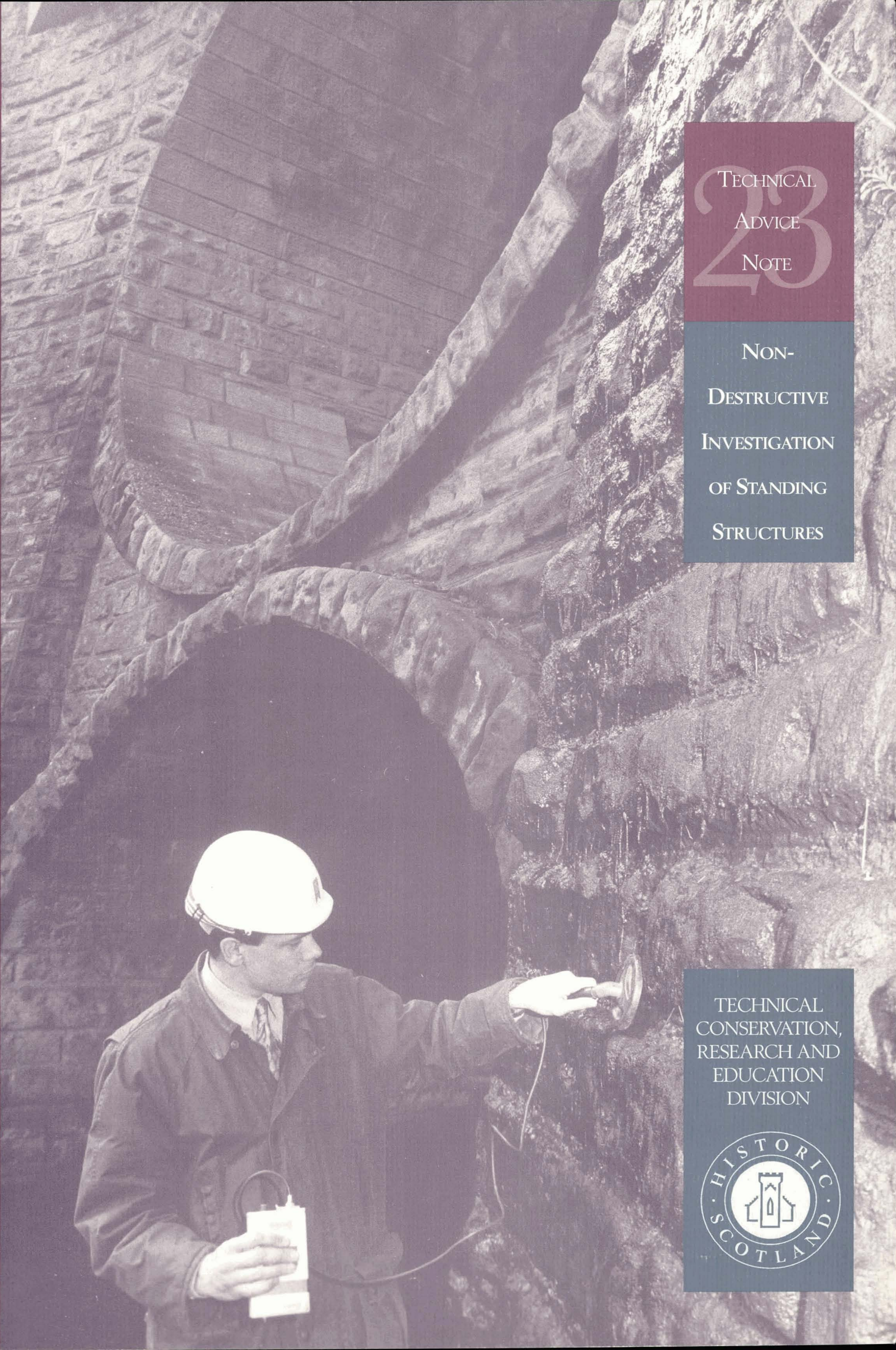
TAN 23

NON-DESTRUCTIVE INVESTIGATION OF STANDING STRUCTURES



TECHNICAL ADVICE NOTE

23

NON-DESTRUCTIVE INVESTIGATION OF STANDING STRUCTURES

TECHNICAL CONSERVATION, RESEARCH AND EDUCATION DIVISION

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NON-DESTRUCTIVE INVESTIGATION OF STANDING STRUCTURES

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FOREWORD

Minimum intervention has for many years been a key tenet of conservation philosophy. *The Stirling Charter: Conserving Scotland's Built Heritage*, published by Historic Scotland in January 2000, re-states its importance. The publication of this Technical Advice Note is therefore particuarly relevant and timely.

For sometime many have been aware of the potential usefulness of non-destructive investigation techniques in the conservation of standing structures. An investigation of part of Kildrummy Castle, where concerns had been raised regarding the structural effectiveness of the wall core, was undertaken as a pilot project in 1995. Kildrummy is a ruined thirteenth century castle and a Scheduled Ancient Monument in Historic Scotland care. Traditional methods of assessing the extent and seriousness of decay in the wallcore might have included core-boring or downtaking sections of wall. However, in view of the significance of the fabric, an impulse radar survey was commissioned to allow a more focussed understanding of site conditions.

The results from this work were used to inform future conservation work at the monument and also to shape the development of and provide illustrative material for this note.

This Technical Advice Note covers electro-magnetic (including impulse radar, thermography, metal detection and free electro-magnetic radiation) nuclear and acoustic test methods for use on standing structures. Factors that should be taken into account when planning a non-destructive investigation are also covered. Given the topic being addressed, the language used is, inevitably, more scientific than technical. However, considerable effort has been taken to try to 'translate' the information in such a way that practitioners will find the text helpful and informative.

The guidance provided is not intended to be prescriptive or to be used as a specification for works on site. Instead, this note is intended to act as a primer. The intention is to arm the conservation professional with an understanding of the capabilities and limitations of the various techniques available. This should allow an informed decision to be made on the appropriateness of each technique in any particular situation.

Ingval Maxwell
Director TCRE
September 2001

LIST OF ABBREVIATIONS

Abbreviations used in this document

CAD	Computer aided design
DAT	Digital Audio Tape
FEMR	Free ElectroMagnetic Radiation
GPR	Ground Probing RADAR
HSE	Health and Safety Executive
NAMAS	National Analytic and Accreditation Service
PUNDIT	Pulsed Ultrasonic Non-Destructive Inspection and Testing
RADAR	Radio Detection And Ranging
SONAR	Analogy with 'RADAR' using sonic pulses
UKAS	United Kingdom Accreditation Service
UPV	Ultrasonic Pulse Velocity

ST Units used in this document

G	giga
Hz	hertz
k	Kilo
M	mega
m	milli
µ	micro
s	seconds
v	volt

SUMMARY

The conservation of our architectural heritage has moved from a practical restorative craft to a multi-disciplinary professional team effort. Well intentioned repairs and modifications by previous conservators have all too often resulted in more rapid deterioration of ancient monuments and buildings. Our duty now is to ensure that every effort is made to arrest deterioration of historic fabric. This must apply not only to the visible exterior, but also to the hidden interior of structures and buildings.

This Technical Advice Note is concerned with structural investigation using instrumental (not analytical) methods that allow us to inspect and monitor the hidden internal structure without the need for invasive or destructive inspection. These methods facilitate the recording of easily accessed information that can inform the future maintenance and conservation of the structure.

Rapid developments in electronics, instrumentation and data acquisition technology during the latter half of the twentieth century have provided a wealth of new methods of recording and evaluating the built heritage in a non-invasive manner, such that there is much less need for ‘opening up’ to discover the condition and arrangement of structural materials. At the same time this has generated an enormous volume of information which can all too easily become lost or inaccessible.

The information recovered by a non-destructive investigation is factual, but requires interpretation before it can be used by conservation professionals. Records should be kept of both raw data and the interpretation put on that data at the time of collection to ensure that the reasoning behind any decisions is understood by succeeding conservation professionals.

A number of specialist non-destructive testing companies now exist with the aim of bringing these novel instrumental methods into the field of civil and structural engineering, making them available to conservation professionals. There is however a wide range of of non-destructive investigation methods available, the majority of which are probably unknown to, or generally poorly understood by, architects, engineers and others.

The prime objective of a non-destructive investigation is to provide the conservation professional with all the information required to allow appropriate and valid decisions to be made concerning the conservation of the structure. All investigative methods used should respect the historic fabric of the building and, as far as is possible, avoid interference with or destruction of any element of the historic structure. This imposes a different set of controls on the structural investigator from those he/she normally encounters, and there is always a requirement for a very careful and well considered approach to the way in which the structure is investigated and recorded. The context of an historic building frequently forces the most effective instrument to be set aside in favour of an approach which does not disturb some element of the structure or its contents.

The benefits of non-destructive methods of investigation are clear and, with good planning, they can often provide a much more rapid and cost-effective method of gathering information than the more traditional destructive alternatives.

It is hoped that this Technical Advice Note will foster improved understanding of the range of non-destructive investigative and recording techniques available, and it attempts to identify the most appropriate applications for each. It provides information on the theory behind each technique, its capabilities and limitations, and describes the nature and quality of the results which can be expected. General guidance is offered on the application of each method within conservation projects.

It is not the intention of this document to act as a complete reference work for each of the techniques discussed, but specifically to provide sufficient information to enable a conservation professional to decide upon the methods of investigation or recording which might be most applicable in a particular situation and to direct him or her to the most appropriate specialist from whom further advice and information can be obtained.

FREQUENCY OF VARIOUS NON-DESTRUCTIVE INVESTIGATION TECHNIQUES

The following diagram shows the approximate frequencies of the different wave forms discussed in this Advice Note. Mechanical and electro-magnetic waves are included.

Method	**Wave Form**	**Frequency (Hz)**	
	Gamma		
		1 x 10^{19}	
Radiography			
	X-rays	1 x 10^{17}	
	Ultra-violet	1 x 10^{15}	
ROYGBIV	**Visible**	1 x 10^{14}	
	Infra-red	1 x 10^{13}	
Thermography	**Far infra-red**	1 x 10^{12}	
		1 x 10^{11}	
RADAR	**Micro-waves**	1 x 10^{9}	
	Radio (VHF)	1 x 10^{8}	
		1 x 10^{7}	
			Radio
UPV	**Ultra-sound**		Bands
Impact-echo		1 x 10^{4}	
FEMR			
	Audio-sound		
		1 x 10^{1}	

1 INTRODUCTION

All investigative methods used on historic buildings must respect the fabric of the building and, as far as possible, avoid interference with or destruction of any element of the historic structure. Rapid and cost-effective non-invasive (non-destructive) methods can now be specified which allow information about a building's structure or condition to be gathered without the damage to the finishes and fabric associated with conventional methods. However, they present a challenge as they are outside the conventional skills and knowledge held by those usually entrusted with developing the programme of a conservation project.

Methods

This advice note is intended to introduce the building professional to the range of non-invasive investigation and recording methods available and offer guidance on the proper application of each. It seeks to provide information on the basic theory behind each technique, including their applicability and limitations in certain situations, and the nature and quality of the results which can be expected.

The non-destructive techniques have been grouped in generic categories, specifically:

- electro-magnetic methods (impulse radar, thermography, metal detection, free electro-magnetic radiation)
- nuclear methods (radiography)
- mechanical methods (ultrasonic pulse velocity, impact-echo)

These categories have been carefully selected to associate tests with their common stimulus. This is particularly helpful for considering the applications and limitations of the methods.

A non-technical introduction to testing is provided - including the reliability of non-destructive test results, the importance of calibration, the place of interpretation and the need for sensitive reporting and recording.

The Scope of the Technical Advice Note

This advice note is principally concerned with the investigation of the form, condition and integrity of the materials of standing historic structures, monuments and ruins. Non destructive methods appropriate to ground or archaeological investigations are not included here. There are several well-established techniques used in the field including resistivity, magnetomtry and gravimetry. Impulse radar, however finds application in both ground investigation and investigation into standing structures, and hence is included in the note.

The many non-destructive methods commonly used by the building surveyor for monitoring and detection of moisture are also omitted from this note. These include resistivity, electrical conductivity, capacitance and micro-wave absorption methods for determining moisture content. The Autoclam, Figg Test, Initial Surface Absorption Test and the like, which provide measures of permeability and absorption rates of materials, are not considered. In addition, material testing within this note is restricted to *in-situ* non-destructive methods of condition assessment - laboratory based and chemical methods are therefore also excluded.

Planning and Specification

In addition to providing information on methods of non-destructive investigation and recording, this advice note offers guidance on planning, budgeting and procurement of a non-destructive investigation, and its timing within the programme of a conservation project. Advice is also given on the selection of investigators.

Throughout this note, a distinction has been made between the techniques themselves and the role of the investigator responsible for their selection, application and interpretation. A non-destructive *investigation* is the skilful deployment of selected tests by a suitably experienced specialist and the subsequent collation, analysis and presentation of results, in context, for a specific purpose. The investigator must have a detailed understanding of the theory, applications and limitations of the techniques, combined with professional responsibility and a sympathetic approach toward conservation work. It is important that any prospective investigator has experience of working on historic buildings and therefore both his or her previous experience, and references, need to be thoroughly reviewed.

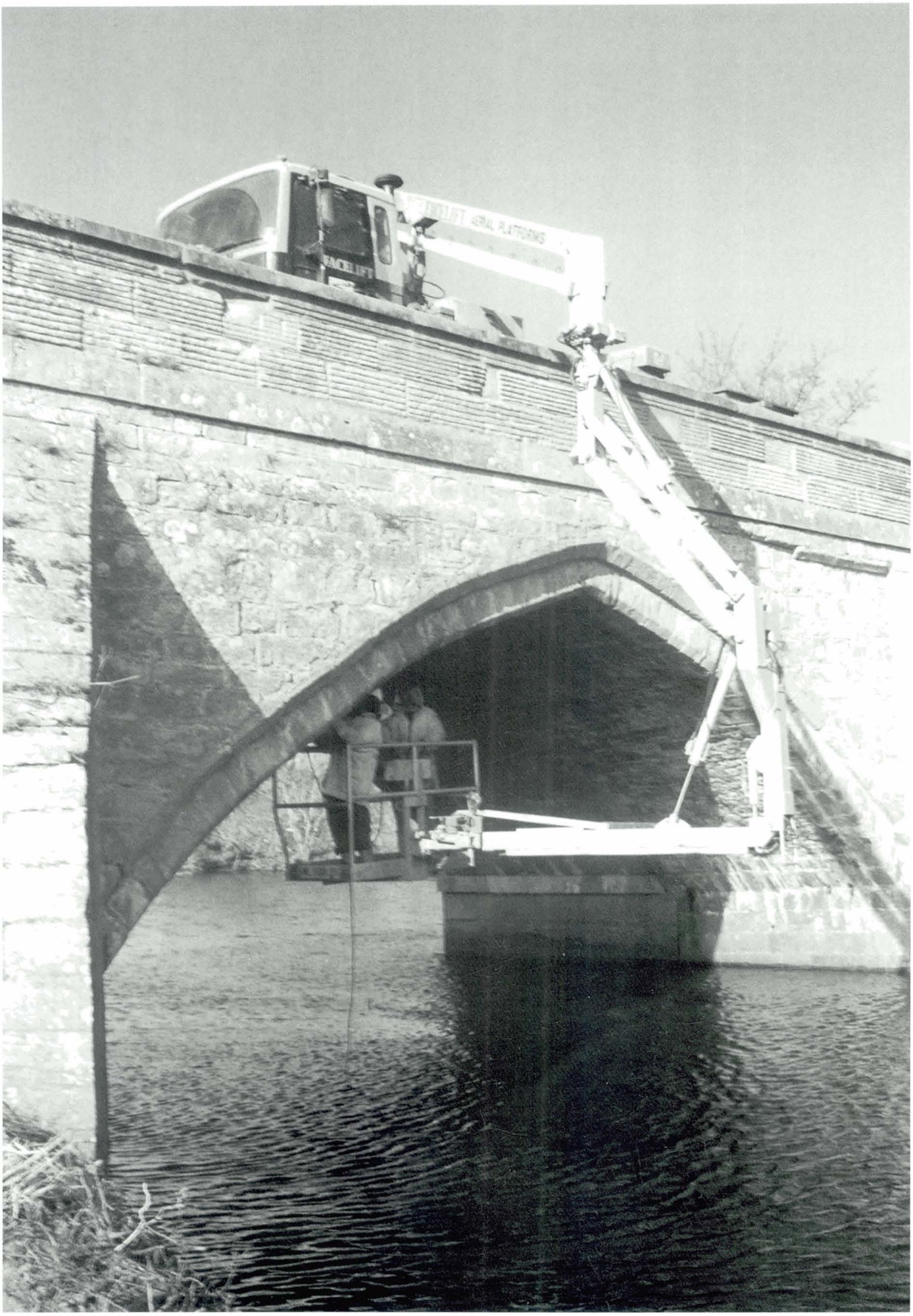


Plate 1 Impulse radar investigation of a masonry arch bridge in progress. Access to the soffit by hydraulic cradle.

2 NON-DESTRUCTIVE INVESTIGATION METHODS

This section provides a general introduction to the techniques of non-destructive investigation discussed in subsequent sections and addresses the basic principles of testing.

2.1 Introduction

Testing, in essence, is the application of a stimulus to an object and the observation, capture, measurement and recording of the object's response to that stimulus. This is as true of the doctor taking an X-ray of a patient's limb as it is of tapping a wall panel to see if it is hollow. All tests can be regarded in this manner including:

- 'simple' tests such as measurement of a distance or volume or mass
- 'destructive' (or 'invasive') tests such as excavating a hole to find the position of a wall footing
- 'empirical' tests such as the loading of a sample of stone to determine its crushing strength
- 'non-destructive' tests such as locating a tie bar in-situ with a metal detector

In each case, the object's response to a stimulus is measured: even measurements such as the photogrammetric survey of a building could be regarded as a test; observing and recording the structure's response to light - yielding information on form, dimension, colour and proportion.

Non-destructive testing means simply that the object should not suffer material damage during the process of stimulation and data capture. These tests are therefore usually carried out in-situ. The tests in this advice note have been categorised as electro-magnetic, nuclear and acoustic, emphasising the nature of the stimuli that each test applies to the object.

Sampling

Most materials and structures display heterogeneities (inconsistencies). Sometimes these anomalies are latent or of no relevance to the non-destructive investigation at hand (e.g. the veining in a marble slab).

In order to identify these anomalies, the normal (or 'control') state must be established. Such a control can only be established accurately if a sufficient number of samples is taken. Clearly the identification of anomalous readings from a sample of three is much more problematic than identifying an irregular result from a sample of twenty.

Note that when considering what constitutes a representative sample:

- the control sample may be unique for each object (i.e. results from one brick structure do not automatically eliminate the need for a control sample from another brick structure)
- the size of the control is not absolute, and will vary according to the test, the object and project constraints such as access (see Chapter 6)

For example, the inspection of five out of twenty distressed or defective window lintels will not tell you the condition of the remaining fifteen lintels. However, if carefully selected, the five may offer an insight into the likely condition of the others by establishing a probable failure mechanism, with parameters that can be used to easily assess the other fifteen lintels.

2.2 Non-Destructive Testing

The range of tests available and the combinations in which they can be applied are extensive. The role of the non-destructive investigations specialist is to apply skill and logic to the selection of the test method, to its application and to analysis of the results. The sample applications given for each of the methods in subsequent sections should be seen as illustrative, therefore, and by no means exhaustive.

Reasons for Choosing Non-Destructive Testing

The motives for specifying non-destructive methods may include:

- the need to preserve the fabric of the object being tested
- the need to recover information about the internal characteristics of an object
- the need to avoid disrupting the object, its environment and/or operation and use
- the need to assess and review large structures rapidly and economically

- the need to target subsequent test regimes that are more expensive and/or disruptive
- other alternatives are not available

Information Recovered Using Non-Destructive Testing

The following are the generic types of investigation which might be considered by conservation professionals:

- verification of known detail (e.g. internal construction of a monument)
- recording hidden detail for the purposes of archive
- identifying heterogeneities (e.g. missing structural details)
- locating specific targets (e.g. locating cramps, flue mapping)
- materials characterisation (e.g. mapping deterioration, the condition of cramps, the loss of fines or presence of cavities in rubble construction)

Optimal Timing of A Non-Destructive Investigation

Testing primarily falls within the 'inspection' phase of a conservation project. However, experience has shown that an investigation also needs to be sequential, where successive tests are selected, and applied, based on the information obtained from earlier tests.

This sequence typically includes:

- *DOCUMENTARY REVIEW*

Desk study of the object, its history and background (including existing records, written reports, anecdotal records, photographic records etc.) This will allow an assessment of the significance of the object to be made and yield valuable information on historic construction methods, materials and phasing. This will help develop the initial hypotheses that focus and describe a reasonable programme of preliminary testing.

- *SITE VISIT*

A preliminary visual study, ranging from a simple overview or 'walk through', but possibly extending to a more detailed audit. An initial visual inspection, with the necessary expert interpretation of the visible defects and their likely causes, is often a valuable pre-requisite to defining what (if anything) requires investigation and what form this investigation will take. For example, water is often the main agent of decay within a structure and an experienced understanding of how the water acts on, and within, the structure can offer clues that can assist in the formation of a hypothesis and hence in the planning of an investigation. Particular attention should be paid to any worsening of building defects noted in the documentary review as this will indicate ongoing instability.

- *PRELIMINARY TESTING*

Typically, this stage may employ a range of non-destructive reconnaissance test methods (e.g. thermography, impulse radar) to provide an overview of the object and refine the historical and visual data gathered in the previous phases.

- *DETAILED TESTING PROGRAMME*

This phase involves a review of previous testing and the deployment of subsequent complementary methods as appropriate. Tests are targeted at very specific queries raised by the combined desk/visual studies and initial testing.

2.3 Quality and Reliability

Common to all testing and central to accuracy and reliability are the methods and procedures used in data capture, storage, retrieval, analysis and interpretation. This is, perhaps, especially true of non-destructive testing, where the information may be only indirectly related to physical attributes. The accuracy (tolerances) of the techniques and calibration procedures are also relevant.

Data Capture, Storage and Retrieval

Capture is usually achieved through one or more receivers, coupled (i.e. attached to or applied) to the object of the survey. The purpose of the couple is to optimise the transfer of signals to the receiver. For some methods, such as thermography or visual surveys, these receivers may be remote from the object, and the coupling medium is air. Other methods require an intimate contact or 'couple' with the object. This may require the use of another material as a medium, such as the gel used in ultrasonics.

A distinction should be made between capture and *storage*. To be reused effectively and reliably, data must be stored. Some forms of capture (e.g. the readout on a display, the audible tone from a metal detector or the reading on a theodolite) may not actually be stored at all. In cases where an automatic log is not carried out it is important that the operator makes some form of manual record of results.

Data may be stored in many forms of hard copy, including paper traces, or in computer files held on digital tapes or discs etc. The main purpose of this, apart from allowing analysis of the data, is the retrieval of raw data at a later date for review or to identify decisions and assumptions that have been made during the course of the project.

The systems used for this process of data capture, storage and retrieval fall under the ISO 9000 Management and Quality Assurance Standards. Adherence to these standards demonstrates that reliable and effective management procedures are in place, an important factor in preserving the accuracy of data handling, analysis and reporting processes. It does not guarantee the quality of testing and its results.

Analysis and Interpretation

All test data requires some form of interpretation and processing. This may be immediate and intuitive (stamping on the floor identifies that it is hollow by the sound that it makes) or deliberate and painstaking.

Interpretation is straightforward when dealing with quantitative measures (how many cramps are there in this wall?). It is less clear when a qualitative or relative assessment must be made, as with matters of method or opinion (Why is this mosaic cracking?). In this case, the selection and testing of a hypothesis should facilitate interpretation. If the hypothesis is refuted then a new hypothesis may be selected and checked. However if the hypothesis is not refuted then it is strengthened and may be checked in another way with another test. This is the classical scientific method and forms the central philosophy of a good investigation.

For example, a crack in the rendered external wall of a building may be due to subsidence, damp, shrinkage or expansion of a finish or substrate, corrosion of embedded ironwork etc. The size, shape and orientation of the crack all give clues, but additional information is required. To this end, a hypothesis is chosen. Let us assume the hypothesis states "the structure is subsiding". We can now ask certain questions to test this hypothesis such as "is the structure prone to subsidence?", "is there evidence of subsidence elsewhere in the structure?", or "what are the material properties of the soil - is it prone to shrinkage?" Clearly some of these answers will come through testing only. The answers will establish the validity of the hypothesis.

Accuracy

The accuracy and allowable tolerances of non-destructive tests are project-specific rather than absolute, although all findings should be traceable to a fixed and stated reference point, in the same way that level surveys are traceable to an original datum.

Accuracy and tolerances are variable and are best understood in terms of what useful and practical information is required from a particular investigation. For example it is clearly unimportant to know the location of a tie to ± 5mm, say, when the number of ties is the actual query, or if the exposure for a physical examination, removal and/or repair can only be carried out to an accuracy of ± 50mm. Similarly the primary value of a plot showing structural condition in the rubble core of a wall may lie in assessing the scale of works (e.g. 40% of the ashlar facing stones are debonded from the core) or regions of major concern (e.g. lower left quadrant, upper six courses etc.) rather than providing definitive boundaries (e.g. between intermediate degrees of separation of ashlar and rubble).

To arrive at the ad hoc assessment of 'useful and practical' expectations of accuracy, the conservation professional should refer back to the aims and the specific objectives of the investigation.

Calibration

When considering raw data from an investigation, there must be some means of establishing the reliability of this data. This requires calibration of the equipment, against known constants (e.g. the velocity of radio waves through standard materials) which are published and available to the scientific community, as well as site specific readings. The investigator should have some system in place for doing this, either externally (e.g. through a body like United Kingdom Accreditation Service) or internally through an audited Quality Assurance system.

Site-specific calibration is particularly valuable - either against objective physical parameters (e.g. velocities, thickness, densities etc.) or features revealed during the interpretation phase - the temptation to withhold some data from the investigator as a 'test' of the reliability of the test findings should be resisted. For example, readings interpreted by the investigator as discontinuities at the back of a retaining wall may take on a whole new significance when it is revealed that an earlier trial hole at the top of the wall uncovered what might be the capping stone on top of a buttress at the rear; those 'discontinuity' readings now can be interpreted as representing the buttress. Further analysis of the signals may be possible, and may reveal periodicity (suggesting a structural design and intent) and may yield valuable information on the actual structural arrangement. By offering as much information as possible to the investigator a more precise interpretation of the data, and therefore the structure, can be made.

2.4 Limitations

No consideration of what a specific test can achieve is complete without a discussion of what the test *cannot* achieve. It is rare and often ill-advised to deploy non-destructive tests in isolation, without reference to some corroborative evidence, be it another test, historical records or visual observations. Non-destructive test data alone is rarely sufficient and the limits to which interpretation may be taken are finite.

From the definition of testing provided earlier, it is clear that testing is employed to 'interrogate' an object, asking specific questions to provide answers. To this end it must be appreciated that all techniques have their own applications and optimum environments where they can be expected to work well. It is these which are set out in the subsequent sections.

There are at least five types of general limitations :

- *COMPLEX OBJECTS OR CONFIGURATIONS*

Where there are many possible factors affecting the response of an object to a stimulus, (e.g. geometry, form, aspect, orientation, condition, boundary conditions etc.) it becomes increasingly difficult to 'interrogate' either the structure as a whole or individual components within it. Therefore the results of tests applied to densely reinforced concrete, multi-layered constructions etc. will be complicated, and their analysis to provide useful and practical information difficult.

- *ACCESS*

Good access is imperative to recover good results (see section 6.2.1).

- *CONDITION*

If the object is in poor condition it may not be possible to provide detailed comments on the construction arrangement, as signals are dominated by the condition responses, e.g. an investigation to locate chimney flues in a wall will be hampered if the wall is missing part of its rubble core - a formed void is frequently indistinguishable from a 'natural' void, other than by its form.

- *DIMENSIONS*

The testing regime should reflect the scope and nature of the problem. Is the problem two dimensional - i.e. in the face of a building only? Is it three dimensional - i.e. are there voids located behind the facing stones of a wall? Is it four dimensional - i.e. is there a time factor involved?

- *SHAPE AND FORM*

Small or thin objects can be difficult to assess. This is a problem when the dimensions of the object are small in relation to the size of the transmitter and/or receiver and the dimensions of the applied stimulus, e.g. wavelength of the signal.

2.5 Licensing and Other Legislative Considerations

The use of many of the instruments described and recommended here is restricted under a broad range of different legislation: brief notes of warning are attached to the description of each technique, but these should not be considered exhaustive, and it is always the responsibility of the user to ensure that any equipment employed is used in a manner fully compliant with any legislation.

Particular attention is drawn to the safety requirements in the application of equipment using ionising radiation: specialist training and safety procedures are required and the equipment should be acquired only from experienced and fully accredited organisations.

Most electronic equipment that is sold or leased in the UK will be compliant with the appropriate legislation for electromagnetic compatibility, but use of equipment involving radio frequency transmission must be compliant with the requirements of the Radio Communications Agency, and valid licences must be held where appropriate.

On certain protected sites (scheduled ancient monuments or monuments in the ownership or guardianship of the Scottish Ministers or of a local authority), Section 42 of the Ancient Monuments and Archaeological Areas Act 1979 applies to the use of metal detectors, but may also apply to many of the methods described in this note as they could be included in the broad definition of a 'metal detector' contained within the Act. Consent is required from the Scottish Ministers for the use of metal detectors on any such site. Advice should be sought from Historic Scotland about the protected status of sites and how to apply for consent.

3 ELECTRO-MAGNETIC METHODS

This chapter deals with tests that apply different kinds of electro-magnetic stimuli to the object under study. The electro-magnetic spectrum includes the light, heat, radio and micro waves we are surrounded by every moment of our lives. Although we cannot necessarily feel or see them, they are real physical phenomena, well researched and understood and whose behaviour is governed by strict rules of physics.

The frequencies of different electro-magnetic wave forms are given on Page 2. Note that some of the techniques discussed are often referred to as geophysical techniques because of their origins as geological prospecting tools.

Each method is discussed under the following sub headings: application, theory and limitations, equipment and operation. The last section covers the collection of data, interpretation and analysis.

3.1 IMPULSE RADAR

Impulse Radar (also known as ground penetrating or ground probing radar) was first developed for use in mapping near-surface geological formations. However it is now recognised as an extremely versatile and powerful technique capable of providing a wide range of information relating to construction detail and condition of a structure and its elements. This includes the location, quantity, nature, shape, disposition and dimension of embedded objects, the identification of different material types and variations in their condition.

The wide range of information recovered frequently facilitates an understanding of the way in which a building or structure has been constructed and how it has been affected by time and use. Used appropriately, radar will provide an overview of the interior of a structure quickly and economically with a minimum of disruption.

3.1.1 Applications of Impulse Radar

Impulse Radar can be used on a wide variety of construction materials including stone, brick, asphalt, cement and concrete. The often sharp contrast of its response to inclusions of air, water, wood and metal within these materials contributes to an overall characterisation of the structure.

It has been used with good effect as the principal investigative tool on bridges and tunnels, ruins, historic buildings, modern concrete structures and archaeological remains. Typical construction information that can be recovered in these environments includes:

- material thickness (e.g. in masonry constructions)
- the identification of metallic fixings (e.g. cramps, dowels) and their condition
- the location of the routes of flues and chases within walls
- the location of services embedded within floors, behind panelling or in the ground
- the identification of variations within material condition (e.g. cavities and voids in fill materials, microcracking of stone and concrete)
- the assessment of bond between materials (e.g. a mosaic to its backing)

Impulse Radar has specific advantages over many other non-destructive techniques in that:

- it is relatively rapid
- it is truly non-destructive, affecting neither structure nor delicate finishes
- it is a mapping technique providing a continuous measurement rather than point samples
- the recovered data contains a wide variety of information
- it facilitates an assessment of the whole structure rather than individual elements in isolation

One further important advantage is that it requires no special surface preparation, working well on stone, plaster, wallpaper and panelling in addition to friable decaying surfaces. This is because the stimulus it applies to the object can be transmitted through air. Minor surface irregularities are not a problem therefore and delicate finishes can be protected by covering in a suitable material such as bubble wrap.

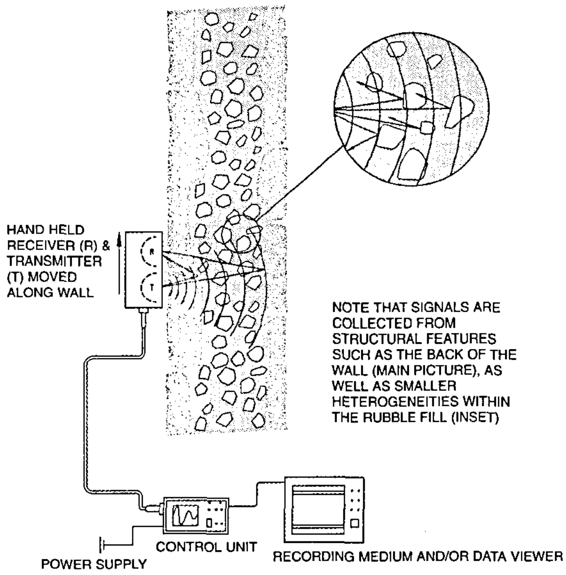
3.1.2 Theory and Limitations of Impulse Radar

RADAR is an acronym for *Radio Detection And Ranging*. The prefix ‘impulse’ or ‘pulsed’ refers to the manner in which the transmitted signal is generated and transmitted into the object, i.e. as a very short burst or pulse. Impulse Radar operates in the same manner as other echo systems such as SONAR (marine echo sounding). It is designed to transmit a pulse of radio energy into a solid material and collect the reflected 'echoes' for recording and interpretation. The major difference from other echo systems is that radar uses electro-magnetic and not mechanical waves.

Just as objects reflect or absorb light waves to varying degrees, so too do they reflect or absorb radio waves. The important difference is that many solid materials that are opaque to light waves will allow the transmission of radio waves. This is because different wavelengths within the electro-magnetic spectrum respond in different ways to different material properties: light waves respond to one set of properties of the material (i.e. optical); radio waves respond to a different set of physical properties (i.e. electrical). Different materials will often have different electrical properties, or will exhibit different electrical properties where their condition differs (e.g. if they are saturated or contain voids, are more or less dense etc.) Impulse Radar measures these electrical differences.

Just as the transmitted signal is a wave, so the echo, or returned signal picked up by the receiver, is also a wave. The various measurements made by the equipment characterise this wave form, including its phase, amplitude, frequency, the continuity of the signal and the time interval between transmission and reception.

The following figure illustrates the basic theory of operation:



NOTE THAT SIGNALS ARE COLLECTED FROM STRUCTURAL FEATURES SUCH AS THE BACK OF THE WALL (MAIN PICTURE), AS WELL AS SMALLER HETEROGENEITIES WITHIN THE RUBBLE FILL (INSET)

Figure 1 Basic theory of impulse radar collecting data from a rubble filled masonry wall.

Radar will be limited by the ability of the material to allow the transmission of electro-magnetic energy. Some materials carry this energy better than others as a result of their electrical characteristics. Some materials are particularly poor carriers, others block it altogether.

Two important characteristics of the transmission of electro-magnetic energy are penetration and resolution.

- *Penetration* is the ability of the material to sustain an electric field and act as a good insulator. In practical terms this defines the depth from which data can be recovered.
- *Resolution* is the process of defining whether those signals are 'useful' - a variable, even subjective, assessment. Note that sometimes the absence of a signal where it is expected can highlight material defects and therefore be reasonably considered 'useful'.

For example, sufficient energy may *penetrate* the structure of a wall so that reflections from the rear face (a large discontinuity) allow the thickness of the wall to be defined. This reflected energy may not be adequate, however, to identify (i.e. *resolve*) individual mortar beds, or iron cramps within the data.

The maximum depth to which useful information can be obtained in one material will vary from one object or structure to another, depending upon the particular condition of the materials under investigation. Penetration varies from depths of 1.5m or more, accompanied by high resolution, in dry, fine grained stone such as chalk and some sandstones. This decreases to about 1m if the material is dressed into coursed and mortared blocks or as little as 500mm if the material is wet, contaminated and fractured.

Some common materials and configurations which affect penetration and resolution are discussed below:

- *Metal and closely spaced metallic features.*

In most instances sheet metal, or a tight mesh such as chicken wire, will act as an impenetrable barrier to radar signals, giving rise to almost total reflection of the transmitted signal's energy. Closely spaced reinforcement (bars at <100mm centres) or multiple layers of reinforcement within a structure may produce signals which mask information from the structure beyond.

- *Water saturated materials.*

A high moisture content effectively slows and attenuates the transmitted signal. If the water makes the material more conductive (e.g. salt water) there will be a further reduction in penetration and resolution of detail. Note that these effects can be used to locate areas of high moisture content within otherwise dry materials.

- *Wet clay-rich materials.*

The high conductivity of wet clays causes a significant reduction in penetration, frequently a problem in domestic rubble filled walls. Dry clays (e.g. bricks) present no such problems.

- *Materials with a high ferro-magnetic content.*

Natural materials with a high iron content, such as some red sandstone will cause rapid attenuation of the radar energy and reduce penetration and resolution of detail. Some bricks, such as blue engineering bricks, may have a similar effect as a result of their haematite content.

- *Heterogeneous materials*

Resolving small discrete targets and objects within a heterogeneous material (e.g. a cable or pipe work in loose fill) is very difficult because of the large number of signals - each void or discontinuity in the heterogeneous material generates a signal (collectively referred to as 'clutter') masking the desired signals.

Most frequently however it is the distress, damage or contamination which has occurred in the life of the structure that will effect the penetration of pulses and resolution of signals.

3.1.3 Equipment

The basic instrumentation for impulse radar testing comprises a signal generator/processor, a transmitter and receiver (also known as antennae) and a recorder. The transmitter and receiver are frequently combined in a single unit known as a transducer which varies in size from a cigar box (high frequency) to a suitcase (low frequency). The transducer is attached by a heavy duty cable to the recorder. The generator/processor or control unit, has some form of signal control (time, gain etc.), a means of viewing the generated and received wave forms and a means of viewing the sampled received signal. The control unit is connected to the recorder. Recording systems can use either digital or analogue data storage and recording formats. Both work in fundamentally the same way, the main differences lie in the way that data is stored and viewed.

Digital systems employ storage media such as hard disks or DAT tapes, and often produce file sizes in the order of 100 Megabytes per hour of work. Data is typically viewed on a small monitor controlled through a keyboard. Analogue systems usually print to paper, and may produce up to 50 metres of paper roll per hour. Data is viewed on the paper and the signals are viewed on a small built-in oscilloscope; control is through switches and dials. Analogue systems tend to be bulkier than digital systems.

A typical working arrangement is shown in Plate 2. Impulse radar equipment weighs a total of approx. 40kg and is powered by 12V car batteries. The equipment, while being shower proof, must be protected against sustained rain.

Digital data can be processed readily off-site to provide detailed analysis but is not easily handled on site. Analogue data is fixed at the time of capture and very accessible to expert interpretation both on and off-site.

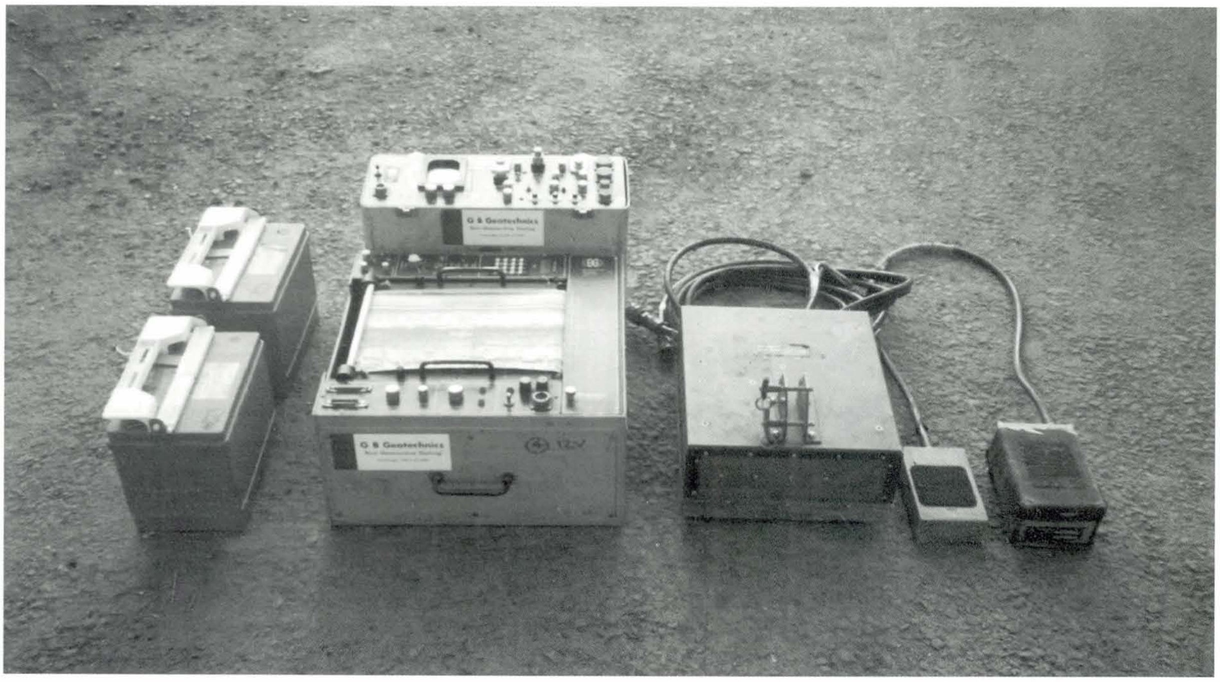


Plate 2 Typical impulse radar equipment (analogue)

The antennae are of different frequency and have different purposes and uses. High frequencies, approx. 1000MHz, or 1 GHz, have shorter wavelengths and small physical 'footprints' (i.e. the area bombarded by the pulses of radio energy). These are high resolution devices which will identify small objects or closely spaced layers. The shorter wavelengths are, however, also absorbed more rapidly in a given material, thus they are of lower penetration than longer wavelength devices with transmission frequencies of 100MHz or lower. These longer wavelength devices are used where greater penetration is required and resolution is not so important - e.g. looking for near-surface geological features.

Table 1 gives some guidelines on the performance of certain transmitter types, under typical circumstances.

3.1.4 Operation

Data Collection

Surveying with Impulse Radar is achieved by drawing a transducer over the surface under investigation at a controlled speed. Plate 3 shows a transducer being drawn across the floor by means of an attached handle. Information is typically collected from a grid of survey lines set out to cover the area under investigation. The optimum spacing between survey lines is governed by the size of the features which are expected to be found, their depth within the structure and the frequency (and hence footprint size) of the transducer being used. For example, an investigation to locate voids within the rubble core of a wall of approx. 600-1100mm in thickness would normally be carried out by collecting data from continuous recordings along a grid of survey lines at approx. 500mm centres, whilst an investigation to locate archaeological features beneath the ground to depths of 2-3m may use a survey grid with survey lines spaced 2m or more apart.

Some types of investigation require that the survey lines are located in response to the expected locations of some specific structural feature. An investigation of ashlar stonework will typically concentrate on the collection of data from a series of horizontal lines located at the positions of the horizontal joints in the wall face (where iron cramps or dowels may be found) and along the centre-line of each block course (where the thickness of the block can be easily measured).

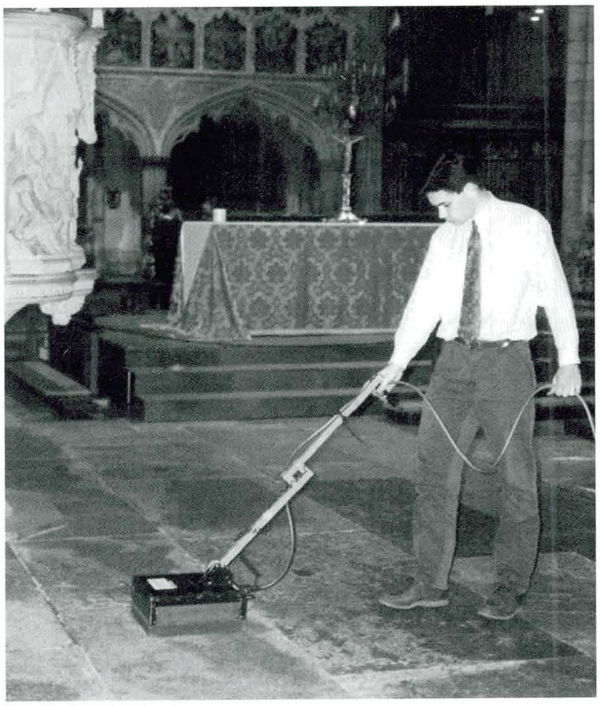


Plate 3 Impulse Radar survey in progress to locate suspended stone flags in a cathedral floor.

Frequency (MHz)	Maximum effective penetration (mm)	Reasonable resolution range (mm)	Typical Uses
1000	800	300	Detailed structural investigations, location of cramps, thickness of stone facing, detection of cracking within materials etc.
900	1300	500	Determining general structural layout, measurement of wall thickness, location of voids and flues, structural changes, locating buried services etc.
500	2200	800	General condition and thickness of walls where >approx. 1500mm thick, locating buried services etc.
300	3500	N/A	Archaeological investigations in near surface, walls and subdivisions
80	5000	N/A	Archaeological investigations of large areas, foundations, floors
35	10000	N/A	Archaeological investigations in large open areas: layout of dwellings etc.

Table 1 Typical Penetration, Resolution and Uses of Different Frequency Transmitters

Surveys are normally carried out by a two person team, one person operating the signal control and recording apparatus and the other controlling the transducer. One person should also monitor the data and make an early appraisal of its implications and the other monitor the structure. Photographs or video film of an anomaly or feature taken during the site work can give added insight to any subsequent interpretation.

Impulse Radar is a rapid technique which requires an appropriate access system. Very detailed information can be collected when moving the transducer at speeds of 10 metres a minute (0.6 km/hr) and prior planning to ensure that enough material can be accessed to maintain that speed is well worth the effort.

The simple requirement for access is that the transducers or antennae are kept in reasonably intimate contact with the surface under investigation (within approx. 30mm) and can be moved at a steady speed along the chosen survey line. Hand access to the surface is best, but an assortment of poles and extending arms can be used to increase the operator's reach. Beyond this, access equipment is needed. This should be kept as simple as possible whilst satisfying the needs of the survey.

Interpretation of Impulse Radar Data

A technique like Impulse Radar requires a high degree of interpretation in order to make sense of the data gathered. The electrical changes of relevance are frequently subtle and deceptive, and are represented as a multi-dimensional (i.e. non-numerical) information stream.

In keeping with non-destructive tests in general, it is never possible to be fully confident that the features detected are in fact what they appear to be: the findings of radar testing are based on a series of indirect measurements and the interpretation of electrical and electro-magnetic signals. For this reason the accuracy of a set of findings relies heavily upon the expertise and experience of those carrying out the interpretation of the data. This expertise is likely to have been built up partly empirically, from the results of many corroborative destructive tests of coring, drilling and exposure, and partly from an in-depth understanding of the physics involved. A good investigator also looks to confirmation from observation, complementary tests and a sound knowledge of the material being inspected.

During the interpretation phase, interaction between the investigator and the building professional is at its most valuable. As a range of hypotheses are being developed and checked, discussion can result in further efficient and fruitful lines of analysis.

Figure 2 shows the relationship between the data recovered during an investigation to locate underfloor chambers and the interpretations made to produce the final drawings. Note the coincidence between each hyperbola in the recovered data and the interpreted void beneath. The collection of a complete data set enables the location and arrangement of the underground network of chambers to be deduced.

Reporting

It is often possible to provide preliminary results immediately after collection of the data, on site, although this is likely to be restricted to marking the location of a particular feature or features of interest, or a brief description of the materials or structural layout. The majority of the results are best presented on drawings of the structure, either in plan, elevation or section, as appropriate. These are generated off-site after a period of data processing.

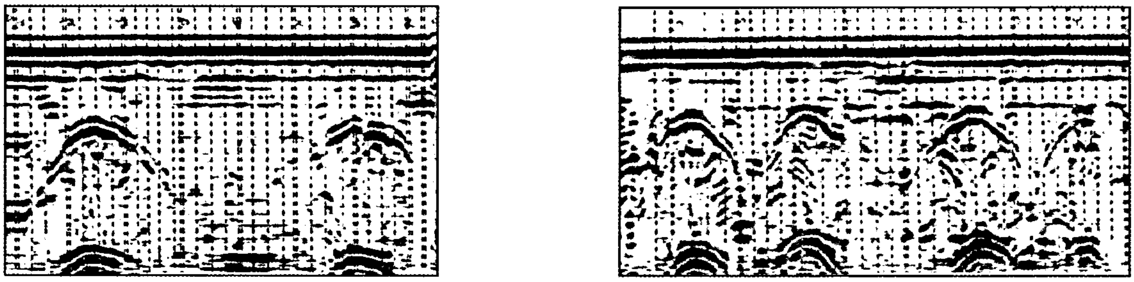
As a rule of thumb, relocation accuracy is typically ±10% of the distance between known points, thus survey marker points at 1m centres will probably produce a survey of features relocated to ±100mm.

3.2 THERMOGRAPHY

Thermography or thermographic imagery detects and records levels of electro-magnetic radiation in the infra-red band - just as photography records levels of electro-magnetic radiation in the visible light band.

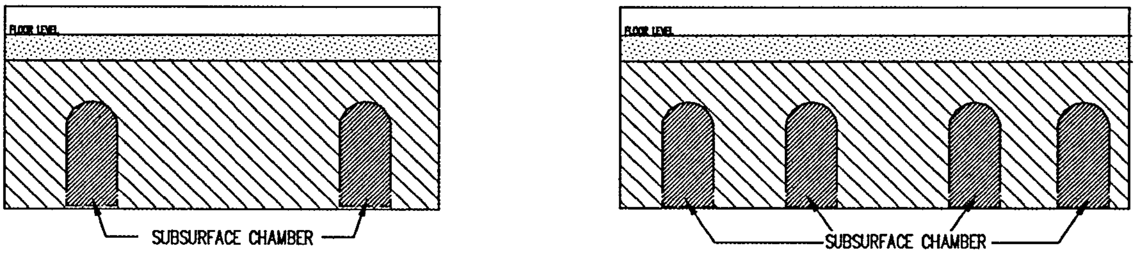
Thermography has been widely used for a number of years as a monitoring and inspection tool for extremes of heat in many different industries such as power generation and refrigeration. Technological developments have increased the sensitivity of the equipment, facilitating its use across a wider variety of environments and tasks where the thermal differences may be small.

The main advantage of the technique is that, like a camera, the system may be operated remotely from the object, images can be produced at speed, and the final result is reminiscent of the form and shape of the visible object. Storage and manipulation is facilitated by the use of digital media, while the nature of the images and data recovered lends itself to a straight-forward preliminary analysis.



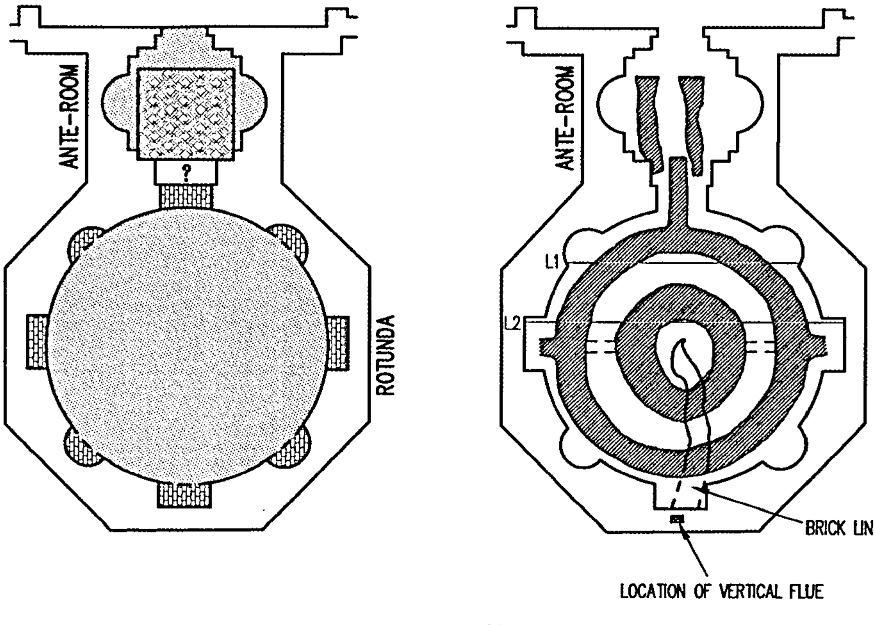
IMPULSE RADAR SCAN L1

IMPULSE RADAR SCAN L2



INTERPRETED SECTION OF RADAR SCAN L1

INTERPRETED SECTION OF RADAR SCAN L2



PLAN - FLOOR CONSTRUCTION

PLAN - LOCATION OF UNDERFLOOR CHAMBERS

KEY

▦ BRICKWORK

▩ STONEWORK

▒ COURSED AND JOINTED STONEWORK

? INDETERMINATE CONSTRUCTION

KEY

—— SURVEY LINE

▨ SUBSURFACE CHAMBER

0 ⎯⎯ 2m SCALE

Figure 2 Sample of impulse radar data recovered and the drawings generated from it during an investigation to locate underfloor chambers

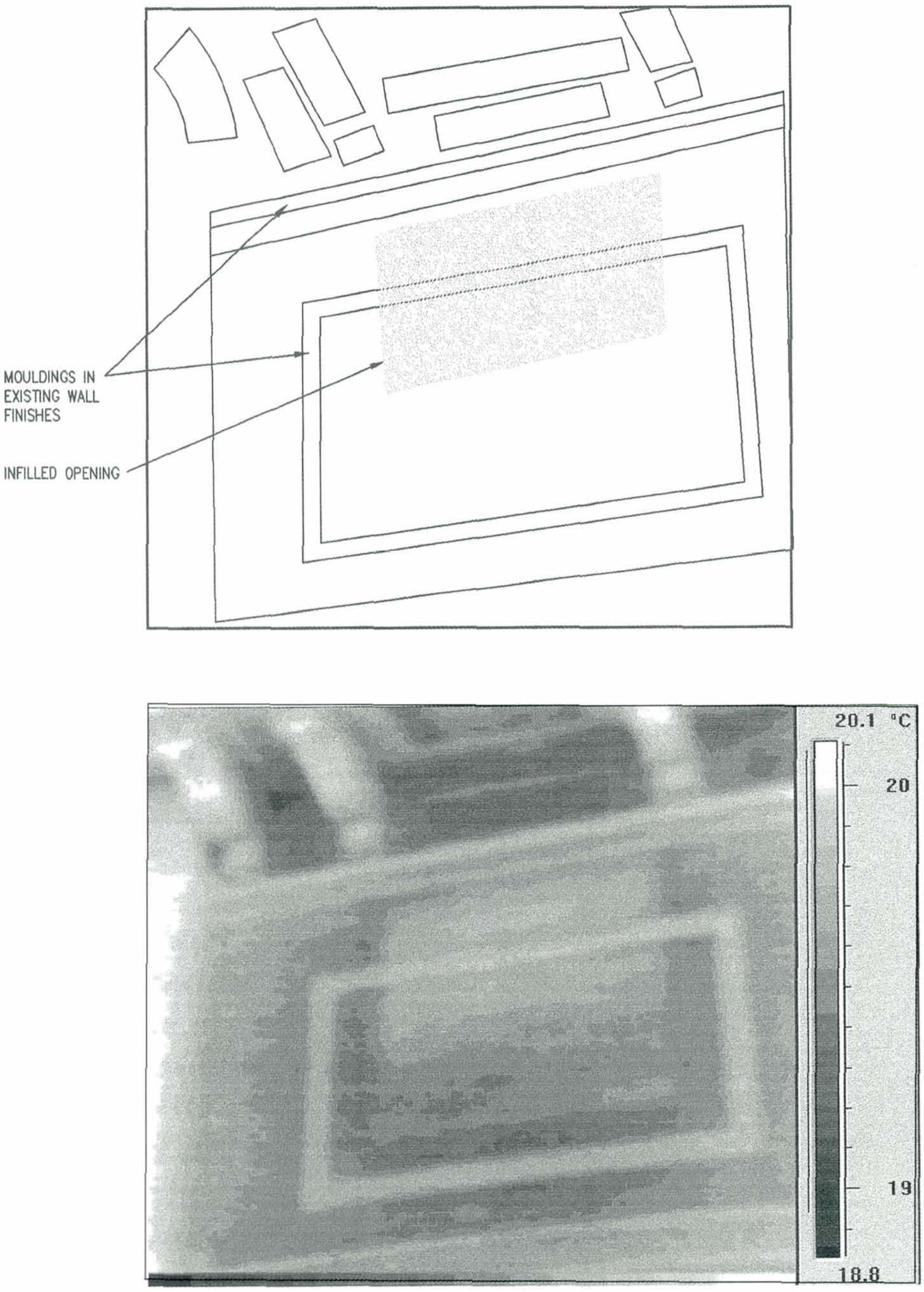


Plate 4 Sample image from a thermographic survey of the interior of a historic building. The change in construction materials behind existing mouldings and finishes shows clearly as a lighter area.

3.2.1 Applications of Thermography

Operation and data capture with a thermographic camera are similar to the use of a video camera, except that spatial definition is generally reduced, depending on the particular instrument. This effectively limits the distance at which small targets can be identified.

The sensitivity of the imager to different wavelengths is of importance in defining the information which can be recovered: the distinction between long and short wave band imagers is discussed in the next section. The optimum wave band for a particular application should be chosen with care, but, in general, long wave thermography is used for structural surveys, and is the main application discussed in this text.

The advantages of rapid and remote operation enable long wave thermography to be employed as a rapid reconnaissance technique in a number of situations:

- to carry out general structural inspections; significant areas of interest may be identified for subsequent, more detailed, investigative work
- to identify changes in materials

- to record construction; alterations made to a structure may be identified because of the differences between original and new materials.

Specific situations where long wave thermography has been successfully used include:

- the identification of construction features such as timber frames, chimney flues or concealed/infilled openings
- the identification of structural defects such as loss of bond, delamination, cracking and voids
- the location and tracking of retained moisture and rising damp
- the detection of services such as hot water pipes, electrical wiring (mains, alarms, telephone etc.)
- the inspection and monitoring of fragile murals.

A sample image recovered during such surveys in shown in Plate 4.

3.2.2 Theory and Limitations of Thermography

Thermal radiation, like light and radio waves, is part of the electro-magnetic spectrum and can be described in terms of amplitude, frequency and/or wavelength. The visible part of the spectrum is the only part to which our eyes are sensitive. Thermal radiation is in the infra-red band, i.e. with a wavelength longer than visible light (red light has the longest wavelength).

All objects warmer than absolute zero emit thermal radiation. The higher the temperature the greater the energy output and the shorter the wavelength. As a rule of thumb, objects we would consider hot, i.e. at or above body temperature, radiate principally *short wave* infra-red, while cooler objects, i.e. around room temperature, radiate *long wave* infra-red. Long wave systems (8 - 12 μm) are more suitable for investigating the structure of historic buildings, therefore, while short wave systems (2 to 5 μm) are most appropriate for locating zones of high temperature heat flow, e.g. identifying hot gases escaping from a chimney, or tracking central heating pipes in a floor.

The middle band (5 to 8 μm) is the characteristic incident radiation from the sun, and most imagers are insensitive to this radiation, which would otherwise blur all images.

The basic principles of optical theory, describing how light waves are transmitted, reflected and refracted can be applied directly to thermal radiation, to provide a basic understanding of the application and use of *thermo*-graphy as a branch of *photo*-graphy. The important distinction to make is that most objects only reflect light, whereas almost all objects we are likely to encounter can also *radiate* or *emit* thermal energy.

The total thermal output measured at the surface of any particular object is affected by three characteristics of the object:

- *Reflectivity* - the amount of external energy that is reflected rather than absorbed by that object
- *Transmissivity* - the amount of energy that is transmitted through an object from a heat source within or beyond the object
- *Emissivity* - the amount of internal energy that can be emitted by the surface of an object

The *reflectivity* of an object can cause high levels of reflected thermal energy which would dominate the observed output from a surface. Generally it is desirable that this is as low as possible. As may be predicted, this is a problem of many 'shiny' surfaces, such as metals, glass and even some glazes.

A material which acts as a good insulator has a low *transmissivity* and may effectively mask deeper heat sources, such as a hot water pipe buried in the ground or under a floor: however, the variable fill in the trench over the pipe, or the materials covering the pipe in a chase may be assessed as the amount of energy reaching the surface varies.

The thermal energy output by an object at any given temperature is dependent on the *emissivity* of its material - its ability to emit thermal radiation. Minor changes in material can have quite different effects on the output. For instance metals have a low emissivity, and thus appear cold to an imager; covered with a paint of high emissivity, the same metal at the same temperature appears 'hotter'. The distinction in emissivity between two limestones from different quarries is normally clearly identifiable even when there is no 'visible' difference.

These properties are shown in Figure 3.

Most building materials such as masonry and concrete have a high emissivity and low reflectivity. Transmissivity of these materials is generally such that while a 'hot' buried object (e.g. a hot water pipe or duct in an old chimney flue), may be detected at depths of 200 - 300mm, a 'cold' buried object (e.g. a drain pipe or empty flue) may not be detected beyond a wall, half a brick thick. The thermal gradient across the materials in the latter case is unlikely to be sufficient to produce an appreciable difference in the emitted radiation at the face.

As with the analysis of impulse radar information, contrast is important; the different properties of broadly similar materials such as blockwork, bricks and mortar can yield surprisingly high levels of definition in the recovered images. Defects are often identified through the contrasting response of

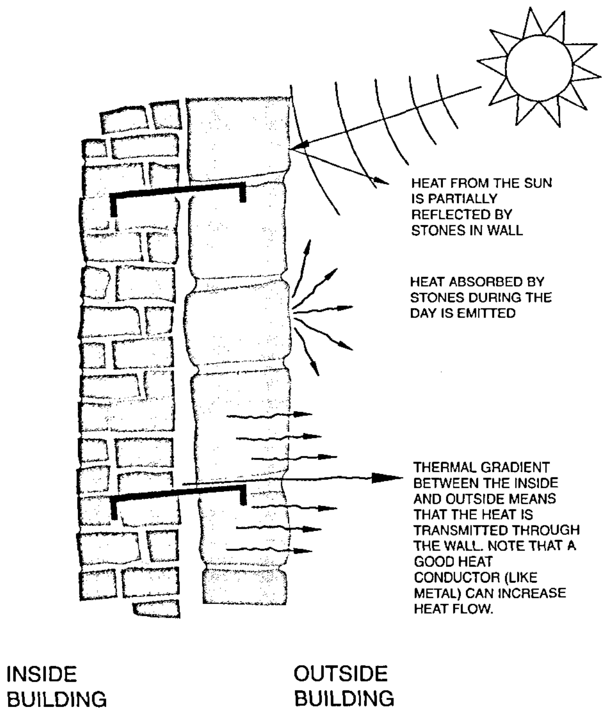


Figure 3 Illustration of three different factors affecting apparent surface temperature of a stone wall.

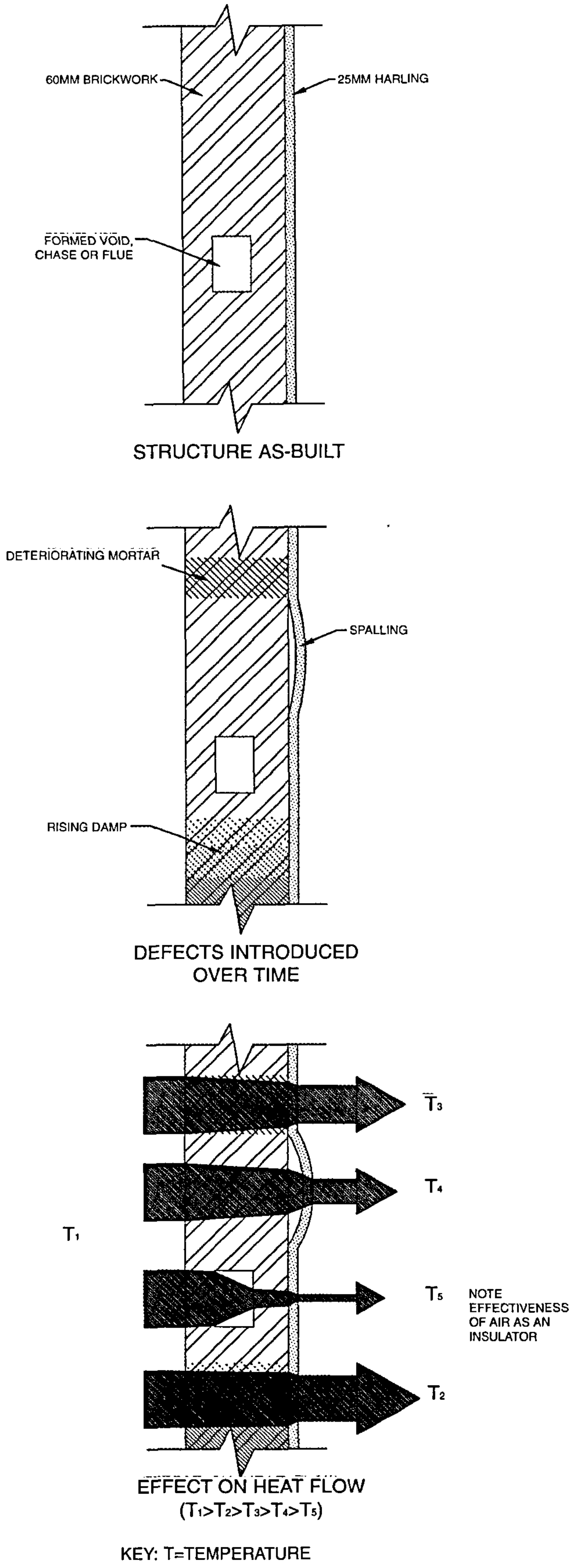


Figure 4 Effect of building materials, thickness, arrangement and defects on heat flow (illustrative only).

apparently similar structures or materials. These include:

- the presence of water, which is a very good conductor of heat - damp patches, such as areas of rising damp or moisture retention, can appear warmer or colder than adjacent, drier areas of the 'host' material
- the quality of mortar beds, both in terms of fill and condition
- delamination of harling and renders, the loss of bond between facing bricks and the bricks behind, the presence of spalling or delamination in stone facings and the loss of bond between facing stones and their masonry core can often be identified as a result of the insulating effect of air gaps
- the presence of voids, be they formed (i.e. chases, flues, etc.) or unformed (i.e. loss of brickwork bond, deconsolidated rubble fill, etc.) which will reduce the heat flow through the wall.

Figure 4 shows schematically those defects discussed above, showing the relative effect of each defect on heat flow through the wall. The effective heat flow through the wall is slightly affected by damp (T2), increasingly affected by deteriorating mortar work (T3) and spalling render/brickwork (T4), and greatly affected by the presence of formed/un-formed voids (T5) [i.e. T1>T2>T3>T4>T5].

It is often just as informative to measure heat *inflow* as it is to measure *output* from an object. This is effectively a measure of the difference in rates with which heat energy is taken up (absorbed) or emitted by the object and its materials. For example, if variations in the finishes of an internal wall need to be identified then the survey could be carried out using only normal thermal cycles. Early in the morning, when the temperature of the surface materials in the wall will have stabilised to ambient air temperature, no heat will flow: by turning on the heating, lights and moving people or other warm bodies through the room , the air will be heated and a flow of heat *into* the relatively cooler wall will result. However, at night, when the room cools as people leave and heating and lights are switched off, the relatively warm materials in the wall will emit heat, and result in a flow of heat *into* the relatively cooler air.

Correctly timing a thermographic survey to coincide with optimal heat flows is crucial and is perhaps the greatest skill required for field thermography. In the case of observing an occupied historic building or monument, heat flow out of the building will be sourced from any solar heat stored plus any transmission of heat from the interior of the building. However, at times during the day it is possible that the thermal response of the wall under investigation may be "swamped" by the incident energy source (i.e. the sun). Variation in the structural formation of a wall and in the quality of build will have an effect on the rate of heat flow and can therefore potentially be mapped by the investigation.

Plate 5 Thermographic inspection in progress. Hand held camera is panned across the wall and the results viewed as an image on the trolley mounted processor. Power is supplied as an unspillable (gel type) 12V car battery.

3.2.3 Thermographic Survey Equipment

Thermographic equipment available on the market today ranges in size from small hand held cameras to relatively large scanners and signal process and control units. Many factors must be considered and applied to the selection of the most appropriate instrument for a particular task. These include wavelength (discussed briefly above), resolution, range and performance and are important considerations for the investigator.

The different systems available record images in a number of ways, from the smallest cameras (very short wave length, relatively inexpensive, recording on film) to sophisticated high resolution digital systems recording direct to disk or tape. Digital storage has the advantage that it allows a great deal of filtering and post-processing to be carried out on the images.

As a guide, the thermographic equipment for surveying historic structures will typically consist of a video sized scanner and control unit. A standard arrangement is shown in Plate 5. This weighs up to 20kg and is powered by a 12V car battery although developments are constantly reducing the size and weight of the equipment. The equipment, while being shower proof, requires protection from sustained rain.

3.2.4 Thermographic Surveys

In the same way that Impulse Radar surveys must balance the requirement for penetration against resolution, surveying with thermographic equipment involves balancing the requirements for perspective (coverage) and the objectives of the investigation (the size and nature of the targets). The scanner must be operated at a distance and aspect appropriate to the object and survey, but close enough to be able to identify the smallest targets.

Data Collection

Since thermographic systems can be operated at some distance from the structure under investigation a great deal of work can be carried out from ground floor level. Where it is necessary to get higher, either neighbouring buildings or powered access platforms offer the fastest, most effective means of access. If a wall has a complex profile or relief, access to any 'blind spots' (e.g. behind carvings, the upper surfaces of cornices etc.) will be required.

As with photography, various focal length lenses are available to suit particular needs. As a rule of thumb, buildings and other structures of up to four storeys can be inspected from ground level. Beyond this, resolution decreases significantly.

For the reasons already discussed, one of the most effective times to carry out a thermographic survey of occupied buildings is on a cold, dry, still night when the heating inside is turned on. This results in the maximum flow of heat through the walls. Failing this, artificial heat sources can be applied and their effect monitored. Direct sunlight is also a good source of thermal energy - its effects are often best monitored at the end of the day.

Interpretation

Extensive knowledge of the principles of heat flow, including conduction, convection and radiation, are required to plan and execute an effective thermographic survey. A detailed discussion of these is beyond the scope of this advice note. Failure to understand these principles can lead to the recording of thermal effects of no interest, or the misinterpretation of results.

The interpretation of thermographic images is not restricted to the simple identification of 'hot' or 'cold' areas. A general knowledge of structures and materials in addition to an understanding of the structure under investigation in particular is required to draw reasoned and informed conclusions about the cause of the 'hot' or 'cold' spots which form an image.

Reporting Thermographic Findings

Detected features can be reported, where appropriate, by direct marking onto the structure or by means of a relocation system that allows transfer of the detected features onto drawings.

There are two principle relocation methods:

- the first (and fastest) is simply to relocate from the physical features in the thermal images. This is particularly helpful when a conventional (optical) video or photographic record is collected simultaneously with the thermographic survey. For example, if surveying the entire wall of a building it is possible to accurately relocate (sometimes to an accuracy of better than ±20mm) by referencing the collected data to each individual stone block. This method has the added advantage of making the relationship between detected features (such as cramps and dowels), and block joints more obvious.
- the second method of relocation should be used where greater precision is required, or the structure under investigation has few distinguishable features (e.g. when a wall is surveyed close up). This technique involves laying out a survey grid with reference 'marks' that are visible to the infra red scanner. The 'marks' generally consist of highly reflective metal shapes or wires, as appropriate. With this system it is normally possible to achieve relocation to an accuracy of better than ±10% of the distance between measured points.

Because of the accessibility of the images recovered by thermography it is sometimes possible to provide preliminary results whilst on site. Results are usually presented either as enhanced thermal images (if features of interest can be easily resolved) and/or interpreted features marked on drawings of the structure, in plan, elevation or section, as appropriate. A sample image was given in Plate 4.

3.3 METAL DETECTION

Of all the non-destructive instruments and tools employed, metal detectors are probably the best known, but have also acquired a notoriety, as they are also the favoured cheap and accessible tool of the treasure hunter. Their use therefore has been severely regulated on any site classified as having any potential archaeological interest. It is a criminal offence (under section 42 of the Ancient Monuments and Archaeological Areas Act 1979) to use a metal detector on a scheduled ancient monument, or a monument in the ownership or gaurdianship of the Scottish Ministers or of a local authority, without the written consent of the Scottish Ministers. It is also an offence to remove from such a monument any object of archaeological or historical interest found using a detector. Advice should be sought from Historic Scotland regarding any proposal to use a metal detector on a standing structure which is a scheduled ancient monument.

3.3.1 Applications for Metal Detection

As their name suggests, metal detectors are used to find metallic 'targets' such as cramps, reinforcement bars in structures and various other conductive 'targets' in archaeological investigations.

Metal detectors all have an effective maximum 'range' within which the presence of the targets is detected. This is extremely variable and depends largely on the target properties (see section 3.3.2) and configuration of the detector's 'search head' (see section 3.3.3). The appropriate range for hand held devices is between approximately 50 and 1000mm, increasing to approximately 3000mm for larger ground searching devices. The technique can also yield limited information on the size, orientation and material type of 'targets' in certain conditions.

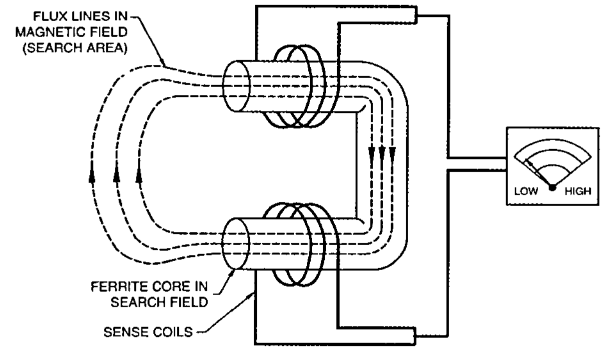
While the relative ease of operation and relatively low equipment cost makes metal detection an extremely accessible technique, failure to understand the principles often leads to unrealistic expectations and disappointing results.

3.3.2 Theory and Limitations of Metal Detectors

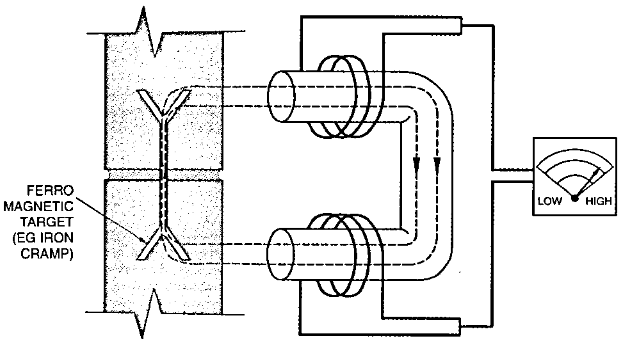
Metal detectors rely on the electro-magnetic phenomenon that an electrical current, passed through a conductive material, will induce a weak magnetic field around the conductor. Conversely, a magnetic field will induce a weak electrical current in a conductive material brought into the magnetic field.

There are two common types of metal detector, each using slightly different principles of operation. They are based on material characteristics of *magnetic reluctance* and *electrical conductivity*. Their use in the different types of detector is discussed in some detail here.

All magnets and magnetic materials have magnetic fields - including the earth. A magnetic field is the area of influence around the magnet where the effects of the magnetic force may be felt - in a metal detector this becomes the search area. A magnetic field can best be thought of as a series of lines (flux lines) circling round a magnet and running from one end to the other through its area of influence, as can be easily

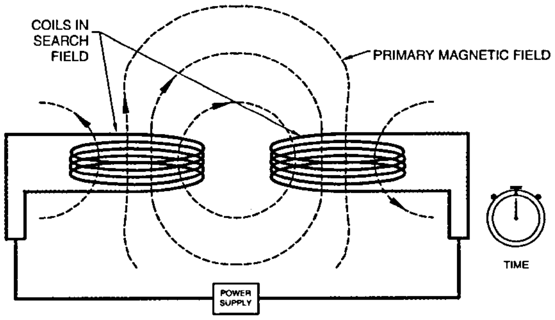


(a) SEARCH HEAD IN FREE SPACE

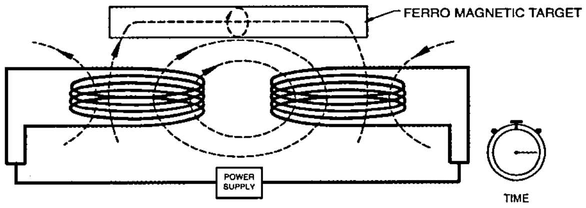


(b) SEARCH HEAD WITH TARGET IN MAGNETIC FIELD

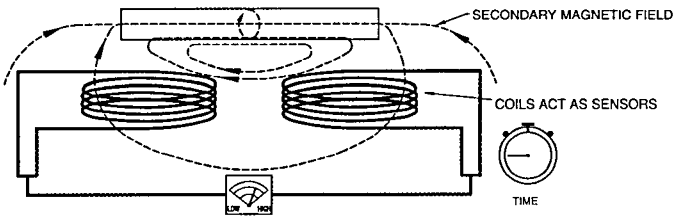
Figure 5 Metal Detection using magnetic reluctance method.



(a) PRIMARY MAGNETIC FIELD WHEN SEARCH HEAD IN FREE SPACE



(b) WEAK "EDDY" CURRENT INDUCED IN TARGET WITHIN SEARCH FIELD



(c) POWER SWITCHED OFF, THE SECONDARY MAGNETIC FIELD IN THE TARGET, GENERATED BY THE EDDY CURRENT IS DETECTED BY THE SEARCH HEAD

Figure 6 Metal Detection using electrical conductivity method demonstrated by placing a magnet beneath a piece of paper on which iron filings have been spread.

The *magnetic reluctance method* involves the measurement of reluctance (or 'resistance') along a magnetic path within a magnetic field. Reluctance is measured using a search head containing two coils wound around the ends of a 'U' shaped ferrite core. An electric current is passed through one of the coils resulting in a magnetic field being generated through and around the ends of the core. This gives the core a northern and southern pole (see Figure 5).

This field induces a current in the second coil. The size of this current is determined by the 'reluctance' of the material in the search area: the higher the reluctance, the lower the current in the secondary coil. Introducing a magnetic object into the search area will alter the reluctance of the search area.

The size of the current through the secondary coil can therefore be used to measure the proximity and size of magnetic targets, such as metallic objects.

Metal detectors which use the principle of magnetic reluctance can produce unstable and/or unreliable readings. This is due largely to the use of ferrite cores in the search heads. The cores, and therefore the readings, can be affected by factors such as temperature and the orientation of the core relative to the Earth's magnetic field. The readings are also influenced by any material with magnetic properties such as magnetite and haematite. Due to this instability, magnetic reluctance has largely been superseded by the electrical conductivity method.

The *electrical conductivity method* uses a search head containing one or more air-cored coils; thus avoiding the problems of the ferrite core. It is sometimes known as a 'pulse induction eddy current' method because it measures the temporary, induced magnetic field of a conductive, metallic target generated by an electrical current in the search head coil.

An electrical current is passed through the coil causing a primary (or transmitted) magnetic field. Unlike the reluctance method, the generated magnetic field is not continuous, but is switched on and off by switching the electrical current in the coil on and off. At the instant that the current is switched off the primary magnetic field collapses. This induces 'eddy' currents to flow in any conductive targets within the search area (see Figure 6).

These eddy currents will decay very rapidly as there is no source of energy to maintain them. While the time scale of this 'persistence' effect is only in the order of millionths of a second, it still outlasts the primary magnetic field. The eddy-currents generate a secondary magnetic field which propagates back to the search head and induces a flow of current in the same coil that generated the primary field (see Figure 6).

The metal detector measures the coil voltage after a delay which is long enough to miss the effects of the collapsing primary field, but short enough to include the eddy-current signal (if present). The resulting signal strength is proportional to both the reflected field strength and its persistence.

Material Properties of Targets

If a target is to be detected by this method, it must be conductive. Some magnetic materials are not conductive and will not always be detected therefore. This is shown in the following table.

Material	Magnetic ?	Conductive ?	Detectable ?
foil, stainless steel	✗	✗	✗
ferrite, iron oxide, mineralised soil	✓	✗	✗
copper, aluminium	✗	✓	✓
iron, steel	✓	✓	✓

Table 2 Effect of Magnetic and Conductive Material Properties on Detection

Non-magnetic materials with poor conductivity such as stainless steel produce an eddy current with a very short persistence, i.e. the current is said to 'decay' rapidly. This decay time is comparable with timings (i.e. sampling delay) in the receiver circuitry and therefore makes it very difficult to measure the return signal from the target. The sample delay time can however be shortened to detect such materials, albeit with a lesser sensitivity.

A *magnetic non-conductor* (e.g. ferrite) will be magnetised by the primary field but demagnetises immediately on removal of the field. Such materials will not induce any signal in the coil therefore.

A *magnetic conductor* however, (e.g. iron) will produce a signal in exactly the same way as a non-magnetic conductor (e.g. copper), but the strength of the response will be magnified by the 'magnetic conductivity' of the target. This phenomenon is related to the target material and the effective size of the target (i.e. its shape and orientation). The concept of 'effective size' of targets is discussed further below.

While these categories account for most metallic target types, in a few situations a significant signal is received from certain non-conductive, magnetic materials. This is due to a phenomenon known as *magnetic viscosity*. When the primary magnetic field is removed from

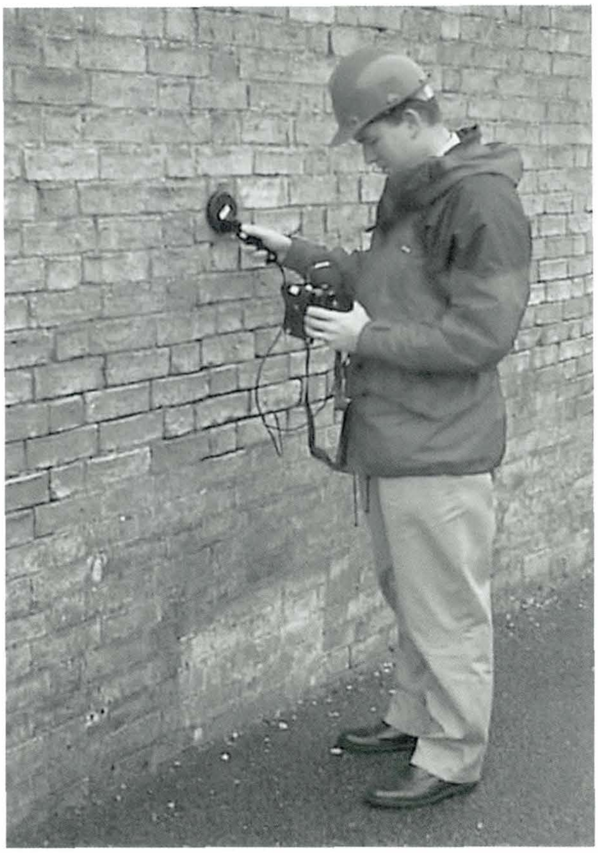


Plate 6 Metal detectors being used to locate metal ties in a brick wall.

these materials the induced magnetic field decays in a 'viscous' (or sluggish) manner, generating a response in the detector. This phenomenon is noted in materials such as slag, engineering bricks and certain concrete aggregates.

Effective Size of Targets

The *effective size* is what is 'seen' by the magnetic field and is partly dependent upon the size, shape and orientation of the target relative to the primary magnetic field. The strongest signal usually occurs when the maximum area of the target is presented to the search field. One way in which the building professional can greatly assist the practitioner is by advising of the likely nature of the targets sought during a metal detection survey.

For all practical purposes, the strength of the signal is dependent upon:

- the area or circumference presented *perpendicular* to the field direction by the target
- the length or thickness of the target *parallel* to the field direction

In the case of *non-magnetic conductors* the signal strength depends predominantly on the first of these factors. The length or thickness of the target parallel to the field has very little effect on the signal strength because the primary magnetic field does not concentrate down the length of the target in the same way as it does for a magnetic target.

In the case of magnetic conductors the signal strength is also dependent on the area perpendicular to the field but the effect is multiplied by a factor which is determined mainly by the length of the target parallel to the field. The length therefore frequently becomes more important than the area in determining the strength of the signal.

Common Errors

From these few comments, it can be seen that extensive knowledge of the principles of operation are required to plan and execute an effective metal detection survey. Limited knowledge of the operation of the equipment can result in misinterpretation of the results in a number of ways.

The most frequent error is the identification of magnetic minerals as metallic targets. Magnetite is one such material and is often found in engineering bricks. Another common error occurs where there are many targets close together - for example, when the search head is placed directly over the space *between* bars on a welded mesh a false positive signal can result.

3.3.3 Equipment

Metal detectors are generally small portable devices. A typical device is shown in Plate 6. The equipment is lightweight, powered by drycell batteries and showerproof.

The metal detector comprises an interchangeable hand-held search head in various sizes and shapes, connected to a control pack. The control pack and search head may be incorporated into a single unit in the larger models (e.g. for ground searching). Generally the detector will have a sensitivity control allowing a limited adjustment to eliminate unwanted background signals. Positive signals are indicated by some form of meter or other signal strength indicator - audible tones (clicks, buzzes or whistles) of varying pitch and intensity are the most common.

Different types of metal detectors can indicate orientation, depth and/or size of known targets (e.g. metal reinforcing bars). Some of these dedicated pieces of equipment (e.g. bar locators) are capable of generating two dimensional images of target layouts on liquid crystal display screens.

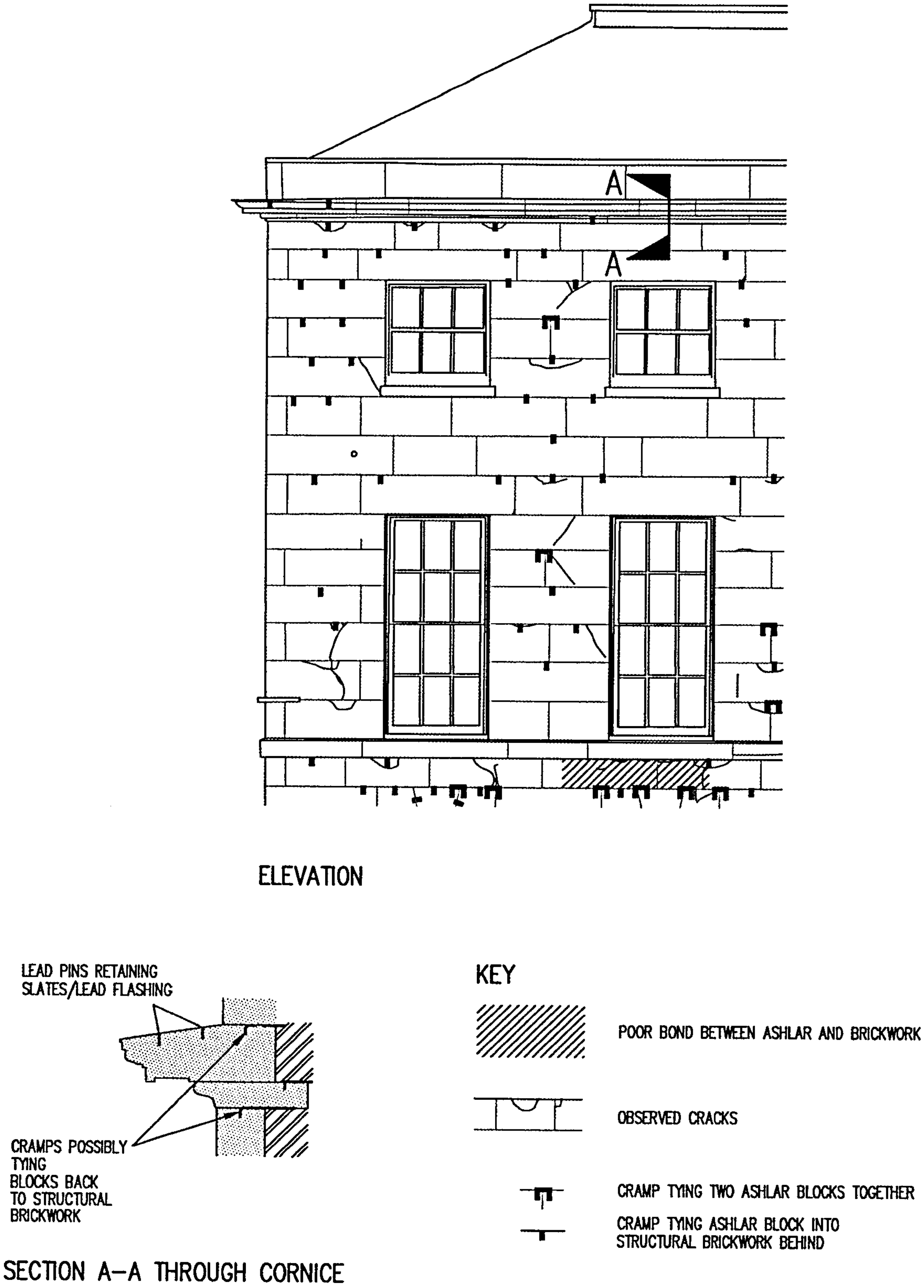


Figure 7 Sample of results from a combined metal detector and impulse radar investigation

3.3.4 Metal Detector Surveys

Data Collection

An investigation using metal detectors is carried out by drawing a search head over the surface of the object. The optimum pattern and spacing between sweeps of the search head is governed by the target properties, including material type, effective size (as described in section 3.3.2) and depth, and the specific properties of the search head used.

Metal detection requires that the search head is in reasonably intimate contact with the surface under investigation. This is most easily achieved if the operator can gain 'hand' access to all areas under investigation. When arranging access it is essential that the search head is not shielded, i.e. the field it generates can operate in all directions around the head. Steel ladders (and scaffolding) should be avoided as they will generate a positive response when they are in the search head's field - wood or aluminium ladders should be used.

When steel scaffolding is used it is preferable to erect it with a gap of at least 300mm between the scaffold and the surface under investigation to reduce the risk of swamping signals from targets in the building with signals from the scaffold. Aluminium scaffolding has the advantage of being non-magnetic and less likely to interfere with readings taken during the investigation.

Interpretation and Reporting

There are essentially two results from a metal detector survey - either there is a target or there is not - and therefore little analysis off site is required. Targets, e.g. metal cramps in stone joints, can either be marked directly onto the structure, if appropriate, or noted on detailed measured survey drawings.

The latter facilitates the accurate relocation of targets by measured reference to physical features, e.g. reveals, mouldings or individual stone blocks. Alternatively a survey grid referenced to some suitable fixed datum point can be reproduced and the targets located within it.

Corroding embedded ironwork often produces cracking or spalling of the host stone; the mapping and cross referencing of these cracks/spalls with the identified metallic targets will increase the confidence of the survey findings.

The form of a metallic target can often be assessed by noting the nature and form of associated surface features such as cracks or spalls. For example, a corroding iron cramp located across the perpend joint between two stones often produces diagonal cracking of the stones adjacent to the perpend joint. In severe cases, the cracks lead to spalls, often exposing the corroded cramp.

The results of an investigation using metal detectors to map cramp locations is shown in Figure 7.

3.4 FREE ELECTRO-MAGNETIC RADIATION

Free electromagnetic radiation (FEMR) techniques cover a family of tools using very similar principles. They were originally used for locating metallic services buried under the ground but have since been adapted to locate a wide variety of targets in other environments. FEMR techniques typically are used to track *known* linear features or targets (e.g. pipes, services and beams etc.) which are not necessarily conductive. This can be compared to metal detectors which are used typically to *find* small conductive targets (e.g. metal cramps in stonework),

3.4.1 Applications of FEMR

Applications immediately relevant to the investigation of historic structures and monuments include:

- tracking metallic services such as power cables, old domestic gas lines, domestic/rain water pipes within walls and floors
- tracking metallic structural units such as tie bars and steel sections
- tracking non-metallic openings such as chimney flues, old sewer lines, cisterns etc.

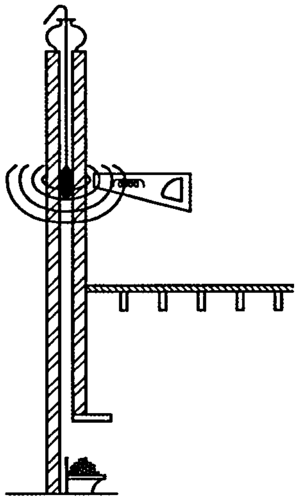
The last of these applications is achieved by introducing a linear conductive element into the otherwise non-conductive target (e.g. a wire along a sewer). In addition to detecting and tracking the targets, in certain circumstances it is possible to give an estimate of depth and the nature of the target (e.g. power cable etc.) where it is unknown.

The effective maximum depth of penetration is extremely variable and ranges between approximately 1m and 15m, depending on the equipment used, the nature of the target and the strength of signal radiated from the target.

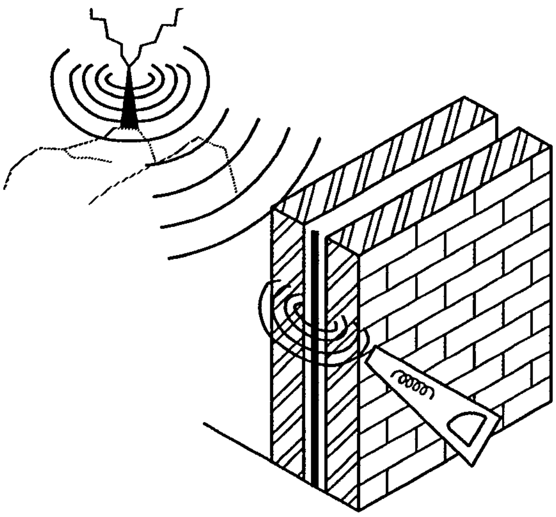
3.4.2 Theory and Limitations of FEMR

FEMR techniques all work by detecting radiated electro-magnetic signals. These can be considered 'active' signals where they have been induced within the target by an actual stimulus. Passive signals, on the other hand, can be defined as all the signals that are present in a target that have not been introduced artificially.

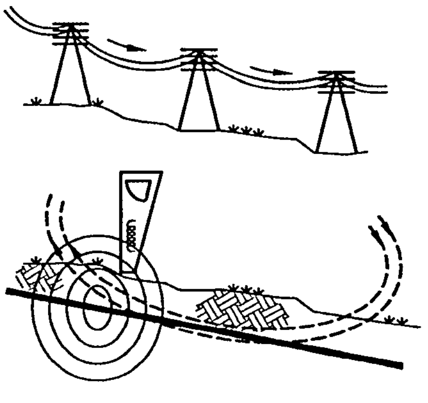
PASSIVE SIGNALS



TRACING THE LINE OF A CHIMNEY
FLUE USING A RADIO SONDE

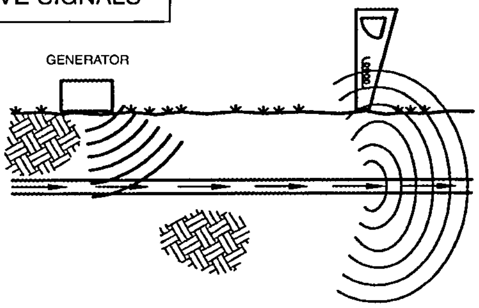


TRACING THE LINE OF A METAL CABLE BURIED IN A WALL
RERADIATING VERY LOW FREQUENCY RADIO SIGNALS

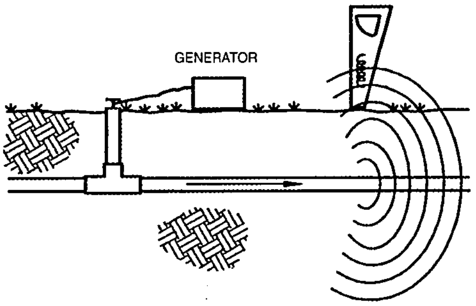


SOME LINES RADIATE MAINS FREQUENCY SIGNALS (50/60Hz)

ACTIVE SIGNALS



GENERATOR INDUCES A CURRENT IN THE TARGET



GENERATOR COUPLED DIRECTLY TO PIPELINE

Figure 8 Examples of applications of FEMR techniques (active and passive)

Plate 7 FEMR methods being used to trace an iron drain pipe behind a wall

FEMR differs from metal detection in that both 'passive' and 'active' signals are detected. The two passive signal frequencies that are most commonly present in linear conductive targets are:

- between 50Hz and 60Hz found in electrical power cables and conductive targets that have passed through the electro-magnetic field generated by the power cables
- between 15kHz and 20kHz found in targets acting as aerials, receiving and re-transmitting long wave radio signals.

Active signals are introduced to the target either by *direct connection or induction*.

Direct connection as its name implies is the introduction of a known signal (of specific frequency) into the target through a direct connection of a signal generator to the target - e.g. if the generator is connected to the stop cock of a water pipe, this introduces a signal which can be measured. It offers the best chance of tracking an individual target through a congested area as the receiver can 'lock' on to the 'known' signal radiated by the target.

Induction is the introduction of a signal to a target by ensuring that it is within range of the magnetic field generated by the signal generator. This is very close to the principle behind some metal detectors which detect the magnetic fields induced in and 'radiated' by conductive targets. It has the obvious advantage that no direct connection to the target is required.

A range of scenarios is shown in Figure 8.

A wide range of frequencies is commonly employed and a number of considerations must be borne in mind when selecting the appropriate frequency. Higher frequencies are better at inducing a signal in a target and travel well on small diameter lines, but transfer of the signal to other targets is more likely. In general, lower frequencies are better at maintaining a signal over longer distances but are more likely to be affected by interference because they are nearer the frequency of mains power. Frequency selection should be based therefore, on an understanding of the target and electromagnetic theory.

Finally, it is important to consider the environment of the target, in particular the material surrounding it. If the target is surrounded by relatively conductive materials (e.g. wet clay) the signal is stronger than if it is surrounded by dry sand or air.

Limitations of FEMR

Complications can occur when the electro-magnetic field emitted by the target becomes convoluted or is cancelled out. This can occur when:

- there are a number of linear conductive targets in close proximity
- target lines change direction
- power cables are wound in such a way as to cancel out the field from the individual wires that make up the cable.

Limited knowledge of the target, environment or equipment can result in failure either to induce a signal, to detect it, or to interpret it correctly.

3.4.3 Equipment

FEMR techniques typically employ a hand-held receiver aerial, operated by itself or in conjunction with a separate transmitter unit. Typical equipment is shown in Plate 7. Generally, the receiver aerial weighs in the order of 5kg, is powered by internal dry cell batteries and is water proof.

As with the metal detecting equipment, the aerial is usually equipped with a sensitivity control allowing a limited adjustment to eliminate unwanted signals. Positive signals are usually indicated by a meter and/or other signal strength indicator such as audible tones (clicks, buzzes or whistles) of varying pitch and intensity.

3.4.4 FEMR Surveys

Some knowledge of electro-magnetic theory is required to effectively plan and execute an FEMR investigation. These surveys are often time consuming, as despite the relative ease of operation, building up a record from essentially abstract signals requires considerable concentration and attention to detail, especially where an area is congested with several targets.

Data Collection

To minimise disruption where a target is fully concealed, an attempt should be made to trace the target by using either a passive signal or an induced active signal. The alternative is direct connection requiring exposure of a small part of the buried target to attach the signal generator which may result in some disturbance of the original fabric.

If a target is to be tracked internally along a floor then furniture may have to be moved. Carpeting and floor finishes do not generally affect the signal. If a target is to be tracked up a wall some form of access to high levels may be required.

In the case of non-conductive targets (such as a clay water pipe or a chimney flue) the introduction of a linear conductive element or a transmitter can present some practical problems that need careful consideration and planning prior to commencement of a survey. These might include obtaining access to an open end of the service.

Interpretation and Reporting

Like the results of a metal detector survey, FEMR readings require little or no off site interpretation and can therefore either be marked directly onto the object or presented on drawings, whichever is more appropriate. The results of a chimney flue location survey using a variety of techniques including FEMR are given in Figure 9.

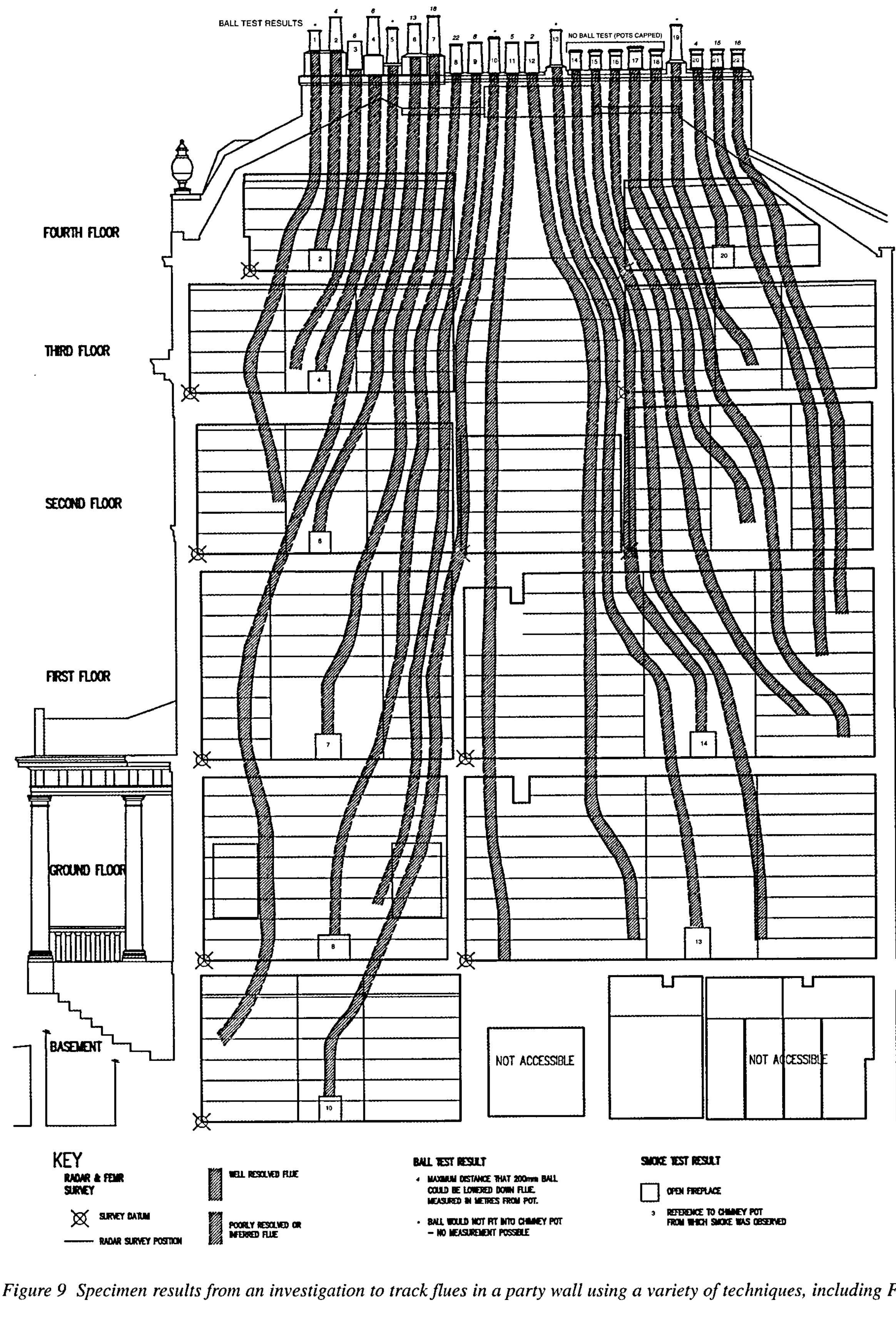


Figure 9 Specimen results from an investigation to track flues in a party wall using a variety of techniques, including FEMR

4 NUCLEAR METHODS

All the techniques discussed in this advice note have been identified by the nature of the stimulus applied (energy input) to the object under investigation. Nuclear inspection methods are those tests which utilise a radio-source of one form or another to stimulate the object. They are used relatively infrequently, largely for reasons of cost and practicality. There are different types of nuclear inspection, known as radiometry (involving simple numerical *measurement*), radiography (the generation of an image on a plate) and radioscopy (the *viewing* of an object).

Radiometric methods include moisture detection and density measurements of building materials, while radioscopy is often used in medical science. Crack detection in welds and metals is a highly specialised area where radio methods may be used, but these are not discussed in detail here; methods for measuring moisture levels and material densities are not discussed here either, as these are available as self-contained instruments.

Only radiography in its simplest form, using a gamma - radio source, is discussed in this section, as this nuclear method most likely to be used in the investigation of historic buildings and monuments. Most of the comments apply equally to the generation of X-rays, which are similarly part of the broad electromagnetic spectrum, (treated in the previous section), but the high energy of this group of techniques calls for special treatment. The basic approach of each technique is similar however and reference to individual alternatives are made at appropriate points in this essentially generic discussion.

It is perhaps more important than in any of the other sections to view radiography as a technique to be applied only by experienced and qualified suppliers, as the implications of its misuse are severe for any conservable objects in the vicinity, as well as being potentially life-threatening.

4.1 Radiography

4.1.1 Applications of Radiography

Radiography can provide an extremely precise and detailed characterisation of an object. It is best known for its use in medical X-rays but has been used, although not extensively, both by museum conservators to investigate paintings, statues (e.g. bronzes), etc., and in structural investigations since the mid 1950s. The most common usage has been by engineers seeking to determine the quality of construction and workmanship in concrete bridges.

In general, radiography is used to investigate a small part of a structure, or an artefact. It is of use where precise detail is a priority (e.g. where the performance of a critical element of a bridge or structure is under investigation) and where the slowness of operation is not a drawback. It is unsuitable for large-scale surveys or as a reconnaissance method and is unlikely to be commissioned as a primary method to answer questions about the overall structure or object.

As with medical X-rays, provided the object under investigation is suitable, radiography can produce an image of remarkable clarity. It can be used, for example, to determine the condition and configuration of timber concealed behind plaster work, an investigation which would otherwise be difficult to carry out non-destructively. The level of definition can be extremely high: for example, the identification of cracks and shakes in wood is possible. The technique is well suited to checking and confirming the adequacy of major structural joints in timber and could be more widely used. However the interpretation of results can be difficult and its operation can present practical problems. These factors must be weighed against the advantage of gaining more detailed information - this is discussed in more detail in section 4.1.2.

Greater use of the technique could be made to supplement other more rapid methods of investigation which produce lower resolution information. For example, radar and metal detectors may be able to identify the location and orientation of cramps in a stone facing, and possibly give an indication of their condition. A radiograph could offer a clear image of the cramp itself, revealing its precise internal form and condition. This level of information might have value where it is important to know the precise nature of the cramp, but where exposure is not an option - for example in the investigation of a statue which has been previously repaired with pins and dowels.

4.1.2 Theory and Limitations of Radiography

All materials are made of atoms. Atoms consist of a positively charged nucleus containing neutrons and protons, surrounded by a ‘cloud’ of negatively charged electrons. Different materials have different numbers of protons, neutrons and electrons, yielding different physical and chemical properties (e.g. density, the type of bond they can form with other materials, their state at a given temperature etc.).

Radioactive materials that occur naturally (e.g. uranium) are different from other materials because their particular atomic arrangement is unstable; they spontaneously decay or disintegrate by 'losing' mass. This is usually accompanied by a release of energy in the form of electromagnetic waves. This rate of decay (a material's 'half-life') can vary from seconds to centuries in different materials. The shorter the half-life the more unstable or radioactive the material.

There are three basic types of radioactive emission:

- *alpha* (α) rays, comprising relatively heavy alpha particles (a positively charged nucleus of two neutrons and two protons)
- *beta* (β) rays, comprising negatively charged electrons (beta particles) moving almost as fast as the speed of light
- *gamma* (γ) rays - electro-magnetic waves with no charge. The X-rays used for medical work are very similar to gamma rays, with a wave length between ultra violet and gamma waves (see Appendix A for the electro-magnetic spectrum).

The different forms of radiation pass through (or are absorbed by) different materials at different rates. The important factors governing this process of absorption are the 'radio density' of the material and its thickness. Alpha rays have very little penetrative effect (approx. 7cm in air) compared to beta particles (approx.750cm in air), and gamma radiation (infinite range in air) are much more penetrative than either. Building materials are penetrated with variable efficiency: organic materials - wood and leather, and simple compositions such as plaster - are easily penetrated, but complex materials such as brick, stone and metals are progressively less so.

A clear distinction needs to be drawn between penetration - the distance over which usuable radiation can be transmitted, and resolution, the ability to identify useful information about objects to be studied. A large cobalt or irridium source may penetrate 1000mm of masonry, but a nail will only reasonably be detected in a wall at about 300mm from the point of observation, and its size and shape accurately determined at about 150mm. Scatter of the radiation from objects between the target and point of observation blur the image.

Similarly, portable X-ray equipment is limited in penetration by the energy levels, and in resolution by the distance of the imaging plate from the object. A competent and experienced practitioner will advise on the correct equipment, and the maximum resolution achievable in the particular materials.

Nuclear methods of investigation offer a means of identifying the type and arrangement of different materials in an object by their differential absorption or dispersion of radioactive particles. Effectively there are two methods of radiography, both involving exposing an object to a radioactive source and recording the effects. These are:

- through transmission
- back scatter

Radiography takes advantage of the sensitivity of some materials to radiation in the same way as photography records light reflected from an object. A radiographic image is formed by exposing fluorescent screens or photographic material to the radiation after it has 'scattered' or passed through the object.

Through Transmission Imaging

Through transmission, as its name implies, places the object under investigation between the radioactive beam and the screen or radioactive sensitive material. This 'detector' records those particles which pass through the object and impinge upon it (this is described further in section 4.1.3). Objects and features located by this method are therefore seen in silhouette. Medical X-rays are an example of *through transmission.*

Back Scatter

Back scatter methods place the detector on the *same* side of the object as the radioactive beam to recover dispersed particles in the manner of an echo sounder (described further in section 4.1.3). This method is used for measuring material density and moisture content. It is an indirect method of investigation as it measures the *effect* of exposing the object to the radio source.

Density is measured on the basis of the scatter and attenuation (weakening) of the radiation while moisture is measured by the capture of hydrogen ions which are generated by the hydrogen nuclei present in water, produced as a result of the exposure to the radiation.

Practical Considerations

With nuclear methods of investigation, a balance must be struck between the need for information and the disruption, risks, cost and effort required to recover it. Specific considerations include:

- *Health & Safety*

The key question here is: can a safe environment be ensured for people - operatives, staff, and bypassers - during the course of the survey? Exposure to radioactivity is a well documented health hazard and great care must be taken to avoid long term exposure to radioactive sources. This may also generate a further question: is it acceptable to restrict access to the public and/or occupants for a long period during data collection? Some form of shielding or screens (often lead) will almost certainly be required to prevent unnecessary exposure of people and objects to the radioactive source while data is being captured. This almost certainly precludes the use of radiography on an exploratory or reconnaissance basis. The investigator should be fully aware of the relevant legislation surrounding the control, use and transportation of radioactive materials - this information is readily available from the Health & Safety Executive.

- *Effects of Exposure to Radiation on Materials*

In buildings containing delicate finishes or housing furniture and other artefacts, careful consideration should be given to the problems of placing protective screening for objects and people. The screening is heavy and often cumbersome, giving rise to the possibility of accidental damage, particularly as it will often require repositioning for each image. In addition, little is known of the potential damage to finishes and materials at a molecular and/or atomic level, particularly when more penetrative, highly radioactive sources are used. However, for most forms of survey, the levels of exposure to radioactivity are low and of short duration, therefore there is negligible residual effect or contamination of the structure or object under investigation. As with medical X-rays, danger can come from repeated or prolonged exposure to the radioactive source. The technicians exposed daily to the equipment and sources wear, or work, behind some form of shielding, while a patient receiving a single exposure does not.

- *Access*

This is discussed further in Chapter 6, however it is worth noting that of all the methods discussed in this note, the equipment required for radiography is among the heaviest and least manoeuvrable. Coupled with a requirement for very specific positioning and perspectives, the success of the survey is particularly dependent upon appropriate access being achieved.

- *Rates of progress*

Progress is relatively slow and laborious. Typical photographic plate sizes are 25 x 20 cm, which is a very small image in terms of the total surface of a building. While average exposure times in the order of 10s for a partition wall formed of 150mm lath and plaster over timber can be expected, positioning the plate and source such that the optimum results are achieved takes a considerable time, as does the arrangement of a safe working environment.

4.1.3 Equipment

Radiographic equipment is bulky and cumbersome but essentially portable. For through transmission, the transmitter and detector are placed separately on either side of the object. Various sources or transmitters can be used to generate the source of radiation the object is exposed to, usually in the form of a focused beam. These include electrically powered guns and elements like Cobalt 60. A picture of a transmitter is shown in Plate 8. The detector contains an imaging screen, which fluoresces with a white light when excited by the beam. The light generated exposes a photographic film within the cassette, and an image of the internal structure is formed.

In *radioscopy*, the film can be replaced with a video camera or any other system that responds to visible light. This introduces further sophistication to the equipment and increases its size and complexity.

Although radiometry has not been discussed in detail in this advice note, it is worth noting that *radiometric* moisture and density gauges can be of use in conservation work. They are relatively compact, simple pieces of equipment, that frequently use the back scatter principle, described previously, for measurement. The radioactive source is placed against the surface or within the body of the material, by means of a probe. If required the detector can be placed in the body of the material, also by means of a probe. In this sense the technique is not always non-destructive - some disturbance is inevitable if a probe is to be placed within the fabric.

4.1.4 Radiographic Surveys

Health & Safety

With any nuclear method of investigation there are stringent Health and Safety regulations governing the operation, handling and transportation of the radioactive source. Adequate protection for both operatives and the public must be ensured and a period of notice of the use of such a source can be required. Further information is readily available from local offices of the HSE. **Both nuclear and all radiographic methods must only be undertaken by qualified experts who are contracted to provide a safe working environment for their activities which complies with current regulations and recommendations.**

Specification

A precise specification and definition of the scope of work is essential to the success of a nuclear method of non-destructive testing because of the cost penalty and practical difficulties which arise when site work has to be repeated. If the precise images required of the object are not recovered, if they are out of focus or blurred or taken from the wrong perspective, the test must be repeated. The critical and detailed nature of the information which prompts the commissioning and justifies the cost of a nuclear method, is unlikely to be provided by partly successful results.

Plate 8 Portable Radioactive Source (COBALT 60)

Data Collection

The selection of the correct source is critical and depends on the expected overall absorption. Less penetrative radiation can offer a better definition between materials but must penetrate sufficiently to produce the information required.

For through transmission radiography, the source (transmitter) is typically an electrically driven gun, as used in dental surgeries, which directs a beam into the object. Alternatively a radioactive source may be used to guide the particles into a focused stream.

Particular attention has to be paid to keeping the beam perpendicular to the plate (receiver): oblique angled shots produce distorted images with considerable interference from scatter, which blurs the image. The best results are obtained when the plate is close to the hidden feature, although clustered and/or distant objects will be blurred. It may be necessary to take an image from both sides therefore.

When using X-ray equipment a stable power source will be required. Single phase mains is normally adequate although power consumption is too large to allow the use of batteries - making the technique unfeasible in remote environments unless a heavy generator can be provided.

Interpretation

Consideration has been given in this note to the simplest form of equipment, where an image is captured on a photographic plate. Traditionally plates must be developed before the quality and coverage of the image can be established. This effectively prevents an in-situ interpretation, although relatively portable processors and the development of X-ray sensitive film (as opposed to exposure of photographic film to X-ray sensitive fluorescing materials) offer a reduction in processing times.

The radiographs generated are full scale images which require careful interpretation. Simple inclusions such as nails in wood (a very high contrast and distinctive shape) can be readily identified while more complex and lower contrast features such as cracks or complex overlays of materials require specialist interpretation. Note that subtler nuances of the image (shadows, marks etc.) can result from non-structural sources (e.g. interference patterns) as well as 'real' features.

Modern *radioscopic* systems, incorporating a video camera with a fluorescing screen, offer more flexible ways of working and allow instant access to the results. Recording onto video tape gives reasonable definition but for high quality definition comparable with photographic plate, a digital recording system is required.

Reporting

A radiography report should include both a copy of the original radiograph and a written and/or graphic interpretation. In complex constructions this will almost certainly include a dimensioned drawing of the object investigated, as revealed in the radiograph.

5 ACOUSTIC METHODS

The third category of non-destructive methods covers techniques that apply mechanical stimuli to an object and measure and record the object's response. These are distinct from other 'physical' tests such as smoke or ball tests (used for flue location) or endoscopy which are not discussed here as they are considered essentially intuitive. Methods for testing and measuring the dynamic response of a whole structure are also excluded from this section as these are not considered to be of direct relevance to the conservation of historic buildings and monuments.

This advice note limits its discussion therefore to the testing and measurement of materials, structures and small objects by two mechanical methods: ultrasonic pulse velocity (UPV) and impact-echo.

5.1 Introduction to Acoustics

Before any methods are considered in detail, it is helpful to understand the basic theory of acoustics.

We are all familiar with the 'tap' test in its various forms, e.g. rapping knuckles on a plastered wall to locate timber studs, stamping on a floor to identify voids below, the wheel tapper hitting a train wheel with a hammer to check its integrity. Each of these tests applies a physical stimulus and measures the acoustic response of the object by ear. Variations in the tone and volume (i.e. frequency and amplitude) of the response give a qualitative assessment of the condition of the object or the materials behind it. Other characteristics of the response are the phase and wavelength, which, together with the frequency and amplitude describe a *wave.*

Acoustics is the study of sound. Sound waves are mechanical waves produced by a vibrating object in which particles oscillate backwards and forwards about their 'resting' position, i.e. the waves are a *physical* displacement of the media in which they are travelling, therefore (and in contrast to electromagnetic waves), mechanical waves cannot move through a vacuum (e.g. space).

In general terms, as an object vibrates it sends out waves which move or propagate through the medium surrounding the object. The nature of the waves depends upon the elastic properties and density of the medium. In solids, mechanical waves comprise:

- longitudinal or compression waves (Primary or P-waves)
- transverse or shear waves (Secondary or S-waves)
- surface waves (Rayleigh waves)

Usually only longitudinal waves are measured for the simple reason that they are the fastest moving and reach the receiver first. These are cycles, comprising alternating high pressure (compression) and low pressure (rarefaction) zones. The waves move at different speeds depending on the material and its phase (i.e. whether it is gas, liquid or solid).

Note that fluids such as air, water etc., only support longitudingal compression waves where the displacement is in the same direction as the wave. The human eardrum is coupled to the environment by air - sound therefore is a compression wave.

Uses for acoustics vary from the identification of variations in material integrity (e.g. voids in concrete, depth of cracking in a surface, delamination in a sandstone block) to the establishment of certain material and element parameters (e.g. compressive strength of stone or brick, material density, slab thickness).

5.2 Ultrasonic Pulse Velocity Measurements

Ultrasonic pulse velocity (UPV) measurement is a simple point test of material integrity and arrangement. It works by measuring the time travelled by an acoustic pulse through a material over a fixed distance; this is then used to calculate a velocity which may be compared for variation against a known constant. This is explained in more detail in section 5.2.2

5.2.1 Applications of UPV

The measure of velocity is used in two ways:

- minor variations are attributed to changes in elastic modulus and are used to comment on in-situ strength
- major variations (beyond those reasonably explained by changes in strength) are attributed to discontinuities or cracks in the material.

It is therefore likely to be used later in an investigation, after more general reconnaissance methods have identified areas of the object for further detailed study. It is a simple test in principle and has been used for many years around the world, particularly (in an engineering environment) for the study of concrete integrity.

The travel time of the acoustic pulse in milli seconds (ms) is measured, and comprises the raw data. This does not allow an intuitive interpretation. Therefore, before conclusions can be drawn, it is wise to look for insight from other reports and information. These may be simple visual records or reports from other non-destructive methods. The investigator is looking for supporting evidence to explain and/or support the readings obtained.

Typical applications include:

- the assessment of material compressive strength
- the assessment of material integrity - for example in masonry lintels
- the identification of cracks and their depth in materials such as stone, concrete etc.

More sophisticated instrumentation which measures and records other signal properties (e.g. amplitude and phase) can be used for more extended studies including:

- material thickness - for example in plaster work, stone slabs
- locating delaminations in a laminar structure - peeling of 'thick' finishes, separation between plaster coats, spalling stonework.

It is worth noting that metallic as well as non-metallic objects can be assessed with this method; ultra-sonics are used in industry, including the aerospace industry for assessing the integrity of welds.

5.2.2 Theory and Limitations of UPV

Mechanical waves travel through different solids at different velocities; this is independent of their frequency. Note that the range of frequencies used by UPV are beyond the audible range, approximately 20 kHz to 300 kHz, hence they are referred to as ultrasonic.

UPV measures the velocity of compression waves, and the velocity of a wave through a material is a function of:

- the density of the material
- the elastic properties of the material
- the type of wave.

Velocity Calculation

To calculate the velocity, the time *(t)* taken for a pulse to travel a known distance *(d)* between the transmitter and receiver is measured. The velocity *(v)* is then calculated as follows:

$v = d / t$

Once the acoustic pulse velocity for a material is known it can be used in one of three ways:

- to give an indication of *material integrity*
- to calculate the *mechanical properties* of the materials (e.g. elastic moduli, uni-axial compressive strength)
- to identify local variations within the materials.

An assessment of *material integrity* is normally achieved by comparing the calculated pulse velocity against the published 'benchmark' velocity for the same material (this figure can also be calculated). Velocities which differ significantly from the benchmark values may indicate areas where the material integrity has been compromised (e.g. micro-cracking, delamination, cracking etc.). Statistical analysis of the collected data allows local variations to be found within the material even in the absence of benchmark readings: it is assumed that variations between results obtained from the same material in similar areas of an object indicate a change in material condition.

In the same way, *mechanical properties* obtained by this technique should not be used as absolute measurements but can be used to indicate variations in strength: as the velocity in a simple and undamaged medium will be a function of the density (e) and elasticy (r), measuring the velocity in a constant density medium will give the elasticity, from which the strength can be derived. Few building materials are sufficiently homogeneous for this simple relationship to apply absolutely. This does not however preclude its use as a relative tool, looking for changes or dicontinuities in a material, or the estimation of broad categories of strength.

Figure 10 shows the approximate relationship between acoustic velocity and compressive strength for concrete, although the same approximate relationship fits for most materials: best fit empirical values have been used and the shaded area of either side of the curve gives an approximation to the error margins. At the bottom left of the graph the velocity levels off at the typical velocity for uncemented gravel - about 1.8Km/s, and at the top right at about 4Km/s is high quality hardened concrete. In between is the range of interest where an approximately linear relationship exists between strength and velocity, which can be used to determine the residual strength of a material which has been damaged through stress or decay.

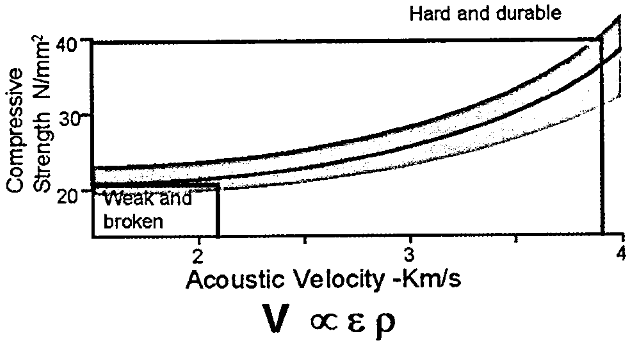


Figure 10 Relationship between acoustic pulse velocity and compressive strength of concrete

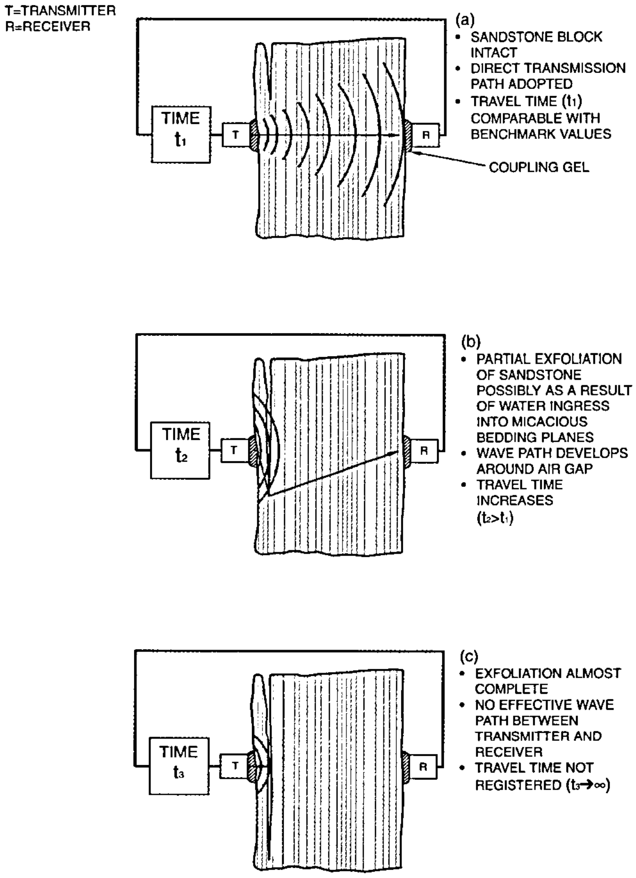


Figure 11 UPV in operation on a face bedded sandstone block

Material	Velocity (m/s)
Steel	6000
Granite	5400
Cast Iron	5000
Timber (Ash - along grain)	4700
Concrete	4000
Sandstone	3000
Timber (Ash - across grain)	1390

Note the variation in wave velocities between measurements taken across the grain and along the grain for ash.

Table 3 Typical Ultrasonic Pulse Velocities for Common Building Materials

Energy Considerations

Acoustic energy will pass from one medium to another, providing that the material properties of both media are sufficiently similar. As the differences between properties increase, the proportion of energy reflected at the interface between the media increases. Therefore, a wave travelling through a *compressible* medium such as a gas (e.g. air) will not transmit a high proportion of its energy into a stiff elastic medium such as mortar or concrete, and vice versa. However a wave travelling through an *incompressible* medium such as water, will transmit most of its energy into another medium such as mortar. Where both materials are solids, the amount of mechanical energy transmitted from one to the other depends on their relative elasticity and the mechanical couple between them - i.e. the ability to transfer the mechanical wave between the two materials. When a crack or mechanical discontinuity exists within the material, the mechanical couple cannot be sustained and the travelling wave is 'obstructed' by the discontinuity. Such features are manifested either by variations in travel times (e.g. the wave finds an alternative route between transmitter and receiver, avoiding the discontinuity) or by no coherent reading whatsoever (no continuous path can be found between transmitter and receiver within the maximum time range measured by the instrument).

Two simple examples are illustrated in Figure 11.

The pulse transmitter and receiver must be mechanically coupled to the surface of the material to be investigated. As discussed briefly above, a compressible medium, such as air, will prevent almost any energy transmission between the transmitter/receiver and object, so a better coupling medium must be used (e.g. a liquid), which will readily transmit the compression waves.

The transmitter and receiver may be placed on opposite sides of the object for 'direct' measurement, or on the same surface for 'indirect' measurements. Note that the strength of signal detected for any particular *indirect* measurement is only about 1 - 2% of that detected for the equivalent *direct* measurement

Defect Characterisation

Where there are a number of cracks and different defects (e.g. damp patches, voids and other inclusions within the material etc.) the wave paths can become complex, effectively preventing the use of point measurements to characterise them.

To cope with these situations, work is progressing on the development of mathematical methods known as tomography. These use a number of different wave path measurements through an object to build up a 'pseudo-section' through the object. These are well developed in medical and physiological research but there are inherent difficulties in structural assessments (variable signal strength and velocities) which prevent a simple transfer of technology.

Other Considerations

Two additional and important factors affecting an investigation using mechanical methods are energy loss and target definition or resolution.

Energy loss, or *attenuation*, is a reduction in signal strength per unit wave length. This means that signal strength is lost as the wave passes through a material (i.e. if the distance travelled by the wave increases, the strength of the received signal decreases) - effectively placing a theoretical limit on the range of the particular equipment configuration being used.

Target definition or *resolution* is based on the target's ability to reflect the wave form, i.e. the resolution of a given target is influenced by the wavelength of the signal. As the wavelength shortens to approach the size of the particles forming the matrix of a heterogeneous material, such as concrete, the wave form is scattered, resulting in energy loss and reduced penetration. Consequently, longer wavelengths give greater penetration. The resolution is reduced however as the ratio of wavelength to target size increases - shorter wavelengths do not offer great penetration but provide better target definition or resolution.

The required resolution of any target is determined by reference to the needs of the end user. Simple detection of a feature may be sufficient in some cases, whereas in other cases a fuller characterisation is required.

In conservation work the principal limitations to a UPV investigation relate to ease of access as follows:

- UPV works best when readings are direct. Practically this means that transmitter and receiver should be placed on opposite sides of the object where possible (e.g. opposite faces of a stone block). Where this is not possible, transmitter and receiver can be placed side-by-side on the same face.
- a good couple is required between both the transmitter and receiver and the structure. This ensures a good transmission of the pulse from the transmitter into the object and from the object back into the receiver. This is achieved by the application of a water soluble gel or grease to the surface of the structure and the face of the transmitter and receiver to give a high viscosity or thixotropic fluid couple. Clearly this gel cannot be applied in conservation work where there is a risk of damage to or discolouration of the original fabric of the building. Careful testing of a small and inconspicuous area must be undertaken before this method is applied.

Other more general limitations include the following:

- transmission through a material requires that the material does not interfere with the ultrasonic pulses, i.e. the ratio of wavelength to matrix/particle size is sufficiently large. Effectively this means that aggregates in materials such as concrete should be no larger than approximately 16mm.
- the geometry of the object can complicate results - the best results are obtained from monolithic structures with a simple form.
- data collection is relatively slow and many readings should be taken to recover a statistically significant sample to allow the identification and elimination of anomalous readings.

5.2.3 Equipment

In its simplest form, UPV generally requires the use of a hand held transmitter and receiver connected to a control unit. A typical arrangement being used in indirect measurement mode is shown in Plate 9. Some systems offer a profile of the received wave form, either on a cathode ray oscilloscope or liquid crystal display. Less sophisticated systems offer a simple numerical output. The equipment weighs approx. 10 kg, is powered by internal drycell batteries and is dust and shower proof.

Plate 9 Typical UPV survey in operation (indirect arrangement of couples both on the same side of the object being tested)

Since the collection of the data using point measurement devices is relatively time consuming, scanning techniques have been developed that increase the rate of sampling by mounting the transmitter and receiver onto rollers, which allow it to be moved across the surface of the material. The major problem with these scanning systems, as with any UPV device, is the need to achieve an effective coupling between the transducers and the structure.

5.2.4 UPV Surveys

When carrying out a UPV investigation, the selection of the appropriate frequency/wavelength of the transmitted mechanical wave is vitally important.

Different UPV systems have been developed for different materials and have different time ranges. If the working range of the equipment (i.e. the time envelope within which the receiver expects to receive a signal after the pulse has been transmitted) is exceeded there is a danger that secondary shear waves will be detected instead of the primary compression waves. This will provide misleading and false velocity readings.

There are two other important site considerations: data collection (including distance measurement) and the system of referencing.

Data collection - for best results, access is required to both sides of the object (direct measurement). Ideally surface finishes should be relatively smooth to facilitate a good couple.

Referencing - Logging of the results should be carried out in accordance with good field practice. All readings, including errors and repeat readings, should be recorded along with their location and comments as necessary. Note that for effective velocity calculation, the distance between the transmitter and receiver (the assumed path length) must be measured to a good degree of accuracy, typically ±1%.

Due to the discrete numerical nature of the UPV as a 'point' test, readings should never be treated in isolation. A statistical sample, while laborious to recover, will offer much greater confidence in the accuracy of the results. Statistical analyses (distribution curves, standard deviations etc.) will play a part in the processing of the raw data.

To enable accurate *relocation* of any detected features to the structure, a survey grid can be measured out across the area of interest, referenced to some suitable fixed datum point (usually the corner of a building, ground level etc.) and marked on the surface with measuring tapes, string, water soluble materials (e.g. chalk) or non-marking adhesive tape, as appropriate. All identified features can then be referenced to this survey grid by marking a measured survey drawing or sketch. With this system it is normally possible to relocate to an accuracy of better than ±10% of the distance between known points.

Particular attention should be made to keep a record of results from raw data through statistical analysis to interpretation. Results can and often should be presented in a variety of ways, including tabular format, statistical graphs and interpreted strengths or defects marked onto measured survey drawings.

5.3 IMPACT-ECHO

The basic theory behind this technique has already been covered in the Introduction to Acoustics (section 5.1) and many of the principles of operation are similar to those for UPV (section 5.2). To avoid repetition additional comment has been offered only where there are significant differences, or clarification is needed.

5.3.1 Applications of Impact-Echo

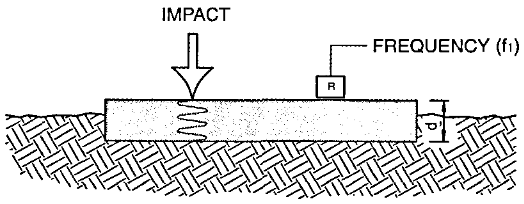
Impact-echo was developed in the 1980s, primarily for detecting flaws in concrete, although the principles that it employs may be used in a wider field with care and discretion. This technique is generally only used to calculate the depths and condition of whole structures or large monolithic bodies of a solid material, and is best suited to structures of uniform composition and thickness such as slabs and blocks of material. Metallic materials can be assessed in this manner also.

Unlike UPV, which quantifies a *point* or *material* response of an object to a mechanical stimulus, impact-echo records the *holistic* response of the object. It is therefore likely to be used qualitatively to identify anomalous responses, prior to a more detailed investigation to characterise the extent and nature of any defects.

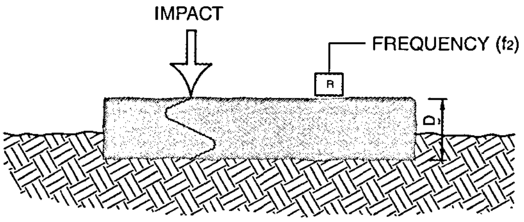
The information recovered is complex, requiring considerable processing and analysis of the wave form and frequency spectrum. It is therefore wise to compare the conclusions with results from other methods of investigation for corroboration (even if these are simply visual records or reports).

5.3.2 Theory and Limitations of Impact-Echo

Impact-echo (also referred to as 'dynamic impedance', loosely meaning resistance to dynamic vibration) is a member of the family of pulse-echo methods and works on much the same acoustic principles as ultrasonics: a pulse of mechanical energy is transmitted into a solid object and its behaviour recorded for interpretation. The pulse is normally introduced by a hammer blow, perhaps via a rubber mat, which provides higher accelerations and lower frequencies than used in ultrasonic methods; transducers are normally coupled via pressure: before proceeding care should be taken that the energy introduced is unlikely to exceed the elastic limits of the object - i.e. it does not damage it! The method therefore tends to be appropriate only to wood, stone and metallic objects which do not appear to be in a friable or brittle condition. This is illustrated in Figure 12.



(a) STONE SLAB (THICKNESS d) VIBRATES WITH RESONANT FREQUENCY (f1)



(b) THICKER SLAB (D>d) VIBRATES WITH DIFFERENT RESONANT FREQUENCY (f2)

Figure 12 Basic theory of impact-echo method

Plate 10 Equipment used for impact-echo method

The different names for the method stem from the different parts of the process:

- the *method* used to excite the object, i.e. by transmitting a pulse of energy into it (generally a hammer is used - hence sometimes referred to as a 'bump' test)
- the *behaviour* of the object (i.e. its mechanical impedance)
- the *characteristics* of the mechanical wave and 'echo' or reflected wave form measured by the transducer.

The transmitted energy propagates through the object as a mechanical wave and causes it to vibrate. The characteristics of this vibration are dictated in part by the mechanical impedance of the object, which is affected by the condition and arrangement of its materials.

In practice this means that two apparently similar structures (e.g. two stone columns) can have a different mechanical impedance for any one of the following reasons:

- if their condition is different,
- if the distribution of the materials within them is different, i.e. one of them is defective (e.g. cracked) or is constructed differently (e.g. has keyed or interlocking components)
- if there are different 'boundary conditions.' (These refer to the environment the object is in, whether it is fixed to or in contact with another object or material. Thus differences in the impact-echo results will allow differentiation of a slab spanning a void from one that is supported along its length.)

Wave Characteristics

Typically the mechanical wave measured has a fundamental frequency with a number of 'overtones'. The fundamental frequency has the greatest intensity while the overtones are frequencies of lower intensity that are simple multiples of the fundamental frequency. This is a direct parallel to sound: a musical note is rarely pure (i.e. a simple wave form of one frequency) and the presence of overtones give a note its characteristic quality or timbre.

The wave form recovered is complex and needs to be reduced to its constituent parts before analysis can commence, and causes are attributed to the behaviour of the object.

5.3.3 Impact-Echo Equipment

The equipment itself comprises:

- a hammer or other means of 'bumping' the object to input energy (acting as the transmitter)
- a receiver for measuring the object's response
- a control box and signal processor

Typically the equipment is lightweight, rugged, portable and splash-proof. Instant hard copy printouts are obtainable if a portable printer is available (Plate 10).

An acrylic 'recoil-less' hammer is generally used. This ensures that enough energy is transmitted into the object to excite its natural frequencies. A metal hammer will sometimes bounce on impact, resulting in several energy "inputs" into the structure which will complicate readings. Such a hammer may also damage the object.

5.3.4 Impact-Echo Surveys

Operation is similar to the UPV equipment in that a receiver is placed on (and mechanically coupled via a high viscosity or thixotropic fluid to) the surface of the object. Generally it is placed close to and on the same surface as the point of impact (i.e. the hammer, acting as a transmitter). This is unlike UPV where it is preferable to have transmitter and receiver placed on opposite faces of the object.

At the beginning of the testing the equipment must be optimised and calibrated which will slow progress where a large number of objects are to be tested. Thereafter, data collection is essentially quick and discreet however.

The 'bump' required to transmit energy into the object will vary from object to object but data collection is non-destructive for robust materials such as stone, mortar, wood and concrete. More fragile materials such as plaster and ceramics are less suited to this method.

6 PLANNING AN INVESTIGATION

This chapter considers contractual issues relevant to the successful specification and procurement of a non-destructive investigation by the conservation professional. Conservation professionals are strongly advised to ensure that only specialists familiar with the variety of non-destructive methods available and experienced in their application on similar projects are appointed to undertake an investigation.

6.1 Preparing for a Non-Destructive Investigation

6.1.1 Timing the Investigation

A typical programme for conservation work organised and managed by the conservation professional comprises five distinct phases:

1. inspection of object or structure
2. structural assessment
3. specification of repairs/actions
4. costing of repairs/actions as part of an economic assessment
5. implementation of the conservation works

A non-destructive investigation can contribute information to the first three phases and is optimally placed close to the beginning of the project. The range of information that can be expected from a non-destructive investigation is discussed in more detail in Chapter 2. The investigation can recover a wide range of data which will provide the conservation professional with information that will aid decisions on consequent actions, and the investigation may therefore sit on the project's critical path. Time must be allowed for the 'raw' data to be analysed or processed before the information required for the assessment of the structure or object can be presented.

6.1.2 Defining the Scope of the Investigation

To define effectively the scope of an investigation involving new or unfamiliar technology the conservation professional needs to develop a clear and realistic expectation of the assessment process and its results.

A brief must be generated that is wide ranging but offers specific guidance to the investigator - the result must be an analysis that is neither too broad, resulting in irrelevant detail, or too restrictive - pre-supposing the outcome of the investigation. It is important to bear in mind that an *investigation* is being specified and not a *test*. It is wise for the specification to avoid being overly definitive so that the investigator can recommend alternative or additional techniques as appropriate. The investigator should also be expected to recommend and develop methodologies in consultation with architects, engineers, surveyors, archaeologists and other conservation experts. The investigator's ability to produce and communicate a unique methodology is one of the key indicators of the quality of any proposal.

Careful consideration of the following points can help to define effectively the scope of an investigation:

- overall project constraints, objectives and timetable.
- the reasons for which a non-destructive investigation is being considered - missing information, gaps in the structural record, any poorly understood material or structural defect, failure mechanisms etc. Often it will be necessary to assess the importance/significance of the missing information and set this against the costs of the investigation.
- the type of information required - this could relate to quantity, location, orientation, condition etc. - and preferred presentation format (verbal, drawings, digital files, software compatibility etc.)
- the physical extent and location of key areas from which data will be recovered - note that this may be determined by access constraints, although at all times a statistically significant set of data is required.
- the *value* of the information being sought. This can be particularly helpful in assessing budget considerations, on occasion a marginal increase in budget might offer a long term gain.
- subsequent processes for which the information may be required, including the potential re-use of the information, as part of an archive, in other areas of the structure etc.

Note that it is good practice for the investigator to collect some data from a 'control' area similar to, but distinct from, the area under investigation. This is particularly appropriate where a defect is being investigated and a comparative analysis of data is required.

6.1.3 Estimating Budgets for An Investigation

Charging Structures

The costs of a non-destructive investigation can be conveniently split into two categories:

- professional fees (time based - closely comparable to hourly rates of other professionals, e.g. structural engineers)
- expenses (including subsistence, travel, equipment costs and charges).

This model can be applied to the three distinct phases of an investigation: data collection, analysis/consultation and reporting (see Table 4), in addition major expenditure on particular items, such as access, can be shown separately.

Category	Fee (Time Based)	Expenses
Data Collection	10 %	80 %
Analysis and Consultation	75 %	10 %
Reporting	15 %	10 %
	= 100 %	= 100 %

Table 4 Typical Distribution of Fees and Expenses Across the Three Phases of an Investigation

This model is largely independent of the test method or methods employed - as would be expected where information, rather than the technology used to acquire it, is the dominant consideration. It also helps to quantify costs for additional consultation, comment and report by the investigator beyond the scope of the original commission.

Typical Costs

Time spent on collection and analysis is the major cost element in a non-destructive investigation. The conservation professional must assess the impact of two factors on this:

- the size of the structure, object or area
- the nature of the information required.

The size of the structure, object or area that must be investigated will influence the amount of time that must be spent collecting a representative sample. This will affect the site expenses and the amount of time spent in analysis: more data collected means more data requiring analysis.

The nature of information required will affect the strategy of the investigation and therefore the choice of techniques deployed. Similarly the required information will influence the level of analysis and discussion in the final report - is a simple report required (e.g. indicating quantities and locations) or is a higher degree of interpretation required (e.g. mechanisms of failure)?

Some guidelines are helpful and Table 5 indicates typical relative timings for some common types of investigation that might be specified.

Investigation	Information Required	Techniques	Time on Site	Comment
Identify flues in a party wall	Line, dimension, condition and number of flues	Impulse radar, FEMR, physical tests	2 days (2 rooms on 4 levels)	Can also use closed circuit TV.
Establish the construction and condition of a masonry cornice	Identify elements within cornice, location, nature and origin of defects	Impulse radar, metal detection	1 - 2 days (approx. 30m long)	Access costs may be high - depends on complexity of cornice
Locate formed voids (tombs, graves etc.) beneath stone floor	Location plan	Impulse radar, Impact Echo	1 day to cover approx. 1500m2	Churches etc.
Condition of stone window mullions	Identify flaws	UPV, impulse radar	1 day to survey 20m length	Access is critical
Construction and condition of massive masonry wall (e.g. retaining wall, lock)	Construction, material thickness, areas where material lost, voids	Thermography, impulse radar	1 day to cover area up to 150m2	Access to both sides of wall where possible
Condition of harling, mosaic or render or stonework spalling	Identify areas that are damp or efflorescing	Thermography (UPV)	1 day to cover area up to 300m2	Depends on minimum size of delamination

Table 5 Typical Investigations, Techniques and Associated Site Works

Equipment hire is an additional factor sometimes included in the costing of different tests. The capital cost of equipment is high and facilities exist to rent complex equipment on an ad hoc basis. This becomes a consideration for the conservation professional if timing of the investigation works is critical, or specific equipment guidelines and configurations are designated by the investigator (e.g. long wave thermography vs. short wave thermography, certain frequencies of transducer).

The timings quoted should be used as rough guides only - each investigation and object will require individual consideration.

6.1.4 Selecting an Investigator

The value of non-destructive investigations is recognised across a wide range of fields. However, care should be taken by conservation professionals to distinguish between the following:

- *providers* of non-destructive test equipment (manufacturers and hire companies)
- *operators* of non-destructive test equipment
- *consultants* who use non-destructive test methods within the context of an investigation - and their field of expertise (archaeological/ground investigations, modern structures, historic structures, conservation work etc.)

The distinction between operators and consultants is frequently blurred in this developing field. Checks made against the following points will help ensure a reliable assessment of competence:

- The number of staff and their experience in this type of work
- Involvement in similar previous projects (structure/object and material type, client, type of investigation, findings and cost)
- Client references
- Quality Assured management systems for collection and analysis of data, project management etc.
- Relevant NAMAS standards (National Accreditation of Measurement and Sampling) for equipment calibration.

In this developing field, professional accreditation is not always practical or relevant - unless it is to an affiliated discipline (such as structural engineering). Some specialised and self-regulatory bodies have been formed within the field such as The British Institute of Non-Destructive Testing. Membership of the various bodies and adherence to their codes of conduct is not mandatory but is usual amongst reputable and established providers of equipment, testing, investigation or consultancy services.

Having compiled a list of two or three suitable investigators for the work, a quotation for works should be requested. This should be in the form of a technical proposal accompanied by a financial proposal.

Contract Structures

The ideal contract structure should encourage a relationship between the conservation professional and investigator where the expertise of the investigator can be brought to bear on the problem at hand, fully informed and guided by the conservation professional.

Discussion should occur at all stages of the investigation: in determining recommendations for appropriate methods, their deployment, the interpretation/collation of data and presentation of findings. For example, an appropriate, bespoke methodology can be developed during a preliminary discussion of the problem. It will often be necessary to make allowance for trials and calibration, and agree details of alternative methods and/or a mechanism for handling variations arising from the unsuccessful application of any one method. The sequential nature of a non-destructive investigation often requires that preliminary results influence selection and deployment of subsequent investigation methods. This is not entirely open ended or without definition and the investigator can be expected to discuss possible scenarios dependant on the outcome of preliminary testing.

The use of highly prescriptive procurement methods such as a Bill of Quantities in providing a cost per unit area is rarely appropriate except where the commission is a large, test-based investigation, dominated by data collection costs (site works, the number of tests deployed, sample frequency etc.). These tests typically involve the use of relatively simple equipment and instrumentation and require a low level of interpretation on site prior to collation and analysis.

6.1.5 Elements required in a Quotation for Work

Following an initial briefing in which the full available information is laid out, the investigator should be required to produce a detailed technical proposal which sets out:

- how the investigation will be structured
- what methods will be used and why they have been selected
- what their limitations are

- logistical considerations
- what will be reported
- a provisional timetable.

In addition, the financial proposal should contain

- charges and rates for the proposed work
- if appropriate, a cost benefit analysis of the proposal(s).

Evaluating Proposals

Where separate proposals are being compared, a scoring system, similar to that described briefly below, can be used in order to allow a balanced appraisal that will ensure the optimum combination of price and effectiveness. This appraisal should identify three separate characteristics of each proposal: technical aspects of the proposal, financial aspects and references stating the experience of the investigator.

A system of weighted scores can then be adopted where the proposals are scored relatively, for example, the most experienced investigator receiving the highest mark in that category. Note that all financial proposals falling within the predicted budget should receive the maximum mark of 4 - otherwise the greatest cost receives the lowest score.

Similarly the integrity of the technical proposals can be judged against factors such as the choice of an appropriate methodology, the assessment of likely progress and results, the level of pragmatic understanding demonstrated by details of limitations and weaknesses etc. given. A good indication of the quality of a technical proposal lies in the specialist's discussion and rejection/recommendation of different techniques, tailored to the specific requirements of the conservation professional. This will quickly establish the breadth of the specialist's experience and show their ability to communicate with and therefore work alongside the conservation professional.

Table 6 shows how the scoring system might apply to two proposals neither falling within the projected budget but with Proposal 1 promising a cheaper service from a relatively inexperienced source, that is technically less acceptable.

Element	**Total Marks Available**	**Proposal 1**	**Proposal 2**
Financial elements	4 marks	3	1
Technical elements	3 marks	1	3
Investigator's experience	3 marks	2	3
Total	10 marks	6	7

Table 6 System for scoring proposals

Such a system ensures that a balance of cost, value for money and confidence in the results can be struck, although it may be considered unwieldy for investigations with budgets under £5000.

6.2 During and After the Investigation

There are many factors to consider during the ongoing investigation. This section draws attention to three areas of particular importance: access, health and safety and reporting.

6.2.1 Access Considerations

Many non-destructive techniques require that the surveying equipment is placed close to or on the object being investigated. For these techniques, the quality of access to an object during the course of the investigation critically affects:

- the extent of the area that can be surveyed
- the progress of the investigation, and the consequent effects on time and cost.

The decision on access type and performance will be dictated by the requirements of the survey and the site conditions. These may include:

- The maximum height/depth/length to which access is required will generally determine the type of equipment necessary, together with the length of time the equipment has to be in place.
- The means of gaining entry to, and moving within, the site may limit the selection of access equipment.
- The terrain (topography and surface strength) within the site.

This checklist should identify most common dangers - gravel borders, flowerbeds, ornamental gardens or decorative lawns adjacent to external walls. Note that larger machinery can have high axle loads and should not be located over cellars etc. or close to basements, embankments etc. Ladders similarly can exert high point loads.

Access Methods

Access is needed in a wide variety of situations: working at height, working over or near to water, in confined spaces, below ground, on or near to public highways etc. These and other scenarios are discussed briefly in the next section on Health and Safety, however the most common situation encountered when inspecting or surveying buildings is working at height.

Various methods of reaching a point above ground or floor level on a building are available and the cost of each should be weighed against the risk of restricting the information gathered, in all cases it will be necessary to ensure the safety of operators or bystanders.

Full fixed scaffolding

Full fixed scaffolding properly erected with platforms every 2.5 metres usually provides the safest and most effective access to the majority of structures. It can be costly, however, and is therefore normally an option only when other works are planned. Temporary scaffold towers ('Zip-Up' type) provide a reasonable alternative for access to no more than three storeys.

Suspended Access Platforms

Suspended access platforms provide a simple, convenient and rapid means of accessing the face of a building, provided that the face is vertical with no projections: they can be readily erected and moved, but need a competent scaffold erector on site to do this, which adds to their cost.

Powered Access Platforms

Powered access platforms are available in two main types: scissor types which extend vertically upwards and hydraulic arm or 'cherry picker' type platforms, comprising a bucket or platform at the end of a telescopic, articulated hydraulic arm. Both types can be deployed rapidly. In general, survey coverage is slower than with fixed scaffold but the overall cost saving can be significant because of the cheaper access equipment rental charges. These platforms allow highly flexible access, ideal for surveying complex forms. They are heavy however (to maintain stability) so careful consideration must be given to positioning the vehicle. Examples of the use of powered access platforms for two different investigations are shown in Plates 1 and 11.

As a rule of thumb, an articulated hoist should always have at least 15 - 20% greater reach than that assumed to be needed for the survey. For access to small areas a scissor-type platform with a relatively large platform area may be sufficient, but for larger areas a platform mounted on the end of a telescopic hydraulic arm normally provides the most effective means of gaining access.

Ladders

Ladders are a cheap access system, offering hand access to a small area. However, the temptation to overreach is great and can easily lead to toppling, especially if the ladder cannot be tied securely, or where the ladder is moved frequently. They may be appropriate if only a small area is to be inspected, however.

Plate 11 Photograph of survey being carried out from hydraulic hoist

6.2.2 Health & Safety

Legislation

The Management of Health & Safety at Work Regulations 1992, together with the Construction (Health, Safety & Welfare) Regulations 1996, and subsequent amendments and updates, place a requirement on both employers and the self employed to make and maintain a sufficient and suitable risk assessment, such that they take at all times the measures necessary to comply with Health & Safety law.

It is taken throughout as an absolute that this will be done, and that the conservation professionals involved in the assessment of historic structures are already well acquainted with these measures, and their application to their tasks.

This document is an inappropriate medium to provide instruction on this, and general comments only are given: any professionals unacquainted with the provisions are advised to obtain further advice and information from local offices of the Health and Safety Executive (HSE).

General

The nature and severity of risks presented at a site vary widely. The conservation professional should be able to provide the investigator with information on all hazards prior to preparation of a proposal so that plans can be made to minimise the risk to the health and safety of the investigation team, other people in the vicinity of the site and the general public. Similarly the conservation professional should expect the investigator to provide a health and safety policy as a part of their technical proposals, demonstrating an awareness of the risks posed by the site, and by the proposed methods of working, and describing measures for mitigating them.

Risk Assessments

All sites should be subject to a general risk assessment. Where this reveals a need for specialist training, certification or experience then this must be allowed for in the programme and budget of the project. Potentially hazardous work environments include:

- building sites
- working in or near open excavations
- working at height
- tidal zones and sites adjacent to or over water
- closed/confined spaces
- sites beneath overhead workings
- sites adjacent to/on public highways
- sites in close proximity to high voltage cables.

Extensive literature is available offering advice on dealing with the specific and general risks of working in these and other environments. The following comments address the health and safety considerations of working with access equipment. They are not intended to replace official guidelines, with which conservation professionals should familiarise themselves. Additional health and safety considerations for working with particular non-destructive methods are included in the relevant chapters of this advice note.

Safe Working with Access Equipment

Reference should be made to the HSE sheets referred to in the text.

Where access equipment is used it must be:

- clean and fully operative
- well maintained and with relevant certification
- used in the manner intended by its designers.

Trained operatives should be responsible for installation and operation of all types of mechanical access equipment although some access equipment is operated by the hirer. In these instances, training must be provided by the hire company. The user of the equipment should also read any literature, warning signs and labels supplied with or affixed to the equipment.

When using scaffolding, it is of primary importance to ensure the stability of the construction. The stability of a scaffold will be affected by the way it is used, and it is important that the right sort of scaffold is erected for the intended work. There should be means of protecting bypassers from falling materials and equipment and means of restraint to prevent individuals working on the scaffold from falling off it. The scaffold must be inspected before use and inspections carried out by a competent person at intervals not exceeding seven days and the results recorded in a Register. Only competent scaffolders should erect, alter or dismantle scaffolds. Before erecting a scaffold on a public highway the appropriate highway authority must be contacted and permission obtained.

Details and guidelines on the safe use of scaffolds can be found in HSE Information Sheet *General Access Scaffolds and Ladders*, Construction Sheet No. 49 and HSE Information Sheet *Tower Scaffolds*, Construction Sheet No. 10 (revision 3).

Ladders are primarily a means of gaining access to a workplace; they can also be used as working platforms in their own right for work of short duration for which they have been assessed as suitable. However the need, common to many NDT methods, to carry equipment, accommodate trailing cables etc. means that ladders are unlikely to provide a safe working platform in many cases. If work is to be carried out from a ladder then it must be properly secured and the correct grade used.

6.2.3 Analysis and Reporting

Analysis

Interim or draft reports may be reasonably expected during the course of an investigation or even, exceptionally, on site. Discrete sections of data cannot usually be analysed in isolation, but frequently require the context of the whole data set, including any control data, for a confident interpretation. It is important in planning the investigation that a realistic time frame is agreed for the proper interpretation and analysis of any results - premature interpretation often relies primarily on experience from similar sites, rather than the specific test results obtained in the current investigation.

Presentation of Results

The nature of the information required at different stages and any preferred or required presentation formats should be discussed. Archive requirements should also be considered at the outset and standards for presentation and format decided. It is inappropriate to present results exclusively in technical terms or as simple numerical data. The information presented should be unambiguous and reveal a clear line of reasoning between the raw data and the conclusions drawn. Factual and interpretative conclusions should be clearly identified at all times - note that raw data from non-destructive tests is not usually presented within the final report.

Results are often presented through graphical means, either as graphs or sketches, photographs, sections, plans and elevations. The quality of the drawings provided can vary from a simple hand-drawn sketch to detailed scale drawings produced to a pre-agreed standard on a CAD system, depending on the specific requirements and budget of the client.

Measured Surveys

The accurate recording of the results of a non-destructive investigation will be assisted if measured survey information can be made available in advance as results can be overlaid directly onto the measured survey. If accurate survey drawings of the structure already exist in a CAD (computer aided design) format the provision of these drawings, on a computer disk (in a compatible format) will save time and improve the accuracy of the presentation of results from the investigation.

Plate 12 Aerial view of Kildrummy Castle

7 CASE STUDY: KILDRUMMY CASTLE

7.1 Purpose of the Investigation

This ruined thirteenth century fortress-residence was restored and partially reconstructed around 1900.

In 1991 a facing stone came away during raking out and repointing. The stone appeared sound and hard, but had been face-bedded, and had split on the bed approximately 100mm from the front face. Its rear tail had decayed and reverted to sand. The exposed wall core was completely saturated. It is likely that the impermeable cementitious mortar used in the 1900 work had trapped moisture in the walls, leading to saturation of the rubble-filled medieval cores, dissolution of the bonding matrix and loss of structural integrity.

At this stage (December 1991) the remedial action mooted included the provision of weep holes (to allow the water in the core to drain out) and a french drain. Grouting and other structural measures might follow if required. Investigation of the wall conditions by the drilling/taking of cores was suggested. The extent and seriousness of the problems required to be ascertained and the most appropriate forms of remedial action determined.

On consideration, core borings were thought too destructive, so an initial investigation using a non-destructive method was seen as appropriate. This work was also viewed as a pilot project to explore the use of non-destructive methods of investigating building problems. Electro-magnetic methods were being developed at that time for use on structures, and impulse radar in particular appeared to give promising results, providing useful information on a wide range of aspects (such as indicating different materials concealed within the structure and their condition, and the presence of voids or metallic objects).

The presence of the brief was to provide detailed and comprehensive information on the structure and condition of the walls, including the nature and dimensions of the construction materials, the locations of cavities or cracks within the walls, the location and condition of any metallic ties, and information on the moisture contents of the materials and the movement of water through the structure.

7.2 Details of the investigation

The investigative method chosen was impulse radar (an electro-magnetic method; see section 3.1), because it could give information on a number of factors, quickly and without any physical impact on the castle fabric.

The budget (in 1994/5) resulted from agreement on what constituted a reasonable scope of work, giving enough information to be useful both to inform conservation policy for the monument and to provide a case study for this TAN. Travel and subsistence, survey work and writing up/reporting elements were allowed for in the estimates.

The selection of an investigator: the use of impulse radar for building investigations is a highly specialised field, in which there are very few experienced contractors. Approaches were initially made to three organisations in order to assess their suitability, but ultimately the most experienced company in the field was chosen despite its higher fee, because it was the only one judged to satisfy the criteria of having sufficient experience and an extensive database for comparative purposes.

Timing was not critical, except that co-ordination with the regional staff was required as they were to provide access to the areas included in the survey. A pre-survey meeting was held on site to agree the sample areas and method of access to the walls. As impulse radar requires close contact with the surfaces being monitored, temporary scaffolding towers (complying with CDM regulations) were decided on.

The survey (1 and 2 March 1995): two days were spent surveying four locations (the maximum number possible in this time). The size of each survey area resulted from the wall configuration and the scaffold provided. Data was collected from a grid at 500mm centres vertically and 1m horizontally.

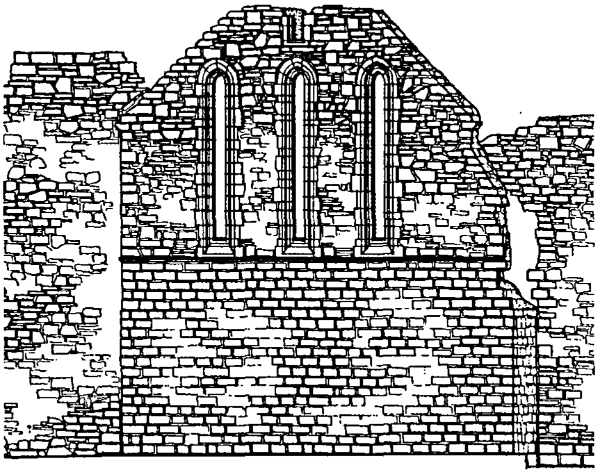


Figure 13 Elevation of chapel gable (north-east wall), Kildrummy Castle

7.3 Conclusions of the Investigation

- Specific information was obtained on the construction of the walls; thickness of the facing stones (generally 200 to 350mm), mortared nature of the rubble infill, etc.
- A generally high moisture content was found in the walls, especially deep in the walls (the further from the surface, the higher the moisture level).
- Poor contact and voids in walls were located (giving routes for water penetration), which were extensive, particularly in the north-west curtain wall. Vertical joints were reasonably tight. A large void showed at the base of the Warden's tower, which may prove to be either a cavity, or an actual chamber.
- New lime pointing (north-west curtain wall, 1990s) showed confusing results, the reasons not being clear.
- No evidence of metallic fixings was found.

Specific Recommendations:

- that the void at the base of the Warden's tower should be investigated further; and
- that a re-examination of the walls in the summer, when moisture levels were reduced, might give better penetration by impulse radar.

7.4 Subsequent conservation at Kildrummy Castle

Since the initial impulse radar survey was carried out, there has been no further impulse radar investigation. The possible chamber discovered by the investigation in the base of the Warden's tower has been left undisturbed.

The cementitious pointing (which remains everywhere but on the north-west curtain wall) has been drilled into by Historic Scotland masons, the object being to see if it could be removed in order to replace it with a lime mortar, and any voids filled. However the hard pointing proved to be at least 150mm deep, and it was felt that any attempt to remove it would be likely to cause more damage to the stonework than leaving it in place. The surface of the pointing was scabbled back so that the mortar is now recessed within the joints and stone decay is minimised.

The Historic Scotland engineer was consulted on whether remedial works were needed to the walls in light of the decayed core. His advice was that in the short term, since there was no surface evidence of strain (cracks and movement in the stonework face) it could be safely left, and that the two skins of stonework were probably thick enough and strong enough to contain the core in a stable position despite its condition.

However, in the longer term, based on the evidence of widespread dampness and decay in the wall cores, he suggested that further monitoring should be initiated, and follow-up repair works considered. The monitoring would include removal of facing stones in two or three selected areas (where the worst voids had been found) to inspect the core, and also a programme of monitoring the moisture content using probes, over a period of two to three years. In addition there was a concern that there could be movement in the Warden's tower and this should be monitored and recorded. Weep holes should be provided along the base of the north-west wall where it acts as a retaining wall. Following the monitoring process, consideration could be given as to whether works of grouting or stitching would be appropriate, and expert advice sought on the methods to be adopted.

7.5 Considerations on the use of impulse radar

In the case of Kildrummy Castle, this investigation turned out to be relatively expensive for the amount of information obtained. It had already been established that the core was damp, and that it had broken down and shifted in places, and that the backs of some stones were decayed. What was needed was further information on whether this was an isolated case or spread throughout the castle, and whether the problem was worse or better elsewhere. Because the cost prohibited a full survey, it was not possible to get a complete picture of the wall conditions, but a range of areas was sampled and the defects proved to occur in each of these, indicating that they probably occurred throughout.

The excessive humidity of the core and its mortared rubble character were confirmed by the investigation and it was clear that there were many voids behind the surface stonework. But the high moisture content of the core blocked the return of more information. Examination of moisture movement would have required additional surveys for which there was no budget.

However, the investigation carried out at Kildrummy Castle caused no damage to the fabric of the monument and retrieved some very useful information on the condition of its internal structure. The general depth of the surface skin of stonework was measured, and the nature of the rubble in the core (where it registered) and the lack of metal cramps were noted. These factors informed the engineer's assessment of the stability of the walls and his recommendations on further action.

Plate 13 Repair works at Kildrummy Castle in the early twentieth century.

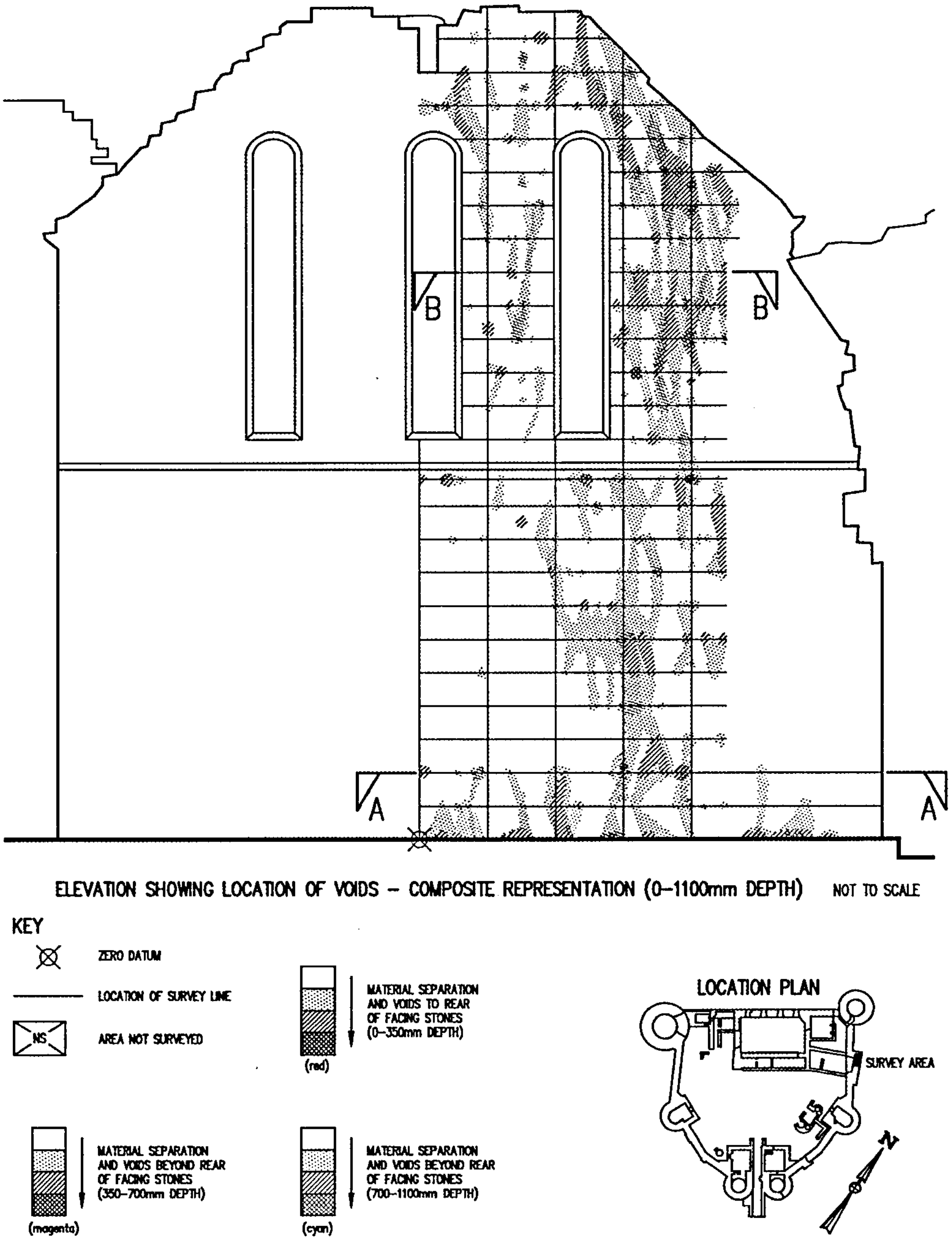
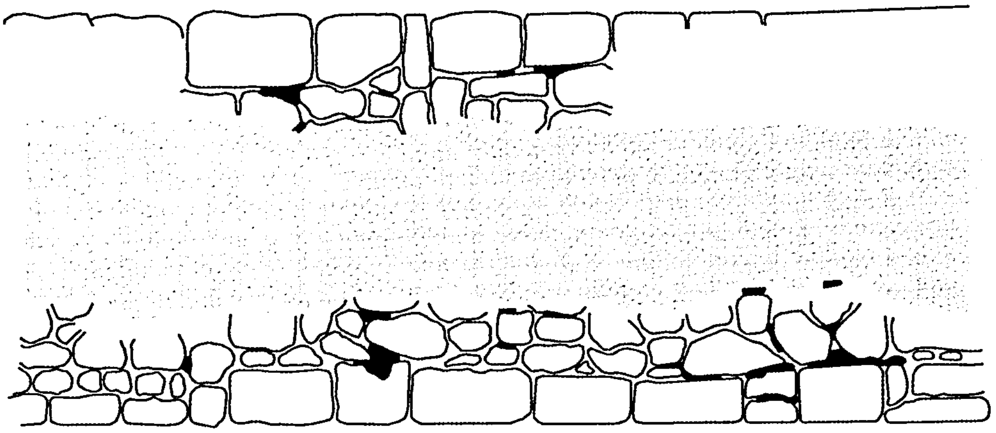
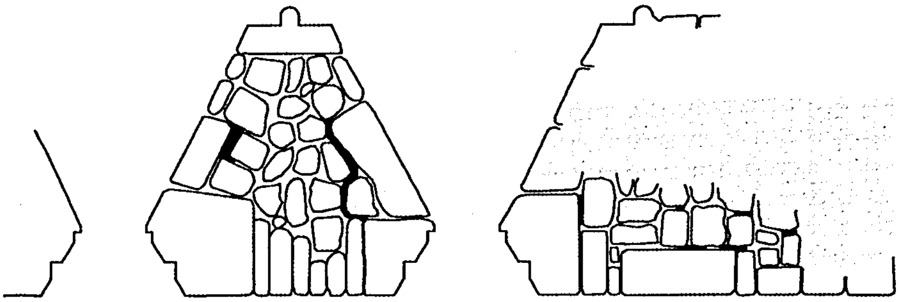


Figure 14 (a)

Figures 14 (a) and 14 (b)
Specimen results from a non-destructive investigation of Kildrummy Castle walls (structure and condition)



PLAN ON A–A NOT TO SCALE



PLAN ON B–B NOT TO SCALE

KEY

░ AREA FROM WHICH NO DATA HAS BEEN RECOVERED DUE TO SIGNAL ATTENUATION (VERY WET OR FEATURELESS MATERIALS)

■ POOR CONTACT BETWEEN MATERIALS RESULTING IN MATERIAL SEPARATION AND VOIDS

Figure 14 (b)

8 BIBLIOGRAPHY

The following texts offer a variety of general and specific information for the interested reader.

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Free Electro-Magnetic Radiation

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Various papers and authors, 1993, *Concrete Civil Structures, Proceedings of Fifth International Conference on Structural Faults and Repair*

Health & Safety

Various information sheets are available from the Health & Safety Executive which cover various aspects of safe working environments and access in some depth, including:

General Access Scaffolds and Ladders, HSE Construction Sheet No. 49 - safe use of scaffolds and ladders

Tower Scaffolds Construction, HSE Information Sheet No. 10 (revision 3) - safe use of tower scaffolds

Construction (Health, Safety and Welfare) Regulations 1996

Health and Safety at Work etc. Act 1974 - general references to legislation

Management of Health and Safety at Work Regulations, 1992

Provision and Use of Work Equipment Regulations 1992

Manual Handling Operations Regulations, 1992

Ionising Radiations Regulations (this document is currently being updated.

Additional advice and information can be obtained from local offices of the Health and Safety Executive which provides up-to-date information sheets and guidance for safe working practices.

9 GLOSSARY

The purpose of this glossary is to provide a brief explanation of some of the technical terms commonly encountered when describing and using Non Destructive Investigative techniques: the list is not exhaustive, but covers most of the terms contained within the Technical Advice Note. The object is to be useful rather than to provide definitive text book explanations.

Antenna/Aerial/Transducer
Converts the driving power into a radiated signal, and converts signals returned from the material investigated into electrical information.

Antenna efficiency
The extent to which an aerial converts the driving power into radiated energy.

Attenuation
A general term for the reduction in magnitude, amplitude or intensity of a physical quantity, arising from absorption, scattering or geometrical dispersion.

Clutter
Unwanted signals, for example on a radar system, that are caused by extraneous signals or echoes.

Coupling factor
A measure of the extent of energy transfer from one system or material into another.

Decibel/dB
A dimensionless unit used to express the ratio of two powers. Often associated with volume or signal amplitude.

Dielectric
Any material that can sustain an electric field and is a good insulator - dielectrics contain no free charges but the material may be polarised at molecular or microscopic levels.

Directional aerial
An aerial that is a more effective transmitter or receiver of energy in certain directions.

Dynamic Range
The range, normally expressed in decibels (dB), over which useful information can be recovered from an instrumentation system from the smallest signal resolvable above the system noise to the largest signal the system can handle.

Eddy Current
The current induced in a mass of conducting material by a varying magnetic field.

Effective Radiated Power
The total radiated power of an aerial.

Emissivity
The amount of internal energy that is emitted by an object.

FEMR
Free Electromagnetic Radiation (see Chapter 3).

Filter
Any system that preferentially passes signals within certain frequency ranges whilst suppressing those in others. Soil acts as a Low-Pass Filter, suppressing higher frequency signals.

GPR
Ground Probing/Penetrating Radar.

GPR/Impulse Radar
Generic terms identifying types of low power systems used for echo sounding. GPR is commonly used as the systems were first developed for penetrating the ground, whereas Impulse Radar describes the way in which the sounding system operates.

Systems which transmit a low energy electromagnetic pulse at radio frequencies into solids and collect the reflected signals for subsequent processing and manipulation (See Chapter 3).

Impulse
A unidirectional disturbance that rises rapidly to a maximum and dies away smoothly (without significant oscillations) to zero.

Jitter
Timing noise in the composition of the signal in the sampler.

NDI
Non-Destructive Investigation.

Periodicity
The time taken for an oscillating object to complete one complete cycle.

Plane Polarisation
Oscillations which are in a single plane are described as plane polarised.

Pulse
A single transient disturbance, or one of a regular series of such disturbances.

Pulse Repetition Frequency
The frequency at which pulses are sent to the aerial for transmission.

Radiation Loss
The natural drop in received power as a receiving antenna of fixed size is moved away from the transmitter.

Radiation Pattern
A diagram showing the spatial distribution of energy from a transmitting aerial - often showing a complicated three dimensional 'lobed' structure.

Reflection Coefficient
When an electro-magnetic wave reaches any boundary between two transmissive media, it undergoes partial reflection - thus the reflection coefficient describes the ratio of the reflected energy to the incident energy.

Reflectivity
The amount of external energy that is reflected rather than absorbed by an object.

Relative Permittivity
A measure of the ease with which materials allow charges to polarise under the influence of an applied electric field: the ratio of the capacitance of a particular dielectric material of defined dimensions, to that of a vacuum of the same dimensions. Also referred to as *Dielectric Constant.*

Sampler
That part of the receiver system which converts the radio frequency signals recovered by the antennae into a low frequency electronically representation that can be processed. This is normally an analogue stage.

Scabbled
Roughly faced with a pick, chisel or hammer.

Signal to noise ratio
A measure of the quality of the received data: the ratio of the signal power to noise power *at the point of observation*, measured in dB. A signal processing and recording system may have a good signal to noise ratio, but if the overall ratio falls too low (e.g. the antenna is 'noisy'), any useful information is lost in background signals.

Spectrum
The full range of the electro-magnetic spectrum covering all radiation including microwaves and visible light. With a lower case 's', it refers to the range of frequencies in a given signal or time series.

SW
Short Wavelength. The band of wavelengths in the electromagnetic spectrum from 3 to 5.50m.

Target
Any object that is being investigated.

Target Characteristics
Simplistically, these are the size and dielectric properties of the target. In practice, the dielectric contrast and nature of the boundary between the target and its surroundings will also have a significant effect.

Transmission Loss
The loss of signal power along the wave path due to dissipation, partial reflection at boundaries and scatter from objects contained within a medium.

Transmissivity
The rate at which energy can be transmitted through an object: in thermography, the ability of a material to sustain a heat flow.

Travel Time
The time taken for a radiated pulse to travel between two points: two way travel is the time taken for a pulse to travel from an antenna to a reflective surface and back again.

UPV
Ultrasonic Pulse Velocity (see Chapter 5)

Velocity
The speed at which a wave group travels through a dielectric medium, which is constant provided the electrical properties of that medium do not change.

10 USEFUL ADDRESSES

The following organisations, referred to in the main body of the advice note, may be contacted for further information. Addresses are correct at time of publication.

British Institute of Non Destructive Testing
1 Spencer Parade
Northampton
NN1 5AA
Tel No: 01604 630124
Fax No: 01604 231489
Email: info@bindt.org

UKAS (United Kingdom Accreditation Service)
21 - 47 High Street
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TW13 4UN
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Health & Safety Executive
Belford House
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Tel: 0131 247 2000
Fax: 0131 247 2121

NAMAS (See details for UKAS)

Euro GPR (Formerly Impulse Radar Users Association)
PO Box 1381
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Tel: 01788 536389
Fax: 01788 550152
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