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EVALUATION OF TUFF AS A WASTE ISOLATION MEDIUM*

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ABSTRACT

Tuff is of interest for use as an isolation medium for high heat producing wastes because it provides highly sorptive minerals and suitable thermomechanical properties. Also, tuff is widespread in areas that offer long and deep groundwater flow paths. The occurrence and geologic/hydrologic setting of tuff are discussed. The properties of the rock are discussed and compared with other isolation media. The favorable and unfavorable aspects are presented. Also, unresolved issues are discussed along with the investigative program for addressing these issues.

INTRODUCTION

Two objectives of the Department of Energy's program for the management of radioactive waste are to determine the feasibility of geologic isolation of waste and to provide appropriate sites for waste isolation. The investigations under the auspices of DOE's National Waste Terminal Storage (NWTS) Program address these objectives by using the concept of a "defense in depth," based on an integrated system of barriers starting with the wastes and including engineering emplacement design factors, the host rock and the local and regional geologic/hydrologic setting. In applying the "defense in depth" concept two general views, near field and far field, can be used to study the effects of emplacing waste for geologic isolation. The near field studies focus on the effects of the heat load per canister, short-term time dependence of the waste thermal power, engineered barriers for the canister placement geometry and spacing, and near field thermal/mechanical rock properties. The far field studies consider

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the effects due to the averaged waste emplacement density, longterm time dependence of the waste thermal power, heat transfer due to long-term conduction, convection and water flow in aquifers, radionuclide migration, and far field thermal/mechanical properties. The Nevada Nuclear Waste Storage Investigations (formerly the NTS Terminal Waste Storage (NTS/TWS) Program)² as a part of DOE's NWTS Program is currently investigating the Nevada Test Site (NTS) and adjacent areas for potential repository sites. The NNWS Investigations are actively evaluating locations on NTS by geologic and geophysical exploration and evaluating emplacement media by laboratory and in situ testing. The media being studied include argillaceous rock, granite and tuff. This paper addresses the evaluation of tuff as a host rock for storage of spent fuel or high level waste. The Nevada Operations Office provides the project management for the NNWS Investigations. Evaluation of tuff as an emplacement medium as one of the subtasks in the project is a cooperative effort between Sandia Laboratories and Los Alamos Scientific Laboratory, with the field exploration activities directed by the U.S. Geologic Survey.

GENERAL CHARACTERISTICS OF TUFF

The term tuff is used to describe a class of rocks which is formed by the hot dense debris cloud resulting from the explosive eruption of a volcano. Tuffs are formed by the compaction of the volcanic ash from the cloud. The mode of eruption and emplacement of the ash allows tuff to be divided into two primary types, ash fall and ash flow.

Ash fall tuff is formed when cooled and solidified glass fragments settle from the cloud. Ash flow tuff results from the rapid eruption and spreading over the land surface of a hot dense ash cloud. The rock-forming ash is deposited in thick hot sequences with temperatures high enough for the fragments to be plastic or molten. If the deposition temperature exceeds approximately 500°C, the rock formed may be welded due to compaction and plastic flow under its own weight. The debris from a single eruption may be tens to a few hundred meters thick. The ash fall tuff is generally highly porous and unconsolidated; whereas, the ash flow tuff exhibits a wide range of properties, depending on the degree of welding. The welded tuff is a dense and mechanically strong rock with a relatively high thermal conductivity. Silicic tuff eruptions usually occur in a rapid series. When the magma chamber responsible for these eruptions is emptied, subsidence of a

circular crustal block can occur to form a caldera. A single unit can be formed from a series of ash flow units upon cooling after very rapid, hot eruptions. The thickest units of welded tuff and devitrified tuff (i.e., crystallization of glass fragments) exist within calderas.

Large volumes of silicic tuffs older than 1.5 million years occur in many parts of the western United States. These tuffs are quite abundant in the Great Basin physiographic province and are found distributed in and around numerous volcanic centers and calderas. The Timber Mountain-Oasis Valley caldera complex alone has produced more than 5000 km³ of ash-flow tuff,3,4 which is accompanied by lava flows and ash fall tuff. This complex, which was active from 16 to 9.5 Myr before the present, is composed of as many as six overlapping calderas. This caldera complex lies, in part, on the Nevada Test Site.

Most of the Great Basin consists of closed hydrologic systems with internal surface drainage. Again, the Timber Mountain-Oasis Valley complex lies in a closed hydrologic system which has the added feature that the area did not support lakes during the Pleistocene. Tuff can act either as an aquifer or aquitard depending on the degree of in situ permeability. In general, welded tuff is moderately permeable because of fractures, while nonwelded tuff has low permeability. However, there are many known exceptions to this generalization.

TUFF PROPERTIES

The availability of large volumes of tuff in a favorable hydrologic system is desirable. Coupled with the hydrologic system and long flow paths are the high sorptive characteristics of tuff. The combination of all these factors provides a good barrier against radionuclide migration. These features of tuff have been pointed out by Smyth, et al.⁵ Typical sorption ratios of tuff are compared with other geologic media in Table I.6,7,8,9 Bentonite, as a good sorption medium, has been included in the table as a reference. The sorptive ratios of zeolitized tuff are comparable to those of tuffaceous alluvium and argillite and are generally better than those of granite, salt and basalt. The sorptive ratio of three different welded tuffs are shown in Table II.10

Typical physical properties of tuff are shown in Table III. Since the porosity of tuff is inversely proportional to the degree

TABLE I

Approximate Sorption Ratios for Several Geologic Media (ml/g)

| <u>Elèment</u> | Zeolitized | Tuffaceous Alluvium | Climax <u>Granite</u> | Eleana <u>Argillite</u> | <u>Basalt</u> , | Rock <u>Salt</u> | <u>Bentonite</u> | |
|----------------|------------|------------------------|--------------------------|----------------------------|-----------------|---------------------|------------------|-----|
| Sr | 300 | 200 | 15(5) ^a | 100(200) | 100(200) | 0.1 | 2,000 | |
| Cs | 600 | 7,000 | 400(700) | 1,000(1,000) | 700(300) | 0.1 | 2,000 | |
| Ba | 700 | 5,000 | 100 | 1,000 | * | * | 5,000 | |
| Eu | 6,000 | > 20,000 | 300 | 20,000 | 4 | н. | > 10,000 | 202 |
| Pu | 10,000 | > 1,000 | (5,000) | (300) | (20) | , u | a, | |
| Am | 7,000 | | (60,000) | (3,000) | (200) | # | : # | |
| | | | | | 1550 | | | |

^aValues in parentheses are from RHO-ST-4 (1977):⁸ Non Pre-Equilibrated Water.

| | Densely Welded (Glass, Moderate Zeolitization) | Partially Welded (Devitrified, Low Zeolitization, Microgranite) | Partially Welded (No Glass, High _Zeolitization)_ | | |
|-----------------------------------------|------------------------------------------------------|--------------------------------------------------------------------------|---------------------------------------------------------|--|--|
| | 10,000 | 50 | 300 | | |
| | 20,000 | 200 | 600 | | |
| | 4,000 | 400 | 700 | | |
| | 30 | 200 | 6,000 | | |
| | 200 | 2,000 | 10,000 | | |
| | 200 | 1,000 man | 7,000 - | | |
| Cation Exchange Capacity (MEQ/100 g) | 75 | 2 | 17 | | |
| Surface Area (m ² /g) | 7.5 | 3.3 | 10 | | |

TABLE II Approximate Sorption Ratios at 20°C for Various Welded Tuffs (ml/g)

TABLE III Comparison of Tuff Properties Data

| | Nonwelded Tuff | | Welded | Tuff | | |
|--------------------------------------------|------------------------------------|------------------|-----------------|---------------------|-------------------|--|
| Property | Range | Typical | Range | Typical | Units | |
| Bulk Density | 1.5-2.1 | 1.9 | 2.0-2.4 | 2.2 | Mg/m ³ | |
| Porosity | 25-55 | 35 | 2.0-25 | 10 | Vol% | |
| Water Content | 10-25 | 18 | 2-10 | 6 | Wt% | |
| Thermal Con- | | | | | | |
| ductivity | 0.8-0.4 | 0.6 | 1.2-1.9 | 1.6 | W/m K | |
| Specific Heat | 0.8-1.7 | 1.4 | 0.8-0.9 | 0.85 | kJ/kg K | |
| Linear Thermal | ••• | | 11 | | noying it | |
| Expansion | 12 4- 15 | 1.1 | C 10 | 10 0 | w1 o-6 | |
| Coerricienc | +2 10 -15 | <u> </u> | 0-18 | 12.5 | XIU /K | |
| Youngs Modulus | /-9 | 8 (b) | 23-41 | 30 | GPa | |
| Poisson's Ratio Uniaxial Compressive | <0.1-0.25 | 0.15 | | · | | |
| Strength | 720 | 25 | | 117 | MDa | |
| Toncilo Stwonath | 0114 | 07 | ~ = 4 | 117 | mra MD- | |
| Tensile Strength | 0.1-1.4 | 0.7 | ~~~ | | мра | |
| Permeability | 10 ⁻⁶ -10 ⁻³ | 10 ⁻⁴ | < 1.4 x 10-3 | 10 ^{-5(c)} | darcys | |

(a) Thermal expansion behavior of nonwelded tuff is extremely rate-dependent and highly variable with temperatures.

(b) Range given for nonwelded is for 0 to 200°C; "typical" value might be applicable at 100°C.

(c) In situ permeability data is that of Winograd and Thordarson¹² (1975) as summarized in Smyth, et al.⁵ (1978).

of welding, the welded tuff is more dense than the nonwelded. The porosity range for welded and nonwelded tuff is fairly large. Therefore, high water contents are possible for both types of tuff with nonwelded tuff having the highest values. Nonwelded tuff generally has a low thermal conductivity, and higher heat capacity resulting from the higher water content. Lappin¹¹ has shown that the thermal expansion of welded tuff is not a strong function of mineralogy or porosity over a temperature range from 0° to 500°C. The welded tuff is well behaved; it expands monotonically with increasing temperature, and, to a first approximation, its expansion is rate independent. Thermal expansion of nonwelded tuff, in contrast, is very complex. Significant contraction can occur as water is evolved. The water comes from two sources, that present in pores and that incorporated in the mineral structure. The expansion/contraction of nonwelded tuff is a function of both porosity and mineralogy and has a marked rate dependence.

The mechanical behavior of the two tuff types also is quite different. As shown in Table III, the uniaxial compressive strength of welded tuff is much greater than for nonwelded tuff. Preliminary tests done by Wawersik¹² and Olsson¹³ indicate that welded tuff behaves as a linear elastic material until brittle failure occurs. Tests were run for ambient and 200°C temperature. The results showed that for these temperatures, the strength is essentially temperature independent. The nonwelded tuff does not act as a linear elastic material because of the higher porosity. The strength of the nonwelded tuff is less than the welded tuff and reduces with increasing temperatures.

The in situ permeabilities are also compared in Table III.¹⁴ It should be noted that the matrix permeability of welded tuff is very low but because of the brittle nature of the rock, fracture permeability does exist and makes up the higher values in the range stated. The nonwelded tuff matrix permeability can be quite low also, with the higher values also showing a contribution from fractures.

The properties of the welded and nonwelded tuff are compared with typical property values of other possible waste host media in Table IV. The welded tuff properties fall within the range of values given by other rocks with the exception of water content which is higher. The nonwelded tuff as properties (e.g., heat Conductivity and thermal expansion) which are lower in value or more complex than for the other rocks.

TABLE IV

Comparison of Material Properties Data for Six Rock Types Being Studied as Potential Repository Media

| Property | Welded <u>Tuff</u> | Nonwelded Tuff | <u>Basalt</u> | <u>Granite</u> | Salt | <u>Argillite</u> | Units |
|-------------------------------|-----------------------|-------------------|---------------|----------------|-------------|------------------|---------------------------|
| Bulk Density Porosity | 2.2 10 | 1.9 35 | 2.9 0.5- | 2.6 0.5-2 | 2.2 0.5- | 2.6 9 | Mg/m ³ Vol% |
| Water Content Thermal Con- | 6 | 18 | 13 | 0.8 ii | 0.25 | 3.5 | Wt% |
| ductivity Specific Heat | 1.6 | 0.6 1.4 | 1.5 1 | 4 | 7 1 | 2.5 1 | W/m K kJ/kg K |
| Linear Thermal Expansion | | | | | | | -6 |
| Coefficient Youngs Modulus | 12.5 30 | 8 | 5.4 70 | 7 70 | 40 7 | 12 7 | X10 °/K |
| Ratio Uniaxial | | 0.15 | 0.26 | 0.25 | 0.4 | 0.35 | |
| Strength | 117 | 25 | 200 | 200 | 30 | 40 | MPa |
| Strength | | 0.7 | 14 | 1.4.0 | NA | 1.9 | MPa |

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<u>Note</u>: Materials data for basalt, granite and salt are from Agapito, Hardy, and St. Laurent, 1977.¹⁵ Materials data for argillite are from Lappin and Cuderman, 1978.¹⁶ Water contents for granite and basalt are from Clark, 1966.¹⁷

MODELS OF TUFF IN THE GREAT BASIN

Multiple Barrier Model

The tuff in the Great Basin may have a good multiple barrier system to prevent radionuclide migration to the biosphere. A conceptual geologic cross section of the principal geologic features of the southwest region of the Nevada Test Site,¹⁸ Fig. 1, illustrates the possible barriers associated with assumed repository locations. All locations are in welded tuff except the one shown in granite. The locations in the caldera on the right are in a stable resurgent dome. The locations towards the center of the figure are outside the volcanic craters in the outer ring structure of the caldera. In all of the cases considered, the hydrologic flow traverses long paths through zeolitized tuffs before passing through the carbonate aquifer toward the ground water discharge points south of the NTS.

Thermal Modeling

A thermal analysis using the stratigraphy of the two possible repository locations shown in the center of Fig. 1 was performed to determine what burial density might be possible. This location is approximately that of the Yucca Mountain exploratory hole. The analysis used a one-dimensional model for both ten-year-old high level waste and spent fuel and was based on an assumed maximum allowable temperature for the location. The results are shown on Fig. 2 for three different values of geothermal flux. The geothermal flux value for the Yucca Mountain area is approximately 1.56 μ cal/cm²sec. The 711 meter horizon is the depth at which the partially welded tuff of the Bullfrog Member of Crater Flats tuff begins.

The curves represent the maximum permissible power density at a given depth into the Bullfrog member for which far field boiling of water does not occur. The boiling temperature was assumed to be determined by the hydrostatic pressure of a standing water column with its base located at the repository horizon and its top located at the static water level (46.5 meters). This assumes that the in situ permeability is sufficient for communication over the entire length of the water column. The other assumption was that the repository is closed. Therefore, the results apply to a time after the operating phase. Under these assumptions the maximum allowable power densities for the Yucca Mountain area for an assumed 760 meter repository depth are 150 kW/acre for HLW and 125 kW/acre for SF(U0₂).





SUMMARY

The information presented in this paper allows a preliminary evaluation to be made of tuff as a disposal medium for nuclear waste. The evaluation is summarized by defining the favorable aspects, unfavorable aspects and unresolved issues for tuff. These aspects and issues have been defined collectively by participants in the project from Sandia Laboratories, Los Alamos Scientific Laboratory, and the United States Geological Survey and are summarized below. Also, a brief statement is given describing the needed investigations as defined by the NNWS Investigations to address the unfavorable aspects and unresolved issues. The basic conclusion is that tuff should be investigated further as a waste disposal medium.

Favorable Aspects

1. Sorptive properties--The most attractive feature of tuff as a waste-isolation medium is the natural barrier to potential radionuclide migration due to favorable cation sorption characteristics.

2. Occurrence in regions offering multiple natural barriers--Sequences of welded tuff, zeolitized tuff and tuffaceous alluvium in the Basin and Range Physiographic Province provide a natural barrier system or "defense at depth" in an arid to semi-arid region which is dominated by regional ground water flow systems having long deep flow paths and a small flux. The hydrologic flow system within the Great Basin Section of the Basin and Range discharges into closed drainage basins.

3. Existence at appropriate depths--Tuff exists in sufficient thicknesses and at suitable depths to provide protection of potential repository sites from possible exposure by erosion.

4. Thermomechanical properties of welded tuff--Welded tuff has suitable thermomechanical properties for waste isolation because the values of the thermal conductivity, heat capacity, thermal expansion and strength are similar to other igneous rocks such as granite and basalt. Preliminary calculations indicate that tuff can dissipate the thermal loads associated with either spent fuel or high level waste.

Unfavorable Aspects

1. Potential for volcanism--Tuff occurs in the Basin and Range province which includes some areas exhibiting relatively recent volcanism. It is possible, with geologic studies to identify sites of past volcanism where renewed activity is highly improbable, for example, within calderas which have completed their evolutionary cycle, in regions containing only very old volcanic rocks or in areas that are distant from deep-seated structures that may serve as magma pathways.

2. Seismicity and faulting--The regions where tuff is widespread and regions where there is a history of tectonic activity. Because the region is seismically active, location of active faults and seismically inactive areas are more easily defined. The ability to predict ground motion is enhanced by the accumulation of an abundant local seismic data base. Breaching of a repository by a fault is a concern in seismically active areas, but the general degree of hazard can be evaluated for specific areas.

3. Fracture permeability of welded tuff--Welded tuff may be highly fractured due to cooling joints and/or tectonic stresses, potentially creating moderate to high fracture permeability. This fracture permeability can be avoided by selecting sites where the fractures are closed either by the deposition of minerals or by alteration products. Avoidance of open fractures might be unnecessary where a body of welded tuff is hydrologically isolated by enclosure in less permeable, zeolitized tuff.

Unresolved Issues

1. Water content--The effects of heat and radiation on a medium that may contain as much as 10 percent by weight of water are unknown. The water in tuff is present in pores and joints, and adsorbed and chemically bound in hydrated minerals. Hydrostatic pressure increases, possibly leading to hydrofracture, and the potential for near-canister convective circulation in joints are issues that need to be resolved. Pervasive hydrothermal alteration of the minerals could release water or change mechanical, thermal and hydraulic properties of the host rock. Together with the effects of radiolysis, this alteration might also release noncondensible volatiles. Although results of preliminary and unsophisticated experiments offer

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hope that the dominant zeolites are stable for short periods in thermal environments to 500°C, geologic evidence suggests that they may be metastable above approximately 250°C.

2. Definition and modeling of complex bodies and media--The mode of tuff genesis produces deposits that are vertically and laterally variable. Furthermore, in their region of dominant occurrence, tuff bodies are commonly displaced by small faults even in relatively stable structural blocks. Therefore, our capability to identify a mass that is sufficiently large to host a repository involves great reliance on the continued development of surface and subsurface geological and geophysical techniques. The geologic complexity of tuffs will require sophisticated modeling of the thermomechanical response of a repository and its enclosing volume. At the present time, the preliminary lithologies have been modeled and the thermophysical property data base has been initiated but is as yet inadequate.

3. Field identification of enclosed welded tuffs--The few field investigations conducted to date have not identified occurrences of welded tuffs sufficiently enveloped in zeolitized tuffs to provide a thermally stable host with a continguous, downgradient sorptive mass.

4. Resource conflicts--metal ores and other potentially valuable minerals are associated with some tuff deposits. The ores are believed to be related to hydrothermal solutions emanating from the magma responsible for the volcanism. Therefore, potential zones of mineralization must be identified and evaluated during exploration for repository sites. Additionally, any siting activities must be cognizant of the resource value of ground water in arid and semi-arid regions.

The Nevada Nuclear Waste Storage Investigations are currently addressing the issues and unfavorable aspects for tuff as stated above. The water issue is being studied by both laboratory and field tests. The phenomenological studies and accumulation of a data base for tuff is being studied in the laboratory and the field. An existing mine is available in both welded and nonwelded tuff with a nominal 430 meter overburden for conducting in situ tests. An extension of the mine is being designed for an in situ laboratory to conduct rock mechanics and radionuclide migration experiments in an in situ environment.

In summary, there are important reasons for a continued interest in tuff. First, tuff assemblages provide both highly sorptive minerals and suitable thermomechanical properties. Second, tuff is widespread in areas that offer long and deep ground water flow paths. These factors are significant elements in the concept of multiple natural barriers, which traditionally has been considered desirable for successful waste isolation. Although there are significant potential difficulties and unresolved issues associated with radioactive waste isolation in tuffs, the unfavorable aspects are all site dependent, and both the unfavorable aspects and unresolved issues appear surmountable.

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