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THE CLIMAX GRANITE, NEVADA TEST SITE, AS A HOST
FOR A ROCK MECHANICS TEST FACILITY RELATED TO THE
GEOLOGIC DISPOSAL OF HIGH LEVEL NUCLEAR WASTES.

by

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**Lawrence
Livermore
Laboratory**

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FOREWORD

This document was prepared under support from the Department of Energy's National Waste Terminal Storage Program.

In 1979-1980, the author was a member of the DOE/USGS/ESTP Rock Mechanics Subgroup on Geologic Disposal of Radioactive Waste, and of the National Research Council's Committee on Rock Mechanics Research Requirements. This paper benefited from numerous discussions with colleagues, both inside and outside of the Lawrence Livermore National Laboratory. However, the author is the only one responsible for the statements contained herein.

The contributions of Dr. L. D. Ramspott who provided the Bibliography Section and Ms. L. D. Burrow who typed the manuscript are gratefully acknowledged.

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EXECUTIVE SUMMARY

This document discusses the potential of the Climax pluton, at the Nevada Test Site, as the host for a granite rock mechanics test facility related to the geologic disposal of high level nuclear waste. The Climax granitic pluton has been the site of three nuclear weapons effects tests: Hard Hat, Tiny Tot, and Piledriver. Geologic exploration and mapping of the granite body were performed at the occasion of these tests. Currently, it is the site of the Spent Fuel Test (SFT-C) conducted in the vicinity of and at the same depth as that of the Piledriver drifts. Significant exploration, mapping, and rock mechanics work have been performed and continue at this Piledriver level - the 1400 (ft) level - in the context of SFT-C.

The Climax pluton is believed to extend several thousands of feet deep under the deepest level mined out so far: the 1400 level. Whereas this level is considered not to be saturated, it is projected from regional geology that the pluton should be saturated at deeper levels. An exploration hole has been drilled and is being monitored to try and confirm this. The matter of saturation has arisen because any granite repository is likely to be emplaced in a saturated environment. The question also was asked by the Department of Energy: "What rock mechanics tests can be conducted in the partially saturated granite of the Climax site (1400 level), that will have general applicability to the design of hard rock repositories in saturated conditions". We consider this question to be a subset of the broader question: "Can the Climax site - i.e. the Climax pluton - be host to a rock mechanics facility, in which testing will be performed that will have general applicability to the design of hard rock repositories, where both saturated and unsaturated conditions will exist in space and time". As much as possible, one would attempt to perform the tests at the current (1400) level, so as to minimize or eliminate future testing at greater depth, which would require deepening of the existing shaft.

Our discussion considers both aspects of the broader question: the generic issues involved, and the specific attributes of the Climax site. To make this document self-contained, we first recall the R and D needs for design of high

level waste repositories in hard rock, with emphasis on granite. Next, we present the current state-of-affairs concerning the way in which research is proceeding to meet those needs. Then, we address the specific rock mechanics tasks which must be performed in the near future. We attempt to assess how the degree of saturation of a granitic body will impact upon the relevance of the task results. Concurrently, we consider the Climax site and attempt to establish which of the proposed tests can meaningfully be performed at the 1400 level and which others would preferably be conducted in a deeper, saturated, level in the Climax pluton.

Based on our technical discussions, and on the review of the significant geological and rock mechanics work already achieved in the Climax pluton, based also on the ongoing work and the existing access and support, it is concluded that the Climax site offers great opportunities for a rock mechanics test facility. It is not claimed, however, that Climax is the only possible site or the best possible site, since no case has been made yet for another granite test facility in the United States.

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1. INTRODUCTION

The mined geologic burial of high level nuclear waste is now the favored option for disposal. The National Waste Terminal Storage (NWTS) Program, designed to achieve this disposal (17,22), includes an extensive rock mechanics component, related to the design of the waste repositories. A comprehensive rock mechanics R and D technical plan was submitted in 1980 by a panel of experts, to the Department of Energy (18). The plan considers the five current candidate rock types: basalt, granite, salt, shale, and tuff. The Office of Nuclear Waste Isolation (ONWI) has followed with its own plan (89). Another document, prepared under the auspices of the National Research Council, also discusses rock mechanics questions of interest in nuclear waste disposal (61). In addition, within the past two years, there have been at least three important related symposia (5,44,48). The rock mechanics R and D contemplated include testing in the field and in the laboratory, as well as model development and verification. For the hard rocks, these tasks will best be performed in conjunction with rock mechanics test facilities (18). From the generic standpoint, a concentrated effort at one location, in a given rock type, will optimize the coherence of the test results, as opposed to having separate efforts on-going at various geographic locations. It will also enable a concentrated modeling effort and facilitate model validation.

This document discusses the potential of the Climax pluton, at the Nevada Test Site, as the host for a granite rock mechanics test facility related to the geologic disposal of high level nuclear waste. The Climax granitic pluton has been the site of three nuclear weapons effects tests: Hard Hat, Tiny Tot, and Piledriver. Geologic exploration and mapping of the granite body and its surroundings were performed at the occasion of these tests. Information on these previous studies is given in the Bibliography section of this report, which follows the Reference section. Currently, the Climax granite is host to the Spent Fuel Test (SFT-C) conducted in the vicinity of and at the same depth as that of the Piledriver access drift. Significant exploration, mapping, and rock mechanics work have been performed and continue at this Piledriver level - the 1400 level - in the context of SFT-C. Reports are available on the

scope of SFT-C (69,70,71), on the 1979 mine-by experiment (44,76), on the 1980 geomechanics in-situ program (40), on a recent analysis of the mine-by (41), and on the on-going geotechnical (90), seismic (51), and hydrological studies (57,58). Note that the availability of geological, geotechnical, and hydrological information from various locations in the Climax pluton fits well with the recommendation of the ESTP subgroup that testing should be performed at various levels in a repository formation (18). Consistent with the accepted definition of rock mechanics (18,61), geochemical and nuclide migration studies are not discussed here, although some are also taking place in the Climax facilities.

The Climax pluton is believed to extend several thousands of feet deep under the deepest level mined out so far: the 1400 level (52). Whereas this level is considered not to be saturated, it is projected from regional geology that the pluton should be saturated at deeper levels (58). An exploration hole has been drilled and is being monitored to try and confirm this (58). The matter of saturation has arisen because any proposed granitic repository is planned to be in a saturated environment (17). The question also was asked by the Department of Energy (14): "What rock mechanics tests can be conducted in the partially saturated granite of the Climax mine (1400 level), that will have general applicability to the design of hard rock repositories in saturated conditions". We consider this question to be a subset of the broader question: "Can the Climax site - i.e. the Climax pluton - be host to a rock mechanics facility, in which testing will be performed that will have general applicability to the design of hard rock repositories where both saturated and unsaturated conditions will exist in space and time". In space and time, because, even if the repository itself is in a saturated zone, some overlying regions will likely be partially saturated and their properties will influence the long-term behavior of the repository system; and because the host granitic bodies are likely to have very low permeabilities (9), so that, due to mining, operation, and ventilation of the repository over several years, a zone of partial saturation will be created inside the repository. Hence, tests in saturated rocks are not the only ones which are relevant to high level waste disposal in granite.

Our discussion considers both aspects of the broader question: the generic issues involved, and the specific attributes of the Climax site. To make this document self-contained, we first recall the R and D needs for design of high level waste repositories in hard rock, with emphasis on granite. Next, we present the current-state-of-affairs concerning the way in which research is proceeding to meet those needs. Then, we address the specific rock mechanics tasks which must be performed in the near future. We attempt to assess how the degree of saturation of a granitic body will impact upon the relevance of the task results. Concurrently, we consider the Climax site and attempt to establish which of the proposed tests can meaningfully be performed at the 1400 level, and which others would preferably be conducted in a deeper, saturated, level in the Climax pluton. As much as possible, one would attempt to perform the tests at the current (1400) level, so as to minimize or eliminate future testing at greater depth, which would require deepening of the existing shaft.

In summary, we are dealing in parallel with three distinct questions:

- . is Climax an appropriate site for improving our methodology of testing the thermal, hydraulic, and mechanical response of jointed rock masses?
- . what is the sensitivity of various rock mechanics tests and analyses to the degree of rock mass saturation?
- . what are the possibilities for extrapolating local test results in granite plutons, along horizontal and vertical directions?

Whatever progress this document achieves in answering the above questions, it is likely that these discussions also will contribute to the evaluation of the relevance of other rock mechanics programs in unsaturated hard jointed rocks, at Hanford (12), at Idaho Springs (45), or elsewhere.

2. THE ISSUES AND THE R AND D PROGRAM

2.1 Rock Mechanics Issues for Granite

The "critical" issues for granite have been summarized under four general headings (18) as being:

Rock Mass Characterization

- . Fracture geometry including spacing, orientation, continuity, aperture, and heterogeneities
- . Stress-deformation law for discontinuities including influence of temperature, effective stress, pore pressure, and aperture
- . Permeability of discontinuities as a function of stress, temperature, aperture, and normal and shear deformations
- . Thermomechanical and hydrological scale effects from laboratory to field.
- . Determination of in situ state of stress

Modeling:

- . Predictions for discontinuous rock masses with regard to thermal field, induced stresses, displacement and hydraulic behavior
- . Verification in generic rock types

Field Testing:

- . Design and monitoring of coupled thermomechanical and hydraulic response of repository

Repository Engineering:

- . Definition of design methodology and design criteria for repository design

In addition, several other issues were judged to be "important" (18):

- . Influence of moisture content on strength and deformation of rock mass
- . Time-dependent mechanical behavior of rock mass at sustained elevated temperatures

- Predictions for non-elastic rock mass behavior (creep, fracture, etc.)
- Limiting conditions for thermal decrepitation, disintegration, and induced fracturing in the near field
- Structural stability of pillars and rooms under sustained thermal loading
- Influence of thermal perturbation on background seismicity levels
- Definition of engineering conservatism to ensure long term isolation of nuclear waste within the repository system, given the uncertainties in definition of the geologic/geohydrologic system

As could be expected, the listing and ranking of issues for basalt is word for word identical to the one for granite (18).

2.2 On-Going Nuclear Waste Projects in Granitic Rocks

There are three well documented U.S. rock mechanics efforts related to nuclear waste disposal in granitic rocks:

- the Lawrence Livermore National Laboratory (LLNL) Spent Fuel Test (SFT-C) in the Climax Stock of the Nevada Test Site (NTS) (1,2,10,11,21,40,41,56,57,58,60,70,71,76,90)
- the Lawrence Berkeley Laboratory experimental program in the Stripa Mine, Sweden (15,25,44,48,62,65,93)
- the program conducted in the Colorado School of Mines (CSM) experimental mine, at Idaho Springs, Colorado, by CSM and Terra-Tek (45)

Outside the United States, the Stripa operation is being expanded to include participation by several other nations, and the project will include testing of a full scale backfilling scheme (13). Also, in Canada, plans are being made for some field activities to start in 1981 in the Underground Research Laboratory (URL), in Manitoba. In summary, Table I shows the activities of current U.S. programs, the level of knowledge relevant to these activities, and the proposed R and D for the future (18).

Table 1. Summary of U.S. Rock Mechanics Research in Granitic Rocks, Related to Nuclear Waste Isolation (18)

TOPIC	CURRENT R&D			ADEQUACY OF	PROPOSED R & D*		
	LLNL	LBL	CSM	KNOWLEDGE	LLNL	LBL	CSM
<u>Rock Mass Characterization</u>							
Geologic Mapping	X	X	X	Fair	X	X	X
Enhanced Core Recovery				Fair			
Geophysical Structural Mapping	X	X		Poor	X		
Lab. thermo/mech. tests on rocks	X	X		Adequate	X	X	
Lab. hydraulic tests on rocks	X	X		Fair	X	X	
Lab. thermo/mech tests on joints		X		Poor		X	
Lab. hydraulic tests on joints		X		Fair		X	
Field rock mass deformability	X	X	X	Fair	X	X	X
Field rock mass strength				Poor			
Field thermal prop. of rock mass	X	X	X	Fair	X	X	X
Field fluid conductivity	X	X	X	Fair		X	X
<u>Modeling</u>							
Thermal	X	X		Adequate	X	X	
Thermo-mechanical	X	X		Fair	X	X	
Thermo-hydraulic		X		Poor		X	
Hydro-mechanical		X		Fair	X	X	
Thermo-hydro-mechanical		X		Poor		X	
<u>In-Situ Testing</u>							
Field heater tests	X	X		Fair	X	X	
Large-scale permeability		X		Fair		X	
In situ stresses	X			Fair	X	X	
Room & pillar thermo-mech.	X			Fair	X		
Regional flow perturbation				Poor		X	
Induced seismicity	X			Poor	X		

*This does not mean that funds have been committed.

2.3 Future Rock Mechanics Research Needs

Figure 1 is the current ONWI definition of major milestones in the NWS Rock Mechanics Program (89). Of the 39 milestones listed, 28, marked by arrows, are relevant to granite. Figure 2 is a recent attempt at summarizing the degree of completion of the R and D program recommended for granite (18).

At present, the several separate research projects in granite do not constitute a comprehensive and cohesive program. This situation would be greatly enhanced by the procurement of a dedicated rock mechanics test facility, where the required generic studies can be conducted (18). A rock mechanics facility is defined as a field site where in situ testing can be performed, where materials can be retrieved for controlled laboratory testing, and where the rock mass can be instrumented for its response to support development and verification of models. The identification of potential granite repository sites must also proceed with all deliberate speed, so that site specific studies can be initiated (81).

FIGURE 1: MAJOR MILESTONES IN THE NNTS ROCK MECHANICS PROGRAM (89)

Figure 2: Estimated Status of the Technical Elements Required For Development of a Repository in Granite (18)

3. GENERIC ROCK MECHANICS AND CLIMAX

The generic program elements are discussed under the seven headings of:

- . geologic characterization
- . in-situ stresses and temperatures
- . hydraulic testing
- . thermal testing
- . mechanical testing
- . modeling
- . repository engineering.

3.1 Geologic Characterization

Whether water is present or not, geologic characterization is the cornerstone of our ability to build and verify adequate mechanical and hydraulic models (78,92). Figure 3 illustrates the relationship between geologic and hydraulic characterization.

Figure 3: Relationship Between Geologic and Hydraulic Characterization (25)

Geological mapping is concerned with the spacing, orientation, continuity, filling and general spatial distribution of fractures, as well as the identification of rock materials bounded by these fractures. Most aspects of this mapping are not impeded by the degree of saturation. This is true of: surface mapping (82), development of enhanced core recovery methods (53,73), development of improved three-dimensional analysis of visual borehole inspections (50,77), and geophysical mapping (49). For shear wave reflection surveys, the fluid content of fractures will affect the maximum depth of penetration of the survey (86), but does not preclude such testing. The mineralogy of joint fillings could be sensitive to degree of saturation, if hydro-thermal alteration can take place, upon heating of the rock after repository loading. It is commonly accepted that rock temperatures will not exceed 200°C (48). This number is within the range of temperatures for alteration of some clay minerals (55). So, the impact of the degree of saturation on joint fillings will be site specific. Climax can provide generic information on the behavior of clay minerals which exist there. The techniques used to establish joint mineralogy are not impeded by degree of saturation. In summary, the degree of saturation does not affect our ability to improve the methodology for geologic characterization.

As for the extrapolation of data from unsaturated to saturated zones it is not controlled by degree of saturation either. In granitic bodies, the control is rather through the faulting. Commonly, one observes a reasonable homogeneity of jointing within each geological block or structural domain defined as a rock mass region bounded by faults (88). On the other hand, joint set attributes, including orientation, can change from block to block. The question of extrapolation will hinge upon the presence or absence of such faults creating different blocks. At Climax, there is a good correspondence between the quartz monzonite joints mapped in the Piledriver drifts (52), and those mapped in the SFT-C drifts (90) located several tens of meters away in a horizontal plane. At Stripa, Sweden, detailed mapping of the test adits in granite also revealed "a high degree of continuity" of fracture orientations over an area extending several tens of meters horizontally (64). Regarding the vertical direction, the mean attitudes of the three joint sets

at SFT-C and Piledriver are compared in Table 2 to the mean attitudes of the three joint sets mapped on the surface of the quartz monzonite, at the Tiny Tot site. The Tiny Tot mapping was 750 m away laterally from the Piledriver shaft and 420 m above the SFT-C/Piledriver level (52).

Table 2: Comparison of Mean Joint Set Orientations at the Piledriver/SFT-C and Tiny Tot Locations, in the Climax Stock.

	Piledriver/SFT-C		Tiny Tot	
	Strike	Dip	Strike	Dip
Joint Set 1	N32W	22NE	N62W	20NE
Joint Set 2	N64W	Near Vertical	N69W	Near Vertical
Joint Set 3	N35E	Near Vertical	N30E	Near Vertical

The agreement in orientations is quite remarkable over a slant distance of more than 900 metres. This could mean that the jointing is equally consistent, at depth, below the 1400 level.

The ESTP subgroup has recommended that an exploration shaft be sunk at the site of each proposed repository, and that exploration and rock mechanics testing be performed at successively deeper levels from the shaft (18). The rock mass overlying the repository horizon must be characterized to some extent, for proper modeling. If the variability of the site geology and rock mechanics properties is not significant, then the testing performed during shaft sinking would enable a reduction of the testing to be performed at repository level. Tests and exploration at that level would be carried only far enough to confirm, or deny, the homogeneity of the whole site. At a granite site one would expect the homogeneity to be an inverse function of the local faulting.

3.2 In-Situ Stresses and Temperatures

The question of temperature is trivial since the determination of initial values can be made easily whether the rock is dry or wet (70).

In-situ stresses are required input to any structural model of a repository. It is now an accepted fact that horizontal stresses cannot be estimated (43). They must be measured. Recent analysis of tests in granite indicates the same can be true of vertical stresses in plutons (40). So, we must assume that the three-dimensional stress ellipsoid can only be obtained by measurement. Steady progress has been achieved in our ability to measure rock stresses. However, jointed rocks do present special problems, and our stress-measuring technology for granite is only fair (1,20,37,61,79). The problems exist in several areas: the mechanical aspects of the tests, such as sensitivity and reliability of the hardware (44); the difficulty in calibration of some gages (1,20); the difficulties in making true three-dimensional measurements at a point; the influence of jointing on the assumptions underlying the tests (37,40); the frequent need to proceed from strain measurements to stress calculations, using elusive stiffness properties (36); or the requirement for knowing elusive strength properties, as in the analysis of hydraulic fracturing (30). Hence, research and development must be pursued in stress measurements (89). Climax is a possible site for this type of research, considering the stress information which has been developed to date through overcoring in the Hard Hat drifts (63) and Piledriver drifts (95), and, at the SFC-C site, through overcoring (21), undercoring (40), and borehole jack fracturing (40). New test results could thus be compared to results previously obtained, in order to verify new or improved methods.

As for the water, there is no published evidence indicating that partial rock mass saturation will impede stress measurements, unless the hardware is water sensitive. However, some questions may be raised regarding the use of strain relief and hydrofracturing methods in partially saturated rocks. In particular, analysis of hydrofrac stress measurements required a knowledge of rock formation water pressures (30). Currently, there is no technology to measure the negative water pressures which possibly could exist in partially saturated jointed rocks (60). Also, in the case where water pressures did

exist in the course of a strain relief type of stress measurement, one would measure total stresses, rather than the required effective stresses. When the rock permeability is high, drainage will eliminate water pressures around the boreholes and slots used in the tests. With very low permeabilities (9), a possible approach would be to use forced air to dessicate the immediate region around the boreholes or slots. Water pressures would not be expected to build up again, negatively or positively, during the absolute stress measurements which are essentially short-term.

Regarding the spatial variation of stresses in granite bodies, little information is available today (43). Data obtained at SFT-C are concentrated over a distance of a few tens of meters (21,40). The Hard Hat data consisted of secondary principal stresses with the maximum component, at 30° to the vertical, equal to twice the minimum component (63). Those data are too scarce for a useful comparison with SFT-C data. Deep overcoring measurements are underway at Stripa. The results have not yet been published.

3.3 Hydraulic Testing

The initial hydraulic parameters are the position of free water surface(s) and the hydraulic heads at desired locations. In partially saturated rocks, one does not expect to be able to describe these parameters because of their extreme variability. Granitic rocks are also known to exhibit heterogeneous hydraulic conditions governed by underground flow barriers, which may create so-called "perched" water tables. However, these heterogeneities are not expected within the geologic blocks defined previously. In such blocks it is more likely that a definite free surface can be identified. It is commonly accepted that its position in jointed rock can be established in open holes (42,58). At Climax, the UG-2 hole has been drilled down from the SFT-C level to a slant distance of 180 m, giving a vertical distance of 156 m. A steady water level is now being observed in this hole, 144 metres below the floor of the SFT-C drifts (59). Because this result comes from one hole only, it is premature to conclude that a pluton water table has been located. However, this vertical distance is about the one which had been forecast for a water table, on the basis of a regional hydrogeological study (58).

Regarding fluid conductivity, it is becoming clear that the in-situ permeability of crystalline rocks is not predicatable within a factor of 10^5 ; it must be measured by testing (9). The technology exists for measurements on rock samples (83) and joint samples (24,47), in the laboratory. But geometric scale effects make it very doubtful that results obtained on small size samples can be used to predict field conductivities of granite bodies (91). The use of very large cores, 1 metre or so in diameter, is being considered as an alternative (16,93). However such a procedure could be questionable due to the extreme sensitivity of permeability to disturbance of the fractures, which may be associated with core removal and transport.

In the field, there are three options for measuring permeability: borehole tests (84,94,96), block tests (27), and the macropermeability test (62,93). Steady-state and transient injections of water or air in boreholes are the most common procedures. Standard analyses of borehole tests assume an equivalent continuum. Increasing the length of the test chambers between packers sometimes will satisfy this assumption. Standard interpretation also assumes the medium to be saturated. Some analysis is available for partially saturated soils (80) but none for partially saturated jointed rocks. In partially saturated or dry zones, one would first be required to saturate the test volume and confirm its saturation. The research in support of this paper has not revealed any accepted methodology to assess the degree of saturation of hard rock volumes. Block tests may provide a realistic opportunity to try measuring and controlling it. For example, resistivity measurements across the block should be quite sensitive to changes in saturation. On the other hand, the feasibility of controlling wetting by water injection or drying by air injections could be time-constrained by very low fluid conductivities of the granite (9). Also, there is no guarantee that a block size would be sufficient to eliminate the scale effect; that is to provide a "representative elementary volume" (25). The macropermeability test recently conducted in the Stripa granite (62) is an indirect measurement whose analysis is not summarized by an analytical formula, as is the case for borehole tests. Rather, its interpretation relies upon complementary use of numerical models, to calculate an equivalent fluid conductivity of the rock mass around the test chamber. It is a passive test which would not be attempted in a non-saturated region, for lack of ways to analyze it.

At Climax, three campaigns of gas injection tests in boreholes have been reported: in the Hard Hat tunnels (8,54), and between the Piledriver and SFT-C tunnels (2). The last ones gave permeability values comparable to that of intact granite; so it is assumed that the tests did not intersect fractures. The Hard Hat tests were conducted in partially saturated granite and the analysis was based on single phase gas flow; the validity of this approach was not verified.

The discussion leads to concluding that in-situ permeability tests in partially saturated rocks are subject to several questions regarding data analysis. Such tests may be justified under development of new methodologies. But, today, it would be presumptuous to extrapolate their results to saturated conditions. With this in mind, we could try to develop ways of saturating and verifying the saturation of initially non-saturated test blocks, so that the information can be used for fully saturated conditions.

3.4 Thermal Testing

Our current knowledge of the thermal properties of granitic rocks (conductivity, diffusivity and expansion) is based upon both laboratory results (15,31,32,33) and field experiments (26,27,44,48,69,70,71,93). The Climax granite has been host to a preliminary heater test (69) and now to the large scale Spent Fuel Test (70,71). Following the Stripa heater tests, the joints were shown not to be influential in purely thermal predictions (15). Whether the granitic materials are dry, fully saturated, or partially saturated, the measurement of their thermal properties is performed with similar technology and reliability (44,70). As shown in Table 1, the above considerations have led the ESTP Subgroup to conclude that thermo-mechanical tests on hard rock materials, and pure thermal modeling were areas of adequate knowledge today; the only such areas in fact (18).

Regarding the water, the water content in a fully saturated granite at depth is expected to be quite low; one percent is probably an upper limit. The heat capacity and the heat conductivity of this water will not make the thermal

properties of granite in place vary significantly with the degree of saturation. At room temperature, the diffusivity of Barre and Westerly granites, increases by 11 to 15%, from dry to full saturation (32). Although regional flow could be affected by the thermal output of the repository over many years (72), the analysis of heater tests at Stripa, where the granite is certainly wetter than at Clímax, has indicated that conduction is the overriding mode of heat transfer and that convection did not affect temperature distributions in the near field, around the test caverns (15). In addition, temperature gradients are decreasing in the far field. So, the near-field and far-field thermo-mechanical effects from field heater tests should not be very sensitive to degree of saturation. The same discussion applies to heated block tests. In the very near field, one may expect some rock decrepitation around heater holes, unless temperatures are kept suitably low. Current plans call for temperatures to be limited accordingly (89). Regarding the change in thermal properties with depth, current laboratory testing methods can provide the answer for given sets of temperature and pressure.

In summary, there does not seem to be a need for additional pure thermal testing in granite. Further heater tests or heated block tests would be needed only in the context of mechanical and hydraulic studies.

3.5 Mechanical Testing

The deformability and strength of rock masses is best estimated through a combination of field tests and laboratory measurements. The effect of scale on the test results precludes limiting oneself to laboratory testing (39). On the other hand, the laboratory tests must be a part of the estimating process (31). The effect of moisture content can be discussed for material properties such as static and dynamic moduli, long-term strength, and fracture toughness, and for joint properties such as stiffness, strength and dilatancy.

Figures 4 to 6 show a comparison of strength results for three granites in a dry versus saturated condition. In figure 4, it can be seen that the peak strength of Westerly granite in short-term tests is not significantly influenced by saturation(19). In these tests, care was taken to provide enough water for saturation up to failure. The long-term strength, indicated

Relative volume as a function of mean pressure during uniaxial stress loading of dry Westerly granite. Volume decrease observed during hydrostatic loading is plotted for reference.

Relative volume as a function of mean pressure during uniaxial stress loading of saturated Westerly granite containing 0.8% water. Volume decrease observed during hydrostatic loading is plotted for reference.

Figure 4
(after reference 19)

1. Envelope for dry specimens determined from mean normal stress and maximum shear stress
2. Envelope for dry specimens determined from normal and shear stresses and observed failure angle
3. Envelope for saturated specimens determined from mean normal stress and maximum shear stress
4. Envelope for saturated specimens determined from normal and shear stresses and observed failure angle

Figure 5: Strength Envelopes for Dry and Saturated Fine-Grained Granite From the Climax Mine, Colorado (references 66 and 67).

Figure 6: Strength Envelopes for Dry and Saturated Medium-Grained Granite From the Climax Mine, Colorado (references 66 and 67).

by the stress level when reversal occurs in the direction of volumetric strain (6), remains the same in all but the erratic results of the 50 MPa saturated series. In figures 5 and 6, strength envelopes are shown for two granites from another Climax mine -- the one located in Leadville, Colorado. There appears to be only a slight decay in short-term peak strength due to the water saturation (66,67). In another study on Westerly granite (87), the short-term strength decreased by about 11% upon saturation. This result is consistent with other findings on crack growth in silicate rocks (88)

Static and dynamic modulus and Poisson's ratio are shown for the Stripa granite in figure 7 (65). The static modulus tends to decrease with saturation; the change is about 10%. Poisson's ratio stays within 2% from dry to saturated. Dynamic Young's moduli for both granites from Climax, Colorado, are shown in figures 8 and 9 (46,47). There, the dynamic modulus tends to increase with the saturation; the change is around 30%. Altogether the above changes can be characterized as modest; particularly the static values which are the ones used in analysis.

Figure 7: Static and Dynamic Modulus, and Poisson's Ratio for the Stripa Granite (65).

Figure 8: Dynamic Moduli for Dry and Saturated Fine-Grained Granite From the Climax Mine, Colorado (references 66 and 67).

Figure 9: Dynamic Moduli for Dry and Saturated Medium-Grained Granite
From the Climax Mine, Colorado (references 66 and 67).

As for thermo-mechanical effects, almost all the repository rock will be at temperatures below 200⁰ C (48). Strength results for Westerly granite (4) and Charcoal granodiorite (23) are presented in figures 10 to 12, as a function of temperature. Both the tensile and compressive strengths of Westerly granite appear to be insensitive to temperatures up to 200⁰C. The tensile strength of the granodiorite is also insensitive. If the compressive strength of the granodiorite follows the same patterns, the extrapolations on figure 10, between 20⁰C and 200⁰C, should probably be as indicated by dashed lines. In summary, the combination of the above thermal and saturation data indicates that mechanical testing of the granite materials in a partially saturated condition is relevant to their behavior in saturated condition. The test results are not expected to vary drastically. In particular, little variation is expected if the stress levels are kept at or below the onset of dilatancy, to insure long-term strength.

However, the above conclusion does not readily extend to the whole rock mass. In hard rocks, the stiffness and the strength of the rock mass will be governed by the weakest components, i.e. the fractures. The effect of water on the mechanics of joints depends upon the nature of the materials filling the fractures and on the morphology of the fractures (28,29,38). Procedures exist to test geological discontinuities in the field and in the laboratory. But additional improvements are needed such as tests to measure normal joint stiffness (40). In the presence of saturated, clay-filled joints, the degree of drainage in the tests must be controlled, and the in-situ moisture content must be preserved (28). It is common knowledge that water will drastically reduce the shear stiffness and strength of joints which contain clays. However, the differences in stiffness and strength, attributable to the degree of saturation, have no major impact on our understanding of the joint behavior, or on our capacity to test it, or on our ability to model joints.

Rather than attempting to characterize the rock materials and the joints separately, one must use an approach which involves both, over much larger volumes than the laboratory sizes. This can be done through medium- and large-scale field tests, as well as through estimating procedures which incorporate laboratory testing, geologic characterization, and empirical

Ultimate strength versus temperature for charcoal granodiorite. Triangles (Δ) represent specimens heated to 1000°C , cooled, and deformed at 25°C , 50 MPa. Open square ($\square$) represents three unconfined specimens heated to $900-1000^{\circ}\text{C}$, cooled, and then deformed at 25°C .

Figure 10 (reference 23)

- Triaxial compression strength of thermally cycled Westerly granite.

Figure 11 (reference 4)

Brazilian tensile strength versus maximum thermal cycle temperature. Vertical bar denotes the range of results.

Figure 12 (reference 4)

correlations. An example of such integration was recently reported, regarding the in-situ deformability of the Climax granite at NTS (40). Whereas some hard rock deformability tests such as plate, dilatometer, and jack tests must be analyzed with caution (7, 36), there is no published evidence that their results are affected by the degree of rock mass saturation. For the petite sismique test (7,40), it is conceivable that the frequency of shear waves may respond to changes in water content in the fractures (65). Additional tests can be performed at Climax on a generic basis, to improve the usefulness of methods such as the petite sismique, which have shown promise.

As for the in-situ strength of hard rocks, so few field strength tests have been conducted that one cannot judge the saturation effect on their results (39,61). In particular, the data base for hard rocks is almost non-existent. The main concern should be with estimating long-term strength of rock pillars and abutments (6,35,75). Failure will be primarily governed by the joints, but, as in rock slopes, it is quite possible that it could also propagate into rock material bridges. This can occur when the joints are not continuous and/or when their orientation with regard to the principal stresses is such that the rock material itself may fail first, as can be shown with simple models (85). This possibility indicates a need to improve our understanding of discrete fracture propagation in rock (46,74).

Also, little is known of the long-term strength of joints and of the influence of scale on joint properties (3). Improvements in test methodology and analysis are required, to determine important properties such as normal joint stiffness and mean aperture, which are needed in mechanical and hydraulic studies. Few estimates have been obtained for the in-situ normal joint stiffness of granite (40). The expansion of an in-situ data base covering saturated and unsaturated conditions is required to estimate long-term repository stability, because various parts of the repository rock formation will have various degrees of saturation. This testing does not have to await access to a saturated granite mass. Once access is gained, however, shear tests also can be performed in the saturated medium for confirmation of the expected effects of full saturation. While it is not the only possible site, Climax certainly offers an attractive location, because of the geomechanical properties information previously obtained there.

3.6 Modeling

Modeling per se does not fall under the classification of rock mechanics tests. However, it must integrate results from thermal, hydraulic, and mechanical tests (48). It is clear, from the previous discussions, that the presence or absence of water and its degree of saturation will dictate the degree of sophistication to which the models must be conceived. If the analysis of the verification experiments is also complicated by saturation or lack of it, the confidence in the models and their perceived usefulness will be detrimentally affected; so, the impact of the saturation on modeling will be felt both on the algorithms to be developed, on their verification, and on the procedures to obtain required properties for calculation.

It is sometimes said that the sophistication of our models has overtaken our ability to provide the required input. As detailed in recent publications (18,44,48,61), the numerical models, for example, have greatly multiplied and increased in sophistication in the past five years. On the other hand, it is also true that they are seriously deficient, if not totally incapable, in modeling some of the most basic aspects of our problem, such as discrete three-dimensional discontinuities, ubiquitous three-dimensional discontinuities, and three-dimensional failure (61). These last three examples of shortcomings can certainly be remedied without concern for water saturation since we cannot yet model the dry case. Hence, the opportunity to do model verification experiments in a dry or partially saturated hard rock mass should be exploited in full, now. Climax offers a site where new, three-dimensional, models can be compared to the results of sophisticated two-dimensional models (34,41).

3.7 Repository Engineering

Under this heading we can regroup both design and construction which, again, are not rock mechanics tests per se. The design optimization of underground caverns (35,43) is a logical integration of the results of field observations, laboratory measurements, and modeling. Hence, it is really premature to consider design in our present discussion, since we must first resolve issues related to its components. As for hard rock construction, which we take to

include excavation, ventilation, mining systems, and backfilling, much of its technology is certainly well established and fairly insensitive to the details of saturation which we have discussed thus far. The required refinements in construction to increase the reliability of repositories are currently under study in a granitic gneiss (45). No concern has been expressed by the parties involved that the degree of rock mass saturation would detract from the usefulness of the results of that study.

4. SUMMARY

In its Reference and Bibliography sections, which are complementary, this document lists 77 reports of geological and rock mechanics work related to the Climax pluton. Another 70 references cover other site specific and generic information relevant to hard rock waste repositories. The generic and site specific conclusions drawn from this review are summarized as follows:

Characterization:

- There already exists a significant amount of data on the geologic attributes of the Climax Stock, down to the 1400 (SFT-C) level.
- These data show a remarkable consistency of the joint orientations over large vertical distances.
- The geologic characterization process is mostly insensitive to degree of rock mass saturation.
- Climax is well suited as a site for refinement of geologic characterization methods.

Stresses:

- Both vertical and horizontal stresses must be measured in jointed rock bodies. They can not be estimated.
- The Climax stock has been the site of several stress measurements, at various locations.
- The partial saturation of a rock mass may interfere with the analysis of hydrofracturing stress measurements.
- No evidence of water effects was reported in strain relief types of stress measurements at the SFT-C or Hard Hat levels.
- It is not known yet whether uniform horizontal stresses and uniform vertical stress gradients can be reasonably assumed in granite plutons.
- Climax is well suited as a site for refinement of stress measuring techniques, including deep hydrofracturing in a saturated zone.

Hydraulic:

- . Phreatic surfaces can be established from open holes in granitic rock masses.
- . At Climax there is some initial indication that a water table may exist in the pluton, 144 metres below the 1400 level.
- . In-situ permeability of crystalline rock masses is not predictable within a factor of 10^5 ; it must be measured by testing. Its variability can be considerable over short distances.
- . Methods used to estimate this fluid conductivity have included large core tests, borehole tests, block tests, and macropermeability testing. Geometric scale can have an overriding effect on test results.
- . There is no proven technology to analyze in-situ permeability tests in partially saturated jointed rock.
- . There is no proven technology to establish the degree of saturation of a granitic rock mass. Electrical resistivity measurements in hydraulic block tests may be a possible approach. Such an attempt can be performed in the 1400 level at Climax.
- . If successful, the above approach could permit in-situ permeability determination by saturation of an initially unsaturated volume of granite.

Thermal:

- . Both the current methods for thermo-mechanical testing of hard rock materials, and pure thermal modeling, are adequate for repository analysis.
- . In-situ thermal properties of granite are not expected to vary significantly with saturation for a given set of pressure and temperature.
- . The change of granite thermal properties with depth can be properly characterized from laboratory tests.
- . Past and current field thermal tests in a non-saturated region of the Climax stock are adequate for thermal characterization of a saturated region of the stock.

Mechanical:

- The short-term strength, static modulus, and static Poisson's ratio of granite materials are not very sensitive to the degree of saturation, over the range of pressures and temperatures expected in repositories. The long-term strength, indicated by the onset of dilatancy, appears to be even less sensitive.
- For joints, in-situ shear test procedures exist to accommodate the presence of water.
- Direct, large-scale deformability test procedures are not sensitive to the degree of saturation. However, indirect measurements such as the petite sismique may respond to changes in saturation. More generic research is indicated in this area.
- The data base for large scale, long-term and short-term strength of hard rock masses is practically nil. Such information is badly needed to provide repository design strength parameters.
- Because of the previous and current mechanical testing performed there, Climax is an attractive site for future large scale deformability and strength tests.

Finally, Table 3 is an attempt at answering in a concise form the following three questions regarding the Climax granite as host to a rock mechanics facility:

- A: has this type of test been performed in the Climax pluton.
- B: can this testing be performed, in a useful and meaningful fashion, in the partially saturated portion of the pluton.
- C: can this testing be performed, in a useful and meaningful fashion, in a fully saturated region of the pluton.

The table brings out three main points:

- a large amount of rock mechanics R and D already has been performed in the Climax pluton.
- a large majority of the required R and D can be conducted in a partially saturated level; this includes all tests which do not involve hydraulic components.
- access to a deeper, saturated, level would enable a completion of all generic tests outlined.

Table 3. Rock Mechanics R and D and a Climax Facility.

	A	B	C
<u>Geologic Characterization</u>			
Diamond drill core recovery	Yes	Yes	Yes
Enhanced core recovery	No	Yes	Yes
Discontinuities visual mapping	Yes	Yes	Yes
Seismic exploration	No	Yes	Yes
Geotomography	Yes	Yes	Yes
Visual borehole inspection	Yes	Yes	Yes
Rock mass rating (KMR)	Yes	Yes	Yes
Q-Rating	Yes	Yes	Yes
<u>Stress Measurements</u>			
Overcoring	Yes	Yes	Yes
Undercoring	Yes	Yes	Yes
Flat jacks	No	Yes	Yes
Borehole fracturing with jack	Yes	? ¹	? ¹
Hydrofracturing	No	?	Yes
<u>Hydraulic Tests</u>			
Piezometric level	Yes ²	No	Yes
Borehole injection	Yes	?	Yes
Block permeability	No	?	Yes
Macropermeability	No	No	Yes
<u>Thermal Tests</u>			
Heated block test	No	Yes	Yes
Heater array test	Yes	Yes	Yes
<u>Deformability Tests</u>			
Block test	No	Yes	Yes
Borehole jack	Yes	Yes	Yes
Petite Sismique	Yes	Yes	Yes
Tunnel relaxation	Yes	Yes	Yes
Normal joint stiffness	No	Yes	Yes
Shear joint stiffness	No	Yes	Yes
<u>Strength Tests</u>			
Joint direct shear tests	No	Yes	Yes
Pillar strength test	No	Yes	Yes
<u>Modeling</u>			
Thermal analysis 2-D	Yes	Yes	Yes
Thermal analysis 3-D	Yes	Yes	Yes
Jointed flow analysis 2-D	No	No	Yes
Jointed flow analysis 3-D	No	No	Yes
Jointed mechanical analysis 2-D	Yes	Yes	Yes
Jointed mechanical analysis 3-D	No	Yes	Yes
<u>Engineering</u>			
Blast design	No	Yes	Yes
Backfilling and sealing	No	Yes	Yes

¹The reliability in jointed rocks is not established.

²In a downhole from the 1400 level

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