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MINERAL SOURCES OF WATER AND THEIR INFLUENCE ON THE SAFE DISPOSAL OF RADIOACTIVE WASTES IN BEDDED SALT DEPOSITS

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MASTER

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Mineral Sources of Water and Their Influence on the Safe Disposal of Radioactive Wastes in Bedded Salt Deposits.

Susan Mary Fallis

MINERAL SOURCES OF WATER AND THEIR INFLUENCE ON THE SAFE DISPOSAL OF RADIOACTIVE WASTES IN BEDDED SALT DEPOSITS

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ABSTRACT

With the increased use of nuclear energy, there will be subsequent increases in high-level radioactive wastes such as Sr^{90}, Cs^{137}, and Pu^{239}. Several agencies have considered the safest possible means to store or dispose of wastes in geologic environments such as underground storage in salt deposits, shale beds, abandoned dry mines, and in clay and shale pits. Salt deposits have received the most favorable attention because they exist in dry environments and because of other desirable properties of halite (its plasticity, gamma-ray shielding, heat dissipation ability, low mining cost, and world wide abundance). Much work has been done on bedded salt deposits, particularly, the Hutchinson Salt Member of the Wellington Formation at Lyons, Kansas.

Salt beds heated by the decay of the radioactive wastes may release water by dehydration of hydrous minerals commonly present in evaporite sequences or water present in other forms such as fluid inclusions. More than 80 hydrous minerals are known to occur in evaporite deposits. The occurrences, total water contents (up to 63%) and dehydration temperatures (often less than 150° C) of these minerals are given. Since it is desirable to dispose of radioactive wastes in a dry environment, care must be taken that large quantities of water are not released through the heating of hydrous minerals.

Seventy-four samples from four cores taken at Lyons, Kansas were analyzed by x-ray diffraction. The minerals detected were halite, anhydrite, gypsum, polyhalite, dolomite, magnesite, quartz, feldspar, and the clay minerals illite, chlorite, kaolinite, vermiculite, smectite, mixed-layer clay, and corrensite (interstratified chlorite-vermiculite). Of these, gypsum, polyhalite and the clay minerals are all capable of releasing water when heated. Graphs relating diffracted x-ray intensities to the percent of gypsum and anhydrite present in samples composed primarily of halite and/or shale are presented.

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CHAPTER I

INTRODUCTION

Energy sources

Sources of energy have changed greatly within the United States within the past century. Wood fuel was a major source up to the 1880's after which coal dominated the energy scene by suppling over one-half of the U.S. energy needs. Utilization of oil and natural gas increased significantly in the late 1940's and at present supplies over three-quarters of our energy (Tape, Pittman, and Searl, 1964). Within the past decade the world has increased its yearly consumption of energy by 5%, and this trend is expected to continue to the year 2000.

Coal, oil, and natural gas are non-renewable resources; therefore as these sources of energy are depleted new means of power generation must be sought to satisfy our ever-expanding energy requirements. Potential sources which are high on the priority list for research and development include tidal, solar, geothermal, and nuclear energy. Tidal, solar and geothermal sources are all limited to where the plants may be geographically located. Nuclear power has been on the world scene for 30 years. As of June 30th, 1972, there were 26 nuclear reactors, and a more efficent, less costly, less polluting liquid metal fast breeder reactor or catalytic nuclear burner demonstration plant is to be built in Oak Ridge, Tennessee (Weinberg, 1972).

Radioactive wastes

With expanding development and the use of nuclear energy, the amount of radioactive wastes will also increase (Table 1). A major concern is

Table 1. Estimated radioactive wastes in the United States (Staff of Oak Ridge National Laboratory, 1970).

	LIGHT WATER REACTORS				LIQUID METAL FAST BREEDER REACTORS		
	1970	1980	1990	2000	1985	1990	2000
Accumulated radioisotopes							
Sr^{90}, megacuries	3.98	962	4340	7085	31.8	300	2465
Cs^{137}, megacuries	5.27	1280	5800	9530	78.3	740	6070
Pu^{239}, megacuries	0.00009	0.022	0.107	0.196	0.013	0.128	1.114

how to dispose of or store high and low-level radioactive wastes that are, at present, useless by-products (Weinberg, 1972; Hammond, 1972). Two radionuclides present in radioactive wastes, strontium 90 (Sr^{90}) and cesium 137 (Cs^{137}) have half-lives of 25 and 33 years, respectively. Yet these isotopes will not become harmless by decaying to stable daughter products for an estimated 1000 years because of the amount of wastes that has already been produced. Until the stable daughter product stage is reached, these isotopes are potentially dangerous to man and the environment. Plutonium 239 (Pu^{239}), a transuranium isotope, is a more serious problem for its half-life is more than 24,000 years. Therefore Sr^{90}, Cs^{137}, and Pu^{239} are radioactive wastes which require long-term management.

Presently, radioactive wastes are stored above ground in specially made vats that must be monitored for leakage. The vats have a life span of about 5 years. Each time the wastes are transferred from the decaying vats to new vats, there is a chance of spillage or contamination. Intermediate level radioactive wastes have been stored at Oak Ridge National Laboratory in pits in impervious Conasauga shale. The pits were monitored for seepage and after a year and a half, leakage of ruthenium and nitrates to the ground surface and into small streams could be detected (Hess, 1957).

Long term disposal

In 1957, the Committee on Shallow Disposal of Radioactive Wastes considered several geologic environments that could be suitable for the storage of radioactive wastes. Bedded salt and salt domes were considered to be the most favorable environments for such storage. Other environments (Hess, 1957) in order of preference are:

1. Underground storage in shale.
2. Infiltration into low permeable beds with a suitable high clay content for the fixing of radioactive material in place.
3. Disposal in deep abandoned dry mines.
4. Disposal in covered clay and shale pits.

The advantages of disposal in salt deposits are:

1. Salt flows plastically at low temperatures and pressures which will help seal wastes containers and seal major and minor fractures within the salt.
2. Rock salt is approximately equal to concrete for gamma-ray shielding.
3. Salt permits the dissipation of heat from the decay of wastes.
4. The presence of salt is direct evidence for a dry environment.
5. The storage in salt incurs low development costs.
6. Salt deposits are in great abundance and the use of such deposits would not result in the total loss of a natural resource.

The major salt deposits in the United States are shown in Figure 1. This includes deposits which may be considered potential disposal sites in the United States (Figure 1), such as:

1. The Permian basin of Kansas and Oklahoma.
2. The Delaware basin of west Texas and eastern New Mexico.
3. The Michigan basin.
4. The Silurian salt of New York, Pennsylvania and Ohio.
5. The Williston basin of North Dakota and Montana.

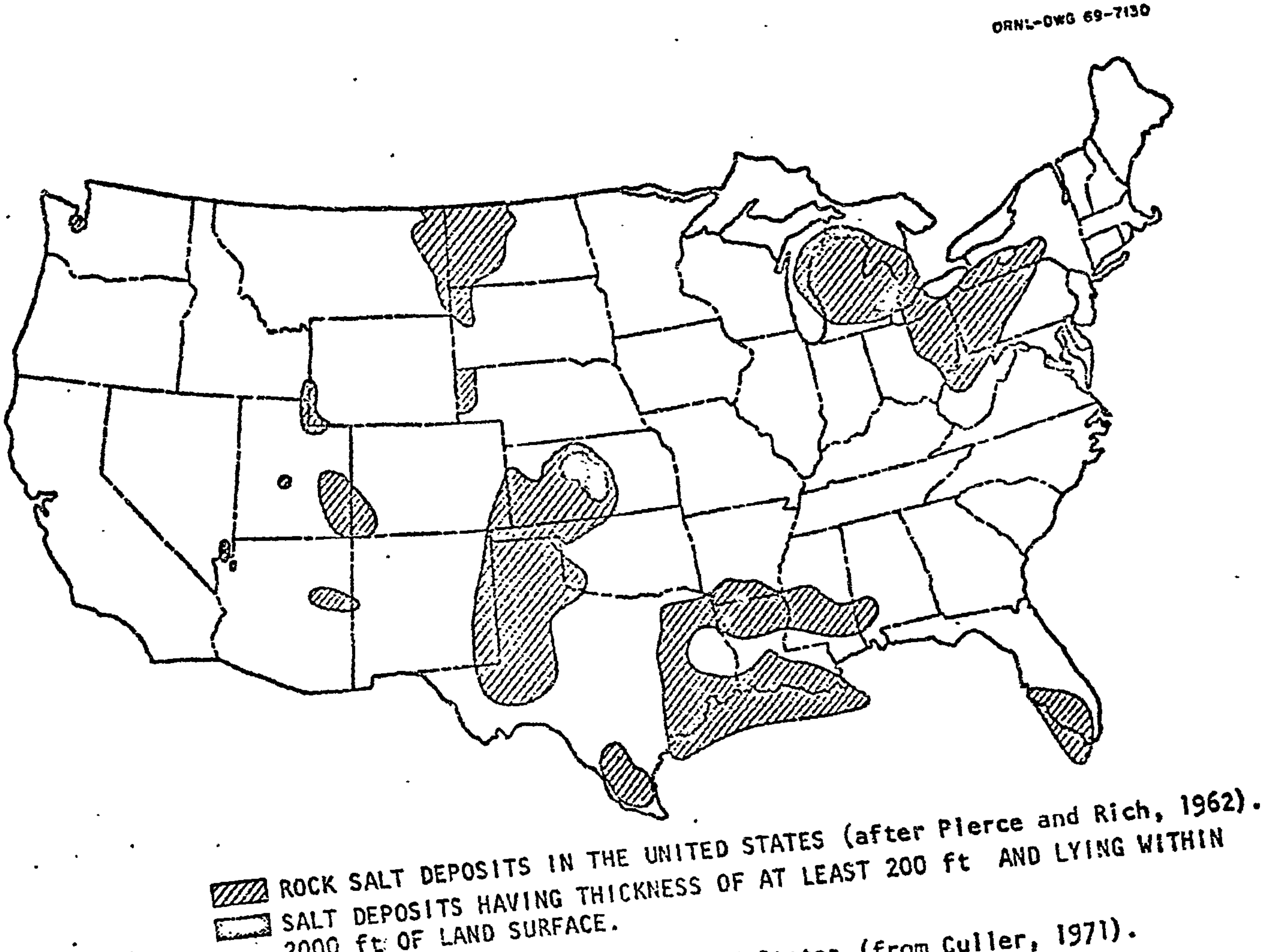

Figure 1. Rock salt deposits in the United States (from Culler, 1971).

Salt domes such as those located in the Gulf Coast area, have been considered for the storage of wastes but additional problems must be solved before domes can be used. Salt domes have formed from the upward movement of plastic salt through overlying sediments or sedimentary rocks. It would not be desirable to dispose of radioactive wastes in a salt dome unless it could be determined that there was little or no possibility of upward movement of the salt mass in the future.

Purpose of study

Disposal in bedded salt deposits has been tentatively chosen because of their physical properties. Since salt is soluble in water, the presence of salt attests that the salt is cut off from ground water. Thick, impermeable strata (shales) are commonly present between the salt and the local ground water system, protecting the salt from water in the overlying, more permeable strata.

A question arises: since it is desirable that the wastes be stored in a solid form protected from water, would water be released during the heating of the minerals in the storage area. Although some research has been conducted on salt that contains fluid inclusions (Bradshaw and others, 1968), mineral sources of water in evaporite sequences do not appear to have been considered in any detail.

Under contract with the Union Carbide Nuclear Corporation (Subcontract number 3670), a study was begun to determine how serious this problem might be. This study had the following goals:

1. To search for information concerning evaporite minerals and evaporite sequences.
2. To specifically study the mineralogy of cores taken by the

Atomic Energy Commission at Lyons, Kansas - a site that has been considered for a pilot study of radioactive waste disposal.

3. To determine the dehydration characteristics of selected samples from the Lyons cores.

This thesis includes information concerning the nature of evaporite minerals and evaporite sequences and the results of x-ray diffraction analyses of 74 samples from the Lyons cores. Petrographic descriptions of these samples and information concerning the dehydration characteristics are presented in the Final Report for Sub-contract number 3670 by Kopp and Fallis (May 31, 1973).

CHAPTER II

POTENTIAL SOURCES OF WATER IN ROCKS AND MINERALS

Water sites

One of the primary reasons for considering bedded salt deposits for the storage of radioactive wastes is that such deposits occur in dry environments. At the same time, we need to determine what will happen as the surrounding rocks are heated during the decay of wastes.

Water can be present in several forms: as ground water, connate water, fluid inclusions, ad- or absorbed water, and water or hydroxyl of crystallization. Generally, water can be driven off at relatively low temperatures (<200°C), but higher temperatures may be needed to drive off the water of crystallization or hydroxyl ions.

Since salt is soluble in water, ground water is not generally associated with deep salt deposits, but the salt may come in contact with the ground water as the deposit is brought closer to the land surface by erosion. Connate water is water trapped within sediments. This form of water may eventually be brought to the land surface by rising ground water through faults and fissures. Minor salt flats, such as the Chilean nitrate deposits (Borchert and Muir, 1964) have been formed in this manner. Salt springs were sought in the early exploration for salt domes (Billings, 1954).

Water present in brine filling negative crystal cavities or along healed fracture and cleavage surfaces, are fluid inclusions. The brines may represent redistributed connate water or trapped water of crystallization released from nearby hydrous minerals. Bradshaw and others (1968) heated 1 to 2 pound salt samples which contained numerous fluid inclusions, up to 400°C. The samples, which came from the Hutchinson salt mine at Hutchinson, Kansas, fractured violently at about 280°C. Later, In situ high temperature tests were performed in holes 10 inches (25 cm) in diameter and 10 feet (3.04 m) deep. At approximately 280°C shattering took place at the hole rock interface, and as the heat migrated into the salt (no shale was present) the shattering increased and water was released. About 190 ml of water was released from 1.8 cubic feet (.54 cubic m) of salt.

Ad- or absorbed water is water that is held in between particles or on particle surfaces. Such water may have originated as connate water or been derived from the dehydration of hydrous minerals, and generally is driven off at temperatures in the range of 60-150°C.

Water of crystallization and hydroxyls are structurally bound in a crystal lattice at the time of formation and thus become essential parts of the chemical composition of the mineral. Dehydration of hydrous minerals may be accomplished by slowly increasing the pressure if a denser, anhydrous phase exists or by heating the mineral above its decomposition temperature. In nature, these effects are illustrated by the gypsum-anhydrite-gypsum diagenetic cycle. Gypsum ($CaSO_4 \cdot 2H_2O$) deposited from sea water is subsequently buried and altered to anhydrite at depths greater than 2000 feet (609 m). Later, as the secondary anhydrite is brought close to the surface by erosion, gypsum replaces the anhydrite and becomes the dominant species in near surface strata (Murray, 1964).

Some minerals contain very high percentages of water in their crystal lattices such as mirabilite, epsomite, bischofite, inderite, natron, etc., but these minerals are not too common in bedded salt deposits. Hydrous minerals that are present in evaporite sequences are listed in Table 2 by chemical group and in order of decreasing weight percent water. Their initial breakdown temperatures based on differential thermal analysis (DTA) are also listed.

According to Culler (1971), the temperature expected in a salt formation after approximately 34 years of burial is 250°C immediately adjacent to the waste containers and the temperature decreases to 110°C at 100 feet (30 m) above and below the wastes (Figure 2). Forty hydrous minerals listed in Table 2 have a minimum DTA (differential thermal analysis) decomposition temperatures below 200°C, and therefore could lose all or at least part of their water.

Occurrences of evaporite minerals

As part of this study, a review of the literature was made to determine the nature and extent of occurrence of hydrous minerals in regions presently being considered as potential sites for wastes disposal or that might be considered at some future time. More than 100 minerals are known to occur in evaporite sequences and over 80 of these are hydrous.

Table 3 lists many of the known occurrences of hydrous minerals in evaporite sequences. The data in Table 2 and Table 3 indicates not only the large number of possible hydrous phases but also their widespread distribution, both in terms of the environment in which they were deposited, and also their wide geographic distribution. Brief descriptions of some of the more important typical environments and localities are given below.

Table 2. Hydrous minerals found in evaporite deposits and associated rocks.

Mineral[1]	Formula	Wt.% H_2O	DTA data °C[2]
Hydrated Sulfates			
Mirabilite	$Na_2SO_4 \cdot 10H_2O$	55.91	100-200
Epsomite	$MgSO_4 \cdot 7H_2O$	51.16	52-215
Hexahydrite	$MgSO_4 \cdot 6H_2O$	47.32	nda[2]
Pentahydrite	$MgSO_4 \cdot 5H_2O$	42.78	nda
Picromerite	$K_2Mg(SO_4)_2 \cdot 6H_2O$	26.84	87
Kainite	$K_4Mg_4Cl_4(SO_4)_4 \cdot 11H_2O$	21.71	85-220
Bloedite	$Na_2Mg(SO_4)_2 \cdot 4H_2O$	21.54	110-210
Gypsum	$CaSO_4 \cdot 2H_2O$	20.93	110-212
Leonite	$K_2Mg(SO_4)_2 \cdot 4H_2O$	19.65	170
Uklonskovite[3]	$Na_2Mg_2(SO_4)_2(OH)_2 \cdot 3H_2O$	18.00	350
Loweite	$Na_4Mg_2(SO_4)_4 \cdot 5H_2O$	14.65	210
Kieserite	$MgSO_4 \cdot H_2O$	13.02	60-160
Leonhardtite[4]	$MgSO_4 \cdot 4H_2O$	13.02	nda
Bassanite	$CaSO_4 \cdot \frac{1}{2}H_2O$	6.19	170-210
Polyhalite	$K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$	5.98	160-350
Syngenite	$K_2Ca(SO_4)_2 \cdot H_2O$	5.49	155-285
Goergeyite[5]	$K_2Ca_5(SO_4)_6 \cdot H_2O$	2.06	430-505
Hydrated Chlorides			
Bischofite	$MgCl_2 \cdot 6H_2O$	53.17	120-150
Tachyhydrite	$CaMg_2Cl_6 \cdot 12H_2O$	41.76	nda
Carnallite	$KMgCl_3 \cdot 6H_2O$	38.90	125-160
Hydrohalite	$NaCl \cdot 2H_2O$	38.12	nda
Trudellite	$Al_{10}Cl_{12}(OH)_{12}(SO_4)_3 \cdot 30H_2O$	37.54	nda

Table 2. Continued.

Mineral[1]	Formula	Wt.% H_2O	DTA data °C[2]
Zirklerite	$9(Fe,Mg,Ca)Cl_2 \cdot 2Al_2O_3 \cdot 3H_2O$	21.23	170-190
Douglasite	$K_2FeCl_4 \cdot 2H_2O$	11.54	nda
Erythrosiderite	$K_2FeCl_5 \cdot H_2O$	5.47	nda
<u>Hydrated Borates</u>			
Hungchaoite[6]	$MgB_4O_7 \cdot 9H_2O$	49.74	nda
Inderite	$Mg_2B_6O_{11} \cdot 15H_2O$	48.27	140-160
Borax	$Na_2B_4O_7 \cdot 10H_2O$	47.23	60-90
Kurnakovite	$Mg_2B_6O_{11} \cdot 13H_2O$	44.72	nda
Sassolite[7]	$B_2O_3 \cdot 3H_2O$	42.81	nda
Inyoite	$Ca_2B_6O_{11} \cdot 13H_2O$	42.18	110-140
Hydrochlorborite[8]	$Ca_4B_8O_{15}Cl_2 \cdot 22H_2O$	41.91	183
Carboborite[9]	$MgCa_2(CO_3)(B_2O_3(OH)_4) \cdot 8H_2O$	39.37	168-240
Inderborite	$CaMgB_6O_{11} \cdot 11H_2O$	39.36	nda
Ulexite	$NaCaB_5O_9 \cdot 8H_2O$	35.55	195-200
Macallisterite[10]	$2MgO \cdot 6B_2O \cdot 15H_2O$	35.24	-7 H_2O at 140
Pinnoite	$MgB_2O_4 \cdot 3H_2O$	32.96	310
Lueneburgite	$Mg_3(PO_4)_2B_2O(OH)_4 \cdot 6H_2O$	32.78	150
Tincalconite	$Na_2B_4O_7 \cdot 5H_2O$	30.91	155-160
Meyerhofferite	$Ca_2B_6O_{11} \cdot 7H_2O$	28.20	225
Kernite	$Na_2B_4O_7 \cdot 4H_2O$	26.32	160-185
Hydroboracite	$CaMgB_6O_{11} \cdot 6H_2O$	26.15	325
Gowerite[11]	$CaB_6O_{10} \cdot 5H_2O$	25.76	150-190
Probertite	$NaCaB_5O_9 \cdot 5H_2O$	25.63	140
Kaliborite	$KMg_2B_{11}O_{19} \cdot 9H_2O$	24.10	275

Table 2. Continued.

Mineral[1]	Formula	Wt.% H_2O	DTA data °C[2]
Sulfoborite	$Mg_6H_4(BO_3)_4(SO_4)_2\cdot 7H_2O$	23.05	nda
Teepleite	$Na_2B_2O_4\cdot 2NaCl\cdot 4H_2O$	22.45	nda
Nobleite[12]	$CaB_6O_{10}\cdot 4H_2O$	21.84	nda
Colemanite	$Ca_2B_6O_{11}\cdot 5H_2O$	21.19	350-410
Ginorite	$Ca_2B_{14}O_{23}\cdot 8H_2O$	19.38	100
Priceite	$Ca_4B_{10}O_{19}\cdot 7H_2O$	18.05	160-295
Strontioginorite[13]	$(Sr,Ca)_2B_{14}O_{23}\cdot 8H_2O$	15.67	nda
Tunellite[14]	$SrB_6O_9(OH)_2\cdot 3H_2O$	14.04	nda
Preobrazhenskite[15]	$Mg_8B_{10}O_{13}\cdot 5H_2O$	12.10	600
Strontioborite[16]	$4(Sr,Ca)O\cdot 2MgO\cdot 12B_2O_3\cdot 9H_2O$	11.60	nda
Howlite	$Ca_2SiB_5O_9(OH)$	11.51	530
p-Veatchite	$SrB_6O_{10}\cdot 2H_2O$	9.37	nda
Braitschite[17]	$7(Ca,Na_2)O\cdot RE_2O_3\cdot 11B_2O_3\cdot 7H_2O$	7.60	nda
Bakerite	$Ca_4B_4(BO_4)(SiO_4)_3(OH)_3\cdot H_2O$	7.22	nda
Hilgardite[18]	$Ca_8(B_6O_{11})_3Cl_4\cdot 4H_2O$	5.73	nda
Parahilgardite[18]	$Ca_8(B_6O_{11})_3Cl_4\cdot 4H_2O$	5.73	nda
Kurgantaite	$(Sr,Ca)_2B_4O_8\cdot H_2O$	5.70	nda
Aksaite[19]	$Mg(B_3O_3(OH)_4)_2\cdot H_2O$	5.31	nda
<u>Hydrated Carbonates</u>			
Natron	$Na_2CO_3\cdot 10H_2O$	62.96	140
Gaylussite	$Na_2Ca(CO_3)_2\cdot 5H_2O$	30.41	145-175
Trona	$Na_3H(CO_3)_2\cdot 2H_2O$	19.92	170
Pirssonite	$Na_2Ca(CO_3)_2\cdot 2H_2O$	14.88	nda
Thermonatrite	$Na_2CO_3\cdot H_2O$	14.52	100

Table 2. Continued.

Mineral[1]	Formula	Wt.% H_2O	DTA data °C[2]
Hydrated Nitrates			
Darapskite	$Na_3(NO_3)(SO_4)\cdot H_2O$	7.35	150
Hydrated Silicates			
Smectites[20]	$(\frac{1}{2}Ca,Na)_{0.7}(Al,Mg,Fe)_4$ $(Si,Al)_8O_{20}(OH)_4\cdot nH_2O$	23	100-215
Loughlinite[21]	$NaO_2\cdot 3MgO\cdot 6SiO_2\cdot 8H_2O$	21.16	nda
Vermiculite[20]	$(Mg,Ca)_{0.7}(Mg,Fe,Al)_6$ $(Al,Si)_8O_{20}(OH)_4\cdot 8H_2O$	21	100-155
Opal[22,23]	$SiO_2\cdot nH_2O$	20	65-300
Phillipsite[23]	$(\frac{1}{2}Ca,Na,K)_3Al_3Si_5O_{16}\cdot 6H_2O$	16.5-20	nda
Heulandite[23]	$(Ca,Na_2)Al_2Si_7O_{18}\cdot 6H_2O$	16	100-270
Corrensite[20]	Mixed layer Chlorite-Vermiculite	15	90-130
Mordenite[23]	$(Na_2,K_2,Ca)Al_2Si_{10}O_{24}\cdot 7H_2O$	14	90-100
Laumontite[23]	$CaAl_2Si_4O_{12}\cdot 4H_2O$	14	70-130
Glauconite[20]	$(K,Na,Ca)_{1.2-2.0}(Fe,Al,Mg)_4$ $(Si,Al)_8O_{20}(OH)_4\cdot nH_2O$	14	100
Analcite[23]	$NaAlSi_2O_6\cdot H_2O$	8	300-480

1. All data is taken from Dana's System of Mineralogy, 7th edition, volume II, Palache, C., Berman, H., and Frondel, C., editors, (1951), unless stated otherwise.

2. Lowest reported decomposition temperature from Scifax Differential Thermal Analysis Data Index Cards compiled by R.C. MacKenzie (1962). nda indicates no data available.

3. Slyusareva, (1965).

4. Braitsch, (1971, p. 12).

5. Braitsch, (1971, p. 8).

6. Chun, and others (1965).

Table 2. Continued.

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7. Allen, (1957).
8. Chien, and others (1965).
9. Hsieh, and others (1965).
10. Schaller, and others (1965).
11. Erd, and others (1959).
12. Erd, and others (1961).
13. Braitsch, (1960).
14. Clark, (1964).
15. Braitsch, (1971, p. 22).
16. Braitsch, (1971, p. 23).
17. Braitsch, (1971, p. 24).
18. Found in the Choctaw salt dome of Louisiana.
19. Clark and Erd, (1963).
20. Deer, and others (1962).
21. Fakey, and others (1960).
22. Braitsch, (1971, p. 21).
23. Deer, and others (1963).

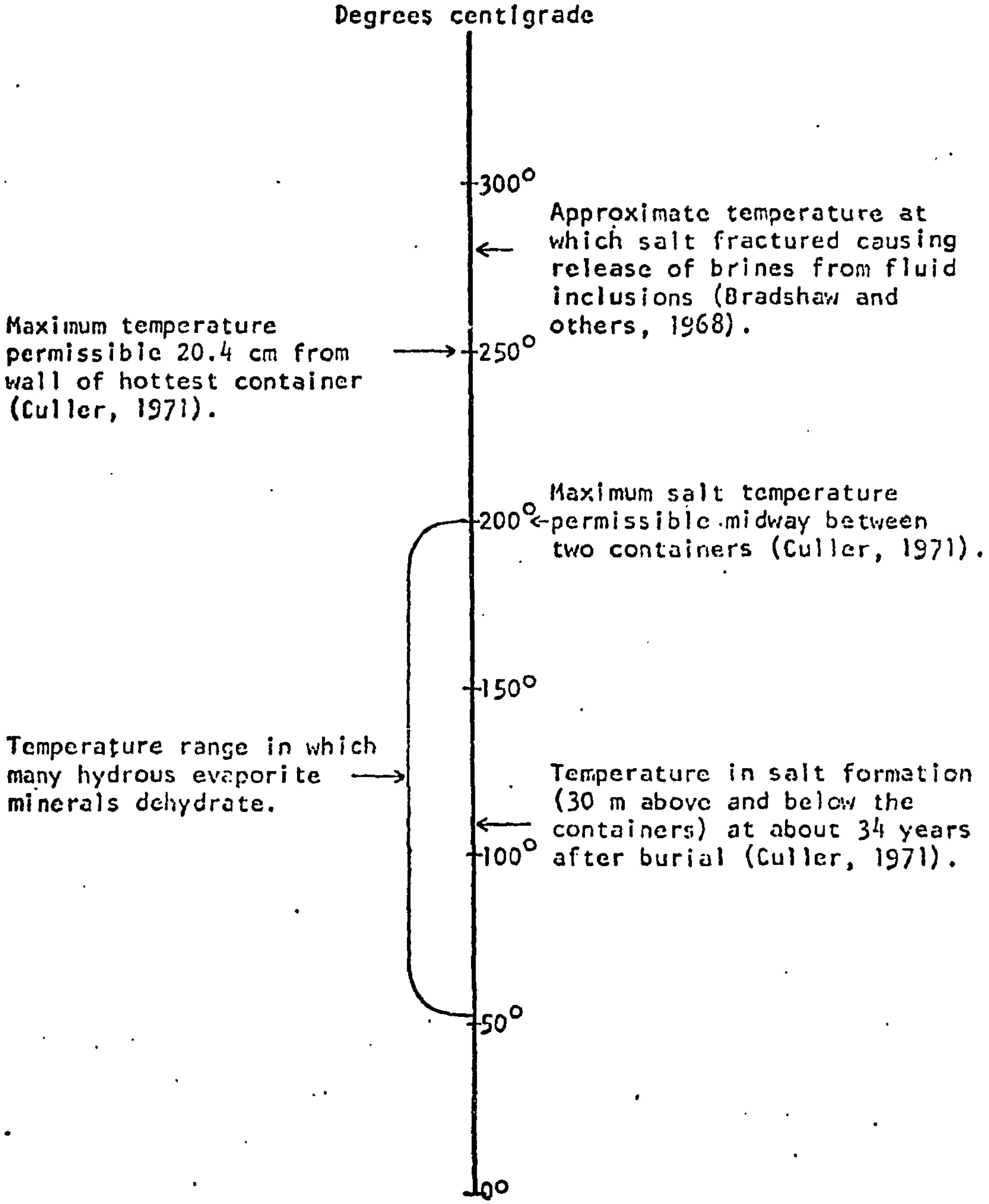

Figure 2. Estimated temperature gradient adjacent to radioactive waste containers.

Table 3. Typical occurrences of hydrous minerals in evaporite deposits and associated rocks (listed in same order as Table 2).

MINERAL[1]	BEDDED U.S.	BEDDED E./W. GERM.	BEDDED USSR	BEDDED OTHER	INDER[2] DIAPIR	SALINE LAKES	CLASTIC[3] SEDIMENTS	ALTERATION[4] PRODUCT
Mirabilite						x		
Epsomite						x		x
Hexahydrite						x		x
Pentahydrite								x
Picromerite		x		x				x
Kainite	x	x	x	x				x
Bloedite		x		x		x		x
Gypsum	x	x		x				x
Leonite	x	x						x
Uklonskovite[5]			?				x	
Loweite		x		x				
Kieserite	x	x	x	x				
Leonhardtite[6]								x
Bassanite								x
Polyhalite	x	x	x	x				
Syngenite		x		x				

Table 3. Continued.

MINERAL[1]	BEDDED U.S.	BEDDED E./W. GERM.	BEDDED USSR	BEDDED OTHER	INDER[2] DIAPIR	SALINE LAKES	CLASTIC[3] SEDIMENTS	ALTERATION[4] PRODUCT
Goergeyite[7]								
Bischofite		x	x					x
Tachyhydrite		x						x
Carnallite	x	x	x	x				
Hydrohalite						x		
Trudellite						x		
Zirklerite		x						
Douglasite		x						x
Erythrosiderite		x						x
Hungchaoite[8]						x		
Inderite					x	x		
Borax						x		
Kurnakovite					x	x		
Sassolite[9]						x		
Inyoite					x	x		
Hydrochlorborite[10]							x	

Table 3. Continued.

MINERAL[1]	BEDDED U.S.	BEDDED E./W. GERM.	BEDDED USSR	BEDDED OTHER	INDER[2] DIAPIR	SALINE LAKES	CLASTIC[3] SEDIMENTS	ALTERATION[4] PRODUCT
Carboborite[11]						x		
Inderborite					x			
Ulexite					x	x		x
Macallisterite[12]						x		
Pinnoite		x						x
Lueneburgite	x	x						
Tincalconite						x		
Meyerhofferite						x		x
Kernite						x		
Hydroboracite		x			x	x		
Gowerite[13]						x		
Probertite						x		
Kaliborite		x			x			
Sulfoborite		x						
Teepleite						x		x
Nobleite[14]						x		

Table 3. Continued.

MINERAL[1]	BEDDED U.S.	BEDDED E./W. GERM.	BEDDED USSR	BEDDED OTHER	INDER[2] DIAPIR	SALINE LAKES	CLASTIC[3] SEDIMENTS	ALTERATION[4] PRODUCT
Colemanite					x	x		
Ginorite						x	x	
Priceite						x		x
Strontioginorite[15]		x						
Tunellite[16]						x		
Preobrazhenskite[17]					x			
Strontioborite[18]				x				
Howlite						x		
ρ-Veatchite		x		x		x		
Braitschite[19]	x							
Bakerite						x		
Hilgardite[20]								
Parahilgardite[20]								
Kurgantaite					x			
Aksaite[21]						x		
Natron						x		

Table 3. Continued.

MINERAL[1]	BEDDED U.S.	BEDDED E./W. GERM.	BEDDED USSR	BEDDED OTHER	INDER[2] DIAPIR	SALINE LAKES	CLASTIC[3] SEDIMENTS	ALTERATION[4] PRODUCT
Gaylussite						x		
Trona						x		
Pirssonite						x		
Thermonatrite						x		
Darapskite						x		
Smectites[22]							x	
Loughlinite[23]							x	
Vermiculite[22]							x	
Opal[24,25]					x		x	
Phillipsite[25]							x	
Heulandite [25]							x	
Corrensite[22]							x	
Mordenite[25]							x	
Laumontite[25]							x	
Glauconite[22]							x	
Analcite[25]							x	

Table 3. Continued.

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1. All data is taken from Dana's System of Mineralogy, 7th edition, volume II, Palache, C., Berman, H., and Frondel, C., editors, unless stated otherwise.

2. Inder salt diapir of southwestern Russia.

3. Clastic sediments include minerals that may be present as impurities within the salt or as minerals within clastic rock units (shale, sandstone, etc.) which are associated with salt beds.

4. Minerals which have formed from leaching, weathering, or dehydration of another mineral.

5. Slyusareva, (1965).

6. Braitsch, (1971, p. 12).

7. Braitsch, (1971, p. 8).

8. Chun, and others (1965).

9. Allen, (1957).

10. Chien, and others (1965).

11. Hsieh, and others (1965).

12. Schaller, and others (1965).

13. Erd, and others (1959).

14. Erd, and others (1961).

15. Braitsch, (1960).

16. Clark, (1964).

17. Braitsch, (1971, p. 22).

Table 3. Continued.

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18. Braitsch, (1971, p. 23).
19. Braitsch, (1971, p. 24).
20. Found in the Choctaw salt dome of Louisiana.
21. Clark and Erd, (1963).
22. Deer, and others (1962).
23. Fakey, and others (1960).
24. Braitsch, (1971, p. 21).
25. Deer, and others (1963).

Evaporite deposits

Most major evaporite deposits were formed in large marginal seas in which evaporation in an arid climate exceeded inflow of both marine and fluvial water. Usigilio in the mid-1800's evaporated water from the Mediterranean Sea (Landes, 1960) and found that the first precipitate was calcium carbonate and hydrous calcium sulfate (gypsum) followed by sodium chloride (halite) with minor amounts of magnesium sulfate and magnesium chloride. In the controlled experiment the process was allowed to go to its final stage of precipitation of Mg-salts (and K-salts if potassium is present in the parent liquid), yet in nature the process is often interrupted by the addition of water either as an influx of sea water over a barrier and/or by the flow of fresh water into the basin from a low continental area. Detrital materials (sands and clays) are usually washed in, particularly in the former case and act as an impermeable layer preventing re-solution of the underlying salts. Evaporite deposits may be divided into two types:

1. Terrestrial or saline type where there is an inflow of fluvial water into interior basins under arid conditions.
2. Marine type which results from the periodic inflow of ocean water over a barrier to a shallow marginal sea and subsequent evaporation under arid conditions.

Saline lakes

Ancient saline lakes are not presently being considered as sites for the disposal of radioactive wastes because they do not attain great thicknesses that are thought to be necessary for disposal sites and whereas marine evaporites usually contain large amounts of halite, lake deposits are very impure. Therefore, no attempt is made to subdivide the typical mineral occurrences for saline lakes presented in Table 3 (p. 17).

Saline lakes form in interior basins such as the Salton Sea in southern California, the Great Salt Lake of Utah, and the Red Sea and Dead Sea of the Middle East. The major hydrous minerals present in saline deposits are carbonates (trona and natron) and sulfates. The playa lakes of Death Valley, California are noticeably rich in borate minerals derived from the weathering of the surrounding country rocks. Saline deposits included under this heading are found in the playas of southern California, western Nevada, and in North Africa, Kashmir, India, and southwestern USSR north of the Caspian Sea.

Marine deposits

The major bedded deposits within the United States included in Table 3 (p. 17) are located in the Permian basin of New Mexico-Texas and Kansas-Oklahoma, and the Paradox basin of the Colorado Plateau. The southeastern New Mexico-west Texas evaporites are present in three distinct formations: the Castile Formation, Salado Formation, and the uppermost Rustler Formation. The Castile Formation is composed of halite and anhydrite with thin muds and limestones (Borchert and Muir, 1964). Above the Castile lies the Salado Formation which covers a much wider area and mineralogically is more complex containing a wide range of potash salts. The Rustler Formation has undergone extensive erosion, therefore very few evaporites are present.

The Paradox member of the Hermosa Formation of Utah and Colorado contains several potash minerals associated with halite but the deposits have not been exploited to any great extent at the present time. The Permian basin of Kansas-Oklahoma will be described in a later chapter.

The bedded deposits in Germany (both East and West) are represented by the Stassfürt evaporite deposit of the North German Salt Basin which is in north-central West Germany and a small portion of western East Germany. This deposit is composed of anhydrite-halite-clastic layers in the lower and uppermost zones reflecting interruptions in the evaporation cycle by the influx of water into the basin. The middle zone consists of polyhalite, kieserite, and carnallite denoting the last stages of evaporation coupled with geothermal metamorphism upon burial (Landes, 1960, p. 49; Borchert and Muir, 1964)

Bedded deposits in the USSR are of Devonian and Permian age. The Devonian deposits are more extensive in area being found from the Baltic Sea to the Moscow basin in western Russia. The Permian evaporites extend along the western flank of the Ural Mountains in western Russia. The deposit consists of halite, gypsum, anhydrite, and potash minerals. South of the area (north of the Caspian Sea) salt domes are exploited. It is within this area that the Inder salt diapir is located which contains an abundance of rare hydrous borate minerals.

Other bedded deposits are found in northwestern Austria, the Paris basin of France and Yorkshire, England an extension of the Zechstein basin of North Germany.

CHAPTER III

MINERALOGY OF CORES FROM LYONS, KANSAS

Introduction

The Permian salt deposits of Kansas-Oklahoma are found in central Kansas and western Oklahoma and part of the Texas Panhandle. The salt has been mined for several decades, the east-central Kansas portion of the basin being exploited most. Salt deposits exist in three Middle Permian formations: the Blaine Formation (Nippewalla Group), the Stone Corral Formation (Sumner Group), and the Wellington Formation (Sumner Group). The salt associated with the Blaine Formation and the Stone Corral Formation is limited to western Kansas while the Wellington Formation is located in central Kansas and western Oklahoma (Figure 3).

A pilot radioactive waste disposal site was originally chosen in the Hutchinson salt member of the Wellington Formation at Lyons, Kansas in Rice County (Figure 4). This site was selected because it fulfilled most of the criteria for a disposal site. The Hutchinson salt member of the Wellington Formation in the east-central section of the basin is approximately 300 feet (91 m) thick and lies at a depth of about 1000 feet (304 m) of the surface. The site is also situated in an area of low seismicity. The salt is separated from three aquifer zones above by a 300 foot (91 m) impermeable shale layer thus preventing re-solution of the salt below and possible contamination of the water system above (Committee on Radioactive Waste Management, 1970).

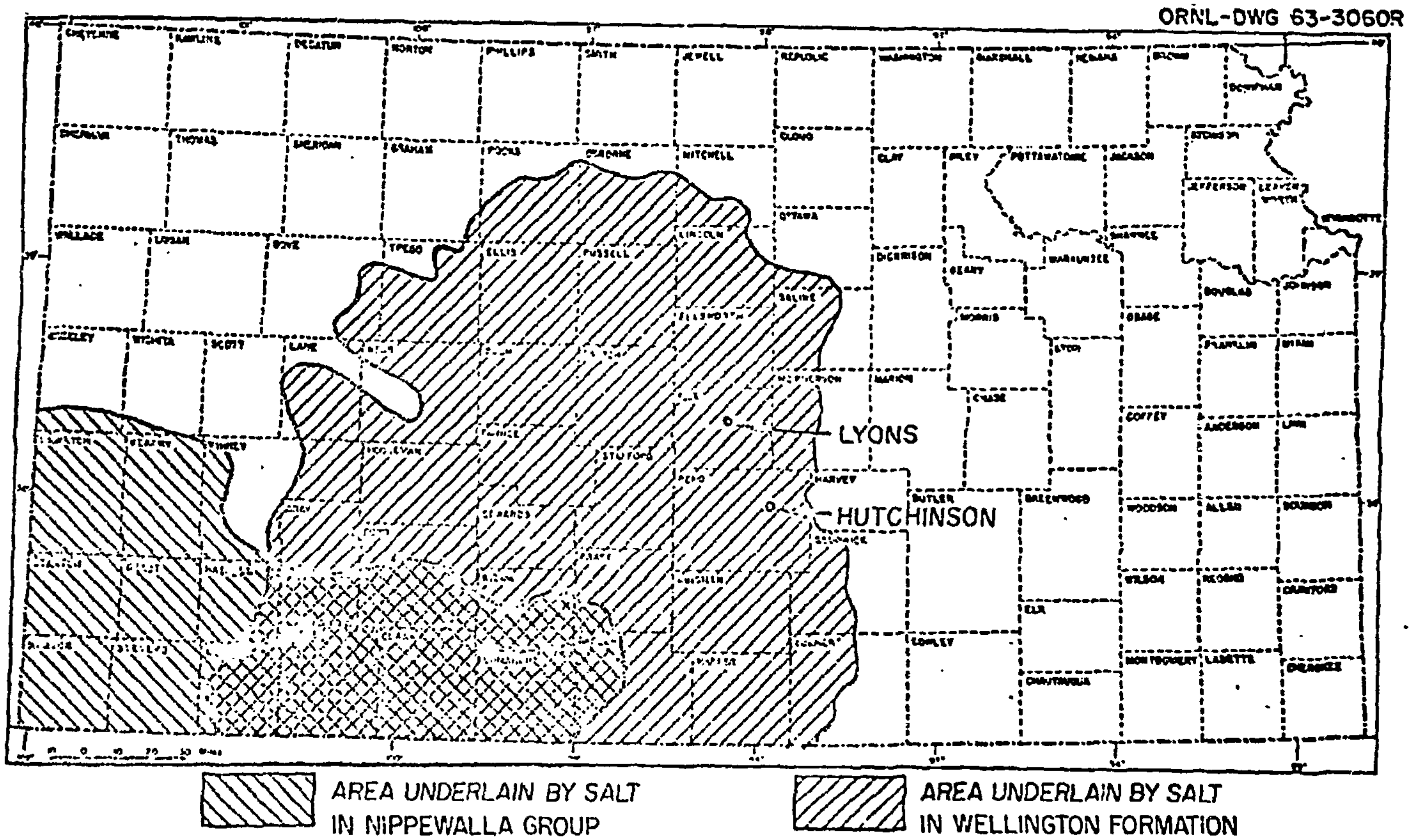

Figure 3. Location of salt-bearing formations in Kansas (from Bradshaw and McClain, 1971).

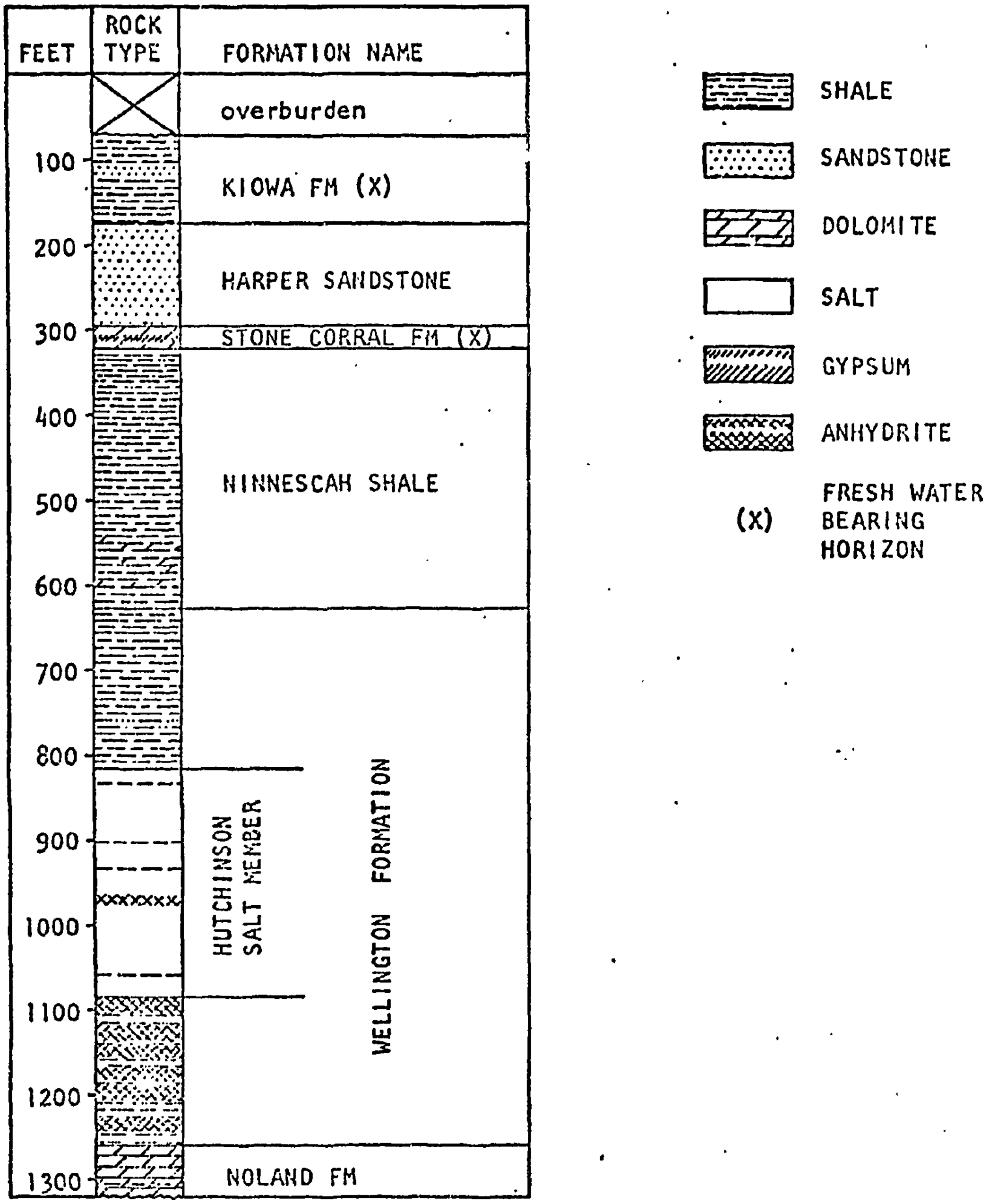

Figure 4. Generalized stratigraphic column taken from AEC #1.

Sample preparation

Samples from two drill cores were received from Lyons, Kansas in early 1972. The samples were coded by the depth at which they were taken and were prefixed by either AEC-1 (a 6 inch (15.3 cm) core) or by AEC-2 (a 4 inch (10.2 cm) core). AEC-1 and AEC-2 were drilled at NE-NE-NE-NW, Sec.26 Twp 19S, Rge 8W and 30'N of center N/2, Sec.35, Twp 19S, Rge 8W, respectively. Selection of samples from AEC-1 and 2 was based in part on the presence of gypsum, anhydrite, and red salt as stated in the drill hole log. Two other short cores, floor core #4 and roof core #21 were drilled in the floor of the experimental entry and the roof of the original mine, respectively.

The core arrived wrapped and sealed in plastic bags. Some of the samples received, particularly the fissile shale samples, were broken into several fragments. These samples were not used because of the probability of contamination by drilling fluids or by mineral growth on the rock surfaces. The samples were prepared by dry cutting two 7 cm x 4 cm x 1 cm blocks normal to layering; one for x-ray analysis and the other for petrographic analysis previously reported (Kopp and Fallis, 1973). Each block was dry sanded to obtain a clean fresh surface. The samples were broken in a jaw crusher to 4-5 mm fragments, split several times until approximately 5 grams remained. All samples were gently ground with a proccelain mortar and pestle and sieved to pass through a 325 stainless steel mesh sieve.

Each sample was pressed to a thin (2-3 mm) wafer by filling an aluminium cup (3 cm x 8 mm) approximately two-thirds full and placing the cup under 5000 psi pressure for 5 minutes. Pelletized samples were used instead of the conventional hand-packed aluminium holders because:

1. Uniformity of pressure and time results in more uniform samples.
2. Peak sharpness and intensities are increased.
3. The wafers are storable, thus the same surface may be x-rayed at a later date.

A Norelco X-ray Diffractometer was used to determine the minerals in each sample. At first samples were run at various scales to determine the general mineralogy. Later, all samples were run at 100 scale (at a time constant of 2 seconds) to amplify the smaller peaks in order to identify the less abundant minerals. Generally, samples were scanned from 4° to 50° 2θ.

Identification

To facilitate identification, the positions of three major peaks of gypsum, anhydrite, polyhalite, and halite were plotted in different colors on a mylar overlay. A second sheet was prepared with the major peak(s) for kainite, bischofite, hexahydrite, epsomite, leonite, picromerite, sylvite, thenardite, glauberite, vanhoffite, calcite, dolomite, and rinnerite. Diffractograms were prepared for halite, gypsum, anhydrite, polyhalite, keiserite, epsomite, calcite, dolomite, quartz, and feldspar. These patterns were compared with unknown patterns, all the known peaks were eliminated and the remaining peaks were identified by use of the ASTM reference files.

Mineralogy

The minerals present in AEC-1 and AEC-2 include: halite, anhydrite, gypsum, carbonates, quartz, clay minerals, and feldspar. Floor core #4 and roof core #21 are composed of halite, anhydrite and polyhalite. Tables 4 through 7 in the Appendix give the mineral description for each sample selected for analysis, corresponding rock description, and the amount by weight percent of gypsum and anhydrite.

Since gypsum and its dehydrated counterpart anhydrite are common minerals in evaporite sequences, it was desired in this study not only to note their occurrence in the section but also to estimate the amount present by comparing the intensity of major peaks of the samples with the intensity of peaks of known amounts of prepared standards. Quantitative analysis by x-ray diffraction has been discussed in several papers (Ballard, and others 1940; Gross, and others, 1944; Ballard and Schrenk, 1946; Carl, 1947). Problems that may be encountered in this method of analysis are:

1. The known standards which are prepared must be similiar in mineralogy to the sample that is to be estimated.
2. The components that make up the standard must be mixed thoroughly.
3. The mixed standards must be packed in each holder using the same amount of pressure for the same amount of time. The use of pellets eliminates the pressure/time problem.
4. The method is more applicable to samples of simple mineralogy for it is easier to simulate the mineralogy of a simple rock than a rock of complex composition.

Preparation of gypsum and anhydrite standards

As discussed before, some samples were run to determine the general mineralogy of the cores. Typical mineral associations were determined and from this data a total of 37 standards were made; 10 for gypsum/shale; 9 for anhydrite/shale; 8 for anhydrite/halite; and 10 for anhydrite/halite/shale. Three of the components which made up each standard were taken from actual core samples from the Lyons site:

gypsum	AEC-1-305.7
anhydrite	AEC-1-1198.1
shale	AEC-1-481.8

The halite from the Lyons core contained many impurities such as disseminated clay, therefore, a specimen from Redmond, Utah was purchased for the standard. After grinding and sieving the minerals to pass through a 325 mesh sieve, the proper amount of each standard was weighted on a Mettler balance (± 1mg) for a total sample of 2.5 grams. Each vial containing anhydrite was mixed for 5 minutes while the gypsum/shale was mixed for 2 minutes on a Genie Vortex. The standards were pelletized in the same manner as the core samples. The major peaks for gypsum (7.7 Å) and anhydrite (3.49 Å) were scanned, the intensities measured and converted to radiation counts.

Maximum peak height in counts per second were plotted against weight percents in four graphs for each set of standards (Figures 5-8) and the best fitting line was calculated from a linear regression program on a Series 700 Wang Programming Calculator. A confidence interval of 80% was also calculated and is represented on the graphs by two dashed lines on each side of the best fitting line. Therefore, in a sample containing gypsum and shale (see Figure 5), if the 7.7 Å gypsum peak registers 600 radiation counts, one is 80% confident that the sample contains 22% gypsum ± 2.87%. Note that the degree of accuracy decreases at the outer limits of the line (the confidence interval lines flange outward), and

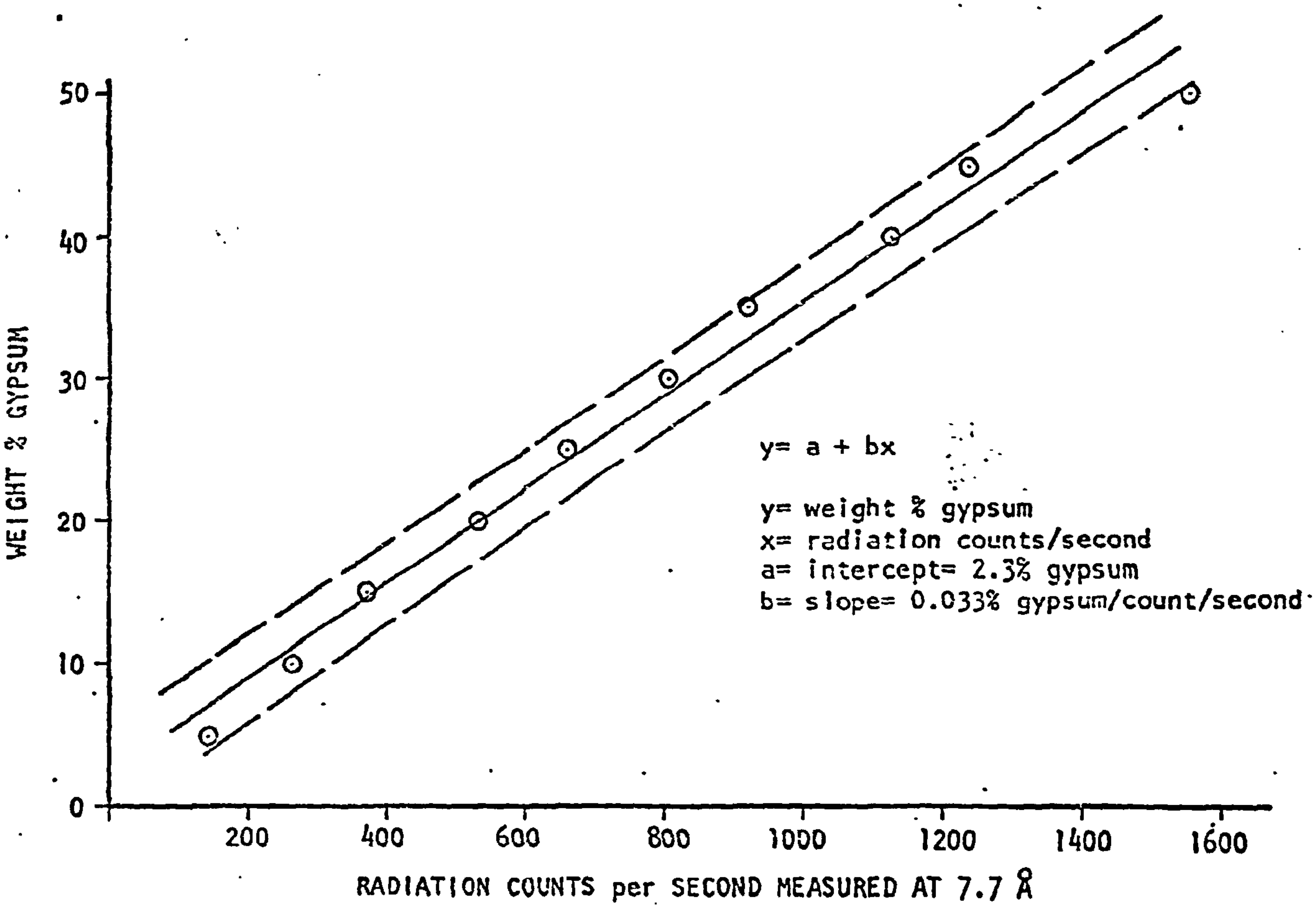

Figure 5. Gypsum/shale standards.

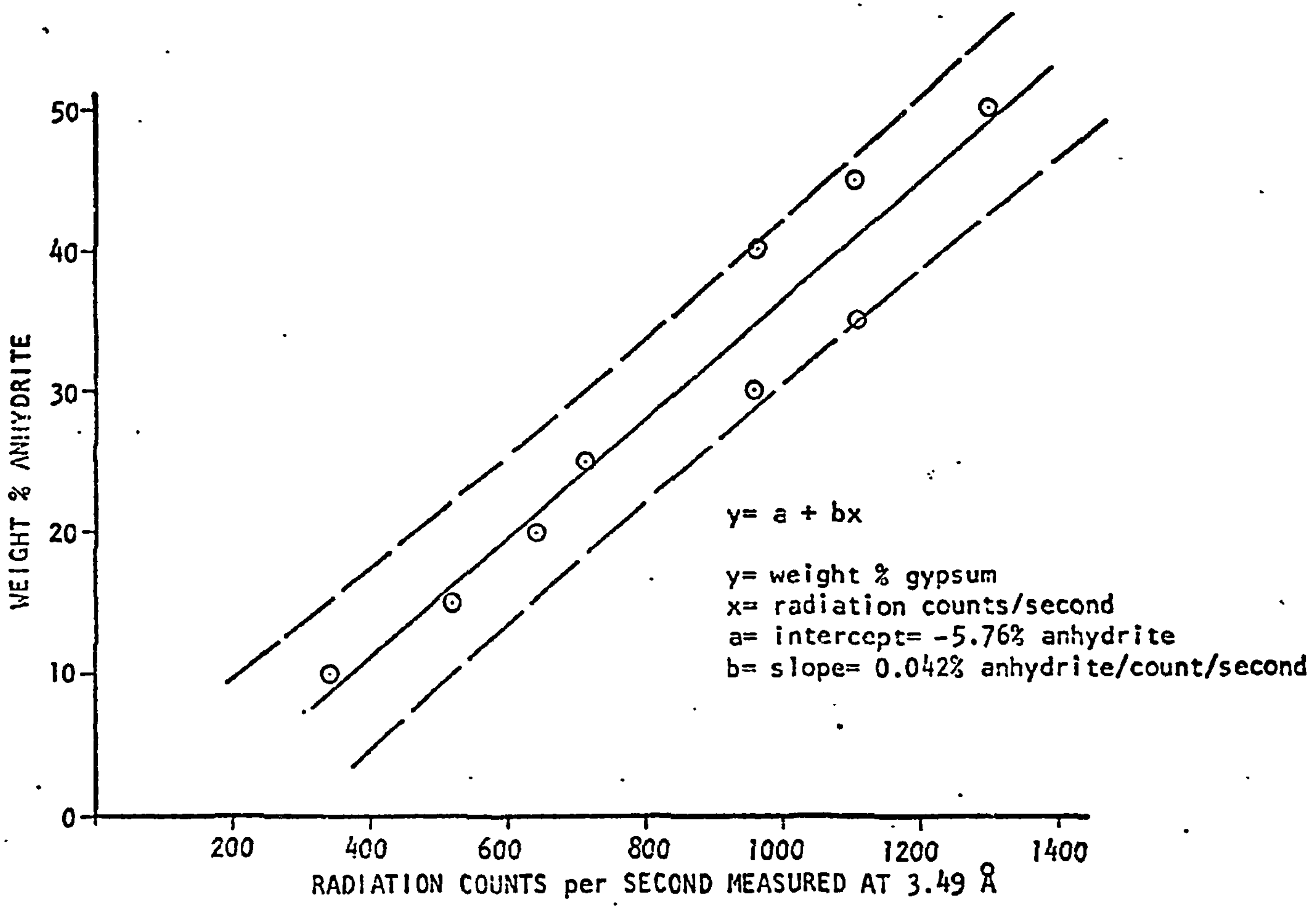

Figure 6. Anhydrite/shale standards.

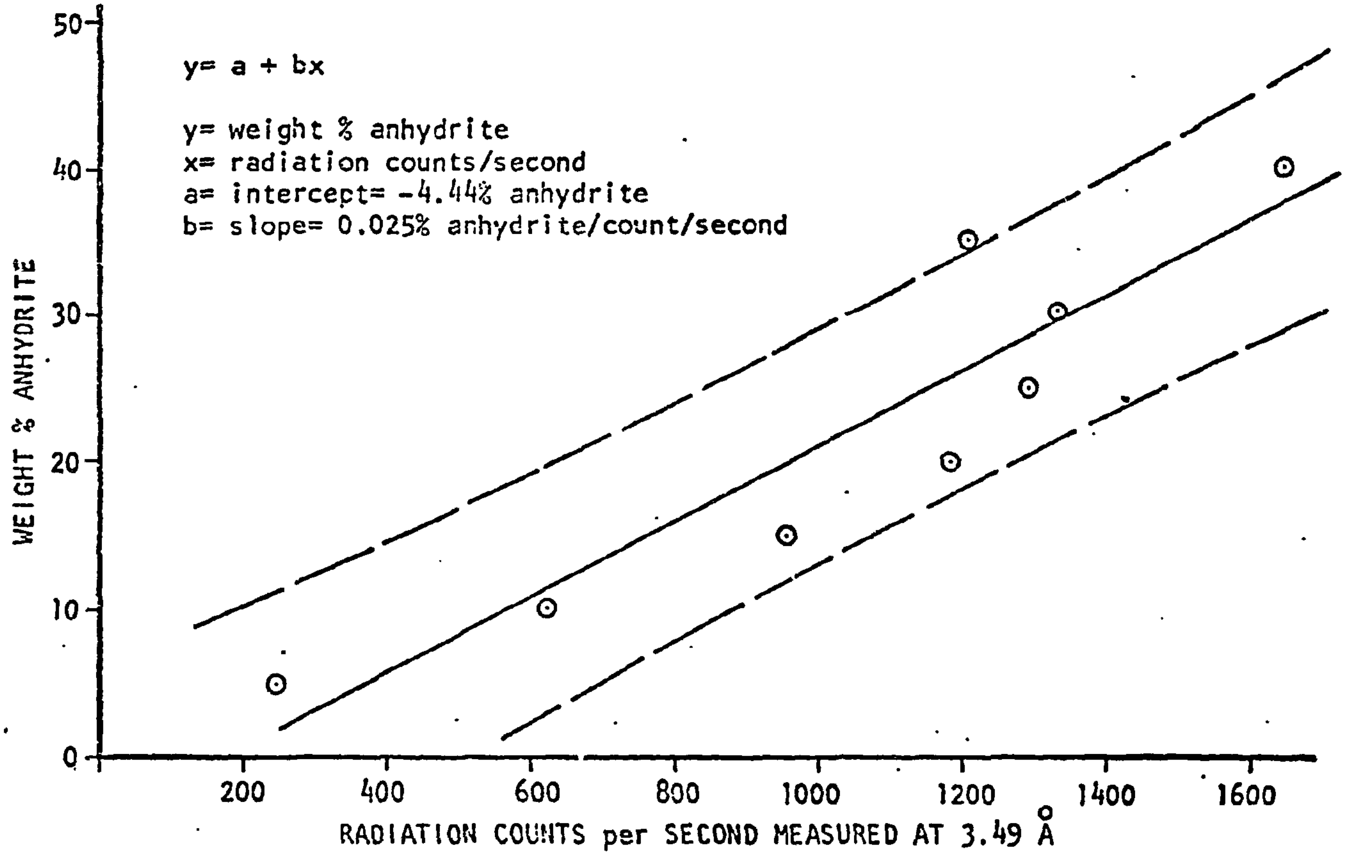

Figure 7. Anhydrite/halite standards.

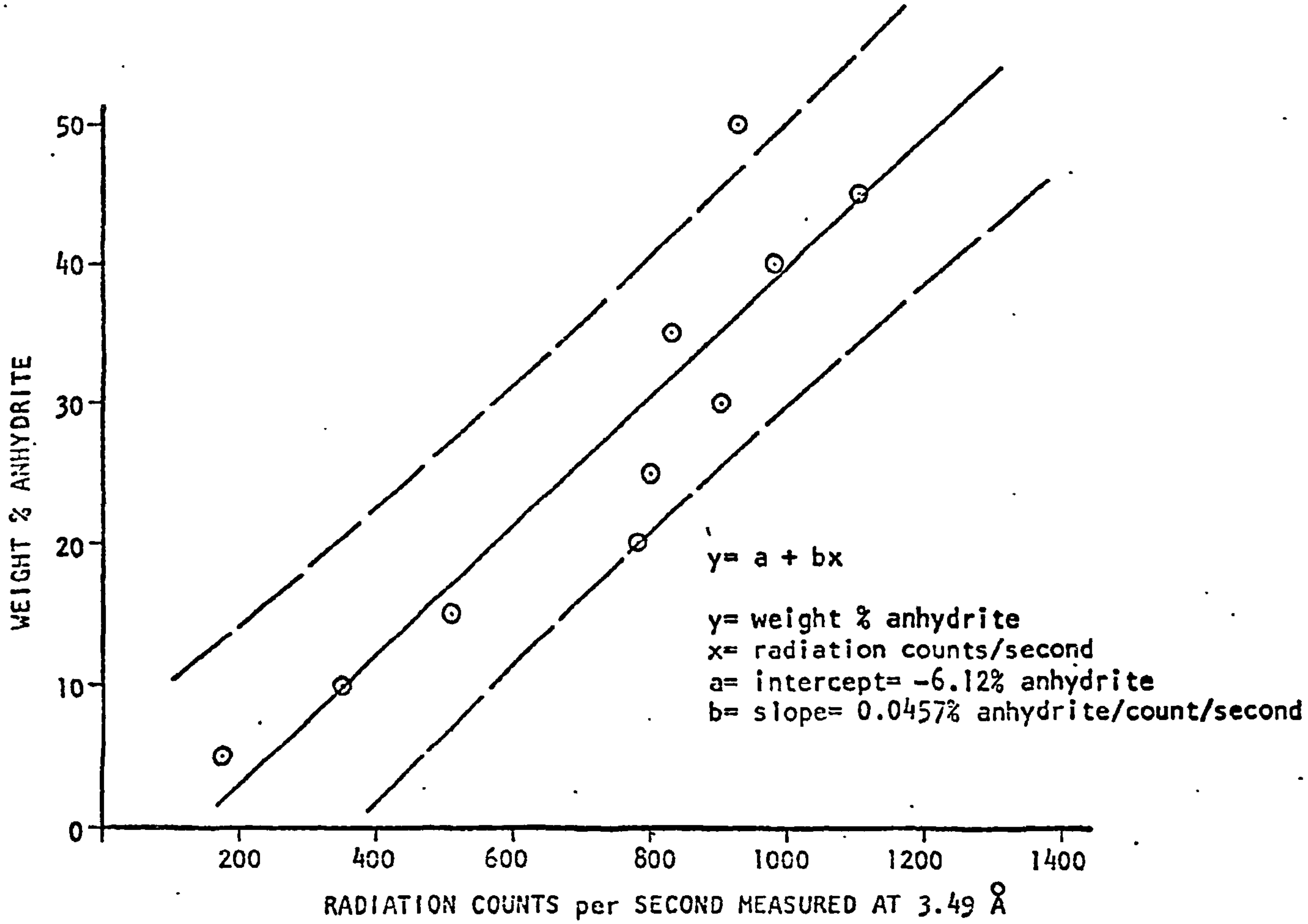

Figure 8. Anhydrite/halite/shale (5% shale constant) standards.

with the amount of scatter of the points on each graph (compare gypsum/shale with anhydrite/halite/shale which shows an accuracy of ± 9.96% at 600 radiation counts). The scatter on each graph could be reduced by x-raying different areas of each pellet 3 to 5 times and averaging the figures and also by a more thorough mixing of the standards. The graphs were used to determine the weight percentages of gypsum and anhydrite present in the core samples which are presented in the Appendix.

Halite

Halite was identified by its strong major peak at 2.87 Å and strong regularly spaced peaks at 1.99 Å, and 1.628 Å. Halite occurs in the samples examined from AEC-1 in the interval from 803.8 to 1130.4 feet and consists of two types: as moderately to coarsely crystalline bedded salt (4 mm to 15 mm) and as fracture fillings and nodules of reddish brown halite. Bedded halite is translucent to opaque, the opaqueness depending upon the amount of disseminated clay and other impurities. Fractures filled with red salt occur in the uppermost and lowermost portions of the salt section and are associated with bedded shale. At first the red salt was thought to be polyhalite but powder camera patterns of vein material proved that it was halite, the red coloration probably due to finely disseminated iron oxide particles (Jones, 1965).

Gypsum and anhydrite

Gypsum is very common in the upper portion of the section in AEC-1 from 305.7 to 618.8 feet and is present in small amounts (<1%) in samples at 1120.0, 1161.0, and 1228.0 feet. Gypsum occurs as a bed (>5.5 cm) at 305.7 feet. In other samples the gypsum is associated with clay minerals, quartz, and a trace of dolomite, and occurs as laminae, nodules and as fracture fillings (1-8 mm) in shale.

Anhydrite occurs primarily in the lower half of the core, and was first observed in sample AEC-1-729.3. In this section of the core and in the salt below, anhydrite commonly occurs as light gray laminae associated with shale laminae and beds, denoting seasonal influx of water and clastic material (Borchert and Muir, 1964, p.38; Braitsch, 1971, p. 253; Landes, 1960, p. 59). Between 1125.5 and 1215.0 feet anhydrite is the dominant mineral and is associated with shale of various shades of gray with minor amounts of dolomite. Except for a trace amount in AEC-1-1130.4, halite is not present in this portion of the section. Near the base of the core, rock anhydrite is interbedded with anhydritic shales.

Polyhalite

Polyhalite was detected in only three samples in roof core #21. The mineral occurs as moderate red brown disseminated blebs and as irregular laminae (7 mm) associated with clear to cloudy salt with less than 5% anhydrite. Other samples, from roof core #21 and floor core #4, consist of halite and anhydrite. Polyhalite is closely associated with halite making x-ray identification difficult since the major peaks of polyhalite (2.89 Å and 2.912 Å) are close to the major halite peak of 2.82 Å. Identification of polyhalite was confirmed by the presence of two closely spaced peaks near 6 Å.

Carbonates

Two carbonate minerals, magnesite and dolomite, are present in the AEC-1 samples. Magnesite was detected only in AEC-1 in samples at 771.1, 780.4, 804.6, 866.8 and 938.0 feet. In samples at 804.6 and 866.8 feet in the upper portion of the salt, magnesite is the major mineral, but as the amount of salt decreases, dolomite becomes the major carbonate mineral. The same relationship is discussed by Jones (1965) in a paper concerning the petrography of a core drilled south of Hutchinson, Kansas.

Quartz, feldspar, and clay minerals

Detrital minerals present in the cores include quartz, feldspar, and the clay minerals illite, chlorite, kaolinite, vermiculite, smectite (montmorillonite), mixed-layer clays and corrensite. Quartz is easily identified by a sharp peak at 3.33 Å. Feldspar was detected only in AEC-1-780.4, 815.9, and 1233.8 and in AEC-2-1014.0. The feldspar variety was not determined.

Since another research group was responsible for analysis of the clay mineralogy of the cores, the clays were not studied in great detail. However patterns that showed distinct major clay peaks at 14 Å, 10 Å, and 7 Å were analyzed to aid in the petrographic and static heating studies reported by Kopp and Fallis (1973).

The procedures for the preparation and identification of clay minerals was taken from Warshaw and Roy (1961) and Carroll (1970). Thirty-two powdered samples were filtered in distilled water to remove soluble salts and an elutriated slide was prepared for each sample selected. The samples were then:

1. X-rayed from 4 to 15° 2θ.
2. Heated at 375° C for 12-15 hours.
3. X-rayed from 4 to 15° 2θ.
4. Heated at 600° C for 1 hour.
5. X-rayed from 4 to 15° 2θ.

6. Peak shifts and intensity changes were compared in each set of patterns.

Illite and chlorite occur throughout the section, illite occurring in all the samples selected for clay analysis. These two clays essentially make up the disseminated clays in the salt section. Mixed-layer clay is present in AEC-1-920.8, 942.5, 1063.8, and 1077.1. Vermiculite and smectite were detected in the shales above the salt section and kaolinite occurs in scattered samples above and below the salt and within the salt in AEC-1-920.8.

Corrensite, a hydrous mixed-layer clay of regular interstratified chlorite and vermiculite which occurs in hypersaline environments was identified in AEC-1-1085.5, 1120.0, 1130.4, and 1185.5. A broad 12 Å peak was present on each pattern after being heated for one hour at 600° C which, according to Warshaw and Roy (1961), is indicative of corrensite.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Summary and conclusions

Previous studies done by the Committee on Waste Disposal of the Division of Earth Sciences (Hess, 1957) have shown that bedded salt deposits are an acceptable dry geologic environment for the disposal or storage of radioactive wastes, such as Sr^{90}, Cs^{137}, and Pu^{239}. Evaporite sequences were chosen because these deposits are essentially free of water. Yet water may be present in salt deposits in such forms as: connate water, fluid inclusions, ad- or absorbed water, and as water or hydroxyl of crystallization. Of main concern in this study is the presence of water of crystallization which is water bound to the crystal lattice. Over 80 hydrous minerals with a water content ranging from less than 5% to as much as 63% water by weight are known to exist in evaporite sequences. The salt near the radioactive cannisters is expected to attain temperatures below 250° C by the decay of radioactive wastes, yet at least half of the hydrous evaporite minerals can dehydrate at temperatures below 200° C.

Overall, the mineralogy of the Hutchinson Salt Member of the Wellington Formation appears to be rather simple as compared with other large deposits such as the Permian deposits of New Mexico-Texas, the Stassfürt salt deposit of Germany, or the California borate deposits. X-ray analysis of samples from four cores from Lyons, Kansas reveals the presence of halite, anhydrite, gypsum, polyhalite, dolomite, magnesite, quartz, feldspar, and the clay minerals illite, chlorite, kaolinite, vermiculite, smectite, mixed-layer clays, and corrensite. Of these, gypsum, polyhalite, vermiculite, smectite, mixed-layer clays and corrensite are potential sources of water.

Gypsum was detected 350 feet above the proposed site as beds and fracture fillings in shale. Trace amounts of gypsum were also found within the salt section. Polyhalite was found in the roof core #21 which pierced a known polyhalite bed approximately 16 feet above the roof (1016.0 feet) of the existing salt mine. The clay minerals vermiculite and smectite were detected in shales above the salt section and within the salt (AEC-1-1063.8). Corrensite, a hydrous clay composed of regularly interstratified chlorite-vermiculite, was detected in four samples immediately below the salt.

According to Kopp and Fallis (1973) water loss upon heating decreases with depth. The lower rocks have undergone natural dehydration due to the weight of the overlying sediments and/or the normal increase in temperature with depth. Samples in the upper portion of the section which contained gypsum showed an average weight loss of 17% when heated for 24 hours at $102 \pm 3^{\circ}$ C. Corrensite-bearing samples averaged a 5% weight loss, and typical shales lost approximately 6-7%.

Suggestions for further study

1. In the study by Kopp and Fallis (1973), the maximum amount of water that could be released from the Lyons rocks were determined at one (1) atmosphere. The effects of overburden (confining pressure) are unknown. Since the rock units are expected to collapse into the burial chamber, it would be desirable to determine the dehydration characteristics of major evaporite minerals under confining pressure.

2. Previous studies concerning the migration of brines in rock salt have been limited to experiments of heating (2.5 cm) specimens of salt and measuring the movement of the brines towards the heat source. More information is needed to determine the long range migration of such brines in a thermal gradient such as would be established at a waste repository.

3. It is possible that in spite of every precaution taken, that water will migrate into the waste containers. Research is needed to determine what will happen then. Will the water become contaminated? Will it stay put in the vicinity of the wastes or will it migrate away when the thermal gradient changes. Are there any means - physical or chemical - which can prevent either the migration of brines into the waste containers or away from them at some future time?

All things considered, the disposal of radioactive wastes in bedded salt deposits appears to be the most acceptable solution for the next several decades.

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APPENDIX

EXPLANATION OF TABLES 4,5,6, and 7

1. All footage is in feet from drill collar.
2. All colors refer to the color of the rock when it is dry dry (Goddard, 1963).
3. Capital letters indicate major minerals. Small letters indicate minor minerals except in the case of quartz and clay minerals which are always denoted by small letters.
4. The weight percent of gypsum and anhydrite is given only from 5 to 50% which are the limits of the standards.
5. ND - not detected in slabs taken for bulk analysis but seen in core samples.
6. <u>Rock descriptions</u>

an - anhydrite (ic)
arg - argillaceous
bd - bed
bk - black
bl - blue
bn - brown
cl - clay
crs - coarse
dis - disseminated
dk - dark
dol - dolomite (ic)
Fe - iron
fis - fissile
fl - filled (ing)

fn - fine
fr - fracture
grn - green
gy - gray
gyp - gypsum
hal - halite
inc - inclusions
irr - irregular
lam - laminated (ae)
lay - layered
lt - light
mas - massive
mat - material
mc - mudcrack

6. Rock descriptions continued.

med - medium

mic - micaceous

min - mineral

mod - moderate

neg - negative

nod - nodule

og - orange

ol - olive

pa - pale

pk - pink

pt - particle

r - red

sh - shale

sur - surround

v - very

w - with

wh - white

yel - yellow

7. Mineral abbreviations

c - chlorite

co - corrensite

d - dolomite

i - illite

k - kaolinite

m - magnesite

ml - mixed-layer clays

s - smectite

v - vermiculite

Table 4. Mineralogy of AEC-drill core #1 - - bulk samples

Footage	Lithological Descriptions	Gypsum	Anhydrite	Halite	Quartz	Feldspar	Carbonates	Clays	Weight % Gypsum	Weight % Anhydrite
305.7	GYPSUM, med dk gy, med xln.	X							>50	
426.5	SHALE, lt ol gy, lt bl gy, gyp bd (1.8 cm).	X			x		d	i	>50	
481.8	SHALE, pa r w gy pk and med gy lam of sh, mc.				x		d	i,c,v,ml		
530.6	SHALE, grn gy w yel gy sh lam (.5 mm), nod (3 cm) and fr (1-8 mm) fl w gyp.	X			x				>50	
542.8	SHALE, gy grn w gy ol gyp nod (3-10 mm), Fe pt (3 mm) on core surface.	X			x			i,k	43	
618.8	SHALE, dk gy, mic, fr (1-8 mm) fl w gyp.	X			x		d	i,c,ml	29	
635.0	SHALE, dk grn gy to grn gy.				x		d			
647.5	SHALE, gy bl w med gy cl lam, mic, fr (.5-4 mm) fl w gyp.	ND			x			i,c,k,s,ml		
674.5	SHALE, gy r w fr (3-4 mm) w gyp.	ND			x			i,ml		
696.4	SHALE, bn gy w lt bn gy lam (1-3 mm), irr fr (2-3 mm) fl w cl.				x		d			

Table 4. Continued.

Footage	Lithological Descriptions	Gypsum	Anhydrite	Halite	Quartz	Feldspar	Carbonates	Clays	Weight % Gypsum	Weight % Anhydrite
699.6	SHALE, dk gy w lt ol gy cl lam (.25-1 mm).				x		D	i,k,v,ml		
711.9	SHALE, dk gy w lt ol gy and lt gy cl lam (.5-3 mm).				x		D	i,k,ml		
714.9	SHALE, grn gy, irr lt gy cl lam (.5-2 mm).				x		D	i,c,ml		
729.3	SHALE, dk gy w lt ol gy cl lam (.25-2 mm).		x		x		D			<5
755.0	SHALE, med gy w lt gy lam (.5-1 mm), fis, min growth on surface.		x		x		D	i,c,ml		<5
771.1	SHALE, med dk gy w med gy to v lt gy an nod (.25-6 mm).		x		x		D,m	i,c,v,ml		7
780.4	SHALE, med dk gy w dk gy lam (.5 mm), min growth on surface.				x	x	D,m	i,c,s,ml		
784.3	SHALE, dk gy to med gy, fis, min growth on surface.		X		x		d	i,c,s,ml		16
803.8	SHALE, med lt gy w mod r bn salt in fr fl (1-6 mm), fis, min growth on surface.			x	x		d	i,c,k,ml		

Table 4. Continued.

Footage	Lithological Descriptions	Gypsum	Anhydrite	Halite	Quartz	Feldspar	Carbonates	Clays	Weight % Gypsum	Weight % Anhydrite
804.6	SHALE, grn gy w mod r bn salt fl fr (1-4 mm) and nod (1.3-4 cm), min growth on surface.		x	X	x			i,c,s,		<5
806.6	SHALE, med lt gy w br gy lam (2-4 mm) w min growth on surface, mod r bn salt fr fl (.5-3 mm).			X	x		d	i,c,v,ml		
815.9	SALT, mod og pk, gy og pk to clear, crs xln (7-15 mm) w med lt gy dis cl.		x	X	x	x		i		<5
851.1	SHALE, med dk gy w lt gy an nod and lam, mod r bn fr fl (.2 mm) and nod (1 mm), min growth on surface.		X	x	x			i,c		18
866.8	SALT, clear, v crs xln (>1.5 cm), dk gy to gy bl dis cl.		x	X			M			<5
880.6	SALT, clear w dk gy dis cl, mod r bn inc.		x	X	x					<5
886.4	SALT, gy bk due to dis cl, mod crs xln (5-8 mm), neg xls (1.5 mm).		X	X	x					37
920.8	SALT, clear w med dk gy to dk gy dis cl, mod r og hal sur nod, lt bn inc.			X	x			i,c,k,ml		

Table 4. Continued.

Footage	Lithological Descriptions	Gypsum	Anhydrite	Halite	Quartz	Feldspar	Carbonates	Clays	Weight % Gypsum	Weight % Anhydrite
938.4	SHALE, pa ol to gy grn w yel gy lam (1-3 mm), min growth on surface, mod r bn fr fl and nod of hal.		x	x	x		m	i,c,ml		<5
942.5	SALT, clear w med dk gy cl dis, crs xln, neg xls (.25-2 mm).		x	X						<5
960.0	SALT, clear w med lt gy cl lam (5 mm), mod r og hal fr fl (.5-1 mm), dk gy dis cl.		X	X	x			i,c		36
986.6	SALT, clear, crs xln, med dk gy dis cl and mod r bn hal.		X	X	x		d			28
991.0	SALT, clear, mod xln, med dk gy dis cl and mod r bn hal (.3-1 mm).		X	X						30
994.0	SALT, clear to gy og, mod to crs xln, med gy dis cl, med gy cl lam (>1 cm) w mod r bn fr fl of hal, neg xls fl w bl mat.		X	X	x					19
1021.3	SALT, clear, crs xln w med gy dis cl,		x	X	x					<5
1033.2	SALT, clear, med dk gy dis cl, mod r bn hal nod (2-10 mm).		x	X						<5

Table 4. Continued.

Footage	Lithological Descriptions	Gypsum	Anhydrite	Halite	Quartz	Feldspar	Carbonates	Clays	Weight % Gypsum	Weight % Anhydrite
1063.8	SALT, clear w med dk gy cl lam (7 mm), mod r bn hal inc, min growth on cl surface.		x	X	x			i,c,v,s,ml		<5
1073.7	SALT, clear, crs xln, med dk gy dis cl.		x	X						<5
1077.1	SALT, shaly, clear to gy og w med dk gy dis cl, mod r bn fr (.5-1.5 mm) in sh, min growth on surface.			X	x		d	i,c,ml		
1084.4	SHALE, anhydritic, med dk gy to lt gy, hal nod, min growth on surface.		X	x	x		D			28
1085.5	SHALE, dolomitic, lt ol gy w med lt gy dol, mod r bn hal fr fl (1-5 mm).		x	x	x		D	i,c,co		<5
1101.2	DOLOMITE, yel gy to v lt gy, mas, min growth on surface.		x	x	x		D			<5
1120.0	SHALE, ol gy w lt ol gy lam (.5-3 mm), min growth on surface.	x	x	x	x		d	i,c,co	tr	<5
1125.5	ANHYDRITE, med gy w med dk gy cl lam (.5-1 mm).		X				d	ml		50

Table 4. Continued.

Footage	Lithological Descriptions	Gypsum	Anhydrite	Halite	Quartz	Feldspar	Carbonates	Clays	Weight % Gypsum	Weight % Anhydrite
1130.4	SHALE, dk grn gy to grn gy w irr lam (4-8 mm) of med gy an, min growth on surface.		X	x	x			I,c,co		17
1134.5	ANHYDRITE, med gy w lt ol gy cl lam (1-3 mm),		X		x					35
1142.6	ANHYDRITE, med gy to med dk gy w med dk gy cl lam, min growth on surface.		X		x		d			>50
1152.3	ANHYDRITE, med gy w med lt gy cl lam (2-5 mm).		X		x					>50
1161.0	ANHYDRITE, med dk gy w med gy cl lam (2-4 mm), min growth on surface.	x	X		x		d		tr	>50
1185.5	SHALE, anhydritic, grn gy w bn gy cl sur med gy an nod.		X		x			I,k,co		43
1198.1	ANHYDRITE, med gy.		X		x		d			>50
1210.6	ANHYDRITE, med gy, Fe pt on core surface (.5 mm).		X							>50
1215.0	ANHYDRITE, shaly, med gy w grn gy cl nod, min growth on surface.		X		x			I,k		>50

Table 4. Continued.

Footage	Lithological Descriptions	Gypsum	Anhydrite	Halite	Quartz	Feldspar	Carbonates	Clays	Weight % Gypsum	Weight % Anhydrite
1228.0	SHALE, med dk gy, min growth on surface.		x		x		D	i,c,ml		<5
1233.8	SHALE, anhydritic, grn gy w irr med gy an nod, min growth on surface.		X		x	x	D	i,c		26
1239.9	SHALE, anhydritic, dk grn gy w med lt gy an lam (.5-5 mm), min growth on surface.		X				d	i,k		49
1249.0	ANHYDRITE, arg, med gy w grn gy sh lam (.5 mm).		X		x					>50
1260.0	SHALE, dk gy to v lt gy w wh an nod (1-2 mm), fis, min growth on surface.		x		x		D	i		<5
1293.5	SHALE, grn gy w dk gy mat fl fr (.25 mm), min growth on surface.		x		x		D			<5

Table 5. Mineralogy of AEC-drill core #2 - - bulk samples

Footage	Lithological Descriptions	Gypsum	Anhydrite	Halite	Quartz	Feldspar	Carbonates	Clays	Weight % Gypsum	Weight % Anhydrite
790.0	SALT, clear to pa og w med gy dis cl, med dk gy an nod (1 x 3 cm), neg xls.		X	X	x			i,c,ml		34
868.4	SALT, clear to pa og, grn gy to med gy irr cl nod, mod r og to mod r bn hal nod (4-5 mm), neg xls.		x	X	x			i,c,ml,co(?)		8
925.8	SALT, clear to dk gy w dk gy dis cl (1-5 mm).		X	X	x			i,c,ml		19
1014.0	SHALE, dk gy w gy grn lam, med gy an nod (1-10 mm).		X		x		D	i,c,ml		18
1092.8	DOLOMITE, shaly, v lt gy to lt gy, fis in cl lam.				x		D	i,c,ml		

Table 6. Mineralogy of AEC-floor core #4 - - bulk samples

Footage*	Lithological Descriptions	Anhydrite	Halite	Polyhalite	Weight % Anhydrite
2.0	SALT, clear w dk gy dis mat, neg xls.	X	X		18
3.4	SALT, clear w med dk gy dis mat, v lt gy irr lam of an.	x	X		8
5.0	SALT, clear w med dk gy dis mat, mod xln (8-10 mm), neg xls.	x	X		<5
6.7	SALT, clear w dk gy dis mat, neg xls.	X	X		47
10.6	SALT, clear w med dk gy dis mat, crs xln, neg xls (1 mm).	X	X		32

* Approximate footage below the floor of the experimental entry.

Table.7. Mineralogy of AEC-roof core #21 - - bulk samples

Footage*	Lithological Descriptions	Anhydrite	Halite	Polyhalite	Weight % Anhydrite
2.9	SALT, clear to gy og w med dk gy an lam (2 mm), neg xls.	X	X		39
7.5	SALT, clear to gy og w minor dis cl and lam (3 mm) of dis cl (an?).	X	X		24
13.0	SALT, clear w med dk gy dis cl (.25-1 mm), mod xln, minor blebs of mod r bn salt (2-5 mm).	x	X		<5
14.5	SALT, clear w dis and nod of mod r bn salt (2-15 mm), med dk gy dis cl, neg xls.	x	X	x	<5
16.1	SALT, clear to gy og w mod r bn salt lam (7 mm), minor med dk gy dis mat.	x	X	x	<5
16.3	SALT, clear to gy og w mod r bn dis salt in 3 cm lay, med dk gy dis mat in in 5 mm lay, neg xls.	x	X	x	<5

* Approximate footage above the roof of the original mine.

[redacted]

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