. *APT Bulletin* 31:2/3 (2000): 39-44.

<sup>65</sup> Of course, the “acceptable limits” can vary greatly by project. Dossett, Jim, “Case Studies in the Repair of Masonry-Clad, Steel-Framed Buildings,” *APT Bulletin* 45.1 (2014): 28-29, describes a case-study project at Rittenhouse Plaza, where a careful stone-by-stone disassembly of the limestone arch was used as the basis of the construction documentation for repairs.

program that is not driven by the technology available, but instead by knowledge and experience of those applying it.

The two charts reproduced below are typical of the type of analysis that exists in current publications as a guide for developing a non-destructive testing strategy for assessing concealed conditions in historic buildings. The chart in **Figure 3-2**, from an APT Journal article dealing specifically with wood investigation, cross-references several methods of investigation with the factors that can be determined from each method.

FACTORS	METHODS						
	Remote visual inspection	Resistance drilling	Infrared thermography	Stress waves	Visual grading	Digital radioscopy	Moisture measurements
Measure moisture content			Limited				Yes
Locate deterioration	Limited	Yes	Limited	Limited		Yes	
Quantify deterioration	Limited	Yes		Limited		Limited	
Assess strength				Limited	Estimate		
Determine modulus of elasticity				Estimate	Estimate		
Identify hidden construction details	Yes	Limited	Limited			Yes	
Locate and assess fasteners						Yes	

*Figure 3-2: Nondestructive Evaluation of Wood: Factors that can be determined using NDT.<sup>66</sup>*

While this chart is a useful starting point for understanding specific NDT techniques as they apply to wood, it is limited in its value as a planning tool by several important factors. First, this chart focuses on a single material, which makes it useful only at the micro scale or for the rare building constructed entirely of wood. Second, it does not include any consideration for the cost of

<sup>66</sup> Anthony, "Nondestructive Evaluation: Wood," 2.

the different tests, or the expertise required to conduct them. Third, it focuses on NDT only, rather than the broader range of subsurface investigation methods that include probes and visual assessment. Finally, by using a list of specific conditions as the “factors”, its use in planning an investigation would depend on prior knowledge of what concealed fabric or deterioration exists.

The chart in **Figure 3-3** is another example of a comparative chart that provides background information but has shortcomings as a planning tool.

General	Destructive		Nondestructive w/ Minor Repairs			Nondestructive								
	Sampling (Cores)	Bond Wrench Test	Flatjack / Shearjack	In-situ Load Testing*	Petrography	Visual / Optical**	Ground Penetrating Radar (GPR)	Ultrasonic Pulse Velocity (UPV)	Impact Echo (IE)	Rebound Hammer / Surface Tests	Metal Detection (Induction)	Radiographic	Infrared Thermography (IRT)	Half-Cell Potential
Relative Cost (\$, \$\$, or \$\$\$)	\$\$	\$\$	\$\$	\$\$\$	\$\$\$	\$	\$\$\$	\$\$\$	\$\$\$	\$	\$	\$\$\$	\$\$\$	\$\$
Complexity/Experience Needed (L=Low, M=Medium, H=High)	L	M	M	H	H	M	H	H	H	L	L	M	M	L
Condition														
In-place strength?	G	G	E	E	A			A	A	A				
In-place uniformity?	G		G		G	A	G	G		G		G	G	
In-place deformability?			E	E				A	A	A				
In-place stress?			E											
Crack location?						A		E	E			G		
Crack movement?									G					
Performance under load?		E	E	E										
Rebar size, location, cover?	E						G				E	E	A	
Anchor and tie locations?								E			E	E		
Voids in grout?						A	E	A	A			E	G	
Voids in masonry?						A	E	A	A			E	G	
Corrosion of rebar?						A								G
Durability problems?				E		A		G						

E = Excellent information, reliable method  
G = Good information, somewhat variable or vague results  
A = Approximation only, highly variable or inexact

Figure 3-3: Appropriate Test Methods to Evaluate or Investigate Various Masonry Conditions.<sup>67</sup>

<sup>67</sup> Harvey, et al., 2.

This chart is more detailed than the first, and does contain additional useful information. It gives some indication of the relative costs of each test, and does include some destructive tests in addition to NDT methods. Yet, the way the costs are described is not detailed enough for planning (it is unclear what “\$\$\$” means in real dollars), and it does not include the full range of subsurface investigation methods. Like the chart above, it focuses only on one material and uses a list of specific conditions as the basis for comparison.

The matrix in **Figure 3-4** represents an alternative way of analyzing the relative strengths and weaknesses of each of the technologies and techniques described in this chapter. Each method is described in terms of the key factors that may impact its selection:

- Cost of the equipment required
- Cost of the labor required to utilize the technology
- Scale at which the technology can be utilized (macro vs. micro)
- Level of expertise required to operate the equipment and obtain useful results
- Accuracy and level of detail of the resulting information

Areas that are the “strong suit” of a particular method are highlighted in green; areas of particular weakness are highlighted in red.



	Equipment Cost	Labor Cost	Specialized Expertise Required	Scale	Accuracy / Detail	Suitable Materials / Assemblies	
Archival Research	n/a	Generally low, although it may increase for projects with significant amounts of documentation or difficult-to-access archives.	Most archival documentation can generally be understood without specialized knowledge.	When archival documentation is available, it is generally large-scale, dealing with the building as a whole.	Level of detail varies greatly, typically increasing for more recent (20 <sup>th</sup> -century) buildings. Accuracy also varies, and is difficult to verify.	All	
Recording & Visual Assessment	Minimal for basic equipment such as digital cameras (as little as \$200), binoculars (as little as \$100, and awls (\$10).	Generally low relative to the amount of information obtained about overall condition.	While expertise and experience are invaluable in any assessment, visual recording & assessment is a basic skill for all professionals in the field.	One of the greatest advantages of visual assessment is that it can be tailored specifically to a wide variety of project sizes/types.	Limited to conditions with visible evidence	All	
Non-Destructive Examination Methods	Borescopes & CCTV	Borescopes and CCTV rigs can range in cost from \$100 to nearly \$10,000. More expensive models include advanced features such as integrated measurement and video capture.	Generally low for each location, although it can be time-consuming if special access is required (ie, for chimneys) or if many locations are necessary.	Results are visual and are generally fairly intuitive for professionals knowledgeable about the assemblies they are observing.	Borescopes and CCTV rigs are relatively small-scale, and are focused on a specific area.	Level of accuracy is high, since concealed elements are directly visually observed. Detail generally varies depending on the price of equipment.	Suitable only for hollow assemblies such as wood-frame walls or chimneys.
	Moisture Meters	Moisture meters range in cost from \$100 to \$500. More expensive models purport to offer higher levels of precision or interconnectivity.	Individual measurements are easily taken at a rapid pace, although it can be time-consuming if special access is required or if many locations are necessary.	No expertise is required to operate the equipment; however, it is important to have the experience to interpret the results properly.	Moisture meters provide only a "point" measurement. While an organized program of testing can be used to widen the range, it can be difficult to interpret these varying results.	One of the biggest disadvantages of moisture meters is the wide variety of accuracy.	All materials can be surveyed with a moisture meter. The results are more accurate for materials with known properties such as wood.
	Thermal / Infrared Testing	Thermal cameras range in cost from \$250 to \$20,000. More expensive models offer higher resolutions and a variety of advanced features.	For passive thermography, labor cost is generally low relative to the amount of information obtained about overall condition.	Actual photography is easy to conduct, but the results require skill to interpret and can be misleading if improperly interpreted by novices.	Thermal imaging can be easily adapted to surveys of varying scales, using overall photographs as well as details.	The level of detail is limited by the fact that only the surface temperature can be measured. Accuracy varies depending on how well the underlying condition is represented by changes in surface temperature.	All
	Radiographic Testing	Modern x-ray cameras cost approximately \$5,000.	Labor cost is generally quite high, since x-ray imaging takes significant setup time.	Specialized expertise is required both to setup the imaging and interpret the results.	Focused technology generally applied to smaller areas.	The level of accuracy is highly dependent on the type of assembly; detailed three-dimensional information is difficult to ascertain.	The assemblies for which x-ray imaging can be applied is limited; its most common use is for locating fasteners within wood.
	Metal Detection	Metal detection equipment can be purchased for as little as \$200, but units that offer more accuracy and control can be as much as \$1,500.	Individual measurements are easily taken at a rapid pace, although it can be time-consuming if special access is required or if many locations are necessary.	Actual detection is easy to conduct, but the results require skill to interpret and can be misleading if improperly interpreted by novices.	Focused technology generally applied to smaller areas.	Level of accuracy is high with the proper skill and experience; detail is limited by its nature as a binary measurement.	Can only be used to detect ferrous metals within other assemblies such as masonry or wood.
	Impulse Radar / Ground-Penetrating Radar	GPR equipment generally ranges from \$3,000 – \$5,000.	Because GPR requires direct access to the surfaces and careful calibration, it can be extremely labor intensive.	Requires a high level of expertise to conduct testing and interpret results.	Focused technology generally applied to smaller areas.	Under proper conditions, the level of accuracy and detail provided by GPR can be very high.	Most commonly used for masonry assemblies, but can also be applied to wood framing.
	Acoustic Testing	Manual acoustic testing can be conducted with a rubber mallet that costs \$20.	Individual measurements are easily taken at a rapid pace, although it can be time-consuming if special access is required or if many locations are necessary.	Actual detection is easy to conduct, but the results require skill to interpret and can be misleading if improperly interpreted by novices.	While it is a "point" measurement, acoustic testing can be applied to larger areas if controls are in place to compare results.	The level of accuracy is highly dependent on the type of assembly; detailed three-dimensional information is difficult to ascertain.	Most commonly used for masonry.
	Pulse-Echo / Impact-Echo Testing	Equipment generally ranges from \$4,000 to \$10,000.	Because these techniques require direct access to the surfaces and careful calibration, they can be extremely labor intensive.	Requires a high level of expertise to conduct testing and interpret results.	Focused technology generally applied to smaller areas.	The level of accuracy is highly dependent on the type of assembly; three-dimensional information is difficult to ascertain.	Generally only applied monolithic masonry such as concrete slabs.
Selective Probes	n/a	Selective probes vary greatly in cost; small probes may be less expensive than corresponding NDT methods, while large probes may incur significant expense.	Probes are generally conducted by a contractor skilled in historic buildings.	Given the impacts on building fabric, probes and destructive examination are generally undertaken only at select areas of concern.	Level of accuracy and detail are high, since concealed elements are directly visually observed.	All	

Figure 3-4: Comparative summary of subsurface investigation methods (by author)

## 4. Developing a Comprehensive Subsurface Investigation Program

### 4.1 Preamble

The previous chapters have outlined the importance of documenting concealed conditions, both “healthy” and “unhealthy”, and have described some of the techniques available to assist in this effort. This background information is essential; however, an understanding of goals and specific technologies is insufficient for the preservation architect tasked with organizing a comprehensive assessment and subsurface investigation of concealed conditions.

The most important concept is to understand that this type of investigation is a series of trade-offs. It is practically impossible to determine all there is to know about the concealed conditions in any building. The job of the preservation architect is perhaps more about asking the right questions than it is about the impossible task of having all of the answers. In his article on the concept of ambiguity in building investigation, preservation engineer Donald Friedman summarizes this central conflict:

*What is particularly frustrating about ambiguity for building professionals that the information needed to have an easily solvable problem exists but cannot be determined for external reasons, such as costs, limitations on areas of work, or time pressure. It would be far easier to accept the effort and difficult design choices that ambiguous information forces on professionals if the information simply could not be found.<sup>68</sup>*

In his view, information about concealed conditions at the start of any project essentially falls into two categories: the unknown, and the unknowable. The limits on separating the unknown

---

<sup>68</sup> Friedman, 44.

from the unknowable is driven by several factors: the background information available; the nature of the building; the cost of finding the data on the particular unknowns; the amount of time available for the investigation; and the skills and training of the investigator.<sup>69</sup>

While there will never be a “one-size-fits-all” approach that applies to all types of buildings and projects, this chapter describes several fundamental concepts that should form the basis of any successful investigation:

- Understanding of the proposed work
- Balancing cost and risk
- Understanding of the available methods
- Focus on results (rather than techniques)
- Hierarchy of investigation methods
- Utilizing an iterative approach
- Understanding extent, variation and range

The first two concepts deal primarily with determining the required level of information, while the last five deal mainly with the methodology for obtaining this information. Combined, they provide a basis for planning or evaluating any investigation of concealed conditions.

## **4.2 Key Concepts**

### **4.2.1 Understanding of the Proposed Work**

The first step in any project is to determine, if possible, how and where the proposed scope of work can potentially be impacted by concealed conditions. In a comprehensive

---

<sup>69</sup> Friedman, 44.

assessment or restoration/renovation of a historic building, this may not narrow the focus of an investigation greatly; however, in projects with a set goal, such as a re-roofing project or exterior envelope restoration, it is essential that the scope of work helps focus the investigation, to avoid unnecessary expenditure of both time and money on issues irrelevant to the project scope.

With this in mind, though, the scope of work for a project often changes as the design progresses. The architect must be aware that alterations to the design or scope, such as relocation of a proposed elevator, or rerouting of mechanical pathways, may necessitate additional investigation. Concealed conditions that were previously determined to have no impact on the proposed work may now be critical.

#### 4.2.2 Balancing Cost and Risk

In addition to determining the range of potentially impactful concealed conditions, which can include both fabric and deterioration, it is critical to determine the level of accuracy and detail required for recording each condition. Since no project has an unlimited budget for subsurface investigation, this becomes a delicate exercise in allocating investigative resources to those conditions that have the greatest potential impact.

As described in Section 2.2, these potential impacts can fall into four major categories: damage to valuable concealed historic fabric; hidden deterioration that will continue if not repaired; conditions that prevent the work from being implemented as designed; and issues related to construction cost and risk management. Any of these may have a significant impact on the technical quality of the design as well as the cost of construction.

All of the potential risks must be understood and balanced against the cost of investigating a particular concealed condition. For example, even a \$1,000 non-destructive investigation

program that yields extremely accurate and detailed information on a concealed condition may not be an efficient use of resources, if the condition only requires an additional \$2,000 to repair/mitigate in the worst-case scenario. Conversely, a \$100,000 program of specialized investigation and targeted probes may be entirely justified on a preservation project with complex construction – such as a steel-frame building with masonry cladding – and a multi-million dollar budget.

Assessment and investigation must be considered for what they are: an important component of an overall risk-management strategy for dealing with concealed conditions. Other proven project implementation strategies, including phased construction, early selective removals packages, and establishment of adequate construction contingencies, must also be utilized. By taking this comprehensive approach, preservation professionals can achieve the delicate balance between the cost of evaluating concealed conditions and the risks presented by any conditions left undocumented.

#### 4.2.3 Understanding of Available Methods

Just as important as understanding of the scope of work and the risks concealed conditions present is an understanding of the methodologies available for investigation. As described in Chapter 3, there is a wide range of available techniques and technologies for investigating concealed conditions, each with its own advantages and disadvantages, and with a wide range in cost, time and expertise required. While the preservation architect does not need to be a specialist in every NDT technique, it is important to develop a basic understanding of the available technologies in order to be an “informed consumer”. Many investigation programs involve a consultant specifically responsible for NDT, but this does not relieve the architect from the

need to understand the techniques employed. Otherwise, the project is at the mercy of the NDT provider, who has a vested interest in selling services that may or may not have any true value for the project.

#### 4.2.4 Focus on Results

In addition to determining the level of information required about concealed conditions, it is critical that the investigation itself focus on specific and measurable results rather than the techniques or technologies themselves. This generally involves taking the range of potential concealed conditions and framing them as specific, answerable questions that can then be investigated and answered. As an illustration, consider the following two statements, both of which express a requirement for understanding a concealed condition:

- It is important to investigate the concealed conditions below the floor in Area X
- What are the dimensions, configuration, and physical condition of the floor framing members in Area X?

While it may seem like an academic distinction, there are significant practical implications to the way in which the investigation is framed. Problem statements of the second type are much more likely to yield a successful result, particularly when the non-destructive examination component of an investigation is conducted by a consultant.

The first statement may appear to provide a broad directive that allows for indiscriminate application of testing technologies over the full area, which can lead to wasted time and cost on investigations that are not relevant to the proposed project. From the perspective of an NDT consultant, different technologies provide a different “view” of the area – radiographic testing may provide information on the location of fasteners, while thermal imaging may provide locations of

insulation or other anomalies – and so, these technologies are applied without considering whether this information is truly valuable. Therefore, the poor framing of the problem statement has the potential to encourage a technique-centric approach that is rarely cost-effective.<sup>70</sup>

By contrast, the second statement asks a series of questions which can be answered with a measurable level of confidence. Whether through non-destructive examination or a targeted series of floor probes, the specifics of dimension, configuration and condition can be addressed in a systematic fashion, using the most cost effective methods. When each question is answered with a satisfactory level of accuracy and detail, no further investigation is required.

#### 4.2.5 Hierarchy of Subsurface Investigation Methods

The methodologies and techniques described in Chapter 3 followed a sequence reflecting the framework underlying most evaluation programs:

- archival research, recording and visual assessment methods are used to define the basic parameters of the problem;
- non-destructive testing is used selectively to investigate specific areas of concern;
- probes are conducted to confirm findings.

This sequence can be understood using a similar thought process to the illustrations included in Chapter 2. **Illustration 4-1** illustrates how an investigation would logically proceed along this path, maximizing the information obtained relative to the cost of the investigation.

---

<sup>70</sup> A perfect example of this effect can be seen when companies or individuals purchase a large or expensive piece of testing equipment. In an effort to “justify the cost”, the specific technology may be applied to every investigative situation without considering whether it is truly useful.



**Illustration 4-1:** Chart showing an idealized progression of investigation.

As with the charts shown in Chapter 2, the exact form of the curve may vary greatly for specific buildings, conditions and types of testing.

Of course, this sequence is only a general guideline, and does not provide a “one-size-fits-all” approach that can be applied to any project. In the real world, investigative programs require an understanding of how to plan and execute the crucial first steps, when the nature and extent of concealed conditions is completely unknown. They necessitate proper planning for advancing to the next “stage” of the program, when the current technique becomes decreasingly effective. Finally, they require judgement to determine when it is appropriate to consider an alternative sequence (for example, using selective probes early in the investigation process).

Refer to **Section 4.3** and the flowchart for a detailed analysis of how this general hierarchy informs a typical subsurface investigation program.



#### 4.2.6 Utilizing an Iterative Approach

When considering the sequence of assessment, it is critical to understand that the process is by no means a linear one. The most effective investigation programs are structured to take advantage of “feedback loops”, using new information to inform the next stages of the process. For example, infrared thermography intended to map a building’s moisture profile may reveal evidence of previously unanticipated concealed deterioration.

In concert with a results-oriented approach, this type of iterative thinking prevents the investigation from being driven by indiscriminate application of “preferred” technologies or techniques. As new information is gained, new questions are formed; these questions may require an entirely different set of methods and tools.

#### 4.2.7 Understanding Extent, Variation and Range

The concepts of extent, variation and range are closely related. Extent refers to the scale of the concealed condition investigated. For example, some conditions (e.g., subfloor materials or types of masonry backup walls) may affect large portions of a building or structure, while others (e.g., types of fasteners or small pipe penetrations) are limited in size. Variation refers to the distinction between conditions that occur repeatedly throughout a building (e.g., typical steel connections or undersized floor joists) and those that are unique (e.g., specialized framing at a dome). Range refers to the degree of difference among the conditions throughout the building or structure (e.g., minor oxidation in a steel beam versus major rusting resulting in section loss).

While seemingly straightforward, an understanding of scale and variation can have a significant impact on the efficiency of an investigation program. When working with a limited budget for assessment, it is generally more valuable to focus on conditions that are large in extent,

to maximize the benefit of the available testing. It is also necessary to understand the level of variation, particularly if a testing program uses a “sampling” approach to extrapolate findings to other similar components. Similarly, any investigation must at least take into account the “one-off” conditions, whether known at the outset or as a result of unexpected variation. Finally, the potential range of the condition must be taken into account, in order to pinpoint areas where investigation should focus on identifying worst-case scenarios to inform project planning.

#### **4.3 Conclusion: Structuring an Investigation Program**

As this thesis has demonstrated, the investigation and assessment of concealed conditions is a highly subjective endeavor, more an art than a science, and it must be informed by ethical judgement as well as knowledge and experience. A wide range of methods, from visual inspection to probes, fall under the category of subsurface investigation. They must each be utilized in an informed manner, balanced against the requirements of the individual project, which may include diverse goals such as the protection of historic fabric or the control of construction cost. While no single methodology can be outlined for how to approach this complex problem, the seven basic concepts described above provide a basic framework for how the assessment and investigation of concealed conditions in historic buildings should be approached. The flowchart in *Illustration 4-2* demonstrates how these concepts can be applied to develop a systematic investigation sequence for a historic building.

The first step should always be to develop an initial list of potentially impactful concealed conditions. This list should be as comprehensive as possible, based on the scope of the proposed project, knowledge of the building type, and any specific site conditions or program-related requirements. Some typical examples include:

- In 20<sup>th</sup>-century buildings constructed with a steel frame and masonry façade, the condition of the structural steel members may need to be determined;
- In a project that includes the insertion of a new elevator, the depths of foundation walls may need to be investigated to determine the requirements for underpinning;
- For a project that includes the insertion of new mechanical, electrical and plumbing systems, the location and configuration of existing pathways and chases is critical to understand;
- In a building that has had several building campaigns over the course of its history, it may be important to confirm where concealed historic fabric may exist.

This initial assessment serves as a guide for the first stages of the investigation, which generally begins with archival research. By compiling and reviewing available materials, such as historic drawings and documents relating to previous interventions, the design team can develop a “clinical history” of the building and understand how it has changed over the course of its lifetime. Archival research may provide clues to some of the questions raised in the initial assessment; conversely, it often raises entirely new questions. For example:

- Original construction drawings for historic buildings may indicate the designed location of vertical chases
- Original construction specifications may describe construction processes that are known to lead to specific deterioration conditions (e.g., ferrous anchors in a masonry wall)

With a basic understanding of the building’s basic timeline, the next key step is to accurately record the as-found conditions of the structure. While this recording is limited to visible surfaces, it does create a set of baseline documents that forms the “background” for documenting

later investigations. In addition, depending on the techniques used, the recording process itself may reveal areas where impactful concealed conditions may exist. For example:

- Laser scanning may reveal distortions in floors and ceilings that are not immediately obvious with visual investigation;
- The process of measurement may reveal an unexpected variation in wall thickness between two adjacent rooms.

With base drawings developed, the team can begin a visual assessment and recording of visible deterioration conditions. Like the as-found recording, this assessment is limited to fabric that is readily observable; however, it often reveals valuable clues about what lies beneath the surface. For example:

- In masonry buildings, a variety of observable conditions such as efflorescence, missing mortar, and biological growth may indicate moisture issues;
- Cracks or other visible distress in a façade may indicate potential issues with the underlying structure;
- Evidence of previous repairs in an area may present a need for additional investigation of the deterioration that necessitated them.

After these initial investigations – archival research, comprehensive recording, and visual assessment – are complete, the design team should be in the position to develop a documentation package that delineates all of the potential concealed conditions that may impact the proposed work. These conditions can then be “filtered” based on the overall project parameters, such as the construction budget, the budget for investigation, the scale and extent of each condition, and the expected variation. The result will be a detailed list of concealed conditions that require

investigation because of their material effect on the proposed project. As described in **Section 4.2.4**, the list should be framed in terms of specific, answerable questions about physical condition, such as:

- What is the overall pattern of moisture infiltration in the building envelope?
- What is the extent of non-observable delamination in the masonry units on the building exterior?
- What are the locations of the anchors that tie the masonry façade back to the steel structure, and what material are they fabricated from?

With the basic parameters of the problem in place, the process of selecting the proper technology or technique for examining each condition can proceed. The decisions made at this stage are often the “crux” of the investigation, presenting the greatest challenge and having the most impact on its success. Given the overwhelming range of available subsurface investigation (SI) methods, from simple digital-image enhancement to complex electromagnetic testing, an exhaustive analysis of the potential of each technique is practically impossible for most projects. Instead, it is more beneficial to organize the SI approach into two parallel tracks.

The first track should include “basic” NDT methods, which includes any technique that can yield a large amount of information relative to the required cost of investigation. The goal of this first pass is to obtain a breadth of data, at a basic level of detail, without expending the full investigative budget. The NDT methods utilized in this first effort vary on a project-by-project basis, but generally include the use of simple, inexpensive tools such as borescopes and moisture meters, as well as more advanced NDT techniques such as thermal imaging that provide value by being easily applied to large areas. It is absolutely critical that the identification of techniques to be

included in this effort, and the locations where they are to be applied, must take into account the issues of extent, variation and range described in **Section 4.2.7**. Examples of basic NDT methods applied to concealed conditions as part of the first stage of an investigation include:

- Borescope investigation to verify a steel framing connection detail that is indicated by archival research to be typical throughout the building
- Thermal imaging of physically inaccessible areas of a building, in order to determine whether any anomalies exist that should be investigated further
- CCTV investigation of chimney flues or drain lines to determine blockages and condition

After the first pass with basic NDT techniques is conducted, the information on some of the concealed conditions may be sufficient for the treatment to be defined and specified. In other areas, for some projects, the information may be insufficient in accuracy or detail, and additional investigation may be required. These areas, along with any conditions identified as not being suitable for investigation with basic NDT techniques, are candidates for the application of more advanced NDT methods.

The goal of this second pass is generally to obtain detailed data about conditions of special significance. This significance may result from their potential extent, their high potential cost, or their impact on the potential design of a new intervention. As with the first pass, the specific methods utilized in this effort vary, but generally include specialized technologies such as impulse radar and impact-echo testing. It may also include basic techniques applied in a more systematic manner or in more difficult-to-access areas. Like the first pass, the design of this investigation must take into account extent, variation and range. Examples of advanced NDT methods applied to concealed conditions in a second pass include:

- Impulse radar used to determine the extent of voids in a masonry wall where evidence of distress was noted by previous assessment;
- Metal detection to locate anchors and attachment points for a monumental stained glass window to be removed as part of a project;
- Active thermography used to pinpoint precise locations of leaks in a flat roof;
- Use of a lift to obtain access to specific areas for additional borescope testing locations.

After this second specialized investigation is completed, additional concealed conditions will have been investigated to a sufficient extent that they can be properly planned for and treated.

In many projects, though, there may exist a range of conditions for which both visual assessment and NDT techniques either did not provide sufficient information, or were ill-suited for the investigation required. In these cases, probes and destructive examination are often a next logical step.

A program of selective destructive examination can be used to confirm the findings of previous investigations, as well as investigate conditions that are not suitable to any NDT method. The irreversible nature of destructive examination makes it is absolutely critical that the work be planned and sequenced carefully; however, it does not necessarily have to be a last resort. Probes can sometimes offer a cheaper alternative to NDT investigation, particularly in cases where the fabric in question would need to be removed anyway as part of the proposed work. Examples of the use of probes include:

- Confirmation, in a single location, that an NDT technique utilized to map mortar loss within the full extent of a stone wall was obtaining accurate results;

- Removal of later ceilings to reveal the original historic ceiling above, in order to confirm its location and assess its condition;

After the completion of the full range of methods of investigation, from archival research to destructive probes, the concealed conditions in a building can hopefully be understood at a level that allows the design team to make informed decisions about treatment approaches and their anticipated costs. Of course, concealed conditions may exist that simply cannot be discovered with the available techniques, or within the available time frame or budget for investigation. In this case, it is important that the team consider additional risk management strategies such as those discussed in *Chapter 2*.

While it is impossible to completely eliminate the risk presented by concealed conditions in existing buildings, the systematic approach outlined above represents a methodology that can limit their impact and allow for successful project planning and implementation for a wide range of projects. It provides architects, engineers and preservation professionals with a framework for decision-making that balances the cost of an investigation at each step with the potential benefits it provides. It is only with this type of logical qualitative thinking that the investigation of concealed conditions can be successfully integrated into the practice of preservation architecture.



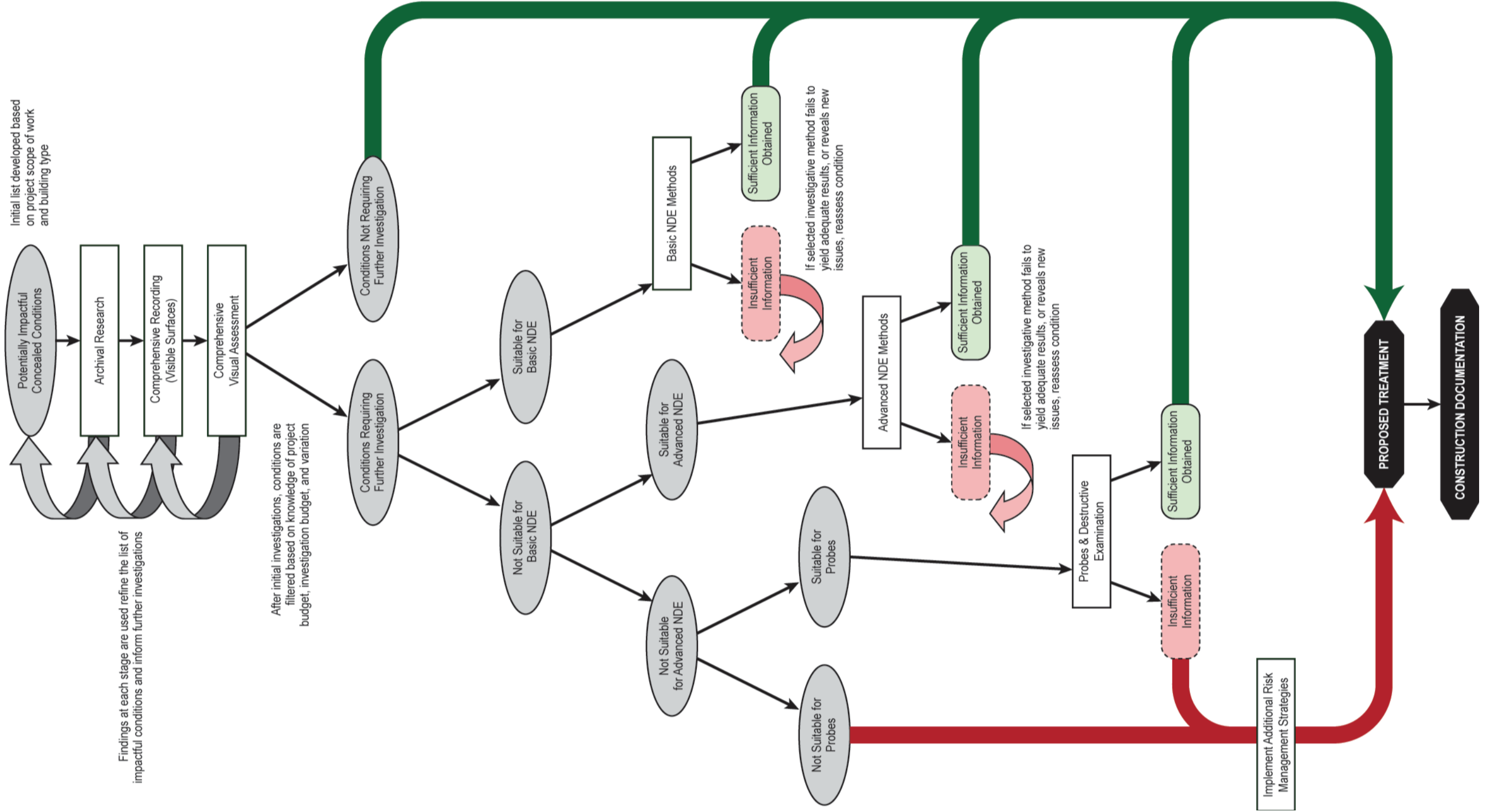


Illustration 4-2: Flowchart showing basic approach to subsurface investigation in historic buildings

## 5. Bibliography

- American Institute of Architects. *AIA Document A201-2007, General Conditions of the Contract for Construction*. Washington, DC: AIA, 2007. AIA Contract Documents Software. Digital Version. 8 Nov. 2014.
- American Institute of Architects. *AIA Document B101-2007, Standard Form of Agreement Between Owner and Architect*. Washington, DC: AIA, 2007. AIA Contract Documents Software. Digital Version. 8 Nov. 2014.
- American Institute of Architects. *AIA Document B201-2007, Standard Form of Architect's Services: Design and Construction Contract Administration*. Washington, DC: AIA, 2007. AIA Contract Documents Software. Digital Version. 8 Nov. 2014.
- American Institute of Architects. *AIA Document B205-2007, Standard Form of Architect's Services: Historic Preservation*. Washington, DC: AIA, 2007. AIA Contract Documents Software. Digital Version. 8 Nov. 2014.
- Anthony, Ronald W. "Condition Assessment of Timber Using Resistance Drilling and Digital Radioscopy." *APT Bulletin* 35:4 (2004): 21-26. Web. 10 Nov. 2014. <http://www.jstor.org/stable/4126416>
- Anthony, Ronald W. "Nondestructive Evaluation: Wood." *APT Practice Points* 10. APTI, 2010. Web. 14 Oct. 2014. <http://www.jstor.org/stable/41000035>
- ASTM International. "ASTM E2270-14, Standard Practice for Periodic Inspection of Building Facades for Unsafe Conditions", ASTM International, West Conshohocken, PA, 2014, [www.astm.org](http://www.astm.org).
- ASTM International. "ASTM E2356-14, Standard Practice for Comprehensive Building Asbestos Surveys", ASTM International, West Conshohocken, PA, 2014, [www.astm.org](http://www.astm.org).
- Bransby-Zachary, Charles, George Ballard and Avigail Charnov. "Nondestructive Evaluation (NDE) of Embedded Iron and Steel." *APT Bulletin* 45.1 (2014): 5-11. Web. 11 Nov. 2014. <http://www.jstor.org/stable/23723864>
- Brown, Paul Wencil and James R. Clifton. "Nondestructive Techniques for Evaluating Metallic Artifacts of Historical Interest." *Bulletin of the Association for Preservation Technology* 8.4 (1976): 2-21. Web. 10 Nov. 2014. <http://www.jstor.org/stable/1493580>

- Cecire, Ashley Skye. *Nondestructive Evaluation of Historic Structures*. (Master Thesis). Massachusetts Institute of Technology, Cambridge, MA. 2003.
- Clark, Kate. "Informed Conservation: The Place of Research and Documentation in Preservation." *APT Bulletin* 41.4 (2010): 5-10. Web. 11 Nov. 2014. <http://www.jstor.org/stable/41000031>
- Dossett, Jim. "Case Studies in the Repair of Masonry-Clad, Steel-Framed Buildings." *APT Bulletin* 45.1 (2014): 27-35. Web. 11 Nov. 2014. <http://www.jstor.org/stable/23723867>
- Friedman, Donald. "Ambiguity in Building Investigation: A Study of Sampling and Decision-Making with Field Data". *APT Bulletin* 31:2/3 (2000): 39-44. Web. 10 Nov. 2014. <http://www.jstor.org/stable/1504659>
- Gilberg, Mark, Claudia Riegel, Bob Melia, and Jack Leonard. "Detecting Subterranean Termite Activity with Infrared Thermography: A Case Study." *APT Bulletin* 34:2/3 (2003): 47-53. Web. 10 Nov. 2014. <http://www.jstor.org/stable/1504822>
- Hart, David M. "X-Ray Analysis of the Narbonne House." *Bulletin of the Association for Preservation Technology* 6.1 (1974): 78-98. Web. 10 Nov. 2014. <http://www.jstor.org/stable/1493413>
- Hart, David M. "X-Ray Investigation of Buildings." *Bulletin of the Association for Preservation Technology* 5.1 (1973): 9-21. Web. 10 Nov. 2014. <http://www.jstor.org/stable/1493364>
- Harvey, Jr., Donald W. and Michael P. Schuller. "Nondestructive Evaluation: Structural Performance of Masonry." *APT Practice Points* 09. APTI, 2010. Web. 14 Oct. 2014. <http://www.jstor.org/stable/20749121>
- Hum-Hartley, Susan. "Nondestructive Testing for Heritage Structures." *Bulletin of the Association for Preservation Technology* 10.3 (1978): 4-20. Web. 10 Nov. 2014. <http://www.jstor.org/stable/1493664>
- Ihlseng, M.C. "The Modulus of Elasticity in Some American Woods, as Determined by Vibration." *Van Nostrand's Eclectic Engineering Magazine* 19 (1878): 8-9. Web. 15 Dec. 2014.
- Kaplan, Marilyn E., Marie Ennis, and Edmund P. Meade. "Non-destructive Evaluation Techniques for Masonry Construction." *Preservation Tech Notes - Masonry Number 4*. National Park Service, 1997. Web. 21 Oct. 2014. <http://www.nps.gov/tps/how-to-preserve/tech-notes/Tech-Notes-Masonry04.pdf>

- Kevlin, Mary Joan. "Radiographic Inspection of Plank-House Construction." *Bulletin of the Association for Preservation Technology* 18.3 (1986): 40-43. Web. 10 Nov. 2014. <http://www.jstor.org/stable/1494117>
- Kubba, Sam A. A. *Architectural Forensics*. United States: McGraw Hill, 2008. Print.
- Lavoie, Catherine C. "The Role of HABS in the Field of Architectural Documentation." *APT Bulletin* 41.4 (2010): 19-24. Web. 11 Nov. 2014. <http://www.jstor.org/stable/41000033>
- Linton, Linnea M. "Delaminations in Concrete: A Comparison of Two Common Nondestructive Testing Methods." *APT Bulletin* 36:2/3 (2005): 21-27. Web. 11 Nov. 2014. <http://www.jstor.org/stable/40004701>
- Livingston, Richard A. "Nondestructive Testing of Historic Structures." *Science and Technology in Historic Preservation*. Ed. Ray A. Williamson and Paul R. Nickens. New York, NY: Kluwer Academic/Plenum Publishers, 2000. 97-120. Print.
- Mason, James A. "Nondestructive Analysis of and Strengthening Design for a Historic Church Tower in Kentucky." *APT Bulletin* 36:1 (2005): 35-43. Web. 10 Nov. 2014. <http://www.jstor.org/stable/40003950>
- Mellett, James S. and Shelley E. Smith. "Using Ground-Penetrating Radar to Investigate Historic Masonry Buildings." *APT Bulletin* 41:2/3 (2010): 47-56. Web. 11 Nov. 2014. <http://www.jstor.org/stable/20749123>
- Miller, Hugh C. "Preservation Technology Comes of Age in North America: Part 1." *APT Bulletin* 37:1 (2006): 55-59. Web. 11 Nov. 2014. <http://www.jstor.org/stable/40004681>
- Miller, Hugh C. "Preservation Technology Comes of Age in North America: Part 2." *APT Bulletin* 37:2/3 (2006): 61-65. Web. 11 Nov. 2014. <http://www.jstor.org/stable/40004691>
- National Park Service. "Secretary of the Interior's Standards for Architectural and Engineering Documentation." NPS, 1983. Web. December 2014. [http://www.nps.gov/history/local-law/arch\\_stnds\\_6.htm](http://www.nps.gov/history/local-law/arch_stnds_6.htm)
- National Park Service. "HABS Guidelines: Recording Historic Structures and Sites with HABS Measured Drawings." NPS Heritage Documentation Programs – HABS, 2008. Web. December 2014. [http://www.nps.gov/hdp/standards/HABS\\_drawings.pdf](http://www.nps.gov/hdp/standards/HABS_drawings.pdf)
- Ortega, Richard I. "Seeing with Different Eyes: NDE of Embedded Steel at Yale University." *APT Bulletin* 45.1 (2014): 21-26. Web. 11 Nov. 2014. <http://www.jstor.org/stable/23723866>

- Rosina, Elisabetta and Elwin C. Robison. "Applying Infrared Thermography to Historic Wood-Framed Buildings in North America." *APT Bulletin* 33:4 (2002): 37-44. Web. 10 Nov. 2014. <http://www.jstor.org/stable/1504807>
- Rosina, Elisabetta and Jonathan Spodek. "Using Infrared Thermography to Detect Moisture in Historic Masonry: A Case Study in Indiana." *APT Bulletin* 34:1 (2003): 11-16. Web. 10 Nov. 2014. <http://www.jstor.org/stable/1504847>
- Ross, Robert J., Lawrence A. Soltis, and Patrick Otton. "Assessing Wood Members in the USS Constitution Using Non-Destructive Evaluation Methods." *APT Bulletin* 29:2 (1998): 21-25. Web. 10 Nov. 2014. <http://www.jstor.org/stable/1504514>
- Schuller, Manfred. *Building Archaeology*. ICOMOS, 2002. Print.
- Schuller, Michael. "Nondestructive Evaluation in a Preservation-Engineering Curriculum." *APT Bulletin* 44.1 (2013): 41-46. Web. 11 Nov. 2014. <http://www.jstor.org/stable/41827069>
- Silman, Robert. "Applications of Non-Destructive Evaluation Techniques in Historic Buildings." *APT Bulletin* 27:1/2 (1996): 69-73. Web. 10 Nov. 2014. <http://www.jstor.org/stable/1504503>
- Skarneas, George C. "From HABS to BIM: Personal Experiences, Thoughts and Reflections." *APT Bulletin* 41.4 (2010): 47-53. Web. 11 Nov. 2014. <http://www.jstor.org/stable/41000038>
- Slaton, Deborah. "Preservation Brief #43: The Preparation and Use of Historic Structure Reports." National Park Service, 2005. Web. December 2014. <http://www.nps.gov/tps/how-to-preserve/briefs/43-historic-structure-reports.htm>
- Sparks, S. Patrick and Marc E. Badoux. "Non-Destructive Evaluation of a Historic Wrought-Iron Truss Bridge in New Braunfels, Texas." *APT Bulletin* 29:1 (1998): 5-10. Web. 10 Nov. 2014. <http://www.jstor.org/stable/1504542>
- Staley, Ronald D. "Successful Preservation Implementation: A Planned Approach to Risk Management." *APTI Practice Points 01*. APTI, 2010. Web. 11 Nov. 2014. <http://www.jstor.org/stable/40004688>
- Streeter, Kelly. "Information Technology for Building Documentation." *APT Bulletin* 41.4 (2010): 33-38. Web. 11 Nov. 2014. <http://www.jstor.org/stable/41000036>
- Swanke Hayden Connell Architects. *Historic Preservation: Project Planning & Estimating*. Kingston, MA: R.S. Means Company, Inc., 2000. Print.

The American Society for Nondestructive Testing. "Introduction to Nondestructive Testing." ASNT, 2012. Web. 14 December 2014.

Trujillo, Nicole, Thomas E. Boothby, and Erik Valentino. "Nondestructive Evaluation of Brick Masonry Using Air-Coupled Impact-Echo Analysis." *APT Bulletin* 44.2/3 (2013): 35-42. Web. 11 Nov. 2014. <http://www.jstor.org/stable/41982403>

Watt, David. *Surveying Historic Buildings*. Michigan, USA: Donhead, 2011. Print.

## 6. Index

acoustic emission testing, 26  
acoustic testing, 35  
archival research, 18, 19, 21, 25, 38, 49, 53, 54, 56, 58  
borescopes, 20, 27, 55  
construction cost, 46, 52  
HABS, 1, 9, 10, 21, 24, 62, 63  
impact-echo testing, 36  
impulse radar, 33, 34, 37, 56  
metal detection, 32  
moisture meters, 28  
probes, 2, 17, 19, 20, 21, 28, 38, 39, 41, 47, 49, 50, 52, 57, 58  
pulse-echo testing, 36  
radiographic testing, 30, 62  
thermography, 4, 28, 29, 38, 51, 57  
visual assessment, 19, 20, 21, 25, 27, 35, 38, 41, 49, 54, 57