REVIEW OF TOOLS AND TECHNIQUES TO MONITOR REPOSITORY EXCAVATIONS

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ABSTRACT

This report provides a summary of tools and techniques for monitoring the stability of underground openings in rock that may be applicable to underground openings at a potential Yucca Mountain repository. Monitoring methods typically used in and around underground openings and their suitability for monitoring in a repository environment of high temperature and radiation are reviewed. Means of interpreting measurements to identify and characterize damage around the underground openings are discussed, along with implications for developing a contingency plan for maintenance of the underground openings. Geotechnical monitoring aspects included in a U.S. Department of Energy performance confirmation plan document are examined in the context of the findings of this study. Aspects of the plan related to monitoring the performance of underground openings are in general, consistent with some of the monitoring tools and techniques identified in this report.

CONTENTS

Section Page

ABSTRACT . . . iii
FIGURES . . . vii
TABLES . . . ix
ACKNOWLEDGMENTS . . . xi
EXECUTIVE SUMMARY . . . xvii

1 INTRODUCTION . . . 1-1

2 DEFINITIONS AND BASIC CONCEPTS . . . 2-1

2.1 Monitoring . . . 2-1
2.2 Disturbance, Damage, and Progressive Failure . . . 2-1

3 MONITORING OF UNDERGROUND OPENINGS IN ROCK . . . 3-1

3.1 Monitoring Objectives . . . 3-1
3.2 Geotechnical Monitoring . . . 3-1
3.2.1 Borehole-Based Techniques . . . 3-2
3.2.2 Tunnel-Based Techniques . . . 3-4
3.3 Geophysical Monitoring . . . 3-7
3.3.1 Borehole-Based Techniques . . . 3-8
3.3.2 Tunnel-Based Techniques . . . 3-10
3.4 Other Monitoring . . . 3-11

4 DEEP GEOLOGIC REPOSITORY MONITORING . . . 4-1

4.1 Repository Conditions and Monitoring Time Frame . . . 4-1
4.2 Key Objectives of Monitoring and Relevant Parameters . . . 4-2
4.3 International Experience . . . 4-3
4.3.1 Studies of Excavation Damage . . . 4-3
4.3.2 Tools and Techniques Used at Experimental Facilities . . . 4-5
4.3.3 Temperature and Radiation Considerations . . . 4-9
4.4 Recommended Tools and Techniques for Repository Monitoring . . . 4-10

5 APPLICABILITY OF MONITORING TOOLS AND TECHNIQUES AT A POTENTIAL YUCCA MOUNTAIN REPOSITORY . . . 5-1

5.1 Description of the Potential Repository . . . 5-1
5.1.1 Site Description . . . 5-1
5.1.2 Repository Excavations . . . 5-1
5.1.3 Ground Support . . . 5-2

CONTENTS (continued)

Section Page

5.2 Underground Monitoring at Yucca Mountain 5-3
5.2.1 General 5-3
5.2.2 DOE Performance Confirmation Plan 5-4
5.2.3 Monitoring Aspects of the DOE Performance Confirmation Plan 5-5
5.2.3.1 Drift Inspection 5-18
5.2.3.2 Thermally Accelerated Drift Near-Field Monitoring 5-18
5.2.3.3 In-Drift Monitoring in the Thermally Accelerated Drift 5-19
5.2.3.4 Subsurface Mapping 5-19
5.2.3.5 Construction Effects Monitoring 5-20
5.2.3.6 Thermally Accelerated Drift Thermal-Mechanical Monitoring 5-20

6 MONITORING UNDERGROUND OPENINGS AT A POTENTIAL YUCCA MOUNTAIN REPOSITORY 6-1

6.1 Monitoring System Description 6-1
6.2 Contingency Planning and Maintenance to Reduce Need for Extensive Repair 6-5
6.2.1 Alarm Conditions 6-5
6.2.2 Maintenance 6-5
6.2.3 Extensive Repair 6-6

7 CONCLUSIONS AND RECOMMENDATIONS 7-1

8 REFERENCES 8-1

APPENDIX A Summary of Monitoring Tools and Techniques for Underground Openings and Potential Repository Applications

FIGURES

Figure Page

2-1 Definition of the Excavation Disturbed Zone, Excavation Damaged Zone, and Failed Zone in Highly Stressed, Sparsely Fractured Rock 2-2
2-2 Illustration of Two Mechanisms Contributing to the Progressive Failure Process . . . 2-3

3-1 (a) Inclinometer Probe and (b) In-Place Inclinometer 3-2
3-2 (a) Magnetic Probe Extensometer and (b) Multiple Point Borehole Extensometer . . 3-3
3-3 Stress Monitoring Tools 3-4
3-4 Vibrating Wire Instruments 3-5
3-5 Laser Scanner 3-6
3-6 SMART Cable Bolt with Integral Deformation Monitoring 3-8
3-7 Micro-Velocity Probe Used for Interval Velocity Surveys 3-9
3-8 Microseismic Monitoring of the Mine-by Test Tunnel 3-10

4-1 Retrievable Extensometers Used for the Mine-By Experiment at Atomic Energy of Canada Limited Underground Research Laboratory 4-6

5-1 Schematic Drawing of Ground Support and Engineered Barriers in an Emplacement Drift 5-3

TABLES

Table Page

4-1 International Underground Laboratories 4-4

5-1 Summary of Monitoring and Testing Activities in the U.S. Department of Energy Performance Confirmation Plan (Bechtel SAIC Company, LLC, 2004) 5-5

6-1 Summary of Tools and Techniques Likely Applicable for Monitoring Performance of Underground Openings at a Potential Yucca Mountain Repository 6-3

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: Sources of data are referenced in each chapter. CNWRA-generated data contained in this report meet quality assurance requirements described in the CNWRA Quality Assurance Manual. Data from other sources, however, are freely used. The respective sources of non-CNWRA data should be consulted for determining levels of quality assurance.

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A draft version of this report was prepared by RSRead Consulting, Inc. (RSRCI) under a subcontract (No. 499883N) with CNWRA in May 2004. The content of the current report is not substantially different from the previous report, except for a discussion of information that has become available since then regarding the performance confirmation plan for a potential Yucca Mountain repository. Any new developments in monitoring tools and techniques since May 2004, therefore, may not be found in the state-of-the-art review provided in this report.

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EXECUTIVE SUMMARY

This report was developed to support U.S. Nuclear Regulatory Commission staff preparation to review a performance confirmation plan provided as part of a license application for a potential Yucca Mountain nuclear waste repository. The report provides a summary of tools and techniques for monitoring the stability of underground openings in rock that may be applicable to underground openings at a Yucca Mountain repository. Monitoring methods typically used in and around underground openings and their suitability for monitoring in a repository environment of high temperature and radiation are reviewed. The report examines geotechnical, geophysical, and other monitoring tools and techniques, considering both borehole- and tunnel-based applications. Specific examples of available instruments are provided. Approaches to interpreting measurements to identify and characterize damage around underground openings are discussed.

The unique aspects of monitoring in an underground repository are identified, and examples of monitoring at international nuclear waste facilities are summarized. Recent developments in other nations provide insight into proposed monitoring methods for repositories. Based on the tools and techniques identified for underground monitoring and considering the specific requirements for a nuclear repository, a general suit of monitoring tools and techniques is recommended.

Current information indicates the Yucca Mountain repository would be located above the water table in volcanic tuff. Other international repository concepts have targeted primarily crystalline rock, clay, or salt. Most of these are below the water table. This and other aspects of the potential Yucca Mountain repository were examined to provide a context for evaluating the applicability of various monitoring tools and techniques.

A U.S. Department of Energy (DOE) document describing its performance confirmation plan for a Yucca Mountain repository was examined. Elements of the DOE plan related to geotechnical monitoring of underground openings are summarized in this report. The geotechnical monitoring aspects of the DOE plan currently are described in general terms without specific information about tools and techniques. Overall, the geotechnical monitoring approach described in the plan is consistent with many of the monitoring tools and techniques described in this report.

Tools and techniques likely applicable to a Yucca Mountain repository are discussed. A discussion also is provided of using monitoring, site-specific contingency planning, and maintenance to reduce the need for more extensive repair. The report provides several conclusions and recommendations related to geotechnical monitoring of a nuclear waste repository at Yucca Mountain. The main conclusions are as follows:

- There are many tools and techniques available for geotechnical monitoring of underground openings in rock. These technologies, along with complementary geophysical and other monitoring tools and techniques, are generally applied in civil and mining applications under moderate operating conditions to monitor changes in the rock mass around underground openings or in the ground support systems and structures within underground openings. Combined with characterization activities to quantify initial

conditions and rock properties, such tools and techniques can be used in a predictive sense to identify abnormal behavior associated with damage development prior to the failure of an opening.

- Many of the monitoring technologies reviewed have been incorporated into studies at nuclear waste disposal research sites to assess the development of damage and progressive failure of the rock mass around underground openings. Specialized instruments also were developed in such studies. Many of the studies, with a few exceptions, involved applications of instruments under ambient temperatures and low radiation conditions. Some of the studies, however, provided useful information on the longevity of instruments under more severe hydrogeological and temperature conditions. In general, instrument longevity is a major issue for long-term preclosure monitoring.

- There has been some testing of instruments under elevated temperature and radiation conditions. Radiation tends to damage electronic components and has a detrimental effect on some fiber optics. Vibrating wire instruments that can function under elevated temperature, high radiation conditions, and saline groundwater conditions have been developed for special applications. These types of instruments are good candidates for application in a nuclear waste repository, but further testing and development may be needed to ensure satisfactory long-term performance under severe operating conditions. New developments in fiber optics-based monitoring systems appear promising.

- The Yucca Mountain waste-disposal design concept may accommodate instrumentation installed both within the emplacement drifts and in boreholes. Boreholes drilled from observation drifts (and possibly other underground openings) can provide good coverage of the near-field rock mass. A combination of borehole-based, emplacement drift-based, and surface-based monitoring systems could provide monitoring coverage sufficient to identify damage development in the underground openings.

- Many of the monitoring activities described in the DOE performance confirmation plan document (Bechtel SAIC Company, LLC, 2004) are related to hydrogeological and geochemical conditions and properties within or near the natural and engineered barriers. Monitoring activities associated with drift stability and related changes in near-field rock mass conditions are described in general terms. The descriptions provided indicate the activities could be implemented using some of the tools and techniques identified in this report.

- Maintenance could be linked to monitoring through specific alarm and warning criteria. Such criteria usually are site-specific and need to be established using baseline monitoring data and improved as knowledge of the project grows with the interpretation of monitoring data. Detailed records of ongoing maintenance could be an important component of the knowledge base needed to link observed occurrences with maintenance needs. An important role of monitoring repository openings could be to reduce the need for extensive repair by using continuous data on rock mass conditions to identify and rectify changing ground conditions before such changes can progress to more extensive rock failure.

Reference

Bechtel SAIC Company, LLC. “Performance Confirmation Plan.” TDR–PCS–SE–000001. Rev. 05 ICN 00. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004.

1 INTRODUCTION

This report was prepared to support U.S. Nuclear Regulatory Commission staff performance confirmation technical activities, which will include review of the DOE performance confirmation documents and evaluation of the results of any U.S. Department of Energy (DOE) performance confirmation testing or analysis. A license application for a Yucca Mountain repository likely will include a design for stable underground openings to support repository operations. The repository operations may include: (i) waste emplacement; (ii) ventilation; (iii) monitoring, maintenance, and performance confirmation; (iv) waste retrieval, if necessary; and (v) closure operations such as the emplacement of drip shields or backfill.

A design for stable underground openings likely will incorporate a monitoring and maintenance program. Assessment of such a design therefore would include an evaluation of the technical adequacy of the monitoring and maintenance plan included in the design. The anticipated conditions at a nuclear waste repository that would entail special considerations in terms of monitoring and maintenance may include high temperatures and radiation levels within the emplacement drifts. A DOE performance confirmation program likely will include monitoring the stability of underground openings (e.g., Bechtel SAIC Company, LLC., 2004).

This report provides a review of tools and techniques for monitoring the stability of underground openings in rock that may be applicable to underground excavations at a Yucca Mountain repository. Monitoring methods typically used in and around underground openings and their suitability for monitoring in a repository environment of high temperature and radiation are reviewed. Approaches to interpreting measurements to identify and characterize damage around the underground openings are discussed, along with implications for developing a contingency plan for maintenance of the underground openings.

Basic concepts used in the report are defined in Chapter 2, followed in Chapter 3 by a description of tools and techniques used to monitor underground openings. Chapter 4 examines experience gained from international programs on deep geologic repository monitoring and highlights tools and techniques used at experimental facilities in several countries. Chapter 5 examines aspects of a potential nuclear waste repository at Yucca Mountain that may affect the applicability of specific monitoring tools and techniques at the repository. A DOE performance confirmation plan for the potential repository also is discussed in Chapter 5. Recommendations are provided in Chapter 6 for tools and techniques likely to be applicable for geotechnical monitoring of underground openings at the potential repository.

2 DEFINITIONS AND BASIC CONCEPTS

2.1 Monitoring

Monitoring implies continuous or periodic observations and measurements of engineering, environmental, or radiological parameters to help evaluate the behavior of components of the repository system or the impacts of the repository and its operation on the environment (International Atomic Energy Agency, 2001). Repeatable characterization activities to determine specific changes in properties or characteristics of the natural environment by means of direct or indirect measurement or testing are considered monitoring techniques for the purposes of this report. The report focuses on those monitoring techniques related specifically to the development of damage or instability around underground openings.

2.2 Disturbance, Damage, and Progressive Failure

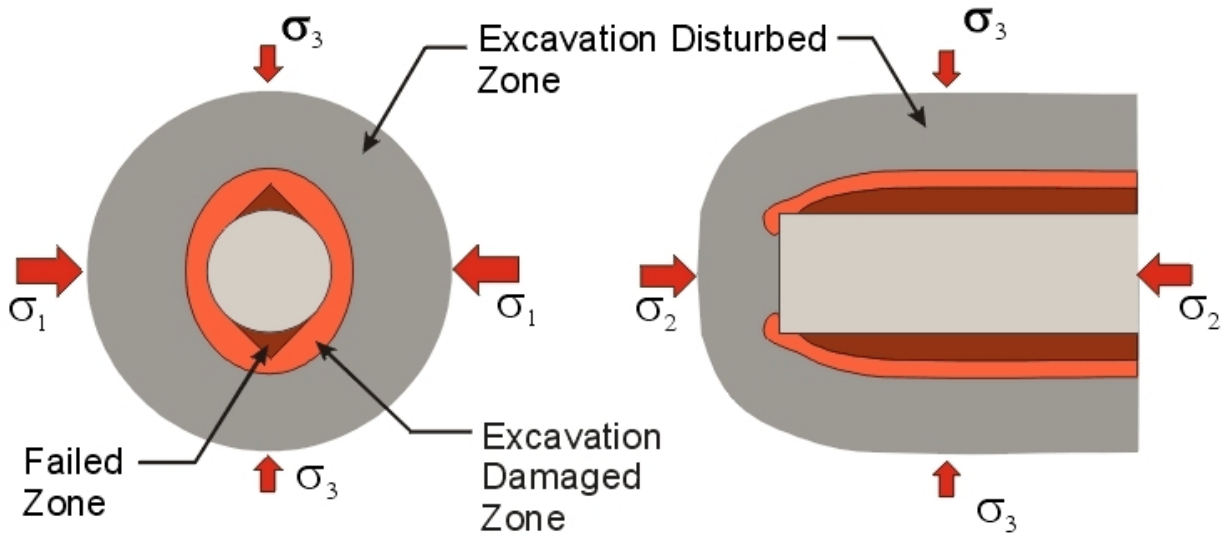


Figure 2-1. Definition of the Excavation Disturbed Zone, Excavation Damaged Zone, and Failed Zone in Highly Stressed, Sparsely Fractured Rock (Read, 1996). Reprinted by Permission of Canadian Nuclear Society.

Excavation in rock causes disturbance in the surrounding rock mass because of preexisting solid and fluid forces in the rock that are changed by the process of excavation (Fairhurst and Damjanac, 1996). In rock mechanics literature, the terms excavation disturbance and excavation damage are often used interchangeably to describe the effects of excavation on the near-field region around an underground opening. In sparsely fractured rock masses, the disturbed zone (Figure 2-1) is considered the region around the opening that experiences significant static or dynamic stress change owing to excavation, resulting in reversible changes in rock mass properties. A smaller damaged zone, characterized by irreversible changes in material properties caused by induced fracturing, may develop within this disturbed zone. There may also exist a failed zone where rock near the opening is fractured to the point of detachment. These zones may develop progressively due to changing boundary conditions or time-dependent behavior of the rock mass (Read and Martin, 1996; Read, 1996).

In fractured rock masses, stress changes associated with excavation may induce deformation on preexisting fractures with or without the development of new fractures near the opening. In this case, the strength characteristics of the fractures dominate the rock mass behavior. The sparsely damaged and disturbed zones may be indistinguishable from one another and may extend a considerable distance from the excavation.

In both sparsely fractured and fractured rock masses, damage may also develop as a result of other types of loading (e.g., thermal or hydraulic loading) and displacements on existing fractures. Degradation of rock mass strength due to chemical alteration, desiccation, saturation, or other processes may also contribute to the development of damage around an underground excavation.

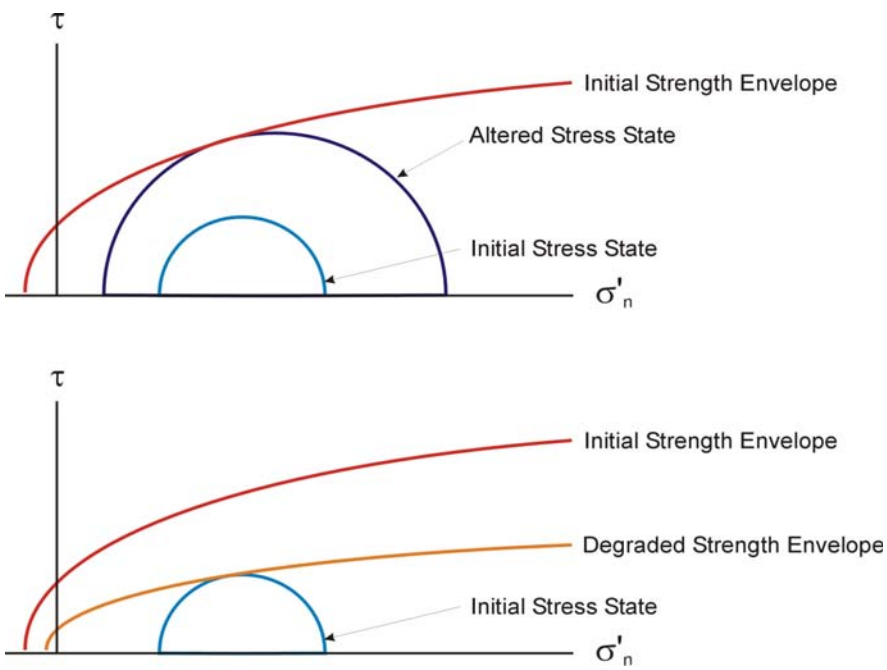


Figure 2-2. Illustration of Two Mechanisms Contributing to the Progressive Failure Process: Stress Alteration Around an Underground Opening (Top), and Strength Degradation Due to Changes in Rock Mass Characteristics (Bottom). The Vertical Axis in These Plots Is Shear Stress, and the Horizontal Axis Is Effective Normal Stress.

In each of these cases, the ongoing development of damage may lead to failure of the rock mass that progresses into the rock mass away from the periphery of an underground opening. This process is termed “progressive failure” (Read and Martin, 1996). The main processes contributing to progressive failure are alteration of the *in situ* stress state of the rock mass and strength degradation of the rock mass. These phenomena are illustrated schematically in Figure 2-2. The relative contribution of each of these phenomena depends on the *in situ* conditions and the characteristics of the rock mass. Once initiated, progressive failure may be

difficult to arrest because the active failure zone may reach a state of meta-stable equilibrium and may consequently be very sensitive to minor changes in boundary conditions (Read, 1996).

3 MONITORING OF UNDERGROUND OPENINGS IN ROCK

A literature review was conducted to identify standard geotechnical techniques for monitoring the stability of underground openings as well as state-of-the-art geotechnical instruments and technologies that are either available or under development for use in underground environments. In addition, current technologies associated with geophysical and other monitoring of underground openings were considered. This review was supplemented with information obtained through direct contact with instrument suppliers. The findings of the literature review are summarized in Table A–1 (Appendix A) and discussed this chapter. It should be noted that the products and suppliers mentioned in the review are meant as examples of available technologies, not endorsement of the specific products or suppliers identified.

3.1 Monitoring Objectives

Monitoring in underground openings related to mining or civil projects in rock may be undertaken for several reasons: (i) to enhance occupational safety of personnel and equipment during construction, (ii) to confirm performance of the underground opening within design limits during its operational lifetime, and (iii) to identify anomalous behavior that may be a precursor to instability of the underground opening. Although similar objectives may exist across different disciplines, the importance of monitoring may vary substantially depending on the risk associated with instability of underground openings in different situations. Given the environmental conditions of high temperature and radiation in a nuclear waste repository, the potential consequences of a breach in the multi-barrier system designed to contain radionuclides, and the long time periods over which monitoring is required, monitoring of repository performance is considered an essential component of nuclear waste management worldwide.

3.2 Geotechnical Monitoring

Geotechnical monitoring in this report relates primarily to the mechanical and thermal-mechanical response of the rock mass. The initial conditions of importance are the *in situ* stress state, piezometric elevation, and temperature of the rock mass. The rock mass properties, geological structure, and fracture characteristics determine the rock mass response to changes in these initial conditions. The key parameters to be monitored using geotechnical tools and techniques are changes in stress, pore pressure, and temperature; and displacement (or strain) resulting from these changes. Physical changes in rock mass and fracture characteristics are also important, as these affect both the deformation behavior and strength, as well as the hydrologic properties and conditions, of the near-field rock mass.

In relatively brittle rock, damage development in the rock mass around an underground opening may include shear, extensile (opening) or contractile (closing) modes of deformation on existing fractures, and the development of new fractures. Depending on the nature of the rock mass and the *in situ* stresses around the underground opening, displacements in excess of those predicted by elastic theory may occur as a result of dilation and increased crack volume at the micro- or macro-scale. In blocky rock conditions, complex displacement patterns may develop around an underground opening, with some fractures opening, and others closing. Blocks bounded by opening-mode fractures at the periphery of the underground opening may loosen and fall from the crown or sidewall of the opening under gravitational loading. Such unstable

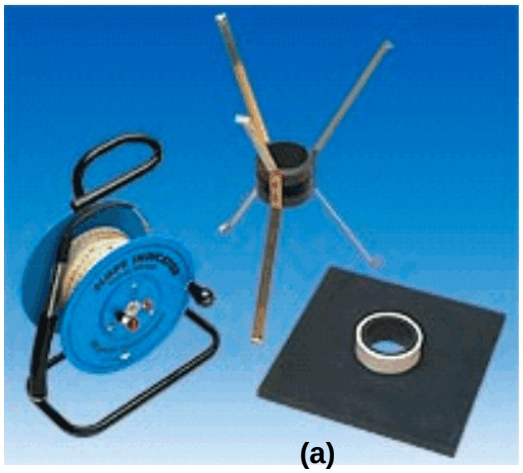
blocks are typically identified in key block or similar analyses.

Damage development may also be manifested as a decrease in deformation modulus of the rock mass or a drop in compressive stresses near the opening. In addition, the zone of damage may be desaturated due to its increased hydraulic conductivity relative to the surrounding rock mass. These characteristics lend themselves to specific characterization and monitoring methods to identify changes in properties and conditions around underground openings.

3.2.1 Borehole-Based Techniques

As shown in Table A–1, there are a number of borehole-based techniques to assess the deformation of the rock mass around an underground opening and the ground surface deformation associated with underground excavation or other operations. Underground excavation is expected to cause radial displacement of the rock mass around an opening and subsidence of the ground surface. Heating of the rock mass will tend to exacerbate the radial displacement around the opening and cause heave or uplift of the ground surface. Tiltmeters, inclinometers, sliding micrometers, and extensometers are used to measure borehole deformation that occurs in response to underground excavation or to changes in thermal or hydraulic boundary conditions of the underground opening. In these cases, the deformation pattern of the rock mass is determined by point measurements of tilt (i.e., angular deviation from vertical) or axial strain along the borehole, depending on the instrument used. Time domain reflectometry cables have also been used to identify the depth of shearing in a borehole.

Inclinometer probes (Figure 3-1a) are used in boreholes drilled within 30 degrees of vertical, although horizontal inclinometer probes also exist (Slope Indicator, 2006). In-place inclinometers (Figure 3-1b) provide a means of automated continuous monitoring at a specific horizon. Probe-type or rod extensometers (Figure 3-2) include several different anchor types and associated components. These instruments can be installed in boreholes drilled at various angles from within an underground opening to provide profiles of radial displacement with time.



(a)

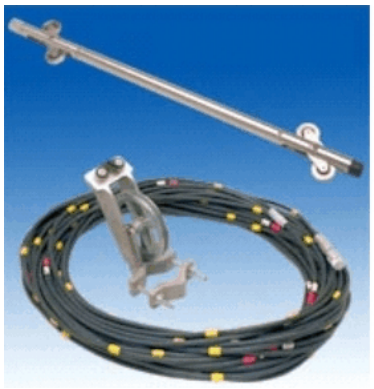
(b)

(a)

Figure 3-2. (a) Magnetic Probe Extensometer and (b) Multiple Point Borehole Extensometer (Geo Slope Indicator, 2006) (Courtesy of Durham Geo Slope Indicator; Reprinted With Permission)

Alternatively, boreholes can be drilled from ground surface or from adjacent excavations to install instruments close to an underground opening for monitoring purposes. Common technologies associated with these instruments to facilitate automated continuous monitoring include electrolytic tilt sensors, potentiometers, linear variable differential transformers, and vibrating wire sensors. Commercial instruments using fiber-optics technology are also being introduced (RocTest Telmac, 2006). Of these technologies, vibrating wire sensors have been preferred for long-term monitoring because of their stable design and ability to operate in temperatures up to 80 °C [176 °F]. Specially-manufactured titanium and high-temperature vibrating wire instruments are also available for more sever underground environments (Geokon, Inc., 2006). Fiber-optic sensors offer reduced reliance on electronics and stable performance (Inaudi, et al., 1998).

A number of stress monitoring tools are borehole-based (Figure 3-3). These include the



borehole deformation gauge, the borehole stress meter, various strain gauge-based stress

Figure 3-1. (a) Inclinometer Probe (Slope Indicator, 2006) (Courtesy of Durham Geo Slope Indicator; Reprinted With Permission) and (b) In-Place Inclinometer (Geokon, 2006) (Courtesy of Geokon, Inc.; Reprinted With Permission)

cells, and hydraulic pressure cells (Geokon, Inc., 2006). While many of these tools are typically used to characterize the initial *in situ* stress state in conjunction with the overcoring method, they can also be applied to monitor stress changes with time. Triaxial strain cells installed in boreholes using epoxy have been known to creep with time and with variations in temperature (Thompson, et al., 1990). Their suitability for monitoring reliably beyond a period of a few years has not been proven.

The deformation modulus of the rock mass can be determined using a borehole dilatometer or borehole jack (Boart Longyear Interfels, 2006). Testing involves an inflatable downhole tool that measures both pressure and displacement simultaneously to determine the modulus. The dilatometer measures change in borehole diameter in three directions and can be used in rock masses with modulus values between 50 MPa [7.2 ksi] and 20 GPa [2,900 ksi]. Although typically used as a characterization method to establish initial properties for analysis and design, repeat measurements in the same borehole can provide an indication of changes in the modulus with time resulting from damage development near the underground opening.

Temperature of the rock mass is monitored using strings of thermocouples, thermistors, or resistance temperature devices (Thompson, et al., 2003). Special high-temperature vibrating wire temperature sensors (Figure 3-4) have been developed to work in the range of 0 to 200 °C [32 to 392 °F] (Geokon, Inc., 2006). Sensors are usually deployed in boreholes to provide automated continuous monitoring of the temperature distribution around an underground opening. Alternatively, a thermometer probe can be used to measure the temperature profile along a borehole in repeated manual surveys.

(a) **(b)** **(c)** **(d)** **(e)**

Figure 3-3. Stress Monitoring Tools: (a) Borehole Pressure Cells, (b) Biaxial Stress Cell, (c) Borehole Stressmeter, (d) Soft Inclusion Stress Cell, and (e) Borehole Deformation Gauge (Geokon, Inc., 2006) (Courtesy of Geokon, Inc.; Reprinted With Permission)

Pore pressure and hydraulic properties of the near-field rock mass can be determined in a number of ways. A variety of vibrating wire piezometers (Figure 3-4) can be installed in boreholes to monitor changes in pore pressure around an underground opening (Geokon, Inc., 2006). Vibrating wire technology is generally considered stable and reliable for

long-term monitoring of pore pressure.

The hydraulic characteristics of isolated spatial interval can be quantified using different types of hydraulic tests such as pressure pulse and drawdown tests. To assess the pore pressure profile in small intervals near an underground opening, special excavation damage assessment packers have been developed (Martino, 2000). Specially designed packer-extensometer tools that simultaneously measure axial displacement and pressure injected into an isolated fracture have been developed to measure fracture stiffness (Thompson, et al., 1990). In addition, tracer tests have been used in conjunction with hydraulic packer testing to assess the flow characteristics and diffusion properties of the rock mass. While most of these techniques are considered characterization methods, they can be used to monitor changes in the near-field if repeated in successive campaigns.

Downhole hydraulic transmissivity probes, such as the SEPPI probe developed by ANDRA (Bauer, et al., 1995), have been used to characterize the transmissivity profile of the near-field rock mass to identify the extent of damage. Likewise, pneumatic testing in boreholes using either vacuum permeability or air injection tests has been used to assess the permeability of the zone of damage near an underground opening (Jakubick and Franz, 1993; Cook, 2000).

3.2.2 Tunnel-Based Techniques

As shown in Table A–1, many techniques for monitoring inside an underground opening do not require boreholes in the near-field rock mass. The development of damage around an underground opening is manifested as dilation of the rock mass. This process results in more deformation of the tunnel periphery than predicted by the elasticity theory. If the tunnel is supported, there may be a corresponding deformation of the tunnel support system or load

Figure 3-4. Vibrating Wire Instruments: (a) Temperature Sensor (Soil Instruments, Ltd., 2006) (Courtesy of Soil Instruments, Ltd.; Reprinted With Permission) and (b) Piezometers (Geokon, Inc., 2006) (Courtesy of Geokon, Inc.; Reprinted With Permission)

(a) (b)

transfer from the rock mass to the support system. Therefore, monitoring both the tunnel periphery and the support system is useful in identifying damage development.

Convergence arrays are used during construction in many civil and mining projects to monitor tunnel closure resulting from the tunnel advance away from the monitoring array and the development of damage. If *in situ* stresses and rock mass properties are known, it is possible to calculate the expected deformation around the opening. By comparing the predicted and measured deformation, inelastic deformation associated with damage can be identified. It should be noted that convergence arrays installed within tunnels record only a portion of the total deformation response and therefore require some interpretation to estimate the amount of prior deformation that is not recorded (Read, 1994).

A vibrating wire convergence meter provides automated measurement of tunnel dimensions, but, like all conventional convergence arrays, obstructs traffic in the tunnel while measurements are being taken. The development of instruments based on laser ranging principles to automatically measure distances between fixed points on the tunnel periphery may provide a solution to traffic obstruction. Unobtrusive fiber-optic deformation sensors have also been used to measure the tunnel curvature from which convergence can be back-calculated (Inaudi, et al., 1998).

An alternative to the conventional convergence array is the tunnel profile monitoring system (RST Instruments, 2006). This system comprises a number of linked arms fixed to the tunnel wall to monitor deformation. Spatial displacement of pins and arms resulting from tunnel deformation registers as tilt and displacement readings. These measurements are analyzed to determine changes in the tunnel geometry of the measurement plane. Monitoring of these instruments can be automated using a data logging system. This system, once deployed, does not obstruct traffic in the tunnel.

To monitor changes in the geometry of the entire tunnel, a precision laser scanner (Figure 3-5) was used to conduct successive surveys of underground openings (Riegl, 2006). Unlike conventional tunnel survey approaches that require reflective prisms (e.g., Kontogianni and Stiros, 2003), these systems use a dense grid of laser pulses or stereographic camera images to map the three-dimensional surface of the tunnel. The devices can create a detailed surface map of a tunnel very rapidly. Successive images are compared to calculate geometrical changes, volume changes, and areas of instability. In the event of localized failure, the geometry of the failed zone and the resulting debris within the tunnel can be calculated provided that the instrument can be set up in the tunnel. Similar systems have been installed on specialized rail cars to conduct regular inspection of tunnels. The photo scanner may also be used to facilitate tunnel mapping.

A similar approach has been used to conduct infrared thermography surveys in tunnels (Chandler, 1999). This method is based on the principle that fractures in the near-field rock mass (i) will respond differently to transient thermal conditions than the surrounding rock mass and (ii) can be identified by heating and cooling a tunnel segment while scanning the rock mass with an infrared thermographic scanner. The device is mounted on a suspended rail system to allow it to travel along a controlled line to produce thermal images of the tunnel wall. Resulting anomalies on the processed image are identified as fractures. This is a labor intensive system and requires significant disturbance to normal tunnel operations.

In situations where structural support (e.g., steel sets or reinforced concrete) is installed in a tunnel, deformation of the support system can be monitored using fixed tiltmeters, strain gauges attached to rebar or steel supports, or strain meters embedded in concrete (Geokon, Inc., 2006). Ongoing deformation of the support system may be an indication of damage development and progressive load transfer to the supporting structure.

In instances where there are surface cracks in the rock mass or the concrete, crack meters can be installed across the crack to measure changes in aperture with time. These types of instruments are based on vibrating wire technology and can be automatically datalogged. Graduated crack tell-tales are simple devices that provide manual readings of changes in crack aperture.

There are several instruments listed in Table A–1 that are designed to measure changes in stresses in the support system. Concrete stress cells are flat-jack type instruments that can measure the radial and tangential stress in a concrete liner. A flat-jack type total pressure cell at the rock-support interface provides a direct measure of the load transfer from the rock mass to the support system. In rock bolt support systems, load cells can be attached to bolt collars to measure changes in tension in the bolt. Instrumented cable bolts to measure deformation and load in the rock mass (Figure 3-6) are used in mining applications to provide real-time monitoring of the support system (Mine Design Technologies, 2006).

To characterize the deformation modulus of the rock mass on a large scale, plate loading tests using large hydraulically activated flat jacks have been conducted in sawed slots in the tunnel

Figure 3-5. Laser Scanner (RIEGL USA, 2006)
(Courtesy of RIEGL USA; Reprinted With Permission)

periphery (Boart Longyear Interfels, 2006). Tunnel jacking (or plate loading) tests have also been conducted using a system that spans the tunnel to load the rock mass (George, et al., 1999). Borehole extensometers are used in conjunction with this system to monitor the displacement profile in the rock mass resulting from the applied load. These types of tests can be repeated to assess changes in rock mass properties, but they are labor intensive and location specific.

The hydraulic properties of the zone of damage near a tunnel could be measured in several ways (e.g., Chandler, 1999). This includes the construction of a water reservoir using dams to create a static head of water and monitoring of flow rate into a slot excavated orthogonal to the tunnel axis. Another option is the development of a sealed bulkhead and pressurization of water within the room to assess flow characteristics under pressure (Chandler, et al., 2002). Both of these tests are major undertakings and are not likely to be included as regular repeated monitoring exercises.

3.3 Geophysical Monitoring

Geophysical monitoring is based on physical principles of wave propagation through the rock mass. The velocity of compressional (P) and shear (S) waves calculated from travel times along direct, reflected, or refracted ray paths figure prominently in geophysical monitoring techniques. Dynamic elastic properties of the rock mass can be determined from the measured P- and S-wave velocities using known relationships (Young and Collins, 1999). Repeated velocity surveys can therefore monitor changes in the rock mass properties caused by damage development. These changes typically include reductions in wave velocities that are dependent on the damage characteristics (i.e., crack density/volume and orientation relative to the ray direction). Relative changes in P- and S-wave velocities can also be used to assess desaturation of the rock mass. In addition, passive seismic monitoring of waves induced by fracturing or microcracking in the rock mass provides direct monitoring of damage development

Figure 3-6. SMART Cable Bolt With Integral Deformation Monitoring (Mine Design Technologies, Inc., 2006) (Reprinted by Permission From Mine Design Technologies, Inc.)

Figure 3-7. Micro-Velocity Probe Used for Interval Velocity Surveys (Read and Chandler, 2002) (Reprinted With Permission from Ontario Power Generation)

(Young and Collins, 1999).

3.3.1 Borehole-Based Techniques

There are several borehole-based velocity survey techniques that are used to characterize damage around underground openings. Interval velocity surveys are conducted in a single borehole using a sliding probe with two seismic transducers at a fixed spacing (Figure 3-7). This tool provides a profile of P- and S-wave velocities parallel to the borehole axis at a constant transducer interval. The spacing of the transducers affects the depth to which the ray paths travel in the rock containing the borehole. Repeat surveys can detect changes in the velocity profile related to damage development, but require that the borehole in which the measurements are taken does not deteriorate over time.

Downhole seismic velocity surveys that use a variable source-receiver distance are also common (Alheid and Knecht, 1996). In this case, the seismic source is usually located at the tunnel wall, and the receiver is positioned at different depths in a single borehole. While relatively simple to conduct, the variable spacing between the source and the receiver complicates the interpretation of the extent and character of the damage near the tunnel wall (i.e., the average velocity between the source and the receiver is measured).

Crosshole seismic velocity surveys require two boreholes to characterize the velocity of the rock mass in the panel between the holes (Holcomb, et al., 2002). Simple crosshole surveys involve parallel boreholes with the source and the receiver in different holes at the same depth from the tunnel periphery. By moving the source and the receiver in a synchronized fashion, a profile of velocities orthogonal to the borehole axis with depth can be developed. This provides information for a larger volume of rock than single borehole surveys and is not as sensitive to localized damage around the borehole itself.

A variation on the crosshole survey involves moving the source and the receiver independently in adjacent boreholes to create a network of intersecting ray paths through the panel between the boreholes (Martino, 2002). Inversion of the data from these ray paths is conducted to develop tomographic images of the velocity structure of the rock mass. Similar images of dynamic elastic properties can also be produced from these data. For this method of seismic tomography, the boreholes used for the survey need not be parallel. However, precise survey control of the boreholes and sensor locations is required in order to reduce uncertainty and eliminate artifacts in the resulting tomographic images.

The development of damage in brittle materials is accompanied by microseismic or acoustic emission events generated by the formation of new cracks or deformations on existing fractures. Passive monitoring using an optimized array of hydrophones, geophones, or triaxial accelerometers provides the means of tracking the temporal and spatial history of microseismicity associated with damage development around underground openings (e.g., Figure 3-8) (Young and Collins, 1999). Source location and source mechanism analysis can interpret the extent of damage and the mechanisms involved in damage development (i.e., shearing versus tensile or implosional events). Passive microseismic monitoring (ESG Solutions, 2006) is used extensively in underground mining in hard rock, and in investigations related to petroleum production (e.g., monitoring the development of hydraulic fractures during well stimulation). Depending on the arrangement of sensors and the level of microseismic activity, data recorded by the passive microseismic array can be inverted to develop a three-dimensional velocity model (Maxwell, et al., 1996). Care is required in interpreting this velocity model as the dynamic elastic properties (and hence the velocity) are stress-dependent; it is therefore important to differentiate stress effects from those caused by damage (Read and Chandler, 2002). Microseismic monitoring technology has been applied successfully in a number of underground mines (Canadian Nuclear Safety Commission, 2002).

Passive acoustic emission monitoring (ESG Solutions, 2006) is conducted in much the same way as microseismic monitoring except that the volume of rock under consideration is several orders of magnitude smaller because a much higher frequency range is being monitored. Ultrasonic sensors are emplaced in boreholes near the tunnel wall at precisely known locations to provide focused localized monitoring. This technique has also been used to monitor the performance of critical concrete structures in underground openings such as tunnel bulkheads (Young and Collins, 1999). Both acoustic emission and microseismic monitoring provide a noninvasive means of assessing the development of damage and increasing instability in rock mass and can be key components of a long-term monitoring program.

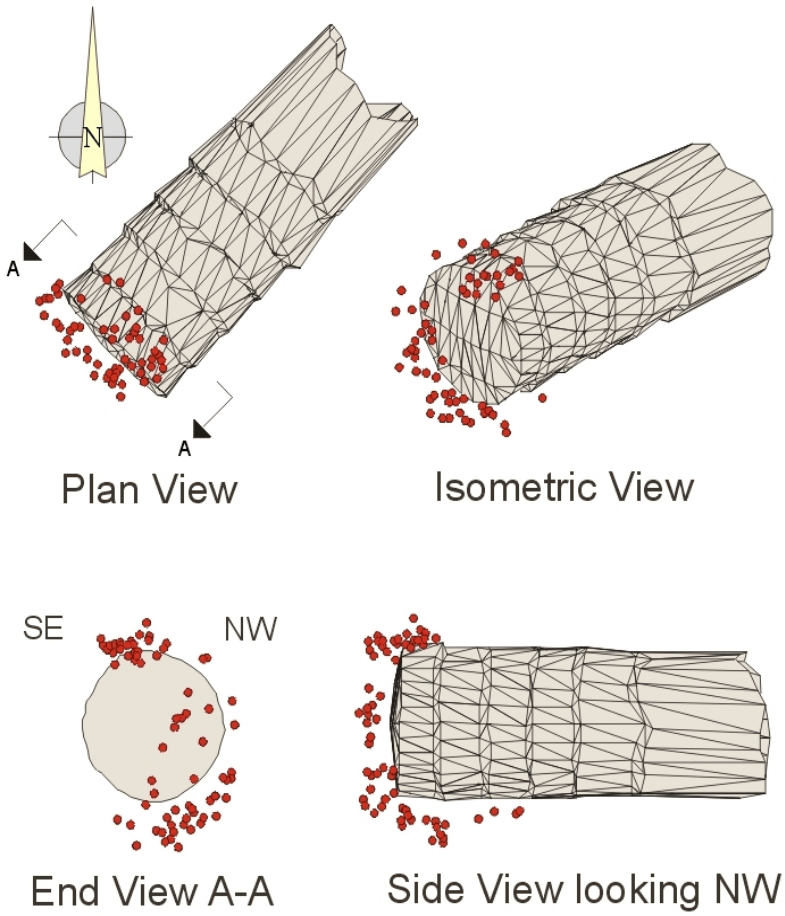


Figure 3-8. Microseismic Monitoring of the Mine-By Test Tunnel (Read and Chandler, 2002) (Reprinted With Permission of Ontario Power Generation)

3.3.2 Tunnel-Based Techniques

Tunnel-based geophysical techniques involve the use of geophones mounted on the tunnel surface to detect reflected or refracted waves (Young and Collins, 1999). The interpretation of these data is based on an assumption of impedance contrast between different layers in the rock mass or between discrete fractures and relatively intact rock. The extent of the zone of damage is interpreted as the boundary between two zones of different impedance. These techniques use standard seismic methods of interpretation and require repeat surveys in a tunnel to assess changes with time. Ground-penetrating radar has come into prominence of late as another tool based on reflection of waves from fracture surfaces or the boundary between layers of distinct impedance (Momayez and Hassani, 1995).

Ground vibration monitoring using portable blast monitoring systems measures ground acceleration and air pressure associated with underground blasting (RST Instruments, 2006).

This information provides an indication of the seismic history experienced in the underground opening and may provide some insights into the expected depth of damage based on modeling studies. This is particularly important for blocky rock masses that may experience temporary loosening of blocks from the tunnel periphery as a result of dynamic stresses acting on the rock mass during blasting.

Geoelectric surveys have been used in some instances to map resistivity and phase shift around an underground opening to identify changes in saturation and porosity (Alheid, 2002). Geoelectric profiles are produced using normal direct current resistivity measurements and alternating current resistivity and phase shift measurements. Electrical-resistance tomography involves installing electrodes into the rock mass and measuring the resistivity of the rock mass between the electrodes. This technique has been used at Yucca Mountain to create electrical resistance tomograms of changes in water saturation resulting from heating the rock volume (Blair, et al., 1999). Thermal neutron logging has also been used at Yucca Mountain to measure water saturation before, during, and after heating an *in situ* volume of rock (Blair, et al., 1999). This is a standard well-logging technique that measures neutron radiation as a means of determining water saturation.

3.4 Other Monitoring

In addition to the previous monitoring methods listed in Table A–1, there are some supporting characterization tools and techniques. Corelogging provides the means of directly identifying natural fractures in the core from the rock mass. Core damage (e.g., discing) is not necessarily indicative of *in situ* damage, and core samples should be used with caution to infer *in situ* properties. Resin injection in a small pilot hole to preserve the structure of the rock mass followed by overcoring of the rock containing the pilot hole is a more elaborate means of acquiring the representative core from the rock mass for direct observation of fracturing and damage. Borehole television or video cameras can be used to image the borehole wall to provide direct observations of fracturing near the tunnel periphery. Although these are not true monitoring methods, repeated campaigns of coring and borehole observations can provide evidence of changes or progression of damage near the opening (Read and Chandler, 2002, 1999).

Geological mapping of underground openings can be done on a photo base to identify lithologic variations, surface traces of fractures, and other structural geology features. Comparative maps or photos from different mapping campaigns can provide evidence of increased surface cracking related to damage development. Laboratory testing of the samples from various lithologic units identified in the geological mapping is typically conducted to determine common rock properties. Specialized testing conducted on core samples is used to assess rock properties and coupled thermomechanical, hydromechanical, and thermoporoelastic parameters (Read and Chandler, 2002). Hydrogeochemical sampling is also conducted to assess potential implications of groundwater chemistry on the long-term performance of support structures and instrumentation (Thompson and Simmons, 2003). These activities can be used in a monitoring program to provide a basis for predicting the expected behavior of the rock mass and for identifying deviations from the expected behavior.

Radiological monitoring is conducted in underground openings, drainage and ventilation systems to measure radiation level within the tunnel, groundwater, and air. Continuous monitoring of water pumped from underground workings is a regulation in some jurisdictions to

ensure that the level of naturally occurring radioactive materials does not exceed a safe limit. Likewise, air quality is monitored continuously to ensure the occupational safety of workers. Standard radiological monitoring instruments are available for these purposes (Canberra, Company, 2006).

In addition to these tools and techniques, standard climatic data (air temperature, relative humidity, barometric pressure, and wind speed) are measured continuously in underground excavations to assess environmental conditions that may affect rock mass response or damage development. Surface-based measurements of precipitation using standard tipping buckets or other equipment provide information for quantifying potential infiltration events. Seepage monitoring has been used to correlate inflow into excavations and precipitation events. These types of measurements are not directly related to the stability of underground openings, but provide insight into the potential long-term conditions of the rock mass.

4 DEEP GEOLOGIC REPOSITORY MONITORING

The information reviewed in Chapter 3 is reviewed further in this chapter in the context of a deep geologic repository. Examples of applications of the tools and techniques at international nuclear waste disposal research facilities are summarized in this section. Both monitoring and characterization tools/techniques are considered because some of the characterization techniques may lend themselves to repeat application to track changes in properties or conditions. Technologies that are well-suited to a repository environment involving high temperature and radiation are identified.

4.1 Repository Conditions and Monitoring Time Frame

Monitoring in a deep geologic repository environment has many similarities to other underground monitoring applications. However, there are several unique aspects of nuclear waste repositories that require consideration in planning a monitoring program.

Emplaced nuclear waste is heat-generating. The underground emplacement of nuclear waste will produce thermal loading of individual underground openings containing the waste and the surrounding rock mass. Depending on the type of waste, spacing of waste containers, types and characteristics of engineered barriers, and other details of the specific emplacement concept being implemented, the maximum temperature of the emplacement drifts may be close to 100 °C [212 °F] or higher. Consequently, monitoring instruments, cables, and other components must be compatible with a high temperature environment.

The environment within each drift is expected to become progressively more radioactive with time due to the presence of the nuclear waste packages and possibly the accumulation of naturally occurring radioactive materials. The characteristics of the radiation emitted from waste packages will vary with the nature of the nuclear waste and the effectiveness of the engineered barriers designed to prevent transport of radionuclides away from the waste containers. Any container breach through corrosion or impact may create a sudden increase in the level of radioactivity within a drift, the ventilation air stream, and potentially the groundwater system. Monitoring instruments therefore must be capable of functioning in a high radiation environment. Radiological monitoring also may be done in conjunction with any monitoring program to assess the radiological risk to workers and the environment and the radiation impact on instrumentation.

In addition to these two considerations, the time frame for monitoring a nuclear waste repository is typically orders of magnitude longer than the time frame for monitoring underground openings associated with conventional civil or mining projects. Monitoring instruments therefore must be robust, stable, and reliable for long-term application in an underground environment characterized by high temperature and radiation. Likewise, means of retrieving, recalibrating, or replacing instruments are major considerations in planning a monitoring program.

Typical plans for the development of a deep geologic repository for high-level and other long-lived radioactive waste involve a series of stages, beginning with the definition of the disposal concept, and followed by site selection and characterization, construction, operation, extended monitoring, decommissioning, and closure (e.g., Simmons and Baumgartner, 1994; International Atomic Energy Agency, 2001). The preclosure phase includes all activities conducted prior to the final sealing of the repository and can be of considerable length

depending on the quantity of waste to be emplaced and the length of the monitoring period. At the Yucca Mountain site, for example, the operational phase and subsequent monitoring phase could be on the order of 100 years (DOE, 2001). Monitoring data would be used to establish baseline conditions or parameters early in the preclosure period and to identify temporal changes in these conditions or parameters during the remainder of the preclosure period and part of the postclosure period (i.e., the period following permanent closure of the repository).

4.2 Objectives of Monitoring and Relevant Parameters

In the context of excavations for a nuclear waste repository, the monitoring objectives and associated parameters of relevance are as follows:

- Quantify initial conditions and changes in boundary conditions that may cause the development of excavation damage and instability of underground openings. Relevant parameters include stress, pore pressure, temperature, geochemistry, radioactivity, and geological characteristics and properties of the rock mass.

- Compare the geomechanical response of the rock mass resulting from changed boundary conditions with baseline predictions to assess the performance of the underground openings relative to design limits established for the operational period. Relevant monitoring parameters are displacement (or strain), pore pressure change, stress change, temperature change, induced microseismicity, change in radioactivity, and changes in seepage (flow rate and geochemistry).

- Characterize changes in rock mass properties resulting from changed boundary conditions, damage development, and progressive failure of the near-field rock mass that may affect the rock mass response. Relevant parameters are deformation moduli, seismic velocity, porosity, moisture content, degree of saturation, density, thermal and hydraulic properties, and fracture characteristics (geometry, frequency, aperture, and orientation).

- Identify anomalous behavior related to damage development and progressive failure of the rock mass around the underground excavation that exceeds established design limits. Relevant parameters are displacement (or strain), stress change, and microseismicity.

- Provide data to assess the consequences of progressive failure of the rock mass on the performance of engineered barrier systems within the underground openings and the natural barrier represented by the geosphere, and plan remedial action if warranted. Relevant parameters are changes in tunnel geometry, volume of displaced material, microseismicity, temperature, and radioactivity.

Based on the Canadian disposal concept (Simmons and Baumgartner, 1994), monitoring activities could be performed near the source of contaminants, far from the source to monitor atmospheric effluents, or in the host rock. Monitoring the rock would be undertaken using measuring instruments installed in and around the underground excavations. These instruments would record temperature, rock stress, acoustic emissions or microseismic events, and the deformation of the rock on a continuous or frequent basis. Monitoring would be progressively discontinued to allow for the sealing of emplacement drifts and access tunnels.

While the purpose for monitoring a nuclear waste repository is primarily performance-related (i.e., to decrease the likelihood of a release of radionuclides to the environment), there are some potential detriments associated with monitoring that must be factored into the overall assessment of safety related to the disposal concept to help optimize the monitoring program design. These potential detriments include the following (International Atomic Energy Agency, 2001):

- Radiation doses to personnel carrying out monitoring
- Degradation of materials in the repository resulting from delay in putting engineered barriers in place while monitoring programs are completed
- Formation of pathways through the barriers by installation of monitoring equipment leading to increased potential for radionuclide migration within or around the repository
- An increased likelihood of human intrusion or adverse impacts by natural or induced processes (e.g., flooding) if repository access is kept open to allow monitoring
- Interference with other repository operations

4.3 International Experience

4.3.1 Studies of Excavation Damage

Studies of damage development and fracturing caused by excavating underground openings have been undertaken by many international organizations evaluating concepts for nuclear waste disposal. Table 4-1 provides information on some of the major underground investigation sites where these studies have been conducted. Many of the studies are documented in the proceedings of two international workshops held in Winnipeg, Canada (OECD/Nuclear Energy Agency, 1988; Martino and Martin, 1996). A subsequent international workshop in Toronto, Canada (Martino, 2002), provided an update on studies of excavation-induced damage conducted in Sweden, France, Germany, United States, Finland, and Canada. The impact of damage around underground openings on repository performance was the topic of a specialty conference held in Luxembourg (EURATOM, 2003).

A number of tools and techniques used to monitor or characterize damage development around underground openings in the studies mentioned in the foregoing paragraph are summarized in Table A–2 (Appendix A) along with references. The summary describes specific examples of the use of each tool or technique within the programs. Table A–2 highlights representative examples; is not intended to be an exhaustive compendium of all monitoring applications at each site.

As in Table A–1, the various tools and techniques for monitoring underground excavations have been classified into six main categories: mechanical, thermal, hydraulic, geophysical, geological, and geochemical. Of these, there are many tools and techniques in the mechanical,

Table 4-1. International Underground Laboratories (Read and Chandler, 2002)			
Country	**Site(s)**	**Operator**	**Rock Type**
Canada	Underground Research Laboratory	Atomic Energy of Canada Limited	Granite
Sweden	Aspo Stripa	SKB and International Partners	Granite Granite
France	Meuse/Haute-Marne Tournemire	ANDRA IPSN	Argillite Clay Shale
Germany	Asse Gorleben	BFS/BGR BFS/BGR	Salt Salt
Switzerland	Grimsel Mont Terri	NAGRA and International Partners	Granite Opalinus Clay
Belgium	HADES (Mol)	SCK-CEN	Boom Clay
United Kingdom	Sellafiield	NIREX	Volcanics
USA	Yucca Mountain Waste Isolation Pilot Plant	DOE DOE	Volcanic tuff Salt
Finland	Olkiluoto	Posiva Oy	Gneissic tonalite
Japan	Kamaishi Tono Mizunami Horonobe	JNC JNC JNC JNC	Granite Sedimentary Granite Sedimentary

geophysical, and hydraulic categories and fewer in the other categories. Only one technique related to geochemistry is listed. Although it is recognized that changes in geochemical conditions in the excavation damaged zone can have significant effects in terms of long-term transport properties, understanding potential geochemical changes has not been a large focus for excavation damage studies.

It should be noted that not all techniques are applicable to every environment. For instance, ground penetrating radar is affected by the composition of the rock mass—in clayey media, the depth of radar penetration is substantially less than in crystalline rock. Likewise, most nuclear waste repositories are expected to be located below the water table. Consequently, hydraulic monitoring around underground excavations is considered to be an important component of most monitoring programs. Yucca Mountain is an exception in this regard, because the repository would be located above the water table (DOE, 2001).

In many cases, there are several similar tools that have been developed by different organizations (see Table A–2). Bauer, et al. (1995), for example, list several downhole permeability probes similar to the SEPPI probe used at the Underground Research Laboratory

and Äspö. Standard laboratory tests have not been described in detail in Table A–1; however, some unique tests are mentioned in Table A–2 (^{14}C–PMMA-method).[1] Likewise, full-scale experiments to characterize damage in the near-field rock mass have not been included in the review of tools and techniques as these are considered beyond the scope of a practical excavation monitoring program. However, it is recognized that early study of prototype systems is valuable in selecting monitoring options and in building confidence in long-term system performance.

4.3.2 Tools and Techniques Used at Experimental Facilities

Studies at international nuclear waste disposal research facilities provide a broad view of approaches to damage monitoring and characterization in a variety of rock mass conditions. The ZEDEX experiment (Emsley, et al., 1997) at Äspö and the Mine-by Experiment at the Underground Research Laboratory (Read and Martin, 1996; Read, 1996) are perhaps the most comprehensive studies on rock mass damage monitoring and characterization of the damaged zone around excavations in moderately and sparsely fractured crystalline rock masses, respectively. Studies at Mont Terri (Martin, et al., 2002) and HADES (Lebon, et al., 1996) illustrate both the similarities and the unique characteristics of clay compared to crystalline rock. The Waste Isolation Pilot Plant (Holcomb, et al., 2002) and other investigations in salt (Alheid and Knecht, 2002) give additional insight into the nature and character of the damage around openings in brittle materials that display long-term creep. These findings provide insight for planning monitoring and characterization activities at a repository site.

In most international programs, rock mass monitoring has been incorporated into the investigations to gain an understanding of the mechanical; hydraulic; and, to a lesser extent, thermal responses of the rock mass to excavation. Many investigations, such as the Mine-By Experiment (Read and Martin, 1996), have used instruments installed prior to tunnel excavation to monitor the complete excavation response. These types of instruments are typically complemented with conventional measurements taken within the tunnel during excavation (e.g., convergence measurements). Convergence arrays, extensometers, inclinometers, triaxial strain cells, piezometers, thermistors/thermocouples, and hydraulic packer systems have been used in instrumentation arrays installed at specific locations at the URL to monitor shaft and tunnel excavation (Davison, et al., 1994). Figure 4-1 shows two types of extensometers used in the Mine-By Experiment.

The combination of these instruments provides measurement of the displacement (strain), pore pressure, and temperature responses of the rock mass, along with seepage rates and groundwater chemistry changes with time. Data collected at these arrays have also been used to back calculate far-field *in situ* stresses, near-field deformation properties, and rock strength properties (Read and Martin, 1996). Similar location-specific monitoring systems have been used in Japan (Sugihara, et al., 1999) and Sweden (Emsley, et al., 1997) and were proposed for use in the United Kingdom (Mellor and Davies, 1996) prior to cancellation of the experimental program at Sellafield, United Kingdom in 1997. Such systems likely will be used in preclosure monitoring of repositories worldwide.

[1]The Carbon-14 Polymethylmethacrylate–method.

(a) **(b)**

Figure 4-1. Retrievable Extensometers Used for the Mine-By Experiment at Atomic Energy of Canada Limited Underground Research Laboratory: (a) BOF-EX extensometer and (b) ED-EX Extensometer (Read and Martin, 1996) (Reprinted With Permission of Atomic Energy of Canada Limited)

Remote monitoring of rock masses has included in many cases acoustic emission and microseismic monitoring. In applications to characterize and quantify rock mass damage near repository excavations, acoustic emission and microseismic monitoring have typically been conducted jointly with velocity measurements to determine velocity variations with distance away from an excavation (Maxwell, et al., 1996). Much of this acoustic emission and microseismic technology has been advanced through investigations at the URL in Canada (Young and Collins, 1997) and ZEDEX, and other studies at Äspö in Sweden (Young, 1999). Acoustic emission monitoring of damage development has also been applied to rock types other than crystalline rock (e.g., stiff clays or argillaceous rock) in Mont Terri and Tournemire (Cabrera, et al., 1999) and salt in Asse, Germany (Alheid and Knecht, 1996). This technique offers a means of actively monitoring a relatively large volume of rock to identify the development of damage in near real-time. It is particularly attractive because sensors can be deployed in boreholes remote from the opening to measure phenomena that may occur some distance from the sensor positions. The applicability of passive seismic systems for long-term monitoring for nuclear waste repositories has been studied in Canada (Canada Nuclear Safety Commission, 2002).

Characterization of rock mass damage around excavations has involved a variety of complementary tools and techniques. Geophysical approaches measuring seismic velocity, either directly between sensors or indirectly in refraction and reflection techniques, combined with visual geological methods (i.e., corelogging, mapping, photography, borehole imagery) and hydraulic techniques measuring permeability have been effective in defining the extent, character, and properties of the damage around an underground opening (Read and Chandler, 2002). Velocity changes with time have been widely used to infer rock property changes through correlations with dynamic properties (Young and Collins, 1999). *In situ* mechanical testing, such as plate loading tests to determine deformation modulus, have been used at Yucca Mountain (George, et al., 1999) and in Japan (Tatsuoka, et al., 1997), but are not commonplace in other programs. Back analysis of measured strains and displacements has also been used to assess changes in near-field rock mass properties (Read, 1994).

Laboratory-based techniques (e.g., ^{14}C–PMMA-method)[2] to measure microfracturing and porosity profiles, and the helium-gas method to measure effective diffusion coefficients and permeability coefficients have been applied successfully (Autio, 1996). In addition, sophisticated new laboratory testing techniques have been developed to measure coupling parameters associated with thermoporoelastic behavior (Read and Chandler, 2002). Standard laboratory tests on rock samples are used to determine geomechanical, thermal, and coupled properties required for numerical simulations.

Direct measurement of hydraulic properties of the damaged zone using short-interval pulse tests has shown that permeability in this zone in relatively low stress environments can be several orders of magnitude higher than in the undisturbed rock mass (Simmons, 1992). Connected permeability tests have been useful in characterizing the large-scale hydraulic conductivity of tunnels excavated in different stress environments and using different excavation techniques (Chandler, 1999). For the Mine-By Experiment, the hydraulic conductivity in a localized highly-damaged zone was about eight orders of magnitude higher than in the surrounding rock mass. For example, in room 209 at the Underground Research Laboratory, excavated in a relatively low stress environment, the increase in hydraulic conductivity was about six orders of magnitude in the floor of the tunnel (Simmons, 1992). However, the fractures associated with this increase were relatively short and not continuous between blast rounds (i.e., that did not extend from one blast round to the next).

Predictions of the hydraulic response around tunnels have generally met with limited success (Olsson and Winberg, 1996). Over-prediction of inflow by an order of magnitude has been common for excavation response experiments conducted in Sweden and Canada in rock containing preexisting fractures. Relationships linking transmissivity to the normal stress across the fracture have not explained the smaller than expected inflows. Similar relationships linking transmissivity to shear displacement have been more effective in explaining behavior observed in the room 209 experiment at the Underground Research Laboratory, but not results from studies at Stripa in Sweden. Other explanations for the observed hydraulic behavior have included dynamic effects of blasting on the fracture, degassing of groundwater due to reduced pressure resulting in two-phase flow effects, and chemical precipitation or dissolution of minerals on fractures. Kelsall, et al. (1982) recommended that macropermeability tests be conducted as part of investigations to characterize the excavation damaged zone.

In assessing the properties of the excavation damaged zone, it is important to differentiate effects due to damage from those due to disturbance. Barton (1996) illustrates that the modulus is dependent on confining stress and that stress redistribution effects associated with disturbance can outweigh the effects of damage within about one radius of a tunnel. Similar effects were noted for compressional velocity near a tunnel. In jointed rock, stress disturbance effects can change the rock mass velocity significantly by opening or closing joints. In sparsely fractured rock, these velocity effects are more likely to be associated with damage and stress changes in the immediate vicinity of the tunnel. Barton (1996) describes a method for relating a modified Q-value to the deformation modulus and seismic velocity, with corrections for depth and porosity. The Drift-Scale Test at Yucca Mountain demonstrates direct measurement of important rock mechanical properties required for numerical modeling, such as the deformation modulus (George, et al., 1999).

Based on the studies reviewed, there are several processes or mechanisms that can affect the

[2] Ibid.

transport-related characteristics of the damaged zone around an underground opening. In drill-and-blast tunnels, the explosive charge density has been shown to influence the extent and severity of damage in the near-field. Damage is often more prevalent in the floor of such excavations because higher explosive charge densities are typically used in lifter holes in this area (Emsley, et al., 1997). However, in low stress environments, connected permeability associated with blast-induced damage may not be continuous across blast rounds (Simmons, 1992). Mechanically-excavated tunnels, such as the tunnel boring machine drift in the ZEDEX experiment (Emsley, et al., 1997), generally exhibit less damage associated with the excavation method. In contrast to low stress environments, stress-induced damage in high stress environments may create a continuous zone of connected permeability along the axes of both drill-and-blast and mechanically-excavated tunnels (Read, 1996). Moreover, thermal loading can exacerbate existing, or create new, damage around underground openings (Read, et al., 1998a). In fractured environments, excavation may induce displacements on existing joints that exceed values predicted by continuum models (Simmons, 1992). Chemical reactions in fractures and desaturation around underground openings can also affect near-field transport properties and inflow into tunnels (Thompson and Simmons, 2003).

From the studies considered, the extent of excavation-induced damage around underground openings is generally limited to within one tunnel radius of the excavation (in some cases to only a few centimeters), although excavation disturbance in weak rock masses (e.g., Boom clay) has been predicted to extend about two tunnel diameters from the opening. The character of fractures and microcracks associated with damage is a function of the rock type, the *in situ* stresses, and the excavation method, among other things. Fracturing or cracking tangential to the tunnel wall was commonly observed in the studies, particularly in weak rocks. Radial fracturing or cracking was observed in some cases, particularly in the vicinity of blast holes and in regions of tensile stress (e.g., the sidewall of the Mine-by Experiment). In general, the character and extent of damage around an underground opening was found to vary positionally and to depend on the preexisting state of the rock mass and the near-field conditions experienced during the course of excavation. Consequently, in order to effectively monitor damage development, instruments need to focus on the near-field zone close to the underground opening and need to be of sufficient number to reflect the variability in damage at different positions around the opening.

The reliability and accuracy of geotechnical instruments for long-term application has been inferred from some of the experimental activities at the Canadian URL (Martino, 1995) and elsewhere, but was directly assessed in the thermal simulation of drift experiment in the Asse salt mine in Germany.[3] In this case, stress monitoring probes, convergence measuring devices, temperature gauges, backfill settlement measuring devices, backfill pressure gauges, and extensometer transducers were recovered from a backfilled drift after up to 14 years of service. Recalibration showed that most sensors were operating within the manufacturer's specification. Failures were attributed largely to instrument cabling issues. These results suggest that the particular instruments used at this site were suitable for monitoring for a decade or longer. Reliability checks on the instruments helped resolve the cause of discrepancy between modeled and measured results.

[3]Bollingerfehr, W., S. Heusermann, J. Droste, and T. Rothfuchs. "Reliability and Accuracy of Geotechnical Instruments During 10 Years of *In Situ* Application." *Poster Presentation at the Euradwaste '04, 6th European Commission Conference on the Management and Disposal of Radioactive Waste, March 29–April 1, 2004*. Luxembourg City, Luxembourg. 2004.

The results of a European Commission thematic network on the role of monitoring in a phased approach to geological disposal were presented at the Euradwaste '04 conference in Luxembourg in March 2004.[4] A report summarizing the findings of this project was to be issued early in 2004. Approaches to monitoring in 10 different national programs in Europe and their dependency on disposal concepts were reviewed in the project. Although monitoring programs are expected to vary between countries, the basic reasons for monitoring were identified as follows: (i) to establish baseline conditions, (ii) to demonstrate regulatory compliance, (iii) to support performance assessments, and (iv) to promote awareness of the broader technological, societal, and political context within which the repository program must exist. The keys to a successful monitoring program were identified as the ability to monitor as specified; the ability to interpret data; the ability to monitor without compromising operational safety, barrier performance, and postclosure safety; the ability to monitor under repository environmental conditions; and the ability to monitor over long periods of time in areas that may be remote and where access is difficult. The advantages and disadvantages of different categories of sensors (electrical, optical, and electromagnetic signals) and their respective transmission properties were identified in the project. The final report from this European Commission project provides a good reference for planning and evaluating a monitoring program.

4.3.3 Temperature and Radiation Considerations

Radiation tolerance testing of instruments is not typically performed, but there were a few instances identified in the review where it was necessary. Applied Geomechanics, Inc. (2006) conducted accelerated aging tests on four surface mount tiltmeters in a radiation sterilization facility. The tiltmeters were dosed with 0.36 to 9.76 megarads of gamma radiation from a Cobalt 60 source. The integrated circuits on the printed circuit assemblies in the tiltmeters failed within one hour from the start of irradiation. The resistors and most of the capacitors continued to function after 9.76 megarads of irradiation, and the tilt sensors were undamaged. This testing showed that tiltmeters could be used under radiation conditions as long as the signal conditioning electronics were shielded or the electronics were located in an area that was not irradiated {up to 100 m [328 ft] from the sensor}.

Vibrating wire sensors for different instruments have also been tested and modified for high temperature and corrosive environments. Special titanium sensors were developed for long-term (50 year) monitoring applications at the Äspö site in Sweden. The sensors appear particularly well suited for use in radioactive environments. Over the past 15 years, Geokon, Inc. (2006) has supplied a number of vibrating wire load cells and pressure transducers to the Savannah River Site in Georgia. The load cells were installed in series with a hydraulic ram that pressed a plug into a stainless steel canister used to store vitrified hot waste. The plug was held in place at some specific load and then welded in place by a high amperage resistance weld. The pressure sensors were used to measure the pressure in pipes carrying a nuclear slurry. Electronic sensors originally used for the monitoring gradually broke down as a result of the radiation. The vibrating wire sensors, which are more electromechanical by design, were able to withstand the radioactive regime.

The use of fiber-optics-based instruments for monitoring in radioactive environments is an area

[4]Barlow, S., M. Hugi, and S. Mayer. "Monitoring in a Staged Approach to Disposal." *Poster Presentation at the Euradwaste '04, 6th European Commission Conference on the Management and Disposal of Radioactive Waste, March 29–April 1, 2004*. Luxembourg City, Luxembourg. 2004.

of active research. Based on information from Roctest Telemac (2006), fiber-optics-based sensors may be affected by high radiation, inducing a phenomenon called Glass Darkening due to the formation of colored centers. This is partially reversible by heating the fiber above a certain temperature level, but it is theoretically a limitation for fiber optic sensors in radiation environments. There are certain types of fibers that are more resistant (low OH content) and may be more suited to nuclear applications. Temperatures of 100 °C [212 °F] are manageable with these sensors. Electronic sensors generally do not perform very well because of the noise generated by radiation; therefore, fiber optic sensors may be more suitable depending on the level and type of radiation. Fiber optics instruments reduce the reliance on potentially radiation-sensitive electronics and provide alternate means of measuring displacement, temperature, hydrogen concentration, and radiation dose. Other applications are also possible.

The SOMOS project (Borgemans, et al., 2004) was aimed at developing a long-term reliable fiber-optic monitoring system for nuclear waste repositories. The three sensor types evaluated were exposed to a radiation environment to assess the effects of radiation on performance. A slight shift in calibration data was observed for Fiber Bragg Gratings after irradiation in some cases. These results suggest that further developments in fiber-optics-based instruments are possible and that these instruments are applicable to at least some radioactive environments.

4.4 Recommended Tools and Techniques for Repository Monitoring

The studies at international nuclear waste disposal research sites highlight the use of combined systems of instruments to monitor the development of damage and progressive failure in a repository setting. In most of the cases studied, the emplacement drifts containing the waste packages would be backfilled following waste emplacement, therefore permanently limiting direct access to the emplacement drifts. Based on studies for deep geologic repositories below the water table, the following instruments are recommended for primary use in identifying and quantifying damage and the conditions responsible for its development:

- Multipoint Extensometers—arrays of eight multipoint instruments spaced at regular intervals along an underground opening; vibrating wire technology to be used to minimize temperature effects and increase longevity; special titanium components may be specified to minimize corrosion and radiation effects on electronics (e.g., Geokon, Inc., 2006); adaptable to blocky rock masses by strategically selecting anchor locations; retrievable anchors provide a means of instrument replacement if required.

- Tunnel Profile Monitoring System—arrays of linked mechanical arms to provide continuous automated measurements of tilt and displacement without interfering with normal drift operations; to be installed close to extensometer arrays to provide gross deformation response of the underground opening and changes in tunnel geometry with time; instruments may require special shielding and radiation testing.

- Tunnel Scanning System—regular laser and photo scans of each excavation to provide full coverage of emplacement drifts and a complete record of geometry change with time; instruments are temperature and radiation sensitive and would require modifications for regular application in a hot, radioactive environment; special rail mounts could be devised to allow robotic operation for automated scans.

- Temperature Sensors—multiple instruments deployed either in extensometer array

boreholes or in adjacent arrays to provide a temperature distribution around the opening at regular locations along each emplacement drift; specially-modified, high-temperature titanium vibrating wire instruments provide reliable performance in hot radioactive environments (e.g., Geokon, Inc., 2006); manual thermometer probes can also be used to provide temperature profiles in boreholes, allowing recalibration of the instrument between surveys.

- Piezometers—multiple instruments deployed in arrays of eight boreholes to provide a pore pressure distribution around the opening at regular locations along each emplacement drift; specially-modified, high-temperature titanium vibrating wire instruments provide reliable performance in hot radioactive environments (e.g., Geokon, Inc., 2006); rubber packer systems are likely not robust under extreme environmental conditions.

- Acoustic Emission/Microseismic Monitoring System—arrays of acoustic emission/microseismic sensors deployed in boreholes drilled from surface or from adjacent excavations to place sensors strategically around emplacement drifts; provides ongoing passive monitoring with real-time event location and source mechanism analysis to identify damage development and progressive failure; velocity surveys between sensors can provide an indication of rock mass properties along specific ray paths; triaxial accelerometers or geophones would be specified depending on the rock type and seismic characteristics.

In conjunction with the installation of these instruments, borehole and tunnel-based characterization activities (corelogging, mapping, photography, and borehole imagery) could be conducted to characterize the conditions around the underground openings. Depending on the repository position relative to the groundwater table, borehole transmissivity or neutron logging surveys could be conducted in tandem with interval velocity surveys to develop a baseline of velocity, permeability, and water saturation. Crosshole tomography could be conducted in the extensometer array boreholes to create tomographic images of velocity and dynamic property distribution around the openings. Borehole camera surveys could provide visual evidence of damage. In addition, laboratory testing on the core could provide initial properties for use in numerical modeling for performance evaluation.

These monitoring and characterization activities could be augmented with other tools and techniques depending on the type of support system and materials to be used in a repository. Any instruments installed in the underground openings would have to be designed to sustain high temperature and radiation conditions.

5 APPLICABILITY OF TOOLS AND MONITORING TECHNIQUES AT A POTENTIAL YUCCA MOUNTAIN REPOSITORY

This chapter discusses aspects of a potential repository at Yucca Mountain that may affect the applicability of specific monitoring tools and techniques at the repository. The monitoring aspects of a DOE performance confirmation plan for the potential repository (Bechtel SAIC Company, LLC., 2004) also are discussed.

5.1 Description of the Potential Repository

5.1.1 Site Description

The potential repository at Yucca Mountain would be located in volcanic rocks of the Topopah Spring Tuff unit at a depth of about 200 to 500 m [650 to 1,640 ft] below surface. The water table at the potential site is approximately 500 to 800 m [1,640 to 2,625 ft] below the ground surface. Consequently, the proposed repository would be situated in the unsaturated zone above the water table. The combination of volcanic tuff as the host rock and the repository location above the water table represent two unique aspects of the Yucca Mountain repository concept relative to other international repository concepts.

As detailed in the Yucca Mountain Science and Engineering Report (DOE, 2001), the host rock for a potential repository must be strong enough to sustain the excavation of stable openings that can be maintained during repository operations and that would isolate the waste for an extended period after closure. The rock must also be able to absorb heat generated by the waste without undergoing changes that could threaten the ability of the site to safely isolate the waste. DOE indicated the Topopah Spring Tuff would satisfy these criteria (DOE, 2001).

An important characteristic of the volcanic rock of the Topopah Spring Tuff is the presence and abundance of lithophysae, which are bubble-like holes in the rock caused by trapped volcanic gas at the time of formation. The average lithophysae range from about 1 to 50 cm [0.4 to 20 in], with a maximum size of about 1 m [3.3 ft]. Within the potential repository horizon, there are four distinct zones: the upper lithophysal zone, the middle nonlithophysal zone, the lower lithophysal zone, and the lower nonlithophysal zone.

Fractures are common in the Topopah Spring Tuff unit and provide potential pathways for water to flow through the rock mass. Fracture networks are well-connected except in the lithophysal zones where the degree of connectivity may be lower. Fracture density varies both vertically and laterally with variations in tuff properties.

5.1.2 Repository Excavations

The DOE has considered a repository design at Yucca Mountain with a capacity of 70,000 metric tons of heavy metal. The details of the design are contained in the Yucca Mountain Science and Engineering Report (DOE, 2001) and numerous supporting documents. The design is intended to meet the functional requirements established for the facilities while

maintaining flexibility to accommodate different construction approaches, a variety of radioactive waste container sizes, a range of thermal operating modes, and design optimization to enhance the overall performance of the repository.

Under a high-temperature operating mode scenario, the subsurface area required for waste disposal would be about 1,150 acres. This area would increase to about 2,500 acres if a lower temperature operating mode scenario were adopted. The design entails horizontal emplacement drifts excavated to a 5.5-m [18-ft] diameter at a center-to-center drift spacing of 81 m [266 ft]. The drifts vary in length and would be excavated off the east and west mains with an azimuth of 252 degrees. The drifts would be excavated using a tunnel boring machine, minimizing the damage induced during excavation. Approximately 85 percent of the emplacement drifts would be in the lithophysal horizon and 15 percent in the nonlithophysal zone. The emplacement drift should allow periodic inspection, testing, and maintenance of structures, systems, and components before permanent closure. The design would include other openings (e.g., access mains, ventilation exhaust mains, and raises) and several ventilation shafts (DOE, 2001).

The Performance Confirmation Plan (Bechtel SAIC Company, LLC, 2004) proposes the use of one or two thermally accelerated drifts (i.e., drifts that are artificially heated to assess thermal and thermal-mechanical effects) and associated observation drifts to gain insight into near-field thermal effects. This complements thermal-mechanical testing conducted in the Drift-Scale Test at Yucca Mountain.

5.1.3 Ground Support

According to the Yucca Mountain Science and Engineering Report (DOE, 2001), the functional requirements of the ground support system are to provide structural support for the subsurface repository openings; to protect waste packages against rockfall, loosening of rock blocks, and fracturing and surface deterioration of the rock mass surrounding each opening; to maintain adequate subsurface operating envelopes (dimensional clearances); and to provide for monitoring of ground control performance. Other functional requirements[1] include facilitating waste retrieval, ensuring personnel safety, allowing for geological mapping, and utilizing materials acceptable to performance assessment during postclosure.

[1]Duan, F. and M. Boand. "Ground Support Studies and Design Status." *Presentation to NRC Repository Design and Thermal-Mechanical Effects Key Technical Issue Technical Information Exchange, Las Vegas, Nevada, May 6–8, 2003. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 2003.*

A ground support design described by DOE[2] involves the use of 3.0-m [10-ft]-long stainless steel friction bolts spaced at 1.25 m [4 ft] supporting 3-mm [0.1]-thick Bernold-type perforated stainless steel sheets installed in a 240 degree arc around the drift periphery for the full length of each emplacement drift. DOE explained that it expects the design to meet the design criteria of compatibility with rock mass geology and potential failure modes; monitoring, inspection, and maintenance; material acceptability and longevity; constructability; and flexibility. Figure 5-1 is a schematic drawing of the most recent emplacement drift design, showing the support system and the engineered barriers.[3] Modified support designs would be used for the nonemplacement openings,[4] including the use of full grouted carbon steel rock bolts supporting welded wire fabric.

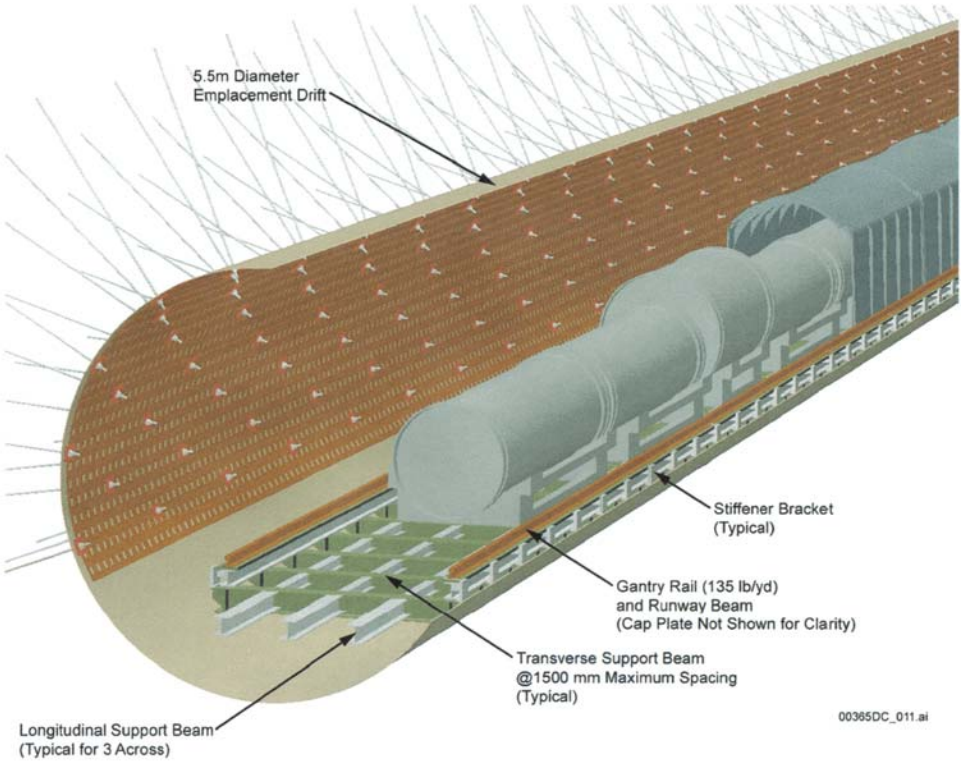


Figure 5-1. Schematic Drawing of Ground Support and Engineered Barriers in an Emplacement Drift (Harrington, 2003)

[2]Harrington, P. "Repository Design Status." *Presentation to the Advisory Committee on Nuclear Waste, 147th Meeting, November 19–20, 2003.* Las Vegas, Nevada. 2003. <www.nrc.gov/reading-rm/doc-collections/acnw/tr/2003/nw111903.pdf>

[3]Ibid.

[4]Duan, F and M. Board. "Ground Support Studies and Design Status". *Presentation at the U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange on Repository Design and Thermal-Mechancial Effects, May 6–8, 2003.* Las Vegas, Nevada. 2003.

5.2 Underground Monitoring at Yucca Mountain

5.2.1 General

Different types of monitoring likely would be performed during various phases of a repository at Yucca Mountain. Preclosure safety monitoring would be conducted to provide a safe working environment for onsite personnel and visitors during the preclosure period. This would include safety measures such as fire sensors and alarms and radon gas measurement. Performance confirmation would include geologic mapping of subsurface conditions, monitoring of conditions in and around emplacement drifts, monitoring of other factors important to postclosure performance, and assessment of postclosure implications. The monitoring activities should be such that would not adversely affect the ability of the natural and engineered barrier systems to meet the performance objectives.

As pointed out by Simmons, et al. (2003), it is important that the recorded monitoring data are true representations of processes taking place in the repository, not artifacts of the instrumentation system or its effect on the local environment. This implies that more than one technique would be needed for observing parameters related to important processes occurring within a repository. Furthermore, testing of the monitoring system components should establish the reliability of both the instruments and the collected data. The major instrument design issues include longevity of the instrumentation and systems; maintenance, replacement, and calibration of the instrumentation *in situ*; and effective noninvasive postclosure monitoring that does not affect repository safety or waste isolation.

5.2.2 DOE Performance Confirmation Plan

Based on a description provided in the Yucca Mountain Science and Engineering Report (DOE, 2001), performance confirmation monitoring would be conducted from a series of observation drifts located at a different depth than the emplacement drifts. The observation drifts would be used to provide access to drill boreholes for monitoring instruments. The temperature in the drifts would reach approximately 46 °C [115 °F], within the acceptable range for human access. Radiation within the observation drifts would not exceed natural background levels as the drifts are not directly connected to the emplacement drifts. Fiber-optics technology would be deployed in the observation drifts to provide a communication link to dataloggers located outside the openings in alcoves.

In addition to the observation drifts, ventilation cross-drifts at the same elevation as the emplacement drifts, and other experimental drifts and ventilation openings, could be used for further instrumentation. The datalogging equipment and other instruments would be located in alcoves. For example, seismometers would be located in two seismic alcoves to monitor the subsurface response to potential seismic events.

A remote radio-controlled inspection gantry would perform routine inspections and collect data within the emplacement drifts. The gantry would be electric, using the emplacement drift rail system. An onboard high-resolution articulated, closed-circuit television camera and a series of high-intensity lights; thermal and radiological sensing instruments; and possibly other instruments would provide real-time data during inspections.

DOE indicated that the development and testing of instrumentation and monitoring technologies

would be undertaken to qualify their functionality in high temperature and high radiation environments. Candidate technologies would be field tested to investigate how to minimize downtime associated with instrument failures, replacement, and recalibration.

5.2.3 Monitoring Aspects of the DOE Performance Confirmation Plan

The Performance Confirmation Plan (Bechtel SAIC Company, LLC, 2004) describes a strategy to (i) collect, evaluate and, report data used to confirm the basis for estimates of repository performance; and (ii) preserve the ability to retrieve waste. The regulatory requirements (10 CFR 63 Subpart F—Performance Confirmation Program) that should be addressed through a performance confirmation plan include:

- Confirm that subsurface conditions, geotechnical, and design parameters are as anticipated and that changes to these parameters are within the limits assumed in the Licence Application.
- Confirm that the waste retrieval option is preserved.
- Evaluate the effectiveness of design features intended to perform a postclosure function during repository operation and development.
- Monitor the waste package condition.

Considering these requirements in the context of the natural and engineered barriers of the potential repository, 20 monitoring and testing activities are identified in the Performance Confirmation Plan (Table 5-1). Each selected activity may combine parameters that relate to a specific feature of barrier capability, total system performance, or regulatory requirements. Some activities support confirmation of waste retrievability, or disruptive events parameter confirmation. The activities would be planned in detail using technical work plans and performance confirmation test plans, which would be implemented using field work packages, technical procedures, scientific notebooks, and a process of work orders and test work authorization for field work. The phased nature of repository construction would allow progressive development of performance confirmation approaches. Performance confirmation would continue during repository construction and through operational emplacement of waste, concluding if and when repository closure is licensed.

Of the activities listed in Table 5-1, several relate specifically to drift stability, and confirmation of waste retrievability. *In situ* drift stability would be confirmed primarily by monitoring rockfall in the underground facility using regular inspection of nonemplacement drifts and periodic inspection of emplacement drifts (Drift Inspection). The mechanical condition of thermally accelerated emplacement drifts would be monitored to detect significant physical changes or degradation in drifts (Thermally Accelerated Drift Thermal-Mechanical Monitoring). Mechanical and deformational response of the emplacement and main drift excavations would be monitored prior to emplacement (Construction Effects Monitoring). The test methods described in the Performance Confirmation Plan reflect general approaches and demonstrate one or more possible methods for meeting the objectives of each test. The descriptions would be modified as needed in the Performance Confirmation Test Plans to support eventual implementation and accommodate future advances in technology and investigative approaches. Activities that are currently planned to take place in loaded emplacement drifts include seepage monitoring,

periodic inspection of drifts to confirm retrievability of waste packages, dust build-up monitoring, and monitoring of waste packages. The main activities in the Performance Confirmation Plan that are related directly or indirectly to monitoring the performance of underground excavations and long-term response of the surrounding rock mass are described in the following subsections.

5.2.3.1 Drift Inspection

DOE indicates its planning for drift inspection is at a preliminary stage and is based mainly on monitoring conducted in the Exploratory Studies Facility, alcoves and enhanced characterization of repository block cross drift. Monitoring is based largely on visual observations made using remote cameras recording video, still, and infrared images. Stereographic photography is considered a means of quantifying changes in the drift geometry. Collection of supporting information on in-drift environmental conditions (e.g., temperature and radiation level) is also envisioned, but there are no specific details regarding equipment or instrumentation for these purposes. Convergence measurement data using remote monitoring equipment is mentioned but no details are provided. Regularly scheduled monitoring of selected emplacement drifts will be performed. Following significant seismic events, monitoring emphasis will be directed at areas with susceptible geologic features identified during emplacement drift mapping to evaluate movement or damage to engineered systems.

5.2.3.2 Thermally Accelerated Drift Near-Field Monitoring

The near-field properties in the immediate vicinity of the thermally accelerated drifts would be monitored as a surrogate for anticipated conditions during the thermal pulse and changes that may result after the thermal pulse in the fractured unsaturated rock above and below the repository horizon. Monitoring would be conducted periodically at an interval not yet determined. Three field thermal tests have been conducted to obtain an understanding of the thermal-hydrologic-mechanical-chemical coupled processes and to provide data for enhancing confidence in the model analyses: the Drift-Scale Test, Large-Block Test, and the Single-Heater Test (Bechtel SAIC Company, LLC, 2004). These tests provide the preliminary basis for this monitoring activity.

DOE indicates monitoring would be largely borehole-based in this activity, with arrays of boreholes drilled dry from remote openings or alcoves. Rock cores would be used for assessing *in situ* moisture content and water chemistry. In-hole neutron and induction logging techniques are planned to provide direct measurements of *in situ* moisture content in the vicinity of boreholes, while crosshole tomography using electrical resistivity and ground-penetrating radar surveys is planned to provide information on moisture distribution in crosshole panels. Air permeability tests in selected boreholes will provide direct measurement of fracture permeability. Water samples from these boreholes will be collected and analyzed to assess the source of the seepage water.

Table 5-1. Summary of Monitoring and Testing Activities in the U.S. Department of Energy Performance Confirmation Plan*					
Activity	**Description**	**Candidate Parameters**	**Purpose**	**Barrier or Process**	**Tools and Techniques**
General Requirements Testing and Monitoring (Natural and Engineered Barriers)					
Precipitation monitoring	Monitoring of precipitation and composition analysis	Precipitation rate, quantity, spatial and temporal distribution, and chemical composition (hydrochemistry)	To evaluate the precipitation input parameters that relate to seepage modeling	Upper Natural Barrier	Tipping bucket gauge, storage gauge, chemical analysis
Seepage monitoring	Seepage monitoring and laboratory analysis of water samples (from bulkheaded alcoves on the intake side of the repository and in thermally accelerated drifts)	Seepage rate, locations, quantity and chemical composition, ventilation air barometric pressure, ventilation air temperature, ventilation air relative humidity	To evaluate results from the seepage model	Upper and Lower Natural Barriers	Seepage monitoring (video of locations and flow rate measurements) and sampling, chemical analysis of seepage, barometric pressure transducers, humidity and temperature probes, wind speed sensors, and thermocouple psychrometers
Subsurface water and rock testing	Laboratory analysis of chloride mass balance and isotope chemistry based on samples taken at selected locations of the underground repository	Chloride mass balance; isotopic composition for U, Sr, O, ^{3}H, $^{36}Cl/Cl$, ^{99}Tc, and $^{129}I/^{127}I$	To evaluate assumptions for fast paths used in unsaturated zone model	Upper and Lower Natural Barriers	Pore water chloride and rock/fracture coating isotope sampling from core, ion chromatography, isotope and dissolved ion analysis, bulk rock analyses, fracture coating analyses

Table 5-1. Summary of Monitoring and Testing Activities in the U.S. Department of Energy Performance Confirmation Plan* (continued)					
Activity	**Description**	**Candidate Parameters**	**Purpose**	**Barrier or Process**	**Tools and Techniques**
General Requirements Testing and Monitoring (Natural and Engineered Barriers)					
Unsaturated zone testing	Testing of transport properties and field sorptive properties of the crystal-poor member of the Topopah Spring Tuff in an ambient seepage alcove or a drift	Sorption parameters, van Genuchten parameters describing fractures and matrix, colloid or colloid facilitated transport parameters, fracture density, apertures, coatings, air permeability, seepage, alcove temperature, and relative humidity	To evaluate sorption coefficients used in the unsaturated zone model	Upper and Lower Natural Barriers	*In situ* transport and sorption testing, fracture mapping, single and crosshole air-injection and water release testing, crosshole tracer testing, unsaturated flow testing, relative humidity and temperature monitoring, laboratory analysis of samples
Saturated zone monitoring	Monitoring of water level and hydrochemical sampling of the saturated zone upgradient beneath and downgradient of Yucca Mountain	Water level and hydrochemical indicators (Eh, pH, radionuclide concentrations, colloid characteristics)	To evaluate hydrologic and chemical parameters used with the saturated zone flow model	Lower Natural Barrier	Water level monitoring in wells, sampling and analysis of water chemistry

Table 5-1. Summary of Monitoring and Testing Activities in the U.S. Department of Energy Performance Confirmation Plan* (continued)					
Activity	**Description**	**Candidate Parameters**	**Purpose**	**Barrier or Process**	**Tools and Techniques**
General Requirements Testing and Monitoring (Natural and Engineered Barriers)					
Saturated zone fault hydrology testing	Hydraulic and tracer testing of fault zone hydrologic characteristics, including anisotropy, in the saturated zone	Transmissivity, hydraulic conductivity, water flux or specific discharge, effective flow porosity, longitudinal dispersivity, sorption parameters, parameters describing diffusion between flowing and stagnant water, and colloid or colloid-facilitated transport parameters (Eh, pH, natural colloid concentrations, including anisotropy)	To evaluate fault parameter assumptions in the saturated zone flow and transport models	Lower Natural Barrier	Monitoring of water levels during ambient and stress conditions, field sample collection, *in situ* and laboratory analysis of samples, single and crosshole hydraulic pumping and tracer tests using hydraulic packer systems
Saturated zone alluvium testing	Tracer testing at the Alluvial Test Complex using multiple boreholes measuring parameters in the alluvium	Transmissivity, hydraulic conductivity, water flux and specific discharge, effective flow porosity, longitudinal dispersivity, sorption parameters, parameters describing diffusion between flowing and stagnant water, and colloid or colloid-facilitated transport parameters (Eh, pH, natural colloid concentrations	To evaluate inputs and assumptions for the saturated zone flow and transport models	Lower Natural Barrier	Monitoring of water levels during ambient and stress conditions, field sample collection, *in situ* and laboratory analysis of samples, single and crosshole hydraulic pumping and tracer tests using hydraulic packer systems, injection pump back testing

Table 5-1. Summary of Monitoring and Testing Activities in the U.S. Department of Energy Performance Confirmation Plan* (continued)					
Activity	**Description**	**Candidate Parameters**	**Purpose**	**Barrier or Process**	**Tools and Techniques**
General Requirements Testing and Monitoring (Natural and Engineered Barriers)					
Drift inspection	Regular inspection of nonemplacement drifts and periodic inspection of emplacement drifts, thermally accelerated drifts, and other underground openings using remote measurement techniques, as appropriate	Temperature (as a surrogate indicator of evaporating seepage), seepage, rockfall size and frequency monitoring, ground support conditions, engineered barrier component positions, drift continuity	To evaluate drift stability assumptions, both within emplacement drifts and non-emplacement drifts, and rockfall size or probability distributions. Also supports confirmation of retrievability	Engineered Barrier System, Retrievability	Gantry-mounted sensors to measure temperature and other environmental conditions; cameras (with stereographic, video, still, and infrared capabilities) to make observations of potential drift seepage, crown or rib degradation, rail or waste package misalignment, obstruction or damage; convergence rate measurements using remote sensing equipment.

Table 5-1. Summary of Monitoring and Testing Activities in the U.S. Department of Energy Performance Confirmation Plan* (continued)					
Activity	**Description**	**Candidate Parameters**	**Purpose**	**Barrier or Process**	**Tools and Techniques**
General Requirements Testing and Monitoring (Natural and Engineered Barriers)					
Thermally accelerated drift near-field monitoring	Monitoring of near-field coupled processes (thermal-hydrologic-mechanical-chemical) properties and parameters associated with the thermally accelerated drifts	Rock mass moisture content, temperatures, air permeability (fracture permeability), mechanical deformation, mechanical properties, water chemistry	To evaluate coupled process results from the thermal-hydrologic-chemical-mechanical models	Upper and Lower Natural Barriers	Borehole-based monitoring in arrays drilled from remote openings or alcoves; core testing for moisture content and hydrochemical analyses; neutron and induction in-hole logging for moisture content measurements; electrical resistivity tomography and ground penetrating radar crosshole surveys; air permeability testing; hydrochemical analysis from borehole water samples; rock displacement measurements using multi-point borehole extensometers, acoustic emissions, or tiltmeters temperature monitoring; stress measurement
Dust buildup monitoring	Monitoring and laboratory testing of quantity and composition of dust on engineered barrier surfaces	Quantity, physical properties, and chemical composition of dust deposited on waste package, drip shield, rail, and ground support surfaces	To evaluate assumptions of dust buildup and potential chemical effects	Engineered Barrier System	Remotely operated vehicle equipped with cameras and remote sampling devices to collect samples laboratory analysis of dust composition

Table 5-1. Summary of Monitoring and Testing Activities in the U.S. Department of Energy Performance Confirmation Plan* (continued)					
Activity	**Description**	**Candidate Parameters**	**Purpose**	**Barrier or Process**	**Tools and Techniques**
General Requirements Testing and Monitoring (Natural and Engineered Barriers)					
Thermally accelerated drift in-drift environment monitoring	Monitoring and laboratory testing of gas composition; water quantities, composition, and ionic characteristics (including thin films); microbial types and amounts; and radiation and radiolysis within a thermally accelerated drift	Temperature, relative humidity, gas composition, radionuclides, pressure, and radiolysis, thin films evaluation, condensation water quantities, composition, and ionic characteristics including microbial effects	To evaluate assumptions used in in-drift physical and chemical environment models	Engineered Barrier System	Sampling and analysis of water (ionic species), gas (atmospheric and effects of radiolysis), microbial species; monitoring of radiation, temperature and relative humidity
Geotechnical and Design Monitoring and Testing					
Subsurface mapping	Mapping of fractures, faults, stratigraphic contacts, and lithophysal characteristics	Fracture characteristics, fault zone characteristics (offset, location, age), stratigraphic contacts, and lithophysal characteristics	To evaluate results from integrated site models	Upper and Lower Natural Barriers	Field mapping of fractures, faults, stratigraphic contacts, and lithophysal characteristics; limited sampling for laboratory examination; high resolution digital photography to create a mapping base
Seismicity monitoring	Monitoring regional seismic activity; observation of subsurface and surface (large magnitude) fault displacement after significant local or regional seismic events	Event detection, event magnitude, event location, strong-motion data collection and analysis, seismic attenuation investigations {within 50 km [31 mi]}.	To evaluate annual probability distribution as a function of intensity	Disruptive Event, Retrievability	Seismometers and digital recorders in a seismic monitoring network; geologic assessment of fault displacements associated with earthquake events

Table 5-1. Summary of Monitoring and Testing Activities in the U.S. Department of Energy Performance Confirmation Plan* (continued)					
Activity	**Description**	**Candidate Parameters**	**Purpose**	**Barrier or Process**	**Tools and Techniques**
Geotechnical and Design Monitoring and Testing					
Construction effects monitoring	Monitoring construction deformation and measurement of mechanical properties	Drift convergence, tunnel stability, engineered ground support systems, geotechnical parameters at selected locations	To evaluate tunnel stability assumptions under ambient conditions	Upper Natural Barrier, Retrievability	Strain gages, convergence arrays, single- and multipoint borehole extensometers, and rock bolt load cells; camera and laser deformation monitoring and observations to be tested
Thermally accelerated drift thermal-mechanical monitoring	Monitoring drift and invert shape and integrity in a thermally accelerated drift	Drift convergence, drift shape, drift degradation, ground support visual condition, rail alignment, invert visual condition, pallet visual condition, waste package alignment, and spacing	To evaluate drift degradation assumptions under thermal conditions	Engineered Barrier System, Retrievability	Strain gages, convergence arrays, single- and multipoint borehole extensometers, and rock bolt load cells; camera and laser deformation monitoring and observations to be tested

Table 5-1. Summary of Monitoring and Testing Activities in the U.S. Department of Energy Performance Confirmation Plan* (continued)					
Activity	**Description**	**Candidate Parameters**	**Purpose**	**Barrier or Process**	**Tools and Techniques**
Design Testing (Other than Waste Package)					
Seal testing	Laboratory testing of effectiveness of borehole seals followed by field-testing of effectiveness of ramp and shaft seals; testing, as appropriate, to evaluate the effectiveness of backfill placement	Borehole seals materials, configuration, performance; shaft seals materials, configuration, performance; ramp seals materials, configuration, performance; laboratory and field hydraulic and pneumatic seal effective permeability	To evaluate design assumptions for effective seals	Engineered Barrier System, Upper Natural Barrier	Laboratory and field testing of borehole seals and sealing technologies; large-scale field testing of shaft and ramp seals and sealing technologies; air permeability testing; associated materials testing

Table 5-1. Summary of Monitoring and Testing Activities in the U.S. Department of Energy Performance Confirmation Plan* (continued)					
Activity	**Description**	**Candidate Parameters**	**Purpose**	**Barrier or Process**	**Tools and Techniques**
Monitoring and Testing of Waste Packages					
Waste package monitoring	Remote monitoring for evidence of external corrosion of the waste package	External visual corrosion and possibly internal pressure of the waste package	To evaluate waste package integrity and confirm the absence of leakage and leak paths	Engineered Barrier System	Visual observation of waste packages and future technologies to sense differential pressure between waste package interior and outer sections
Corrosion testing	Corrosion testing in the laboratory of waste package, waste package pallet, and drip shield samples in the range of representative repository thermal and chemical environments; laboratory testing of general corrosion, phase transformations of Alloy 22, and localized corrosion	Alloy 22, Type 316 stainless steel, and titanium alloys (Grade 7 and 24) mass loss rate; passive current density; surface dissolution; open circuit potential, critical potential; stress crack corrosion; microbial effects; surficial passive film stability; and mechanical properties	To evaluate results of corrosion models	Engineered Barrier System	Planned interval laboratory tests for general corrosion and other types of corrosion as per ASTM standards; passive film analysis; thermal aging testing to assess phase transformation and changes in mechanical properties; electrochemical testing

Table 5-1. Summary of Monitoring and Testing Activities in the U.S. Department of Energy Performance Confirmation Plan* (continued)					
Activity	**Description**	**Candidate Parameters**	**Purpose**	**Barrier or Process**	**Tools and Techniques**
Monitoring and Testing of Waste Packages					
Corrosion testing of thermally accelerated drift samples	Corrosion testing in the laboratory of waste package, waste package pallet, and drip shield samples exposed to conditions in the thermally accelerated drifts; corrosion model applicability and laboratory testing of general corrosion, phase transformations of Alloy 22, and localized corrosion,	Thermally accelerated drifts exposed Alloy 22, Type 316 stainless steel, and titanium alloys (Grade 7 and 24) mass loss rate, passive current density, surface dissolution, open circuit potential, critical potential, stress crack corrosion, microbial effects, surficial passive film stability, and mechanical properties	To evaluate results of corrosion models	Engineered Barrier System	Planned interval laboratory tests for general corrosion and other types of corrosion as per ASTM standards, passive film analysis, thermal aging testing to assess phase transformation and changes in mechanical properties, electrochemical testing

Table 5-1. Summary of Monitoring and Testing Activities in the U.S. Department of Energy Performance Confirmation Plan* (continued)					
Activity	**Description**	**Candidate Parameters**	**Purpose**	**Barrier or Process**	**Tools and Techniques**
Monitoring and Testing of Waste Packages					
Wasteform testing	Wasteform testing (including waste package coupled effects) in the laboratory under anticipated in-package conditions	Radionuclide release rate; dissolution rate; environmental and hydrochemical indicators (Eh, pH, colloid characteristics); bare waste form dissolution; fuel rod wasteform dissolution, including cladding degradation, failure and unzipping rate, and wasteform/waste package performance under coupled chemical environments	To evaluate results of wasteform degradation models and evaluate in-package expected conditions	Engineered Barrier System	Laboratory testing (including wasteform/package coupled effects) under internal waste package conditions to monitor water accumulation from humid air exposure, water chemistry, and the mobile fractions of annual dose-critical radionuclides to evaluate source-term models

*Bechtel SAIC Company, LLC. "Performance Confirmation Plan." TDR–PCS–SE–000001. Rev. 05 ICN 00. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004.

In addition to investigating hydrogeologic aspects of the near-field, *in situ* stress and displacement would be monitored. Displacement monitoring would be accomplished using either multipoint extensometers installed in boreholes or arrays of high resolution tiltmeters to investigate development of a three-dimensional deformation field in the heated rock mass. Acoustic emission monitoring is also mentioned, but no details are provided on how this figures into the overall monitoring scheme. In general, a large number of tiltmeters would be needed to assess the deformation field around an underground opening, particularly in fractured or blocky rock. Likewise, extensometers would provide point measurements at specific locations but are prone to complications from fractures if boreholes are not logged before instrument deployment. These aspects are not discussed in the DOE Performance Confirmation Plan.

The importance of stress measurements is emphasized to confirm the expected reversal in principal stress directions upon heating, identify stress-induced failures, and detect stress reductions related to sudden deformation caused by fracturing or failure of the rock mass, however, specifics on such measurement techniques are not provided for this activity. Like displacement monitoring, stress change monitoring in fractured rock (with or without lithophysae) is complicated by the discontinuous nature of the rock mass. Point measurements of stress change may or may not be representative of stress changes in the near-field resulting from heating the rock mass. Pressurized slot testing in the Exploratory Studies Facility and enhanced characterization of repository block cross-drift are given as examples of *in situ* methods that have been used previously to develop a strength envelope for the *in situ* rock mass. However, given geologic variability within the repository horizon, these results may be location-specific.

To assess coupled thermal-mechanical and thermal-hydraulic effects, commercially available resistive temperature devices or other types of temperature sensors would be installed in arrays of vertical boreholes. These instruments would measure near-field temperature distribution with time. This type of installation could also be completed in other array configurations provided there are enough point measurements to accurately contour the temperature data.

5.2.3.3 In-Drift Monitoring in the Thermally Accelerated Drift

This companion activity to the other activities associated with the thermally accelerated drifts is focused on determining the characteristics of gas, water, microbes, and radiation/radiolysis within the drift environment. In addition, monitoring in-drift temperature, radiation level, and relative humidity is planned. These monitoring parameters are of general use in planning inspections and interventions in the case of off-normal conditions. These measurements should be supplemented with ongoing monitoring of barometric pressure and wind speed to assess ventilation performance.

5.2.3.4 Subsurface Mapping

This activity provides basic data for assessing the stability of drifts. Digital photography will be used to create photomosaic bases for underground mapping. The mapping results are used to create perimeter maps of the underground openings and to confirm geologic models. Emplacement drifts will be mapped once each drift is completed, the tunnel boring machine and construction utilities are removed, and the exposed rock is cleaned using a specially-designed, high-pressure air and water system. Permanent ground support will be installed following geological mapping, thus precluding comparative mapping at later stages. Visual changes in

the character of geologic features may therefore be difficult to assess after ground support is in place, depending on the type of support system employed. Mapping in unsupported drifts may pose a hazard to personnel and may require a mobile protective cage to reduce risk associated with potential rockfalls. The introduction of water to the exposed rock may also accelerate degradation of the near-field rock mass.

Non-emplacement drifts will be mapped immediately behind the trailing gear of the tunnel boring machine with permanent ground support in place. Shaft mapping will be conducted in a similar fashion from the bottom deck of the shaft sinking Galloway or from a specially designed mapping platform. Depending on the type of ground support, geologic maps of these openings will not be as detailed as those from the emplacement rooms.

5.2.3.5 Construction Effects Monitoring

This activity provides direct measurement of the performance of underground openings in the repository under ambient temperature conditions, focussing on drift convergence, tunnel stability, and engineered ground support systems. Evaluation of rock properties at select locations is also included in this activity. These parameters are expected to vary spatially within the repository. Measurements are intended to be used to back-calculate rock mass moduli.

Previous construction monitoring in the Exploratory Studies Facility and enhanced characterization of repository block cross drift focussed primarily on assessing drift stability using strain gages installed on steel sets, vertical and horizontal tunnel convergence pins, single- and multipoint-borehole extensometers in the near-field, and rock bolt load cells. Similar techniques are planned to monitor construction effects in repository excavations. In addition, testing of camera and laser monitoring of drift deformations prior to waste emplacement will be conducted to assess these techniques for use in monitoring emplacement drifts following waste emplacement.

The proposed monitoring provides relevant information on tunnel performance under ambient temperature conditions but may be limited by in-drift installation of instruments. Typically up to about one-third of tunnel convergence occurs ahead of the tunnel face; consequently, installation of displacement instruments close to the advancing face will miss a significant portion of the rock mass deformation response. Also, near-field rock mass behavior may become increasingly nonlinear/nonelastic with distance from the tunnel face, thus complicating the analysis of measured convergence data. Read (1994) demonstrated that convergence measurements alone are insufficient to back-calculate the *in situ* stress tensor and that the ratio of principal stresses and the constitutive behavior of the near-field rock mass may preclude reliable stress back analysis or assessment of excavation damage and rock mass moduli. The missed portion of the convergence response was also shown to vary as a function of the axial stress component, tunnel face shape, and other parameters. The use of load cells to measure rock bolt loads is an accepted practice that can be automated to provide near-real time monitoring data.

5.2.3.6 Thermally Accelerated Drift Thermal-Mechanical Monitoring

DOE indicates this activity would involve monitoring the stability and condition of thermally accelerated emplacement drifts, specifically drift convergence, drift shape, drift degradation, ground support visual condition, rail alignment, invert visual condition, pallet visual condition,

waste package alignment, and spacing. Results would be used to evaluate drift degradation assumptions and analyses under thermal conditions and would provide direct confirmation of drift stability. This activity is a follow-up to the construction effects monitoring and drift inspection activity under thermal conditions and is based on similar deformation monitoring tools and techniques. Measurements of vertical and horizontal closure may be hampered by the emplaced waste packages and the high temperature, high radiation environment. Remote monitoring using both cameras and lasers is envisioned to provide stereographic observations and measurements of drift deformation. Measurements using these devices will initially be taken monthly and will likely decrease in frequency as time passes.

Automated convergence measurements using tunnel profile monitoring, for example, are not considered in the Performance Confirmation Plan, albeit the specific details associated with this monitoring activity are yet to be defined. Provision for additional space between waste packages in select locations could also be considered to overcome line-of-sight issues. In addition, the plan does not mention extending the monitoring strategy developed in this and related activities (Construction Effects Monitoring and Drift Inspection) for general application in emplacement drifts. Monitoring one or two thermally accelerated drifts may provide information to test numerical models of drift performance, but the results may be difficult to use for repository-wide applications because of the variability of rock conditions.

6 MONITORING UNDERGROUND OPENINGS AT A POTENTIAL YUCCA MOUNTAIN REPOSITORY

This chapter provides a discussion of tools and techniques likely to be applicable for monitoring the performance of underground openings at a potential Yucca Mountain repository. A discussion also is provided on using site-specific contingency planning aimed at identifying and rectifying changing ground conditions as necessary to reduce the need for more extensive repair.

6.1 Monitoring System Description

Thompson and Simmons (2003) describe an approach to long-term monitoring that uses both non-invasive and invasive methods. Non-invasive measurements use remote methods or boreholes less than 10-m [32-ft] deep drilled from the surface to avoid penetrating the waste exclusion zone (i.e., a buffer zone around the repository). Invasive measurements require the drilling of boreholes from the surface or from the excavated underground openings. In any monitoring program, it is important to minimize perturbations to the rock mass caused by the instrument installation. Any boreholes that penetrate the near-field rock mass within the waste exclusion zone, for example, must be constructed with care to avoid creating a preferred pathway for groundwater movement. Monitoring component and demonstration tests is viewed as one means of assessing the long-term behavior of specific repository sealing systems and components that might otherwise be compromised by monitoring in emplacement drifts. The thermally accelerated drifts proposed for Yucca Mountain could be an example of component testing to assess the reliability of long-term drift stability and degradation predictions.

At Yucca Mountain, the disposal design may not include backfilling the emplacement drifts. This important distinction relative to other disposal concepts, coupled with the fact that the repository would be located in the unsaturated zone above the water table, and that the emplacement drifts would be supported using mechanical systems, may allow the use of certain unique monitoring options for underground openings during the preclosure period. Such conditions may allow preclosure monitoring installations both within the emplacement drift and in boreholes drilled from the emplacement drift (if permitted). In concert with instruments in other boreholes drilled from the observation drifts (and perhaps the ventilation and access mains), there would be an opportunity to provide broad coverage of the near-field rock mass around at least some of the emplacement drifts. The instruments installed in the emplacement drifts would be retrievable (where possible) to allow repair, recalibration, and removal as needed. All instruments, with the exception of designated long-term, noninvasive installations near the surface, would be removed at the end of the preclosure period where practicable. Any instruments installed in the emplacement drifts should be designed to sustain high temperature and radiation conditions.

Various tools and techniques likely to be applicable for monitoring the performance of repository excavations and related responses of the near-field rock mass at Yucca Mountain are listed in Table 6-1. The tools and techniques are focussed primarily on measuring changes in stress, displacement, temperature, and physical characteristics of the rock mass associated with excavation-damage development and instability. Piezometers and other hydraulic instrumentation are not included due to the unsaturated conditions at the repository horizon. Humidity sensors in the emplacement drifts could be used to detect changes in seepage. Drift temperature and ventilation conditions could also be monitored to provide supporting

information required for drift inspections. Characterization activities (e.g., corelogging, mapping, and laboratory testing to confirm rock mass characteristics) could be conducted routinely to augment the knowledge-base regarding the near-field rock mass around the emplacement drifts. Other complementary techniques described in Table A–1 to monitor hydraulic and chemical conditions, or changes in related properties, could also be incorporated as part of an overall monitoring effort, but are beyond the scope of this report.

The tools and techniques identified in Table 6-1 for monitoring repository excavations are, in general, similar or more advanced than those described in the Performance Confirmation Plan. Recognizing that many of the activities in the Performance Confirmation Plan would not be undertaken until construction, it is anticipated that the details of these activities would be developed progressively. The monitoring experience summarized in this report may therefore provide a valuable resource for reviewing a detailed plan.

6.2 Contingency Planning and Maintenance to Reduce Need for Extensive Repair

6.2.1 Alarm Conditions

In conjunction with monitoring instrumentation, it is necessary to establish baseline monitoring data and alarm thresholds for different types of instruments. Alarm thresholds are associated with specific decision points and actions as described in the general methodology for data management in the Performance Confirmation Plan (Bechtel SAIC Company, LLC, 2004). Baseline monitoring provides an indication of the normal range of specific parameters. Alarm thresholds are based on design limits or other critical values associated with a particular parameter. For some measurements, such as rock bolt load, the measured value can be compared directly to a design limit. For other types of data, such as microseismic or displacement data, a certain amount of interpretation is needed to determine an alarm condition. For example, a certain level of microseismic activity (events per hour) or localization of the microseismic events may trigger an alarm.

An important characteristic of alarm thresholds is that they are site-specific and, therefore, unique for each installation. The alarm thresholds would be revised as necessary as a project matures, based on an increase in knowledge about rock mass response and associated implications for repository performance. In the Canadian disposal plan, for example, action levels will be defined and monitoring results will be compared with these levels to determine whether any action needs to be taken. Each action level will be defined with respect to an observable condition or a measurable parameter value (Atomic Energy of Canada Limited, 1994).

Table 6-1. Summary of Tools and Techniques Likely Applicable for Monitoring Performance of Underground Openings at a Potential Yucca Mountain Repository			
Parameter	**Instruments**	**Location**	**Monitoring Frequency**
Near-field displacement pattern with time	Vibrating wire multipoint extensometers	Installed using retrievable anchors in two-dimensional arrays of eight boreholes drilled from within the emplacement drifts and complementary boreholes drilled from observation drifts; hole collars would be sealed and shielded to prevent seepage into drifts and radiation exposure of instruments; can be replaced or recalibrated, if necessary	Automated continuous
Near-field temperature distribution with time	Vibrating wire temperature sensors or thermocouples	Installed in boreholes drilled from the emplacement drifts or the observation drifts to provide coverage of the near-field; hole collars would be sealed and shielded to prevent seepage into drifts and radiation exposure of instruments; can be replaced or recalibrated, if necessary	Automated continuous
Near-field stress changes with time	Vibrating wire stress cells or borehole deformation gauge	Stress monitoring instruments installed in radial boreholes drilled from the emplacement drift; hole collars would be sealed and shielded to prevent seepage into drifts and radiation exposure of instruments; can be replaced or recalibrated, if necessary	Automated continuous
Near-field seismic velocity with time	Geophones or accelerometers	Crosshole tomography between radial boreholes in the emplacement drift; requires dedicated boreholes with fixed sensors and shielding at the hole collar	Automated intermittent
Near-field acoustic emissions and microseismicity	Acoustic emission/ microseismic (AE/MS) monitoring system	Arrays of acoustic emission/ microseismic sensors deployed in boreholes drilled from observation drifts to place sensors strategically around emplacement drifts; sensors grouted in place	Automated continuous

Table 6-1. Summary of Tools and Techniques Likely Applicable for Monitoring Performance of Underground Openings at a Potential Yucca Mountain Repository (continued)			
Parameter	**Instruments**	**Location**	**Monitoring Frequency**
Near-field fracture characteristics with time	Borehole camera surveys	Arrays of dedicated boreholes drilled from the emplacement drift or observation drift to characterize the fracture patterns and changes in fracture aperture in the near-field	Manual intermittent
Near-field water saturation pattern with time	Thermal neutron probe and electrical resistivity tomography	Surveys in available boreholes to measure water saturation profiles; can be repeated if boreholes are not used for other purposes	Manual intermittent
Near-field permeability with time	Air permeability injection or vacuum system	Surveys in available boreholes to measure permeability profiles; can be repeated if boreholes are not used for other purposes	Manual intermittent
Changes in two-dimensional tunnel geometry with time	Tunnel profile monitoring system	Installed on the drift perimeter close to extensometer arrays within the emplacement drifts; shielding of instruments and cables required	Automated continuous
Changes in three-dimensional tunnel geometry with time	Tunnel laser and photo scanning system	Installed on a robotic rail-mounted frame or gantry to take regular laser and photo scans of each emplacement drift; instruments are temperature and radiation sensitive and would require modifications for regular application	Robotic intermittent
Stress change in rock bolts	Vibrating wire load cell or SMART bolt technology	Load cells installed at collars of a number of rock bolts in the emplacement drift to monitor load transfer from the rock mass to the bolt; or install a number of instrumented rock bolts to assess deformation along bolt and load distribution; requires shielding of instruments and cabling	Automated continuous
Far-field microseismicity	Microseismic monitoring system	Arrays of microseismic sensors deployed in shallow surface boreholes to provide long-term, noninvasive monitoring of the repository	Automated continuous
Surface deformation	LIDAR or precision leveling system; tiltmeters	Array of fixed benchmarks and tiltmeters at surface to detect subsidence and heave of the ground surface	Automated intermittent

An alarm condition for a particular instrument would prompt review of the instrument data. This would allow the cause of the alarm to be diagnosed to ensure it was not a result of instrument malfunction. Typically, an alarm on one instrument would not be sufficient to initiate maintenance or emergency response procedures. Alarms on related instruments would generally be evaluated collectively using some form of a majority vote algorithm. Such an algorithm would poll the various instruments in a particular area for evidence of multiple alarms associated with damage development or rock failure. On the basis of the majority vote, a warning would be issued to initiate maintenance or emergency response procedures. Different warning levels could be established to identify the severity of the behavior under investigation.

6.2.2 Maintenance

Maintenance during the preclosure period would include regular inspection of emplacement drifts and repair of the ground support system as necessary to ensure its functionality. Additional inspections may be prompted by indications of increasing instability of an underground opening detected by a monitoring system. Emplacement drifts would be periodically inspected using remote controlled inspection gantries to document the conditions of the ground support systems inside the drifts. If conditions that could result in rock or ground support failure developed, appropriate maintenance and repairs would be scheduled. Gantries would not be left in the emplacement drifts due to radiation exposure. Special equipment and protective gear would be necessary to allow human entry into an emplacement drift.

Detailed records of ongoing maintenance would be an important component of the knowledge-base to link observed phenomena with maintenance need. As knowledge about the rock mass response increases and certain phenomena or combinations of events are better understood, the ability to predict failure of rock mass around underground openings would improve. This, in turn, would enhance the effectiveness of maintenance, targeting areas on a priority basis, and could help reduce the need for extensive repair.

6.2.3 Extensive Repair

The need for extensive repair could result from conditions such as drift wall deterioration, rock fall, and associated blockage of the rail system. Such conditions also may entail temporary relocation of waste packages. Such conditions may develop rapidly if related to a seismic event, or slowly if related to other causes. Such situations could necessitate the initiation of several actions, such as (i) monitoring and detailed characterization of the damage, (ii) development of a case-specific contingency plan, (iii) cleanup and removal of debris, (iv) stabilization of the drift (including ground support repairs or replacement), (v) restoration of rail tracks and other damaged structures and utilities, and (vi) establishment of radiation controls and other administrative controls for relocation of waste packages, as needed.

DOE (2001) indicates the drift temperature may need to be reduced to < 50 °C [< 122 °F] when necessary to allow operation of monitoring and retrieval equipment. A high ventilation rate (e.g., 47 m^3/s) could be used to provide blast cooling to reduce the drift temperature as needed (DOE, 2001).

In the event of a ventilation failure after waste emplacement, it could take about two to three weeks for the drift wall maximum temperature limit to be exceeded under the high-temperature operating mode (DOE, 2001). To maintain thermal goals, any required repairs would have to be

completed and the ventilation system restarted during this period (DOE, 2001). If equipment recovery or drift maintenance were to become necessary, human entry into an emplacement drift would be possible only after all the waste packages have been temporarily relocated to a different drift and after increased ventilation has lowered the ambient temperature of the drift to below 50 °C [122 °F].

A rockfall large enough to block the rail access and ventilation system or damage one or more waste packages could cause difficult conditions. Such a scenario could hamper the control of temperature in the drift using normal ventilation methods and would entail a different approach (other than the normal rail-based approach) for retrieval of waste packages. Human entry into the affected drifts would be difficult due to the high temperature and high radiation levels in the drift. If left unattended for a long time, the temperature increase in the drift could compromise the spent-fuel cladding if waste packages are buried and thermally insulated by rock debris.

One benefit of monitoring repository excavations, would be to reduce the potential for occurrence of such a scenario by providing continuous data on rock mass conditions and forewarning of changing ground conditions that may indicate accelerating progressive failure. Early warning would permit inspection and assessment of ground support and retrieval of waste packages as necessary to allow emplacement drift remediation prior to a major rockfall. For this reason, monitoring and maintenance of repository excavations could enhance repository safety, particularly as it pertains to the emergency response workers, in addition to helping to maintain the retrievability of nuclear waste, as needed.

7 CONCLUSIONS AND RECOMMENDATIONS

This report provides a discussion of tools and techniques for monitoring the stability of underground openings that may be applicable at a potential Yucca Mountain repository. The discussion consists of a description of tools and techniques used to monitor underground openings, experience gained from international programs on deep geologic repository monitoring, and aspects of a potential nuclear waste repository at Yucca Mountain that may affect the applicability of specific monitoring tools and techniques at the repository. A DOE performance confirmation plan for the potential repository also is discussed, and recommendations are provided for tools and techniques likely to be applicable for monitoring the performance of underground openings at a Yucca Mountain repository.

The following conclusions are based on information provided in the report:

- There are many tools and techniques available for geotechnical monitoring of underground openings in rock. These technologies, along with complementary geophysical and other monitoring tools and techniques, are generally used in civil and mining applications to monitor changes in the rock mass around underground openings, or in the ground support systems and structures within underground openings. Combined with characterization activities to quantify initial conditions and rock properties, these tools and techniques can be used in a predictive sense to identify abnormal behavior associated with damage development prior to failure of an opening.

- Many of the monitoring technologies reviewed have been incorporated into studies at nuclear waste disposal research sites to assess the development of damage and progressive failure of the rock mass around underground openings. Some specialized instruments have also been developed for such studies. Most of the studies focussed on applications of instruments under ambient temperature and low radiation, but some of the studies provided useful information on the longevity of instruments under less favorable hydrogeological and temperature conditions. In general, instrument longevity could be a major issue for long-term preclosure monitoring.

- There has been some testing of instruments under elevated temperature and radiation conditions. Radiation tends to damage electronic components and has a detrimental effect on some fiber optics. Vibrating wire instruments that can function under elevated temperature, high radiation conditions, and saline groundwater conditions have been developed for special applications. Such instruments may be good candidates for application at a Yucca Mountain nuclear waste repository, but further testing and development would be needed to ensure their long-term performance under the repository conditions. New developments in fibre optics based monitoring systems show promise.

- The Yucca Mountain disposal design may include conditions, such as unbackfilled emplacement drifts located above the water table, that are favourable to instrumentation installed both within the emplacement drifts and in boreholes drilled from the emplacement drifts. Also, boreholes drilled from the observation drifts (and possibly other underground openings) could provide good coverage of the near-field rock mass. The expected behavior of the near-field rock mass appears generally understood, although there may be some uncertainty in predicting the extent and character of the

damaged zone around an emplacement drift and in assessing the influence of lithophysae and other heterogeneities in the rock mass. A combination of borehole-based, emplacement drift-based, and surface-based monitoring systems could be used to provide a reasonable monitoring coverage of the repository during the preclosure period to identify damage development and progressive failure. Some borehole-based installations may be of limited use in rock containing abundant lithophysae.

- The DOE Performance Confirmation Plan provides a summary of planned monitoring activities for a potential repository at Yucca Mountain to comply with regulatory requirements. Many of the activities are related to hydrogeology, geochemistry, and changes in hydrogeological and geochemical conditions and properties within or near the natural and engineered barriers. Monitoring activities associated with drift stability and related changes in near-field rock mass conditions and properties are generally associated with maintaining the option to retrieve emplaced nuclear waste if necessary. The activities are not planned to be implemented until construction in most cases and are therefore not described in detail in the current plan (Bechtel SAIC Company, LLC, 2004). The general descriptions in the Performance Confirmation Plan are consistent with some of the monitoring tools and techniques described in this report.

- Contingency planning and maintenance can be linked to monitoring through specific alarm and warning criteria. Such criteria are site-specific and would have to be refined using baseline monitoring data from the repository and application of the observational approach, increasing the knowledge-base associated with interpretation of the monitoring data as the project matures. Detailed records of ongoing maintenance would be an important component of the knowledge-base to link observed phenomena with maintenance needs. One benefit of using this approach is to reduce the occurrence of scenarios that may necessitate extensive drift repair or waste-package relocation by providing continuous data on rock mass conditions and forewarning of changing ground conditions that may indicate accelerating progressive failure.

Based on the information in this report, the following recommendations have been made:

- Analyses of rock mass stability under realistic repository conditions should be performed to quantify the extent and character of damage around underground openings. The effects of heterogeneity in the rock mass should be considered. In addition, design details associated with the emplacement drifts and ground support should be incorporated appropriately into such analyses. This is a necessary step in designing a monitoring system to focus on the areas of most interest.

- The robustness of specific instruments that may be used for long-term monitoring should be tested or confirmed with manufacturers. In particular, the susceptibility of specific instruments to high temperature and high radiation conditions should be determined, and developments to address any identified shortcomings in performance should be initiated. This also applies to associated components such as cables and dataloggers.

- Fibre-optics instrumentation should be explored in more depth. This is a relatively new area of monitoring technology, and further developments are likely in the near future. Field tests comparing different types of instruments under the applicable conditions are recommended to qualify them for use in a repository.

- A detailed methodology for contingency planning based on monitoring data should be developed, recognizing the evolving nature of knowledge gained from the monitoring system. This methodology would involve developing and refining associations between maintenance work and measurable phenomena.

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APPENDIX A

Summary of Monitoring Tools and Techniques for Underground Openings and Potential Repository Applications

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
Mechanical					
Tilt Meter	Instrument to measure angular deviation at a specific location; comprises direct current powered servo accelerometers to measure angular deviation from vertical (tilt) in two orthogonal directions; can be installed in shallow boreholes or mounted to a rock exposure or structural element	Analogue direct current signal directly proportional to the sine of the angle of tilt	Change in tilt with time in two orthogonal directions at a specific location resulting from rotational deformation of the ground or structure	Requires installation using grout or a sand pack in a shallow borehole or secure attachment to a rock exposure or structural element; an array of sensors deployed over a specific area is needed to map deformation of the ground surface resulting from changes in subsurface conditions; provides continuous automated monitoring of deformation with time; maximum operating temperature of the vibrating wire tilt meter is about 50 °C [122 °F]; other models operate up to 70 °C [158 °F]	Monitoring ground subsidence caused by underground excavation or collapse of openings or surface heave caused by subsurface heating; monitoring deformation of structural elements such as support systems in underground openings
Inclinometer	System to measure angular deviation profile in a borehole; comprises plastic or fibre-glass casing installed in a subvertical borehole {within 30 °C [86 °F] of vertical}; slots in casing guide a servo accelerometer-based probe to measure angular deviation over contiguous depth intervals in two orthogonal orientations	High-level voltage output directly proportional to the sine of the angle of inclination of the long axis of the probe from vertical	Depths of active shear planes and magnitude/direction of lateral displacements with time; profile of orthogonal two-dimensional displacements perpendicular to the axis of the casing relative to the initial baseline profile	Requires installation in a vertical or subvertical borehole and repeat manual surveys and data processing to develop plots of lateral displacement with depth; spiral indicator can be used to check casing for spiral to correct readings; probe can be replaced with multiple in-place accelerometers to provide continuous automated monitoring at specific depth intervals; maximum operating temperature of the vibrating wire probe is about 50°C [122 °F]; in-place inclinometers operate up to about 80°C [176 °F]	Monitoring shear displacement in the rock mass near an underground opening if installed above or below the opening (either from surface or from within the opening) or lateral deformation of the rock mass if installed adjacent to an underground opening

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
Sliding Micrometer	System to measure axial displacement in a measurement casing comprising couplings with metallic measuring marks connected by a protective plastic casing grouted in a borehole; spherical end of one type of instrument locks into conical couplings and a linear variable differential transformer (LVDT) measures the relative displacement between couplings on successive passes to develop an axial strain profile along the borehole; inclusion of two inclinometer sensors in the TRIVEC instrument allows determination of the three-dimensional (3D) displacement vector; alternate coupling styles in different instruments (e.g., INCREX system)	Axial strain in contiguous intervals along a borehole; tilt in two orthogonal directions if TRIVEC probe is used	Axial displacement along a borehole; 3D displacement vector along a borehole if the TRIVEC probe is used	Requires installation of casing in boreholes drilled either from surface or from inside an underground opening; multiple boreholes at various angles allow definition of displacements in various locations around an underground opening; manual measurements required in each borehole; maximum operating temperature of about 40°C [104 °F]	Monitoring the displacements around an underground opening in successive manual measurement campaigns to identify loosening, damage development, and progressive failure in the near-field rock mass
Extensometer	Instrument to measure relative displacement between fixed points in a borehole; several varieties include rod-type multiple point borehole extensometer (MPBX) using rods connected to fixed anchors to measure displacement relative to a reference plate at the borehole collar; borehole fracture monitor extensometer (BOF–EX) using downhole LVDTs measuring relative displacement between fixed	Relative position of fixed anchor points in a borehole determined from either direct measurement of distance between a reference plate and the end of a rod or changes in potentiometric or vibrating wire signals from an electric measurement head that are related directly to displacement	Deformation pattern around underground excavations based on relative displacement between fixed anchor points in boreholes to develop radial displacement profiles at borehole locations with time or tunnel advance	Requires installation in boreholes; can be installed in advance of excavation in boreholes from remote openings to capture complete excavation response using a variety of anchor types; can be automated to provide continuous monitoring by adding an electrical reference head using vibrating wire transducers, LVDTs or linear potentiometers; multiple installations in a radial array	Monitoring the radial deformation response of the near-field rock mass induced by excavation advance, heating, damage development, or progressive failure; multiple installations in a two-dimensional (2D) plane help identify the extent of damage or disturbance around an underground opening and associated changes in opening geometry

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
	mechanical anchors; sonic or magnetic probe extensometers using a probe to measure fixed anchor locations on the basis of magnetic signatures from the anchors; flexible rod extensometers are pre-assembled with anchors to facilitate installation; excavation damage extensometer (ED–EX) developed by Atomic Energy of Canada Limited to measure relative displacements over short intervals close to an underground opening			provide assessment of changes in near-field rock mass conditions; maximum operating temperature of vibrating wire displacement transducer measurement head and some anchors is 80°C [176 °F]; ED–EX provides detailed measurements close to the surface of an underground opening	
Convergence Array	System to measure changes in tunnel dimension; may comprise pins installed in perimeter of an underground opening read manually with a tape extensometer or a similar instrument using fixed length wire connectors, or a spring-loaded rod-mounted instrument to gauge tunnel dimension between two contact points; vibrating wire options are also available; recent advances using fixed laser-based electronic distance measurement instruments provide automation options without obstructing the underground opening	Distance between points on the perimeter of an underground opening	Change in span or cross-sectional geometry of an underground opening with time or tunnel advance	Requires repeat manual readings of distance between pins using mechanical instruments to provide deformation or change in opening geometry with time or tunnel advance; rod-type or laser-based systems can provide continuous automated monitoring of underground openings; requires installation and operation within the underground opening; maximum operating temperature of the vibrating wire convergence meter is about 80 °C [176 °F]	Monitoring deformations and changes in geometry of the periphery of underground openings in a plane orthogonal to the opening axis to identify damage development and the onset of progressive failure

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	***Interpreted Quantity***	**Application Details**	**Relevance to Monitoring Underground Excavations**
Tunnel Profile Monitoring System	System to measure change in tunnel geometry at a 2D array; instruments involve linked mechanical arms each with a tilt sensor and a displacement transducer	Angular deviations and displacement	Change in tunnel geometry with time	Requires a number of linked mechanical arms fixed to the tunnel wall to monitor deformation; each arm contains a high accuracy displacement sensor and precision tilt meter; spatial displacement of pins and arms resulting from tunnel deformation registers as tilt and displacement readings; provides automated continuous monitoring of changes in tunnel geometry in the measurement plane	Monitoring deformations and changes in geometry of the periphery of underground openings in a plane orthogonal to the opening axis to identify damage development and the onset of progressive failure
Tunnel Scanning System	System to create 3D digital images of the an underground opening; uses a high-precision laser scanner to scan the surface with a dense grid of laser pulses	Travel time of a laser pulse from the scanner to a surface and back; orientation of the ray path	Database of 3D coordinates and reflection intensity for points on the surface	Requires set up of the laser scanner in an underground opening; longitudinal axis of the scanner is set almost horizontal parallel and orthogonal to the tunnel axis; no special lighting is required; single scan takes about 3 minutes; approximately 10 m [32.8 ft] of the inner tunnel surface is recorded for a typical excavation profile; the scanned grid can be 2 cm [0.8 in] by 2 cm [0.8 in] upwards; accuracy of +/-10 mm [0.4 in]; possibility of automation using fixed installations in underground openings; range 2 to 200 m [6.6 to 656 ft]; analysis software provides multiple display options	Monitoring the change in tunnel geometry and the volume of failed material with time using repeat surveys; can be used to quantify deformation of the entire tunnel.
Strain Gauge or Strain Meter	Instrument to measure uniaxial strain in supporting structures (concrete, steel	Change in vibrating wire frequency directly related to uniaxial strain	Strain in underground support structures or in the near-field rock mass if	Requires welding to steel structures or embedment in concrete or grout; hydraulic	Monitoring deformation of supporting structures such as liners, arches, and rock

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
	arches, cable bolts) for underground openings; variety of types for arc welding to steel structures or reinforcing bar, direct embedment in concrete, and grouting in boreholes in soil or rock		installed in short boreholes	or mechanical anchors can be used in boreholes; provides continuous automated monitoring of strains at specific locations within or close to the underground opening; maximum operating temperature of a vibrating wire strain transducer is about 80 °C [176 °F]	bolts to identify load transfer from the rock mass to the support system; may indicate loosening, damage development or progressive failure of the rock mass
Crack Meter	Instrument to measure changes in the aperture of surface cracks; installed by attaching two threaded anchors on opposite sides of the crack then bridging the gap between anchors using the crack gauge to measure relative displacement between anchors; triaxial crack meter provides three orthogonal measurements to determine total movement and direction of movement; instrument operates using vibrating wire technology	Change in vibrating wire frequency directly related to displacement between anchors	Deformation of surface cracks in rock or concrete; 3D deformation if a triaxial crack meter is used	Requires access to a surface crack; instrument installed across the crack; limited range of about 30 mm [1.2 in] movement; provides continuous automated monitoring of crack aperture with time; maximum operating temperature is about 70 °C [158 °F]	Monitoring of visible crack aperture on the surface of underground excavations to identify potential loosening of blocks or changes in aperture related to thermal variations or damage development and progressive failure
Borehole Deformation Gauge	Instrument to measure borehole deformation resulting from overcoring; USBM-style gauge measures deformations in the plane orthogonal to the borehole axis; deformations are used to back analyze initial stress state based on elastic theory	Change in borehole diameter in several directions	Initial biaxial stress state in the plane orthogonal to the borehole	Requires installation in a borehole followed by overcoring to measure the deformation response; assumes elastic behavior of the rock to calculate stresses; valid only in competent, elastic rock; provides a single measurement at a specific location	Characterizing initial *in situ* stress state in the rock mass around an underground opening to assess potential for instability; can be used to monitor stress changes with time in some applications

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
Borehole Stress Meter	Instrument used to measure uniaxial stress changes in rock; comprises high strength steel proving a ring wedged tightly across one diameter inside a borehole; vibrating wire used to determine change in diameter of proving ring; can be installed in boreholes up to 30-m [98-ft] long	Change in vibrating wire frequency directly related to change in uniaxial stress	Change in uniaxial compressive stress between contact points of the proving ring in a borehole	Requires installation in a borehole in competent rock; provides continuous automated monitoring of stress change with time; multiple cells in different locations and orientations required to assess 3D stress changes; maximum operating temperature of the vibrating wire transducer is about 80 °C [176 °F], but high temperature version operating at up to 200°C is available	Monitoring changes in compressive stress in the near-field rock mass to assess damage development, progressive failure, and thermal-mechanical response of the rock mass
Biaxial Stress Meter	Instrument to measure biaxial compressive stress changes in rock; comprises a high strength steel cylinder with multiple vibrating wire sensors oriented at 60-degree intervals grouted into a borehole; allows principal stress changes to be measured in the plane perpendicular to the stressmeter axis	Change in vibrating wire frequency directly related to change in biaxial stress	Change in biaxial compressive stress orthogonal to borehole axis	Requires installation and grouting in a borehole in competent rock; provides continuous automated monitoring of biaxial stress change with time; multiple cells in different locations and orientations required to assess 3D stress changes; maximum operating temperature of the vibrating wire transducer is about 80 °C [176 °F] but a high temperature version operating at up to 200 °C [392 °F] is available	Monitoring changes in compressive stress to assess damage development and progressive failure, and thermal-mechanical response of the rock mass
Triaxial Stress Cell	Instrument used in conjunction with overcoring to measure the initial triaxial state of stress in rock; based on CSIRO hollow inclusion concept with 9 or 12 electrical resistance strain gauges encapsulated in the wall of a thin-walled epoxy pipe; instrument is	Strains in a borehole associated with stress change	Initial triaxial stress state or stress changes in the rock mass around a borehole	Requires epoxy grouting in a borehole; overcoring used to determine the initial stress state acting in the rock mass around a borehole; CSIRO cell can be used for continuous monitoring of stress changes for up to 2 years; maximum operating temperature is 50 °C	Characterizing initial *in situ* stress state in the rock mass around an underground opening to assess potential for instability; can be used to monitor stress changes with time in some applications

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
	epoxy grouted in a borehole; alternate designs include the CSIR triaxial strain cell with three independent strain gauge rosettes glued to the borehole wall			[122 °F]; stable resistor used for temperature compensation; glue creep can be an issue for long-term use	
Hydraulic Borehole Pressure Cell	Instrument used to measure uniaxial stress change in rock; comprises two steel plates welded together to form a slender flat-jack that is grouted into a borehole; space between plates is filled with hydraulic oil and a high pressure stainless steel line connects the plates to a stainless steel pressure transducer	Change in vibrating wire frequency directly related to applied pressure	Change in uniaxial stress orthogonal to the cell	Requires installation in a borehole; provides continuous automated monitoring of stress change with time; multiple cells in different locations and orientations required to assess 3D stress changes; maximum operating temperature of the vibrating wire pressure transducer is about 80 °C [176 °F]	Monitoring changes in compressive stress in the near-field rock mass to assess damage development, progressive failure, and thermal-mechanical response of the rock mass
Concrete Stress Cell	Instrument designed to measure tangential and radial stresses in shotcrete or concrete tunnel linings; comprises two rectangular steel plates welded together to form a flat-jack with a de-aired fluid occupying the space between the plates; a vibrating wire pressure transducer is used to measure pressure of the cell fluid	Change in vibrating wire frequency directly related to fluid pressure	Radial and tangential stress	Requires installation in fresh concrete prior to curing; cell is expanded after the concrete has cured; multiple cells required to assess stresses in different parts of the tunnel lining; provides continuous automated monitoring of lining stress with time; maximum operating temperature of the vibrating wire pressure transducer is about 80 °C [176 °F]	Monitoring changes in stress in shotcrete or concrete linings of underground openings; changes in stress may indicate loosening of the rock mass, damage development, or progressive failure
Total Pressure Cell	Instrument to measure contact earth pressure on the surface of a concrete or steel structure; comprise two stainless steel plates welded together to form a flat-jack filled with de-aired oil; pressure in chamber	Change in vibrating wire frequency directly related to applied pressure on cell	Contact pressure between concrete or steel tunnel supports and the rock mass	Requires installation between rock and tunnel support at the time of support installation; provides continuous automated monitoring of contact pressure on the tunnel support system with time;	Monitoring load transfer from the rock mass to the support system installed in an underground opening to assess loosening, damage development, and progressive failure of the rock mass

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
	fluid is converted to an electrical signal via a vibrating wire pressure transducer			vibrating wire pressure transducer maximum operating temperature is typically 80 °C [176 °F]	
Load Cell	Instrument used to assess uniaxial compressive load; used in conjunction with rock bolts to assess load on bolts; comprises a cylinder of high-strength, heat treated steel with multiple vibrating wire strain gauges located around the circumference of the cell	Change in vibrating wire frequency directly related to applied compressive load	Compressive load	Requires installation in conjunction with rock bolts or cable anchors; provides continuous automated monitoring of compressive load with time; maximum operating temperature of the vibrating wire pressure transducer is about 80 °C [176 °F]	Monitoring changes in load on rock bolts to identify loosening of the rock mass, damage development, and progressive failure around underground openings
Instrumented Cable Bolt	Instrument to measure deformation and load in the rock mass while providing ground support; used in mining applications to provide real-time monitoring as part of the support system	Relative displacement between anchor points	Deformation and load distribution in cable bolt	Requires installation in a borehole; specially developed cable bolt with the central king wire replaced with a tempered stainless steel hollow tube; six anchor points are fixed at desired locations along the tube and are discretely tied to a potentiometric readout head; differential movement of the anchor points is used to evaluate the strain and load in the cable	Monitoring changes in load distribution on cable bolts to identify loosening of the rock mass, damage development, and progressive failure around underground openings
Borehole Dilatometer	Instrument to perform deformability testing of soil or rock in boreholes; cylindrical probe comprising a steel body covered with a reinforced rubber sleeve; the sleeve is inflated using nitrogen gas; deformation of the borehole is measured using three LVDTs	Displacement and pressure	Rock deformation modulus	Requires testing in an HQ {96 mm [3.8 in]} to HD {101 mm [4.0 in]} borehole; provides coupled displacement and pressure data from which modulus can be determined directly; suitable for rock with a Young's modulus between 50 MPa [7.25 ksi] and 20 Gpa [2.9 × 10^3 ksi]; repeat measurements may provide	Characterizing rock deformation modulus in the far-field rock mass and in the near-field around an underground opening to assess possible softening near the opening

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
				information on the change in rock mass modulus with time; requires access to the underground opening to perform testing	
Plate Loading Testing System	System used to measure the *in situ* deformation modulus of rock; flat-jack comprises two stainless steel plates welded together and filled with de-aired oil or other fluid; pressure in chamber fluid is converted to an electrical signal via a vibrating wire pressure transducer; displacement is measured displacement transducer or other means depending on test set up	Displacement and pressure	Rock deformation modulus	Requires testing in a slot or across an opening to measure the pressure-displacement relation for the *in situ* rock mass; modulus determined from the pressure-displacement response; can be repeated to assess changes in modulus, but requires access to the underground opening and may entail significant equipment set up	Characterizing the large-scale *in situ* rock deformation modulus in the near-field around an underground opening
Thermal					
Thermistors and Thermocouples	Instrument to measure temperature; vibrating wire type sensors consist of a stainless steel body to which the vibrating wire element is attached; other instruments are based on relation between resistance and temperature; typically deployed as a string comprising multiple instruments; thermocouples are based on the relationship between temperature and the voltage generated by a coupling of two different metals at different temperatures; resistance temperature device (RTD) and	Change in vibrating wire frequency, resistance or voltage directly related to temperature	Temperature at instrument location	Requires installation in a borehole; multiple sensors required to measure temperature distribution around an underground opening; provides continuous automated monitoring of temperature with time; maximum operating temperature of the vibrating wire sensor is 200 °C [392 °F]; thermocouples are available either as bare wire 'bead' thermocouples which offer low cost and fast response times, or built into probes; Type K Chromel/Alumel is the 'general purpose' thermocouple; it is available	Monitoring temperature distribution around an underground opening to assess response to temperature changes within the opening

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
	thermometer probe are other examples.			in a wide variety of probes; thermocouples are available in the -200 °C [392 °F] to +1,200 °C [2,192 °F] range; sensitivity is approximately 41μV/°C	
Infrared Thermography	System used to identify fractures in the near-field rock mass; involves repeat thermographic surveys of a tunnel using infrared imaging equipment; tunnel is heated then cooled to identify thermal anomalies indicative of existing fractures near the tunnel; imaging equipment travels on a horizontal rail system suspended from the crown of the tunnel	Infrared	Temperature anomalies	Requires set up of equipment from the crown of the tunnel; temperature conditions varied for a period of time to heat then cool the rock mass; access to tunnel required; significant effort to conduct the test; experimental in nature	Characterizing fracturing around an underground opening
HYDRAULIC					
Piezometers	Instruments for measuring fluid pressures such as groundwater elevations and pore pressures; installed in a borehole within a sand pack to measure response at a particular location; some vibrating wire models do not require sand pack; borehole is grouted once instrument is installed; vented models compensate for changes in barometric pressure	Change in vibrating wire frequency directly related to fluid pressure	Pore pressure at a specific location	Requires installation in boreholes around underground openings to determine pore pressure distribution with time; provides continuous automated monitoring of pore pressure at specific locations near the underground opening; maximum operating temperature for a standard vibrating wire pressure transducer is 80 °C [176 °F] but high temperature versions are available	Monitoring of pore pressure response with time to assess drawdown, rock mass hydraulic properties, and coupled thermal-hydraulic response
Hydrogeology Packer System	System of pneumatically or hydraulically inflated packers to isolate specific	Fluid pressure versus time	Pore pressure in a specific interval of a borehole; hydraulic conductivity of	Requires installation in a borehole; multiple packers in a borehole provide a profile	Monitoring of pore pressure response with time around an underground

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
	intervals in a borehole for hydraulic measurements and/or groundwater sampling; packers comprise rubber reinforced membrane with steel or aluminum heads; pressure transducer used to measure pressure of fluid in interval; excavation damage assessment (EDA) solid rubber packer systems used to isolate short intervals near an underground opening to measure pore pressure profile; various hydraulic tests can be performed in the packed off interval to assess hydraulic properties of the rock mass		the interval	of pore pressure along the borehole; hydraulic testing can be conducted in the packed off intervals to determine hydraulic conductivity of the rock mass; pressure transducers in each interval provide continuous automated monitoring of pressure with time at specific locations; relatively long rubber bladder lengths in conventional packers preclude small closely-spaced monitoring intervals and measurements close to excavation perimeter; groundwater sampling from specific intervals possible with conventional multi-packer systems; EDA packers are suited for permanent installation in boreholes for long-term monitoring of the near-field zone	opening to assess the hydromechanical and hydrothermo-mechanical responses of the rock mass; repeat measurements of hydraulic conductivity to identify loosening, damage development and progressive failure of the rock mass
Packer-Extensometer System	System used to measure the coupled hydro-mechanical response of a discrete fracture; comprises two inflatable packers and an extensometer in one integrated borehole instrument	Fluid pressure and displacement	Coupled hydromechanical response of discrete fractures; fracture stiffness	Requires installation in a borehole intersecting a natural fracture; fracture is isolated by the packers; fluid pressure is increased and the associated displacement on the fracture is measured; provides plot of displacement versus pressure from which fracture stiffness can be determined	Characterizing the stiffness of discrete fractures around underground openings or in the far-field rock mass
Downhole Hydraulic Transmissivity Probe	Instrument to measure the interval permeability in a single borehole at different radial distances from an	Pressure-pulse decay	Transmissivity or permeability in rock adjacent to a borehole	Requires testing in a single borehole; adversely affected by highly conductive natural fractures; rock must be	Characterizing the intrinsic permeability of the rock mass around underground openings to identify the

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
	underground opening; involves steady state or pulse testing over very small intervals to measure hydraulic characteristics of the rock mass; probe comprises a small injection chamber, two small mechanical packers, two chambers of leakage recovery, and two standard packers			saturated in order to conduct the test; very sensitive to conditions of the rock mass near the testing borehole	extent of damage near the opening
Hydraulic Pressure Pulse and Drawdown Tests	Tests conducted in short boreholes in an underground excavation to assess the hydraulic properties of the excavation damage zone; involves standard hydraulic testing equipment including packers and pressure transducers	Pressure-time response following change in hydraulic pressure	Transmissivity of the damaged zone	Requires testing in a series of boreholes to define the characteristics and extent of excavation damage around a tunnel; not conducive to long-term monitoring; provides specific characteristics of the near-field rock mass at the time of measurement	Characterizing the transmissivity and extent of excavation damage around an underground opening
Humidity Sensor	Instrument to measure relative humidity in an underground opening; used to detect seepage into an underground opening	Voltage or current	Relative humidity	Requires mounting in ventilation stream; electronics operate up to 55°C; based on resistive change of bulk polymer sensor	Monitoring seepage as an indicator of changing ground conditions around an underground opening

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)

Tool or Technique	General Description	Measured Quantity	Interpreted Quantity	Application Details	Relevance to Monitoring Underground Excavations
Pneumatic Testing	Downhole air injection or vacuum test to assess hydraulic properties of the near-field rock mass; several boreholes instrumented with packers and pressure transducers	Pressure-time response following change in pneumatic pressure	Permeability	Requires testing in boreholes; multiple boreholes can be instrumented and characterizes in one injection test; some automated systems allows autonomous acquisition of large amounts of data; others require manual surveys; extraction tests generally preferred to injection tests due to artificial opening of fractures from over-pressuring; equations to estimate permeability from these tests given by several authors	Characterizing the permeability of discrete intervals in the near-field rock mass; repeat measurements can be used to assess changes associated with damage around an underground excavation
Tracer Test	Technique to assess hydraulic properties of the rock mass using tracers in hydraulic tests; involves injection and recovery of tracers in boreholes or slots near the opening	Tracer concentration and hydraulic pressure with time	Flow and diffusion properties of the rock mass	Requires *in situ* testing within an underground opening; slots or boreholes are required for tracer release and collection; test can be designed to measure hydraulic properties of far-field features such as fracture zones or the near-field rock mass; hydraulic properties are back-analyzed using measured pore pressure and concentration with time responses	Characterizing the hydraulic properties of the near-field rock mass; repeat measurements can be used to assess changes associated with damage around an underground excavation
Connected Permeability Test	Large-scale *in situ* test to directly measure the connected permeability and hydraulic conductivity in the invert of an underground opening; requires a measuring slot in the invert orthogonal to the axis of the opening, and a reservoir of water contained by two	Seepage rate and hydraulic head	Hydraulic conductivity	Requires *in situ* testing in an underground opening and construction of a reservoir and measuring slot; possibly adversely affected by unsaturated or highly fractured ground conditions; not easily repeatable as a monitoring activity.	Characterizing the hydraulic properties of the near-field rock mass around an underground opening

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
	partial height dams across the opening; can also be set up as a full-scale test using a sealed pressurized chamber				
Geophysical					
Interval Seismic Velocity Surveys	Technique to measure the seismic velocity in a borehole over a fixed interval; microvelocity probe (MVP) used in a borehole to take measurements over contiguous intervals; the probe comprises two transducers at a fixed spacing in an aluminum housing that is pushed progressively down a borehole using aluminum rods	Compressional and shear-wave travel time between two sensors on the probe	Interval seismic velocity in direction of borehole	Requires manual survey of an array of boreholes to determine the velocity structure of the rock mass around an underground opening; velocity profile calculated on the basis of measured travel time between transducers with a fixed separation distance within a single borehole; spacing of transducers determines depth of penetration away from the borehole; variations in transducer caps, wall contact and borehole diameter may influence results; borehole damage may impede or affect signal transmission between transducers; vaseline or other acoustic couplant is used to couple sensor to borehole wall; signal to noise ratio and frequency content of the signals are constant due to the fixed raypath length, and interval velocities are measured directly (no smoothing required); measurements are rapid and easy to conduct	Characterizing the interval compressional and shear wave velocity profile radial to an underground opening to identify the extent of damage around the opening; repeat surveys can be used to monitor changes in velocity in the damaged zone with time

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
Downhole Seismic Velocity Surveys	Technique to measure the seismic velocity between a seismic source at the wall of an opening and a downhole receiver at variable depth in a borehole; receiver may comprise a piezoelectric accelerometer and the source may be a hammer blow at the surface of the underground opening	Compressional and shear-wave travel time between source and receiver	Average compressional and shear-wave velocity between source and receiver	Requires manual surveys in a borehole to develop a profile of average velocity versus separation distance between source and receiver; downhole measurements suffer from decreased signal to noise ratio with increasing depth; increased raypath length results in decreased frequency content of signal; measurements are fast and low cost with easy determination of source to receiver distance; open cracks between source and receiver can degrade signal; damage is characterized by decreased velocities	Characterizing the average compressional and shear wave velocity profile radial to an underground opening to identify the extent of damage around the opening; repeat surveys can be used to monitor changes in velocity in the damaged zone with time
Crosshole Seismic Velocity Surveys	Technique to measure the seismic velocity between a seismic source in one borehole and a downhole receiver in another; source/receivers comprise piezoelectric transducers or MVPs in separate parallel boreholes to develop a profile of tangential velocity versus distance from the opening	Compressional and shear-wave travel time between source and receiver in parallel boreholes	Average compressional and shear-wave velocity between source and receiver in parallel boreholes	Requires manual surveys to measure travel time between source and receiver in parallel boreholes; accurate borehole surveys are needed to precisely locate the source and receiver; errors associated with sensor mislocation can be large, especially for short raypaths; adequate borehole coupling is needed for signal transmission; borehole damage may impede coupling, and signal transmission	Characterizing the average compressional and shear wave velocity tangential to an underground opening to identify the extent of damage around the opening; repeat surveys can be used to monitor changes in velocity in the damaged zone with time

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
Crosshole Seismic Tomograpic Surveys	Technique to measure the average seismic velocity between a seismic source in one borehole and a downhole receiver in another along many raypaths in various directions; source/receivers comprise piezoelectric transducers or MVPs in separate boreholes to develop a tomographic map of average velocity around an underground opening	Compressional and shear-wave transit time along many raypaths in 2D panels between boreholes	Seismic velocity or dynamic mechanical properties in 2D panels between boreholes	Requires manual surveys to measure travel time between source and receiver over a large number of raypaths between boreholes; the tomographic image in 2D panels is used for detection of fracturing and lithologic changes; results can be displayed as contours of velocity, or converted to elastic properties such as dynamic Young's modulus and Poisson's ratio through known correlations; accurate borehole surveys needed to precisely locate source and receiver; errors associated with sensor mislocation can be large, especially for short raypaths; adequate borehole coupling needed for signal transmission; borehole damage may impede coupling, and signal transmission; velocity affected by stress, saturation, and other factors in addition to damage	Characterizing the average compressional and shear wave velocity in 2D panels between boreholes to identify the extent of damage around an underground opening; repeat surveys can be used to monitor changes in velocity in the damaged zone with time
Seismic Refraction Surveys	Technique used to measure transit time of compressional, shear and refracted waves to identify the extent of damage around an underground excavation; sensors can include geophones or accelerometers along the surface of an underground opening; uses a single source with multiple receivers	Compressional, shear, and refracted wave transit times in rock near the tunnel wall	Seismic velocity structure near an underground opening	Requires manual surveys at specific locations along an underground excavation; detection of refracted waves is used to identify the interface between damaged and intact rock (represented by a contrast in acoustic impedance); used to estimate depth of damage; multiple lines required to characterize damage around an underground excavation;	Characterizing the depth of refraction around an underground opening that may indicate damage to the rock mass; repeat surveys can be used to monitor changes in the damaged zone with time

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
				depth of penetration of acoustic signal (i.e., depth of detectable fractures) may be shallow depending on equipment and rock properties; acoustic impedance contrast needed between damaged and intact rock for technique to work	
3D Velocity Imaging	Technique to develop 3D velocity images using detonations at known locations in an underground opening; blasting caps or induced seismicity can be used as the source; geophones or accelerometers are used as receivers; sensors arranged in an optimized array around the underground opening compressional wave travel time	Compressional wave travel time	Velocity structure	Requires a 3D array of sensors to interpret the velocity structure and manual placement and detonation of seismic sources; factors affecting application of technique are stress state, excavation dimensions, seismic transmission, sensor distribution and access; separation of stress-induced and damage-induced effects can be problematic in some cases	Characterizing the average compressional and shear wave velocity in a 3D volume to identify the extent of damage around an underground opening; repeat surveys can be used to monitor changes in velocity in the damaged zone with time
Ground Vibration Monitor	Instrument to monitor ground vibrations due to blasting; comprises an automated seismograph and standard seismic sensors to capture full waveform data	Ground vibration or acceleration	Energy release and ground acceleration during excavation	Requires manual monitoring of blasting using a portable blast monitor; can be automated using in place sensors to record waveform data; can be used to monitor tunnel boring machine excavation but different sensitivity required for tunnel boring machine versus drill-and-blast excavation	Monitoring the ground acceleration associated with blasting and excavation of underground openings to assess dynamic boundary conditions
Seismic and Radar Reflection Surveys	Technique using either seismic or electromagnetic waves to detect fracturing and changes in water content in the near-field rock mass	Seismic velocity, attenuation, and slowness	Velocity and attenuation anomalies	Requires manual survey of the underground opening to detect fracture zones and geologic structure in the near and far field; both attenuation and velocity/slowness	Characterizing the extent of damage around an underground opening; repeat surveys can be used to monitor changes in the damaged zone with time

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
				tomograms are used in conjunction with geological information of site to identify fracture zones; brine tracer tests are used to develop radar attenuation difference tomograms; electromagnetic methods are not suitable for clayey materials due to shallow depth of penetration	
Geo-Electric Surveys	Technique used to map resistivity and phase shift around an underground opening to identify changes in saturation and porosity; based on DC resistivity, and AC resistivity and phase shift measurements	Resistivity and phase shift of the rock mass	Extent and distribution of damaged and/or desaturated zones	Requires a manual survey at a specific location within an underground opening; results are affected by concrete and other support structures; provides an indication of areas of desaturation and changed porosity that may indicate damage	Characterizing the extent of desaturation and changes in porosity around an underground opening that may indicate damage to the rock mass; repeat surveys can be used to monitor changes in the damaged zone with time
Electrical-Resistance Tomography	Technique involves installing electrodes to determine electrical resistance of the rock mass; water saturation inferred from test results	Voltage and current	Water saturation	Requires installation of electrodes in the rock mass and continuous monitoring of voltage and current to calculate resistance; electrical resistance is related to saturation through Waxman-Smits equation; provides an electrical resistance tomogram of the near-field rock mass	Characterizing water saturation of the near-field rock mass and monitoring changes in saturation related to damage development and heating
Thermal Neutron Logging	Standard geophysical well-logging technique to measure water saturation near a borehole; downhole tool used to measures counts per second from a neutron source with depth in a borehole	Counts per second	Water saturation	Requires manual downhole logging with a neutron source; provides a profile of counts per second versus depth to identify degree of water saturation	Characterizing water saturation of the near- and far-field rock mass and monitoring changes in saturation related to damage development and heating
Microseismic	Technique to monitor	Waveforms associated with	Temporal and spatial	Requires installation of an	Monitoring of the spatial and

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
(MS) Monitoring	microseismic activity around an underground opening; system typically incorporates triaxial accelerometers or geophones to record induced microseismicity associated with damage development and progressive failure; typical array of sensors provides time-stamped full waveform data to allow source location and source mechanism analysis	induced microseismicity	distribution of microseismic events, source parameters, and source mechanisms	array of sensors in an optimized 3D pattern to provide coverage of individual or multiple underground openings; sensors are installed in boreholes that may be drilled remotely from the opening; sensor characteristics and arrangement depends on the rock mass properties; higher source location accuracy possible for spherical focal coverage and higher quality rock; borehole-sensor coupling can be achieved mechanically or by grouting sensors in place; system requires calibration for each installation using source detonations at known positions; monitoring volume is dependent on the operating frequency; real-time visualization of event locations and source parameters is available or soon to be available	temporal history of microseismic activity associated with damage development and progressive failure of the rock mass around an underground opening; provides direct identification of new fracturing and movement on existing fractures; allows mapping of the extent and characteristics of the zone of damage and changes with time

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
Acoustic Emission (AE) Monitoring	Technique to monitor acoustic emission activity around an underground opening; system typically uses ultrasonic sensors to record induced acoustic emissions associated with damage development and progressive failure, and to measure velocity between sensors; provides accurate source locations of very high frequency events within a relatively small monitoring volume	Waveforms associated with induced acoustic emissions	Temporal and spatial distribution of acoustic emission events, source parameters, and source mechanisms	Requires installation of an array of high frequency ultrasonic sensors in one or more boreholes close to an underground opening; provides accurate source locations of very high frequency events within a monitoring volume of about 1,000 m^3 [35,315 ft^3], sensors are semi-permanently installed making the boreholes inaccessible for other characterization techniques while the system is in place; calibration of each installation is required; system can also provide *in situ* velocity measurements at regular time intervals; system can be completely automated to provide real-time remote monitoring	Monitoring of the spatial and temporal history of acoustic emission activity associated with damage development and progressive failure of the rock mass around an underground opening; provides direct identification of new fracturing and movement on existing fractures; allows mapping of the extent and characteristics of the zone of damage, and changes with time
Geological					
Corelogging	Direct observation of fracturing, geological variability, and discing in drill core to assess near-field conditions	Observations of lithology and fracture characteristics in core	Natural fractures and excavation damage *in situ*	Requires core orientation to determine true fracture orientations; discing-type damage in core is unrelated to damage *in situ* and can mask excavation-induced damage; velocity of core typically less than that of the *in situ* rock mass indicating core damage; technique is useful for identifying natural fracture characteristics; corelogging protocols are well-established	Characterizing the physical properties and fracture characteristics of the near-field rock mass around an underground opening

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
Borehole Television or Video Camera	Direct observation of geological variability, natural and induced fractures, and breakouts in boreholes from camera images; camera is a specially designed tool to provide a 360° image of the borehole	Observations of lithology and fracture characteristics in boreholes	Visible extent of damage and natural fracturing; fracture orientations	Requires boreholes that intersect the near-field rock mass; microcracks, borehole breakouts and blast-induced fractures can be observed in boreholes; scratches on borehole wall can sometimes be misidentified as narrow cracks; equipment and processing software is commercially available	Characterizing the physical properties and fracture characteristics of the near-field rock mass, and the extent of damage around an underground opening
Resin Injection and Sampling	Technique to inject resin into fractures in the near-field rock mass to preserve structure then recover a core sample for direct observation of fracture characteristics	Observations of fracture characteristics in core	Extent and character of damage in the near-field rock mass	Requires pilot hole to inject resin; injection pressure must be kept low to avoid overpressuring and opening fractures; vacuum techniques can also be used; technique preserves fracture aperture and orientation; allows the analysis of the fracture network from representative samples from the damaged zone; technique not suitable for long-term monitoring	Characterizing the physical properties and fracture characteristics of the near-field rock mass, and the extent of damage around an underground opening
Geological Mapping	Direct observation of geological variability, natural and induced fractures in excavations	Observations of lithology and fracture characteristics in excavations	Geological structure and excavation damage around excavations	Requires access to an underground excavation; can be conducted using a photobase or digital imagery; generally difficult to repeat once support systems are in place in an opening; geological variability can affect the mechanical response and damage characteristics of the near-field rock mass; visible fracturing is limited to the exposed surfaces; depth of radial fracturing can be determined by overcoring	Characterizing the geology and fracture characteristics of the near-field rock mass exposed in an underground opening

Table A–1. Summary of Monitoring Tools and Techniques Used for Underground Openings (continued)					
Tool or Technique	**General Description**	**Measured Quantity**	**Interpreted Quantity**	**Application Details**	**Relevance to Monitoring Underground Excavations**
				visible fractures; mapping procedures, protocol, and associated systems are generally well-established	
Laboratory Testing	Standard and nonstandard laboratory tests to assess rock and fluid properties	Various measured quantities	Thermal-mechanical-hydrological-chemical and coupled properties	Requires standard and non-standard tests to measure representative properties of the rock mass	Characterizing rock mass properties
Geochemical					
Hydro-Geochemical Sampling	Technique to assess groundwater chemistry and changes with time	Water chemistry	Age of formation and inference to transport properties	Sampling of pore water to determine composition of pore fluids; repeat measurements required to detect changes	Characterizing rock mass fluids to assess effects on the near-field rock mass

Table A–2. Examples of Tools and Techniques Used in Krepository Studies to Monitor and Characterize Excavation Damage		
Tool or Technique	**Specific Examples**	**Typical Equipment and Operational Details**
Sliding Micrometer	Underground Research Laboratory of the Atomic Energy of Canada Limited (URL)—Used during shaft sinking and the Room 209 Experiment to assess two- or three-dimensional deformations associated with excavation (Simmons, 1992).	URL—Manual repeat measurements to assess deformation of casing with depth. Typically installed ahead of the tunnel face.
Extensometer	URL—Room 209 Experiment compared three types of extensometers for use in excavation response monitoring (Simmons, 1992). Borehole fracture monitor extensometers (BOF–EXs) used for Mine-by Experiment monitoring (Read and Martin, 1996). Kamioka—High-accuracy extensometer using a laser displacement sensor developed in Japan for accurate displacement measurements underground (Tamai and Kosugi 1995). Äspö—Extensometers used to measure displacement associated with ZEDEX tunnel excavation (Emsley, et al., 1997).	URL—BOFEX uses DC-LVDT with repeatability of ± 6 μm [2.4×10^{-4} in], and range of ±6 mm [0.2 in]. Incremental measurements taken between anchors. Mechanical screw-type anchors used at URL in 76-mm [3-in]-diameter boreholes; other anchor types available. Minimum anchor spacing about 0.3 m (Read and Martin ,1996). Kamioka—Field testing and equipment details not reported (Tamai and Kosugi, 1995). Äspö—Multi-point extensometers with seven anchors and range of ± 10 mm [0.4 in]; accuracy 0.2 mm [7.9×10^{-3} in] (Emsley, et al., 1997).
Excavation Damage Extensometer (ED–EX)	URL—ED-EX developed by Atomic Energy of Canada Limited (AECL) for use in Mine-by Experiment to provide detailed measurements of displacements in excavation damaged zone (EDZ) (Read and Martin, 1996).	URL—ED–EX extensometer uses AC-linear variable differential transformers (LVDTs). Incremental measurements taken between anchors. Mechanical screw-type anchors used at URL. Minimum anchor spacing about 0.1 m [0.3 ft]. Installed in 38-mm [1.5-in]-diameter boreholes drilled in tunnel (Read and Martin, 1996).
Convergence Array	URL—Used routinely in Mine-by Experiment and other excavation response experiments (Read and Martin 1996). Äspö—Used in ZEDEX to assess convergence during excavation of tunnel boring machine (TBM) and drill-and-blast tunnels (Emsley, et al., 1997).	URL— Kern distometer and Invar wire measurement lines used to assess convergence. Calibration frame used to calibrate instrument. Other similar tools available. Äspö—Soil Instruments tape convergence meter used with measurement studs installed 300 mm [11.8 in] from face in TBM, and 2 m [6.6 ft] from the face in the drill-and-blast tunnel. Three measurement lines used in drifts (Emsley, et al., 1997)
Crack Meter	Kamioka—Five joint deformeters installed in two boreholes at private underground laboratory in Japan prior to tunnel excavation. Excavation-induced displacement on joint measured as tunnel advanced (Tamai and Kosugi, 1995).	Kamioka—Joint deformeter comprises three orthogonal plates and LVDTs with a range of -2.5 to +2.5 mm, and an accuracy of 0.001 mm [3.9×10^{-5} in]. Measures three components of displacement (Tamai and Kosugi, 1995).

Table A–2. Examples of Tools and Techniques Used in Krepository Studies to Monitor and Characterize Excavation Damage (continued)		
Tool or Technique	**Specific Examples**	**Typical Equipment and Operational Details**
In Situ Stress Measurement	Mont Terri—Several techniques such as borehole slotter, under and overcoring, and hydraulic fracturing used to estimate *in situ* stress tensor (Bossart, et al., 2002). URL—Many different stress measurement techniques tested and compared at the URL (Chandler, et al., 1996). Äspö—Far-field stress measurements taken 15–20 m [49–66 ft] from excavations throughout HRL, and in vicinity of ZEDEX tunnels after excavation (Emsley, et al., 1997).	Mont Terri—Equipment for the various techniques not described, but follow standard practice (Bossart, et al., 2002). URL—*In situ* stresses characterized by over-coring, under-excavation, back analysis, and other methods. Stress measurement techniques described by Chandler (1999). Äspö—Stress measurements conducted by overcoring CSIRO triaxial strain cells (Emsley, et al., 1997).
Borehole Dilatometer	URL—Applied in upper URL shaft investigation and in Room 209 Experiment. Demonstrated that modulus is stress-dependent around openings (Simmons, 1992). Kamaishi—Lower deformation modulus measured within 0.5 m [1.6 ft] of the drift wall in Kamaishi Mine compared to higher values measured between 1 and 6 m [3.3 and 19.7 ft] from the wall (Sugihara, et al., 1996).	URL—Borehole-based instrument with high-strength stainless steel shaft and an adiprene membrane; pressure capabilities in excess of 70 MPa [10.2 ksi] (Simmons, 1992). Instrument details given by Koopmans and Hughes (1990). Kamaishi—Performed in three 10-m [32.8 ft]-long boreholes drilled horizontally, 45 degrees upward and vertically downward. Cyclic loading used to maximum of 20% of the unconfined compressive strength.
Plate Loading Testing System	Yucca Mountain—Plate loading tests using flatjacks conducted in niche near Heated Drift Experiment to determine rock mass modulus (George, et al., 1999).	Yucca Mountain—Rock mass loaded horizontally using flat jacks constructed of 304 stainless steel sheets butt welded to stainless steel tubing along edges. MPBX extensometer installed in rock to measure displacement (George, et al., 1999).
THERMAL		
Thermistors and Thermocouples	URL—Different thermistors and thermocouples used for Heated Failure Tests (Read and Martin, 1996).	URL—Specifications site and application specific.
Infrared Thermography	URL—Used in Mine-by Experiment to assess floor of tunnel for fractures (Chandler, 1999)	URL—Special imaging equipment mounted on a suspended horizontal rail. Tunnel heated then allowed to cool to identify anomalies (Chandler, 1999).
HYDRAULIC		
Piezometers	URL—Vibrating wire piezometers used in the Room 209 Experiment to monitor pore pressure of the Room 209 Fracture during excavation (Simmons, 1992).	URL—GEOKON vibrating wire piezometer installed in a borehole. Reliable instrument sensitive to small changes in pressure. Based on vibrating wire technology.
Hydrogeology Packer System	URL—Room 209 Experiment used hydraulic packers to seal boreholes and to monitor pressure around advancing tunnel. Multiple straddle-packers used to isolate interval containing fracture (Simmons, 1992).	URL—Baski inflatable packers typically used for routine applications. High pressure rating and expansion ratio. Minimal outside diameter and large interior diameter. Long sealing section that conforms to uneven

Table A–2. Examples of Tools and Techniques Used in Krepository Studies to Monitor and Characterize Excavation Damage (continued)		
Tool or Technique	**Specific Examples**	**Typical Equipment and Operational Details**
	Mont Terri—new packer system developed for use in Opalinus clay. Measurement interval bounded with undeformable stiff packer sections sealed by resin injection (Thury and Bossart, 1999).	sides in a borehole {typically about 1 m (3.3 ft)}. Borehole sizes range from 50 to 760 mm [2.0 to 30 in]. Pressure ranges from 0.3 to 70 Mpa [0.04 to 10.2 ksi]. Mont Terri—Highly porous tube of sintered steel installed in measurement interval in slightly over-sized borehole. Resin used to secure device to formation (Thury and Bossart, 1999).
Excavation Damage Assessment Packer System	URL—Hydrogeological boreholes instrumented with excavation damage assessment and regular packers in advance of tunnel excavation. Permitted small intervals to be monitored close to tunnel periphery (Martino, 2000).	URL—Small interval packer system developed by AECL to characterize hydraulic properties of EDZ. Zones as small as 100 mm [3.9 in] separated by 25-mm-thick hydraulically activated packers.
Packer-Extensometer (PAC–EX) System	URL—Room 209 Experiment used packer-extensometer instruments to assess the coupled response of the Room 209 Fracture to excavation (Simmons, 1992).	URL—Combination of extensometer and packer technology developed by AECL. Specifications unavailable.
Downhole Hydraulic Transmissivity Probe	URL—Pulse testing conducted using SEPPI probe in 76-mm [3-in]-diameter radial boreholes in TSX to determine the extent of damage and transmissivity of the near-field rock (Martino, 2000). Äspö—SEPPI probe used in twelve 3-m [9.8 ft]-long, 86-mm [3.4 in]-diameter boreholes drilled at different angles to assess extent of EDZ in ZEDEX TBM and drill-and-blast tunnels. Undisturbed matrix permeability about 2×10^{-19} [2.2×10^{-18} ft^2] to 3×10^{-19} m^2 [3.2×10^{-18} ft^2]. Natural fractures adversely affected pulse tests and obscured damage near TBM tunnel. TBM tunnel damage to 20 cm [7.9 in] depth; drill-and-blast damage to 80 cm [31.5 in] depth in floor; 25 cm [9.8 in] depth in wall. Floor EDZ permeability >100 times matrix permeability; EDZ elsewhere from 10 to 40 times matrix permeability (Emsley, et al., 1997).	URL—SEPPI probe comprises a small injection chamber {5 cm [2.0 in]}, 2 mechanical packers {7 cm [2.8 in]}, 2 chambers of leakage recovery, and 2 standard packers 35-cm long. Total length of probe is 226 cm [8.9 in]. Lengthening tube required for near-wall measurements. Syringe-type pump injects water at high pressure, injected volume measured to 0.1 mm^3 [6.1×10^{-4} in^3]. Either steady state {intrinsic permeability > 10^{-17}m^2 [1.1×10^{-16} ft^2]} or pulse testing {intrinsic permeability < 10^{-17} m^2 [1.1×10^{-16} ft^2]} can be performed. Äspö—Pulse test parameters: initial injection chamber pressure = 1.5 Mpa [0.2 ksi], pulse magnitude = 0.5 Mpa [0.07 ksi], pressure fall-off registered over about 300s. Drained bulk modulus and matrix bulk modulus 48 and 56 Gpa [7 and 8 ksi], respectively. Porosity = 1%. Measurements taken every 5 cm [2.0 in] between 8 and 50 cm depth, every 10 cm [3.9 in] between 50 and 100 cm [19.7 and 39.4 in] depth, and every 20 cm [7.9 in] from 100 cm [39.4 in] depth to end of hole.
Hydraulic Pressure Pulse and Drawdown Tests	URL—Used in the Room 209 Experiment to assess *in situ* transmissivity in floor of tunnel (Simmons, 1992). Mont Terri—Hydraulic cross-hole testing conducted in EDZ using injected water (Bossart, et al., 2002) Äspö—38 pairs of pressure build-up tests with data before and after excavation analyzed for ZEDEX project. Results inconclusive due to uncertainties affecting data (Emsley, et al., 1997)	URL—Conducted in 100-mm [3.9-in]-long packer-isolated intervals to determine depth of EDZ. Standard procedures for borehole-based hydraulic tests (Simmons, 1992). Mont Terri—Standard procedures followed (Bossart, et al., 2002). Äspö—Tests involved installing packers in boreholes and monitoring the pressure build-up with time. Standard equipment used. Difference flow measurements taken using specially-designed downhole flowmeter. Flow measurements made using thermal pulse method and thermal dilution

Table A–2. Examples of Tools and Techniques Used in Krepository Studies to Monitor and Characterize Excavation Damage (continued)		
Tool or Technique	**Specific Examples**	**Typical Equipment and Operational Details**
	URL—Used in array of boreholes in Room 209 Experiment to assess *in situ* transmissivity around excavation (Simmons, 1992).	method (Emsley, et al., 1997) URL—Standard equipment and procedures for borehole-based hydraulic tests.
Pneumatic Testing	Yucca Mountain—Air permeability tests conducted in alcoves off the main drift before and after alcove excavation to assess the influence of excavation on permeability. Both single-hole and cross-hole tests conducted using an automated control system (Cook, 2000). URL—Used in the Room 209 Experiment to assess *in situ* transmissivity in floor of tunnel (Simmons, 1992). Äspö—Hydraulic properties measured before and after excavation using pressure build-up tests to determine transmissivity (Emsley, et al., 1997).	Yucca Mountain—Inflatable rubber sealing bladders manipulated independently to divide borehole into 14 different possible zones. Zone resolution 0.3 m. Up to seven boreholes instrumented at one time. Pressure monitoring used transducers accurate to 0.5 kPa [0.07 psi]. Mass flow controllers used to inject constant mass-flow rate of air during each test (Cook, 2000). URL—Conducted in short boreholes in floor of Room 209 to assess permeability of EDZ. Involves nitrogen injection into, or air evacuation out of, the unsaturated of partially saturated volume of the rock mass. Drainage area on order of metres (Simmons, 1992). Mont Terri—Tests conducted in 40-mm [1.6-in] diameter radial holes. Involved installing mechanical double-packer with 10-cm [3.9-in] interval in test hole. Observation holes with single packer located 15–25 cm [5.9–9.8 in] from test borehole. Tests conducted in successive intervals further from excavation. Detection limit of 5×10^{-16} m^2 [5.38×10^{-15} m^2] (Bossart, et al., 2002). Äspö—Pressure build-up tests used double packer system. Inflatable rubber packers 1 m [3.3 ft]-long, spaced 1 m [3.3 ft] for tests in radial boreholes; spaced 3.5 m for tests in axial boreholes. After excavation difference flow measurements estimated transmissivity (Emsley, et al., 1997)
Tracer Test	URL—TSX tracer test conducted to examine likely hydraulic properties of EDZ around clay bulkhead key (Masumoto, et al., 2002).	URL—TSX tracer test conducted using NaI and Na-fluorecein tracer injected into pressurized side of TSX chamber. Sampling of tracer conducted using EDA packers installed in hydrogeological boreholes radial to tunnel.
Connected Permeability Test	URL—Room 209 Connected Permeability Test conducted in a drill-and-blast tunnel under moderate stresses (Simmons, 1992). Mine-by Connected Permeability Test conducted in mechanically excavated tunnel under high stresses (Chandler, 1999). TSX Connected Permeability Test conducted in drill-and-blast tunnel in high stress environment (Martino, 2000).	URL—Concrete dams and reservoir used to create constant head conditions. Measured seepage rate into a drilled slot under a known head of water through a known cross-sectional area of flow. Bentonite strips used to seal concrete-rock interface. Effect of flow length on connected permeability assessed by lengthening dam in stages.

Table A–2. Examples of Tools and Techniques Used in Krepository Studies to Monitor and Characterize Excavation Damage (continued)		
Tool or Technique	***Specific Examples***	**Typical Equipment and Operational Details**
GEOPHYSICAL		
Interval Seismic Velocity Surveys	URL—Prototype Keele Microvelocity Probe (MVP) used to measure interval velocities in 1-m [3.3 ft]-long boreholes to assess EDZ extent in Mine-by tunnel (Maxwell, et al., 1998). Arrays of radial MVP boreholes drilled in several ESS tunnel segments to characterize extent and nature of EDZ; second generation Keele MVP probe used for these measurements (Read, et al., 1998). Velocity measurements taken every 5 cm [2.0 in] in first 1 m [3.3 ft] and every 10 cm [3.9 in] in remainder of 16 boreholes (two arrays) in TSX tunnel to identify EDZ (Martino, 2002). Grimsel—Downhole measurements of interval velocity using BGR mini-sonic probe identified extent of EDZ close to excavation (Alheid and Knecht, 1996). WIPP—Compressional wave velocity measured in array of 12 holes drilled horizontally in an alcove wall to assess EDZ in salt. Holes aligned with line bisecting the corner of the room. (Holcomb, et al., 2002). Äspö—Interval seismic velocity measurements taken to characterize the EDZ in the ZEDEX project (Emsley, et al., 1997).	URL—Keele MVP fits in a 76-mm [3 -in]-diameter borehole. Transducers used in prototype probe were 1-MHz ultrasonic piezoelectric sensors spring-mounted to borehole wall. High voltage/high frequency pulser provided source signal. Sensor spacing determines depth of penetration around borehole. Spacing of 80 and 145 mm [3.2 and 5.7 in] used in TSX; sensors sensitive in 100–300 kHz range; whole waveforms recorded at 2 MHz. Cross-correlation technique used to improve accuracy; estimated $\Delta V_P = \pm 14$ m/s [46 ft/s] and $\Delta V_S = \pm 8$ m/s [26 ft/s] for TSX tunnel (Collins and Young, 2002). Grimsel—BGR Mini-sonic Probe comprises pneumatic hammer source and two piezoelectric accelerometers spaced 10 cm [3.9 in]. Pneumatic cylinders provide clamping. Signal frequency range 10 to 40 kHz, recording system sampling rate 10 MHz (Alheid and Knecht, 1996). WIPP—Fixed measurement interval of 33 cm [13 in] in 100-mm [3.9 in]-diameter holes. Piezoelectric transducers used as transmitters/receivers 300 kHz PZT-5A piezoelectric disks. Sensors coupled to borehole with corn syrup; spring pressure of 400 kPa [58 psi]. Systematic error about 1%. Signal 100 V square pulse. Recorded on digital oscilloscope (Holcomb, et al., 2002). Äspö— BGR mini-sonic probe and Keele MVP used. BGR probe comprised sources, pneumatic hammers, two receivers separated by 10 cm [3.9 in], each with two piezoelectric accelerometers. Signals recorded by a four-channel digital storage oscilloscope (Emsley, et al., 1997).
Downhole Seismic Velocity Surveys	Kamaishi—EDZ is characterized by lower P- and S-wave velocities relative to rock further from opening. At Kamaishi, P-wave velocity within about 75 cm [29.5 in] of drift wall was 30–50% lower than that of intact rock. S-wave velocity decreased by 60% within about 50 cm [19.7 in] of drift wall (Sugihara, et al., 1996). Grimsel—Downhole measurements involved moving a piezoelectric accelerometer receiver along 3 to 5-m [9.8 to 16.4-ft] deep 86-mm [3.4-in]-diameter boreholes; mechanical hammer used at tunnel wall as source. Discrete open discontinuities detected at Grimsel (Alheid and Knecht, 1996). Äspö—P-wave seismic velocity and acoustic resonance measurement in short radial holes to characterize ZEDEX EDZ (Emsley, et al., 1997)	Kamaishi—Hammer source recorded by downhole sensors with dominant frequency 200–500 Hz. Conducted every 25 cm [9.8 in] up to 5 m [16.4 ft] from opening, and every 50 cm [19.7 in] further from opening to 20 m [66 ft]. Used to identify velocity from boreholes and changes with depth downhole at Kamaishi (Sugihara, et al., 1996). Grimsel—Method for converting average velocities to interval velocities with depth described by Alheid and Knecht (1996). Äspö—Borehole probe with accelerometer; seismic signal generated by pendulum hammer at wall of drift; signals recorded with signal analyzer (Emsley, et al., 1997).

Table A–2. Examples of Tools and Techniques Used in Krepository Studies to Monitor and Characterize Excavation Damage (continued)		
Tool or Technique	**Specific Examples**	**Typical Equipment and Operational Details**
Crosshole Seismic Velocity Surveys	WIPP—Crosshole measurements of compressional wave velocity in array of twelve 100-mm [3.9-in]-diameter holes drilled horizontally to assess the EDZ in alcove wall (Holcomb, et al., 2002). Äspö—Seismic velocity anisotropy studies in ZEDEX used two MVPs in cross-hole mode (Emsley, et al., 1997).	WIPP—Crosshole raypaths nominally 1 m [3.3 ft]. Piezoelectric transducers used as transmitters/receivers 300 kHz, PZT-5A piezoelectric disks. Sensors coupled to borehole wall with corn syrup; spring pressure of 400 kPa. Sensors located to within ±1 mm [0.04 in]. Nonsystematic errors estimated to cause uncertainty in cross-hole path length less than 3 mm [0.12 in] (Holcomb, et al., 2002). Äspö—Probes comprise 1 MHz transducers as transmitter/receiver. Both P- and S-waves generated and received (Emsley, et al., 1997).
Crosshole Seismic Tomographic Surveys	URL—Mine-by Experiment pre and postexcavation far- and near-field surveys in radial and rectangular panels used to identify extent of EDZ, lithologic variability, and anisotropy (Read and Martin, 1996). TSX postexcavation surveys in four panels in two borehole arrays delineated extent of EDZ and some geologic variability (Martino, 2002). Kamaishi—Tomogram shows reduced P-wave velocities within about 2 m [6.6 ft] of drift wall; resolution restricted by cell size used in interpretation (Sugihara, et al., 1996). Grimsel—Swept Impact Seismic Technique (SIST) used to improve survey resolution between boreholes over distances of tens of metres. Low power impact source generates a series of seismic pulses using a swept impact rate rather than single-pulse piezoelectric and electromagnetic sources. Used to detect and characterize rock mass discontinuities (Cosma and Enescu, 2001). Äspö—Seismic tomography used to map P- and S-wave seismic velocity and attenuation in several planes around ZEDEX tunnels (Emsley, et al., 1997).	URL—Mini-CHARTS system (AECL) used with mechanical downhole clamping in 76-mm-diameter boreholes. Sensors operated in 10 to 80 kHz range. Near-field surveys extended 3 m [9.8 ft] or more radially into rock. Far-field surveys conducted over 33 × 40 m[108 × 131 ft] panel from short boreholes. Estimated uncertainty in horizontal and vertical velocity 0.3% and 0.4%, respectively. Kamaishi—Sparker used as source at Kamaishi. Dominant P-wave velocity 3,000–4,500 Hz. Geophones and hydrophones used as receivers placed along drift wall and in boreholes. Span between receivers was 0.5 m [[1.6 ft]. Cell size for back analysis was 1 m [3.3 ft]. Both back-projection (BTP) and algebraic reconstruction (ART) methods used to analyze results (Sugihara, et al., 1996). Grimsel—SIST used for investigation depths to 1 km [0.6 mi] in 46 to 100 mm [1.8 to 3.9-in]-diameter boreholes; frequency band 500–2,500 Hz, clamping by wedge or fluid coupling using water. Äspö—High resolution seismic tomography surveys used specially-built borehole sondes. Main components: borehole source with downhole power module to drive piezoelectric transducer and multireceiver borehole probe with eight piezoelectric transducers spaced 0.15 m [0.5 ft] apart (Emsley, et al., 1997).
Seismic Refraction Surveys	URL—Seven horizontal survey lines used in TSX tunnel to delineate extent of damage. Damage ranged from 0.01 to 0.71 m[0.03 to 2.3 ft] in surveys (Martino, 2000). Kamaishi—Extent of EDZ characterized by depth of reflector at Kamaishi Mine. P-wave velocity structure interpreted as two-layers, with inner layer 50-cm [19.7-in] thick and P-wave velocity of 50 to 80 percent of intact rock further from opening (Sugihara, et al., 1996).	URL—Fifteen accelerometers with frequency range 1 Hz to 10 kHz transducers coupled to rock in blasthole half-barrel remnants. Pulse provided by Schmidt hammer. Sampling frequency 62 kHz (Martino, 2000). Kamaishi—Hammer source used to generate P-wave. Refracted waves from boundary of EDZ received by geophones set every 50 cm [19.7 in] in a line 11.5-m [37.7-ft] long along the drift wall at Kamaishi (Sugihara, et al., 1996).

Table A–2. Examples of Tools and Techniques Used in Krepository Studies to Monitor and Characterize Excavation Damage (continued)		
Tool or Technique	**Specific Examples**	**Typical Equipment and Operational Details**
	Asse—Surveys performed in walls of the Asse salt mine in Germany. Measurements taken with different source and receiver distance. Results indicated anisotropic microcrack structure oriented preferentially parallel to drift wall (Alheid and Knecht, 1996).	Asse—Source receiver distance varied from 0.1 to 4.8 m [0.3 to 15.8 ft] in steps of 0.1 or 0.2 m [0.3 or 0.7 ft]. Velocity distribution calculated from travel time versus distance function. No boreholes necessary for this method. Lower resolution than borehole measurements (Alheid and Knecht, 1996).
Three-Dimensional (3D) Velocity Imaging	URL—Blasting caps detonated in short boreholes in Mine-by tunnel to measure P-wave travel time to individual microseismic (MS) sensors. Results back analyzed in terms of 3D velocity structure (Maxwell, et al., 1996). Velocity images also produced using induced microseismicity as source to obtain velocity structure in seismically-active regions (Maxwell, et al., 1996).	URL—Conducted using existing MS system installed for Mine-by Experiment. Detonation locations surveyed accurately. Velocity image showed decreased values in tensile sidewall region of tunnel, and increased velocity at the tips of the breakout notches in the tunnel. MS activity corresponds with transition from region of low to high velocity, defining active edge of damaged zone (Maxwell, et al., 1996).
Ground Vibration Monitor	Äspö—Ground vibration and acceleration monitored during ZEDEX excavation to estimate amount of energy released into rock mass during excavation.	Äspö—Excavation monitoring performed with triaxial transducers at four stations at 3-m [9.8-ft] intervals in boreholes. TBM vibration monitored with velocity transducers; blasting monitored with accelerometers. Signals recorded by signal analyzer and transient recorder (Emsley, et al., 1997).
Seismic and Radar Reflection Surveys	Grimsel—Borehole logging techniques used for detecting properties at distances of a few meters or less from transmitter. Reflection techniques, vertical seismic profiling and tomography effective over distances of at least 100 m [328 ft] to identify structural features. Radar and seismic tomograms pixel dimension of 2.5 m [[8.2 ft] provided lower bound on resolution (Martel and Peterson, 1991). Äspö—Radar and seismic reflection processing mapped presence and orientation of fractures near ZEDEX tunnels. Velocity of electromagnetic waves (radar) used to estimate average water content of rock volume. Tunnel radar survey also conducted on both walls, floors and roof of ZEDEX tunnels (Emsley, et al., 1997).	Grimsel—Information on rock anisotropy and porosity can be obtained by using receivers that detect compressional waves and vertical and horizontal shear waves. Three-component information allows fracture density and orientation to be estimated. Specific equipment details not given (Martel and Peterson, 1991). Äspö—Borehole radar measurements used RAMAC system; directional antennae used with nominal frequency 45–50 MHz; transmitter-receiver separation 7 m [2.3 ft]. Received signal sampled at 600 MHz with 512-sample points; each signal stacked 32 times to reduce noise. Tunnel radar survey used the Norwegian Geotechnical Institute step frequency GPR system; short dipole antenna {0.4 m 1.3 ft]} with center frequency of 350 MHz and antenna separation of 0.3 m [1.0 ft]; long dipole antenna {1.2 m [3.9 ft]} with center frequency of 120 MHz and antenna separation of 1.0 m [3.3 ft]. Spacing between measurement points 0.1 m [0.3 ft]. Resolution about 0.5 m [1.6 ft] for fracture plane dimension (Emsley, et al., 1997).
Geo-Electric Surveys	Mont Terri —Geo-electric profiles using normal DC resistivity measurements and AC resistivity and phase shift measurements to identify the EDZ (Alheid, 2002).	Mont Terri—Details on equipment not provided.
Electrical-Resistance Tomography	Yucca Mountain—Used in Single Heater Test to map changes in water saturation resulting from heating rock volume (Blair, et al., 1999).	Yucca Mountain—Automated data collection system measuring voltage and current in a number of electrodes with time. Data processed to produce electrical resistance tomograms (Blair, et al., 1999).

Table A–2. Examples of Tools and Techniques Used in Krepository Studies to Monitor and Characterize Excavation Damage (continued)		
Tool or Technique	**Specific Examples**	**Typical Equipment and Operational Details**
Thermal Neutron Logging	Yucca Mountain—Used in the Single Heater Test to measure water saturation before, during and after heating of *in situ* volume of rock (Blair, et al., 1999).	Yucca Mountain—Standard well-logging technique.
MS Monitoring	URL—Over 25,000 acoustic emission (AE) or MS events recorded during Mine-by Experiment corresponding to damage development and progressive failure. Largest moment magnitudes recorded near advancing tunnel face. Time-dependent and time independent moment tensor analysis used to assess micromechanics of fracturing (Maxwell, et al., 1996; Read and Martin, 1996). Continuous monitoring of induced microseismicity in frequency range 0.1 to 50 kHz prior to, during and after excavation of TSX tunnel, and during operation of the experiment, synchronized with AE monitoring (Martino, 2000).	URL—16 triaxial accelerometers with frequency range of 50 Hz to 10 kHz grouted in boreholes used for Mine-by Experiment; excellent focal sphere coverage with source location uncertainty of roughly ±0.25 m [0.82 ft]. Sampling rate 50 kHz (Read and Martin 1996). Sixteen triaxial accelerometers provided source location accuracy of ±0.5 m [1.6 ft] for small scale high frequency seismic events around the TSX tunnel (Martino, 2000). Hydrophones used in the URL shaft extension monitoring. All triaxial accelerometers installed in 96-mm [3.8-in]-diameter boreholes.
AE Monitoring	URL—Measured AE events in Mine-by sidewall primarily tensile, some shear events; most locate within 0.35 m [1.15 ft] of wall; low P-wave velocity measured within first 0.5 m [1.6 ft] of wall; anisotropy in three-dimensional velocity structure suggests multiple microcrack sets in sidewall region (Carlson and Young, 1993). In Heated Failure Tests, heating caused AE activity in floor of tunnel, including shear displacement on large observed fractures, and AE events associated with breakout development in 600-mm [23.6 in]-diameter borehole (Falls and Young, 1996). Continuous monitoring of induced acoustic emissions in a small rock volume near clay key in TSX synchronized with MS monitoring showed time-dependent growth of EDZ (Young and Collins, 1999). Äspö—AE monitoring detected spatial and temporal distribution of microcracks associated with excavation of ZEDEX tunnels. AE events in TBM tunnel concentrated at tunnel face and within 1 m [3.3 ft] of tunnel wall; most events within 0.1 m [0.3 ft] of tunnel perimeter. Some scattered events further from tunnel indicated slip on existing fractures. In drill-and-blast tunnel, AE events extended to about 0.7 m [2.3 ft] from perimeter; more extensive in floor of tunnel. AE event rate was about 10 times that for the TBM tunnel. Velocity measured as excavation proceeded showed only 5 m/s [16.4 ft/s] decrease in velocity around both drill-and-blast and TBM tunnel (Emsley, et al., 1997).	URL—Sixteen 1 MHz ultrasonic sensors installed in four 1-m [3.3-ft]-long subhorizontal radial boreholes in the sidewall of the Mine-by tunnel, spaced 0.6 m [2.0 ft] in a diamond pattern. For the Heated Failure Tests, 16 MHz ultrasonic sensors installed in four 4-m 13-ft]-long vertical boreholes in the floor of the widened Mine-by tunnel, spaced 1.8 m [5.9 ft] apart in a square pattern. Frequency range of sensors in the TSX was 50 to 5,000 kHz, providing accurate source location of small scale high frequency seismic events to within 3 cm [1.2 in]. Äspö—Sixteen ultrasonic sensors with integral 40 dB preamplifiers deployed up to 35 m [115 ft] down four boreholes approximately parallel to the test tunnel in ZEDEX project. Boreholes 6.5 m [21 ft] apart and in place prior to tunnel excavation. Sensors spaced 1.2 m [3.9 ft] apart in each hole. Receiver frequency range 40 to 100 kHz. Four-channel digital oscilloscope used to record data. Accuracy of locations about 100 mm [3.9 in] (Emsley, et al., 1997).
GEOLOGICAL		
Corelogging	URL—All instrument and characterization holes from major URL experiments, including TSX and Mine-by Experiment, have been logged. Geological data summaries of these holes have been completed.	URL—Corelogging system includes computer database and processing software, and specific logging procedures. Core laboratory includes core photography and storage facilities.

Table A–2. Examples of Tools and Techniques Used in Krepository Studies to Monitor and Characterize Excavation Damage (continued)		
Tool or Technique	**Specific Examples**	**Typical Equipment and Operational Details**
	Kamaishi—Core logging at Kamaishi indicates low velocity zone corresponding to region where open cracks with apertures of 1 to 3 mm [0.04 to 0.12 in] exist (Sugihara, et al., 1996). Äspö—Corelogging conducted for ZEDEX to assess near-field conditions (Emsley, et al., 1997).	Äspö—Corelogging completed to SKB standards. Geotechnical logging using Q and RMR complemented results from corelogging (Emsley, et al., 1997).
Borehole Television or Video Camera	URL—All MVP boreholes surveyed in TSX tunnel (Martino, 2000) and in ESS tunnel segments (Read, et al., 1998b). Kamaishi—BTV surveys indicate low velocity zone corresponds to region where open cracks with apertures of 1 to 3 mm [0.04 to 0.12 in] exist (Sugihara, et al., 1996). Äspö—Borehole television surveys conducted in holes around ZEDEX tunnels (Emsley, et al., 1997).	URL—RCS–1600 miniature color television camera equipped with adjustable lighting used at the URL. Images captured on videotape (Martino, 2000). Äspö—Front viewing color camera and side-looking scanning television camera used to identify geological features in boreholes (Emsley, et al., 1997).
Resin Injection and Sampling	Mont-Terri—Overcoring of resin-filled EDZ fractures conducted in Opalinus clay (Bossart, et al., 2002).	Mont Terri—Resin injected in small pilot hole and allowed to polymerize before overcoring. Injection hole 40-mm [1.6-in] diameter and 1.3 m [4.3-ft] deep (Bossart, et al., 2002).
Geological Mapping	URL—All underground excavations mapped at the URL, including TSX access tunnels and main test chamber. Detailed mapping of fracture zones and induced fracturing in the URL shaft conducted during excavation (Read and Chandler, 2002). Kamaishi—Fractures over 3 m [9.8 ft] in length included in mapping at Kamaishi. Frequency of fractures in granodiorite was 0.8/m (Sugihara, et al., 1996). Mont Terri—Fracture mapping and line counting conducted along walls of niches excavated in walls of underground drifts. Oxidation phenomenon (gypsum crystal growth) observed within 0.7 m [2.3 ft] of original drift wall (Bossart, et al., 2002). Äspö—Mapping conducted in test drifts for ZEDEX project to identify damage, natural fractures and lithologic variability. Dye penetration tests conducted in slots to identify fractures (Emsley, et al., 1997).	URL—Mapping procedures, standards, and geological database to maintain information. Photo mosaics used for detailed mapping. Special cage developed for mapping in the URL shaft during construction. Slots and boreholes provide additional exposure (Read, 1996). Mont Terri—Standard mapping practices used in niches excavated to observe depth of fracturing around original tunnel (Bossart, et al., 2002). Äspö—Fractures >0.5 m [1.6 ft] mapped. Mapping followed normal SKB standards complemented by collection of rock mass quality Q and RMR data (Emsley, et al., 1997).
Laboratory Testing	Kamaishi —No correlation between rock properties and distance from drift observed at Kamaishi. Frequency of microcracks observed through microscopy highest within 0.25 m [0.82 ft] of drift wall; believed to be blast-induced (Sugihara, et al., 1996).	Kamaishi—Unconfined and triaxial compression tests, Brazilian tests, physical properties tests. Microscopy used to identify damage in samples treated with fluorescent resin (mixture of acrylic resin and fluorescent paint) under ultra-violet light.

Table A–2. Examples of Tools and Techniques Used in Krepository Studies to Monitor and Characterize Excavation Damage (continued)		
Tool or Technique	**Specific Examples**	**Typical Equipment and Operational Details**
	Äspö—Detailed laboratory studies of samples from radial boreholes in ZEDEX tunnels examined for crack damage (Emsley, et al., 1997). Olkiluoto—Laboratory tests conducted on intact and damaged rock samples to determine porosity, effective diffusivity and permeability (Autio, et al., 1998).	Äspö—Laboratory measurements made on 4 cm [1.6 in] cubic samples prepared from cores from different depths. Measurements under saturated and dry conditions included isotropic compression tests, permeability measurements, P-wave velocity measurements, mercury porosimetry, unconfined compressive strength, Young's modus, and thin sections for microcrack analysis (Emsley, et al., 1997). Olkiluoto—Samples cored from large-diameter borehole walls; tested using He-gas method and ^{14}C-PMMA method. Scanning electron microscope and optical microscopy used to assess fracture characteristics in EDZ (Autio, et al., 1998).
GEOCHEMICAL		
Hydro-Geochemical Sampling	Mont Terri—Hydrogeochemical sampling conducted in 20–30-m [66–98-ft]-long boreholes to assess age of pore fluids in different locations relative to main fault. Evidence of very old fluids in far-field (Thury and Bossart, 1999).	Mont Terri—Boreholes packed off with specially-developed packers to collect water. Standard techniques used to analyze water composition (Thury and Bossart, 1999).

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