TECHNICAL SUPPORT FOR GEIS:
RADIOACTIVE WASTE ISOLATION
IN GEOLOGIC FORMATIONS

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Volume 7

Baseline Rock Properties-Basalt

April 1978

Prepared By

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UNION
CARBIDE

OFFICE OF WASTE ISOLATION
OAK RIDGE, TENNESSEE

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Volume No.	Volume Title	Prepared by*
TM-36/1	Executive Summary	SAI
TM-36/2	Commercial Waste Forms, Packaging and Projections for Preconceptual Repository Design Studies	SAI
TM-36/3	Stratigraphies of Salt, Granite, Shale and Basalt	D&M
TM-36/4	Baseline Rock Properties-Salt	D&M
TM-36/5	Baseline Rock Properties-Granite	D&M
TM-36/6	Baseline Rock Properties-Shale	D&M
TM-36/7	Baseline Rock Properties-Basalt	D&M
TM-36/8	Repository Preconceptual Design Studies: Salt	PBQD
TM-36/9	Drawings for Repository Preconceptual Design Studies: Salt	PBQD
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TM-36/20	Thermo-mechanical Stress Analysis and Development of Thermal Loading Guidelines	D&M
TM-36/21	Ground Water Movement and Nuclide Transport	D&M
TM-36/22	Nuclear Considerations for Repository Design	SAI
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ABSTRACT

This volume, Y/OWI/TM-36/7 Baseline Rock Properties - Basalt, is one of a 23-volume series, "Technical Support for GEIS: Radioactive Waste Isolation in Geologic Formations, Y/OWI/TM-36" which supplements a "Contribution to Draft Generic Environmental Impact Statement on Commercial Waste Management: Radioactive Waste Isolation in Geologic Formations, Y/OWI/TM-44." The series provides a more complete technical basis for the preconceptual designs, resource requirements, and environmental source terms associated with isolating commercial LWR wastes in underground repositories in salt, granite, shale and basalt. Wastes are considered from three fuel cycles: uranium and plutonium recycling, no recycling of spent fuel and uranium-only recycling.

This report contains an evaluation of the results of a literature survey to define the rock mass properties of a generic basalt, which could be considered as a geological medium for storing radioactive waste.

The general formation and structure of basaltic rocks is described. This is followed by specific descriptions and rock property data for the Dresser Basalt, the Amchitka Island Basalt, the Nevada Test Site Basalt and the Columbia River Group Basalt.

Engineering judgement has been used to derive the rock mass properties of a typical basalt from the relevant intact rock property data and the geological information pertaining to structural defects, such as joints and faults.

PREFACE

Project Background

One of the major problems related to the production of electricity by light-water nuclear reactors is the management of radioactive wastes generated by the use of nuclear fuel. However, the subject is considered amenable to a rational solution, and the technology involved is considered to be well within the capabilities of our present-day technological base.

An important step toward the realization of an effective waste management program is the preparation of the generic environmental impact statement for commercial waste management. A pivotal issue in waste management is the means of providing long-term, permanent storage of these wastes in a manner to best assure their isolation from the biosphere. Analyses spanning two decades have generated the widely supported concept for providing final isolation of these nuclear wastes in deep geologic formations. Therefore, the Office of Waste Isolation* was assigned the responsibility for preparation of those sections of this generic statement dealing with deep geologic waste isolation.

The original concept for deep geologic disposal was first advanced in 1957 when a National Research Council Advisory Committee of the National Academy of Sciences suggested the burial of solid radioactive wastes in salt deposits. To date, the majority of the research, development, and demonstration (RD&D) activities have been in salt. The current United States Department of Energy (DOE) National Waste Terminal Storage (NWTs) program calls for the selection of two sites overlying suitable salt formations by 1979, followed by the construction and start-up in 1985 of one NRC-licensed repository designed for the permanent disposal/ isolation of commercial nuclear wastes in a salt formation at one of these two sites. In addition to this activity in salt, vigorous RD&D programs have been initiated to determine the appropriateness of various hard rocks as host media for a repository.

*Operated by Union Carbide Corporation-Nuclear Division for the Department of Energy.

The deep-geologic-isolation portion of the generic statement considers repositories located in salt, granite, shale, or basalt. The repositories are designed to handle wastes from the nuclear fuel cycle without reprocessing, in which the spent fuel is considered a waste (no reprocessing) or from either of two fuel cycles that include reprocessing--the cycle with uranium and plutonium recycle and that with only uranium recycle. To prepare this contribution, the Office of Waste Isolation contracted with Dames & Moore, Parsons, Brinckerhoff, Quade & Douglas, Inc. and Science Applications, Inc. In order to prepare this description, generic sites were defined, preconceptual repository designs completed, and resource requirements and effluents from the repositories identified. The preconceptual repository designs for the salt host formation were based on more than two decades of analysis and in-situ experimentation. The data base upon which the repository design for the non-salt host formations were based is much more sparse since repository-oriented analyses of these formations have been proceeding only for the last couple of years. For each of the host rocks additional analyses were performed during the conduct of these studies. Details of this additional technical work are described within the twenty-three volumes of this report.

For an overview of these preconceptual repository design studies, the study objectives and scope, and the major study assumptions, the reader is referred to Volume 1 of this series, the Executive Summary (Y/OWI/TM 36/1).

Volume Summary (Y/OWI/TM-36/7)

Basalt is one of the rock types being considered as a possible medium for locating a radioactive waste repository. In order to perform a feasibility study, information must first be collected on the geology, hydrology and rock mass properties of typical basalts. These data can then be used to determine the gravity and thermal loadings associated with different canister configurations and underground layouts. This report is an evaluation of the rock-mass properties of basalt for use in these studies.

The approach taken in this report has been, firstly, to review the formation of basalts in general and to describe typical structures en-

countered. Secondly, basalts from four different parts of the United States have been considered in detail, and all relevant rock properties have been extracted from the literature. Special characteristics of these basalts have also been considered.

A table of intact properties for a typical basalt was drawn up after reviewing the individual tables of intact properties for the Dresser, Amchitka Island, Nevada Test Site and the Columbia River Group basalts. This table was then used in conjunction with a table describing typical geological structures found in basalts, to determine the rock-mass properties of a typical basalt.

Since very few field tests and measurements of large-scale field behavior have been made, a considerable amount of engineering judgement was necessary in arriving at these rock-mass properties. Given the present state-of-the-art and the available field information, these properties are considered to be reasonable but are not unique. Before a repository is designed, and built, a major program of laboratory and field testing will be necessary to determine the necessary rock mass properties for that particular site.

1.0 INTRODUCTION

1.1 GENERAL

Construction of an underground repository for nuclear waste in basaltic rock demands knowledge of all geotechnical aspects of the basalt medium. Basalt, unlike many of the other types of rocks investigated for repository characteristics, is rarely used for construction purposes or as an economic material. The consequence is that there is a lack of knowledge about the physical parameters and their constitutive relationships.

The literature search quickly showed that two pools of information existed: data related to solid-earth geophysics and information related to mining, construction and theoretical studies. The solid-earth geophysics information was not deemed suitable, as it applies to rock at high pressures, up to and greater than 150,000 p.s.i. Hence, these current studies were directed at obtaining all available information from research, mining and construction, and government sources.

1.2 SCOPE

The collection and presentation of rock property characteristics of basalt was approached from the standpoint of discussing information and results from sources throughout the world. However, once the data were collected, it was apparent that the vast majority of research and investigation had been generated within the U.S.A.

The mode of placement and forms of basaltic masses are highly variable. Chapter 2 was written to aid in the understanding of these processes, in order to develop a sound understanding of why strength variations occur within individual flows, and how basaltic sequences show such diverse strength and hydrological characteristics.

Chapters 3, 4, 5, and 6 describing rock properties from basalt areas within the United States. It is acknowledged that accumulations of basaltic rock occur at other areas not discussed in this report, e.g., Utah and New Mexico. The approach was adopted that only basaltic provinces for which rock-property data were available would be presented. Chapter 7 includes a potpourri of data from areas within and outside of

the United States, and certain types of strength characteristics which are not included in Chapters 3 through 6. Chapter 8 includes a discussion of the special characteristics of basalt that must be considered in the design and construction of underground openings. The assigned rock mass properties for a typical basalt are presented in Chapter 9. Research needs are discussed in Chapter 10.

2.0 FORMS AND STRUCTURES OF BASALTIC ROCKS

2.1 GENERAL

The American Geological Institute (1976) ¹ define basalt as an extrusive rock composed of calcic plagioclase and pyroxene, with or without olivine. The rock is fine-grained, and generally dark colored. Basalts poor in olivine and containing orthopyroxene and/or pigeonite are classified as tholeiitic basalts.

Due to the relatively low viscosity and low gas content of the magma, basaltic eruptions typically produce freely-flowing lava flows with a relatively small proportion of tephra (ejected volcanic clastic material).

The lava flows commonly spread to great distances from their vents and fissures, and repeated outpourings at the same place or in the same region build broadly-rounded shield volcanoes or large flat plain or plateau surfaces.

2.2 TYPES OF LAVA FLOW

2.2.1 General

Basaltic lava flows can be separated into several general types. Flows formed on dry land are of three forms - pahoehoe, aa, and block lava. Pillow lavas and hyalclastite flows form when lava is extruded in aqueous environments.

Pahoehoe lava is the fundamental type ². The majority of flows issue from the vents as pahoehoe and change to aa or block lava as they advance downslope. The change and different types of lava are related to the viscosity of the liquid lava and the amount of stirring to which it is subjected. In general, the higher the viscosity and the more the stirring, the greater is the tendency to change.

2.2.2 Dimensions of Flows

Basaltic lava flows include the most voluminous and widespread flows on earth, though not all basaltic lava flows are large. The fastest lava

flows can attain speeds of 15 meters/sec, though 3 meters/sec is more common for a fast flow, and many flows move at barely perceptible rates .

The outpouring of lava in a region may sometimes be on so vast a scale, that the valleys of originally mountainous areas may be completely filled, producing a lava plateau. The Columbia River Plateau is one of the best known examples. The original topography had a relief of over 1500 meters, was completely buried, and new valleys incised in the plateau. This great thickness of lava was attained by the piling up of hundreds of individual flows, averaging only 23 meters ⁴, with the largest some 120 meters thick, and covering a total area of 130,000 sq. km. The Snake River basalts in southern Idaho are Quaternary in age and cover an area of 50,000 sq. km.

Major basalt plateaus outside the U.S.A. are the Deccan of India, with a present area of 500,000 sq. km.; the Parana Plateau basalts of Brazil, covering an area over 750,000 sq. km.; and the Karoo basalts of South Africa, covering over 50,000 sq. km.

Smaller areas of flood basalts are known, some of which are remnants of once much more extensive areas. The "plateau" lavas of the western isles of Scotland are a small surviving portion of a Tertiary basalt province which covered almost one million square kilometers ⁵.

2.2.3 Pahoehoe Lava

The Hawaiian words, pahoehoe and aa, were introduced by C.E. Dutton in 1884, and are now in common use. Pahoehoe lava is characterized by a smooth, billowy or rolling, and locally "ropy" surface. Aa in contrast, has a rough, jagged, spinose and clinkery surface.

Most characteristic of pahoehoe is a gently undulating or hummocky surface that conveys a general impression of smoothness, though in detail it may be covered with tiny sharp projections or a network of interlacing threads. During cooling a very thin skin forms that may be dragged into folds and ridges by movement of the still mobile lava underneath. The curvature of the ridges is convex in the direction of flow and constitutes one means of determining the direction of movement of ancient flows.

Vesicles generally are abundant in pahoehoe flows of average thickness. Thin flows are vesicular throughout and commonly the vesicles are most abundant in the central part. In thicker flows the greatest accumulation of vesicles is close to the top, often with a thin chilled layer of vesicular lava at the base. However, dense nonvesicular flow centers are far less common in pahoehoe than in either aa or block lava.

The vesicles of pahoehoe are characteristically spherical or spheroidal, or composed of partly coalescing spheroids only slightly to moderately distorted. In contrast, the vesicles of aa are very irregular, with many sharp angles and projections. Vesicles may become filled by deposition of secondary materials from circulating ground water to form amygdules.

2.2.4 Aa Lava

Aa lava is blocky, spiny, and slow moving. The most conspicuous and characteristic feature is its exceedingly rough fragmental top. The flow top is often referred to as scoriaceous, though the fragments are not scoriaceous in the sense of being highly vesicular. Hawaii geologists refer to the flow top as "clinker", due to the resemblance of the fragments to clinker formed in the grate of a furnace.

The massive portion of aa flows is generally much less vesicular than pahoehoe except for thick, ponded pahoehoe flows. Most vesicles are less than 2 cm across, and the vesicularity of aa may reach 50 percent, but generally is less than 30 percent².

Waters (1960)⁴ indicates that both in the Columbia River basalt and the olivine basalt of the Cascade Range the bottoms of most aa flows are essentially devoid of clinker, and the massive part of the flow rests directly on the surface over which the flow advanced. The margins of many recent aa flows are continuous banks of loose clinker, without any visible solid rock, though by digging into the clinker for a few meters the central massive part of the flow is reached. The upper clinker layer is essentially continuous over the entire flow surface. Nearly everywhere the clinker top is underlain by massive lava. The thickness of the upper clinker layer ranges from a few tens of cm to 2 to 3 meters, generally being to some degree proportional to the total thickness of the flow.

2.2.5 Block Lava

Block lava differs from aa in that the individual fragments are relatively smooth-surfaced polyhedral blocks, bounded by dihedral angles, and lack the exceedingly rough and spinose character of typical aa². Surfaces of block lava flows are usually very uneven and are covered by irregularly disposed hummocks and hollows with a vertical relief of several meters. Block lava is less vesicular than aa, though the vesicles generally have a similar form. The massive part of the flow and the blocks of breccia generally contain a larger proportion of glass than the corresponding parts of aa flows.

2.2.6 Pillow Lavas and Hyaloclastites

Pillow lavas consist of a mass of more or less ellipsoidal bodies described as pillow-shaped or bolster-shaped, Figure 2-1. Their formation is closely related with formation under aqueous conditions. Basaltic pillows generally range from about 10 cm to 6 or 7 meters in diameter, and grade either laterally or vertically into non-pillowed flows. Pillows are radially jointed with a glassy crust, though jointing is not always present.

Pillows may be tightly molded to each other, commonly they are partly or wholly separated by detrital material, either of ordinary sedimentary origin or the result of granulation of the glassy surfaces of the pillows themselves or of the lava flow that was forming pillows.

Hyaloclastites are composed wholly of angular fragments ranging from 1-2 mm to a few centimeters across, composed mainly of yellowish-brown earthy or waxy palagonite, and are the result of granulation of lava flows in water. In some instances the hyaloclastite overlies a lava flow of the same composition.

2.2.7 Small-Scale Features of Lava Flows

Flowing lava takes many forms of topographic relief. Figure 2-2 contains sketches of some of the more common features. Many flows have a convex surface; the greater the viscosity, of the lava, the greater is the convexity. Lateral ridges are formed when the liquid in the center is drained away. The crest will sag, but because the edges solidify faster

as they are thinner, the sag will leave two ridges, one on each side of the flow.

2.3 JOINTING

Thin lava flows, both pahoehoe and aa, typically are broken into innumerable joint blocks. Two sets of joints exist, one set approximately at right angles to the flow surface, and other parallel to it. Only very rarely is there an approach to regular columnar jointing. The most common joint pattern is an almost square rectangle; the joint blocks tend to be more or less cubic, but on the whole they are decidedly irregular.

Columnar jointing is rare in thin lava flows, it is more common in some of the world's thick basalt lava flows. Excellent examples are Fingal's Cave on the island of Staffa, Scotland; the Devel's Postpile in the Sierra Nevada of California; and the flows of the Columbia River region.

Columnar-jointed flows generally show a two-tiered or three-tiered arrangement. At the base of the flow a set of thick and usually well-formed columns, the colonnade, stands approximately normal to the bottom of the flow. Above is a layer of thinner and less regular columns, showing much irregularity in the column arrangement. The uppermost part of the flow shows jointing normal to the flow surface that may be as coarse or coarser than the lower portion. The upper part of the flow, above the colonnade, is termed the entablature. The entablature can be further subdivided into the entablature and upper collonade.

The upper zone generally is vesicular, whereas the lower zones are dense or markedly less vesicular than the upper zone.

Ideally, the columns are six-sided, with angles approaching 120° , though five-sided columns are usually more abundant than six-sided ones. Columns vary in size, in the colonnade averaging 70 cm in size, and in the entablature generally less than half as thick. The columns are broken by cross-joints, some inclined, but most normal to the edges of the prisms. Some of the cross-joints normal to the columns are straight, but many are curved in cross-section, termed "ball-and-socket" joints by Preston (1930) ⁶.

Columnar jointing is the result of contraction of the lava on cooling, the isotherms gradually moving inward from the cooling surfaces. In thin flows and the surficial part of the thick flows, cooling is rapid, producing irregular or very crudely columnar jointing. Slower cooling results in a gradual accumulation of tension, and when it reaches a certain critical level, rupture occurs.

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Pillow lava in cross-section. Upper pillows sag into hollows between lower pillows. Each pillow has a glassy skin and radial cracks.

FIGURE 2-1. (Ollier, 1972)

Some features of lava flows: (a) Simple convex surface of valley flow. (b) Lateral ridges, formed by sagging of simple convex flow. (c) Toe, at front of lava flow. (d) Toe ridge, formed by sagging behind toe. (e) Broad, flat-topped lava flow. (f) Stony rises formed by collapse of broad lava flow, parts of which remain at accordant heights. (g) Stony rises formed by irregular collapse. (h) Stony rises formed of divided, narrow lobes.

FIGURE 2-2. (Ollier, 1972)

3.0 ROCK PROPERTIES OF DRESSER BASALT

3.1 INTRODUCTION

Since many investigators have tested the Dresser basalt, a large volume of laboratory test data are available. Exceedingly little information addresses the rock mass itself, as the majority of the bedrock is obscured by drift deposits, or is difficult of access; hence, few papers have been published. A summary of the intact properties of Dresser Basalt is presented in Table 3-1.

3.2 DESCRIPTION OF ROCK MASS

3.2.1 Macroscopic Characteristics

3.2.1.1 Lithology

Dresser basalt from Dresser, Wisconsin is an altered basalt at the southwestern end of a belt of igneous rocks of the Middle Keweenawan era that trend northeast to Lake Superior. The volcanic group forming the belt consists of basaltic flows and lenticular beds of conglomerate with a thickness in excess of 20,000 feet in Minnesota ¹.

Exposed sections show that it is composed of many individual flow units, which range in thickness from less than 10 feet to more than 1000 feet. Some of the thinner flow units can be traced intermittently along the strike for more than 25 miles ².

An individual flow unit is characterized by a regular sequence of textures, consisting of a basal aphanitic unit that passes transitionally upward into an ophitic, diabasic, or porphyritic unit, which is overlain by an uppermost vesicular unit. In many flows, the vesicular crust is brecciated, consisting of rubble or fragmental material in which the interstitial spaces are filled with secondary material.

Lenticular beds of conglomerate, or less commonly sandstone, are intercalated with the flows at many localities. Bed thicknesses of conglomerate range from less than 3 feet to more than 300 feet. Occasional beds of tuff and tuff-breccia exist between individual flow units.

In the vicinity of Dresser the beds have undergone considerable hydrothermal or deuteric alteration. The rock has been classified as either an altered gabbro or an altered basalt, though the latter term is the one most commonly used.

3.2.1.2 Geologic Structure

Due to the lack of good exposure, much of the Upper Precambrian structure in east-central Minnesota and Wisconsin is obscure.

The generalized pre-Paleozoic bedrock map of east-central Minnesota and adjoining northwestern Wisconsin is shown in Figure 3-1. Geophysical studies ³ have demonstrated that the flows comprise part of a large basalt block, the St. Croix Horst ⁴ which extends beneath the Paleozoic strata. This basalt block is flanked by basins filled with Keweenaw strata. The block is bounded on the west by the Douglas and Pine faults and on the east by the Hastings fault, which is thought to be an extension of the Lake Gwen fault, Figure 3-2. In Wisconsin, the flows on top of the horst define what appears to be a broad syncline whose axis more or less parallels the bounding faults.

3.2.1.3 Jointing

Few publications could be traced which mention jointing. Krech et al (1971) ⁵ indicate that at one quarry exposure the rock is highly jointed and faulted, though there is no appearance of any definite joint system, the strike and dips ranging through 180 degrees. Due to the irregular fracture pattern, the rock, as exposed at the quarry, appears in the form of unconsolidated blocks, slabs, and wedges.

3.2.2 Microscopic Characteristics

3.2.2.1 Mineralogy

The mineralogy of the flows is poorly known, though chemical analyses indicate that the lavas have intermediate to mafic compositions. The rocks define a subalkaline trend and fall between clearly defined tholeiitic and calcalkaline affinities ¹.

Localized native copper deposits occur in individual flows. Generally the copper is concentrated in stratiform layers defined by the amygdaloidal portions of flow units.

The Dresser basalt tested in most experiments is generally a dark grayish green, ophitic, massive, fine-grained rock. Plagioclase and pyroxene compose about 90 percent of the rock, either in roughly equal amounts or with the feldspar in greater quantities. Magnetite is present between 5-8 percent and there are minor amounts of chlorite, amphibole, sericite, and hematite. The minor mineral constituents are partly dependent on the degree of alteration of the basalt ^{5, 6}.

3.3 PROPERTIES OF INDIVIDUAL DISCONTINUITIES

3.3.1 Joint Stiffness and Strength

No data is available.

3.3.2 Environmental Effects

No data is available.

3.4 PHYSICAL PROPERTIES OF INTACT ROCK

3.4.1 General

The physical properties have been established by many investigators. Most of the research has been carried out by the U.S.B.M. and has addressed two main areas, strength and modulus values, and thermal properties.

3.4.1 Strength and Modulus Properties

Krech et al (1964) ⁵ performed tests to establish the basic parameters required for rapid excavation research. Samples were prepared according to the specifications set forth in the American Society of Testing Materials (ASTM) guidelines. Thirty samples were prepared and tested for each test type, the results are given in Table 3-2.

Morrell and Larson (1974)⁷ of the U.S. Bureau of Mines (USBM) and the Avco Everett Research Laboratory (1972)⁸ similarly obtained basic strength parameters, and these are tabulated in Table 3-3.

Comparing the sets of data, compressive strength ranges from 59,500 to 69,500 p.s.i., and tensile strength from 1,982 to 3,480 p.s.i. Static Young's modulus varies from 12.7 to 14.25 x 10⁶ p.s.i, while Poisson's ratio ranges from 0.261 to 0.2725.

No data could be found on direct-shear-strength characteristics, apart from a value of 42⁰ for the fracture surface coefficient of friction quoted by Lehnhoff and Scheller (1975)⁹. Lindholm et al (1974)¹⁰ investigated the fracture property characteristics under different confining pressures and strain rates, Figure 3-3.

3.4.3 Thermal Properties

3.4.3.1 General

Information on thermal properties was available from fragmentation and related studies. Three properties were normally found; specific heat, thermal conductivity, and thermal expansion. In addition, other characteristics such as fragmentation behaviour and melt point were established.

3.4.3.2 Specific Heat

Tests by Lindroth and Krawza (1971)¹¹, established the heat content and specific heat for basalt at temperatures up to 1,000⁰C. It was found that both parameters are strongly dependent on the chemical composition of the rock. For the Dresser an increase in specific heat of 13 percent occurred over the temperature range 100⁰C to 1000⁰C. A value of 0.23 cal/gm⁰C at 100⁰C increasing to 0.26 cal/gm⁰C at 1000⁰C.

Values of both specific heat and heat content are given in Figure 3-4, and Table 3-4. Douglas and King (1968)¹² pointed out that the experimental accuracy of the specific heat is difficult to estimate, as it changes fairly rapidly in the temperature range 100⁰C to 575⁰C. The percentage of uncertainty, characteristic of the heat content, as determined by the differentiation process, may have to be multiplied by a

factor of two or more. The estimated specific heat values therefore have corresponding errors.

3.4.3.2 Thermal Conductivity

Marovelli and Veith (1965) ¹³ compared thermal conductivities of rock by the transient live source method over a temperature range of -85°F to 1500°F. Values for Dresser Basalt are plotted in Figure 3-5. The conductivity values ranging from 0.75-1.13 BTU/(hr. ft. °F) at the lower and higher temperature respectively.

3.4.3.3 Coefficient of Linear Thermal Expansion

The coefficient of linear thermal expansion increases as the temperature increases. Lehnhoff and Scheller (1975) ⁹ used values of $0.290 \times 10^{-5}/^{\circ}\text{C}$ at 24° to $1.16 \times 10^{-5}/^{\circ}\text{C}$ at 700°C. Full data over the temperature range investigated are presented in Table 3-5. From their research it was clear that with increasing quartz content, the thermal diffusivity and the coefficient of thermal expansion similarly increase.

3.4.3.3 Fragmentation Behaviour

Experimental tests performed by Thirumalai (1970) ¹⁴ indicate that fragmentation of Dresser basalt takes place at around 500°C. An interesting feature is that spalling only occurs when the heat source is implanted within the rock, so creating a thermal inclusion. If the basalt is subjected to surface heating, it is found to be a nonspalling material. Melting occurs with high energy consumption. Figure 3-6 illustrates the build up of tangential stress with temperature.

3.4.4 Hydrological Properties

No data could be found on any hydrological properties.

3.5 ENVIRONMENTAL FACTORS

3.5.1 Time

No data was found to be available on effects of time on rock properties.

3.5.2 Temperature

In general the effect of heating is to permanently reduce the values of both the shear modulus and Young's modulus ⁶. Table 3-6 lists the information for Dresser basalt between 75⁰F and 1500⁰F, Young's modulus decreasing from 15.0 to 7.03×10^6 p.s.i. respectively. Figure 3-7 graphically illustrates the decrease in rock properties. This decrease is thought to be due mainly to discontinuities produced in the specimen by differential thermal expansion of the various mineral rock components.

3.5.3 Swelling Pressure

No data are available.

3.5.4 Irradiation Effects

No information is available on the effects of irradiation on Dresser basalt.

3.6 EXCAVATION CRITERIA

3.6.1 General

To our knowledge, no underground excavations have been made in Dresser basalt. Information is available, however, on the borability of the Dresser basalt.

3.6.2 Subsurface Excavations

As no data are available on excavation procedures or the nature of roof support problems, a brief outline of the borability characteristics of the Dresser is given. This information may be useful in assessing the suitability of employing a boring machine for excavation purposes as opposed to conventional techniques of drilling and shooting.

Morrell and Larson (1974) ⁷ of the USBM performed experiments on disk cutters to define the fundamental relationships governing disk cutter performance in soft, medium, and hard rocks. The Dresser basalt comprises one of the hard rocks selected. Tests were performed to establish the crater depth, tangential cutter force, crater volume, specific energy versus normal cutter force, and crater width versus depth.

The above relationships for the Dresser are given in Figures 3-8 and 3-9. Crater depth is a linear function of normal cutting force, as is the specific energy a function of normal cutting force used to the -0.5 power. Tangential cutting force is a function of the normal cutting force raised to the 1.9 power, and crater width is a linear function of crater depth. Crater volume similarly is a linear function of input energy.

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FIGURE 3-1. Generalized pre-Paleozoic bedrock map of east-central Minnesota and adjoining northwestern Wisconsin showing inferred distribution and structure of Keweenaw flows and clastic strata. (Morey and Mudrey, 1972)

FIGURE 3-2. Inferred geologic section across the St. Croix horst. (Morey and Mudrey, 1972)

FIGURE 3-3. Plot of yield and fracture data in the plane of the hydrostatic and axial stress axis. (Lindholm et al, 1974)

FIGURE 3-4. Comparison of the specific heats for the six rock types.
(Lindroth and Krawza, 1971)

FIGURE 3-5. Inverse thermal conductivity versus temperature, basalt.
(Marovell and Veith, 1965)

FIGURE 3-6. The trend of tensile stress increments of the thermal inclusion at elevated temperatures. (Thirumalai, 1970)

FIGURE 3-7. Elastic moduli and Poisson's Ratio as a function of temperature for Dresser basalt: (Wingquist, 1969)

FIGURE 3-8. Specific energy as a function of normal cutter force. (Morrell and Larson, 1974)

FIGURE 3-9. Relation between creater width, depth, volume, normal and tangential force, and energy for Dresser basalt. (Morrell and Larson, 1974)

TABLE 3-1

INTACT PROPERTIES OF DRESSER BASALTBASIC PARAMETERS

<u>Type of Property</u>	<u>Parameter</u>	<u>Customary English Units</u>
Index	. Unit Weight	187.9 lbs/ft ³
	. Natural moisture content (intact)	-- %
	. Porosity (rock mass)	0.19 %
Stress-strain	. Young's Modulus	13.5x10 ⁶ lbs/in ²
	. Poisson's Ratio	0.264
	. Bulk Modulus	
	. Shear Modulus	6.02x10 ⁶ lbs/in ²
Strength	. Cohesion 1500-3500 Friction Angle psi range	
	. Uniaxial Compressive Strength	63,900 lbs/in ²
	. Tensile Strength	3,200 lbs/in ²
Thermal	. Coefficient of Linear Thermal Expansion	1.6x10 ⁻⁶ /°F
	. Heat Capacity	0.23 BTU/lb-°F
	. Thermal Conductivity	0.75 BTU/hr-ft-°F
Hydrological	. Horizontal Permeability	
	. Vertical Permeability	

TABLE 3-2

DRESSER BASALT TEST RESULTS
(Krech et al, 1964)

Property ¹	Block No. 17		Block No. 28		Block No. 68		Composite	
	Mean	CV ²	Mean	CV ³	Mean	CV ²	Mean	CV ²
Porosity.....pct..	0.16	9.0	0.15	0.05	0.25	12.7	0.19	57.3
Permeability.....um/sec..	(³)	-	(³)	-	(³)	-	(³)	-
Density.....g/cm ³ ..	3.02	0.1	3.01	0.7	3.01	0.1	3.01	0.5
Shore hardness.....	95.0	3.1	93.2	2.5	94.2	1.9	94.1	2.6
Compressive strength.....MN/m ² ..	479	7.91	413	10.7	429	9.16	440	11.0
Do.....10 ³ psi..	69.5	7.91	59.9	10.7	62.2	9.16	63.9	11.0
Compressive Young's modulus								
GN/m ² ..	88.5	2.43	82.1	2.18	87.5	2.42	86.1	4.1
Do.....10 ⁶ psi..	12.8	2.43	11.9	2.18	12.7	2.42	12.5	4.1
Tensile strength.....MN/m ² ..	22.9	24	24.0	38.0	17.6	57.0	22.1	39.7
Do.....10 ³ psi..	3.33	24	3.48	38.0	2.56	57.0	3.20	39.7
Tensile Young's modulus....GN/m ² ..	133	9	121	21	105	23	119	20.2
Do.....10 ⁶ psi..	19.2	9	17.6	21	15.3	23	17.3	20.2
Pulse velocity.....km/sec..	6.77	0.3	6.67	0.3	6.72	0.3	6.72	0.7
Bar velocity.....km/sec..	6.12	0.2	5.99	0.4	6.04	0.5	6.05	1.0
Torsional velocity.....km/sec..	3.86	0.2	3.76	0.4	3.80	0.6	3.80	1.2
Dynamic Young's modulus ⁴ ...GN/m ² ..	113	0.5	108	1.5	109	1.1	110	2.5
Dynamic shear modulus ⁴GN/m ² ..	44.9	0.4	42.5	1.5	43.4	1.3	43.6	2.6
Poisson's ratio ⁴	0.261	1.4	0.266	1.1	0.266	1.5	0.264	1.6

¹Specimen prepared with the long axis perpendicular to the top face (along Z-axis).

²Coefficient of variation, percent.

³Less than 1×10^{-4} um/sec.

⁴Calculation is based on the assumption of isotropy.

TABLE 3-3

PROPERTIES OF DRESSER BASALT
(Morrel and Larson, 1974) and (Avco, 1972)

Commercial Name.	.DRESSER BASALT
Rock Type	.Basalt
Locality	.Dresser, Wisconsin
Compressive Strength, psi	63,610
Tensile Strength, psi	1,982
Shore Hardness, Scleroscope units	85.8
Apparent Density, slugs/ft ³	5.879
Apparent Density, g/cm ³	3.029
Static Young's Modulus, 10 ⁶ psi	14.25
Longitudinal Velocity, fps	21,873
Bar Velocity, fps	19,514
Shear Velocity, fps	12,264
Dynamic Young's Modulus, 10 ⁶ , psi	15.54
Poisson's Ratio	0.2725
Shear Modulus, 10 ⁶ , psi	6.14
Tensile Fracture Stress, n/m ²	1.45x10 ⁷
Thermal Conductivity coefficient A	1.45x10 ⁻⁵
Thermal Conductivity coefficient B	-.15
Coefficient of Thermal Expansion, deg ⁻¹	5.4x10 ⁻⁶

TABLE 3-4

EXPERIMENTAL HEAT CONTENT FOR DRESSER BASALT
(Lindroth and Krawza, 1971)

Dresser basalt	
t, °C	H _t - H ₂₅ , cal/g
99	13.8
103	14.7
201	37.5
203	38.2
310	65.0
311	65.0
423	95
425	95
535	126
536	126
565	134
569	135
650	159
652	159
757	184
758	186
869	214
871	215
1,000	249
1,000	249

TABLE 3-5

PROPERTIES OF DRESSER BASALT USED IN ANALYSES
(Lehnhoff and Scheller, 1975)

Dresser Basalt			
Temp °C	Young's Modulus E, 10 ⁵ kg/cm ²	Poisson's Ratio ν	Coeff. of Thermal Expansion α, 10 ⁵ /°C
24	10.268	0.24	0.290
122	10.054	0.24	0.500
260	9.697	0.22	0.770
371	8.933	0.19	0.940
482	8.504	0.18	1.020
538	8.147	0.16	1.080
593	6.781	0.11	1.160
700	0.010	0.10	1.160

TABLE 3-6

ELASTIC MODULI DATA FOR DRESSER BASALT
(Wingquist, 1969)

	Temperature, ° F ¹									
	75	250	500	700	900	1,000	1,050	1,100	1,300	1,500
YOUNG'S MODULUS, 10 ⁶ psi ²										
Sample 1.....	15.0	14.7	14.2	12.9	12.3	-	-	9.72	7.11	7.03
Sample 2.....	14.4	14.1	13.5	12.5	11.9	11.6	-	9.43	6.46	6.51
Sample 3.....	14.4	14.2	13.7	12.6	12.0	11.6	-	9.81	7.01	6.97
Mean.....	14.6	14.3	13.8	12.7	12.1	11.6	-	9.65	6.86	6.84
Standard deviation...	.35	.32	.36	.21	.21	.00	-	.20	.35	.28
SHEAR MODULUS, 10 ⁶ psi										
Sample 1.....	6.04	5.90	5.82	5.40	5.22	-	-	4.41	3.35	3.31
Sample 2.....	5.80	5.67	5.53	5.22	5.04	4.94	-	4.28	2.99	3.13
Sample 3.....	5.87	5.78	5.62	5.30	5.13	4.97	-	4.40	3.32	3.28
Mean.....	5.90	5.78	5.66	5.31	5.13	4.96	-	4.36	3.22	3.24
Standard deviation...	.12	.12	.15	.09	.09	.02	-	.07	.20	.10
POISSON'S RATIO										
Sample 1.....	0.24	0.25	0.22	0.19	0.18	-	-	0.10	0.06	0.06
Sample 2.....	.24	.24	.22	.20	.18	0.17	-	.10	.08	.04
Sample 3.....	.23	.23	.22	.19	.17	.16	-	.12	.06	.06
Mean.....	.24	.24	.22	.19	.18	.16	-	.11	.07	.05
Standard deviation...	.01	.01	.00	.01	.01	.01	-	.01	.01	.01

4.0 ROCK PROPERTIES OF AMCHITKA ISLAND BASALT

4.1 INTRODUCTION

Amchitka Island is an elongate island situated in the western part of the Aleutian volcanic archipelago, Alaska. It is an entirely treeless, tundra covered area of 115.4 sq. miles between the Bering Sea and the North Pacific (Figure 4-1). It is largely composed of stratified marine and subaerial volcanic breccias and other extrusive rocks.

The stratigraphy, physical rock properties, and hydrological conditions have been investigated, as it has been used by the U.S. Atomic Energy Commission for underground nuclear testing. A synopsis of this data was presented by Sharp (1972)¹, and forms the basis of this chapter. A summary of the intact rock properties is included in Table 4-1.

3.2 DESCRIPTION OF ROCK MASS

4.2.1 Macroscopic Characteristics

4.2.1.1 Lithology

The island is composed of tertiary volcanic rocks which comprise three formations, the Amchitka Formation, the Banjo Point Formation, and the Chitka Point Formation. Figure 4-2 is a stratigraphic section of the three formations penetrated by a nine-inch diameter exploratory hole.

Amchitka Formation - The Formation has a total thickness of 5,600 feet² and comprises lower (older) breccias and hornfels and upper pillow lavas and breccias of Kirilof Point. It is exposed in the SE quarter of the island east of the Rifle Range Fault. The older breccias consist largely of well-indurated, water-laid andesitic volcanic breccias intercalated with thinly-bedded volcanic sediments ranging from coarse sandstone to claystone.

The pillow lavas and breccias of Kirilof Point are mostly andesitic, volcanic and tuff breccias, many chilled and glassy, approaching palagonites. Many of the glasses are altered to nontronite.

Banjo Point Formation - The Formation is exposed along the Pacific from near the middle of Amchitka SE to St. Makarius Point, and over a shorter distance across the island. The Banjo Point Formation is comprised largely of poorly sorted, massively stratified, predominantly basaltic, water-laid volcanic breccias. It has a maximum thickness of 3,580 feet.

The breccia beds contain interbedded volcanic sandstones and siltstones up to 120 feet thick and thin beds of volcanic shale and mudstone. Together these minor members comprise less than ten percent of the formation.

Chitka Point Formation - The Formation covers the NW half of Amchitka. It is comprised of hornblende - andesite pyroclastic and tuff breccias with flows in its lower portions. Total thickness is 2,280 feet. The breccias comprising most of the lower section vary from volcanic conglomerates, through pyroclastic breccias, and possibly volcanic intrusion breccias, to true tuff breccias. Andesite flows are predominantly in the upper section.

Basaltic Intrusive Rocks - Dikes and sills of varying composition occur throughout all the formations on Amchitka.

4.2.1.2. Geologic Structure

Bedding exposed in the SE half of Amchitka has gentle, homoclinal dikes directed to the SW in the older Amchitka Formation and Banjo Point Formation, though the Banjo Point Formation NE of St. Makarius Point has a broad gentle synclinal structure, due to dioritic intrusive masses. Dips within the younger Chitka Point Formation are directed inward toward the island in its NW portion, indicative of a volcano-tectonic depression which has since been filled with the upper sequence of Chitka Point flows.

The principal structures appear to be tilted grabens and fault blocks trending predominantly N 70°E. The grabens trend across the island, alternating with tilted fault blocks and horsts, in which normal relative vertical displacements dominate. The faulting is probably also associated with sizable right-lateral transcurrent movements. The faulting causes repetition of the stratigraphic section along the length of the NW

trending island, particularly eastward of center. Figure 4-3 is a geologic cross-section through Amchitka Island.

4.2.1.3 Jointing

The bedrock is shattered and jointed throughout the island. The master joints, which are near-vertical like the faults, are variable in strike direction but group around the normal to the arc, with a minimum number striking parallel to its trend. The master joint directions do not notably change with locations or rock type throughout the island. Figure 4-4 shows lineament directions for each formation.

In addition to the master joints an infinite number of smaller joints are found in all rock types throughout the island. No specific measurements were made exclusively for basaltic rocks. In general, however, closely spaced jointing is not very common.

The frequency of jointing was found to decrease in the Chitka Point lava flows, the andesite and basaltic intrusives, the quartz diorites, the glassy Kirilof Point breccias and the older breccias of the Amchitka Formation, in that order. Joint spacing varies from 3 inches to 6 feet or more. The pillow lavas, Chitka Point breccias and rocks of the Banjo Point Formation are characterized by widely-spaced joints. Generally joint spacing reflects the fact that joint frequency decreases with increasing bed thickness and rock hardness.

4.2.2 Microscopic Characteristics

4.2.2.1 Mineralogy

Sharp (1972)¹ does not stress the detailed petrographic distinction between the individual flow types or indicate the chemical mineralogical composition of the rock types. The older breccias of the Amchitka Formation are gray to green, often notably glassy, hard, dense and brittle, due to silicification, and have been chloritized, epidotized and zeolitized in places. Around Kirilof Point, the breccias appear holohyaline. Most of the breccias of the Banjo Point and Chitka Point Formations show similar effects of alteration as shown by the Amchitka Formation. No detailed petrology of the basalt was available.

4.3 PROPERTIES OF INDIVIDUAL DISCONTINUITIES

4.3.1 Joint Stiffness and Strength

No data are available.

4.3.2 Environmental Effects

No data are available.

4.4 PHYSICAL PROPERTIES OF INTACT ROCK

4.4.1 General

A full scale testing program was developed to obtain the strength properties of the different rock types and formations on Amchitka. Elastic and other properties were measured, and almost 300 uniaxial compression tests, 500 Brazilian tensile tests, and 40 three-point beam tests were made. Sonic velocities were determined for each of the large samples prior to coring.

4.4.2 Strength and Modulus Properties

Values of wet strength and modulus values are given in Table 4-2¹, for the different lithologies. The dense, older breccias of the Amchitka Formation record the maximum average compressive strength of 37,500 p.s.i., while the glassy breccias of the same formation give the minimum average of 5,500 p.s.i. The dense basalts, quartz diorites, and hornblende-pyroxene andesites show average compressive strengths decreasing from 36,200 p.s.i. to 30,200 p.s.i.

In the remaining rock types, the compressive strength average value of 20,400 p.s.i. for the pillow lavas, 18,300 p.s.i. in the dense flow breccias, 17,200 p.s.i. in the Banjo Point breccias, and 11,900 p.s.i. in the tuff breccias.

The dense basalts have the greatest average value of static Young's modulus of 8.86×10^6 p.s.i. The value decreases from 7.15×10^6 p.s.i. to 6.77×10^6 p.s.i. in the quartz diorites, hornblende-pyroxene

andesites and dense older breccias in that order. The various breccias of the Chitka and Banjo Point Formations all have Young's modulus values below 4.15×10^6 p.s.i. The lowest values were recorded for the glassy breccias of the Amchitka Formation, having an average Young's modulus of 1.85×10^6 p.s.i.

Average values of Poisson's ratio were found to range from 0.17 to 0.28, with the hornblende-andesite breccias of the Chitka Point Formation having the minimum average and the quartz diorites having the maximum. The dense basalts have an average Poisson's ratio of 0.19, from testing 7 samples. The average values of Poisson's ratio are within the range of that generally assumed normal for rocks of fair elasticity. Calculated average values of the modulus of rigidity and bulk modulus generally equal about 40 and 66 percent of Young's modulus for the same rocks, respectively. All durable dry values are given in Table 4-3.

4.4.3 Thermal Properties

No data are available.

4.4.4 Hydrological Properties

Stearns (1942)³ notes the differences in hydrologic properties between subaerial, basaltic volcanics and submarine lavas and pyroclastics of intermediate composition. He indicates that the latter are chiefly of explosive origin, and are often interbedded with ashy shales and other sediments of low permeability. The former type deposits, which pour out beneath the sea, usually result in pillow lavas and breccias, which would be highly permeable if it were not for the secondary minerals sealing them.

These observations of a general nature by Stearns (1942)³ are supported by both observation and hydrologic tests of Amchitka. These tests of a shallow, intermediate, and deep nature were conducted by the U.S. Army Corps of Engineers (1965)⁴. The data obtained by hydrologic testing were in packed-off intervals of a borehole. The values plotted versus depth are relative specific capacities computed from injection or swabbing tests.

Inspection of Figure 4-5 indicates that permeabilities decrease with depth, and that at depths below 4,000 feet they are generally less than 0.1 g.p.d. per sq. ft. At shallow depths values as high as 10 g.p.d. per sq. ft. were found by the U.S. Army, and based on observations of near-surface ground water in rocks, the overall value considering all lithologies approaches 0.5 g.p.d. per sq. ft.¹ at shallow depths.

Field observations and drill-stem testing show that ground water moves largely through tight joints and bedding planes. The hydrologic system is structurally controlled and local conditions include perched water tables, artesian head conditions, near-impermeable vertical and horizontal barriers and zones of secondary mineralization and alteration.

4.5 ENVIRONMENTAL FACTORS

4.5.1 Time

Creep rates were determined by uniaxial compression tests and extrapolated to 200 minutes. Results are tabulated in Table 4-4, and plotted in Figure 4-6. Inspection of this data shows that of the nine rock types tested, only the tuff breccias of the Chitka Point Formation and the glassy breccias of Kirilof Point (Amchitka Formation) give average creep rates categorizing them as viscous, i.e. if at 50 percent of its uniaxial compressive strength and strain rate is greater than 2.0 micro-strains per hour⁵.

The dense basalts and pillow lavas not only have low uniaxial creep rates, but also exhibit the minimum average amounts of irrecoverable strain. This indicates their failure mode to be generally the most brittle of all the rocks tested. The dense older breccias of the Amchitka Formation, which appear harder and more brittle in outcrop, show an irrecoverable strain that is less than the others.

4.5.2 Temperature

No data were found.

4.5.3 Swelling Pressure

No data were found.

4.5.4 Irradiation Effects

No data were found.

4.6 EXCAVATION CRITERIA

4.6.1 General

No significant underground excavations have been constructed. Shafts have been drilled to depths of over 5000 feet with dimensions up to 120 inches and no great problems were encountered. An engineering classification of the different lithologies on the island was developed by Sharp (1972) ¹ and this can be used in a preliminary assessment of cavern stability.

4.6.2 Subsurface Excavations

On Amchitka, drill rigs bored holes to permit installation of the nuclear device. Due to the blocky and massive nature and unconfined strengths of the rock types on the island, no particular problems were encountered so long as fault zones were avoided.

An engineering classification for the different lithologies and joint frequency is given in Table 4-5. The table indicates that the majority of rocks on Amchitka can be expected to range from strong to very strong, and to have failure characteristics in the unfractured and dry state which appear largely elastic. They are comprised of massive beds with layering generally of minor significance and joint spacing of 3 to 6 feet or more. Testing of wet specimens, which is more applicable to the actual excavation conditions, show a decrease in strength, Figure 4-7.

A pattern of resin rock bolts was recommended to be employed during excavation with the addition of wire mesh, expanded metal, or channel iron lagging to support any loose rock that develops. In areas of swelling ground, sealing the rock against changes in moisture content by guniting with flexible liners was suggested.

4.0 REFERENCES

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2. Lee, W.H. and Morris, R.H. Preliminary Lithologic Log of Drill Hole UAE-1 from 5000 to 7000 feet, Amchitka Island, Alaska, USGS 474-47, Clearinghouse, Springfield, 1968.
3. Stearns, H.T. Hydrology of Volcanic Terrains, in Hydrology, Dover, New York, 1942.
4. U. S. Army Engineers. Project Longshot, Amchitka Island, Alaska Geologic and Hydrologic Investigations (Phase I), U. S. Army Eng. District, Anchorage, 1965.
5. Coates, D.F. and Parsons, K.C. Experimental Criteria for Classification of Rock Substances, Int. Jour. Rock Mech. Min. Sci. 3., 1965.

FIGURE 4-1. Index map showing location of Amchitka Island, Alaska, in the Aleutian Chain.
(Sharp, 1972)

SECTION A₁-A₂

SECTION A₂-A₄

SECTION A₄-A₆

(AFTER CARR AND QUINLIVAN, 1967)
(MODIFIED TO REFLECT HOLE LOGS OF APPENDIX A)

HORIZONTAL SCALE - MILES

GEOLOGIC CROSS-SECTION THROUGH AMCHITKA ISLAND

FIGURE 4-3.

FIGURE 4-4 Amchitka photo lineament directions by major rock type. (Sharp, 1972)

FIGURE 4-5. Graphic summary of hydrologic test data, Amchitka Island as obtained from the various deep exploratory holes. (Sharp, 1972)

FIGURE 4-6. Local rock compressive strength vs. creep rate.
(Sharp, 1972)

WET VS. DRY COMPRESSIVE STRENGTHS OF LOCAL ROCK
AVERAGE VALUES OF MAJOR FORMATIONAL AND LITHOLOGIC GROUPS

- LEGEND
- -Tcpl: H-P ANDESITE
 - -Tcpl: DENSE FLOW BRECCIA
 - -Tcpl: H. ANDESITE BRECCIA
 - -Tcpl: TUFF BRECCIA
 - + -Tbp: BANJO PT. BRECCIA
 - -Tb: DENSE BASALTS
 - -TAb: GLASSY BRECCIAS
 - Δ -TAb: PILLOW LAVAS
 - Δ -TAb: DENSE OLD BRECCIAS
 - x -TQd: QUARTZ DIORITE
 - * -TAh: HORNFELS

WET VS. DRY TENSILE STRENGTHS OF LOCAL ROCK
AVERAGE VALUES OF MAJOR FORMATIONAL AND LITHOLOGIC GROUPS

FIGURE 4-7.
(Sharp, 1972)

TABLE 4-1

INTACT PROPERTIES OF AMCHITKA ISLAND DENSE BASALTBASIC PARAMETERS

<u>Type of Property</u>	<u>Parameter</u>	<u>Customary English Units</u>
Index	. Unit Weight	170.4 lbs/ft ³
	. Natural moisture content (intact)	-- %
	. Porosity (rock mass)	2.8 %
Stress-strain	. Young's Modulus	8.86x10 ⁶ lbs/in ²
	. Poisson's Ratio	0.19
	. Bulk Modulus	4.76x10 ⁶ lbs/in ²
	. Shear Modulus	3.72x10 ⁶ lbs/in ²
Strength	. Cohesion 1500-3500 Friction Angle psi range	60 degrees
	. Uniaxial Compressive Strength	36,237 lbs/in ²
	. Tensile Strength	2,249 lbs/in ²
Thermal	. Coefficient of Linear Thermal Expansion	
	. Heat Capacity	
	. Thermal Conductivity	
Hydrological	. Permeability	0.5 gpd/ft ²

TABLE 4-2

AVERAGE ENGINEERING PROPERTIES OF WATER SATURATED AMCHITKA ISLAND ROCKS BY MAJOR ROCK TYPES IN THE RECOGNIZED FORMATIONS (Sharp, 1972)

(2)	(3)	(4)	(5)	(6)	(7)
LEGEND (See Notes)	INCREASED MOISTURE (vol. pct.)	COMPRESSIVE STRENGTH (psi)	TENSILE STRENGTH (psi)	YOUNG'S MODULUS (10 ⁶ psi)	VOLUME OF RUPTURE
CHITKA POINT FORMATION: HORNBLENDE PYROXENE ANDESITE - Tcp1-I					
AVG:	3.5	15,760	1,538	3.32	3.4
MAX:	15.6	28,747	2,548	8.15	8
MIN:	1.2	1,354	95.1	0.29	1
N:	26	20	9	20	23
S:	4.0	8,997	730	2.14	2.0
V:	115.9	58.2	47.5	64.60	58.2
CHITKA POINT FORMATION: DENSE FLOW BRECCIA - Tcp1-II					
AVG:	6.4	10,723	1,720	2.58	2.8
MAX:	10.4	15,184	2,663	4.60	4
MIN:	2.4	6,848	776	1.48	2
N:	10	5	2	5	5
S:	2.9	3,315	1,334	1.21	0.8
V:	46.3	30.9	77.6	47.00	29.9
CHITKA POINT FORMATION: HORNBLENDE ANDESITE BRECCIA - Tcp-I					
AVG:	7.7	7,021	436.7	2.12	2.0
MAX:	17.9	17,098	871	3.66	3
MIN:	3.2	1,931	213	0.58	1
N:	9	8	3	8	7
S:	4.5	4,722	376	1.19	1.0
V:	57.9	67.3	86.1	56.30	50.2
CHITKA POINT FORMATION: TUFF BRECCIA - Tcp-II					
AVG:	14.6	7,225	443	1.31	2.8
MAX:	31.4	16,828	808	3.04	7
MIN:	6.7	651	102	0.21	1
N:	26	22	9	22	23
S:	7.3	4,701	252	0.81	1.6
V:	50.1	65.1	56.9	61.50	57.8
BANJO POINT FORMATION: BRECCIA - TbP					
AVG:	16.6	4,994	940.4	0.98	1.6
MAX:	29.2	22,904	2,481	2.76	4
MIN:	3.7	1,353	134	0.26	1
N:	18	11	7	10	11
S:	7.2	6,174	1,070	0.82	1.1
V:	43.2	123.6	113.8	84.10	68.5
DENSE BASALTS - Tb					
AVG:	2.8	17,866	2,200	4.37	5.1
MAX:	7.7	28,524	2,544	11.21	9
MIN:	1.1	10,945	1,855	2.08	3
N:	10	10	2	10	10
S:	2.2	5,542	487	2.72	2.0
AMCHITKA FORMATION: KIRILOF POINT GLASSY BRECCIAS - Takb-I					
AVG:	8.1	2,898	395	1.00	1.1
MAX:	10.7	4,820	2,035	2.82	2
MIN:	2.7	1,878	269	0.33	1
N:	14	7	6	7	7
S:	2.8	1,168	100	0.88	0.4
V:	34.4	40.3	25.4	88.00	33.2
AMCHITKA FORMATION: KIRILOF POINT PILLOW LAVAS - Takp-II					
AVG:	9.2	16,226	---	2.96	3.7
MAX:	10.5	18,899	---	3.91	4
MIN:	7.6	13,582	---	2.46	3
N:	5	3	---	3	3
S:	1.1	2,659	---	0.83	0.6
V:	11.9	16.4	---	27.90	15.6
AMCHITKA FORMATION: DENSE OLDER BRECCIAS - TAB					
AVG:	3.3	28,502	2,632	6.51	5.3
MAX:	6.9	44,206	3,430	14.28	8
MIN:	0.4	5,496	1,931	1.71	3
N:	17	11	4	11	11
S:	1.0	12,192	676	3.61	1.6
V:	56.0	42.8	25.7	55.40	29.5
EAST CAPE QUARTZ DIORITE: Tqd					
AVG:	1.7	24,450	1,789	5.26	5.3
MAX:	3.0	38,332	2,299	14.38	8
MIN:	0.8	5,994	1,170	1.62	3
N:	37	31	6	31	31
S:	0.5	9,052	454	2.64	1.2
V:	29.0	37.0	25.3	50.10	24.5

NOTES: The average (AVG), maximum (MAX) and minimum (MIN) values determined from the number (N) of specimens in each group, with the standard deviation (S) and percentage variation (V), are given in descending order for each group property across the table. Values in Column 5 represent the increased moisture in the saturated state (after 7 days submersion) over that air dried (14 days) in volume percent.

TABLE 4-3

AVERAGE ENGINEERING PROPERTIES OF AIR DRIED AMCHITA ISLAND ROCKS BY
MAJOR ROCK TYPES WITHIN THE VARIOUS RECOGNIZED FORMATIONS (Sharp, 1972)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
NO.	LEGEND (See Notes)	HARD- NESS	APPARENT SPECIFIC GRAVITY	AIR DRIED PORE SPACE (vol.pct.)	COMPRESSIVE STRENGTH (psi)	TENSILE STRENGTH (psi)	YOUNG'S MODULUS (10 ⁶ psi)	POISSON'S RATIO	RIGIDITY MODULUS (10 ⁶ psi)	BULK MODULUS (10 ⁶ psi)	LONGITUDINAL VELOCITY (fps)	SHEAR VELOCITY (fps)	VIOLENCE OF RUTPURE	STRAIN ENERGY (psi)	INTERNAL FRICTION (deg)	MAGNETIC SUSCEPTIBILITY (emu/cc)
CHITKA POINT FORMATION: HORNBLÉNDE P'ROXENE ANDESITE - Tcp1-1																
1	AVG:	6.0	2.67	3.5	30,256	2,154	6.92	0.23	2.81	4.27	16,322	8,804	6.3	69.6	58	2,662
	MAX:	7.0	2.91	15.6	43,532	3,649	13.31	0.36	5.35	15.85	22,656	10,686	9	134.8	85	3,385
	MIN:	3.5	2.34	1.2	8,968	712	1.60	0.17	0.60	1.57	8,100	5,798	1	21.2	20	1,298
	N:	36	105	26	25	53	25	18	18	18	26	10	85	25	25	12
	S:	1.2	0.13	4.0	10,871	743.0	2.80	0.06	1.30	3.18	3,780	1,902	2.3	31.3	15.0	595.0
	V:	20.4	4.9	115.9	35.9	34.5	40.50	27.40	42.90	69.20	23.2	21.6	36.1	44.9	25.6	22.4
CHITKA POINT FORMATION: DENSE FLOW BRECCIA - Tcp1-1																
2	AVG:	5.2	2.57	6.4	18,368	2,179	4.47	0.18	1.89	2.33	14,693	7,541	5.5	43.8	62	1,904
	MAX:	7.5	2.74	10.4	26,848	3,162	7.83	0.22	3.35	3.95	17,870	9,549	9	81.2	70	3,274
	MIN:	2.5	2.38	2.4	11,828	1,178	3.08	0.14	1.31	1.60	12,179	6,394	1	22.1	54	547
	N:	18	38	10	8	25	8	7	7	7	10	5	33	7	8	6
	S:	1.2	0.11	2.9	5,273.4	625.8	1.55	0.03	0.69	0.85	2,276	1,260	2.6	20.4	6.5	1,102.8
	V:	23.0	4.2	46.3	28.7	28.7	34.74	15.50	33.59	35.62	15.5	16.7	47.3	46.5	10.5	57.8
CHITKA POINT FORMATION: HORNBLÉNDE ANDESITE BRECCIA - Tcp-1																
3	AVG:	4.8	2.47	7.7	13,249	1,501	4.97	0.17	2.12	2.51	12,461	9,038	3.7	22.3	61	1,953
	MAX:	6.5	2.59	7.9	20,126	1,957	8.25	0.19	3.47	4.44	13,214	10,944	8	38.4	82	2,820
	MIN:	3.5	2.07	3.2	3,184	631	1.18	0.15	1.76	1.93	11,190	8,064	1	0.6	40	534
	N:	10	37	9	7	22	7	6	6	6	4	3	29	7	6	4
	S:	0.8	0.13	4.5	5,556.6	360.7	2.14	0.02	0.61	0.85	1,270	1,650	2.4	13.4	14.1	326.3
	V:	17.2	5.1	57.9	49.5	24.0	43.14	11.16	25.37	30.20	13.2	18.3	64.1	60.0	23.2	16.7
CHITKA POINT FORMATION: TUFF BRECCIA - Tcp-1																
4	AVG:	4.2	2.24	14.6	11,934	873	3.36	0.22	1.38	2.00	10,435	6,356	3.1	26.3	58	2,353
	MAX:	7.5	2.55	31.4	22,329	2,070	8.74	0.43	2.39	8.95	14,275	8,019	8	67.4	80	2,930
	MIN:	1.5	1.73	6.7	2,472	154	0.99	0.11	0.45	0.47	6,000	4,528	1	0.5	30	1,487
	N:	40	128	26	25	69	25	21	21	21	21	8	99	25	25	11
	S:	1.7	.19	7.3	6,984.3	528.3	1.67	0.10	0.57	1.87	2,303	1,275	2.4	22.5	12.9	404.1
	V:	40.6	8.7	50.1	53.5	60.5	49.76	44.05	49.04	80.25	22.0	19.8	77.5	85.7	22.2	17.2
BAHJO POINT FORMATION: BRECCIA - Tbp																
5	AVG:	4.0	2.27	16.6	17,230	988	4.28	0.22	1.75	2.55	10,560	7,073	2.5	41.1	60	2,554
	MAX:	7.5	3.09	29.2	49,227	4,283	11.75	0.37	5.00	9.57	18,542	10,308	8	133.6	70	3,563
	MIN:	1.5	1.93	3.7	1,331	208	0.48	0.11	0.44	0.47	3,382	4,116	1	0.4	40	787
	N:	35	82	18	14	49	14	8	8	8	21	4	68	13	15	10
	S:	1.4	0.29	7.2	18,284	1,015.2	4.17	0.10	1.89	4.62	4,119	2,686	2.4	47.4	16.3	907.4
	V:	35.4	12.8	43.2	106.1	102.8	97.43	43.90	82.10	369.49	59.0	38.0	96.6	115.2	23.3	35.5

TABLE 4-3 (Concluded)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
DENSE BASALTS - Tb																
6	AVG:	5.4	2.73	2.8	36,237	2,249	8.86	0.19	3.72	4.76	14,486	10,613	5.9	81.7	60	2,750
	MAX:	7.5	2.93	7.7	51,671	3,688	13.33	0.21	4.01	7.53	19,227	11,910	9	144.2	80	6,020
	MIN:	2	2.17	1.1	18,045	951	4.67	0.17	3.12	3.97	10,594	9,583	1	17.3	30	1,088
	N:	28	63	10	9	43	9	7	7	7	14	4	53	9	10	5
	S:	2.1	0.21	2.2	10,614	751.4	2.45	0.01	0.82	1.21	2,901	964	2.8	40.8	15.5	1,987.2
	V:	38.7	7.9	80.3	25.3	33.4	27.60	5.26	21.32	24.65	20.0	9.1	47.7	50.0	25.6	72.3
ANCHITKA FORMATION: KIRILOF POINT GLASSY BRECCIA - Takb-I																
7	AVG:	4.7	2.24	8.1	5,515	457	1.85	0.27	0.73	1.34	10,883	5,664	1.4	15.8	63	907
	MAX:	7.5	2.34	10.7	8,070	743	4.35	0.40	1.73	3.01	14,505	7,598	3	72.0	70	2,539
	MIN:	3.5	2.15	2.7	2,725	312	0.84	0.20	0.61	0.91	7,863	4,613	1	3.3	48	401
	N:	25	61	14	10	49	10	6	6	6	15	4	60	10	10	6
	S:	0.9	0.04	2.8	1,564.28	100.8	0.98	0.07	0.41	0.78	2,296	1,328	0.8	20.2	8.7	8,212
	V:	20.1	1.8	34.4	20.36	20.3	52.76	26.60	44.21	53.32	21.0	23.5	52.0	128.0	13.77	90.5
ANCHITKA FORMATION: KIRILOF POINT PILLOW LAVAS - Takb-II																
8	AVG:	5.8	2.42	9.2	23,456	2,014	4.46	0.18	1.89	2.32	12,896	7,983	6.8	66.9	60	2,976
	MAX:	7.0	2.54	10.5	27,045	3,465	5.66	0.18	2.42	2.86	15,161	-----	9	102.7	70	3,076
	MIN:	4.5	2.32	7.6	21,591	962	3.56	0.17	1.76	2.16	10,931	-----	3	41.7	40	2,875
	N:	10	25	5	19	3	3	2	2	2	4	1	22	3	3	2
	S:	1.3	0.07	1.1	3,108.96	646.0	1.08	0.01	0.47	0.50	2,169	0	1.6	31.9	17.3	-----
	V:	22.9	3.0	11.9	15.25	32.1	24.28	5.56	22.33	19.72	16.8	0	23.6	47.7	28.9	-----
ANCHITKA FORMATION: DENSE OLDER BRECCIA - Tab																
9	AVG:	6.7	2.77	3.3	37,535	2,901	6.77	0.25	2.71	4.51	16,273	8,859	6.9	109.9	67	3,165
	MAX:	7.5	2.95	6.9	54,140	5,220	10.11	0.38	4.25	6.23	20,000	10,133	9	201.8	75	7,747
	MIN:	2.5	2.56	0.4	9,526	1,161	2.61	0.19	1.84	4.21	10,563	7,218	1	17.4	44	727
	N:	29	72	17	16	41	16	10	10	10	18	7	58	16	17	8
	S:	0.9	0.08	1.8	13,582.69	1,047.6	2.28	0.06	0.81	0.86	2,734	1,040	2.2	54.3	7.3	2,481.9
	V:	13.8	3.0	56.0	30.19	36.1	33.65	23.76	25.64	15.78	16.8	11.7	31.8	49.4	10.9	78.4
EAST CAPE QUARTZ DIORITE - Tqd																
10	AVG:	7.0	2.71	1.7	33,280	2,378	7.15	0.28	2.79	5.42	16,603	9,507	6.2	86.2	64	2,666
	MAX:	7.0	2.86	3.0	48,182	4,010	11.13	0.40	6.64	21.90	20,429	11,319	9	150.7	70	3,607
	MIN:	6.5	2.58	0.8	6,296	1,141	2.85	0.11	1.94	2.21	11,365	8,010	1	7.0	40	1,787
	N:	55	74	37	34	90	33	22	22	22	27	12	134	33	34	16
	S:	0.2	0.05	0.5	10,075.98	622.2	1.84	0.07	0.94	4.07	1,753	827	2.3	34.5	16.1	486.7
	V:	2.1	1.7	29.0	30.28	26.2	25.73	26.65	28.32	61.50	10.6	8.7	36.7	40.1	25.2	18.3

NOTES: The average (AVG), maximum (MAX) and minimum (MIN) values determined from the number (N) of specimens in each group, with the standard deviation (S) and percentage variation (V), are given in descending order for each group property across the table. Values in Column 5 represent increased moisture in the saturated state (after 7 days submersion) over that air dried (14 days), in volume percent.

TABLE 4-4

CREEP AND FAILURE CHARACTERISTICS OF AMCHITA ISLAND
ROCKS UNDER UNIAXIAL AND COMPRESSIVE STRESS (Sharp, 1972)

GROUP No.	LEGEND See Notes	CREEP RATE Microstrains per hours, extrapolated to a time of 200 minutes	IRRECOVERABLE STRAIN Percent, after loading to one-half ultimate strength
CHITKA POINT FORMATION: HORNBLende PYROXENE ANDESITE - Tcp1 - I			
1	AVG:	1.3	4.7
	MAX:	4.0	10.9
	MIN:	0.1	0.2
	N/S/V:	5/1.4/106	5/4.4/92
CHITKA POINT FORMATION: DENSE FLOW BRECCIA - Tcp1 - II			
2	AVG:	1.9	21.2
	MAX:	---	---
	MIN:	---	---
	N/S/V:	1/---/---	1/---/---
CHITKA POINT FORMATION: HORNBLende-ANDESITE BRECCIA - Tcp - I			
3	N/A	No Data	No Data
CHITKA POINT FORMATION: TUFF BRECCIAS - Tcp - II			
4	AVG:	2.8	5.4
	MAX:	3.0	8.9
	MIN:	0.8	1.6
	N/S/V:	3/1.2/56	3/8.6/68
BANJO POINT FORMATION: BRECCIA - Tbp			
5	AVG:	1.0	4.7
	MAX:	1.8	10.0
	MIN:	0.5	0.4
	N/S/V:	6/0.5/47	6/3.1/67
DENSE BASALT - Tb			
6	AVG:	1.0	2.7
	MAX:	1.1	4.5
	MIN:	0.9	0.8
	N/S/V:	2/---/---	2/---/---
ANCHITKA FORMATION: KIRILOF POINT GLASSY BRECCIA - TAKb - I			
7	AVG:	2.8	9.0
	MAX:	3.0	10.6
	MIN:	2.6	7.3
	N/S/V:	2/---/---	2/---/---
ANCHITKA FORMATION: KIRILOF POINT PILLOW LAVAS - TAKb - II			
8	AVG:	0.9	1.7
	MAX:	1.4	2.1
	MIN:	0.4	1.3
	N/S/V:	2/---/---	2/---/---
ANCHITKA FORMATION: DENSE OLDER BRECCIA - TAB			
9	AVG:	1.7	5.4
	MAX:	2.5	0.2
	MIN:	0.7	2.6
	N/S/V:	4/1.0/58	4/2.5/46
EAST CAPE QUARTZ DIORITE - Tqd			
10	AVG:	1.5	11.6
	MAX:	3.0	17.1
	MIN:	0.4	4.6
	N/S/V:	5/1.1/71	5/5.9/51

NOTES: Under LEGEND, N = Number of specimens; S = Standard deviation; V = Co-efficient of variation in percent, respectively.

TABLE 4-5

ENGINEERING CLASSIFICATION OF AMCHITKA ROCKS
(Sharp, 1972)

	ROCK NAME (WITH LOCAL UNIT IN WHICH IT OCCURS)	AIR DRIED SUBSTANCE	ROCK MASS	WET SUBSTANCE
(1)	Hornblende-pyroxene andesite (Chitka Point Fm.: Tcpl-1)	VS, E	M(L), BI	S
(2)	Dense flow (volcanic) breccia (Chitka Point Fm.: Tcpl-11)	S, E	M, Sd(BI)	S
(3)	Hornblende-andesite (volcanic) breccia (Chitka Point Fm.: Tcpl-1)	S, E*	M, Sd	W
(4)	Tuff (volcanic) breccia (Chitka Point Fm.: Tcpl-11)	S, Y	M, Sd	W
(5)	Volcanic breccia (lithic) (Banjo Point Fm.: Tbp)	S, E	M(L), Sd	W
(6)	Dense basalt (Assorted formations)	VS, E	M(L), BI	S
(7)	Glassy (volcanic) breccia (Kirilof Pt., Amchitka Fm.: TAKb-1)	W, Y	M(L), BI	W
(8)	Pillow lavas (Kirilof Pt., Amchitka Fm.: TAKb-11)	S, E	M(L), Sd	S
(9)	Dense older (volcanic) breccia (Amchitka Fm.: TAB)	VS, E	M(L), BI	VS
(10)	Quartz diorite (East Cape: Tqd)	VS, E	M, BI	VS (S)

MASS: (3) Gross homogeneity of formation or unit:

M = Massive

L = Layered (contains layering which would produce parallel lines of weakness).

(4) Continuity of rock substance in the unit:

Sd = Solid (joint spacing greater than 6 ft)

BI = Blocky (joint spacing 3 in. to 6 ft)

Br = Broken (in fragments; would pass 3-in. sieve)

SUBSTANCE: (1) Uniaxial compressive strength of rock substance:

W = Weak (less than 10,000 psi)

S = Strong (from 10,000 to 25,000 psi)

VS = Very Strong (greater than 25,000 psi)

(2) Pre-failure deformation mode of rock substance:

E = Elastic

Y = Yielding (at stress of one-half of uniaxial strength, strain rate is greater than 2 microstrain per hour; or more than 25 percent of total strain is permanent)

5.0 ROCK PROPERTIES OF NEVADA TEST SITE BASALT

5.1 INTRODUCTION

Rock properties of the various lithologies at the Nevada Test Site were required to assist in the interpretation of underground nuclear tests and surface conventional testing of explosives. Basaltic rock covers part of the test site. Hence, data on the geotechnical characteristics is available. The intact rock property data are included in Table 5-1.

5.2 DESCRIPTION OF ROCK MASS

5.2.1 Macroscopic Characteristics

5.2.1.1 Lithology

The Nevada Test site lies north and east of the Las Vegas Valley - Walker Lane shear zone, and east of an area characterized by large Mesozoic plutons. About 30 percent of the test-site area is composed of alluvium-filled basins, with Paleozoic and Upper Precambrian sedimentary rocks covering another 30 percent. The remainder consists primarily of volcanic rocks and related intrusive masses of Tertiary age ¹.

The western and central parts are characterized by numerous volcanic centers, at least five of which gave rise to calderas. The principal volcanic rocks are ash-flow tuffs of rhyolitic and quartz-latic composition.

The Upper Precambrian and Lower Cambrian rocks are dominantly clastic, with quartzite being by far the chief lithology. Rocks of Middle Cambrian through Middle Devonian age are dominantly carbonates. Upper Precambrian and Paleozoic sedimentary rocks have a total thickness of nearly 40,000 feet.

The Devonian rocks are overlain by a Tertiary section more than 30,000 feet thick. Ash flow tuffs of dominantly rhyolitic composition are the most abundant rock type. The oldest rocks crop out along the northern border of the test site and include the tuff of Monotony Valley, which is

the most widespread. Table 5-2 is a list of the principal volcanic unit at the Nevada Test Site.

Most of the basalt tested at the site comes from the Buckboard Mesa in the NW part of the test site, Figure 5-1. The basalt tested ² was mainly derived from a Quaternary flow which had issued from a vent in the vicinity of a cinder cone and had flowed southward, between two rows of low lying hills which have since been eroded, leaving a basalt-capped mesa.

Exploratory NX core drilling indicates that the basalt is composed of two successive flows. The basalt is generally highly vesiculated at the surface. Vesiculation generally decreases with depth. At about 12 to 15 feet below ground surface the basalt becomes quite dense.

5.2.1.2 Geologic Structure

Major geologic structures are shown in Figure 5-2. The Nevada Test Site lies about 50 miles east of the eastern boundary of the Cordilleran eugeosyncline and about 100 miles west of the approximate east boundary of the miogeosyncline.

Mapping in the test site and in the ranges of the east has disclosed several thrust fault systems of Mesozoic age. The best understood of these has been named the CP thrust after the Central Point Hills south of Yucca Flat. This thrust places upper Precambrian and lower Paleozoic rocks over middle and upper Paleozoic strata (Figure 5-3).

The faults in the northern part of the area trend north and appear to be simple normal faults. In the southern part of the area, however, as the Las Vegas Valley shear zone is approached from the north, the faults change strike from north to northeast.

At the site from which the basalt was obtained, Buckboard Mesa, the basalt flow is relatively undissected and caps the mesa, sloping gently south from fissure vents. The mesa basalt is some 5.5 miles long, and about 200 feet thick in the center portion.

5.2.1.3 Jointing

The basalt flow is vertically jointed; core drilling showed evidence of random cooling fractures as well as pockets of badly fractured basalt. At some locations the orientation of flow lines gives evidence of much turbulence ².

5.2.2 Microscopic Characteristics

5.2.2.1 Mineralogy

Dense basalt from Buckboard Mesa, obtained from depths of 13.2 to 157.1 feet was used for testing purposes. Chemical analyses of the rock indicate that it is an andesitic basalt with a moderately high potassium content. The rock is a light grey, dense, fine-grained, unweathered basalt, composed of approximately 66 percent plagioclase feldspar, with lesser amounts of pyroxene, olivine, and magnetite.

The chemical composition is quite uniform, except for local high oxidation of iron. Petrographic examinations reveal that the vesicular facies has somewhat more glass in the matrix. Vesicles mostly range from 1/16 inch to 1/2 inch in diameter and average about 1/4 inch. They are spherical to moderately irregular and are evenly dispersed.

5.3 PROPERTIES OF INDIVIDUAL DISCONTINUITIES

5.3.1 Joint Stiffness and Strength

No data are available at present.

5.3.2 Environmental Effects

No data are available at present.

5.4 PHYSICAL PROPERTIES OF INTACT ROCK

5.4.1 General

The physical properties have been established mainly by the U.S. Army Engineer Waterways Experiment Station. The strength and deformation characteristics of basalt were investigated.

5.4.2 Strength and Modulus Properties

Lutton (1968)³ and Sandia (1962)², provided the major rock property data for the vesicular to dense basalt. Samples were taken for density and compressive strength tests every 3 feet for the first 15 feet and every 5 feet below this level. In total, 146 static compression tests were performed, and are listed in Table 5-3, and plotted in Figure 5-4. From inspection of the data, it is evident that strength decreases with decreasing bulk specific gravity. The more vesicular the basalt the lower is the strength.

Comparing the failure envelopes for vesicular and dense basalt (Figure 5-5), it is apparent that the envelopes for dense basalt have steep inclinations (about 45°) that decrease only slightly at higher confining pressures. The failure envelopes for highly vesicular basalt are steep at low confining pressures, but they decrease rapidly at intermediate confining pressures and slope about zero degrees at 2,000 p.s.i. confining pressure.

Figure 5-6 relates the deviator stress at failure to the confining pressure with the corresponding porosity of the test samples. It is clear that differential stress at failure for igneous rocks with low porosity (< 6 percent) increases markedly with increasing confining pressure. In contrast, differential stress for igneous rocks with high porosities (> 11 percent) tend to level off rapidly and then decrease at higher confining pressure.

Stowe (1969)⁴ investigated the strength and deformation properties of basalt at various loading rates. All the test results are included in Table 5-4. Three static unconfined compressive strength tests were conducted at different loading rates from 1.0 to 1.6×10^7 p.s.i./sec. enabling compressive strength, Young's modulus and Poisson's ratio to be calculated.

The average slow compressive strength of the basalt was 21,460 p.s.i., and the rapid compressive strength was 29,020 p.s.i. Figures 5-7 and 5-8 respectively. Figure 5-9 illustrates decreasing Poisson's ratio with increasing confining pressure.

The slow stress-strain testing for the basalt show that the rock behaves elastically to failure, and the mode of failure is brittle. Rapid stress-strain testing produces a behavioral change to failure, the basalt is elastic to about 45 percent of ultimate strength, then behaves plastically to failure. The rock is characterized by a slight ductile failure, Figure 5-10.

5.4.3 Thermal Properties

No data are available.

5.4.4 Hydrological Properties

No data are available.

5.5 ENVIRONMENTAL FACTORS

5.5.1 Time

No data are available.

5.5.2 Temperature

Kumar (1968)⁵ performed tests to study the effect of stress rate and temperature on the strength of basalt. The twist in the investigation was that instead of increasing the temperature from normal room temperature, it was decreased to that of liquid nitrogen at about 77°K.

The effect of lowering the temperature was found to correlate with increasing the stress rate, Figure 5-11. The conclusion was drawn that the mechanisms of rock fracture are thermally activated.

5.5.3 Swelling Pressure

No data are available.

5.5.4 Irradiation Effects

No data are available.

5.6 EXCAVATION CRITERIA

No data apart from that applicable to nuclear and conventional explosive devices are apparently available.

5.0 REFERENCES

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3. Lutton, R.J. Comparison of Strengths of Dense and Vesicular Types of Basalt. Bull. Assn. Eng. Geol. 5, (1), 1968.
4. Stowe, R.L. Strength and Deformation Properties of Granite, Basalt, Limestone, and Tuff at Various Loading Rates, U. S. Army Eng. Waterways Exp. Station, Misc. Paper C-69-1, 1969.
5. Kumar, A. The Effect of Stress Rate and Temperature on the Strength of Basalt and Granite, Geophysics, 33, (3), 1968.

FIGURE 5-1. Map of the Nevada test site. (Ekren, 1968).

FIGURE 5-2. Map showing Nevada test site and major geologic and physiographic features. (Ekren, 1968)

FIGURE 5-3. Map showing thrust faults in Nevada test site and vicinity.
(Ekren, 1968)

FIGURE 5-4. Relation of compressive strengths and specific gravity.
 (Sandia, 1962)

Mohr circles and failure envelopes for highly vesicular basalt

Mohr circles and failure envelopes for dense basalt

FIGURE 5-6. Relationship between strength and confining pressure for basaltic rocks of different porosity. (Lutton, 1968)

FIGURE 5-7. Stress versus strain curve for basalt. (Stowe, 1969)

FIGURE 5-8. Dynamic stress versus strain curves for basalt. (Stowe, 1969)

FIGURE 5-9. Variation of initial tangent Poisson's Ratio with confining pressure. (Stowe, 1969)

FIGURE 5-10. Ultimate strength versus loading rate for basalt in unconfined compression. (Stowe, 1969)

FIGURE 5-11. Effect of temperature and stress rate on the fracture strength of basalt (Kumar, 1968)

TABLE 5-1
INTACT PROPERTIES OF NEVADA TEST SITE BASALT

BASIC PARAMETERS

<u>Type of Property</u>	<u>Parameter</u>	<u>Customary English Units</u>
Index	. Unit Weight	167.9 lbs/ft ³
	. Natural moisture content (intact)	
	. Porosity (rock mass)	4.6 %
Stress-strain	. Young's Modulus	5.06x10 ⁶ lbs/in ²
	. Poisson's Ratio	0.32 --
	. Bulk Modulus	
	. Shear Modulus	
Strength	. Cohesion 1500-3500 Friction Angle psi range	
	. Uniaxial Compressive Strength	21,460 lbs/in ²
	. Tensile Strength	1,900 lbs/in ²
Thermal	. Coefficient of Linear Thermal Expansion	
	. Heat Capacity	
	. Thermal Conductivity	
Hydrological	. Horizontal Permeability	
	. Vertical Permeability	

TABLE 5-2

STRATIGRAPHIC SEQUENCE AT THE NEVADA TEST SITE
(Ekren, 1968)

AGE	K/Ar DATE	UNIT	LATERAL EXTENT, IN MILES	VOLUME IN CUBIC MILES
T E R T I A R Y		basalt lavas	-----	-----
	7.5 m.y.	Thirsty Canyon Tuff	80	50
	11 m.y.	Timber Mountain Tuff	100	500
		Paintbrush Tuff	70	120
	13.8 m.y.	Belted Range Tuff	60	70-100
	17.5 m.y.	Fraction Tuff	120+	>500
		dacite and latite lavas	-----	-----
		tuff of White Blotch Spring	120+	>500
	26.5 m.y.	tuff of Monotony Valley	120+	1000+
Paleozoic and Precambrian rocks				

TABLE 5-3

TEST RESULTS FOR EXPLORATORY HOLES
(Sandia, 1962)

	1		2		3		4		5		6		7		8		9		10		11		12		13	
	Sp. Gr.	Comp. Str. (psi)	Sp. Gr.	Comp. Str. (psi)	Sp. Gr.	Comp. Str. (psi)	Sp. Gr.	Comp. Str. (psi)	Sp. Gr.	Comp. Str. (psi)	Sp. Gr.	Comp. Str. (psi)	Sp. Gr.	Comp. Str. (psi)	Sp. Gr.	Comp. Str. (psi)	Sp. Gr.	Comp. Str. (psi)	Sp. Gr.	Comp. Str. (psi)	Sp. Gr.	Comp. Str. (psi)	Sp. Gr.	Comp. Str. (psi)	Sp. Gr.	Comp. Str. (psi)
3	2.13	8,020	2.35	9,530	2.200	6,755	2.547	18,930	2.752	31,970	2.46	15,730	2.18	11,965	2.59	15,013	2.574	18,260	2.62	21,140	2.51	14,400	Suitable No Specimen		2.536	13,550
6	2.20	6,490	2.46	9,310	2.039	7,670	2.619	20,990	2.695	30,300	2.48	11,210	2.02	8,650	2.46	6,953	2.619	19,495	2.69	26,395	2.47	7,640	"	"	2.509	8,200
9	2.24	6,435	2.53	9,275	2.532	15,960			2.704	25,465	2.39	9,925	2.07	5,860	2.66	19,760	2.619	18,890	2.63	26,120	2.56	15,280	"	"	2.238	9,060
12	2.44	7,310	2.58	18,545	2.663	24,560			2.773	30,600	2.49	8,215	2.40	20,180	2.63	17,387			2.67	23,900	2.34	7,995	2.663	11,980	2.500	8,645
15	2.32	6,397	2.62	19,390	2.686	23,710			2.705	24,490	2.61	14,760	2.37	19,600	2.62	17,497			2.70	16,320	2.59	15,180	2.481	22,935	2.622	15,030
20	2.55	13,830	2.68	17,715	2.663	18,960			2.743	29,135	2.63	20,700	2.44	22,230	2.64	18,240			2.62	24,940	2.64	19,275	2.751	23,435	2.649	15,935
25	2.58	23,060	2.70	21,290	2.685	22,270			2.513	13,950	2.67	20,205	2.40	20,780	2.64	18,425			2.69	20,890	2.69	27,690	2.642	18,235		
30	2.70	19,060	2.69	20,400	2.676	20,100			2.504	13,400	2.67	19,495			2.57	17,050					2.69	21,600	2.621	20,290	2.654	18,110
40	2.72	22,750			2.693	21,710					2.69	19,945			2.58	17,430					2.69	19,275	2.672	27,100	2.751	20,425
45	2.71	22,750			2.693	25,490					2.68	21,620			2.69	15,500					2.71	18,155	2.683	25,050	2.658	17,685
50											2.70	21,250			2.68	12,953					2.65	20,340	2.693	25,270	2.668	18,070
55											2.70	13,650			2.70	14,130					2.69	20,425	2.679	24,130	2.702	19,465
60											2.65	16,070			2.70	12,646					2.69	19,660	2.697	26,050	2.662	22,835
65																					2.72	20,370	2.538	15,150	2.722	22,180
70																					2.72	17,470	2.593	23,295	2.702	20,040
75																					2.73	17,930	2.672	11,980	2.710	22,780
80																					2.72	23,775	2.559	19,100	2.712	21,960
85																					2.72	21,000	2.632	23,125	2.720	22,640
90																					2.70	21,050	2.647	23,000	2.724	24,045
95																					2.73	19,060	2.633	19,285	2.747	19,060
95																					2.70	21,275	2.742	27,912	2.734	18,590
100																					2.77	23,050	2.707	21,370	2.754	20,500

Compressive strengths are static.

TABLE 5-4

TEST RESULTS FOR BASALT (Stowe, 1969)

Site No.	Depth	Specific Gravity		Porosity	Compressional Wave Velocity	Tensile Splitting Strength	Slow Compression										Rapid Compression				Mode of Failure			
		Bulk Dry	Solids				Unconfined Compressive Strength Test				Triaxial Compressive Strength with Compressional Wave Velocity (V_p)						Unconfined Compressive Strength Test							
							Loading Rate	Strength	Young's Modulus	Poisson's Ratio	Loading Rate	Strength at Confining Pressures of 250, 1,000, and 5,000 psi			Young's Modulus	Poisson's Ratio	Initial V_p	Highest V_p	Loading Rate	Strength	Young's Modulus	Poisson's Ratio		
												250	1,000	5,000										
feet				pcf	ft/sec	psi	psi/sec	psi	10^6 psi		psi/sec	psi	psi	psi	10^6 psi		ft/sec	ft/sec	psi/sec	psi	10^6 psi			
B-1	DA-1	75.5 to 75.5	2.70	2.83	--	15,640	--	1	21,770	4.66	0.26	--	--	--	--	--	--	--	--	--	--	--	--	--
B-2	NCG-38	--	2.68	2.83	5.25	15,850	1,820	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
B-3	DA-1	133.2 to 140.0	2.67	2.82	5.35	16,350	--	500	21,810	4.80	0.29	--	--	--	--	--	--	--	--	--	--	--	--	Shear at 60 degrees from horizontal
B-4	DA-1	138.2 to 140.0	2.67	2.82	5.25	16,370	--	--	--	--	--	50	30,600	--	4.69	0.27	16,060	16,510	--	--	--	--	--	Shear at 63 degrees from horizontal
B-5	NCG-42A	68.5	2.66	2.82	5.39	16,090	--	--	--	--	--	50	--	16,980	--	4.90	0.17	16,020	17,130	--	--	--	--	--
B-6	NCG-45	73.9	2.72	2.84	3.47	15,270	--	500	21,410	5.37	0.32	--	--	--	--	--	--	--	--	--	--	--	--	--
B-7	Calex	--	2.69	--	--	16,430	--	500	22,310	4.30	0.25	--	--	--	--	--	--	--	--	--	--	--	--	--
B-8	Calex	--	2.71	--	--	16,890	--	--	--	--	--	--	--	--	--	--	--	--	2.08×10^5	24,970	3.61	0.27	--	--
B-9	--	156.3	2.73	2.84	3.52	15,670	--	50	22,740	4.17	0.29	--	--	--	--	--	--	--	--	--	--	--	--	--
B-10	--	157.1	2.73	2.84	3.52	16,450	--	--	--	--	--	--	--	--	--	--	--	--	3.1×10^6	28,170	5.00	0.45	--	--
B-11	Calex	--	2.70	--	--	16,730	--	--	--	--	--	--	--	--	--	--	--	--	2.08×10^5	27,520	3.42	0.39	--	--
B-12	NCG-23	49.0	2.74	2.83	3.27	17,700	1,790	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
B-13	DA-2	95.0 to 95.5	2.74	2.83	3.11	17,760	--	--	--	--	--	500	25,620	--	4.46	0.37	--	--	--	--	--	--	--	Shear at 71 degrees from horizontal
B-14	--	13.2	2.68	2.83	5.25	17,650	--	--	--	--	--	1	21,240	--	5.18	0.41	--	--	--	--	--	--	--	Vertical splitting
B-15	NCG-40	61.5	2.68	2.83	5.25	15,460	--	--	--	--	--	--	--	--	--	--	--	--	2.04×10^5	23,360	2.71	0.35	--	--
B-16	NCG-40	61.5	2.68	2.83	5.25	15,910	--	--	--	--	--	--	--	--	--	--	--	--	1.6×10^7	32,120	4.73	0.23	--	--
B-17	NCG-38	64.4	2.69	2.82	4.54	17,550	--	--	--	--	--	--	--	--	--	--	--	--	1.2×10^7	32,390	4.68	0.20	--	--
B-18	NCG-38	64.4	2.69	2.82	4.54	17,050	--	--	--	--	--	--	--	--	--	--	--	--	1.31×10^7	34,580	6.66	0.25	--	--
B-19	DA-2	67.8	2.68	2.82	5.20	17,360	--	--	--	--	--	50	--	--	46,280	6.08	0.16	16,670	18,750	--	--	--	--	Shear at 63 degrees from horizontal
B-20	DA-2	67.8	2.68	2.82	5.24	17,200	--	50	20,730	4.25	--	--	--	--	--	--	--	--	--	--	--	--	--	--
B-21	Calex	--	2.70	--	--	16,800	--	1	22,580	4.71	0.44	--	--	--	--	--	--	--	--	--	--	--	--	--
B-22	Calex	--	2.70	--	--	16,850	--	1	18,920	3.43	0.47	--	--	--	--	--	--	--	--	--	--	--	--	--
B-23	Calex	--	2.70	--	--	16,500	--	--	--	--	--	1	--	27,880	--	4.19	0.42	--	--	--	--	--	--	Shear at 61 degrees from horizontal
B-24	Calex	--	2.69	--	--	16,100	--	--	--	--	--	1	--	33,430	4.65	0.22	--	--	--	--	--	--	--	Vertical splitting
B-25	Calex	--	2.69	--	--	16,250	2,050	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
B-26	Calex	--	2.69	--	--	16,950	--	--	--	--	--	500	--	31,290	--	3.94	0.27	--	--	--	--	--	--	Shear at 75 degrees from horizontal
B-27	Calex	--	2.71	--	--	17,100	--	--	--	--	--	500	--	49,130	4.42	0.31	--	--	--	--	--	--	--	Shear at 70 degrees from horizontal
B-28	Calex	--	2.70	--	--	16,240	--	--	--	--	--	2,740	25,700	--	4.00	0.25	--	--	--	--	--	--	--	Vertical splitting
B-29	Calex	--	2.69	--	--	15,990	--	50	21,250	5.00	0.26	--	--	--	--	--	--	--	--	--	--	--	--	--
B-30	Calex	--	2.72	--	--	16,980	--	--	--	--	--	2,250	--	35,010	--	4.71	0.25	--	--	--	--	--	--	Shear at 74 degrees from horizontal
B-31	Calex	--	2.70	--	--	16,390	--	--	--	--	--	2,250	--	54,000	5.03	0.15	--	--	--	--	--	--	--	Shear at 72 degrees from horizontal
Average			2.69	2.83	4.60	17,140	1,900		21,460	5.06	0.32									29,010	4,40	0.31		

6.0 ROCK PROPERTIES OF COLUMBIA RIVER GROUP BASALT

6.1 INTRODUCTION

The basalt of the Columbia River group underlies a region of about 50,000 square miles in Washington, Oregon, and Idaho, Figure 6-1. The main body of the rock unit lies between the Rocky Mountains on the east and the Cascade Range on the west. Most of the investigations have been directed towards stratigraphical and mineralogical problems, though limited test strength data are available from engineering investigations. A summary of the ranges of intact rock properties is included in Table 6-1.

6.2 DESCRIPTION OF ROCK MASS

6.2.1 Macroscopic Characteristics

6.2.1.1 Lithology

The widespread distribution and local characteristics over three contiguous states make it impossible to describe the Columbia River Group basalts in anything but a general manner. The basalts of the Columbia Plateau were divided by Waters (1961)¹ into two formations, the older Picture Gorge basalt and the younger Yakima basalt.

The Yakima basalt is far more widespread than the Picture Gorge, which the Yakima overlies with at least local angular unconformity. The Picture Gorge flows are known only from central to northeastern Oregon and from the Clearwater Embayment and the Seven Devils region of western Idaho. The Yakima basalt underlies the entire plateau in Washington and occurs in places in northern Oregon and southwestern Washington.

In the central part of the plateau, the basalt has a general thickness of 4,000-5,000 feet. It tapers out on the prebasalt surface at the edges, but the western and southern edges are complicated by the centrally located extension to the west and by the presence of other basaltic lavas of similar age to the south².

The layered basalt accumulated as flow upon flow of highly fluid lava. The lava flows, which constitute the principal stratigraphic units, vary from 10 to 200 feet in thickness, averaging about 100 feet. The flows are made up of one or more arrivals of lava, called flow units; consequently, the stratigraphy of the layering varies considerably from place to place. Small amounts of interbedded sedimentary materials occur, especially in the top 1,000 feet in the west-central part of the basalt region and for the entire thickness at places around the edges of the basalt accumulation. Figure 6-2³ is a composite stratigraphic sequence in the northwestern Columbia Plateau, showing the members within the Yakima Basalt.

6.2.1.2 Geologic Structure

The basalt was folded, warped, and faulted during the tectonic deformation of Pliocene and Quaternary time, the Cascadian orogeny. The area was warped into broad anticlines and synclines; the anticlines formed by the folding are coincident with the present topographic ridges. Figure 6-3 shows the anticlinal mountain ridges of south-central Washington⁴.

6.2.1.3 Jointing

The flows display the forms of jointing characteristics described by Waters (1961)¹ and Mackin (1961)⁵. In general, cooling contraction joints divide the basalt into blocks ranging from 1 inch to 10 feet across, with some form of vertical hexagonal columnar jointing being the most prevalent joint system². The cooling joints are open cracks near the surface but are tightly closed at depth within the thick flows. Joint block surfaces of some lava flows are coated with iron oxide, but the rock is not deeply oxidized except near the land surface in some places.

Two zones of different jointing styles are often found in individual thick flows. Jointing styles are discussed by Swanson (1967)⁶ for the Yakima basalt of the Tieton River area of south-central Washington. An individual flow consists of two parts, the lower zone termed the colonnade which is strikingly columnar and the upper zone, consisting of long slender columns commonly broken into hackly fragments by cross joints, is the entablature, Figure 6-4.

In places some flows divide locally into several slightly vesicular, poorly jointed to non-jointed flow units which are separated by sheets of scoriaceous basalt. Similar structures and joint styles have been reported by Schmincke (1967) ⁷ and are shown in Figure 6-5 for late Yakima-type flows in south-central Washington.

6.2.2 Microscopic Characteristics

6.2.2.1 Mineralogy

The typical Yakima basalt is a uniform black to dark gray rock. Seventy-five percent of the average basalt consists of crystals and microcrystallites of labradorite, augite, and magnetite. The remaining 25 percent occupied by intercrystalline area, is composed of a glassy ground-mass containing microlite beginnings of still smaller crystals ².

Colors are darker with high glass content, and lighter with high clay content caused by marked deuteric alteration. Weathering colors are black to dark gray, except for the reddish-brown platy zones of the colonnade and the gray tops of some altered zones ⁶.

More detailed analyses of some of the basalts tested for strength properties are given below.

Basalt (Lower Granite), Pullman, Washington

This rock consists of 48 percent plagioclase (An_{41}), 16 percent olivine, 18 percent augite, 11 percent glass, 6 percent magnetite, 1 percent apatite and sphene. Corroded olivine granules (0.003 to 0.02 mm) rimmed with dusty magnetite particles are contained within an interstitial glass, and augite. Some zoned plagioclase crystals have grown to lengths of 0.5 mm, thus imparting a porphyritic texture to the rock. Euhedral to corroded subhedral crystals of magnetite are scattered throughout the section. The glass, brown with upper nicols out, is in places partially devitrified to radial growths of acicular crystals.

Basalt (Little Goose), Walla Walla, Washington

This basalt shows a hyalophitic texture in which olivine (26 percent), augite (5 percent), laths of plagioclase (41 percent), and euhedral to subhedral grains of titaniferous magnetite (4 percent) lie in a matrix of dark green, probably iron-rich, glass (25 percent). The average crystal size for augite and plagioclase is 0.2 mm, although several grains are as much as 2 mm long, imparting a porphyritic texture to the whole. The rock is essentially free of alteration products.

Basalt (John Day), Arlington, Oregon

This rock contains subhedral phenocrysts of normal zoned plagioclase (up to 0.8 mm long) in a groundmass of olivine (33 percent), glass (20 percent), titaniferous magnetite (7 percent), and laths of plagioclase An_{46} (total plagioclase is 40 percent). The groundmass minerals are from 0.2 mm to 0.3 mm long. Olivine is intersertal to the laths of randomly-oriented plagioclase. All minerals are free of alteration products.

6.3 PROPERTIES OF INDIVIDUAL DISCONTINUITIES

6.3.1 Joint Stiffness and Strength

No information could be found on joint stiffness though information is available on the frictional properties of joints. Coulson (1970)⁸ performed shear strength testing on artificial surfaces. Three types of surfaces were tested, sandblasted surfaces, surfaced lapped with #80 grit, and #600 grit.

Figures 6-6 and 6-7 contain the minimum, initial and residual coefficients of friction versus normal pressure for Lower Granite Basalt from Pullman, Washington. Table 6-2 tabulates all the shear-strength data for each type of surface.

In general, the dry shear strength is normally higher than the wet shear strength. Comparing the sandblasted, #80, and #600 grit surfaces, the results are not quite so simple. The sandblasted surfaces fall generally between the #80 and #600 grit surfaces, though as the normal pressure changes so does the position of the sandblasted surface in relation to the grit lapped surface.

6.3.2 Environmental Effects

No data are available.

6.4 PHYSICAL PROPERTIES OF INTACT ROCK

6.4.1 General

Physical properties of the Columbia basalts have not been tested as much as the previously documented basaltic geographic areas. The main source of information has been research funded by the U.S. Government or its agencies.

6.4.2 Strength and Modulus Properties

Four sources provided information, Deere et al.⁹ Stephenson and Triandafilidis¹⁰, Atlantic Richfield Hanford Co.¹¹, and Agopito, Hardy and St. Laurent¹².

Deere tested basalt samples from two dam sites on the Snake River, Pullman and Walla Walla, and another dam site on the Columbia River at Arlington, Oregon. Compressive strengths ranged from 32,368 p.s.i. at Pullman to 51,616 p.s.i. at Arlington. The corresponding Young's modulus varying from 7.65×10^6 p.s.i. to 13.4×10^6 p.s.i. A summary of the average physical properties of the three basalts are given in Table 6-3. Figure 6-8 is a plot of Young's Modulus vs. compressive strength for intact rock. The basalt plotting with an average modulus ratio. The stress-strain curves, stress-strain behavior characteristics and sonic pulse velocity are given in Figures 6-9, 6-10, 6-11, 6-12, 6-13 and 6-14.

Stephenson and Triandafilidis (1974)¹⁰ conducted tests on basalt using various strain rates. Basaltic rock from Spokane Air Force Base was tested statically as well as dynamically, utilizing three different methods of applying the loading. The dynamic loadings were accomplished using a ram loader, shock tube, and an air gun. The modulus and Poisson's ratio were about the same as those for the static tests. However, there was a noticeable increase in the ultimate strength of the rock specimens.

Static Young's modulus and Poisson's ratio of 12.0×10^6 p.s.i. and 0.30 respectively were obtained from ten tests. A dynamic Young's modulus and Poisson's ratio of 11.2×10^6 p.s.i. and 0.30 respectively were also

measured. The unconfined strength increased from a static value of 32,8 p.s.i. to 34,920 p.s.i. under dynamic test conditions. Table 6-4 contains the summary of the static and dynamic unconfined compression data. Table 6-5 contains the average tangent moduli from laboratory testing and the stress-strain curves.

The Atlantic Richfield Hanford Co. tests were conducted on basalt cores from the Hanford reservation for the purpose of evaluating radioactive waste storage. Compressive strength tests were performed on five samples from depths of about 2300 feet to 4300 feet, and the compressive strengths ranged from 3400 to to 45,800 p.s.i.¹¹.

Agapito, Hardy and St. Laurent performed a review of geo-engineering data for use in evaluating the Columbia Plateau Basalts as a potential repository site¹². They reported two sets of data on laboratory tests for compressive strenght and elastic properties. These are shown in Tables 6-6, 6-7, 6-8 and 6-9.

6.4.3 Thermal Properties

6.4.3.1 Coefficient of Linear Thermal Expansion

No data are available.

6.4.3.2 Thermal Conductivity, Heat Capacity and Thermal Diffusivity

In a recent study at the Hanford Reservation, laboratory tests were performed on samples of the Columbia Plateau basalt to determine certain thermal properties¹¹. The results of these tests are shown in Table 6-10.

It should be noted that the thermal conductivity of basalt shows a definite increase with increasing temperature. This trend is opposite to that observed in most rock mass, and is believed to be the result of radiative transfer of heat due to the high glass content of basalt. Therefore, the thermal conductivity of basalt is not solely a function of kinetic molecular energy as in most rock types, but contains an additive conductivity term that is electromagnetic in nature.

6.4.4 Hydrological Properties

The basalt underlies the land surface in areas that receive annual precipitation ranging from less than 10 inches to more than 100 inches. The ease with which water at the surface may transfer downward in the basalt depends largely on the position in which the layers of basalt lie. Horizontal flows inhibit the downward flow. If tilted, the downward movement is easier. The records of water levels in wells indicate that the natural recharge of ground water in the basalt is greater where inclined layers of basalt are truncated by the land surface on which streams flow or abundant precipitation falls.

Much of the water in syncline-like structures is under artesian pressure, where it is contained by less permeable layers of basalt or other geologic formations¹³. Figure 6-15 is a diagrammatic cross-section illustrating the direction of ground water movement.

Generally the upper parts of the basalt flows constitute the chief aquifers, and the artesian aquifers have been found to be much more productive than the unconfined basalt aquifers¹⁴. Generally, the integrated porosity sufficient to transmit ground water in quantities that will afford yields greater than 1000 g.p.m., is limited largely to the fractured tops, and stratigraphic zones of rubbly basalt. These permeable zones are only a small part of the basalt, probably comprising less than 6 percent of the top 1500 feet of the basalt².

The chemical quality of the ground water, in general, is satisfactory for ordinary uses of water. Locally it needs improvement for use in steam boilers, aeration to remove hydrogen sulphide gas, softening to lower soap consumption, or, in a few places, treatment to remove iron. A general illustration of the composition of the dissolved solids is shown in Figure 6-16. Silica, calcium, sodium, and bicarbonate are the principal dissolved solids. The average ground water in the top 2000 feet is moderately hard, nearly iron free, and clear.

An extensive review of the hydrologic properties of the Columbia Plateau Basalts has recently been completed¹¹. Laboratory and in-situ tests were performed. Results show hydraulic conductivities range from 3×10^{-3} to 1×10^{-5} ft/day for fractured to dense basalt respectively.

6.5 EXCAVATION CRITERIA

6.5.1 General

Few major structures have been constructed underground in the Columbia River basalt group. Surface excavations have been made at dam sites and these data have already been presented. Only one tunnel was found to have been constructed in the Columbia basalt for which published information regarding excavation criteria was available.

6.5.2 Subsurface Excavations

The Corps of Engineers engineering manual (1973) ¹⁵ gives details of a tunnel constructed for flood control purposes in the Walla Walla district, Lucky Peak, Idaho. The tunnel was circular, 23 feet in diameter and some 1120 feet long. Construction was through a Miocene basalt, which was found to range from hard, massive and columnar-jointed to closely-jointed and fractured rock. Local faults and chemically altered zones were encountered, containing thick clay seams from 1" to 8" in thickness.

Support varied from none to steel sets and lagging, depending on the basalt jointing and alteration characteristics. Excavation techniques equally were dependent on the rock conditions, varying from full face development in good ground to 3 pilot drifts in poor. No water problems were encountered and excavation was by conventional drilling and blasting.

The finished tunnel is designed for a maximum head of 240 feet, with a concrete liner varying from 1 to 9 inches thick and a steel liner from between 1/2 to 3/4 inch thick.

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FIGURE 6-1. Areal extent (stippled) of the Columbia River group in the northern part of the Columbia Plateau. (Waters, 1961)

SYSTEM	SERIES	GROUP	FORMATION	MEMBER AND BED	LITHOLOGY AND THICKNESS
TERTIARY	Pliocene	Columbia River Group	Ellensburg Formation	Ellensburg Formation undifferentiated	Ellensburg Formation undifferentiated. 1300 ft of pebble conglomerate, sand, and mudflows; upper 500 ft basaltic and contains coarse brown sand, remainder andesitic, with beds of fine ash in lower part. Beverly Member: As much as 700 ft of pumice, quartzite-bearing conglomerate, and tuffaceous sand, silt, and clay.
				Beverly Member	Saddle Mountains Member
	Middle Pliocene			Priest Rapids Member	Priest Rapids Member: Four basalt flows, total thickness as great as 220 ft. Basalt is grayish black where fresh, mottled greenish brown where weathered, coarse grained and nonporphyritic. Very large columns as much as 10 ft in diameter are common.
				Quincy Diatomite Bed	Quincy Diatomite Bed: Diatomite as thick as 45 ft, contains a few lenses of silt and clay.
	Miocene		Yakima Basalt	Roza Member	Roza Member: Two basalt flows, total thickness as great as 200 ft. Basalt is dark blue gray or dark reddish gray where fresh, weathers deep red brown, coarse grained and porphyritic. Phenocrysts are not numerous but are present in necks, all outcrops. Phenocrysts are lath shaped and average 1 cm in length. Large columns which break into plates and chips are common.
				Squaw Creek Diatomite Bed	Frenchman Springs Member: As many as five flows, total thickness as great as 375 ft. Basalt is dark gray to black, medium to fine grained and sparsely porphyritic. Phenocrysts are roughly equidimensional, shattered, yellowish white, and average 1 cm in diameter. Some large columns are present, but irregular jointing is common. Pillow zones are common in lowermost flow.
				Frenchman Springs Member	Squaw Creek Diatomite Bed: Diatomite as thick as 17 ft, grades westward to sandstone, fine conglomerate, siltstone, or clay.
				Vantage Sandstone Member	Vantage Sandstone Member: Sandstone as thick as 65 ft. Blue or green where fresh, pale yellow where weathered. Consists of medium grained quartz feldspar rich sand, or a tuffaceous sand, silt, and clay.
				Lower basalt flows	Lower basalt flows: Total thickness generally more than 1000 ft. Basalt is dark gray, fine grained, and well jointed. Columns 1-2 ft in diameter are common. Pillows and spracles more common than in overlying basalt members.

FIGURE 6-2. Composite stratigraphic sequence in the northwestern plateau. (Bingham and Grolier, 1965)

FIGURE 6-3. Map showing anticlinal mountain ridges of south-central Washington, shown by heavy lines. (Waters, 1955)

FIGURE 6-4. Cross-section of idealized Yakima basalt flow from Tieton River area, Washington. (Swanson, 1967)

FIGURE 6-5. Common structures of Late Yakima-type flows in south-central Washington, showing idealized sections through Elephant Mountain (A) and Pomona (B) basalts and typical flow structures (C, D) below the Umatilla Basalt. The horizontal zones are separated by abrupt (A-4, B-5) or gradational (A-5) contacts. The upper (A-1, B-1) and basal (A-3, B-3) zones correspond to upper and lower colonnades, and the central zone (A-2, B-2) to the entablature of Spry (1962, p. 164; modified after Tomkeieff, 1940, p. 96). The upper zones are often somewhat buckled (A-9, B-12, D-4) at the top and may contain vesicles (B-7, C-9) that coalesce into sheets. Straight (C-8) or undulating (B-10) vertical joints divide the zones into prismatic columns that are thick (B-4, C-3), medium (C-1, B-3), or small (A-2, B-2). Other features include hackly columns (A-6, B-7, C-9), flow units (D-1), pillow-palagonite complexes (D-3), spiracles (C-6), niche-jointing (C-10), fan-jointing (B-11), pipe vesicle (A-7, B-8), and vesicle cylinders (A-8).

(Schmincke, 1967)

FIGURE 6-6. Minimum coefficients of friction versus normal pressure for lower granite basalt. (Coulson, 1970)

FIGURE 6-7. Initial residual coefficients of friction versus normal pressure for lower granite basalt.
(Coulson, 1970)

FIGURE 6-8. Engineering classification for intact rock--summary plot igneous rocks, 176 specimens (Deere et al, 1966)

Rock Type	Basalt	
	(Lower Granite)	
Specimen No	11-(04-14, 15)	
L/D	2.070	
γ_a	170.0	pcf
S_n	85.4	
σ_o (ult)	32.4	ksi
Texture	Interlocking	

Note:

- 1) V_p = Dilatational wave velocity
- 2) E_t = Tangent modulus (static)
- 3) E_s = Secant modulus (static)
- 4) M_c = Constrained modulus
 $= \rho V_p^2$ (dynamic)

FIGURE 6-9. Stress-strain behavior and sonic pulse velocity for basalt (lower granite) in uniaxial compression. (Deere et al, 1966)

FIGURE 6-10. Stress-strain curve and Poisson's Ratio for basalt (lower granite) in uniaxial compression

Rock Type	Basalt
	(Little Goose)
Specimen No.	12-(CH-11, 10, 8x 5)5
L/D	2.115
γ_0	176.9 pcf
S_h	88.7
σ_0 (ult)	45.4 ksi
Texture	Interlocking

Note:

- 1) V_p = Dilatational wave velocity
- 2) E_t = Tangent modulus (static)
- 3) E_s = Secant modulus (static)
- 4) M_c = Constrained modulus
= ρV_p^2 (dynamic)

FIGURE 6-11. Stress-strain behavior and sonic pulse velocity for basalt (Little Goose) in uniaxial compression (Deere et al, 1966)

FIGURE 6-12. Stress-strain curve and Poisson's Ratio for basalt (Little Goose) in uniaxial compression to failure (Deere et al. 1966)

FIGURE 6-13. Stress-strain curve and Poisson's Ratio for basalt (John Day) in uniaxial compression to failure. (Deere et al, 1966)

Rock Type	Basalt
	(John Day)
Specimen No	1.3-(DH-75,
	2A, Bx 4)2
L/D	2.084
γ_0	1790
	pcf
S_h	93.3
σ_0 (ult)	51.6
	ksi
Texture	Interlocking

Note:

- 1) V_0 = Dilatational wave velocity
- 2) E_t = Tangent modulus (static)
- 3) E_s = Secant modulus (static)
- 4) M_c = Constrained modulus
 $= \rho V_p^2$ (dynamic)

URE 6-14. Stress-strain behavior and sonic pulse velocity for basalt (John Day) in uniaxial compression. (Deere et al, 1966)

Diagrammatic cross section showing various occurrences of ground water. Water in the aquifers and wells is indicated by crosshatching. Arrows show the direction of ground-water movement. Wells A, C, and D are artesian wells tapping a basalt aquifer confined by impermeable basalt and clay. At wells A and C the land surface is below the piezometric surface of the confined aquifer, and these wells flow. Well B taps an unconfined (water-table) gravel aquifer. Well E taps an unconfined aquifer perched above the regional water table by impermeable strata within the cemented gravel.

FIGURE 6-15. Types of ground water movement in basaltic rocks. (Foxworthy, 1962)

FIGURE 6-16. Selected analyses of the prevalent types of ground water in basalt. (Newcomb, 1972)

TABLE 6-1

INTACT PROPERTIES OF COLUMBIA RIVER GROUP BASALTBASIC PARAMETERS

<u>Type of Property</u>	<u>Parameter</u>	<u>Customary English Units</u>
Index	. Unit Weight	150-192 lbs/ft ³
	. Natural moisture content (intact)	
	. Porosity (rock mass)	
Stress-strain	. Young's Modulus	8.0-16x10 ⁶ lbs/in ²
	. Poisson's Ratio	0.22-0.30
	. Bulk Modulus	
	. Shear Modulus	
Strength	. Cohesion 1500-3500	2100-5600 lbs/in ²
	Friction Angle psi range	45°-60° degrees
	. Uniaxial Compressive Strength	28,000-58,000 lbs/in ²
	. Tensile Strength	1800-3500 lbs/in ²
Thermal	. Coefficient of Linear Thermal Expansion	3x10 ⁻⁶ °F ⁻¹
	. Heat Capacity	0.17-0.23 BTU/lb-°F
	. Thermal Conductivity	0.58-0.78 BTU/hr-ft-°F
Hydrological	. Permeability	1.0-4x10 ⁻³ ft/yr

TABLE 6-2

SHEAR STRENGTH FOR LOWER GRANITE BASALT
(Coulson, 1970)

Dry Surfaces								Wet Surfaces							
N, psi	μ_i	μ_{res}	μ_{min}	$\delta_{res, cm}$	$\delta_{min, cm}$	Curve Type	Surface Damage	N, psi	μ_i	μ_{res}	μ_{min}	$\delta_{res, cm}$	$\delta_{min, cm}$	Curve Type	Surface Damage
Sandblasted Surfaces															
13.9	.733	.707	.693	3.18	0.70	2	G2	12.7	.740	.600	.600	4.10	4.10	2	G2
64.5	.723	.747	.715	3.20	0.30	3	G2	62.5	.613	.611	.603	2.00	0.05	2	G2
129	.720	.770	.720	4.66	0.70	3	G3	139	.667	.720	.667	3.50	0.00	3	G3
253	.730	.785	.730	4.60	0.00	3	G3	250	.670	.720	.653	3.65	0.30	3	G3
516	.634	.708	.634	4.40	0.00	4	G3	558	.571	.684	.571	3.00	0.00	4	G3
833	.647	.705	.647	2.70	0.00	4	G3	817	.575	.710	.575	4.10	0.00	4	G3
1208	.688	.731	.688	2.90	0.00	4	G3	1113	.587	.712	.587	3.70	0.00	4	G5
Surfaces Lapped with #80 Grit															
12.5	.767	.673	.673	3.50	3.50	2	G2	12.9	.733	.587	.587	3.26	3.26	2	G2
127	.733	.760	.723	4.64	0.76	3	G3	69.7	.661	.613	.597	4.00	1.14	3	G2
258	.743	.777	.733	2.04	0.37	3	G3	125	.670	.647	.627	3.10	0.94	3	G3
500	.592	.660	.585	4.50	0.10	3	G3	279	.727	.757	.707	4.00	0.20	3	G3
802	.647	.732	.632	4.40	0.20	3	G3	507	.650	.710	.642	4.50	0.20	3	G3
1098	.662	.773	.638	3.20	0.08	3	G3	791	.568	.730	.564	4.80	0.07	3	G3
								1083	.617	.738	.608	5.10	0.10	3	G3
Surfaces Lapped with #600 Grit															
12.3	.620	.687	.547	2.10	0.08	3	P1	12.3	.573	.620	.533	2.30	0.01	3	P1
61.0	.538	.773	.496	3.80	0.02	3	P1	61.1	.551	.677	.528	4.50	0.04	3	P1
122	.573	.773	.540	2.26	0.03	3	P1	122	.513	.753	.513	3.80	0.00	3	P1
244	.487	.793	.463	2.28	0.01	3	P1	244	.529	.790	.520	-	0.04	3	P1
488	.488	.756	.446	5.00	0.03	3	P2	489	.492	.673	.421	3.00	0.04	3	P2
774	.585	.796	.534	2.50	0.03	3	P2	772	.568	.745	.476	2.80	0.06	3	P2
1163	.569	.785	.535	4.10	0.03	3	P2	1057	.569	.685	.475	1.70	0.05	3	P2

TABLE 6-3

SUMMARY OF AVERAGE PHYSICAL PROPERTIES FOR ROCK
(Deere et al, 1966)

Note:

V% = Coefficient of variation

Group No.	Rock Type and Location		Unit Weight, γ_u		L/D	Compressive Strength		Shore Hardness, S_n		Schmidt Hardness, R		Abrasion Hardness, A_L	Absorption	Tensile Strength
			gms/cm ³	lbs/ft ³		σ_a (ult) psi $\times 10^3$	Load Rate psi/sec	Sides	Ends	All Rds	High 50%	$\frac{1}{\text{Area (in}^2\text{)}}$	% of dry weight	Point Load psi $\times 10^3$
1.1	Basalt (Lower Granite) Pullman, Washington	No. Tests V%	2.73 12	170.2 12 1.0	2.08 12	33.3 8 11.1	36 8	79 960 7.6	86 420 6.9	53 144 9.3	57 72 5.4	122 4 5.4	1.92 1	1.87 2 .3
1.2	Basalt (Little Goose) Walla Walla, Washington	No. Tests V%	2.82 6	175.8 6 .4	2.12 6	43.0 3 5.8	60 2	70 480 6.5	87 240 4.8	54 72 9.3	58 36 5.3	176 4 7.5	.44 1	1.61 1
1.3	Basalt (John Day) Arlington, Oregon	No. Tests V%	2.87 6	179.1 6 .5	2.08 6	51.5 3 4.9	66 2	82 480 6.3	91 240 4.6	55 72 7.3	58 36 6.1	224 8 8.8	.75 1	2.10 1
2.1	Diabase (Palisades) West Nyack, New York	No. Tests V%	2.92 12	182.5 12 .2	2.01 12	35.0 8 11.3	52 8	85 960 6.4	90 440 5.3	57 144 4.3	59 72 2.2	238 4 18.6	.01 1	1.55 2 0.3
2.2	Diabase (Coghins) Culpeper, Virginia	No. Tests V%	3.04 6	189.5 6 .4	2.03 6	46.6 3 5.5	58 3	85 480 5.3	92 240 4.1	55 72 6.0	57 36 3.4	153 4 8.8	.11 1	1.72 1
2.3	Diabase (French Creek) St. Peters, Pennsylvania	No. Tests V%	3.06 6	190.8 6 .3	2.03 6	43.6 3 8.4	59 3	86 480 5.5	93 240 4.5	56 72 5.6	53 36 2.6	240 4 7.0	.17 1	1.77 1
	Dolomite (Oneota) Kasota, Minnesota	No. Tests V%	2.45 12	153.0 12 .6	1.99 12	12.6 8 5.3	24 8	31 480 25.0	35 480 23.1	39 144 11.5	43 72 6.9	22 4 25.1	5.39 1	6.0

TABLE 6-4

SUMMARY OF STATIC AND DYNAMIC UNCONFINED COMPRESSION DATA
(Stephenson and Triandafilidis, 1974)

—Summary of Static Unconfined Compression Data

Rock type (1)	Number of tests (2)	Ultrasonic wave velocity, in feet per second (3)	Unconfined compressive strength, in pounds per square inch (4)	Tensile strength, in pounds per square inch (5)	Static Young's modulus, in pounds per square inch $\times 10^6$ (6)	Pois- son's ratio (7)
Barre granite	12	12,580	28,150	660	6.4	0.23
Cedar City quartz diorite	12	8,000	8,980	205	0.8	0.24
Indiana lime- stone	12	14,200	8,760	325	4.9	0.30
Cedar City sand- stone	12	12,530	16,730	665	4.5	0.27
Washington basalt	10	15,830	32,800	—	12.0	0.30

—Summary of Dynamic Unconfined Compression Data

Rock type (1)	Number of tests (2)	Unit weight, in pounds per cubic foot (3)	Ultrasonic wave velocity, in feet per second (4)	Unconfined compressive strength, in pounds per square inch (5)	Loading rate, in pounds per square inch per second (6)	Strain rate, in inches per inch per second (7)	Young's modulus, in pounds per square inch $\times 10^6$ (8)	Poisson's ratio (9)
Barre granite	12	166.27	12,480	31,030	5.3×10^6	1	6.0	0.20
Cedar City quartz diorite	12	154.12	7,850	13,930	2.5×10^6	2	1.5	0.26
Indiana limestone	12	141.56	13,920	11,480	3.1×10^6	1	4.5	0.33
Cedar City sandstone	6	157.31	12,520	19,560	3.6×10^6	1	4.0	0.25
Washington basalt	5	180.98	15,800	34,920	4.0×10^6	1	11.2	0.30

TABLE 6-5

MODULUS DATA AND STRESS-STRAIN CURVES
(Stephenson and Triandafilidis, 1974)

—Summary of Average Tangent Moduli from Laboratory Tests

Rock type (1)	AVERAGE TANGENT MODULUS, in Pounds per Square Inch $\times 10^6$				
	Average of static tests (2)	Dynamic Tests			
		Ram loader (3)	Shock tube (4)	Air gun (5)	Average of dynamic tests (6)
Barre granite	6.4	7.2	5.8	7.8	6.9
Cedar City quartz diorite	0.8	1.8	2.3	2.2	2.1
Indiana limestone	4.9	5.4	6.1	6.0	5.8
Cedar City sand- stone	4.5	3.9	—	5.0	4.5
Washington basalt	12.0	11.2	10.1	11.0	10.8

—Stress-Strain Curves from Laboratory Tests (1 ksi = 6.9 MN/m²)

TABLE 6-6

(Agapito, Hardy and St. Laurent, 1977)

SUMMARY OF ROCK PROPERTIES
 BACON SIPHON AND TUNNEL - SECOND UNIT
 COLUMBIA BASIN PROJECT
 TESTS BY U.S.B.R.

Specimen No.		Rock Type	Secant 1/ Elasticity GPa	Compressive Strength MPa	Fracture 2/ Mode	Absorption, Percent by Weight	Specific Gravity
DH	Depth						
100	88.3	Basalt	43	81	Across matrix and structure	3.9	2.57
100	101.9	Basalt	53	98	Across matrix and structure	3.7	2.61
100	120.9	Basalt	23	216	Across matrix and structure	2.1	2.74
100	148.7	Basalt	22	83	Across matrix and structure	3.9	2.58
100	152.8	Basalt	22	137	Across matrix and structure	3.7	2.62
100	181.6	Basalt	30	194	Across matrix and structure	2.5	2.65

1/E is given at first cycle of loading, 7MPa stress.

2/Pertains to samples failed in compression tests.

TABLE 6-7

(Agapito, Hardy and St. Lourent, 1977)

SUMMARY OF ROCK PROPERTIES
 BACON SIPHON AND TUNNEL - SECOND UNIT
 COLUMBIA BASIN PROJECT
 TESTS BY U.S.B.R.

Specimen No. D.H.	Depth <u>1/</u>	Rock Type	E <u>2/</u> GPa	Poisson's Ratio <u>2/</u>	Compressive Strength, MPa	Absorption % by Weight	Specific Gravity	Porosity
200	133.21	basalt	45	0.09	176	1.6	2.76	4.4
200	135.53	basalt	74	0.16	204	0.8	2.78	2.2
200	148.75	basalt	59	0.05	109	4.1	2.56	10.4
200	149.55	basalt	49	0.31	89	5.3	2.46	12.9
200	166.06	basalt	54	0.10	125	1.5	2.73	4.2
200	166.42	basalt	55	0.14	104	1.5	2.73	4.0
205	232.69	basalt	58	0.14	180	1.5	2.68	4.2
205	233.50	basalt	66	0.22	192	1.1	2.70	3.1
205	235.54	basalt	36	0.10	179	2.3	2.65	6.0
205	239.53	basalt	<u>3/</u>	<u>3/</u>	139	3.1	2.58	8.0
205	239.81	basalt	<u>3/</u>	<u>3/</u>	125	3.7	2.54	9.4
207	120.33	basalt	77	0.18	293	0.2	2.86	0.6
207	133.60	basalt	72	0.26	229	0.3	2.88	0.9
207	147.98	basalt	80	0.23	241	0.2	2.90	0.6

^{1/}Depth, in feet, is measured to the center of the test specimen.

^{2/}Elasticity and Poisson's Ratio are given for first cycle loading at 7 MPa.

^{3/}No Elasticity run on these test specimens due to large vesicles.

TABLE 6-8

(Agapito, Hardy and St. Laurent, 1977)

SUMMARY OF TRIAXIAL COMPRESSION STRENGTH TESTS
ON CORE FROM THE HANFORD RESERVATION, DDH-1
TESTS BY TELEDYNE TERROMETRICS

Rock Zone	Number of Tests	Compressing Pressure MPa	Average Strength MPa
RM 1	3	0	212
	3	3.5	287
	3	7.0	305
	3	14.0	350
	3	21.0	400
RM 2 (Solid)	2	0	266
	2	7.0	361
	2	14.0	481
	1	21.0	562
	1	28.0	638
RM 1 (With Slip Planes)	1	0	143
	1	7.0	179
	1	14.0	252
	2	21.0	331
	2	28.0	390
RM 3 (All Specimens Contained Many Open Vugs and Pores)	3	0	69
	2	7.0	93
	3	14.0	145
	3	21.0	172
	3	28.0	152
RM 4 (Solid)	2	0	216
	2	7.0	307
	1	14.0	434
RM 4 (With Joints)	1	0	16
	1	7.0	168
	2	14.0	281
	3	21.0	310
	2	28.0	333

TABLE 6-9

(Agapito, Hardy and St. Laurent, 1977)

COHENSION AND FRICTION ANGLES FROM TERRAMETRICS TESTS, DDH-1
HANFORD RESERVATION

Rock Zone	Cohesion MPa	Angle of Internal Friction (Degree)	Porosity (Approx.) (Percent)
RM 1 Solid	38	53	1
RM 2 Solid	38	59	1
RM 3 (Slip Planes)	38	54	1
RM 3 (Vuggy)	15	42	9-15
RM 4 Solid	34	58	1.5
RM 4 (Joint)	31	47	1.8

TABLE 6-10

(Atlantic Richfield Hanford Co., 1977)

THERMAL PROPERTIES OF BASALT AS A FUNCTION OF TEMPERATURE

Sample 1005 Depth = 306 m (1005 ft)

Temperature, T		Density, ρ	Heat Capacity, C_p
$^{\circ}\text{F}$	$^{\circ}\text{C}$	lbs/ft^3	$\text{Btu/(lb)}(^{\circ}\text{F})$
100	37.8	183.6	0.174
200	93.3	183.8	0.186
300	149	184.0	0.198
400	204	184.1	0.210
500	260	184.3	0.222
600	316	184.5	0.234

Temperature, T		Thermal Diffusivity, α	Thermal Conductivity, k
$^{\circ}\text{F}$	$^{\circ}\text{C}$	ft^2/hr	$\text{Btu/(hr)}(\text{ft})(^{\circ}\text{F})$
100	37.8	0.0206	0.657
200	93.3	0.0201	0.687
300	149	0.0196	0.714
400	204	0.0191	0.739
500	260	0.0186	0.762
600	316	0.0181	0.783

Sample 1084 Depth = 330 m (1084 ft)

Temperature, T		Density, ρ	Heat Capacity, C_p
$^{\circ}\text{F}$	$^{\circ}\text{C}$	lbs/ft^3	$\text{Btu/(lb)}(^{\circ}\text{F})$
100	37.8	166.1	0.176
200	93.3	166.2	0.187
300	149	166.4	0.197
400	204	166.5	0.207
500	260	166.7	0.217
600	316	166.8	0.227

Temperature, T		Thermal Diffusivity, α	Thermal Conductivity, k
$^{\circ}\text{F}$	$^{\circ}\text{C}$	ft^2/hr	$\text{Btu/(hr)}(\text{ft})(^{\circ}\text{F})$
100	37.8	0.0200	0.587
200	93.3	0.0195	0.603
300	149	0.0189	0.617
400	204	0.0183	0.629
500	260	0.0177	0.639
500	316	0.0171	0.647

7.0 ROCK PROPERTIES OF BASALT FROM SPECIFIC AND NON-SITE-SPECIFIC AREAS

7.1 GENERAL

Rock properties of other basalts are available from investigations throughout the world. The investigations were generally limited to one parameter, and so do not lend themselves to development of a full chapter. However, it is felt that the most notable information should be mentioned, especially where the data convey insight into the behavioral characteristics of basalt.

In addition, brief coverage will be given to testing results obtained from solid-earth geophysics. This type of information is not directly pertinent to the development of a repository, as it is obtained at stress levels a magnitude or more in excess of that required for repository investigations.

7.2 STRENGTH AND MODULUS PROPERTIES

7.2.1 Laboratory Testing

Wuerker (1956)¹, Clark and Caudle (1961)² and the U.S.G.S. (1974)³ have collected basalt information from different parts of the States and India. Wuerker's, and Clark and Caudle's data reflects results obtained from many sources related to the mining and petroleum industries, and were obtained from the states of Michigan, South Carolina, Idaho, and Hawaii and the country of India. Basaltic type ranges from dense basalt, through altered basalt, to vesicular and amygdaloidal types.

The basalt strength from Michigan ranges from 37,400 p.s.i. to 52,000 p.s.i. in the dense unaltered state. If altered, strengths decreased to 11,800 p.s.i., and were heavily altered and zeolitized to 2,470 p.s.i. Modulus values were given from dynamic testing, Young's modulus ranging from $13.9 - 8.92 \times 10^6$ p.s.i. in the unaltered condition to as low as 0.91×10^6 p.s.i. for the zeolitized basalt.

The information from Idaho is interesting, where it is apparent that the glassy basalts have low strengths, unconfined strength ranging from

3,300-8,370 p.s.i., and Young's modulus can be as low as 0.38×10^6 p.s.i. Full information is given in Table 7-1.

The U.S. Geological Survey (1974)³ collected rock properties for various localities in the States. Many of their data have already been presented, though results from California and Arizona due to the limited quantity of data has not been discussed. Table 7-2 presents information from San Bernadino County, California, and Coconinco County, Arizona.

The basalt from California varies in compressive strength from 8,170 - 38,200 p.s.i., with a range in Young's modulus from $3.1-11.6 \times 10^6$ p.s.i. The compressive strength values from Arizona range from 3,100 - 40,100 p.s.i., illustrating the strength variations with the flow units.

Creep rates were measured by Iida et al (1960)⁴ on specimens of basalt from Japan. Ten specimens of basalt were subjected to stress over a 150-hour period. The two different basalt types are given in Table 7-3. In general the basalts contain at least 50 percent plagioclase feldspar, magnetite and pyroxene in varying proportions. Test results are given in Table 7-4, and are plotted in Figure 7-1. It was observed that the basalt specimens exhibited elastic-flow creep characteristics, and that sometimes the creep rate decreases with the increase of load.

7.2.2 In Situ Testing

Two types of in situ experimentation have been performed on basalts. Plate-loading tests and direct-shear tests. Dodds and Schroeder (1974)⁵ carried out a number of tests on scoriaceous and vesicular basalt. The scoriaceous basalt showed an order of magnitude difference for the range of the tangent modulus (minimum values of 0.1×10^6 p.s.i. to a maximum value of 2.7×10^6 p.s.i.). The vesicular basalt exhibited less variability, with a minimum value of 2.2×10^6 p.s.i. and a maximum of 8.2×10^6 p.s.i. Full data are given in Table 7-5.

In situ shear testing has been reported by Nieble et al (1974)⁶ for basaltic flows in the Parana Basin, Brazil. The tests were performed on either basaltic breccia or on contracts. Figure 7-2, presents the general characteristics obtained from the tests on the basaltic breccias. Results indicate that the breccias behave like dense rock fill.

7.3 THERMAL PROPERTIES

7.3.1 Coefficient of Linear Thermal Expansion

The coefficient of linear thermal expansion relates the change in length of a substance which is caused by a given temperature change to the original length of that substance. The coefficient of linear thermal expansion of a "typical" basalt for the temperature interval $68^{\circ} - 482^{\circ} \text{F}$ is approximately $1 - 4 \times 10^{-6}/^{\circ}\text{F}$ (Table 7-6). For this report, a representative coefficient of linear thermal expansion for the generic intact and rock mass basalt is assumed to be $3 \times 10^{-6}/^{\circ}\text{F}$.

7.3.2 Thermal Conductivity

The thermal conductivity is an expression of the ability of a substance to conduct heat along a thermal gradient per unit degree of temperature change per unit time. Values of thermal conductivity from the literature were tabulated (see Table 7-7) and plotted vs temperature over the temperature range of approximately $32^{\circ} - 1000^{\circ}\text{F}$. Values of thermal conductivity were then selected by observing the slope of the plots from the literature and subjectively evaluating the nature of the generic basalt used in this study. The values so determined are noted in Section 9.0, Tables 9-1 and 9-3.

7.3.3 Heat Capacity

The heat capacity of a substance is the amount of heat required to raise a given mass a given temperature interval. This parameter is expressed in similar dimensions to specific heat, which specifies a given unit mass. Values of heat capacity from the literature were tabulated (Table 7-8) and plotted vs temperature over the temperature range of approximately $68^{\circ} - 600^{\circ}\text{F}$. Values of heat capacity were then selected by observing the slope of the plots and subjectively evaluating the nature of the generic basalt used in this study. The values so determined are noted in Section 9.0, Tables 9-1 and 9-3.

7.4 SOLID EARTH GEOPHYSICS AND HIGH PRESSURE TESTING

The information for this section has been taken from Nafe and Drake (1967) ¹⁴. The majority of the research on rocks of basaltic composition is investigated at pressures up to ten kilobars, i.e. at pressures up to 14.5×10^5 p.s.i.

Figure 7-3 illustrates the change in compressional velocity with confining pressure. For repository studies, the stress range involved would only involve the very lowest portion of the graphs, requiring far more data points. At pressures greater than 2 kilobars, the rate of change greatly decreases; consequently, the existing measurements suffice. Similarly Poisson's ratio undergoes change with increasing pressure, Figure 7-4.

7.0 REFERENCES

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B1: 20.2 kg/cm², 27.5°C. B2: 32.6 kg/cm², 27.5°C. B3: 45.8 kg/cm², 28°C.
 B4: 58.3 kg/cm², 28°C. B5: 73.5 kg/cm², 18°C. B6: 83.1 kg/cm², 28°C.
 B7: 92.3 kg/cm², 28°C. B8: 138.9 kg/cm², 11°C. B9: 161.7 kg/cm², 27.5°C.
 B10: 246.0 kg/cm², 16°C.

FIGURE 7-1. Creep curves for basalt (Iida et al, 1960)

FIGURE 7-2. Shear test results on basaltic breccia.
(Nieble et al, 1974)

FIGURE 7-3. Measurement of compressional velocity to pressures (Nafe and Drake, 1967)

FIGURE 7-4. Variation of Poisson's Ratio with pressure.
(Nafe and Drake, 1967)

TABLE 7-1

PHYSICAL AND MECHANICAL PROPERTIES OF ROCK
(Wuerker, 1959; Clark and Caudle, 1961)

(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)		
TYPE OF ROCK	STATIC ELASTIC CONSTANTS				DYNAMIC ELASTIC CONSTANTS							NO.	GRAIN SIZE (mm.)	COMPRESSIVE STRENGTH		TENSILE STRENGTH (10 ³ PSI)	MODULUS OF RUPTURE (10 ³ PSI)	IMPACT TOUGHNESS IN./IN. ²	MODULUS OF RESILIENCE IN. LB./IN. ³	MOR'S HARDNESS	SCLEROSCOPE HARDNESS	ABRASIVE HARDNESS	WORK INDEX	SPEC. GRAV.
	MODULUS OF ELASTICITY			POISSON'S RATIO	MODULUS OF PLASTICITY		SHEAR MODULUS (10 ⁶ PSI)	POISSON'S RATIO	SPECIFIC DAMPING CAPAC. 10 ⁻⁶	LONGITUD. VELOCITY (10 ³ FT./SEC)	AVERAGE (10 ³ PSI)			RANGE										
	STRESS RANGE (10 ³ PSI)	(10 ³ PSI)	RANGE (10 ³ PSI)		(10 ³ PSI)	RANGE																		
Basalt, (Mich.)					8.92		1.44	0.150	4	15.2	24	0.03-5.6	33.4			3.8	13	62.8	5.00a	69	15		2.85	
" , altered (Mich.)											25	0.1-12.0	11.8						4.16a	53				
" , heavily altered, zeolitic (Mich.)	0-0.0	8.7	5.2	0.12	0.91		0.48	-0.04		5.80	26	0.1-16.0	2.4			0.28	1.9	3.42	6.09		25		2.04	
" , low strength (Medford, Oregon)											27	1.0	24.4	9.87					6.09				2.72	
" , high strength											28		31.5	16.78					6.09				2.74	
" , amygdular, altered, endotized (Mich.)					5.0		1.48	0.09	20	12.7	29	0.1-20.0	17.3			2.1	3.5	57.3	25.4	49	9.2		2.70	
" , heavily altered, calcitized (Mich.)		8.7		0.15							30	0.1-16.0	49.5			4.1	8.8	141.0	5.84a	85	25.0		2.80	
" , (Durham, S. C.)											31											11.41C	2.77	
" , volcanic (Hawaii)	0-0.5	5.14	4.73	0.13	4.68	5.80	2.11	0.11			32											20.11C	3.01	
" , glassy, high strength (Idaho)	0-0.5	5.14	4.73	0.13							33		8.3	5.72									2.62	
" , glassy, medium strength (Idaho)	0-0.5	5.14	4.73	0.13							34		5.45	2.27									2.56	
" , glassy, altered (Idaho)	0-0.5	5.14	4.73	0.13							35		3.30	1.11									2.06	
" , vesicular, high strength (India)	0-1.0	5.10	5.10	0.15	6.59	0.64	2.53	0.25			36		9.85	8.73										
" , vesicular, low strength (India)	0-1.0	5.10	5.10	0.15	3.62	0.27	1.51	0.20			37		2.35	1.36										
Breccia, tuff, high strength (India)	0-0.4	1.29	1.69	0.08	2.86	0.12	1.26	0.16			38		2.35	1.16										
" , tuff, low strength (India)	0-0.4	1.29	1.69	0.08	0.91	0.26	1.43	0.13			39		1.20	0.54										
Claystone, (calcareous siltstone) (Indiana)	0-1.0	5.46		0.26	6.16		2.35	0.31			40		11.2											

TABLE 7-2

ROCK STRENGTH FOR BASALT (USGS, 1974)

<u>State</u>	<u>Compressive Strength (psi)</u>	<u>Young's Modulus (x 10⁶ psi)</u>	<u>Poisson's Ratio</u>
California	16,900	10.80	0.25
	10,100	5.64	0.18
	21,100	4.75	0.17
	8,170	3.10	0.18
	15,500	4.77	0.23
	16,600	7.52	0.23
	38,200	11.60	0.21
Arizona	14,700	--	--
	17,500	--	--
	19,800	--	--
	18,100	--	--
	20,300	--	--
	13,600	--	--
	14,700	--	--
	19,800	--	--
	23,200	--	--
	17,500	--	--
	40,100	--	--
	17,500	--	--
	14,100	--	--
	17,500	--	--
	26,000	--	--
	14,100	--	--
	5,000	--	--
	17,900	--	--
	23,500	--	--
	14,100	--	--
	3,800	--	--
	5,700	--	--
	17,200	--	--
	4,700	--	--
	6,300	--	--
	22,000	--	--
	22,600	--	--
	12,700	--	--
	14,700	--	--
	27,700	--	--
	10,700	--	--
	3,100	--	--
	6,500	--	--
	12,700	--	--
	4,200	--	--
	20,600	--	--
	20,600	--	--
	23,400	--	--

TABLE 7-3

BASALT MINEROLOGY (Iida et al, 1960)

Basalt (old type) (Specimen No. B1, B2, B3, B4)	Genbudo, Akaishi, Toyooka-shi, Hyogo Pref.	<i>Phenocryst</i> : olivine (partly, iddingsite) (20-25%) <i>Groundmass</i> : plagioclase (50%), mag- netite (5-10%), clinopyroxene (10-20 %), rhombic pyroxene (5%).
Two-pyroxene basalt (Vc type) (Ajiro B ₁₀ basalt) (Specimen No. B5, B8, B10)	Ajiro, Atami-shi, Shizuoka Pref.	<i>Phenocryst</i> : plagioclase (bytownite), monoclinic pyroxene, rhombic pyrox- ene. <i>Groundmass</i> : plagioclase (An 55), monoclinic pyroxene, rhombic pyrox- ene, magnetite. Color index >35. Or = 100 Gr = 100 Or + Ab + An < 15.

TABLE 7-4

CREEP RATES FOR BASALT SPECIMENS (Iida et al, 1960)

Specimen No.	Specimen			Max. Stress σ (kg/cm ²)	Young's Modulus E (dynes/cm ² × 10 ¹¹)	Creep rate		Temperature (°C)	Duration Time (hour)
	Thickness a (cm)	Width b (cm)	Length l (cm)			$\dot{\epsilon}_1$ (hour ⁻¹) × 10 ⁻⁶	$\dot{\epsilon}_2$ (hour ⁻¹) × 10 ⁻⁶		
Basalt									
B1	0.61	2.04	10.00	20.2	6.0	0.72	0.00	27.5	180
B2	0.61	2.03	10.00	32.6	5.5	1.53	0.45	27.5	180
B3	0.62	2.02	10.00	45.6	6.9	0.07	0.02	28	250
B4	0.62	2.02	10.00	58.3	7.5	0.06	-0.01	28	250
B5	0.52	1.92	9.72	73.5	7.2	0.00	0.00	18	160
B6	0.63	2.02	10.00	83.4	8.0	0.03	-0.03	28	250
B7	0.61	2.03	10.00	92.3	6.5	-0.13	-0.13	28	250
B8	0.52	1.92	9.72	138.9	8.6	0.00	0.00	11	160
B9	0.63	2.01	10.00	161.7	5.5	0.65	0.20	27.5	180
B10	0.61	2.04	9.72	246.0	7.7	0.00	0.01	16	120

Field Moduli										
	Tangent Modulus $\times 10^6$ psi			Secant Modulus $\times 10^6$ psi			Recovery Modulus $\times 10^6$ psi			Number of Tests
	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	
Scoriaceous Basalt	1.0	2.7	0.1	0.6	1.2	0.1	2.3	4.1	0.5	6
Vesicular Basalt	4.4	8.2	2.2	1.2	1.6	0.6	6.6	11.0	3.2	5

TABLE 7-5
Plate Loading Test Results (Dodds and
Schroeder, 1974)

TABLE 7-6
LINEAR COEFFICIENT OF THERMAL EXPANSION

<u>COEFFICIENT (per °F)</u>	<u>T (°F)</u>	<u>REFERENCES</u>
2.4 - 3.6 x 10 ⁻⁶ (1)	68 - 212	Clark, 1969 ⁷
2.3 - 3.7 x 10 ⁻⁶ (2)	---	ARH-ST-137, 1976 ⁸
3.3 x 10 ⁻⁶ (3)	77 - 482	RICHTER & SIMMONS, 1974 ⁹
3.5 x 10 ⁻⁶ (4)	77 - 482	"
0.9 - 2.0 x 10 ⁻⁶ (5)	77 - 482	"
4.7 x 10 ⁻⁶ (6)	77 - 482	"

1) Basalt

2) Basalt - This value is an estimate only

3) Fairfax diabase

4) Frederick diabase

5) Lunar basalts

6) Cape Neddick gabbro (representative of basalt only in chemical composition).

TABLE 7-7.

THERMAL CONDUCTIVITY

<u>CONDUCTIVITY</u> <u>(BTU/ft.hr.°F)</u>	<u>TEST</u> <u>CONDITIONS</u>	<u>REFERENCE</u>
0.99	--	Ratigan, 1976 ¹⁰
1.16 (1)	95°F	Clark, 1969 ⁷
1.21 (1)	68	Clark, 1969 ⁷
0.98 (1)	86	Clark, 1969 ⁷
1.00 (1)	167	Clark, 1969 ⁷
1.36 (1)	32	Birch & Clark, 1940 ¹¹
1.29 (1)	212	"
1.30 (1)	392	"
1.27 (1)	32	"
1.23 (1)	212	"
1.22 (1)	392	"
1.21 (1)	572	"
1.22 (1)	32	"
1.21 (1)	212	"
1.21 (1)	392	"
1.22 (1)	572	"
1.22 (1)	752	"
0.78 (2)	32	"
0.84 (2)	212	"
0.91 (2)	392	"
0.97 (2)	572	"
1.03 (2)	752	"
1.09 (2)	932	"
0.66 (3)	32	"
0.73 (3)	212	"
0.79 (3)	392	"
0.85 (3)	572	"
1.26	68	LANGE'S Handbook ¹² of Chemistry, 1956.

TABLE 7-7 (Continued)

<u>CONDUCTIVITY</u> (BTU/ft.hr.°F)	<u>TEST</u> <u>CONDITIONS</u>	<u>REFERENCE</u>
0.66	100	ARH-ST-137, 1976 ⁸
0.69	200	"
0.71	300	"
0.74	400	"
0.76	500	"
0.78	600	"
0.59	100	"
0.60	200	"
0.62	300	"
0.63	400	"
0.64	500	"
0.65	600	"

NOTES:

- 1) Diabase values; larger crystals and low glass content make diabase different than basalt.
- 2) Obsidian
- 3) Diabase glass (artificial) probably most similar to flood basalt.

TABLE 7-8
HEAT CAPACITY

<u>CONDUCTIVITY</u> (BTU/ft.hr.°F)	<u>TEST</u> <u>CONDITIONS</u>	<u>REFERENCE</u>
0.36	---	Ratigan, 1976 ¹⁰
0.20	68 - 212 °F	LANGE'S Handbook ¹² of Chemistry, 1956
0.23	212 °F	Parsons 1976 ¹³
0.24	392 °F	"
0.25	572 °F	"
0.174	100 °F	ARH-ST-137, 1976 ⁸
0.186	200 °F	"
0.198	300 °F	"
0.210	400 °F	"
0.222	500 °F	"
0.234	600 °F	"
0.176	100 °F	"
0.187	200 °F	"
0.197	300 °F	"
0.207	400 °F	"
0.217	500 °F	"
0.227	600 °F	"

8.0 SPECIAL CHARACTERISTICS OF BASALT

Basaltic flows show wide ranges in engineering behavior due to their unique depositional and cooling characteristics. The variability in properties within a flow is largely a function of the flow thickness and, hence, the rate of cooling throughout the mass.

Thick flows normally have dense basalt in their lower portions and are jointed, with the joints tending towards five- or six-sided columns. Individual columns average 2-3 feet across and contain cross joints, either inclined or normal to the column. In the other parts of the flow, joint directions become haphazard and far less symmetrical. In a similar way the dense basalt of the lower portion of the flow becomes more vesicular, with increase in porosity in the other portions of the flow. The vesicular upper part changes rapidly into either a slaggy, ropy, or clinker type basalt at the flow top.

Once the flow has solidified, the top surface can undergo weathering while it is exposed to the atmosphere and before it is buried below a subsequent basalt flow.

The engineering behavior, therefore, depends on the portion of the flow which is studied. In the lower part of a flow, the joints are widely spaced and the overall appearance is of a massive nature, with fewer roof-control problems. In the upper part of the flow, joints are closer spaced and the intact strength is lower. Also, the upper portion of the flow is more liable to exhibit signs of weathering, with a further reduction in intact strength.

A further potential problem is due to the increased permeability of the weathered and slaggy top. Situations can develop, where due to the depositional mode, a dense competent lava flow, or a base of a flow, overlies an old flow with a weathered top of highly permeable nature. This old flow, or more correctly old land surface, may have been incised with historical stream beds and channels, into which fresh lava has flowed. As a consequence the basalt can show permeability variations even on the same datum level, if that level cuts an old stream channel.

One other point which should not be overlooked is that many basalts weather to form montmorillonitic-type minerals, which infill joints and fractures. Shear strength of fresh joint surfaces may be high when clean and unweathered, but may undergo a dramatic strength drop when weathered or infilled.

9.0 ROCK-MASS PROPERTIES FOR A TYPICAL BASALT

9.1 GENERAL

The rock-mass properties of a basalt will be considerably different from the intact properties, due to the complex interaction of the rock substance, joint system, joint filling and water effects.

For two important design parameters, namely, Young's Modulus and Unconfined Compressive Strength, the rock-mass values are typically much smaller than the intact values. In each case the rock-mass value is usually obtained from the intact value by multiplying by an appropriate reduction factor i.e.

$$\text{Reduction Factor, } R = \frac{\text{Rock Mass Value (Strength)}}{\text{Intact Value (Strength)}}$$

Considerable judgment is required in selecting a suitable reduction factor. This is because the reduction factor depends very much on geological considerations, such as the joint pattern, joint spacing and joint filling. Although the rock mass properties (and hence, reduction factors) may be determined directly from large-scale field tests, these are time-consuming, and expensive; this largely explains why no large-scale field tests have been reported in the literature.

9.2 INTACT PROPERTIES FOR A TYPICAL BASALT

The intact properties of four basalts from different parts of the United States summarized in Chapters 3 through 6. These properties for specific basalts have been evaluated and combined in Table 9-1 to give the key properties of a typical dense basalt.

9.3 ROCK MASS PROPERTIES FOR A TYPICAL BASALT

Since geological structure plays a very important role in rock-mass behavior, a description of structures found in a typical basalt is presented in Table 9-2. These structures have been taken into account in deriving the rock-mass properties.

The rock-mass properties of a typical dense basalt representative of the lower portion of a thick flow are given in Table 9-3. The moduli and strength characteristics were determined by the use of reduction factors applied to the representative intact data.

It was necessary to use a considerable amount of judgment in arriving at a reduction factor of 0.18 for Young's modulus. A certain amount of weight was given to considerations by Panek (1970)¹ in which the reduction factor is related to the fracture spacing and the width of the excavation. Due largely to the relatively close jointing in basalt, which we have assumed to have an average spacing of about two feet, a reduction factor of 0.18 was chosen. This then gave a Young's modulus of 1.8×10^6 lbs/in² for the rock-mass.

Although jointing also has a considerable effect on rock mass strength it is not considered to be as significant as with Young's modulus. Hence, a reduction factor of 0.45 was used which gives a uniaxial confined compressive strength of 18,000 psi for the rock mass.

The strength of the rock mass is considerably reduced at elevated temperatures. This reduction in strength has been taken into account in the calculations of tunnel and pillar stability; it is discussed further in the report on thermal stress analysis².

The non-linear failure curve that is recommended for a typical basalt at room temperature is shown in Figure 9-1. It may be described by the following three parameters³:

Unconfined compressive strength $C_c = 18,000$ lbs/in²

Curve fitting parameter, $A = 4.5$

Curve fitting parameter, $k = 0.75$

A value of 180 lbs/ft³ was assumed to be the unit weight of the basalt rock mass. Thermal properties at depth were assumed to be similar to the intact properties.

Although isotropic behavior has been assumed in this general study, anisotropic behavior should be investigated at the design stage for a specific repository; for instance, detailed geological mapping and in situ testing will be required at the actual site of the underground repository.

9.0 REFERENCES

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FIGURE 9-1

NON-LINEAR CURVE OF STRENGTH FOR ROCK MASS

TABLE 9-1

INTACT PROPERTIES FOR A TYPICAL DENSE BASALT

<u>Type of Property</u>	<u>Parameter</u>	<u>Value</u>	<u>Customary English Unit</u>
Index	. Unit Weight	185	lbs/ft ³
	. Natural Moisture Content		%
	. Porosity	2.0	%
Stress-strain	. Young's Modulus	10×10^6	lbs/in ²
	. Poisson's Ratio	0.26	--
Strength	. Strength Parameters A k		
	. Uniaxial Compressive Strength	40,000	lbs/in ²
	. Tensile Strength	2,300	lbs/in ²
Thermal	. Coefficient of Linear Thermal Expansion	3×10^{-6}	°F ⁻¹
	. Heat Capacity		BTU/lb-°F
		<u>TEMPERATURE</u>	<u>HEAT CAPACITY</u>
		32°F	0.17 BTU/lb-°F
		212	0.19
		392	0.22
		572	0.23
	. Thermal Conductivity		
		<u>TEMPERATURE</u>	<u>HEAT CAPACITY</u>
		32°F	0.65 BTU/hr-ft
		122	0.69
		212	0.73
		302	0.76
		392	0.79
		572	0.85
		752	0.90

TABLE 9-2

PARTIAL DESCRIPTION OF TYPICAL STRUCTURES IN BASALT

	<u>SET A</u>	<u>SET B</u>	<u>SET C</u>	<u>SET D</u>
Type of Joint	Joint	Joint	Joint	Joint
Filling	Hematite	Nontronite	Calcite	Clean
Orientation (Dip Dir/Dip)	350/85	100/90	230/80	160/10
Opening Width	Tight	Tight	Tight	Tight
Spacing	>6 feet	1-6 feet	1/2-6 feet	1/2-3 feet
Waviness	Planar/Rough	Planar/Rough	Planar/Rough	Planar/Rough
Extents of Joings (Lengths)	~20 feet	~15 feet	~30 feet	~10 feet
Typical RQD: >95%				
Typical Fracture Frequency:	Horizontal: 2 to 0.15 per foot Vertical: 1 to 0.1 per foot			

TABLE 9-3

ROCK MASS PROPERTIES FOR A TYPICAL BASALT

<u>Type of Property</u>	<u>Parameter</u>	<u>Value</u>	<u>Customary English Unit</u>																
Index	. Unit Weight	180	lbs/ft ³																
	. Natural moisture content	---	%																
	. Porosity (rock mass)	0.6	%																
Stress-strain	. Young's Modulus	1.8 x 10 ⁶	lbs/in ²																
	. Poisson's Ratio	0.26	--																
Strength	. Strength Parameters																		
	A	4.5																	
	k	0.75																	
	. Uniaxial Compressive Strength	18,000	lbs/in ²																
	. Tensile Strength	0	lbs/in ²																
Thermal	. Coefficient of Linear Thermal Expansion	3 x 10 ⁶	°F ⁻¹																
	. Heat Capacity																		
		<table><tr><th><u>TEMPERATURE</u></th><th><u>HEAT CAPACITY</u></th></tr><tr><td>32°F</td><td>0.17 BTU/lb-°F</td></tr><tr><td>212</td><td>0.19</td></tr><tr><td>392</td><td>0.22</td></tr><tr><td>572</td><td>0.23</td></tr></table>	<u>TEMPERATURE</u>	<u>HEAT CAPACITY</u>	32°F	0.17 BTU/lb-°F	212	0.19	392	0.22	572	0.23							
<u>TEMPERATURE</u>	<u>HEAT CAPACITY</u>																		
32°F	0.17 BTU/lb-°F																		
212	0.19																		
392	0.22																		
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	. Thermal Conductivity																		
		<table><tr><th><u>TEMPERATURE</u></th><th><u>THERMAL CONDUCTIVITY</u></th></tr><tr><td>32°F</td><td>0.65 BTU/hr-ft</td></tr><tr><td>122</td><td>0.69</td></tr><tr><td>212</td><td>0.73</td></tr><tr><td>302</td><td>0.76</td></tr><tr><td>392</td><td>0.79</td></tr><tr><td>572</td><td>0.85</td></tr><tr><td>752</td><td>0.90</td></tr></table>	<u>TEMPERATURE</u>	<u>THERMAL CONDUCTIVITY</u>	32°F	0.65 BTU/hr-ft	122	0.69	212	0.73	302	0.76	392	0.79	572	0.85	752	0.90	
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