Contractor Report

Permanent Markers Materials Analysis

Waste Isolation Pilot Plant
Carlsbad, New Mexico

August 31, 2000

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Prepared for:

Westinghouse Government Environmental Services Company, LLC
Waste Isolation Division
P.O. Box 2078
Carlsbad, New Mexico 88221

Prepared by:

John Hart and Associates, P.A.
2815 Candelaria Road, N.W.
Albuquerque, New Mexico 87107
(505) 344-7868

602 Harkness Road
Carlsbad, New Mexico 88220
(505) 628-0865

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1.0 Introduction

The U.S. Department of Energy (DOE) is implementing a program of passive institutional controls (PICs) for the Waste Isolation Pilot Plant (WIPP) in response to U. S. Environmental Protection Agency (EPA) regulations 40 CFR 191.14(c) (EPA, 1993) and 40 CFR 194.43 (EPA, 1996) and in accordance with the EPA Certification Decision (EPA, 1998). The purpose of the PICs program is to minimize the potential for inadvertent human intrusion into the repository by documenting the dangers of the repository and by permanently marking its location. The EPA regulations specify that radioactive waste disposal systems must be designated by multiple PICs including permanent markers, long-term records and "other PICs."

The DOE Carlsbad Area Office (CAO) has prepared a PICs implementation plan to facilitate the overall PICs program. The PICs implementation plan is supported by three additional "lower tier" documents, each corresponding to one of three elements that comprise the overall PICs program. These documents are:

> Passive Institutional Controls Records Management Implementation Plan,
> Passive Institutional Controls Awareness Triggers Implementation Plan, and the
> Passive Institutional Controls Permanent Markers Implementation Plan.

This report supports the third of these three plans by documenting assessments of marker materials included in the reference design and as well as potential alternative materials.

The current design for the permanent marker system at the WIPP includes five new markers systems. These systems are:

- Large Surface Markers
- Small Subsurface Markers
- Berm
- Buried Storage Rooms
- Information Center

The permanent markers will be constructed of materials that will be selected through an evaluation process. Candidate materials identified in the Compliance Certification Application (CCA) (DOE, 1996) reference designs will be evaluated against performance criteria described in the Permanent Markers Implementation Plan. The evaluations will be performed using methods identified in the Permanent Markers Testing Program Plan.

Information obtained from literature reviews is provided in this report and has been used to refine the evolving candidate materials lists. The literature review also provides information supporting preliminary evaluations of the candidate materials. This information also is of value in planning laboratory and field tests that will provide additional information necessary to make final marker materials selections.

1.1 Study Objectives

Many materials, both natural and man-made, have been suggested over the years for consideration as permanent markers. It is neither feasible nor desirable to test all of these materials; much information exists to support preliminary materials recommendations. The results of this literature review support determinations of the materials that most likely satisfy the design and performance requirements for each marker system and warrant testing to confirm their selection. The objectives of this literature review are:

- to identify materials that could be suitable for each marker system,
- to evaluate these materials based on information available in the literature and from expert opinion,
- to recommend materials that appear to be best suited for specific marker applications, and
- to identify tests most appropriate for the screening phase of the testing program.

1.2 Study Methods

The work represented in this report was performed primarily as a literature review using information available through printed media (technical journals, text books, research reports), electronic media (worldwide web sites), and technical expert consultation. Inquiries were made to materials vendors concerning the availability of their materials and specifics pertinent to the material properties. Consultants and researchers with materials expertise assisted in directing the research and suggesting alternative materials and identifying those properties most important to marker performance.

1.3 Report Organization

Material design criteria are described in Section 2.0 of this report. Although already discussed in the Permanent Markers Implementation Plan and Permanent Markers Testing Program Plan, the material design criteria are repeated in this section to provide the reader with an overview understanding of the objectives for the permanent markers. The materials specified in the PICs reference design and the material properties relevant to permanent marker performance are identified in Section 3.0. Alternative materials that have been identified both before and during this literature review are described in Section 4.0. Section 5.0 presents the analysis of materials vis-à-vis the design criteria and the comparison between candidate materials for each marker component. The last section of the report, Section 6.0, provides conclusions and recommendations for the first level of material selection and testing in the screening phase of the permanent markers testing program.

2.0 Material Design Criteria

The draft Permanent Markers Implementation Plan (August 31, 1999) documents the design bases for the permanent markers; the design bases consist of performance objectives and performance criteria. The performance criteria are as follows:

- Alert a visitor to the existence of the site,
- Convey a warning of danger,
- Inform the visitor about the nature and degree of danger, and
- Endure in form and function for the longest time possible.

The first three of these performance criteria relate to the form and message conveyed by the markers and are affected in part by the ability of the marker materials to be detected and inscribed. However, the fourth performance criterion relates directly to the marker materials, in particular the durability, strength, and intrinsic value of materials. To satisfy the performance criteria, design criteria have been established (see Section 3.1.3 of the implementation plan), and some of these design criteria apply to the markers materials. Specifically, the following material design criteria are identified in the implementation plan.

(1c) - To alert the visitor to the existence of the site, the material must be obviously anomalous with respect to the natural features (i.e., materials) of the site. The marker material must be detectable.

(3a) - To inform a visitor about the degree and nature of the danger, markers must be able to be inscribed with symbols and letters. For the purposes of this report, this concept is called “inscribability.”

To endure in form and function for the longest time possible, marker materials must be:

(4a) - as resistant as possible to chemical and physical weathering, dissolution, and erosion. The marker material must be durable.

(4b) - able to withstand all foreseeable extreme natural conditions including earthquake, wind, flood, and fire. The marker material must be durable and strong.

(4c) - able to remain stable in form, location, and position. The marker material must be durable and strong.

(4d) - able to resist vandalism. The marker material must be durable.

(4f) - lacking in economic value to be of no interest for scavenging and salvage. The marker material must have low intrinsic value.

Material properties and associated aspects (detectability and inscribability) as related to the design criteria will be explained in the following subsections. It is apparent from the design criteria that durability is the most important property required for the markers materials.

2.1 Durability

Durability is the ability of a material to resist destruction by a number of different forces or mechanisms. Therefore, durability is not a single property but rather a composite of several properties, the combination of which varies with the materials and their intended applications. In general, durability of any candidate marker material is a combination of composition and texture, density, hardness, toughness, erosion resistance, and weathering resistance. The importance of each of these durability properties varies from one marker application to another and from material to material.

Composition and Texture - Composition, or the chemical and mineralogical makeup, is fundamental to material durability. Composition affects the chemical stability of the material and its response to thermal and mechanical stresses, regardless of the other macroscopic properties of the material. Texture is the relationship between crystals or grains within the material, the micro-fabric. Texture affects the amount of surface area per unit volume of material, which may be important in determining how a material will fracture, its strength, and its rate of weathering.

Density - Density is the mass per unit volume of a material. For a solid of a single composition, density also indicates the amount of porosity in the material; i.e., the difference between the specific gravity of the material constituent and the density of the material mass is the pore space in the material. In solids composed of more than one constituent, density indirectly reflects the composition of the material; for any given porosity higher density indicates heavier elements in the material's composition. Therefore, density must be evaluated in the context of both composition and porosity. In general, denser materials are harder and more resistant to weathering and erosion.

Hardness - Hardness is the resistance of a material to penetration of its surface. It is an important durability property because hardness is needed to resist vandalism, accidental impacts, and erosion. However, in the context of this report, hardness is used specifically in reference to resistance to instantaneous, high-energy impact; resistance to erosive forces is considered separately. Hardness is measured differently for rock and concrete than for completely man-made materials such as ceramics and polymers, and each type of hardness testing has its own scale of measurement.

Toughness - Toughness is the resistance of a material to extension of a crack, in effect the opposite of brittleness. It is an important property of ceramics, composites, alloys and other man-made materials that are essentially homogeneous and isotropic, but is not usually used in reference to rock or concrete.

Erosion Resistance - Resistance to erosion may be viewed as a type of hardness, but in this study erosion resistance refers to resistance to mechanical abrasion by fluids (water and air) or by solids suspended in fluid, an ongoing or intermittent process rather than an instantaneous impact event. This distinction is particularly meaningful for heterogeneous materials like rock and concrete, where erosion can work at the crystal or particle level to differentially loosen or remove durable larger particles from a less resistant fine-grained matrix. Several types of abrasion tests can be used, depending on the material to be tested.

Weathering Resistance - In the context of this report, weathering is limited to ongoing or intermittent processes other than erosion that involve a chemical or a mechanical breakdown of the material in place. Chemical weathering includes oxidation, hydration, dissolution and any other process that involve changes in the composition, solubility, or phase of matter. Mechanical weathering includes freeze/thaw, shrink/swell or other cyclic alterations that induce fracturing, disaggregation, or volume changes in the material. Chemical and mechanical weathering processes are so commonly interactive that they are addressed under one heading for this report. Resistance to weathering is a composite of properties that maintain the chemical composition and fabric of the material. Exfoliation is a particular type of weathering process in which thin sheets of rock successively split away from the rock mass in a manner resembling an onion skin. The process is attributed to differential expansion and contraction of the minerals within the depth below rock surface affected by diurnal temperature changes (Whitten and Brooks, 1972).

2.2 Strength

Strength is resistance to nonrecoverable strain, measured by the stress needed to cause a specified amount of yield (yield strength) or rupture (ultimate strength). The type of strength important for any marker depends on the intended function of the marker and the types of loads that it must sustain. Strength is a critical property only for those marker components that must support loads other than their own weights, specifically, the berm and the walls and roof of the information center and the buried storage rooms. All other markers, including the large surface markers, have only their own weights to support and only relatively minor externally imposed stresses.

In the berm structure, the strength of soil or rock material after it has been compacted (mechanically densified) is important in resisting compression (manifested as settlement) and shear stresses due to the weight of overlying materials and cyclic shear stresses due to earthquake-induced ground motion. The deeper the soil or rock layer within the berm, the higher the stresses imposed and the strength required.

The walls and roofs of the information center and the buried storage rooms will be required to carry stresses imposed by the weight of the materials themselves as well as externally imposed loads from wind or overburden as well as earthquakes. Both compressive strength and flexural strength of wall and roof materials must be adequate to carry the maximum expected loads with a substantial factor of safety.

Strength is tested by methods that induce the type of stress (e.g., compressive, tensile) that the material is expected to experience. Although each test for a type of stress is similar from one material to the next, there is a specific test procedure and apparatus for each type of material. However, for all marker materials, compressive strength testing will be needed, using the relevant procedures for unconfined, uniaxial loading conditions, the conditions that will prevail in the marker environments.

2.3 Inscribability

As used in this study, inscribability includes any means of imposing symbols and letters into the marker material. Inscription by carving or sandblasting into a rock surface is the usual method, as envisioned in the reference design, but for the materials analysis the term is used much more broadly. The only constraint is that the messages and symbols required by criterion 3a (see Section 2.0) must be placed into the material, not just applied to the surface. Tests for inscribability will need to try to create inscriptions using actual inscription methods and equipment.

2.4 Detectability

The detectability criterion applies to all markers, by definition, but it is important in materials selection only for those markers that will be buried. Small subsurface markers must be easily recognizable as anomalous when they are uncovered by excavation. Magnets or electromagnetic telltales must be detectable with aboveground magnetic detectors. Radar reflectors must produce a clearly distinct radar anomaly on airborne radar surveys. All other markers must be identifiable by the human eye, a requirement more dependent on configuration than on material of construction.

2.5 Intrinsic Value

Any object that exists in a remote location without active maintenance or security is subject to removal. Large size and weight are obvious deterrents to removal of permanent markers, but if the value of the marker or its material is great enough, it should be expected that someone will be motivated to use any means available to remove the marker intact or in pieces. Therefore, the best deterrent to removal is to use materials that have low intrinsic value. Material value can be readily determined from existing and projected market costs.

3.0 Reference Design Materials

Reference designs for the permanent markers systems are presented in the CCA. Some of the reference designs are more developed than others, with one or more materials proposed. The opportunity exists within the framework of the CCA for review of the reference designs and materials selection with opportunity to propose alternatives as the design review process advances. This section presents an evaluation of the reference materials in relation to the design criteria. Other factors assessed include material availability, transportation and construction logistics, and relative cost. Although cost is not a factor in the selection of materials during the initial screening stage, it is reasonable to consider the relative cost of materials at this point so that materials having extremely high costs without commensurate benefit can be eliminated or given lower priority in future evaluations.

3.1 Granite

Granite is the reference-design material of construction for the large surface markers, information center, and buried storage rooms. Granite was suggested in part because of its history of use in monument construction, its apparent strength and durability, and its availability from several operating quarries around the country.

3.1.1 Granite Properties

Granite is an intrusive igneous rock with visible, well-formed mineral crystals (phaneritic texture) composed of quartz, sodium and potassium feldspars, biotite and accessory minerals. These minerals crystallize from the parent magma in the latter stages of slow cooling, making them more stable in surface environments than minerals that form at higher temperatures in the earlier stages of cooling. Crystals are fused together tightly, leaving very little porosity. The phaneritic texture provides less surface area exposed to weathering and erosion, compared to finer grained materials.

The following descriptions and values are related to material properties and are representative of granite from various sources.

- Density – Granites vary in density depending on composition but have average specific gravity of 2.7 and bulk density of 165-170 pcf (Carmichael, 1989).

- Hardness – The L-hammer hardness of granite ranges from 37 to 100 (dimensionless units). Although this range is wide, it compares favorably with the hardness of other rock types (Carmichael, 1989).

- Strength – Uniaxial compressive strength of granite ranges from 17,000 psi to 104,500 psi (Carmichael, 1989).

- Weathering Resistance – Indices of weathering resistance of granite include porosity and absorption. Fresh granite typically exhibits low values of each, less than 2% and less than 1%, respectively (Cold Springs Granite, 2000; Franklin and Dusseault, 1989). Although these values indicate high resistance to weathering of granite fragments, the phenomenon of exfoliation is widely observed in granitic rock masses.

- Inscribability – Given the widespread use of granite as an ornamental and monument material with inscriptions, there is no need to test its inscribability. The relevant question is the relative ease of inscription of granite versus other materials.

- Detectability – Detectability for granite and other nonmetallic materials is dependent primarily on marker size and configuration (not relevant to this study) but also on readily visible contrasts in color, composition and texture between the marker material and surrounding materials. Such contrasts can be evaluated through experimentation or field studies.

- Intrinsic Value – Monument-quality granite is more valuable than most rock and clearly more valuable than rock commonly found at the surface in southeastern New Mexico.

3.1.2 Use of Granite

Granite is an obvious material choice for the large surface markers and also for small subsurface markers because of its hardness and strength, availability, and history of use in similar applications. However, exfoliation could be a serious problem for the large surface markers, causing loss of the inscription in the rock surface.

Use of granite for large surface markers and for the wall and roof panels of the information center and buried storage rooms is problematic for logistical reasons. The size of the panels presents a challenge to the quarry operator to cut, finish, handle, load and ship large slabs without damage or without activating incipient fractures. Even though the panels would be cut from large blocks of granite that visibly seem to contain no fractures, the rock may contain incipient fractures. The rock fabric is weaker and more susceptible to failure along these fractures.

It is unlikely that large slabs of granite used to construct walls and roof panels would be free of these invisible incipient fractures. These fractures would substantially reduce the strength of the load-bearing panels and the ability of the roof panels to sustain bending movement. Consequently, either a redesign of the buildings is needed to reduce required dimensions and structural loads or other materials should be considered for the load-bearing components.

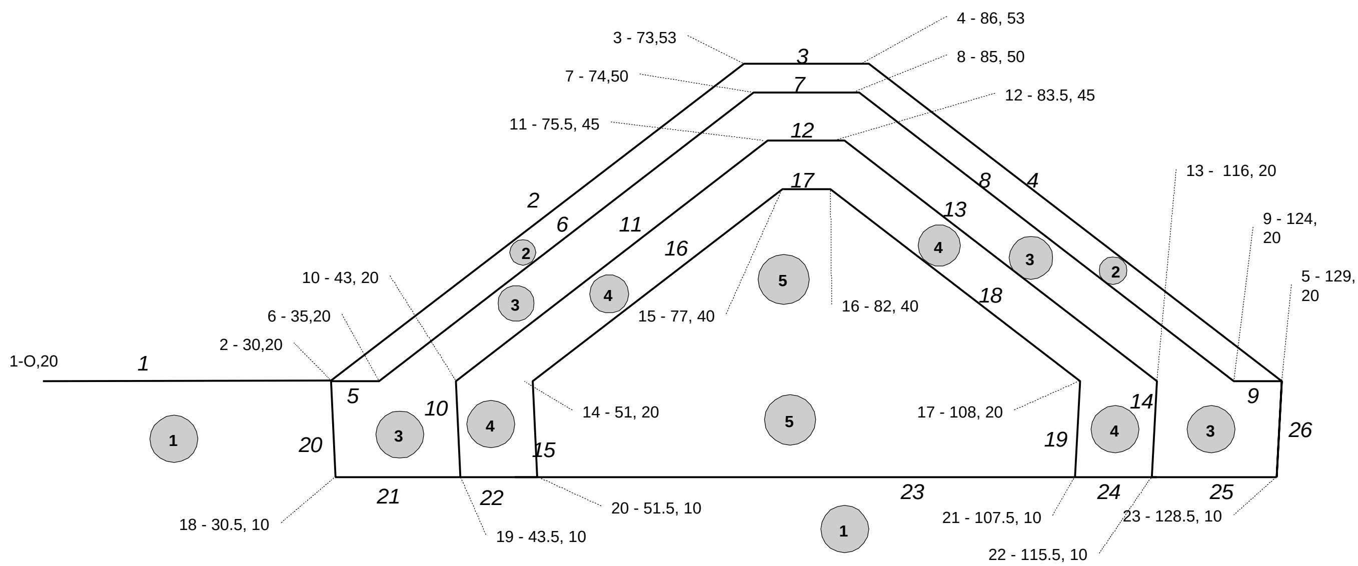
3.2 Local Earth Materials

The reference design for the berm calls for it to be constructed of crushed salt, native soil, caliche, and rock from sources on or near the WIPP site. The crushed salt, presently stockpiled on site, was excavated to form the underground workings at repository level. Native soil is the natural soil of the WIPP site consisting of sand, silt, and some clay. Caliche occurs at shallow depth across the WIPP site and surrounding lands. Rock in the berm will be used for erosion protection so it must be durable; such rock is not found on the site but sources are located within 100 miles of the site. Each of these materials has been evaluated for their proposed use in construction of the berm. The material evaluations are presented in the following subsections.

3.2.1 Salt

The salt excavated from the underground workings consists primarily of halite (sodium chloride) with some potassium salts and anhydrite (calcium sulfate). Salt was included in the reference design to use a material already available in a large quantity at the WIPP site and otherwise not commercially valuable. However, halite is very soluble and has low strength. Sandia National Laboratories (SNL) tested compacted crushed salt to determine its properties for use as backfill material in the underground workings (SNL, 1999). The SNL studies determined that salt permeability was extremely low, about 10^{-17} cm/sec, under laboratory test conditions of 145 psi confining pressure, dry density of 130 pcf (or about 90 % of the theoretical maximum), and porosity of 10-12 %. These results would appear to support a prediction that a salt core in the berm would be functionally impermeable and not susceptible to penetration and consequent dissolution by water. However, the laboratory test conditions are ideal and much different from those that could be achieved in the field using heavy earth working equipment. Typically, field-compacted earth materials can be compacted to densities of up to about 75% of theoretical maximum, or about 98 pcf for salt, leaving porosities of at least 25% (Terzaghi et al, 1996). The confining pressure of the salt core in the finished berm would be 8-25 psi, much less than that used in the Sandia tests. Consequently, a salt core would be less dense and more permeable than would be predicted based on the Sandia results.

Long-term performance criteria 4a and 4c (see Section 2.0) require the berm to be durable and stable; i.e., to be long lasting and structurally sound. To predict the structural performance of compacted crushed salt in the core of the berm, as proposed in the reference design, stability analyses were performed using the computer code SB Slope (Geosystems, 1994). Results of these analyses are illustrated on Figures 1 and 2. The stability analyses predict that the reference-design berm with its salt core would be unstable (factor of safety of less than 1.0 against slope failure by rotational displacement) under both static and pseudostatic (earthquake of 0.1g peak



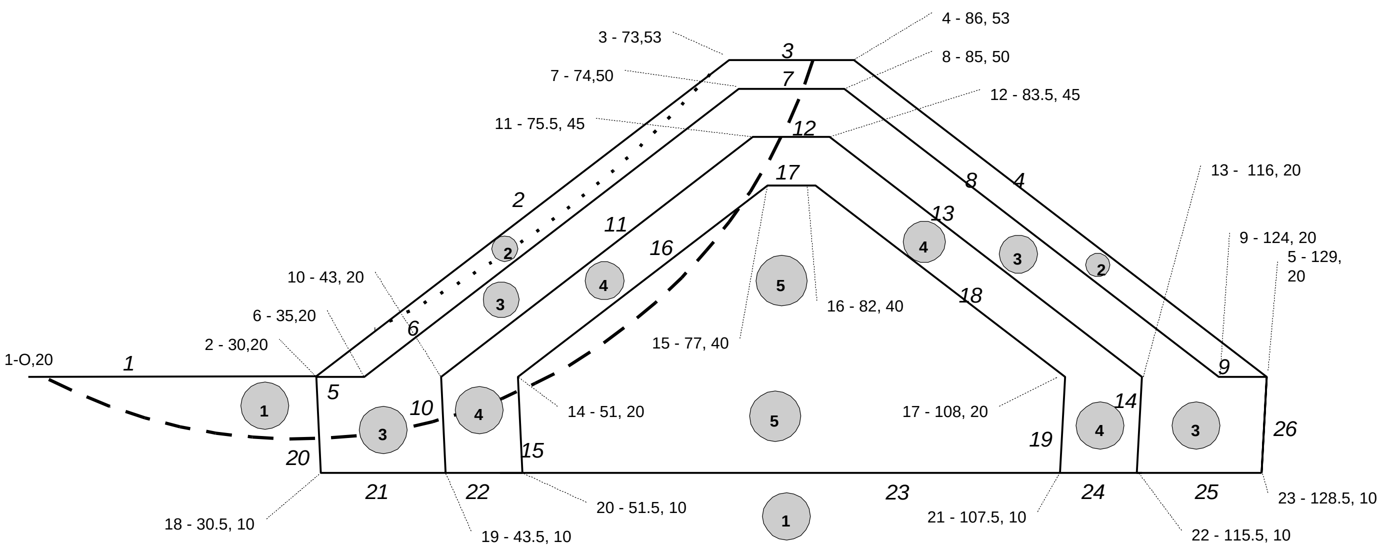
	SOILS	UNIT WT. PCF	FRICTION ANGLE	COHESION PCF
1	NATIVE SOIL	110	25	0
2	SOIL/RIPRAP	140	30	110
3	RIPRAP	107	35	0
4	CALICHE	135	30	0
5	SALT	112	11	110

POINT	X	Y
1	0	20
2	30	20
3	73	53
4	86	53
5	129	20
6	35	20
7	74	50
8	85	50
9	124	20
10	43	20
11	75.5	45
12	83.5	45
13	116	20
14	51	20
15	77	40
16	82	40
17	108	20
18	30.5	10
19	43.5	10
20	51.5	10
21	107.5	10
22	115.5	10
23	128.5	10

LINE	L	R	SOIL
1	1	2	1
2	2	3	2
3	3	4	2
4	4	5	2
5	2	6	3
6	6	7	3
7	7	8	3
8	8	9	3
9	9	5	3
10	10	19	3
11	10	11	4
12	11	12	4
13	12	13	4

LINE	L	R	SOIL
14	22	13	3
15	14	20	4
16	14	15	5
17	15	16	5
18	16	17	5
19	21	17	4
20	2	18	1
21	18	19	1
22	19	20	1
23	20	21	1
24	21	22	1
25	22	23	1
26	23	5	1

Figure 1 - Material And Configuration Parameters Of Reference Design berm



FAILURE SURFACE WITH LOWEST FACTOR OF SAFETY (0.76)
UNDER STATIC LOAD CONDITIONS

FAILURE SURFACE THROUGH CORE WITH LOWEST FACTOR OF SAFETY
UNDER STATIC LOAD CONDITIONS -- 0.88 WITH SALT CORE, 1.27 WITH SOIL CORE

Figure 2 - Reference Design Berm Stability Analysis

ground acceleration) load conditions. The calculated minimum factor of safety for a failure surface through the salt core is 0.88 for static load conditions and would be even lower with earthquake loading. The likely failure surface passes partly through the salt core (Figure 2). If the side slopes of the berm are reduced to a 0.33 grade (3H: 1V) as shown in Figure 3, the pseudostatic factor of safety is still too low, 0.92 (Figure 4). In the reference-design configuration where soil is used in place of salt (see Figure 2), factors of safety are substantially higher, 1.27 for soil core versus 0.88 for salt core, clearly demonstrating that salt lacks the strength needed in the core of the berm. The safety factor with a soil core and 0.33 grade is 1.54 under static load conditions.

Another factor that influences the structural performance of the berm is settlement. All non-indurated earth materials are subject to settlement, generally resulting from densification of material. In typical earthfill construction practice, earth materials are mechanically compacted to increase the fill density, increasing its strength and minimizing its settlement potential. If a fill material is soluble, dissolution can create voids that not only reduce the material mass strength but also make the material susceptible to additional settlement. Such settlement can be non-uniform and large enough to increase the fill's susceptibility to erosion, intrusion by burrowing animals, and structural failure.

3.2.2 Native Soil

The native soils at the WIPP site consist of sand, silt and clay derived from weathering of local rock, alluvial deposition from small streams, and from more recent deposition of windblown sediments. The predominant soil type varies from place to place across the WIPP area but fine sand in low vegetation-stabilized dunes is distributed across the undeveloped portions of the site.

The following italicized text, excerpted from Chapter 2 of the CCA, describes the area soils:

> *Soils of the region have developed mainly from Quaternary and Permian parent material. Parent material from the Quaternary System is represented by alluvial deposits of major streams, dune sand, and other surface deposits. These are mostly loamy and sandy sediments containing some coarse fragments. Parent material from the Permian System is represented by limestone, dolomite, and gypsum bedrock. Soils of the region have developed in a semiarid, continental climate with abundant sunshine, low relative humidity, erratic and low rainfall, and a wide variation in daily and seasonal temperatures. Subsoil colors are normally light brown to reddish brown but are often mixed with lime accumulations (caliche) that result from limited, erratic rainfall and insufficient leaching.*
>
> *A soil association is a landscape with a distinctive pattern of soil types (series). It normally consists of one or more major soils and at least one minor soil. There are three soil associations within 5 miles (8.3 kilometers) of the WIPP site: the Kermit-Berino, the Simona-Pajarito, and the Pyote-Maljamar-Kermit. Of these three associations, only the Kermit-Berino soil series has been mapped across the WIPP site by Chugg et al. (1952, Sheet No. 113). These are sandy soils developed on eolian material. The Kermit-Berino soils include active dune areas. The Berino*

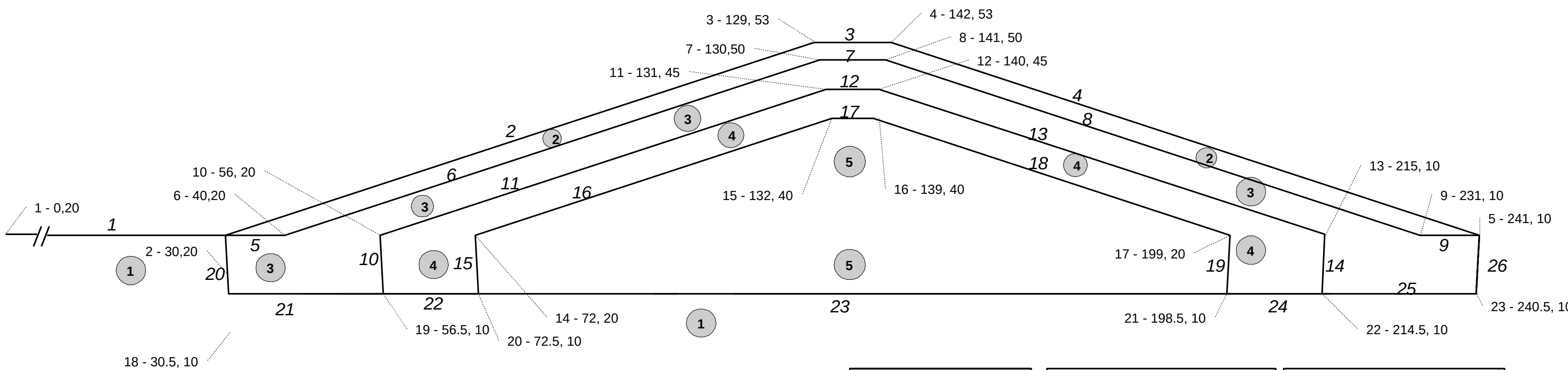
soil has a sandy A horizon; the B horizons include more argillaceous material and weak-to-moderate soil structures. A and B horizons are described as noncalcareous, and the underlying C horizon is commonly caliche. Bachman (1980, 44) interpreted the Berino soil as a paleosol that is a remnant B horizon of the underlying Mescalero. Rosholt and McKinney (1980, Table 5) applied uranium-trend methods to samples of the Berino soil from the WIPP site area. They interpreted the age of formation of the Berino soil as 330,000 ± 75,000 years.

Generally, the Berino Series, which covers about 50 percent of the site, consists of deep, noncalcareous, yellow-red to red sandy soils that developed from wind-worked material of mixed origin. These soils are described as undulating to hummocky and gently sloping (0 to 3 percent slopes). The soils are the most extensive of the deep, sandy soils in the Eddy County area. Berino soils are subject to continuing wind and water erosion. If the vegetative cover is seriously depleted, the water-erosion potential is slight, but the wind-erosion potential is very high. These soils are particularly sensitive to wind erosion in the months of March, April, and May, when rainfall is minimal and winds are highest. These soil characteristics are a consideration for the design of long-term passive controls such as monuments and markers (see Appendix PIC, Section III).

The Kermit Series consists of deep, light-colored, noncalcareous, excessively drained loose sands, typically yellowish-red fine sand. The surface is undulating to billowy (from 0 to 3 percent slopes) and consists mostly of stabilized sand dunes. Kermit soils are slightly to moderately eroded. Permeability is very high, and, if vegetative cover is removed, the water-erosion potential is slight, but the wind-erosion potential is very high.

When used as construction materials in the berm, these soils can be selectively excavated, blended and compacted to achieve any necessary structural properties. The in-place density and cohesion of the native soil will govern its behavior as a foundation material for the permanent markers. These properties are subject to some improvement through procedures such as compaction, consolidation grouting, and other ground improvement procedures. However, it is unlikely that any structural loads imposed by permanent markers would necessarily be greater than the allowable bearing capacity of the in-place soils without improvement of their original properties. The native soil excavated for construction of the berm may be manipulated in various ways to increase strength, including blending of soils, selectively wasting of weaker soils, and additives. After the soils are placed, they can be moisture-conditioned and compacted to achieve close to their maximum potential densities and strengths.

No highly compressible soils or shallow ground water conditions exist within the area of permanent marker placement. Therefore, dewatering or artificial consolidation of compressible or collapsible soils should not be necessary. The design of the berm can be modified in various ways to accommodate the native soils found within the immediate vicinity of the berm.



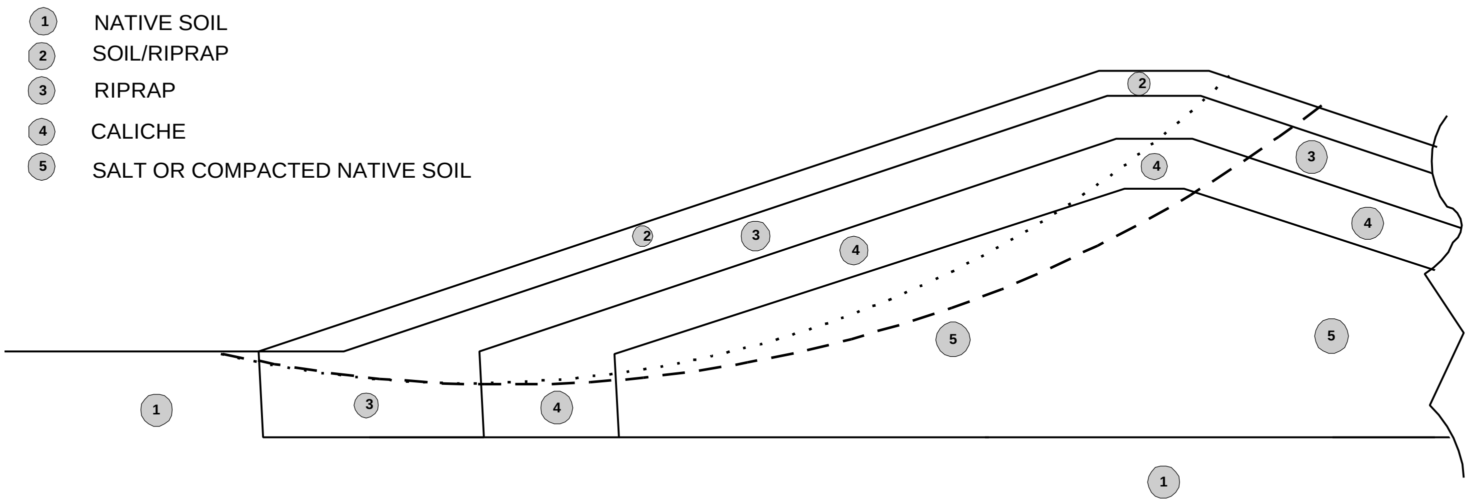
	SOILS	UNIT WT. PCF	FRICTION ANGLE	COHESION PCF
1	NATIVE SOIL	110	25	0
2	SOIL/RIPRAP	140	30	110
3	RIPRAP	107	35	0
4	CALICHE	135	30	0
5	SALT	112	11	110

POINT	X	Y
1	0	20
2	30	20
3	129	53
4	142	53
5	241	20
6	40	20
7	130	50
8	141	50
9	231	20
10	56	20
11	131	45
12	140	45
13	215	20
14	72	20
15	132	40
16	139	40
17	199	20
18	30.5	10
19	56.5	10
20	72.5	10
21	198.5	10
22	214.5	10
23	240.5	10

LINE	L	R	SOIL
1	1	2	1
2	2	3	2
3	3	4	2
4	4	5	2
5	2	6	3
6	6	7	3
7	7	8	3
8	8	9	3
9	9	5	3
10	10	19	3
11	10	11	4
12	11	12	4
13	12	13	4

LINE	L	R	SOIL
14	22	13	3
15	14	20	4
16	14	15	5
17	15	16	5
18	16	17	5
19	21	17	4
20	2	18	1
21	18	19	1
22	19	20	1
23	20	21	1
24	21	22	1
25	22	23	1
26	23	5	1

Figure 3 - Alternative Berm Design Material And Configuration Parameters With 3:1 Sideslopes



. . . . FAILURE SURFACE WITH LOWEST FACTOR OF SAFETY OF 1.27 UNDER STATIC LOAD CONDITIONS, 0.92 UNDER EARTHQUAKE LOADING - _COMPACTED SALT CORE_

— — FAILURE SURFACE WITH LOWEST FACTOR OF SAFETY OF 1.54 UNDER STATIC LOAD CONDITIONS, 1.12 UNDER EARTHQUAKE LOADING - _COMPACTED NATIVE SOIL CORE_

Figure 4 - Alternative Berm Design Stability Analysis With 3:1 Sideslopes

3.2.3 Caliche

Caliche occurs in and near the WIPP site at shallow depths. Several developed caliche borrow pits are within reasonable haul distance of the WIPP site, and some caliche borrow pits could be developed in or near the locations of the permanent markers. The CCA and other project documents discuss the characteristics of the native caliche in some detail. The following italicized text is from Chapter 2 of the CCA:

> *The Mescalero caliche is an informal stratigraphic unit apparently first differentiated by Bachman in 1974, though Bachman (1973, 17, 27) described the caliche on the Mescalero Plain. He differentiated the Mescalero from the older, widespread Ogallala caliche or caprock on the basis of textures, noting that breccia and pisolitic textures are much more common in the Ogallala caliche. The Mescalero has been noted over significant areas in the Pecos drainage, including the WIPP area, and it has been formed over a variety of substrates. Bachman (1973) described the Mescalero as a two-part unit: (1) an upper dense laminar caprock and (2) a basal, earthy-to-firm, nodular calcareous deposit. Machette (1985, 5) classified the Mescalero as having Stage V morphologies of a calcic soil (the more mature Ogallala caprock that occurs east of the WIPP site reaches Stage VI).*
>
> *Bachman (1976, Figure 8) provided structure contours on the Mescalero caliche for a large area of southeastern New Mexico, including the WIPP site. From the contours and Bachman's discussion of the Mescalero as a soil, it is clear that the Mescalero is expected to be continuous over large areas. Explicit WIPP data are limited mainly to boreholes, though some borehole reports do not mention the Mescalero. The unit may be as much as 10 feet (3 meters) thick.*

The caliche materials may be blended to improve their strength and compaction characteristics, or non-caliche soil materials may be added to the caliche for this purpose as well. Other than the differences in composition between caliche and native soil, the density and strength of compacted caliche should be similar to those properties of compacted native soil. However, the handling of caliche will probably be complicated by the great variability in the natural density and hardness of the material in its undisturbed condition. Excavating and processing caliche will probably take more effort and cost more per cubic yard than similar handling of native soil.

3.2.4 Riprap

Rock for riprap is not available within or in close proximity to the WIPP site; however, durable rock sources are known to exist within about 100 miles of the WIPP site, especially in the Guadalupe Mountains. Possible rock types that may be considered for riprap include limestone, basalt and other extrusive igneous rocks, and well-indurated sandstone.

The design of the berm sideslopes (gradient, length) can be varied to accommodate the available riprap rock. The most readily available and least costly rock might not be sufficiently durable to protect side slopes of a certain configuration. In such a case, the side slopes can readily be flattened to a lower gradient, trading off the cost of additional earthwork against the higher cost of importing more durable rock from more distant sources.

3.3 Metals and Metallic Alloys

Various metals and metal alloys have been proposed in the markers reference designs. Characteristics of those proposed are described in the following subsections.

3.3.1 Strontium Ferrite

The reference design material for the buried magnets is strontium ferrite. Although not specifically identified as such in the reference design, the particular material that would most likely be used for magnets is strontium hexaferrite (SrO-$6Fe_2O_3$). This material makes a hard permanent magnet that has high resistance to demagnetization, high remanence, coercivity, and saturation flux density, as well as low initial permeability. The most important properties of strontium hexaferrite are cohesivity and "energy product." The energy product is representative of the energy required to demagnetize the permanent magnet. A large external field is required to demagnetize strontium hexaferrite. Strontium hexaferrite exhibits a strong magnetization after a magnetic field has been applied and removed and is stable even if a certain strength of demagnetizing field is reapplied. The advantages of strontium hexaferrite over other magnetic counterparts include high coercivity and low permeability, low specific gravity, multipolarity on one surface, and the ability to be mixed with plastic and rubber to form magnets (Collins and Hirschfeld, 2000a).

3.3.2 Stainless Steel

Stainless steel has been identified as one of two alternative materials of construction in the reference design for the radar reflectors. The reference design does not specify what particular type of stainless steel is intended; there are, in fact, several types that might be used. Stainless steel 316 and 317 have some of the best long-term durability properties. These are austenitic stainless steels with less carbon or added nitrogen for increased strength. Stainless steel 316 has high corrosion resistance and is resistant to mild oxidizing and reducing chemical environments.

Stainless steel 317 has higher molybdenum content than stainless steel 316, increasing its resistance to corrosion. However, if the radar reflectors are enclosed within a corrosion-resistant coating or protective shell, high corrosion resistance may be unimportant. In this case, stainless steel 304 may be preferable because of its lower cost. Table 1 lists some of the properties of two stainless steels and Inconel.

Table 1. Comparison of Properties and Costs of Reference Design Radar Reflector Metals

Materials	Density (g/cm3)	Hardness (Rockwell)	Tensile Strength (MPa)	Yield Strength (Mpa)	Percent Elongation	Thermal Expansion (Fm/m*K)	Cost ($/lb.)
Stainless Steel 316	7.8	79	579	290	50	16.0	2.50-3.00
Stainless Steel 317	7.8	85	621	276	42.5	16.2	NA
Inconel 625	8.4	190	930	517	42.5	11.5	14-17

Any type of stainless steel should perform satisfactorily in terms of its reflectivity of radar energy. There has been no distinction drawn between the several stainless steels or between stainless steel and other metals with respect to radar reflectivity.

3.3.3 Inconel

Inconel (61Ni-21Cr-9Mo-3.6Nb) has also been identified in the reference design as a material that could be used in the construction of radar reflectors. Inconel 625 is commonly used in chemical processing equipment, aerospace and marine engineering, pollution-control equipment, and nuclear reactors. It is a nickel-chromium-molybdenum alloy with an addition of niobium that acts with the molybdenum to stiffen the alloy's matrix and provide high strength without extensive heat treatments. The alloy is able to withstand a wide variety of corrosive environments; the combination of nickel and chromium provides resistance to oxidizing conditions, and the combination of nickel and molybdenum provides resistance to reducing conditions. The alloy is especially resistant to pitting and crevice corrosion.

3.3.4 Other Metals

Both titanium and hastealloy (hastelloy) are mentioned in the reference design as metals that could be used in the small subsurface markers. Titanium is used in alloys, principally with iron where high strength, corrosion or temperature resistance, or light weight are important. The reference design does not name any specific alloys containing titanium.

Hastelloy is a family of Nickel base superalloys (35+ variations), all of which are relatively expensive (Leslie Chom, ASM International, personal communication, July 21, 2000). Hastelloys are used primarily for highly corrosive, oxidizing and reducing environments. The properties of Hastelloy C-2000 are representative of the group:

- Compostion - 23% chromium, 16% molybdenum, 1.6% copper, >1% carbon and silicon, balance nickel
- Density - 8.50 g/cm3
- Mean coefficient of thermal expansion - 6.9 Fm/m
- Tensile strength - 758 MPa for 0.5 in. thickness

It also has superior pitting and crevice corrosion resistance. Hastelloy can be formed into sheets, bars and plates as well as wire and tube (ASM, 1996).

3.4 Other Materials

Quartz, Lanthanumborate glass, ceramics, and polyethylene are mentioned in the reference design as possible materials for small subsurface markers. Quartz is a mineral with a hardness of 7 on the Moh's Scale, making it as hard as any windblown sand. However, crystalline quartz would be difficult to inscribe and would have to be specially fabricated to create sizes sufficient for the markers.

3.4.1 Lanthanumborate

Lathanumborate glass is a "glass precursor" developed by Owens Corning for the DOE's Savannah River Company containing lanthanum and borate (Peter McGinnis, Owens Corning, personal communication, July 21, 2000). No other information on this material was found through this literature review.

3.4.2 Polyethylene

Polyethylene is soft plastic that can be formulated for a wide variety of uses and, therefore, to have a wide range of properties. According to ASTM D-3550-84, typical primary properties are:

- Density - 0.941-0.955 g/cm3
- Tensile strength at yield - 21 Mpa
- Flexural modulus - 758 Mpa
- Impact strength - >12 ft.lbs/ in.
- Hardness (Shore D) - 65
- Coefficient of thermal expansion - 0.778 x 10^{-4} in./in./ ºF

Polyethylene is readily molded into many shapes and holds even very small symbols and letters, a fact evident in the profusion of bottles, caps and other common imprinted objects. High density polyethylene (HDPE) is widely used as material for pipe and liners for both acidic and alkali liquids; it is chemically stable over a wide pH range. Polyethylene warrants further consideration as a material of construction for the small subsurface markers.

3.4.3 Ceramics

Ceramics are a large group of materials composed of inorganic nonmetallic substances. No specific ceramic is identified in the reference design. The group is too large to address completely; a few specific ceramics are identified and described later in this report as alternative materials.

4.0 Alternative Materials

This review includes an initial examination of a wide variety of materials that may be considered for use either in addition to or in place of materials identified in the reference design. The identification and evaluation of alternative materials focuses primarily on the physical properties and expected performance of the alternative materials, but also considers the availability of such materials, the logistics of obtaining them and transporting them to the WIPP site, and the relative costs of these materials versus those identified in the reference design. Alternative materials evaluated in this study include rock types other than granite, concrete, other metals and metallic alloys, ceramics, and polymers.

4.1 Rock Other than Granite

Several rock types other than granite have been identified as likely to have durability, inscribability, and strength comparable to or better than granite. The initial list of alternative rock types includes basalt, well-indurated sandstone, quartzite, and limestone. Limestone, however, has been discarded from consideration because of its composition (calcium carbonate), which is susceptible to dissolution under even mildly acidic conditions. It is impossible to predict the long-term air quality and potential for acid rain over the service life of the permanent markers. Therefore, the potential for dissolution of the surface features of limestone in that period of time is considered to be too great to give limestone further consideration. Quartzite has also beeen discarded from consideration because of its relative scarcity and because it is difficult to quarry and inscribe due to its extreme hardness.

Transportation cost for rock from sources outside southern New Mexico and west Texas is expected to be an important discriminating factor when selecting alternative rock types. Accordingly, the evaluation of alternative rocks was limited to those that occur at ground surface within 200 to 300 miles of the WIPP site.

4.1.1 Basalt

Basalt is an extrusive volcanic rock that is widely distributed throughout the southwest and, in particular, in the south central and southwest parts of New Mexico, within reasonably short haul distance of the WIPP site. Basalt is composed of sodic feldspars and mafic minerals, those that are on the earlier-crystallizing end of the Bowen Reaction Series. Although these minerals are less stable at ground surface than those that crystallized later in the series, they can be viewed as stable in the relatively short period of performance of the permanent marker system versus the geologic scale of time in which these minerals are commonly referred to as less stable. The hardness of the minerals in basalt is comparable to the hardness of most of the minerals in granite; therefore, basalt should be at least as readily inscribed as granite.

The physical properties that affect durability of basalt compare favorably to those of granite. The density of basalt varies from 130 pcf to 187 pcf (2.08 to 3.0 g/cm^3), reflecting the influence of vesicles (gas-produced voids) on the density of basalt. Because of these voids or holes, vesicular basalt is unsuitable for use in any marker that is inscribed. Non-vesicular basalt will have densities near the upper end of this range as well as compressive strength of up to 104,500 psi and Schmidt L-hammer hardness of 49-85, similar to granite (Carmichael, 1989). Non-vesicular basalt has porosities below 2%, just like granite (Franklin and Dusseault, 1989).

Basalt is evidently at least as erosion resistant as granite in the environment of the southwest, as demonstrated by the persistence of the basalt cap rocks on mesas and elsewhere within New Mexico. In addition basalt is drab and relatively unattractive, and that combined with its widespread occurrence makes it economically less valuable and less attractive to would-be scavengers than granite. The results of a recent survey of petroglyphs (John Hart and Associates, P.A., 2000a) show that very old petroglyphs of Archaic age (1000-6000 years old) are well preserved in basalt in several locations in environments similar to that of the WIPP site. The inscriptions of these petroglyphs were very shallow but have endured for up to several thousand years without observable deterioration.

4.1.2 Well-indurated Sandstone

There is a wide variety of rocks appropriately called sandstone that occur in the southwest. Some of these sandstones are very soft and crumble easily when squeezed or struck; others are extremely hard because they have been lithified in a way that has cemented the sand grains in a tight, durable matrix (well-indurated). Sandstones like this occur in the southwestern quadrant of New Mexico, within reasonable distance from the WIPP site. They also form resistant cap rocks on mesas and have been inscribed by Archaic Indians in several locations in New Mexico, leaving petroglyphs that are up to 6000 years old, readily visible and exhibit little deterioration over that period of time. Some of these petroglyphs are in environmental settings that are more severe with respect to weathering and erosion than the environment of the WIPP site.

Well-indurated sandstone has physical properties at the upper end of the wide ranges recorded for all sandstones, with values similar to granite. Compressive strength, up to 142,000 psi, can be as good as, or even better than, that of granite. Densities of well-indurated sandstone higher than those of granite, up to 207 pcf, have been measured, but L-hammer hardness tends to be lower than for granite, up to 56 (Carmichael, 1989).

4.1.3 Other Potential Alternative Rock Types

The extent of this study has not enabled the investigators to examine all potential candidate rock types that might occur within reasonable proximity of the WIPP site. However, several other rock types are known to occur in southern New Mexico and west Texas that could be examined for possible inclusion as alternative rock types. These include rhyolite and andesite. Both of these are fine-grained igneous rocks that exhibit properties very similar to those of basalt.

4.2 Concrete

In the reference design, the potential use of concrete is limited to the encasement of the radar reflectors. However, the opportunity is left open for other uses, including the material of construction for the large surface markers, the buried storage rooms, and the information center. Widespread examples of crumbling concrete in our modern infrastructure contribute to legitimate concerns about the use of concrete for any applications requiring extreme longevity. However, there are well documented examples in the historic record of concrete used in ancient times that remains intact and durable to the present. If the historic record is used as a reference and recent advances in concrete technology are considered, alternative concrete designs may be developed that have the potential for satisfying the performance criteria.

4.2.1 Concerns About Concrete

Examples of crumbling concrete and failed structures made of concrete are well known to everyone. While few would dispute the strength of concrete as a construction material, many people have legitimate concerns that concrete is not adequately durable to last the thousands of years expected of the permanent markers. There are many causes for the short service life of some concretes, including unsuitable aggregate materials, improper ratios of constituents, contaminated cement, poor workmanship and placement, and insufficient curing times. The last of these causes is frequently the result of construction schedule imperatives that place a priority on removing forms from concrete pours as quickly as possible. Accelerators are often added to concrete mix to obtain an initial set as quickly as possible, which can contribute to the long-term low durability of concrete. The circumstances of construction of the WIPP permanent markers (e.g., unlimited time available for set and cure) offer opportunities to avoid important causes of concrete deterioration.

4.2.2 History of Concrete

Over the course of this study, the literature was reviewed to find descriptions of concrete and cementiceous materials that, in general, have lasted for long time periods. The record is surprisingly strong in this regard.

One of the earliest uses of a cementiceous material is a lime-plastered floor found in the village of Yiftahel in Israel. The site has been determined by carbon-14 dating to be approximately 8850 years old. The floor consists of a base layer and a thin finish layer. The primary constituent of both layers is calcite, with minor amounts of quartz. The base layer was determined to have a compressive strength of 34 Mpa (4930 psi), and the finish layer has a compressive strength of 45 Mpa (6525 psi). Although this floor did not contain aggregate like that used in modern structural concrete, its compressive strength is comparable to that of modern structural concrete in similar applications (John Hart and Associates, P.A., 2000b).

A calcium sulfate-based mortar was used as a cementiceous material and crack filler in open spaces in pyramids in Egypt constructed 4500 years ago. The main constituents are gypsum, anhydrite, calcite, argillaceous limestone, and quartz sand. The gypsum was heat-treated and possessed pozzolanic properties due to the breakdown of clay to amorphous aluminosilicates (John Hart and Associates, P.A., 2000b).

On the Greek island of Rhodes at the ancient city of Kamiros, a water tank was constructed of concrete approximately 3000 years ago. The concrete used in the water tank is a mixture of aggregates consisting of siliceous gravel, granular intermediate calcareous aggregates and fine-grained calcareous aggregates plus volcanic earth and lime as a binder, creating low porosity and good water tightness. The tank remains intact today (John Hart and Associates, P.A., 2000b).

The history of the Roman Empire contains a record visible today of the advanced state of Roman concrete technology. The city of Caesaria in Israel on the shores of the Mediterranean contains a breakwater consisting in part of concrete continually subjected to salt water since around 10 BC. The concrete is made of fieldstone rubble, red clay and lime. In Italy, several Roman aqueducts built nearly 1800 years ago and located as close as 150 meters from the sea still remain intact and functional. These structures were continuously subjected to salt water spray and cycles of wetting and drying. Both the Coliseum completed in AD 82 and the Pantheon completed in AD 128 contain large amounts of concrete. Despite containing no reinforcement, the Pantheon dome is in good condition. The aggregate used in the concrete in the Pantheon ranges from heavy basalt in the foundations through brick and tuff in the upper walls to pumice in the top of the dome (John Hart and Associates, P.A., 2000b).

The Roman Empire constructed nearly 53,000 miles of roads throughout Europe and the Middle East; by comparison, the U.S. Interstate Highway system consisted of 42,000 miles in 1995. The typical Roman road construction design included four courses. The next-to-bottom course, or nucleus layer, was about one foot thick and was made of concrete with small gravel and coarse sand mixed with hot lime and water (Steiger, 1995). Whenever possible, the concrete mix consisted of lime mixed with volcanic rock or sand called pozzolana, named after the place where it was first found, the town of Pozzuoli near Mt. Vesuvius. The pozzolana contained aluminum silicate ash, erupted from the volcano, from which silica was readily liberated by caustic alkalies such as calcium hydroxide. Silica combined with the lime to form a solid cementing material that could harden in water. Pozzolanic materials are still used in many applications to this day (John Hart and Associates, P.A., 2000b).

In Meso-America, the Mayans developed a concrete that has lasted approximately 900 years. In the ancient city of El Tajin in Mexico, the Mayans constructed a concrete roof in which the main components were calcite and quartz with other mineral composites which participated in the pozzolanic reactions. The concrete has been analyzed and found to contain 15% soluble silica, 15% aluminum, 56% lime, and 20% anhydrous cementiceous material, with a pozzolanic index of 0.42, indicating that silica and alumina mobilization is quite substantial. Compositions of this type are commonly known as pozzolanic concrete (John Hart and Associates, P.A., 2000b).

Very recently in Hawaii, a foundation slab was constructed for a temple planned to last for at least 1000 years. The design specifically excluded the use of reinforcing steel. To achieve the high strength and durability required, a high volume fly ash (HVFA) concrete was designed. In this type of concrete, half or more of the cement in the mix is replaced with fly ash. According to the designer, Dr. E. K. Mahta (1999), fly ash concrete is much more durable than normal concrete because it totally eliminates temperature cracking due to its low heat of dehydration and slow cure time. The slab reached a strength of 1000 psi in three days and 3000 psi in three weeks, and the slab is expected to reach 6000 psi strength in a few years (Mahta ,1999).

It is evident from this historical record that the potential durability for cementiceous materials and concrete cannot be judged by the experience of most modern concrete design and construction practices that emphasize volume and speed of placement and early strength at the sacrifice of durability. This is not necessarily the case with all modern concretes, however. Brown (1987) tested two samples of Roman concrete approximately 1900 years old, two samples of Mayan concrete approximately 600 years old, and a referenced sample of modern-day concrete. The samples were subjected to freezing in air and thawing in water, and weight losses were recorded after each freeze-thaw cycle. Brown found that Roman concretes virtually disintegrated after 18-29 cycles. One of the Mayan samples lasted 79 cycles; the other lasted the entire test of 150 cycles with 28% loss. The reference modern-day samples survived the entire 150 cycles with only 6% loss. Brown concluded that even the successful ancient concretes would have suffered substantial deterioration in harsher climates represented by the cyclic freeze-thaw testing, whereas modern concretes can be designed for specific environmental conditions.

4.2.3 Alternative Concrete Design

The combination of historic lessons and modern technology indicate that it may be possible to create a concrete that will be sufficiently strong and durable to last a very long time at the WIPP site, perhaps 10,000 years or longer. Durability is dependent on several factors – permeability, strength, and chemical stability (McKeen, 2000). Low permeability is desirable to reduce, as much as possible, infiltration of water and other mobile materials from infiltrating the concrete. High strength gives the concrete greater capability to resist abrasion and erosion. Chemical stability is needed to prevent or reduce the risk of reactions between incompatible constituents in the mix that could lead to deterioration of the concrete over time. All three of these factors can be optimized by the selection of the proper materials, optimal proportions, and mixing and placement procedures that are designed specifically for the mix and the intended application.

The permanent markers program provides an ideal set of circumstances to use concrete in the most optimal way. Specifically, pace of construction, cure times, and removal of forms are not important considerations in the construction of permanent markers and may be planned to provide the longest cure time needed to obtain optimal durability. Forms can be kept in place and accelerator additives can be avoided in the construction of the permanent markers, allowing the concrete to cure slowly and gain strength gradually, thereby providing the greatest likelihood that the concrete will gradually develop the desired properties.

For the WIPP permanent marker applications, a high-volume fly ash (HVFA) concrete mix appears to be the most appropriate for the achievement of the performance objectives. This type of concrete may also be used in place of granite or other rock in most or all of the other applications for which granite is the reference material. The HVFA concrete would consist of ASTM Class F fly ash as the pozzolanic material that will substitute for a portion of the Portland cement in the mix. The aggregates should be selected to be as stable and non-reactive as possible. The recommended proportions and typical physical properties of such mixes are listed in Table 2 and Table 3, respectively.

Table 2. Typical Mix Proportions for High Volume Fly Ash Concrete (1)

Component	Fly Ash Content		
	Low	Medium	High
Water (kg/m^3)	115	120	110
Type I cement (kg/m^3)	125	155	180
Class F fly ash (kg/m^3)	165	215	220
Coarse aggregate (kg/m^3)	1170	1195	1110
Fine aggregate (kg/m^3)	800	645	760
Air-entraining (ml/m^3)	200	200	280
Superplasticizer (kg/m^3)	3.0	4.5	5.5

1. Source: McKeen, 2000

Table 3. Typical Physical Properties of a Medium Strength Mix HVFA Concrete [1]

Property	Age (days)	Values (MPa)	Values (psi)
Compressive Strength	1	8±2	1160±290
	7	20±4	2900±580
	28	35±5	5070±725
	91	43±5	6240±725
	365	55±5	8000±725
Flexural Strength	14	4.5±0.5	650±73
	91	6±0.5	870±73
Splitting Tensile Strength	28	3.5±0.5	500±73
Young's Modulus	28	35±2	5.1×10^6
	91	38±2	5.5×10^6
Drying shrinkage strain	448	500±50, x 10^{-6} [2]	
Specific creep strain	365	528±40, x 10^{-6} [2]	

1. Source: Bilodeau et. al, 2000.
2. Dimensionless

4.3 Metals and Metallic Alloys

The metals identified in the reference design, strontium ferrite for magnets and both stainless steel and Inconel for the radar reflectors, appear to be appropriate for the designated uses. Additional metals and alloys may also be considered.

Monel K-500 (66Ni-29.5Cu-2.7Al-0.6Ti) is widely used for pump shafts, oil well tools, and instruments, doctor blades and scrapers used in ceramic tape casting, springs, valve trim, fasteners, and marine propeller shafts. It is a precipitation-hardenable nickel-copper alloy with high strength and excellent corrosion resistance in a range of media, including sulfuric acid and alkalis. Inscription of Monel K-500 would be the easiest and least expensive of all the metals considered (Collins and Hirschfeld, 2000a; 2000b). Therefore, Monel K-500 might be considered for the small subsurface markers and for inscribed message plates that could be embedded in another structural medium for any of the other message-bearing markers.

Barium hexaferrite is an alternative to strontium ferrite for magnets. It is one of the most widely used materials for permanent magnets and magnetic recording media (hard disks, floppy disks, and video tapes). It has excellent chemical stability and exhibits a stronger coercive force (H_{cf}) than strontium hexaferrite. However, strontium hexaferrite has a higher coercivity (H_c), remanence (Gauss), and energy product $(BH)_{MAX}$. The properties of these two ferrites are compared in Table 4 (Collins and Hirschfeld, 2000a; 2000b).

Table 4. Properties of Ferrite Materials for Magnets [1]

Properties	Strontium Ferrite ($SrO\text{-}Fe_2O_3$)	Barium Ferrite ($BaO\text{-}6Fe_2O_3$)
Density (g/cm^3)	5.11	5.28
Thermal Expansion (μm/m*K)	~18	18
Coercivity (H_c)	3150	3000
Coercive Force (H_{cf})	3590	3650
Remanance (Gauss)	3550	3200
Energy Product $(BH)_{MAX}$, (MGOe)	3.0	2.5
Flux Density (Gauss)	1730	1600
Curie Temp. (EC)	460	450

1. Source: Collins and Hirschfeld, 2000a; 2000b.

4.4 Ceramics

Ceramics are a group of very versatile materials, some of which offer advantages over rock, concrete, metals or polymers for several marker applications. Most oxides, nitrides, carbides, and other "ides" fall into the class of materials called ceramics. Advantages of ceramics compared to metals and polymers include an excellent combination of properties such as high hardness, high melting temperature, good erosion and wear resistance, good corrosion resistance and relatively low cost. However, ceramic materials, being composed of inorganic nonmetallic substances, characteristically are brittle and fracture with little or no deformation, in contrast to metals that yield and deform. Much research is being done to develop ceramics that will not fracture in a brittle manner, which occurs when a crack rapidly travels through a material with no ductile deformation of the adjacent material. A number of other compounds may be added in varying amounts to enhance strength, density, oxidation and corrosion resistance, toughness and machinability. The use and manufacture of ceramics began about 7000 B.C. and, due to the chemical and mechanical stability of ceramics, they are among the most well-preserved man-made materials in existence today (Collins and Hirschfeld, 2000a; 2000b).

Several modern ceramic materials may be well suited for use as marker materials, specifically aluminum oxide (alumina-Al_2O_3), aluminum oxide-zirconium oxide composite (alumina-zirconia-

Al_2O_3-ZrO_2), and aluminum oxide-yttrium oxide-tetragonal zirconium oxide polycrystalline composite (alumina-yttria-tetragonal zirconia polycrystal-Al_2O_3-Y-TZP) robocast silicon nitride (Si_3N_4), Si_3N_4 with silicon carbide (SiC) whisker addition, SiC-10 wt.% (Al_2O_3+Y_2O_3) (Collins and Hirschfeld, 2000a; 2000b). Properties of these ceramics are listed on Table 5.

Table 5. Properties of Ceramics [(1)]

Ceramic Material	Density (g/cm^3)	Vickers Hardness (GPa)	K_{Ic} Toughness ($MPa*m^{1/2}$)	Thermal Expansion [(2)] ($K^{-1}*10^6$)	Bend Strength (MPa)
Alumina Al_2O_3 (0-2% porosity)	3.9	20.5	3.8	7.9	700
Alumina-Zirconia 80 wt.% Al_2O_3 20 wt.% ZrO_2	4.2	16.5	6.5	8.5	500
Alumina-yttria tetragonal zirconia polycrystal (Y-TZP) Al_2O_3 2 mol. % Y_2O_3 20 mol % ZrO_2	4.5	16.0	7.4	>8.5	620
Robocast Si_3N_4	3.2	14.7	NA [(3)]	3.2	740
Si_3N_4-20 vol % SiC	3.1	~14.7	7.5	3.2	710
SiC–10 wt.% (Al_2O_3 +Y2O3)	3.2	25	7.0	4.9	625

1. Source: Collins and Hirschfeld, 2000a; 2000b
2. At room temperature
3. Information not available

4.4.1 Alumina

Alumina occurs naturally as the mineral corundum, which is better known as the gem-quality crystals ruby and sapphire. Alumina is widely used as a cutting tool material as well as an electronic and insulating ceramic. It has been the basis for insulator applications for the last 55 to 65 years. It is widely used in the manufacturing of automobiles as a cutting tool for repetitive machining on metals. Other applications include the manufacture of porcelain, alumina laboratory ware, crucibles, metal casting molds, high-temperature cements, wear-resistant parts (tiles, seals, etc.), sandblast nozzles, armor, medical components, abrasives, and refractories (Collins and Hirschfeld, 2000a; 2000b).

Alumina has excellent mechanical, thermal, and chemical properties such as high hardness and excellent wear resistance, low porosity, and high temperature strength and chemical stability. In addition, a dense body of strongly bonded alumina is comparatively easy to prepare through conventional ceramic processing methods. Due to alumina's high hardness and brittleness, silicon carbide, boron carbide, or diamond tooling are required for inscription, which can be costly (Collins and Hirschfeld, 2000a; 2000b).

4.4.2 Alumina-Zirconia

Although alumina is superior as a wear resistant material, it lacks a great degree of toughness. However, improvements may be realized by adding ZrO_2. Zirconia has long been used as a ceramic because of its refractory nature. It is commonly employed as a thermal barrier coating over the surface of superalloy gas turbine engine components. In addition, it is employed as oxygen sensors in automobiles, resistance heating elements, and single crystal gemstones. Alumina-Zirconia composite materials have high toughness and strength, with moderate hardness. The lower hardness of the Al_2O_3-ZrO_2 material, compared to single component polycrystalline alumina, is more than compensated by the fact that the toughness is greatly increased by zirconia addition. The addition of ZrO_2 toughens the Al_2O_3 matrix by mechanisms of microcracking and stress-induced transformation. There is a distinct difference in the material toughness and strength based on the volume-fraction of zirconia present in the composite. According to a volume fraction zirconia in alumina matrix study performed by Green et. al (1989) all of the measured toughness results passed through a maximum with increasing volume fraction of zirconia. Consequently, an alumina-zircona composite with approximately 75% tetragonal and 25% monoclinic zirconia particles would give the best erosion resistance of this composite material. The alumina-zirconia composite requires silicon carbide or boron carbide tooling for inscription (Collins and Hirschfeld, 2000a; 2000b).

4.4.3 Alumina-Yttria-Tetragonal Zirconia Polycrystal

In alumina-zirconia ceramic composites with 100% tetragonal zirconia particles (TZP), the bending strength and fracture toughness are increased, and with addition of monoclinic zirconia particles the toughness is increased significantly but not the bending strength. Tetragonal zirconia polycrystal (TZP) plus Y_2O_3 added to Al_2O_3-ZrO_2 a durable, high strength, high toughness ceramic. Inscription of this material requires silicon carbide tooling (Collins and Hirschfeld, 2000a; 2000b).

4.4.4 Robocasted Ceramics

Three other ceramics - silicon nitride (Si_3N_4), Si_3N_4 with silicon carbide (SiC) whisker addition, and SiC with 10 wt.% (Al_2O_3+Y_2O_3) - can be made into marker components by robocasting. Robocasting is a free form fabrication process by which a dense ceramic is formed by computer control. This process yields ceramics of near theoretical density formed directly from a CAD drawing to a finished part within 24 hours. Messages and symbols, made directly by this process without inscription, would be contained within and extend through the marker, not just reside at the surface (Collins and Hirschfeld, 2000a; 2000b).

These three materials demonstrate long time survival in severe elevated temperature, applied stress, and oxidizing environments. Si_3N_4 achieves better strength and fracture toughness than many materials because raising the sintering temperature when fabricating the material changes the grain morphology from granular to needle-like. Increased strength and toughness can also be realized by adding a second phase, such as SiC whiskers. Whiskers are short, discontinuous, rod- or needle-shaped single crystal fibers typically 0.1-3.0 μm in diameter and 5-200 μm in length. Because they are single crystals, they have extremely good strength properties. Whiskers improve material mechanical properties by increasing the flexural strength, fracture energy, and fracture toughness. Si_3N_4 with SiC whisker addition also has one of the lowest brittleness (B) index values. Due to the low brittleness value, Si_3N_4-SiC has excellent erosion resistance as well as excellent corrosion resistance. However, depending on the size of the SiC whisker, this material may be robocast, leaving no need for tooling (Collins and Hirschfeld, 2000a; 2000b).

Silicon carbide, SiC, doped with 10 wt. % (Al_2O_3+Y_2O_3), exhibits desirable properties such as high strength, moderate thermal expansion, a very high degree of erosion resistance due to its high hardness, and excellent corrosion resistance. With the addition of alumina and yttria as liquid-phase sintering additives, a high density SiC material can be made at relatively low temperatures (1850-2000EC). Of the 10 %-additives, a mixture of 25 % yttria with 75 % alumina yields the greatest strength. Silicon carbide is less expensive and more erosion resistant than Si_3N_4, making it somewhat more favorable. Silicon carbide requires diamond tooling for inscription or could be robocast (Collins and Hirschfeld, 2000a; 2000b).

The six ceramic materials described above have properties that make them attractive for use in the large surface markers, small subsurface markers, the information center and the buried storage rooms. Small subsurface markers can be made entirely from one or more of these, and the message panels of the others can be made of ceramic and then embedded in the structural components of these markers. Many combinations and configurations are possible and warrant further testing and evaluation.

4.5 Polymers

Polymers include a large number of materials, but the only one, other than polypropylene, that has been considered for use in the WIPP permanent markers is polyvinyl chloride (PVC). PVC is the most widely used plastic in terms of volume produced. It is used for low-cost piping (flexible and rigid), guards, ducts, tanks, fume hoods, insulative coatings, and corrosion resistant coatings applied to metals. Weak and strong acids and bases, salts, and water do not attack PVC. However, it is less resistant to some solvents and organic chemicals (ketones and chlorinated hydrocarbons). Its total overall chemical resistance is second only to polytetrafluoroethylene (PFTE), which is more expensive than PVC. PVC is a lightweight material (density 1.5 g/cm^3) and has relatively high thermal expansion (17.0 $K^{-1}*10^6$). It also has low bending (tensile) strength, 96.5 Mpa or about 14000 psi (Collins and Hirschfeld, 2000a; 2000b). However, PVC has low cost and can be readily formed to produce nearly any desired size, shape and inscription, making it attractive for the small subsurface markers.

To improve material properties, composites of PVC and other materials such as fiberglass can be produced. These composites are stronger and lower cost than plain PVC. Fillers can be added to PVC to improve ultraviolet light resistance and increase hardness and impact resistance. Calcined clays and water-ground and precipitated calcium carbonates, with less than 3 µm particle size, are the most commonly used filler materials for PVC. Other fillers include silicas, mica, and talc. Clay has a greater stiffening effect on PVC than calcium carbonate, which results in greater hardness and tensile strength, and reduced elongation (Collins and Hirschfeld, 2000a; 2000b).

PVC itself does not have good ultraviolet radiation resistance. For the purpose of ultraviolet light resistance, the best UV screening pigment is carbon black. Typically, 1-3 % is sufficient for protection. UV stabilizers absorb light in the ranges damaging to plastic materials, thus screening the plastic from the effects of the sun's radiation. Nonetheless, fading and discoloration upon exposure to sunlight is difficult to predict on a long-term basis. The first sign of degradation is discoloration, leading to changes in the physical properties such as material embrittlement and loss of tensile strength (Collins and Hirschfeld, 2000a; 2000b).

4.6 Marker Coatings

Glazes or coatings can be used to encapsulate some markers to prevent absorption of water and/or other chemicals that initiate corrosion. Candidate coatings include vitreous enamel for the metal markers and ceramic glaze for the ceramic markers. All of these coatings have an abrasion resistance better than metals or polymers and can be made with a specific composition resistant to any particular corrosive environment present at the site. Glazes are strong in compression and weak in tension. Therefore, the coating must have a lower thermal expansion than that of the marker material so that the glaze is in compression and the marker surface is in tension. This is easily achieved in the fabrication process by proper material selection and by controlling the cooling rate after the coating has been applied to the substrate (Collins and Hirschfeld, 2000a; 2000b).

5.0 Analysis and Comparison of Materials

Findings and conclusions pertaining to materials selections for the permanent markers are provided in this section. These determinations are drawn from the information presented previously.

5.1 Rock Material

Geologic evidence and engineering experience support the use of rock for permanent markers that require durability and strength. A monument survey and other archeological support have documented the inscribability of some rock types and the durability of those inscriptions over thousands of years. Granite, as the reference design rock material of choice, is sufficiently strong and inscribable, given all the historic uses of granite in monuments and buildings, to support its selection for use in the large surface markers, the buried storage rooms, and the information center. However, there is legitimate concern about the durability of granite with respect to the process of exfoliation. Should exfoliation develop on granite, large surface markers and other applications exposed to the environment, the central purpose of the markers would be lost; i.e. the messages inscribed in the outermost layer of lettering would be lost completely as the exfoliation process progresses over time.

Basalt is also sufficiently durable and strong as well as apparently inscribable, based on archeological evidence as documented in the monument survey (John Hart and Associates, P.A., 2000a), to be considered for use in the large surface markers. However, due to the columnar and other regular jointing patterns common in basalt, it is unlikely that large slabs or monoliths of basalts can be quarried and finished for use in the permanent markers as they are presently designed. If basalt were to be used, the large surface marker design would likely have to be modified to incorporate multiple blocks as opposed to the present two-part reference design configuration. However, the abundance and close proximity of sources of basalt, as well as its very low intrinsic value, make it an attractive option among the rock types.

Well-lithified or indurated sandstone appears in several locations within reasonable hauling distance of the WIPP site. At these locations it occurs generally as caprock on mesas or other resistant topographic features. There are insufficient data on these specific sandstone formations to support more than conjecture about how readily available one or more of these sandstones might be for utilization in the WIPP permanent markers. However, the archeological evidence supports a conclusion that the sandstone is sufficiently durable and inscribable for consideration for use in the large surface markers, the buried storage rooms, the information center, and the small subsurface markers.

Both andesite and rhyolite have sustained petroglyphs in good condition for hundreds to thousands of years in environments comparable to that of the WIPP site (John Hart and Associates, P.A., 2000a). There are several locations within New Mexico from which rhyolitic welded tuff as well as andesite might be obtained. There are no known test data on the strength and hardness of these rocks, however, and additional testing would be needed. They occur in resistant outcrops with substantial natural fracturing, implying that it would be difficult to quarry and prepare large monoliths or slabs from these rock types.

Other rock types such as limestone, quartzite, and other igneous rocks not described above might be used, but there is no reason to consider them further when the aforementioned rock types appear, on all levels, to be better and more readily available for use at the WIPP site.

5.2 Concrete

The evaluation of concrete performed in this study indicates that HVFA concrete should be further evaluated and tested for use in the large surface markers, small subsurface markers, the information center, and the buried storage rooms, as well as for protection or encapsulation of the radar reflectors. Concrete can be formulated with constituents in concentrations designed specifically for each application, making concrete as a material family much more versatile than rock materials. The record of ancient uses of concrete that remain in good condition at the present, as well as the advances in concrete technology in recent years, gives reason to believe that apparent frailties, i.e. lack of durability apparent in many civil works today, are more a function of the construction expedients used and priorities set for those facilities rather than any deficiency in concrete technology.

From the information available at this time, a high fly ash content concrete can be designed to have the durability, strength, and potentially the inscribability needed for use in the WIPP permanent markers. The relatively long period of time available for testing concretes in the laboratory and in the field prior to final decision and selection of marker materials provides an ideal opportunity to try one or more high fly ash content concrete mixes.

5.3 Local Earth Materials

A variety of earth materials that occur on or close to the WIPP site are available for use in the construction of the berm, including native soils and caliche. Salt, excavated from the WIPP underground works and stockpiled on site, is not a good material for use in the berm. Its solubility and low strength make it an unreliable material to form the core of the berm, and use at shallower locations in the berm, while structurally of less consequence, nevertheless would not be feasible because of the closer proximity to the infiltrating ground water and the resulting greater risk of dissolution.

Although there are no identified sources of durable riprap rock in close proximity to WIPP, there are sources sufficiently close to be considered in later materials testing and evaluation.

The design of the berm should be based on two considerations: (1) the functional requirements of the berm as a permanent marker system component; and (2) the physical properties of the most readily available earth materials. Native soils of any type including sand, silt, clay, and caliche can be used in a variety of combinations to construct the berm in a configuration that will be structurally stable and resistant to erosion over the required performance life of the marker system (10,000 years). Specifically, the side slopes can be adjusted both in gradient and in configuration to accommodate any available materials not including salt. The berm can also be zoned to include materials with specific properties at the core and in the shell of the berm to perform the required structural functions if specific materials are required for these purposes. However, in general it would appear on first examination that any of the site soils should be usable in the construction of the berm.

5.4 Metals and Metallic Alloys

Suitable candidate metals and metallic alloys are available for use in the magnets and the radar reflectors. Both strontium ferrite and barium ferrite are suitable for making magnets, and the precedent for use of these materials is well established. However, the reference design size of the magnets cannot be achieved using any known metals; therefore, the configuration of the magnets will need to be changed in accordance with the sizes and shapes that material technology can support.

Both Inconel and several types of stainless steel appear to be suitable for use in the radar reflectors. Inconel and stainless steel also appear to be suitable for use in the small subsurface markers; however, it is likely that the cost of small subsurface markers with these or other metals would not be competitive compared to the cost of small subsurface markers made with nonmetallic materials. Both the reference design metals and the alternative metals described above have sufficient properties to meet the performance criteria of the magnets and radar reflectors, with the possible exception of longevity of magnetism. If the corrosion-resistant properties of the metal are unlikely to be adequate to protect the markers for the necessary service life, all of the candidate metals can be coated or otherwise protected against corrosion. The report of Collins and Hirschfeld (2000a) indicates that strontium ferrite is the preferred metal for construction of the magnets, and one of the stainless steels, stainless steel 304, is likely to be the material of choice for the radar reflectors because of cost considerations.

5.5 Ceramics

Ceramics technology has developed rapidly in recent years and provides a large variety of ceramic materials from which to choose for construction of one or more of the permanent markers. These materials are durable, readily inscribable in one or more ways, and sufficiently strong for use in the large surface markers, small subsurface markers, the message panels of the information center, and the buried storage room. Robocasting is an especially attractive means for creating the permanent marker messages, because the message can never be chipped, peeled, or otherwise removed from the surface because the message is cast throughout the entire ceramic structure. The use of ceramics in large structural components of the marker systems will likely be too costly for consideration; therefore, ceramics are most likely to be considered as the media for the inscriptions which would then be encased or included in concrete or other structural materials making up the mass of the marker system.

Based on the evaluations done by Collins and Hirschfeld (2000a), the ceramic materials that look most attractive for further testing and evaluation are alumina, alumina-zirconia, and robocast silicon nitride and silicon carbide. These materials are currently being produced by one or more manufacturers in the United States, and it is likely that as technology expands the manufacturing capacity will also grow and these materials will become more readily available and less costly in the future.

5.6 Polymers

Use of polymers in the WIPP permanent marker system is likely to be limited to those applications in which ultraviolet exposure and abrasion will not be major considerations in durability. Unless protected by coatings or a UV-resistant material such as carbon black, polymers such as polyvinyl chloride (PVC) are not likely to be as durable as ceramics, concrete, and rock materials when exposed to sun and wind. Therefore, if considered for use in the permanent marker system, polymers will probably be limited to the small subsurface markers, coating on magnets or radar reflectors, or perhaps panels in the buried storage rooms.

5.7 Comparison of Materials for Specific Markers

Material comparisons for specific marker systems are provided in the following subsections.

5.7.1 Large Surface Markers

For the large surface markers the material selected must be very durable, with sufficiently high strength to withstand extreme natural loading conditions over long time periods. Inscribability is an important consideration but may be offset by using a combination of inscribable materials imbedded in otherwise very strong materials. Therefore, the large surface marker design might include two or more materials rather than a single material such as rock. The materials that may be considered for the large surface markers include rock (granite, basalt, well-indurated sandstone, andesite, and rhyolite), concrete, and ceramic. Of these materials, several rock types described above are known to be durable enough to last at least 10,000 years, based on geologic and archeological evidence. Durability of high volume fly ash concrete and ceramics must be demonstrated by tests. Strength of all the rock types mentioned, as well as concrete and the ceramics, is more than adequate to satisfy the performance criteria for the large surface markers. All materials are inscribable by one or another method, with ceramics offering the most advanced and precise techniques for inscription. There is some question about whether the fine detail and small script of the reference design messages can be inscribed equally well in any of these material types.

5.7.2 Small Subsurface Markers

Any of the materials mentioned above for the large surface markers, as well as any of the metals and other ceramics and polymers discussed above, would provide adequate durability, strength, and inscribability for the small subsurface markers. However, due to the number of markers that will be fabricated, it is likely that rock and metal can be eliminated from the candidate list due to cost. Polymers are especially attractive for this application because of the ability to stamp or otherwise rapidly produce the markers at a low unit cost. However, mass production at relatively low cost might also be achieved for some ceramics.

5.7.3 Earth Berm

The berm will be constructed of earth materials. The only question is what specific soil types are present in the locations of the berm. The relative advantage of one soil type over the other is not a major issue, because with modern earthmoving, soil mixing, and compaction techniques, a large variety of soils can be used individually or in combination to create a stable earth berm; these materials should be found in the necessary quantities on or in the vicinity of the WIPP site.

5.7.4 Buried Storage Rooms

There is an obvious advantage for any material that can be prepared and cast in place to construct the base, walls, roof and panels of the buried storage rooms. Concrete is the only material that can fit this description. The difficulty and expense of quarrying, cutting to dimension, inscribing, loading, transporting, and setting in place rock slabs is so great that a variety of other design modifications can be made to allow concrete or other material to be used if it can be prepared and placed on site rather than imported. In this case, as for the large surface markers, it is possible that the ideal combination for the buried storage rooms will be either precast or cast-in-place concrete structural members with inscriptions cast into the concrete panels, or concrete panels in which ceramic message plates are imbedded. In the latter case, the most important consideration will be the chemical and thermodynamic compatibility between adjacent materials.

As the reference design for the buried storage rooms shows, there will be loads on the walls and roof that will include both compression and bending. Rock is not well suited to carrying bending loads. Therefore, if rock is used, the design of the buried storage rooms would have to be changed to include closely spaced vertical supports for the roof panel. On the other hand, concrete can be designed to include reinforcing in the form of synthetic fibers, prestressed, or otherwise formed in such a way that it can more readily accommodate bending stresses and moments.

5.7.5 Information Center

The same considerations discussed above for the buried storage rooms apply to the information center. While the information center will not have the earth loads to support that the buried structures would, there will be wind and possibly earthquake loads applied to the information center that must be resisted by the structural components (walls, roof, and base slab, if any). In addition, the exterior walls and the roof of the information center must withstand environmental stresses such as weathering and erosion; therefore, durability is a more important factor for the constitutive materials of the information center than for those of the buried storage rooms. The exterior walls of the information center would be most resistant to environmental stresses if they were constructed of a material with proven long-term durability such as basalt. Basalt blocks could be quarried and cut to fit into a masonry but mortarless wall in which the individual blocks were notched or otherwise fitted tightly against each other to form a structurally stable configuration. The interior walls could also be basalt blocks, but their dimensions would have to be appropriate for both structural support for the room and space for required inscriptions. The roof of the information center could be cut from long blocks of basalt or other rock but could also be readily fabricated of precast concrete panels formed to fit into the basalt walls.

As an alternative, the information center could be constructed of either precast concrete panels or cast-in-place concrete. In either case, the concrete would be of high volume fly ash content, cast in forms, and allowed to cure over long periods of time to obtain the highest possible strength and durability.

Ceramic materials may also be used for the message panels in the information center, either placed in the concrete panels or placed separately within the rock blocks. The selection of or between these materials should be based on further evaluation of rock sources as well as long-term tests on high volume fly ash concrete.

5.7.6 Magnets

Of the two metals evaluated for use in magnets, strontium ferrite and barium ferrite, strontium ferrite appears to be the better material based on the information provided by Collins and Hirschfeld (2000a). However, the utility of using magnets as a component of the permanent marker system should be reevaluated, because the longevity of magnetism in either of these metals cannot be assured for a sufficient period to be meaningful in the design service life of the entire marker system. Rather than trying to produce an active magnetic field as an anomaly, it may be more reasonable to provide another material in some other configuration that would be a passive magnetic anomaly with one or more other survey methods.

5.7.7 Radar Reflectors

The several types of stainless steel, as well as Inconel, that have been evaluated for this application do not appear to have clear advantages one over the other. Therefore, the selection of the material will probably come down to a matter of cost unless the ability to protect one or another of these materials against subsurface environmental conditions is in serious doubt. However, all of these metals can be coated with one or more materials that would be expected to provide sufficient long-term protection against corrosion. The current apparent choice among these materials is stainless steel 304 for cost reasons.

6.0 Results and Recommendations

This review has involved the collection of existing data from a variety of sources and experts. The results of this work and the recommendations made here are interim only, because no testing or exhaustive technical evaluation has been possible within the scope of this study. The recommendations included here are directed at increasing the level of knowledge for which this study provides a foundation.

6.1 Materials Recommended for Testing

Recommendations or further materials testing are provided below by material type.

6.1.1 Rock

The use of granite as a marker material is problematic for several reasons, including cost, high intrinsic value, quarrying and transportation complexities, and the potential for exfoliation over long periods of time. Accordingly, basalt is recommended as an alternative rock warranting further investigation for use in any one or more of the permanent marker systems. Although the recommendation is to emphasize the testing of the physical properties of basalt, other rock types including well-indurated sandstone, andesite, and rhyolite may be tested subsequently, if the results of the testing on basalt indicate that basalt would not satisfy performance criteria.

The selection of the material or materials to be used in the large surface markers, the small subsurface markers, the buried storage rooms, and the information center will be based on multiple considerations, not just material characteristics. One important factor that has not yet been evaluated is the availability and cost of rock materials other than granite. Because of the concern about the long-term durability of granite with respect to its susceptibility to exfoliation, an evaluation of candidate rock materials should include basalt, at a minimum, and perhaps other rock types if considerations of cost and availability of basalt cannot be satisfactorily addressed. However, given the widespread distribution of basalt in the Southwest in proximity to the WIPP site, it is apparent that some additional data about basalt and its potential sources, as well as other rock, should be collected. These data include the following:

- The locations of basalt, indurated sandstone, andesite and rhyolite sources within a distance of 200-300 miles of the WIPP site

- Physical properties of those specific rocks, including durability, strength, and inscribability

- Ownership and accessibility of the rock sources

- Probable cost to acquire and process the rock

6.1.2 Concrete

Although significant data are available on concretes in general and also on high volume fly ash concrete in particular, additional data are needed on the chemical and thermodynamic properties of specific mixes that could be considered for use in each possible marker application. Because a large number of possible concrete mixes for the various applications could be considered, an initial screening of candidate mixes should be made to minimize the number of mixes actually tested. Nevertheless, concrete testing should be exhaustive enough to evaluate all the variables important to concrete durability including fly ash and other pozzolanic material types and concentrations, aggregate types and concentrations, as well as mixing and curing protocols.

6.1.3 Local Earth Materials

Some data are available on soils in the immediate vicinity of the WIPP site, but additional data may be needed about the soils that exist in the proposed location of the berm. Data may be needed to characterize the soil from ground surface down through the caliche layer to document the soil types, thicknesses and lateral extent to evaluate the physical properties and the volumes of the soil that would be available for berm construction.

6.1.4 Metals and Metallic Alloys

For the magnets, strontium ferrite is the preferred metal and should be further evaluated through the tests necessary to determine its durability under anticipated conditions at the WIPP site over the long term. Tests on barium ferrite should be deferred until or unless strontium ferrite proves inadequate or too costly for use in the magnets.

The metals for the radar reflectors are adequately characterized to allow selection of a preferred material, which at this time is stainless steel 304. This material should be tested first for suitability, and then tests should be performed on Inconel 625 and Monel K-500, specifically to compare the durability of these three metals under conditions that simulate the most severe environmental stresses to which they may be subjected in the permanent markers applications. Other stainless steels should not be tested unless the results for these metals show that they are not acceptable.

6.1.5 Ceramics

Selection of ceramic materials is not as apparent at this stage as it is for some of the other material classifications. The primary candidate materials are aluminum oxide (alumina), aluminum zirconia, silicon nitride, and silicon carbide. All four of these materials should be tested through the range of tests needed to determine their inscribability and durability in the potential applications in the large surface markers, small subsurface markers, and the message panels of the buried storage rooms and the information center.

As with metals, considerable data exists on ceramics, and more is being generated at a very rapid pace as the technology expands. However, the application of one or more ceramic materials to the WIPP permanent markers depends on satisfying performance criteria that are in many ways different from performance criteria for other applications of ceramics. Therefore, some additional data are needed that would be specific to applications at WIPP. In particular, additional data are needed on the long-term performance characteristics of ceramics in an open environment that could include both environmental and man-made stresses. These additional data relate to weathering effects on:

- Absorption
- Hardness
- Fracture toughness
- Strength (tensile, flexural, and compression)

Weathering should be simulated by tests that measure:

- Erosion resistance
- Corrosion resistance
- Freeze-thaw response
- Thermal expansion and contraction characteristics
- UV resistance
- Effects of moisture

6.1.6 Polymers

Polymers are also, like ceramics, undergoing a rapid expansion in technology, and considerable data are available on their routine applications; therefore, no additional testing would be needed for such properties. However, in the applications anticipated at WIPP, some additional data needs would develop as a result of the need for the polymers to perform over a service life far beyond that anticipated in most polymer applications. Therefore, the same set of data needs described above for ceramics would apply to whatever polymers might be considered for use in the WIPP permanent markers.

6.2 Materials Testing Recommendations

Recommendations for materials testing are consistent with and expand upon the recommendations made previously in the testing program plan (John Hart and Associates, P.A., 1999).

6.2.1 Rock

Basalt and, if needed, other candidate rock types should be tested to determine mineralogical composition, specific gravity, absorption, sodium sulfate soundness, Schmidt hammer hardness, and Los Angeles abrasion. Standard ASTM procedures should be used. For any potential source of basalt or other rock, the source should be first delineated by a ground survey by qualified geologists and samples obtained to show a representative distribution of the rock from the source including different positions within the basalt flow or rock bed, depth within the source, and variation in visible features such as rock texture. The initial set of tests should be performed on at least 10 samples not less than 20 pounds each. These samples may be grab samples, that is, taken from surface outcrops and other exposures without the need for drilling and coring. However, if this rock is considered qualified after the first round of tests for further consideration, then drilling and coring to obtain additional rock samples and to characterize the rock source in three dimensions should be made, and the core samples should be subjected to an identical set of tests subsequently.

6.2.2 Concrete

The several high-volume fly ash concrete mixes prepared for testing should be tested for compressive strength at the end of three days, three weeks, and three months; and then, if satisfactory at three months, the samples of the mixes should be tested again at one year and three years. At the end of one year and three years, samples should be tested for compressive strength, specific gravity and absorption, sodium sulfate soundness, Schmidt hammer hardness, and Los Angeles abrasion. At the end of three years, samples successful thus far should be tested for all the properties tested at one year and for abrasion resistance by sand blasting and liquid impingement erosion. All mixes, regardless of their test success at 90 days, should be examined petrographically for texture and mineral composition, pore space, and other microscopic characteristics or impurities.

6.2.3 Local Earth Materials

Local earth materials should be tested for grain size distribution, Atterberg limits (plasticity indices), alkali and carbonate content by wet chemistry methods, Standard Proctor Density, and unconfined compressive strength. Materials that are considered for riprap use should be subject to all the same tests as described above for basalt.

6.2.4 Metals and Metal Alloys

If any metals are considered for use in exposed locations, they should be tested for absorption (ASTM 20) and hardness (ASTM E 3 and ASTM E 18, and ASTM E 140). Also, potential environmental and human damages should be evaluated using erosion simulation testing to evaluate solid particle or sandblasting effects (ASTM G 76), and liquid erosion (ASTM G 73). Impacts, or vandalism, should be tested by the Charpy impact test (ASTM E 23). Corrosion tests should be performed using ASTM G 50. The metals should also be tested for tensile strength (ASTM E 8) if they are considered for any use where the marker may be subjected to bending.

6.2.5 Ceramics

For ceramics, porosity, water absorption, specific gravity, and bulk density should be determined using ASTM 20. Hardness should be tested using ASTM E 92. Fracture toughness can be tested by method ASTM E 23. For strengths, a 4-point bend test should be used in accordance with ASTM C 1161. Impact susceptibility from vandalism can be evaluated through the Charpy test, which may also be used to determine fracture toughness in accordance with ASTM E 23. Erosion susceptibility should be tested using procedures ASTM G 76 and G 73. Corrosion susceptibility should be tested by ASTM G 50. ASTM C 1026 is the method to be used for measuring resistance to freeze-thaw cycling. Ceramic materials should also be tested for their resistance to extreme thermal cycling that may be associated with extreme weather conditions or brush fires followed suddenly by hailstorms and torrential rain. There is no established test procedure for this, and one will need to be developed. Resistance to natural weathering, including UV radiation, can be tested with several procedures including ASTM G 90 and G 7.

6.2.6 Polymers

PVC, HDPE and other potential candidate polymer materials, if any, should be tested for all of the environmental exposures that could occur, regardless of whether the materials will be intentionally exposed at ground surface. This is justified by the possibility that through erosion or casual excavation, buried markers may be exposed over a long period of time. Apparent porosity, water absorption, specific gravity and bulk density can be determined using ASTM 20. Indentation hardness should be determined using ASTM D 2583. Fracture toughness may be tested using ASTM E 23. Erosion susceptibility should be tested using ASTM G 76 and G73. UV radiation is a special concern for polymer materials and should be evaluated using ASTM G 90. General weathering susceptibility should be evaluated using ASTM G 7, as well as ASTM D 4364. Accelerated outdoor tests may also be performed where sunlight is amplified in conjunction with cooling devices to prevent overheating. Nonetheless, aging studies should be performed on all the proposed polymeric materials.

6.3 Implications for Marker Configurations and Locations

The reference design describes the materials, configurations and locations for the permanent marker system. All of these are subject to change or refinement. It is apparent as a result of this study that some modifications will be needed in the configurations and possibly the locations of markers.

The reference design configuration for the large surface markers is a two-part stone obelisk that would weigh a total of approximately 125 tons and would be made of granite. Granite and most other rocks are highly brittle materials and will not sustain high tensile stresses or bending moments; consequently, the quarrying, shaping, handling and transportation of very large rock shapes, including prisms and slabs, will be difficult. These rock shapes run a high risk of cracking during the process of removing them from the ground in the quarry and placing them in their locations as markers at the WIPP site. The likelihood of these large pieces surviving this process intact is very questionable and makes the selection of any rock material for these configurations problematic. If rock material is to be used, other configurations should be considered; specifically, multi-component configurations that can be made by assembling regularly-shaped blocks that weigh less than the safe lifting capacity of cranes that might reasonably be available to do the work on an undeveloped site with soft soil conditions. This problem is equally applicable to the slabs of rock called for in the reference design for the buried storage rooms and the information center. The alternative is either to change configurations, as stated above, or to change materials. Materials that can be either cast in place or pre-cast in convenient sizes and shapes are preferable, provided that the physical properties of these materials can satisfy performance criteria. The attractiveness of high-volume fly ash concrete is apparent as a likely solution to this problem.

There is a significant problem using salt as a component of the berm. Salt is not directly related to a problem of configuration or location, because salt itself is incompatible with any configuration of the berm. To use salt in this application, very flat side slopes of the berm would be required; and even with such flat slopes, the longevity of the berm would be in question because of the solubility of salt.

The magnet dimensions described in the reference design (3ft.x 1.5ft.x 1.5ft.) are too large; it is not possible currently or with foreseeable technology enhancements to make magnets of this size (Collins and Hirschfeld, 2000a). Therefore, either the concept of magnets per se or the dimensions of magnets must be revised to match the available technology. An additional problem is the longevity of the magnets; specifically, the decay of magnetism in a relatively short period of time, 100-to-200 years. Because of these factors, the usefulness of magnets comes into question. One alternative could be a marker capable of responding as a passive electromagnetic anomaly, using a mafic rock material such as basalt placed as backfill in a distinctively detectable pattern of trenches with a higher induced electromagnetic signature than the surrounding ground. This design involves materials that are readily available and relatively inexpensive, compared to many individual magnets, and whose function will be indefinite rather than limited to a one-to-two hundred years.

If concrete or other manufactured material is used in place of rock for the construction of the buried storage rooms and the information center, the configuration of these structures may be changed to improve their constructability and structural stability. Specifically, a cylindrical shape may be more stable and less costly to construct than the rectangular prism configuration in the reference design. Because it is not likely that steel reinforcing bar will be used in the concrete design, it will be necessary to either add synthetic reinforcing fibers in the concrete or to design a configuration in which tensile stresses and bending moments will be minimized. A cylindrical configuration can accomplish this while maintaining all of the performance functions and satisfying the performance criteria of these two marker components.

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